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Preface

The *9th Working Meeting on European VLBI for Geodesy and Astrometry* is highlighted by the fact that after only three years of regular VLBI observations at a rate of three to four campaigns per year, the first significant inner-European crustal motion vectors have been determined. In parallel with the NASA/Goddard Space Flight Center, several European groups have produced solutions for the six European stations confirming the northward trend of the two stations of Noto and Matera in Southern Italy. This means that the northward motion of the African plate of about 1 to 2 cm/year is in part translated to Sicily and the Southern part of the Apennine Peninsula. In contrast, the Iberian Peninsula shows relatively little motion with respect to the stable part of central Europe. On the whole, the scenario of motions seen by VLBI can be said to be in good agreement with motions derived from long-term geophysical data.

At present, the VLBI-results are still being evaluated concerning the basic assumptions of the different solutions and steps have been taken to reach a common reference standard in order to guarantee consistency and to allow meaningful comparisons. Several contributions in this volume are dealing with the definition of the global terrestrial and celestial reference frames, and, in particular, the relationship between these systems, i.e. Earth Orientation.

The definition and the maintenance of the celestial reference system (the radio source catalogue) is inherently related to the problem of source structure and its variability. This area forms one of the remaining challenges if the goal of mm-accuracy on the global scale is ever to be achieved. At the same time this field constitutes a bridge to the work of radio astronomers and their quest for trying to understand the physics behind the observed phenomena. The contributions in this volume prove that in spite of the huge difficulties real progress is being made.

The other big challenge on the way to further accuracy improvements in VLBI is represented by the tropospheric refraction, in particular in view of its strong influence on the height component. This is why we are especially grateful for the continued effort that is invested in this topic by the Onsala group, both on the modeling and the observational fronts.

Of course questions about the future of geodetic VLBI remain, in particular in the face of new techniques, such as GPS. Therefore some thoughts about new horizons for VLBI are offered in a final position paper in this volume.

As in the previous workshops, the status reports of the observing stations and the correlator center have been compiled by the relevant groups and are included in these proceedings.

The EC-Proposal for financial support of the operations of the geodetic VLBI-network (see Campbell 1992) has been granted by the end of 1992 and funds are forthcoming since January 1993. The funds obtained provide a level of assistance of about 15 kECU p.a. over three years for each of the 7 participants (Univ. Bonn, CNR Bologna, ASI Matera, CICC Madrid, OSO Onsala, Survey Office Delft, IfAG Wettzell) plus a full position of a project supervisor, who is responsible for scheduling and processing of the experiments.

This time, the Workshop has been held in the pleasant surroundings of the Ahr valley at Bad Neuenahr, some 30 km southwest of Bonn. On behalf of all participants we should like to thank the sponsoring agency IfAG, Frankfurt represented on the spot by its director, Prof. Hermann Seeger and Mr. Riedl who both shared with us the chores of local organizing.

J. Campbell

Geodesy VLBI at the Onsala Space Observatory:

Station Report, 1991–1993

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Abstract. This report describes the geodesy VLBI and related activities at the Onsala Space Observatory for the period 1991–1993. The performed and planned VLBI observations are summarized; changes and improvements in hardware and software are presented; and related measurements using the GPS satellites are briefly described.

1. VLBI Observations

Due to a major antenna upgrade (see below for details) we had two long gaps in the geodetic VLBI observations during the last three year period. The first gap was from September 10, 1991, to January 13, 1992, when the antenna drive system was changed. The second gap was from January 15, 1992, to April 6, 1992, when most of the antenna panels were replaced. Between the two gaps we carried out one IRIS-A and one Europe experiment. The number of geodetic VLBI experiments during 1991–1993 was nevertheless about normal. The main reason was the mobile VLBI campaign during the summer of 1992 with as much as eleven dedicated experiments in addition to the regular observations. In the following we will summarize the observations carried out in the different networks.

IRIS–A and its successors NEOS–A and NEOS–B

The weekly IRIS-A experiments coordinated by the Geodetic Research and Development Laboratory at NOAA in the US have had Onsala participation approximately once per month. The stations in the network have varied but most often they were: Westford, Richmond, and Mojave, in the US, and Wettzell in Germany. In total 22 IRIS-A experiments were carried out at Onsala. Starting in May, 1993, the IRIS-A experiments were replaced by NEOS-A and NEOS-B experiments. The NEOS-A observes once per week using an identical network each time which makes it impossible for stations like Onsala to participate on a monthly basis. Instead a separate network, NEOS-B, has been defined which observes at approximately one month intervals. So far Onsala has participated in three out of four NEOS-B experiments and three more are planned for the rest of this year. The stations used have been: Algonquin Park, Fairbanks, Green Bank, Matera, Onsala, and Wettzell.

The pure European network

The Onsala participation in the European network—including Noto, Matera, Medicina, Madrid, Wettzell, and Onsala—was unfortunately reduced during 1991 and 1992 due to the antenna upgrade mentioned above. Onsala participated in two experiments out of three during 1991, five out of seven in 1992, and so far two out of three this year (the one in April was not carried out due to a malfunctioning H-maser).

The Research and Development (R&D) network

Monthly observations including Onsala in the R&D network, coordinated by GSFC, NASA, started in 1993. The present R&D network consists of Fairbanks, Fort Davis (VLBA), Kokee Park, Los Alamos (VLBA), Onsala, Westford, and Wettzell. So far seven of the first eight experiments have been observed at Onsala. Again the one experiment lost was due to the H-maser failure in April, 1993.

The Polar network

The Polar experiments have been carried out twice per year. The antenna sites are: Fairbanks, Haystack, Kashima, Madrid, Medicina, and Onsala.

Mobile VLBI experiments

During the summer of 1992 Onsala participated as a base station to support the MV-2 occupations at Kirchberg, Karlsburg, Høfn, and Tromsø. Furthermore, one 24-hour experiment was made when MV-2 was located at the Onsala site, approximately 20 m from the permanent GPS tracking station. The vector estimated from the VLBI data has formal errors of 2 mm in the horizontal components and 4 mm in the vertical component [*Potash*, 1992]. The disagreements with conventional surveys and GPS measurements are 2–3 times as large.

In January, 1992, and in March, 1993, Onsala participated in IRIS-A experiments which included MV-2 at Trysil, Norway.

2. Technical Developments and Plans for the Future

Upgrade of the 20 m telescope

The first phase of the 20 m antenna upgrade included a new drive system allowing for faster slewing rates—compared to the previous 0.83°/s in both the azimuth and the elevation coordinate—and new panels of higher accuracy. The new steering system, including numerically controlled motors, resulted in slewing speeds of 2.4°/s in the azimuth coordinate and 1.0°/s in the elevation coordinate. The actual maximum speeds are significantly higher but the new values take into account the acceleration and retardation cycle. The rest of this effect is taken care of by the "setup" times in the scheduling program. Table 1 summarizes the present antenna drive system. The improvement of the rms surface accuracy from approximately 0.23 mm to 0.13 mm has little impact on the S/X band aperture efficiency ($\approx 0.5\%$ at 9 GHz).

A second phase of the antenna upgrade is still under design. This includes two new subreflectors—one smaller for high frequency radio astronomical observations and one larger for S/X-band observations—and the goal is to significantly improve the aperture efficiency of the antenna. The present design has been evaluated in detail by *Jaldehag* [1992] and *Jaldehag et al.* [1993].

TABLE 1.
Antenna Drive System Parameters for the Onsala 20 m Telescope.

Coordinate	Slewing [degrees/minute]	Setup Time [s]	Range [degrees]
Azimuth	144	20	340–740
Elevation	60	10	5–85

HEMT amplifiers

Cooled HEMT amplifiers were installed in the fall of 1991. The total system temperatures in the zenith direction and for fair weather are now approximately 70–80 K at X-band and 50–60 K at S-band. The major contributions to these temperatures are from losses and ground noise pick-up caused by the feed system and the radome. The first time this system was used was during the IRIS-A and Europe experiments in January, 1992.

PC Field System

The new Field System based on a PC (Goddard Space Flight Center standard) has recently been acquired, and will be installed during the fall of 1993 when the software for the steering of the 20 m and the 25 m (astronomy VLBI at L- and C-band only) antennas has been written.

The Onsala Water-Vapor Radiometer (WVR)

The impact of using WVR data for correction of the wet propagation delay has been studied for the experiments carried out during the period 1980–1990 [*Elgered and Davis*, 1993] (this volume).

The planned improvements described at the last working meeting [*Elgered et al.*, 1991] have been accomplished. The WVR has been operating during all except two VLBI experiments since February, 1992. The new system also allows for faster slewing and more frequent data sampling. This is a general advantage but especially it will imply improved estimates of spatial gradients in the wet delay (see, *e.g.*, *Davis et al.* [1993]). Examples of data from the new system are presented by *Jarlemark* [1993] (this volume).

An instrumental comparison was carried out together with two WVRs from ETH, Zürich, during October, 1992, at the Onsala site [*Bürki and Elgered*, 1993].

3. GPS and Other Space Geodesy Related Activities

Maintenance of "footprint" around the 20 m telescope

The continuously operating tracking station (in the CIGNET as well as the IGS networks) at the Onsala site has run during the 1991–1993 period. The earlier Rogue SNR 800 was replaced by a Turbo-Rogue receiver on April 14, 1993.

GPS observations has also been used to monitor the local "footprint" around the VLBI antenna. A summary of these measurements together with results from "conventional" surveys were presented by *Johansson* [1992]. A contribution to the measurement of the footprint has also been obtained from a series of GPS campaigns where, however, the main purpose was to search for a correlation between GPS height residuals and atmospheric water vapor variability. Preliminary results indicate that such a correlation exists over a 100 km long baseline [*Dodson et al.*, 1993].

The SWEPOS network

A GPS network, consisting of 20 stations, within Sweden has been established together with the Swedish National Land Survey. One application of this network is to study the postglacial rebound in Fennoscandia. This project is described in detail by *Johansson et al.* [1993] (this volume).

Gravimetry measurements

Several occupations by gravimeters have occurred during 1992–1993. The first visit was by the Swedish National Land Survey in November, 1992. The next observation period used the absolute gravimeter of the Finnish Geodetic Institute in March 21–23, 1993. Finally, the two absolute gravimeters from NOAA (FG5 102) and IfAG (FG5 101) occupied the site during August 7–10, 1993.

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Status Report: VLBI for Geodesy and Astrometry in the Netherlands '91-'93

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In 1992 the European VLBI community received funding for an upgrade of the European VLBI Network. The construction of a new correlator at the Joint Institute for VLBI in Europe (JIVE) and upgrading the EVN MkIII terminals to MkIV are two of the most important elements of the upgrade. NFRA in Dwingeloo will be the host institute for JIVE.

Westerbork Synthesis Radio Telescope (WSRT)

It is well-known that the lack of a S/X receiver in the Netherlands has limited the possibilities for geodetic VLBI observations.
Installation of the new Multi Frequency Front Ends (MFFE) will solve this problem. However, the MFFE-project is somewhat delayed. The prototype of the Multi Frequency Front End is now planned to be ready in 1994. By that time Westerbork will get a S/X capability which opens up opportunities for more regular participation in (European) Geodetic VLBI campaigns.

Survey Department of Rijkswaterstaat

As mentioned at the preceding Working Meetings in Madrid and Dwingeloo the work on geodetic VLBI is integrated in a broad research program on monitoring land subsidence.

In the past two years, GPS measurements have been used to improve the Netherlands Reference Frame NEREF as an extension of the EUREF GPS network. This NEREF network plays an important role in the connection of (1) the Dutch GPS/SLR site in Kootwijk and the VLBI site in Westerbork and (2) these two reference stations and the tide-gauge benchmarks on the Dutch coast.
Furthermore, in addition to the still growing second order gravity network in the Netherlands, three absolute gravity points have been established including one at Westerbork and Kootwijk.
Regular participation in geodetic VLBI campaigns with the WSRT would also strongly enhance the role of the Dutch reference station at Kootwijk, provided that an accurate geodetic tie exists between Kootwijk and Westerbork. To maintain the vertical position at Westerbork a stable underground height benchmark was placed nearby the WSRT this year.

Continuation of our work under the EC-SCIENCE programme - assistance with schedule optimisation for geodetic campaigns for height determination in particular, assistance at the WSRT and post-processing with the DEGRIAS software - will be concentrated in 1994/1995 on the possibility of participation with the WSRT in geodetic campaigns.

Madrid Summary Report

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A. Instrumentation

The most significant changes relatives to our previous report are:

1. Installation of high density heads in both MarkIII recorders. The new configuration has been routinely used after march 1993.

2. JPL has produced new operational software for the control of the upgraded Mark III terminal.

3. A version of the PC-Field system produced by the Max Plank Institut fur Radiastronomie is maintained as a backup of the JPL operational software and for special applications.

4. Presently there is a limited capability of transferring computer files between the Complex and external users. A complete Internet service will be available soon.

5. As a cooperation between the several spanish users of the MDSCC for Radio Astronomy, a new software package, RA-Tools v2, has been implemented for assisting in the performance of experiments.

6. The JPL WVR and GPS receiver installed at the MDSCC have been used continuously during this period.

B. Research projects

Our main involvement is on:

Analysis of geodetic VLBI experiments

Maintenance and upgrade of OCCAM

Ionophere and Troposphere Calibration of VLBI experiments using GPS data

Analysis of geodetic GPS experiments using GIPSY developped at JPL

Project reports will be presented at the appropriate sessions of the meeting.

MEDICINA STATION REPORT

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The 32m antenna operates since 1985 in VLBI networks for astronomical and geodetic observations. Improvements are continuously needed to enhance sensitivity and flexibility of usage, so development never stops.

- The most recent and valuable upgrading of the antenna was the installation (September 1992) of a new S,X,K band receiver which is mounted on primary focus of the antenna. The receiver is cryogenically cooled and it has dual channel polarisation in each band. All the setting operation of the receiver are remotely controlled via PC. Switching among the several possible working configuration of the receiver itself, takes just a few minutes. This receiver has a System Temperature of 55 K in the S band, 40 K in the X and 110 K in the K band, when they are measured at zenith. The efficiency are 43% (0.13 K/Jy), 48% (0.14 K/Jy) and 35% (0.1 K/Jy) respectively.

- To enhance the sensitivity, 4MHz filters were added inside the 14 MK3 VCR's, allowing double speed recording with double bandwidth (112 MHz). This shall also go with MK4 upgrade.

- A plan has been made to have the antenna able to work properly up to 43 GHz and to have the station 'agile' in changing the observing frequency. First, a 43 GHz receiver was under test through the year and there are hope it will be fully operative at the beginning of 94. Second, a new L band receiver is in progress. It will be put in the primary focus and it will replace the old 18 cm receiver, which needed a huge feed placed in secondary focus, gaining in such a way room in the telescope vertex room to permanently allocate all other receivers.

- The hardware and Venix operating system have been purchased to install the new PC Field System and replace the old HP1000 computer in the next future.

- Experience has been gained on high density head management. Along the year two new heads have been mounted on the Honeywell MK3 tape drive since the old ones worn out.

- Finally, to enhance capability observations in polarimetric field a polarimeter was designed for the 32m dish and its construction is in progress.

Noto station status report.

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1. Introduction

Since 1989 the 32 meters dish of Noto took part regularly in geodetic V.L.B.I. experiments. In fact the first geodetic V.L.B.I. experiment was done in June 1989, an IRIS experiment. Since then the Noto antenna was involved in more than 20 experiments in particular experiments for measuring the enlargement of the distance between North-American plate and Eurasian plate and, in particular in the last two years, the regional deformation in the colliding zone of African and Eurasian plates. Results from that experiments were already presented by Campbell et al. (1993), Ryan et al. 1993, and Zarroa et al. 1993. All these papers coincides on the final evaluation of the horizontal motion for the Noto station, that is about 6 mm/yr toward North, in the reference system of fixed Eurasia (Wettzell fixed, and the line Wettzell Onsala also fixed).

Unfortunately the Noto station have no Markiii DAT, but only an incomplete VLBA terminal with 4 BBC and the recorder. This configuration can be used for radioastronomy but not for geodesy. In the recent past we have used MARKIII DAT from NASA and modules for the O'Higgins stations in Antarctica, before these modules have been shipped to Antarctica. In this way the modules have been tested in several VLBI experiment before to be shipped in a remote land, and the Noto station was equipped with a full compatible VLBA terminal. A MARKIII DAT from NASA covered the beginning of 1992. From November 1992 to July 1993 we have used a MARKIII terminal on loan from NGS, using our VLBA recorder. That have permitted the antenna to participate again in VLBI geodetic experiments after a break of seven months. At the end of July 1993 the MARKIII terminal on loan from NGS was shipped to the new Norwegian station of Ny Alesund, far to the North.

The stations, from december 1992 is equipped with PC UNIX based Field System for driving the VLBA terminal and/or MARKIII terminal, or a combination of both as we did during 1993. The antenna is still driven by HP1000 computer, but it will be very soon replaced by a new PC computer, that already drive the antenna occasionally.

2. Recent activities and future plans

The station was involved in particular in EUROP experiment. This experiment now coordinated by the Bonn group, part of the DOSE program, is intended to study in detail, using the european VLBI network, the regional deformation of Eurasian plate in the colliding zone between this plate and African plate. At present the European VLBI network is made by 6 stations i.e.: Onsala, Wettzell, Madrid, Medicina, matera and Noto. But very soon, by the end of the year or, more realistically, during 1994, Russian and Ukrainian stations should be added. In this way the network will gain more strength both from the geometric and geodetic point of view. In any case the data from the present network, are the best ever collected in a VLBI geodetic experiments, and for that even the small velocity expected at the italian stations (from 4 to 6 mm/yr for Medicina, Matera and Not), are clearly measured, even with only 2 year of measurements.

The Noto station will be involved also for the future in this experiment, even if its actual back-end is not enough for VLBI geodetic observations. In fact we will have 6 BBC from September 1993, and two more will be ordered by the end of the year. In any case we will not have phase cal ground unit until the end of the next year (1994). In any case we will try to borrow few BBC from the international community, for taking part in EUROP experiment, even with an incomplete configuration.

The future plans include the installation of the new S/X receiver, recently produced by our Medicina workshop. It is the improved version of the old S/X receiver that worked at the Medicina stations for years. The receiver was totally modified in both bands and now have 100 K of temperature in both band even if the receiver is uncooled. Also the cross-talk between left

and right polarization, that affected the old Medicina receiver, has been removed. Some work must be done at the primary focus area for installing the new receiver, ant it is planned for next October. We will expect a large improvement from this new receiver, not only for its system temperature, but also because it will be mounted properly in the focus position. Moreover it is expected to see the whole antenna, also in the X band, and not only part as the present one. The HP1000 computer, as soon as the whole set of programs for driving and testing the antenna will be translated for a PC computer, will be substituted.

The station is also active in different spatial techniques, i.e. Laser Ranging and GPS. The Laser Ranging pad was occupied during August 92 by mobile Laser Ranging system. This is the second LR occupations of the station and by the end of the year we will have also an indication of the velocity of the site even with this technique. From the beginning of the next year the station will be equipped with a permanent Rogue GPS receiver, as a part of the permanent GPS italian network installed by Italian Space Agency. Moreover Noto is the reference station for the Catania tide gauge. Noto station and Catania tide gauge was connected via GPS (using also two radiometers), in the framework of an European program studying the mean sea level variations. The first goal of this project is to connect the most important tide gauge of the Mediterraneum, from Gibraltar to Crimea, including Italy and France to a reference point (with position defined by SLR or VLBI or both). The connection was made by GPS at the reference station and at tide gauge site. To improve the quality of the results, in particular in the vertical direction, also two water vapor radiometers, operating at two frequencies, have been used.

3. Data analysis

The data analysis centre is operating in Bologna using an HP9000/360 work station. During 1992 the workstation was updated to a 380, to improve the computing speed. Also the disk space has been enlarged with the new 1.2 Gb disc, the total space available is now 2.1 Gb. The whole set of databases with at least three european station was analyzed. But much work was devoted to the experiments with european stations only. Preliminary attempt to get a "global" solution for european experiments, after some work on the software, and useful suggestions from A. Nothnagel and C. Ma, produced some encouraging results. But after the installation of the new operating system 9.0, some of the programs used in global analysis are no more working. In any case the recently ordered new HP715 workstation is already arrived and will be soon installed in the new site, where the Institute will move at the end of September. With this new workstation the computing power for VLBI data reduction will have a large improvement.

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Status Report of RT-Wettzell

Richard Kilger

This report is an overview of the activities of RT-Wettzell since our last meeting in Dwingeloo, The Netherlands, June 13/14, 1993.
Regarding to our observing activity Wettzell is still a 100% geodetic observatory. Therefore we continued our geodetic observing acticivities continuously through the past 2 years.

NEOS-A (USNO)
This is still one of our most important observing activities. It is also known as POLARIS or IRIS. Through the years, starting in 1979, it has been rebuilt from time to time due to changing situations. A real hurricane destroyed the telescopes in Richmond, Florida, and Kokee, Hawai; Richmond will be off line for ever, Kokee has been restored meanwhile. A budgetary hurricane reduces the capabilities of geodetic VLBI (severe budgetary cuts for the VLBI-groups of Dr. Tom Clark, Goddard Space Flight Center, and Dr. Carter, NGS). Therefore the permanent networks NEOS-A and NEOS-B had to be combined to one net NEOS-A, which is observing once per week starting every Tuesday at 18 UT for 24 hours. Due to financial restrictions the telescope in Westford with the hihghest quantity of polar motion observations since 1979 (POLARIS, IRIS, NEOS, IRIS-Intensives) had to stop it's participation in NEOS-A and has been replaced by RT-Greenbank meanwhile. Good news regarding NEOS-A in this sad context is:
- the participation of RT-Fortalezza, Brasil,
- the homogenuos network with normally
RT-Greenbank, West Virginia, in the center of the network
and around it
RT-Fairbanks, Alaska,
RT-Kokee, Hawai,
RT-Fotalezza, Brasil,
RT-Wettzell, Germany,
The net has a significant extension in North-South and East-West. Additionally most of the distances between the telescopes are close to the radius of the earth.

NEOS-B (USNO)
This session is performed monthly and includes especially
- RT Onsala, Sweden,
- RT Matera, Italy,
- RT Algonquin, Ontario, Canada
and the NEOS-A stations in Green Bank, Fairbanks and Wettzell.

IRIS-INTENSIVE (NGS)
This session is continued unchanged. RT-Westford and RT-Wettzell perform once per day at 6 days per week a 1 hour session; 4 sources are recorded 4 times. Based on NEOS-A measurements the NGS, USA, determines Delta UT1-values.

IRIS-S (NGS)
This session is continued as well. Presently the net consists of
- RT-Westford, Massachusetts,
- RT-Santiago, Chile,
- RT-Fortalezza, Brasil,
- RT-Wettzell,
- RT-Hartebeesthoek, South Africa

R&D (NASA)
This session (RESEARCH & DEVELOPMENT) is done once per month in wide band with 720 MHz bandwidth in X-band, 125 MHz in S-band and 4 MHz in upper side band of VC's.

The net consists presently in USA:
RT-Fairbanks, Alasca,
RT-Westford, Massachusetts,
RT-Kokee, Hawai, and
2 VLBA-stations,
in Europe: RT-Onsala, Sweden, RT-Wettzell.

MOBILE CAMPAIGN WITH MV-2 (NGS+STATENS KARTVERK+IFAG)
In 1992 a moblile campaign was performed using the mobile MV-2. Measurements were done to determine exact coordinates of following sites:
TRYSIL, Norway from Feb 07 to Mar 21,
TOULOUSE, France from May 10 to May 13,
AZORES, Spain from May 29 to Jun 04,
HOHENPEISSENBERG, Bavaria from Jun 15 to Jun 19,
KIRSCHBERG, Saxonia from Jun 24 to Jun 28,
KARLSBURG, Mecklenburg-Vorpommern from Jul 04 to Jul 09,
HVFN, Iceland from Jul 20 to Jul 28,
TROMSO, Norway from Aug 12 to Aug 29.

GLOBAL (NASA)
A session with 8 stations, 4 stations represent the 4 quarters on the northern, 4 stastions the 4 quarters on the southern hemisphere. Therfore it consists of one ring of stations in the northern hemisphere and one ring of stations in the sou- thern hemishere representing the power of 2 POLAR sessions. Additionally the network has 4 strong North-South baselines, as IRIS-S has. Practically, especially in the southern hemisphere the radio telescopes are not distributed ideally. The 8 telescopes never see one single source simultaneously. High subnetting is required.
Number of 2-station observations: 63
Number of 3-station observations: 151
Number of 4-station observations: 162
Number of 5-station observations: 152
Number of 6-station observations: 1
Number of 7-station observations: 0
Number of 8-station observations: 0

EUROPE (BONN)
4 sessions per year are performed; the net consists of
- RT-Onsala, Sweden,
- RT-Madrid, Spain,
- RT-Matera, Italy,
- RT-Medicina, Italy,
- RT-Noto, Italy,
- RT-Wettzell, Germany.

Additional observing programs RT-Wettzell is joining from time to time are:
USNO: NAVEX, NAVEX-G, NAVEX-H, NAVEX-P, NAVEX-S
NGS : YELLOWKNIFE,
NASA: X-ASIA,

Regarding European VLBI we are doing 2 sessions ED3A and ED3B for astronomical investigators.

In the time since our last meeting in Dwingeloo RT-Wettzell did no major technical changes. After 35 000 hours of operation since 1983 we had to replace
- 4 DC motors at the 2 Azimuth gearings
- 2 Az gearings.

Status Report of the MPI Correlator Centre

W. Alef

Max-Planck-Institut für Radioastronomie

1. History and Future of the VLBI Correlators at the MPIfR and our Collaboration with the Geodesists

The Max-Planck Institute for Radioastronomy (MPIfR) has played a major role in European VLBI since the mid seventies. It has run both a MK2 correlator for more than a decade and is still operating a MK3 correlator which has been and will be expanded to serve the needs of both astronomers and geodesists.

Nearly from the beginning the scientists of the Geodetic Insitute of the University of Bonn (GIUB) and later also the Institute for Applied Geodesy in Frankfurt (IFAG) have used and supported the MPIfR correlators.

Let me give a short overview of the developments and highlights of the MPIfR correlators.

1977: A 3 station MK2 correlator (copy of the NRAO design) became operational.

1979: The first Geodetic experiment was correlated (University of Bonn).

1982: A 3 station MK3 correlator (exact copy of Haystack design) was installed and started routine operation.

1983: The first Geodetic MK3 experiment was correlated: MOHEF83 (University of Bonn).

1984: The Bonn geodesists invested in MPIfR MK3 correlator. In return they obtained 25 % of the total correlator time. The geodetic contribution was:

- 1 scientist for 3 years
- correlator hardware
- 1 Honeywell tape drive

1985: The 4th tape drive became operational. This increased the capacity to 6 baselines Mode B or C baselines.

1987: The first high density kit (MK3A) purchased by the geodesists was installed. The need for narrow track playback capability was driven by the geodetic community, in accordance with Haystack priorities list the geodetic observatories were equipped with MK3A first.

1988: The second high density kit purchased by the geodesists was installed.

1990: The European TDU (track density upgrade) project coordinated by MPIfR was successfully finished. All EVN stations were upgraded to MK3A as well as the remaining 3 correlator drives. Astronomical MK3 observations were no longer limited by the lack of tapes. The lack of sufficient correlator power became the new bottleneck.

1990: The new 12 crate MK3A correlator became operational with 5 MK3A tape drives. This increased the capacity to 6 baselines in Mode A and 10 baselines in Modes B or C. The Mk3A correlator designed by Haystack had been modified by MPIfR from the expensive wire-wrap technique to the cheaper multi-wire boards. The old MK3 correlator was mothballed.

1991: EC funds were used to buy a 6th tape drive which together with an existing drive was upgraded to MK4. Also from EC funds a MK4 prototype developed by Penny & Giles was delivered and integrated into the correlator. The throughput of the correlator was thus increased by about 20 to 30 %.

1991: MPIfR, IFAG and GIUB agreed to resurrect the old MK3 correlator: IFAG would buy 3 MK4 drives, Bonn Geodesists would provide HP1000/F computer plus peripherals, MPIfR would provide additional space, cooling system, and manpower. In exchange 30 % of the total correlator time would be reserved for geodesists. IFAG and MPIfR further agreed to jointly buy and run a medium size MK4 correlator.

1992: The aged MK2 correlator was dismantled to make space for the enlarged MK3/MK3A correlator. Correlator data archived on DATs routinely. Re-copying old archive tapes to DATs was started.

1993: An agreement between MPIfR, IFAG and GIUB has been signed to buy and operate a MK4 correlator. As part of this agreement IFAG has ordered a correlator from Haystack/NASA for delivery in 1997. MPIfR will provide housing, cooling, 9 MK4 tape drives, and manpower. According to the agreement MPIfR and the geodesists will pay for and run this correlator on a 50/50 basis. Thus the geodetic community will enjoy 50 % of the correlator time.

NOW: The first part of the 1991 agreement has been put into practice. The MK3A correlator is working again after extensive re-building. It was shut down for nearly 3 weeks. The MK3 correlator is in place and will be operational within 4 to 8 weeks. 3 MK4 drives are in shipment, the computer systems (2 HP1000/F + 1 HP1000/A990) are working.

In order to enable correlation with MK4 drives on the old MK3 correlator an improved MK4 speed control was developed at MPIfR. It was tested and has been installed in 2 MK4 drives a few days ago. Software for post-processing of correlator data on UNIX systems is nearly finished in Haystack. It will be installed in Bonn as soon as it is made available to us.

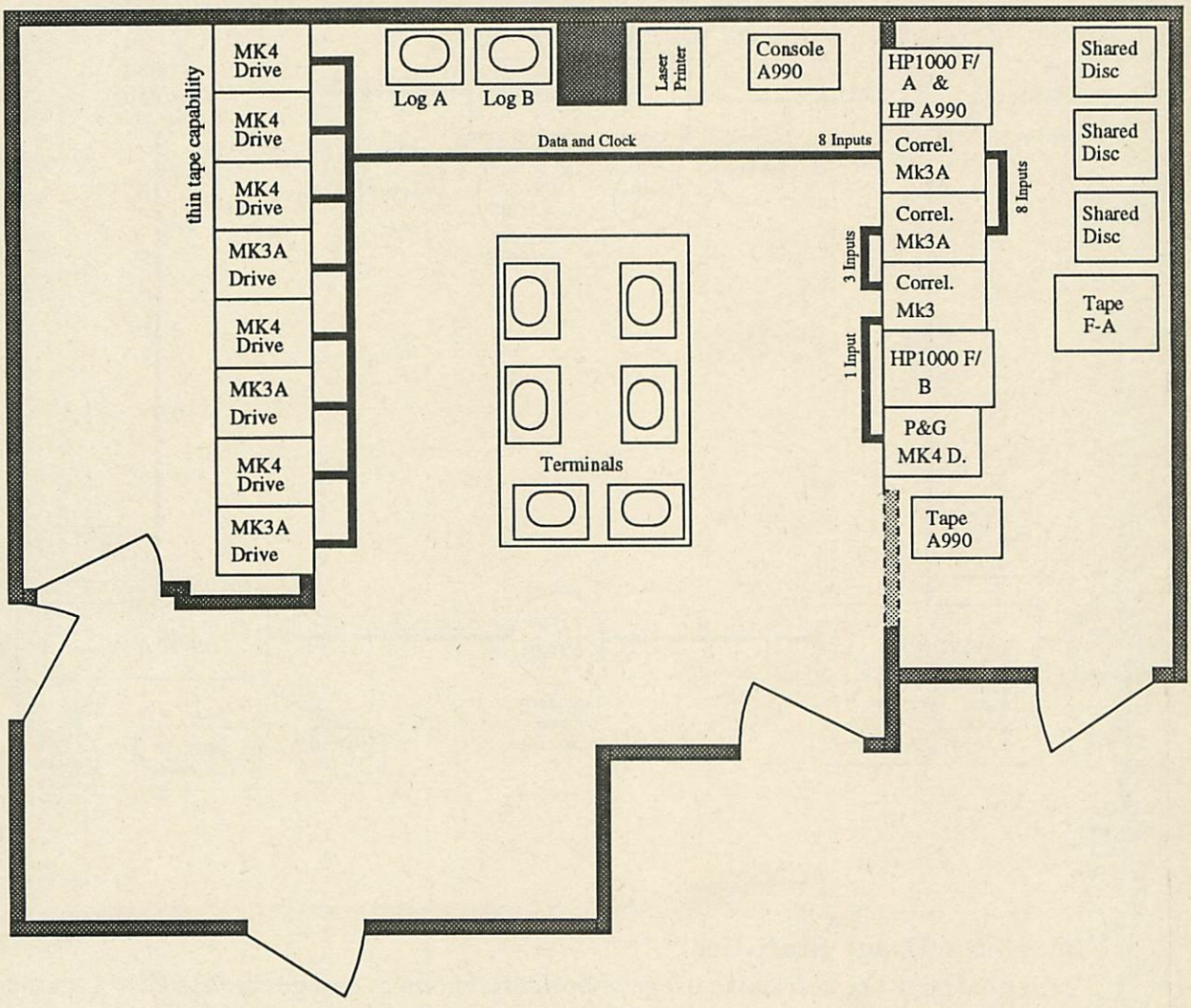
Additional support for astronomical "in absentia" correlation (1/2 scientist) has been provided by JIVE since September.

1994-?: We will continue correlating MPIfR-based as well as EVN and global observations with up to 12 stations. We expect that the astronomical load on the MPIfR correlator will decrease when the VLBA correlator starts production correlation.

1997-2000: The MK4 correlator will be delivered by Haystack. The MK3A/MK3 correlator will be phased out. While the fairly optimistic contract with NASA gives 1997 as the date of delivery, it is not too pessimistic to expect the year 2000 for a working MK4 correlator in Bonn.

2. MK3A/MK3 correlator setup

The changed setup of the correlator room can be seen in the figure below. The correlator and the computers were moved to where the Mk2 correlator used to be. The 3 new tape drives will be put next to the other 5 Metrum drives. The Penny & Giles drive was moved to the other side of the room as well.



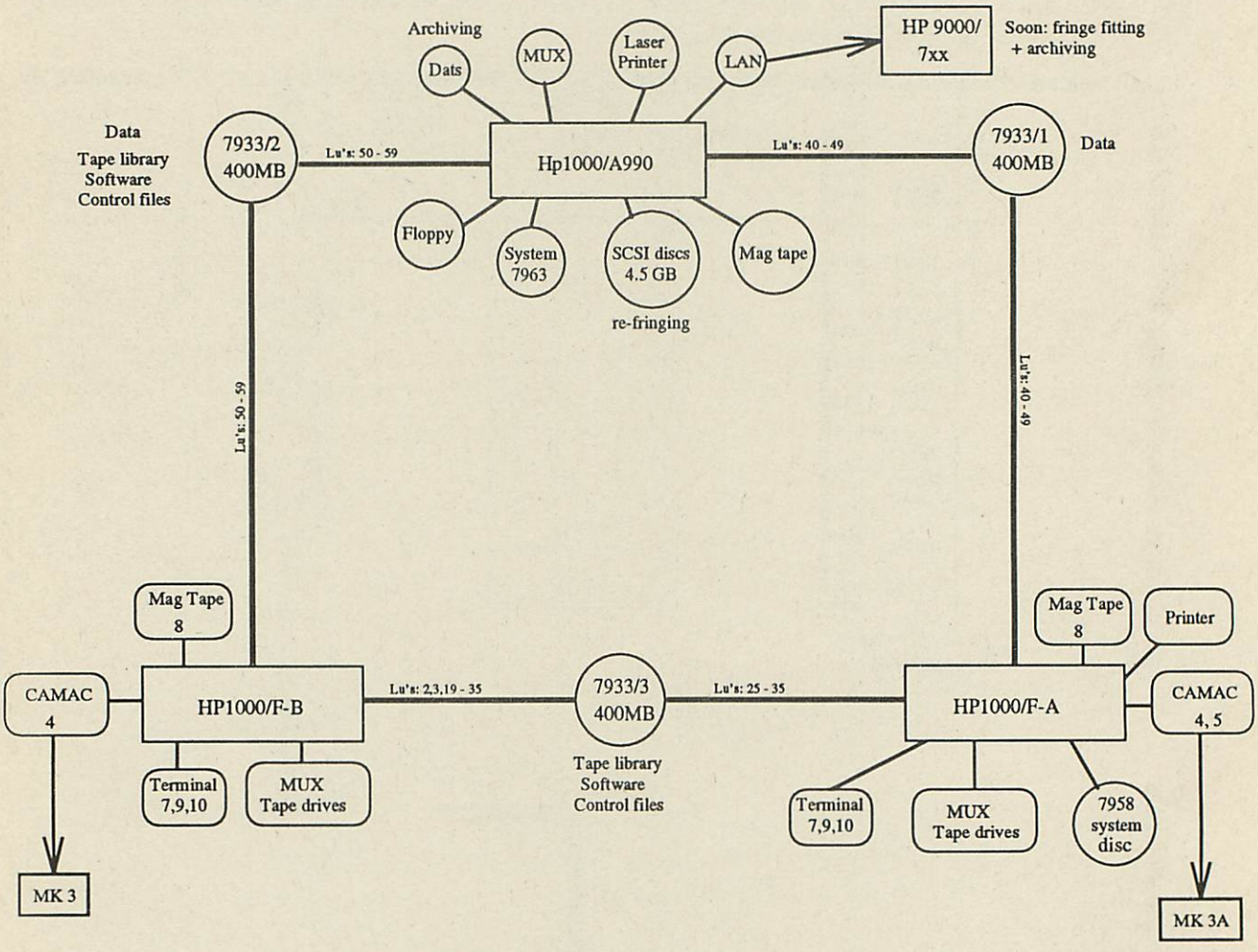
The MK3A correlator has 8 inputs for data and clock signals from 8 tape drives. The old Mk3 correlator has only 4 inputs. 3 tape drives will be connected from the MK3A

through to the MK3 correlator. The Penny & Giles recorder will be connected only to the 4th input of the MK3 correlator.

The 2 correlators will be controlled by 2 computers via 2 control terminals and 2 separate log terminals. It is unfortunately not possible to use both correlators in a combined mode to correlate more stations simultaneously.

The computer setup is unusual as very old hardware has to be used. The 3 computers are coupled in an asynchronous way via 3 shared discs as all computers have to have access to the control files and the tape data base (see figure below).

The A990 is connected to the local ethernet. Soon data will be transferred to one of our HP 9000/7xx computers for fringe fitting and archiving. The speed-up factor for fringe fitting is on the order of about 50 relative to the A990. Work on this "MK4" software is continuing in Haystack.



3. Correlator Usage Statistics

The table about the correlator usage of both astronomers and geodesists shows an increase in correlator usage since 1982 up to a saturation due to the lack of MK3 tapes. The introduction of narrow track recording in 1990 led to an increase in correlator usage by

more than a factor of 3. At present the correlator is operated nearly around the clock except for the time between about 3 am and 7 am in the morning. The re-installed MK3 correlator should help to increase the throughput by about 50 %. It will be used for fringe search during the day and correlation of observations with few antennas during the night.

Year:	1982	1983	1984	1985	1986	1987	1988	1989
Astro [h]	75	651	837	865	997	882	955	833
Geo [h]	0	304	407	591	583	447	898	420
Sum [h]	75	955	1244	1456	1580	1329	1853	1253

Year:	1990	1991	1992	1993
Astro [h]	1583	2243	2689	2103
Geo [h]	1036	1372	1276	745
Sum [h]	2619	3615	3965	2848
				$\sim$ 3820

4. Recent Improvements

- Astronomical users now get their data mostly on DAT for fringe fitting in AIPS. Thus standard correlation is fully done in absentia.
- Powerful computing facilities exist at MPIfR for visitors who want to use the Haystack/MPIfR global fringe fitting software (e.g. mm VLBI) or AIPS.
- An anonymous ftp account for distributing all #A-files was created. This helps users who want to fringe fit in AIPS.
- MPIfR initiated and fully supports the EVN MK3 CAL observations, which are analysed by 2 JIVE scientists for rapid feedback to the stations.
- If sufficient money is available (from EC? EVN?) the remaining 4 MK3A drives will be upgraded to MK4. The advantage is a more than 100 times better replay quality and the possibility to re-play thin tape.
- A new speed control for MK4 drives was developed at MPIfR. It will allow us to use the new MK4 drives with the old MK3 correlator.
- Geodetic data bases are sent via Internet to analysis centres.
- The astronomical backlog is now $\sim$ 7 months; the geodetic backlog is small.

The EUROPE 1993 experiments: A status report from the Bonn Correlator

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- Introduction
  As part of an ongoing campaign four VLBI experiments took or will take place in 1993. The organization of these experiments, which includes scheduling, tape logistics, correlation (fringe search; production runs) and creation and distribution of the Calc and Solve databases is done at the Bonn correlator. This enables us to give a status report of the recently performed experiments. It is meant to give feed-back to the stations which have participated.

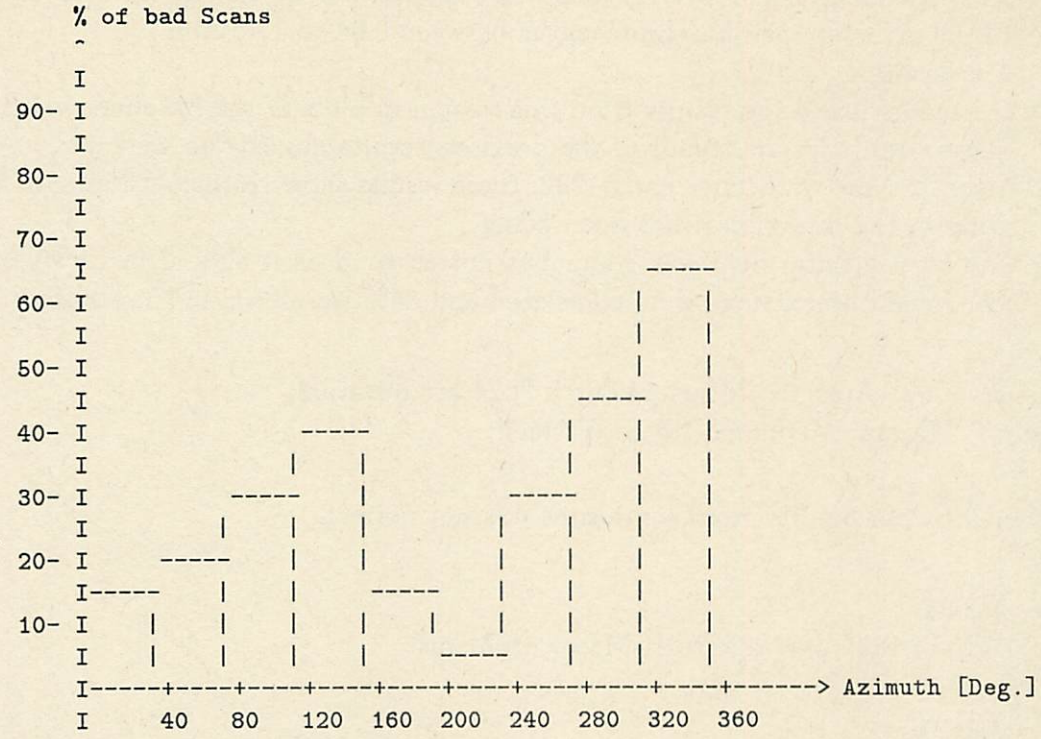
- Activities in 1993

  - Europe-1 '93: Feb.16.; Start 06:30 U.T.; 24 hrs duration;
    Madrid; Matera; Medicina; Noto; Onsala; Wettzell;

    Station performance can be summarized as follows:

    * Noto and Medicina:
      These stations had no data in several defective frequency channels. In Noto channel 4 (X-band) and 11 (S-band) were affected. In Medicina the reverse passes of channel 5 (X-band) showed no data. This could be due to problems with the Base Band Converters or the corresponding connections. For both stations all scans had to be refringed without these channels. In Noto the problem was solved in the next Europe experiment, in Medicina in Europe-3.

    * Matera:
      As in the past the data in frequency channel 14 (S-band) was spoiled by interference. Almost three quarters of the scans were affected. We had to refringe the whole experiment by skipping this frequency. In the following histogram the percentage of bad scans versus azimuth is displayed. The two peaks visible at $\sim$ 120 ° and $\sim$ 320 ° hint at radiation reaching the telescope receiver from the North or South of the site, presumably from a TV-transmitter. We investigated whether any of these signals could be produced by pickup of local TV signals in the IF system. Checking a spectrum of the IF in the range 150-300 MHz showed many peaks, but it was not possible to identify signals from TV transmitters near 200 MHz with known bad VLBI channels. So it might be more likely that e.g. a high frequency link from a studio to a TV-transmitter causes the interferences. This problem should be ionvestigated more detailed in future.



* Madrid, Onsala, Wettzell:
Good data was produced by these stations. At Onsala and Wettzell the first 2.5 hours could not be observed due to an overlap with other VLBI experiments which had priority (IRIS).

* Results:
In the following table statistics for the X-band data are given. For each baseline the number of scheduled scans used in Calc and Solve (2nd col.) and the number of scheduled scans (3nd col.) is given.

Baseline		♯ in C&S	♯ Scheduled
MATERA	–MEDICINA	234	278
MATERA	–NOTO	269	276
MADRID	–MATERA	236	246
MATERA	–ONSALA60	241	259
MATERA	–WETTZELL	257	277
MEDICINA	–NOTO	238	283
MADRID	–MEDICINA	219	261
MEDICINA	–ONSALA60	205	238
MEDICINA	–WETTZELL	215	284
MADRID	–NOTO	245	258
NOTO	–ONSALA60	239	260
NOTO	–WETTZELL	252	278
MADRID	–ONSALA60	215	238
MADRID	–WETTZELL	227	257
ONSALA60	–WETTZELL	258	275

The results of the analysis of this database at the GSFC have been quoted to be "- excellent". The overall weighted delay fit was at a level of 29 ps and the formal errors on the baseline lengths between 0.94 to 1.45 mm.
Jim Ryan:
"I have included the results from this session in plots of the baseline evolutions. These results fit the trends of the previous results almost too well!
After no Noto data since early 1992, these results show Noto continuing to move along in the direction it has been going.
The overall data yield was good, but not as good as it should be. 89% of the scheduled observations were correlated and 84% were used in the solution."

– Europe-2 '93: April 27.; Start 14:00 U.T; 24 hrs duration;
Madrid; Matera; Medicina; Noto; Wettzell;

Again the data quality from some sites was not perfect:

* Onsala:
Did not take part due to H-Maser problems.

* Matera:
Again the problem with the interference in frequency channel 14 appeared. This time only $\sim$ 20% of the observing time was affected and therefor no refringing was done.

* Madrid:
It was the first experiment with narrow track recording. The head positioning worked perfectly.
The time synchronisation at the correlator was problematic, because the decoded clock intervals were not consistent with the framelength of 5 ms. The correlator expects to read 0 or 5 from the ms byte of the clock, but in fact it found 4 and 5; So a change in the CDVR software, which sets 4 to 0, was necessary.
Fortunately this problem was solved in the Europe-3 '93 experiment.

* Medicina:
In half of the scans no data was recorded on X-band frequencies 5 and 6. These correspond to tracks 20 and 6, which are only used in the reverse pass. The problem was found to be a bad connection.

* Results:
The following table again shows a the baseline statistic for the X-band data.

Baseline		# in C&S	# Scheduled
MATERA	–WETTZELL	266	304
MATERA	–MADRID	166	280
MATERA	–MEDICINA	291	304
MATERA	–NOTO	290	307
WETTZELL	–MADRID	159	289
MEDICINA	–WETTZELL	277	312
NOTO	–WETTZELL	264	305
MEDICINA	–MADRID	174	291
NOTO	–MADRID	171	288
MEDICINA	–NOTO	292	308
		====	===
Total		2350	2988
% of sched.scans:		78.6	100

General comment from Jim Ryan:
"Europe-2 is somewhat of a disappointment. Matera S-band had so many low quality codes. However, I restored much of the data and it looked good.
Medicina clock showed a large (-400 to +4000 ps), mostly diurnal wander during the session. Paolo and crew should fix this."
Noto Baselines:
"Chopo ran a batch solution for me last night and the Noto data fit perfectly with the earlier results. It is still chugging along in the same direction."

- Europe-3 '93: Aug. 18.; Start 20:00 U.T; 24 hrs duration;
  Madrid; Matera; Medicina; Noto; Wettzell;
  Noto did not take part because no recording terminal was available. The MK 3 Terminal was shipped to Ny Ålesund and for the new VLBA Terminal not enough BBC's for the geodetic setup were available.
  Additionally Madrid was scheduled only for 12 hours. So only 4 stations ran for half of the experiment. On all baselines fringes were found and the production run has started.

- Europe-4 '93: Dec. 11.; Start 20:00 U.T; 24 hrs duration;
  Madrid; Matera; Medicina; Noto; Onsala; Wettzell; Effelsberg; Ny Ålesund; Crimea;
  Ny Ålesund will not take part and we are still waiting for confirmation of Noto and Crimea.

Next year six Europe experiments will be scheduled. Several new telescopes as Ny Ålesund and Yebes hopefully will increase the number of the stations which will participate in the standard experiments. Additional burst experiments with more stations like Effelsberg and Crimea also are planned. All observations will be correlated at the expanded correlator in Bonn.

Acknowledgement
For their help I would like to thank all colleagues - especially Dr. D. A. Graham.

The Ny-Ålesund Geodetic Observatory

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The Geodetic Institute of the Norwegian Mapping Authority is currently establishing a geodetic observatory at Ny-Ålesund, Spitzbergen (N. lat.=78.9 degrees; E. long.=11.9 degrees). Satellite receivers for GPS and SYRIUS-A are installed and operational. Three meter diameter antennas for direct satellite communication between the observatory and the Institute in Hønefoss, Norway have been installed. Complete Internet services are expected to be operational *primo* January 1994.

A 20 m diameter prime focus VLBI antenna is being installed in Ny-Ålesund during the Summer of 1993 by Radiation Systems, Inc., USA. A complete Mark III unit has arrived, courtesy of NOAA and NASA, to be integrated with the VLBI antenna in September. A maser clock has been installed and is operational, as is a GPS timing receiver. A dual frequency S/X-band receiver has also been lent to us by NASA, and has been slightly modified for operation in arctic conditions. The current estimate for antenna acceptance tests is *medio* October 1993. This is less than two years after funding was made available (January 1, 1992) by the Norwegian Parliament. Plans exist for test runs and participation in geodetic VLBI campaigns in late 1993 and throughout 1994. Staff members of the Geodetic Institute have received observing experience by operating the NASA MV-2 unit from 1991 till 1993. We expect to receive further training through an ongoing collaboration with Tom Clark's group at NASA Goddard Space Flight Center. Basic skills in VLBI analysis is being introduced into the Norwegian VLBI group at the Geodetic Institute in Hønefoss by Nestor Zarraoa.

Some antenna parameters are listed below.

Reflector diameter = 20 m
F/D = 0.43, prime focus feed
Alt-azimuth mounting
Antenna slewing speed = 2 degrees/sec, each axis
Antenna acceleration = 1 degree/sec/sec, each axis

Reflector surface accuracy = 0.61 mm rms
Pointing accuracy = 0.002 degrees rms with no wind; 0.011 degrees at 15 m/s wind

OCCAM V3.2: STATUS REPORT

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Introduction

OCCAM V3.2 is a geodetic VLBI analysis package designed to work on personal computers (PCs). Information about previous versions of the program can be found in Zarraoa et al, 1990 and 1992.

The last version released to the OCCAM users is V3.0. This version, distributed in early 1992, has as major features the use of Kalman filtering inversion to produce the multistation and multiexperiment solutions with geodetic objectives. A new version (V3.2) is being prepared for release in late 1993. This status report describes the major improvements with respect to the previous version.

Current status of OCCAM V3.2

Environment

The program maintains its former structure for use in PCs under DOS. The entire code has been also compiled and adapted to HP9000 Unix workstations, without any major change. The FORTRAN code can be compiled and run in both machines without any modification whatsoever.

Input/Output system

The OCCAM Standard Data Files have been modified in size in order to implement some of the new features. This means that Standard Data Files created by previous versions are no longer supported by OCCAM V3.2

New models implemented

The models recommended in the IERS 1992 Standards (McCarthy, 1992) have been included in the program. A major exception is the "non-rotating origin" concept for the

determination of the Celestial reference frame.

The computation of partial derivatives of station positions has been corrected by polar motion, in order to obtain the estimations in the proper reference system.

The tropospheric models have been revised, especially those not standard in OCCAM, and some bugs have been corrected.

New capabilities in the least squares process

The Earth orientation parameters (x and y wobble and UT1-UTC) can be estimated in the multistation mode. Accordingly, new constraints can be introduced during the analysis: height components of stations and directions of baselines.

New data weighting capabilities allow for a more flexible re-weighting. Automatic data editing tools are also available. The estimation of the stochastic characteristics of the random walk processes modeling the tropospheric and clock parameters can be done automatically.

New release of OCCAM

Further testing of the program is required before releasing V3.2 to the users. The User's Guide and other information must be also updated. The new version will be probably available by the end of 1993 for those users interested in the upgrade.

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VLBI Activities at the Matera Space Geodesy Center

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Abstract

This paper summarizes the present status (to August 1993) of the VLBI activities at the Space Geodesy Center of Matera. The center born in 1983 as an SLR station grew in the recent years including in its facilities a VLBI and a fixed GPS station. It is operated by Telespazio on behalf of the Agenzia Spaziale Italiana and is providing not just high quality data but also data analysis support. In this presentation we focus our attention on VLBI operational capabilities as well as on some preliminary results obtained analysing VLBI data acquired within the EUROPE project.

1 Introduction

The VLBI station became operational at the Center for Space Geodesy (CGS) of the Italian Space Agency (ASI) in Matera in May 1990. Since then it is active in the framework of the most important international programs participating to several experiments. VLBI Data Analysis activities are also performed at CGS for a better understanding of the tectonic motions with specific regards to the European area. The CGS, operated by Telespazio on behalf of ASI, provides full scientific and operational support to the international community using the three main space geodetic techniques: VLBI, SLR and GPS. This paper is focused on the VLBI activities performed at CGS. While the first part describes the operational activities and the system performances, the second one deals with the VLBI data analysis activities, with specific reference to preliminary results obtained from the analysis of the European experiments performed from 1990 to 1992 including a comparison with the recent CGS SLR solution.

2 VLBI system characteristics

The radiotelescope is a 20 meter antenna, with Cassegrain configuration and altazimuthal mount with crossing axes. For both axes the maximum angular velocity is 2 deg/sec. The overall accuracy of the main reflector surface is 0.4 mm RMS. The antenna feed receives the signals in S and X bands. The down-conversions are made with wide band down-converters.

The Data Acquisition Terminal (D.A.T.) is a Mark III-A. Starting from May 1992, the MARK-III D.A.T. is equipped with a narrow track VLBA recorder supplied by Interferometrics Inc. The control system is on a 486 PC.

The time and frequency system is composed of an EFOS-8 Oscilloquartz H-Maser, two HP 5061 B cesium beam and a Sercel GPS receiver. A HP 9000 model 310 M computer system manages all the control and monitoring operations of the time scales. A dedicated underground room, with no active air conditioning, has been built into the rock to host the frequency standards. The temperature variations are within 1°C/month.

Since May 1990, when the VLBI system became operational, Matera partecipated to 104 experiments up to August 1993. In particular in 1992 Matera was involved in 6 experiments coordinated by NASA, 20 coordinated by USNO and 16 coordinated by NOAA. In 1993 Matera is partecipating to the observing programs EUROPE, NAVEX and NEOS.

RF interferencies in the S-band are present due to TV relays. The effect is significant on two S-band VLBI channels.

According to the new VLBI acquisition standards it is planned the upgrade of both the RF receiver and the Mark III DAT.

3 Data Analysis of the EUROPE campaign

3.1 Data processing

The databases used in this analysis are acquired from NASA-DIS. Using SOLVE, for every database, we re-initialized the parametrization and the editing, alredy inserted at the GSFC, and obtained a new database version with our parametrization and editing of outliers. Three solutions, using SOLVE in *GLOBAL* mode, were computed: the first was an INDEPENDENT solution for generate the arc weights used in the others GLOBAL solutions. The second was a VELOCITY solution for estimating the site velocity as global parameters and the last was a BASELINE solution where baselines evolution in time among European stations were estimated.

3.2 Data statistics

The analysis include 11 experiments belonging to the EUROPE campaign since 1990 up to 1993. The following table summarizes the stations present in the databases.

		DEKMMNOWT SFAAEONEO SLRTDTSTU 6SLEIOATL SBBRC LZO EUAI AEU RR N 6LS GG A OLE
1	$90JAN26X	*...****.
2	$90SEP05X	*..****.
3	$90DEC20X	*..****.
4	$91JAN06X	*..*..**.
5	$91SEP08X	*..****.
6	$91DEC01X	**.**..*.
7	$92JAN14X	*..**.**.
8	$92APR08X	*..****..
9	$92MAY12XA	*..**...*
10	$92JUL07X	*.***.*..
11	$92NOV03X	*..**.**.

The sites KARLBURG, EFLSBERG and TOULOSE partecipated to one experiment only and then they will not be considered in the results.

Each solution uses 16103 group delays.

3.3 Adopted models

The models used are implemented in the CALC/SOLVE program and are based on the IERS standards (McCarty, 1989). In particular our solutions adopts the following:

Reference frame:

- Earth rotation parameters from IERS bullettin B.
- DSS65 fixed at the a-priori coordinates.
- Celestial reference frame defined by the values of precession and nutation at January 26, 1990 and fixing the right ascension of the source OJ287 at the a-priori values.

Processing options:

- Dry tropospheric zenith delay estimated using the Saastamoinen model and mapped to the elevation of the observation with the MTT dry model.
- Wet tropospheric delay estimated using a continuous, piecewice linear function with duration of the linear sections of 60 minutes and 50 ps/h constrained in slope.
- Clocks are estimated using a reference station (different arc by arc) and modelling the difference between the reference clock and the other with a second order polynomial plus a piecewise linear function with duration of the linear sections of 60 minutes and $5 \cdot 10^{-14}$ constrained in slope.
- Cable calibrations applied where available.

3.4 Velocity solution

The aim of this solution is to evaluate the site velocties as global parameters. The solution is constrained moving the site DSS65 according to the NUVEL1 model, the direction of the vector from DSS65 to WETTZELL is constrained to change according to NUVEL1 and the vertical rate at NOTO is constrained to zero. The coordinates of the sources and the velocities of the stations are adjusted as global parameters for a total of 132 global parameter estimated. There were 3035 arc parameters, the weighted RMS fit was 43.8 ps and the reduced χ^2 was 1.156

The following table is a summary of the results obtained from the velocity solution. For each station the horizontal velocity is reported as magnitude and azimuth coming out from this solution and, for comparative purpose, the corresponding values obtained from the NUVEL1 model. The stations Matera and Noto have been placed on the African plate while all the other stations have been placed on the European plate. The right side of the table reports the 3σ error ellipses.

Site	CGS93		NUVEL1		Error ellipse			
	Vel. (mm/yr)	Az. (°)	Vel. (mm/yr)	Az. (°)	Vel. (mm/yr)	Az. (°)	Vel. (mm/yr)	Az. (°)
WETTZELL	27.6	56.8	25.5	56.5	0.7	60.8	0.0	0.0
ONSALA	29.3	66.4	24.1	53.9	0.8	45.1	0.6	315.1
NOTO	26.6	45.7	29.8	44.0	1.0	75.6	0.9	345.6
DSS65	25.5	49.9	25.5	49.9	0.0	0.0	0.0	0.0
MEDICINA	27.7	56.4	26.0	56.7	0.7	63.5	0.5	333.5
MATERA	28.1	47.1	29.4	43.0	0.9	71.6	0.7	341.6

3.5 Baseline solution

The purpose of this solution was to produce the time series of the baselines. The coordinates of the stations are adjusted as arc parameters while the coordinates of the sources are adjusted as global parameters. Daily nutations offset are also estimated. There were 81 global parameters and 2870 arc parameters. The weighted RMS fit was 41 ps and the reduced χ^2 was 0.987.

The following table gives, for each baseline, the number of experiments in which the baseline is present, the number of observations used for that baseline, the mean length and the rate.

Baseline	# of sessions	Used/Total obs.	Length (mm)	Rate (mm/yr)
DSS65-MATERA	10	1302/1619	1765812138.5±0.8	-3.8±1.3
DSS65-MEDICINA	10	1091/1257	1378852895.3±0.7	2.0±0.8
DSS65-NOTO	5	758/879	1711832914.3±1.0	-2.6±1.3
DSS65-ONSALA	9	1315/1428	2205023113.6±0.9	1.0±1.1
DSS65-WETTZELL	8	1296/1451	1655418187.1±0.7	1.5±0.9
MATERA-MEDICINA	9	975/1262	597262299.9±0.7	-6.1±1.1
MATERA-NOTO	4	598/831	444532984.8±1.0	-2.2±1.6
MATERA-ONSALA	8	761/1440	1886809333.3±1.1	-9.0±1.5
MATERA-WETTZELL	7	1143/1457	990053379.2±0.7	-5.9±1.1
MEDICINA-NOTO	5	814/883	893724227.4±0.9	-5.7±1.2
MEDICINA-ONSALA	8	1100/1174	1429470393.8±0.9	1.3±0.9
MEDICINA-WETTZELL	7	1019/1080	522461123.3±0.6	0.5±0.7
NOTO-ONSALA	5	843/909	2280154885.1±1.3	-3.9±1.7
NOTO-WETTZELL	4	733/795	1371101056.1±1.1	-3.4±1.8
ONSALA-WETTZELL	7	1376/1465	919660995.8±0.7	0.9±0.8

3.6 Presentation of analysis results

Fig. 1 shows the velocity vectors obtained from the VELOCITY solution. Except that for ONSALA, there is a very good agreement between the velocities provided in the NUVEL1 model and those coming out from the analysis. The model motion for MATERA and NOTO has been obtained by placing the two stations on the African plate.

Fig. 2 through Fig. 5 present the baseline time series. On each plot the rate and the weighted RMS of the linear fit are reported.

Comparison with SLR results is at present possible for the relative motion between Matera and Wettzell where both the techniques are operational. In this case the agreement is impressive. For the comparison the SLR solution CGS93, obtained at the CGS using 10 years of SLR data, is used:

Baseline rate Matera-Wettzell (mm/yr)

VLBI/CGS93	SLR/CGS93
-5.9±1.1	-5±2

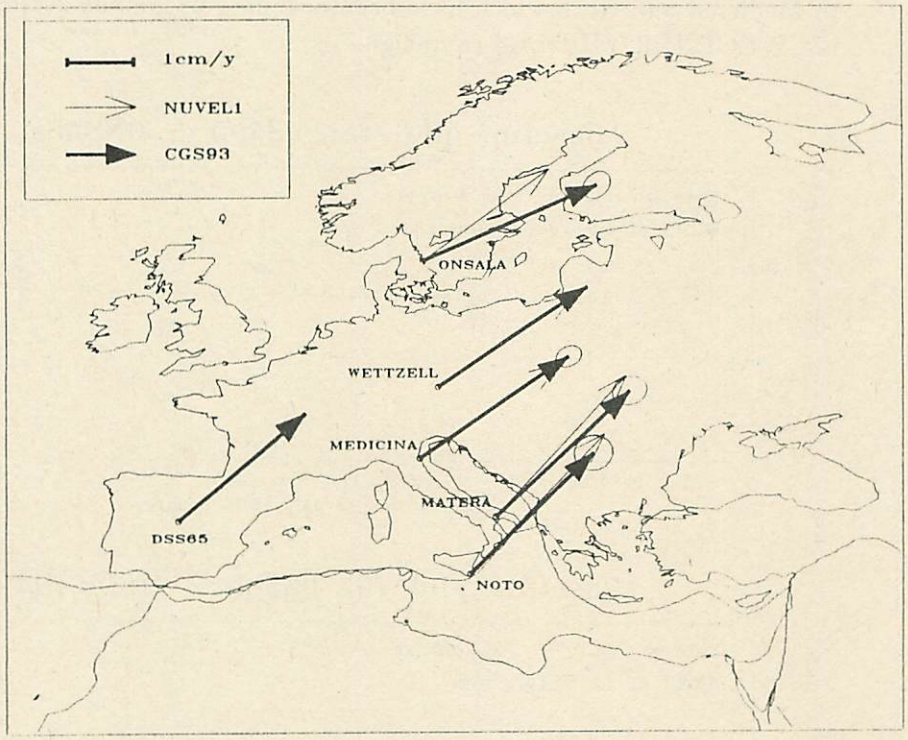


Fig. 1

4 Conclusions

The VLBI station at the Matera Space Geodesy Center is fully operational since 1990 providing a fundamental reference point to the geodetic community.

Preliminary results of the VLBI data analysis of the Europe campaign are confirming the capacity to detect sub-centimeter per year motion.

The first preliminary tectonic motion obtained by VLBI is confirming the correctness of the NUVEL model. In particular a component of Matera motion towards north is confirmed, which can be explained by tectonic models assuming Matera belonging to the African plate. Similar results are obtained in the VLBI solution for the Noto site, but the poor statistics do not allow to make any conclusive statement about its motion.

5 Future plans

We plan to continue the analysis of the EUROPE campaign as new experiments will become available. In particular, further investigation will be carried out to better understand the behaviour of Onsala and to confirm the belongings of Noto and Matera to the African plate.

The parametrization for clocks and atmospheres requires a more detailed analysis in order to establish the duration of the linear sections of the piecewise function and the values for the slope constrains.

As soon as SLR results will be available we plan to extend the comparison to Medicina and Noto which have been occupied by mobile systems within the WEGENER/MEDLAS campaign.

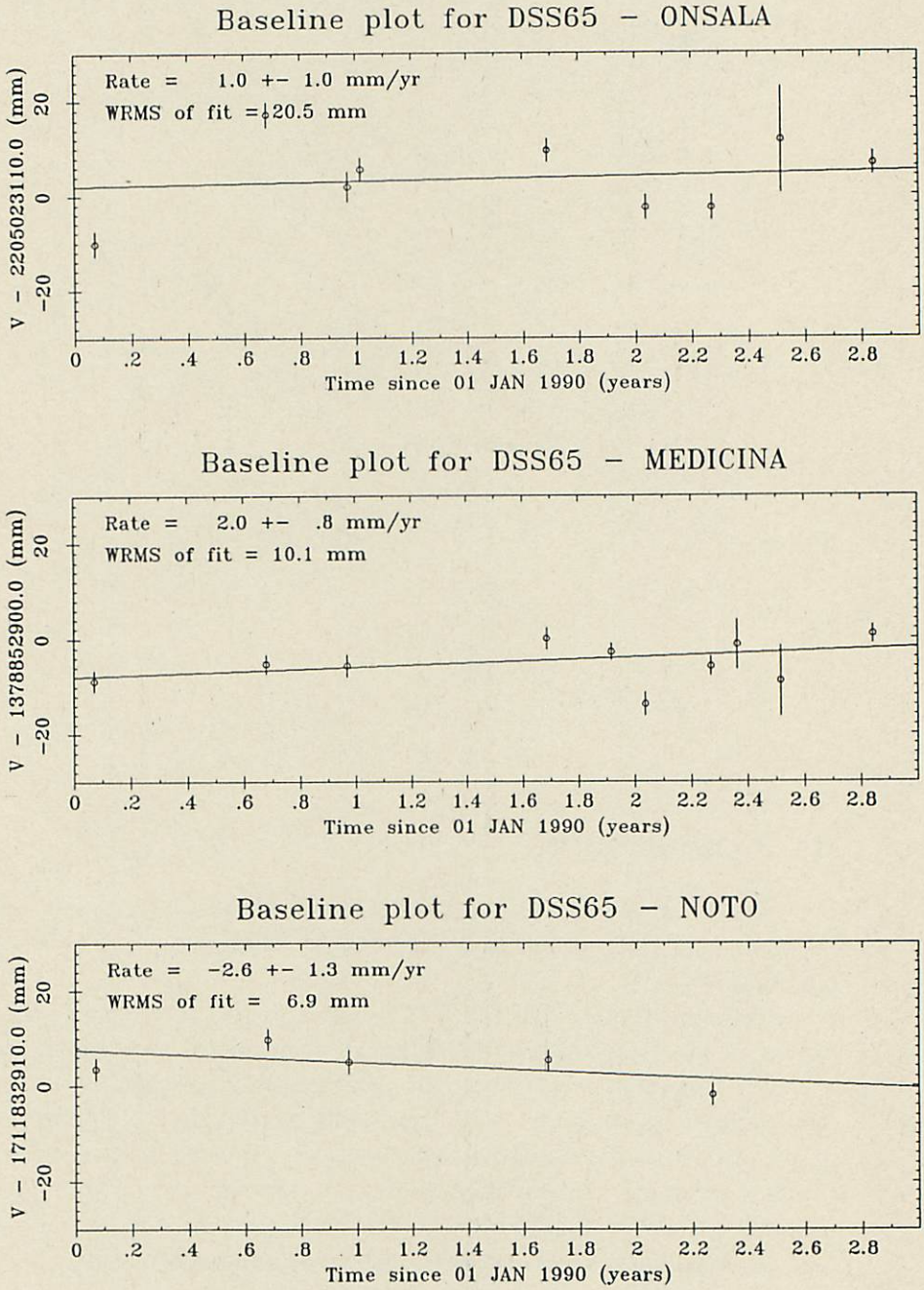
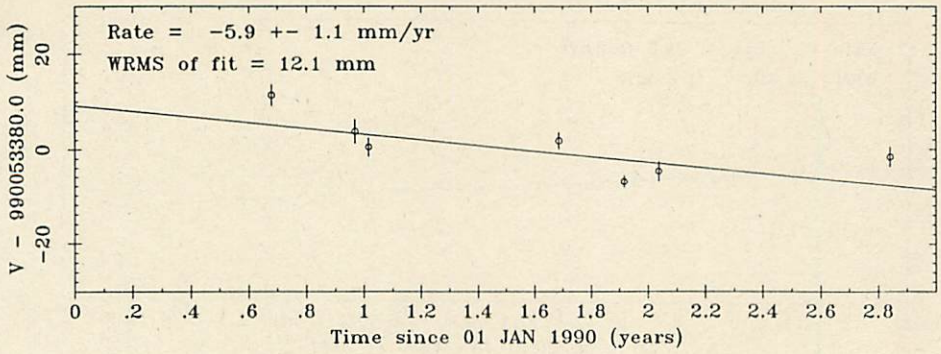
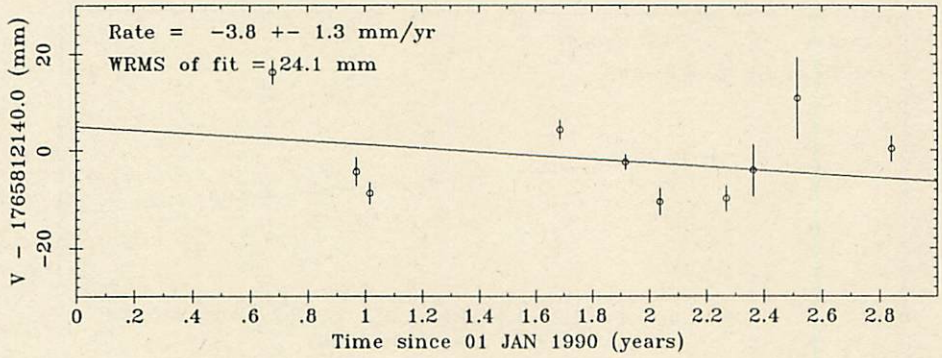


Fig. 2

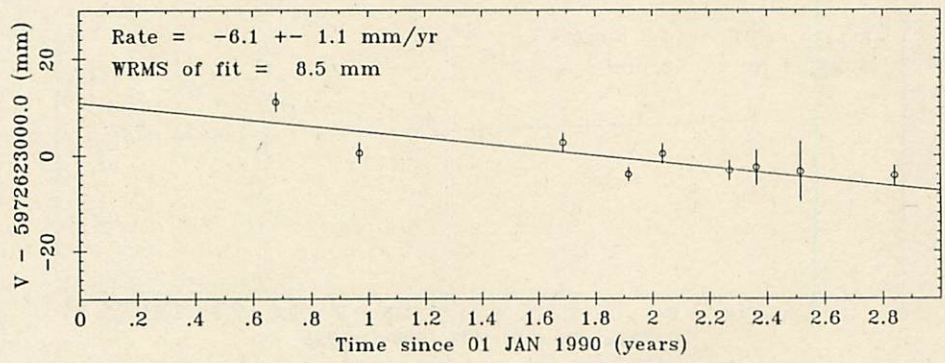
Baseline plot for MATERA - WETTZELL



Baseline plot for MATERA - DSS65



Baseline plot for MATERA - MEDICINA



Baseline plot for MATERA - ONSALA

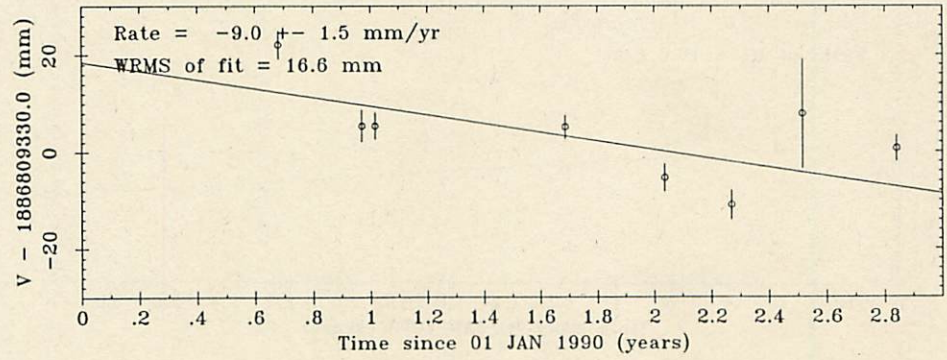
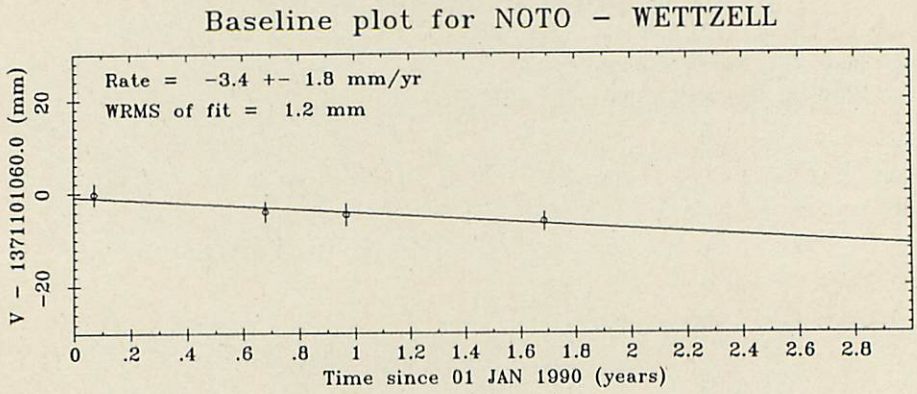
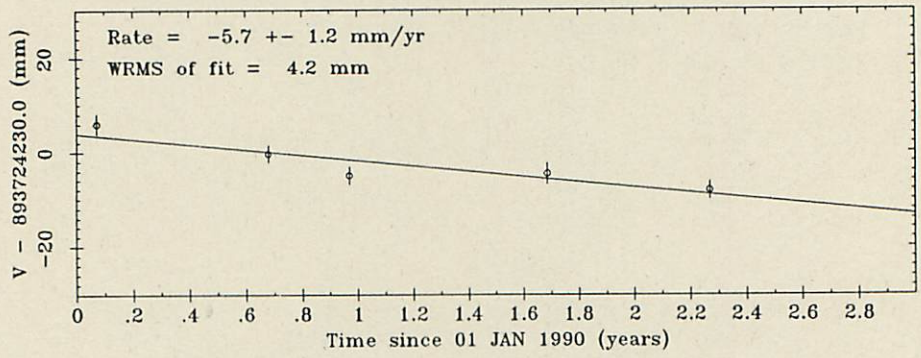
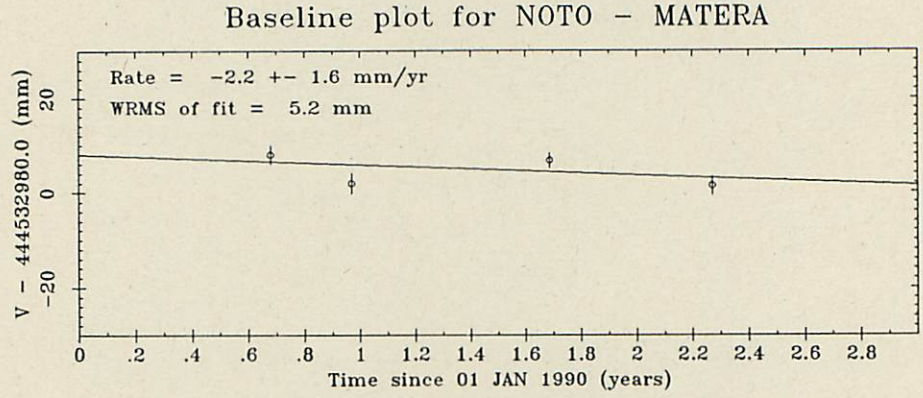


Fig. 3


Baseline plot for NOTO - WETTZELL
Rate = -3.4 +- 1.8 mm/yr
WRMS of fit = 1.2 mm
V - 1371101060.0 (mm)
20
0
-20
0 .2 .4 .6 .8 1 1.2 1.4 1.6 1.8 2 2.2 2.4 2.6 2.8
Time since 01 JAN 1990 (years)


Baseline plot for NOTO - MEDICINA
Rate = -5.7 +- 1.2 mm/yr
WRMS of fit = 4.2 mm
V - 893724230.0 (mm)
20
0
-20
0 .2 .4 .6 .8 1 1.2 1.4 1.6 1.8 2 2.2 2.4 2.6 2.8
Time since 01 JAN 1990 (years)


Baseline plot for NOTO - MATERA
Rate = -2.2 +- 1.6 mm/yr
WRMS of fit = 5.2 mm
V - 444532980.0 (mm)
20
0
-20
0 .2 .4 .6 .8 1 1.2 1.4 1.6 1.8 2 2.2 2.4 2.6 2.8
Time since 01 JAN 1990 (years)

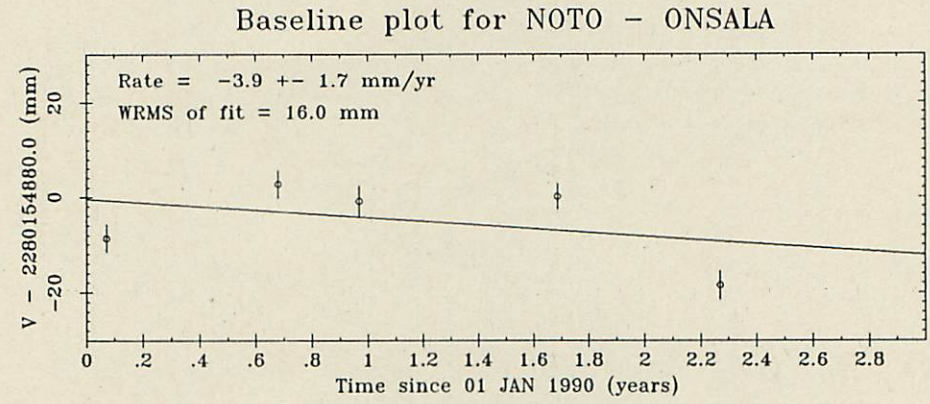
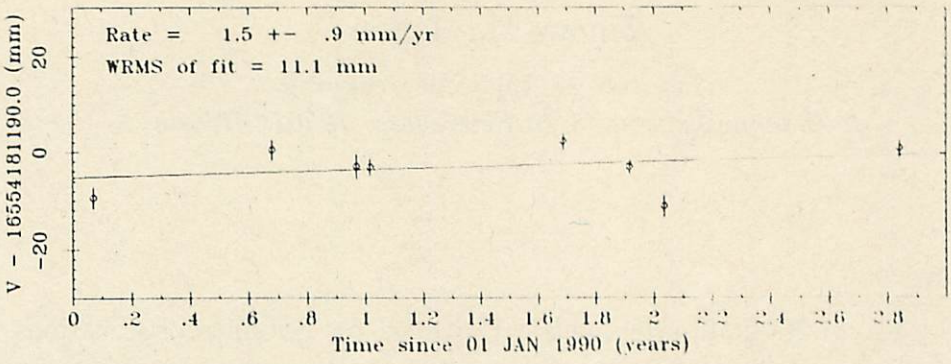
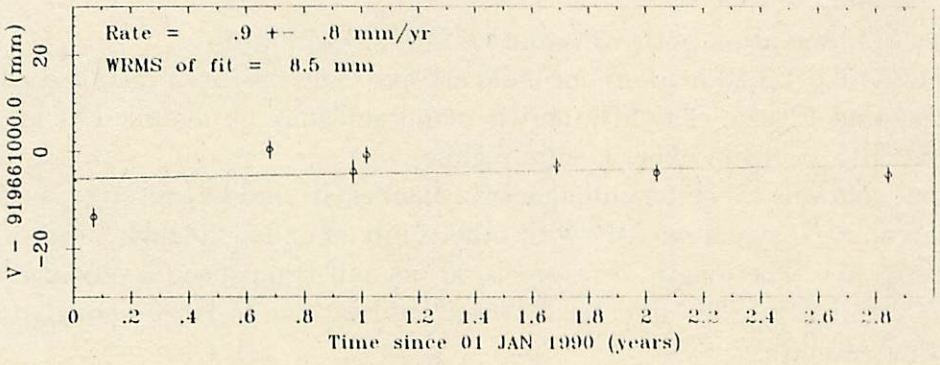

Baseline plot for NOTO - ONSALA
Rate = -3.9 +- 1.7 mm/yr
WRMS of fit = 16.0 mm
V - 2280154880.0 (mm)
20
0
-20
0 .2 .4 .6 .8 1 1.2 1.4 1.6 1.8 2 2.2 2.4 2.6 2.8
Time since 01 JAN 1990 (years)

Fig. 4

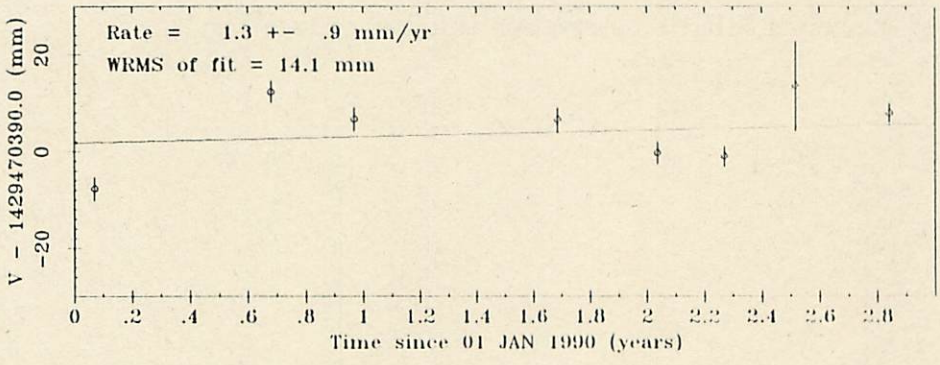
Baseline plot for DSS65 - WETTZELL



Baseline plot for ONSALA - WETTZELL



Baseline plot for ONSALA - MEDICINA



Baseline plot for MEDICINA - WETTZELL

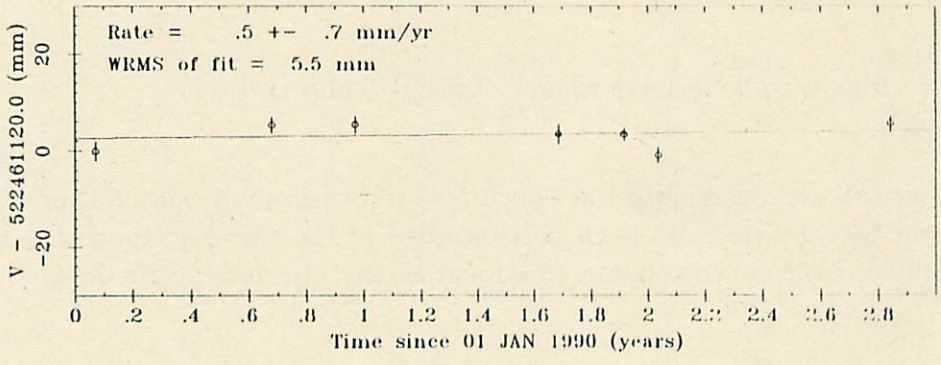


Fig. 5

SIRIUS as a Geodetic Tool

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Introduction

SYRIUS (SYstem Radio Interferometric Universal for Satellite observations) is being developed at the Institute of Applied Astronomy, St.-Petersburg to determine geodetic parameters and satellite orbits [1]. The main properties of SYRIUS are:

– codeless observations;

– capability of observation both GPS and GLONASS satellites.

Five units of SYRIUS had made. Four units are fixed and has been installed at Pulkovo, Svetloe, Badary and Firuza. The fifth unit is mobil and may be installed at an arbitrary place. Now SYRIUS works in experimental regime.

SYRIUS unit contains 1.3 meter antenna, two-channel (L1 and L2) receiver, and recorder. Each unit may operate synchronously with other units or independently according to the observation program. The length of record is 50 ms and time space between consecutive observation is 2 min [1]. This interval between observations is large enough to redirect antenna to other satellite.

1. SYRIUS Observation Data

The general scheme of SIRIUS observation is following (see Fig.1).



Fig. 1. The general scheme of SIRIUS observation

The signal broadcast by satellite 1 at epoch t_1 is recorded at the site 2 at epoch t_2. The signal broadcast by satellite 2 at epoch t_3 is recorded at the site 2 at epoch t_4. These two records are subject to usual correlation treatment as any interferometric data.

Let:

$t_1 \dots t_4$	-	true event epochs,
$t_1^c \dots t_4^c$	-	readings of clocks,
$\vec{r}_1$	-	position of satellite 1,
$\vec{r}_2$	-	position of satellite 2,
$\vec{R}_1$	-	position of site 1,
$\vec{R}_2$	-	position of site 2,
Δt_{sat1}	-	clock offset of satellite 1,
Δt_{sat2}	-	clock offset of satellite 2,
Δt_{site1}	-	clock offset of site 1,
Δt_{site2}	-	clock offset of site 2,
ρ_1	=	$\lvert\vec{r}_1(t_1) - \vec{R}_1(t_2)\rvert$,
p_1	-	pseudorange corresponding to ρ_1,
ρ_2	=	$\lvert\vec{r}_2(t_3) - \vec{R}_2(t_4)\rvert$,
p_2	-	pseudorange corresponding to ρ_2,
τ	=	$t_4^c - t_2^c$,
c	-	velocity of light.

The value τ is measured interferometric delay. Then we have

$$\begin{aligned} p_1 &= \rho_1 + c\Delta t_{site1}(t_2) - c\Delta t_{sat1}(t_1) \\ p_2 &= \rho_2 + c\Delta t_{site2}(t_4) - c\Delta t_{sat2}(t_3) \\ c\tau &= p_2 - p_1 = \rho_2 - \rho_1 + c(\Delta t_{site2}(t_4) - \Delta t_{site1}(t_2)) - c(\Delta t_{sat2}(t_3) - \Delta t_{sat1}(t_1)) \quad (1) \end{aligned}$$

There are four modes of SYRIUS operation.

1. Interferometry.

In this mode satellite 1 and satellite 2 is the same satellite, the epoch t_1 and epoch t_3 is the same epoch. This mode has been described in [1] as main SYRIUS mode. For interferometry we have

$$c\tau = \rho_2 - \rho_1 + c(\Delta t_{site2}(t_4) - \Delta t_{site1}(t_2)), \quad (2)$$

which is equivalent to the difference between two pseudorange measured strictly simultaneously from two sites to the same satellite.

2. Differential pseudorange.

In this mode satellite 1 and satellite 2 is the same satellite, site 1 and site 2 is the same site. This mode has been called in [1] as pseudorange the same as standard pseudorange. In fact we have for this mode

$$c\tau = \rho_2 - \rho_1 + c(\Delta t_{site}(t_4) - \Delta t_{site}(t_2)) - c(\Delta t_{sat}(t_3) - \Delta t_{sat}(t_1)), \quad (3)$$

which is equivalent to the difference between two pseudorange measured from the same site to the same satellite at two different epoch. It is clear that the clock offset differences not include clock shifts but only varying parts.

In this observation mode each SIRIUS unit can operate independently of other units.

3. Nonsynchronous interferometry.

This mode has been developed by authors of [1] to avoid the reduction of interferometric data on the long base. In this case satellite 1 and satellite 2 is the same satellite and

$$c\tau = \rho_2 - \rho_1 + c(\Delta t_{site2}(t_4) - \Delta t_{site1}(t_2)) - c(\Delta t_{sat}(t_3) - \Delta t_{sat}(t_1)), \quad (4)$$

which is equivalent to the difference between two pseudorange measured from two sites to the same satellites at two different epoch. The satellite clock offset differences not include clock shift but only varying part. The last term is only difference between (2) and (4).

4. General case.

This mode corresponds to (1) and is equivalent to the difference between two pseudorange measured independently from two sites to two satellites. This case is only observation mode used two satellite. Evidently, the correlation of two records from two sites is possible only for GLONASS satellites.

2. Comparison with standard receiver

Using the standard GPS or GLONASS receivers we can immediately obtain pseudorange observations p_1 and p_2. Using (quasi-) synchronous pseudorange observations from two sites to the same satellite we can form single difference observation equation [2] which is the same as observational equation (2) for SYRIUS interferometric mode.

The SYRIUS lacks the possibility to observe more than one satellite simultaneously. The minimal time space between observations of two satellites is now 2 min. If possible to neglect the satellite clock drift for such time interval we can form double and triple difference observation equations [2].

Conclusion

As it is shown above all usual observation equation (single, double and triple differences) are available with SYRIUS. The single difference we have immediately from observation in interferometric mode and double difference me can obtain interchanging the observation of different satellites.

The other observation modes can give us new possibility for determination of geodetic parameters and satellite orbits. In addition SYRIUS can operate as standard interferometric and codeless receiver.

Thus SYRIUS provides with all geodetic and orbital determinations without knowledge of navigation codes and can use both GPS and GLONASS satellites.

References:

1. Umarbaeva, N., A.Diakov, A.Egorov, G.Krasinsky, SYRIUS-A observes NAVSTAR in the campaign GIG-91, *Proc. of the AGU Chapman conference on geodetic VLBI: Monitoring global change*, p. 71-81, April 1991

2. Beutler, G., I.Bauersima, S.Fankhauser, GPS software: principles, concepts, trends, and experiences, *Paper presented at the Sowiet-German workshop on industrial and Scientific cooperation in the use of the Global Navigation Satellite System (GLONASS)*, September 1990

THE NEW GENERATION GEODETIC VLBI-SOFTWARE "KIEV-GR2"

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ABSTRACT. The paper is given for the astronomical, geophysical and geometrical models and formulae adopted in "KIEV-GR2", a program for computing the theoretical delay of geodetic VLBI observations and its partial derivatives with respect to physical parameters of interest. The IERS Standards 1992 are used a general reference.

1. Astronomical, Geophysical and Geometric Models

The basic observational equation of geodetic VLBI is given as:

$$t(t)=T2(t+ tg)-T1(t) \quad (1)$$

where t(t) is the observed delay, t the coordinate time, T1 and T2 readings of clock at terminal sites of the baseline. tg is the geometrical delay including the relativistic effects:

$$tg=tp + s*M\,(x1(t) - x2(t+tg))/c \quad (2)$$

where tp is a delay due to propagation media, s - a unit vector along an apparent direction of the radio source referred to a conventional inertial system (CIS), x1 and x2 - instantaneous positions of the observation sites spanning the baseline in question refereed to a conventional terrestrial reference system (CTS), M - the transformation matrix from CTS to CIS, and c - the velocity of light. tp, s, M and x as well as the relation between T and t depend upon various astronomical, geophysical and geometric effects. They can be clacified as follows.

1) Variation of an instantaneous position of an antenna reference point with respect to an observation site reference point. This includes an offset of antenna axes.
2) Variation of an instantaneous position of an observation site reference point with respect to CTS. This includes effects of deformations of the Earth (the Earth tides, the ocean tidal loading, pole tide and proper motion of a station.
3) Rotation of CTS with respect to CIS. This includes rotations due to the polar motion, diurnal rotation, nutation and precession. Matrix M in equation (1) consists of these rotations and is expressed as:

   $$M=PNSW$$

   where matrices P, N, S and W present rotations due to the precession, nutation, diurnal spin and wobble, respectively.
4) Relativistic effects. These include the transformation of the time system between TAI and TDB and Lorenzian space contraction, aberration and gravitational bending of radio wave path.
5) Variations of true and apparent position of radio source with respect to CIS. These include proper motion and parallax. However, these effects are not taken into account.
6) Dilatation of propagation path of radio wave due propagation media such as the solar corona, ionosphere, and dry and wet components of the troposphere. However, we take into account only troposphere effects.

In the following describes sources of the formulae which implement the individual physical and geometric effects adopted in "KIEV-GR2".

1.1 Precession and nutation
The formulae for calculate these effects was taken from IERS Standard [1].

1.2 Earth tide
A displacement of an observation site due to the solid Earth tides is computed by following Wahr's [3] theory calculate according [7,8].

1.3 Ocean tidal loading
Changes of the site position due to ocean tidal loading are not negligible small for sites near the ocean. This effects calculate according [9-10].

1.4 Polar tides calculate according [11-13].

1.5 Proper motion of a stations calculate according AMO0-2 [1].

1.6 Tropospheric delay
The tropospheric delay in the zenith direction due wet and dry components calculate by Brouwer [5]. Mapping function calculate by Devis (F-2.2) [4].

1.7 Wobble
The wobble or polar motion itself is not predictable with a sufficient accuracy. Therefore, observational values from other sources such IERS and IRIS are used as a priori values.

1.8 Relativistic effects
The all of the relativistic effects calculate following Zeller [14].

1.9 Antenna axis offset
The terminal point of a baseline is usually defined as the intersection of the fixed drive axis of the antenna with the plane which is perpendicular to the fixed axis and in which the moving axis lies. If the two axes do not intersect, the reference point moves as the elevation and azimuth change. This effect calculate following Sovers [6].

2. Estimation

"Kiev-GR2" aims to have the most up-todate and consistent physical basis to give the most accurate estimates of physical parameters. As a rule it is the following parameters:

a) parameters of the terminal clock;
b) troposphere delay;
c) polar motion (Xp and Yp);
d) universal time (UT1-UTC);
e) nutation angle (dPSI, dEPS).

Its parameters named "arc parameters" and it must be estimate for each session.

The sources coordinates, stations coordinates, Love and Shida named "global parameters". "Global parameters" can be estimated, with higher accuracy, using the big number observations, which taken during a long time (more then 1 year). "Kiev-GR2" can be estimate only "arc-parameters", because we have not a powerful computer.

3. Earth Rotation Parameters estimated by "Kiev-GR2"

We estimated the Earth Rotation Parameters by "Kiev-GR2" using VLBI-observations IRIS-A network (1984.0 - 1988.0). We used the following model for estimation of the "arc parameters" on the each session:

1) parameters of the terminals clock (peace-vice model with 4-our interval) for each baseline;
2) zenith troposphere delay (peace-vice model with 4-our interval) for each station;
3) polar coordinates (Xp and Yp);
4) universal time (UT1-UTC); 5) nutation angles (dPSI, dEPS).

The our estimation of the ERP is show in the Table 1.

Table 1 was omitted by the editors. The contents of table 1 is available from the authors on request.

We compare this result with IRIS data [2]. It comparison showed following:
internal aquracy bough of this software is equal;
exist systematic difference in Y pole coordinate (5 mas).
The reason of this differences have not explanation.

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IRIS-S Batch Solutions at the Geodetic Institute of the University of Bonn

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Abstract. For several years the VLBI group at the Geodetic Institute of the University of Bonn has been involved in the preparation, correlation and analysis of experiments observed in the IRIS-S project, with the Europe network and with the new station O'Higgins in Antarctica. The databases of the IRIS-S experiments which are observed in monthly intervals form the backbone of most data analyses at the Geodetic Institute including the Europe and the O'Higgins experiments. This paper describes the procedures used in general and in the analysis of the IRIS-S experiments with special emphasis on the parametrization of individual and combined solutions.

1. Introduction

Since 1983 the VLBI group at the Geodetic Institute of the University of Bonn has been involved in the preparation, correlation and analysis of two major groups of geodetic VLBI observations. The first one is the IRIS-S project (International Radio Interferometric Surveying - South) and the second is the series of so-called Europe experiments. In recent months the field of data analysis activities has been extended to the data gathered with the new station O'Higgins in Antarctica (see Hase and Nothnagel, this volume).

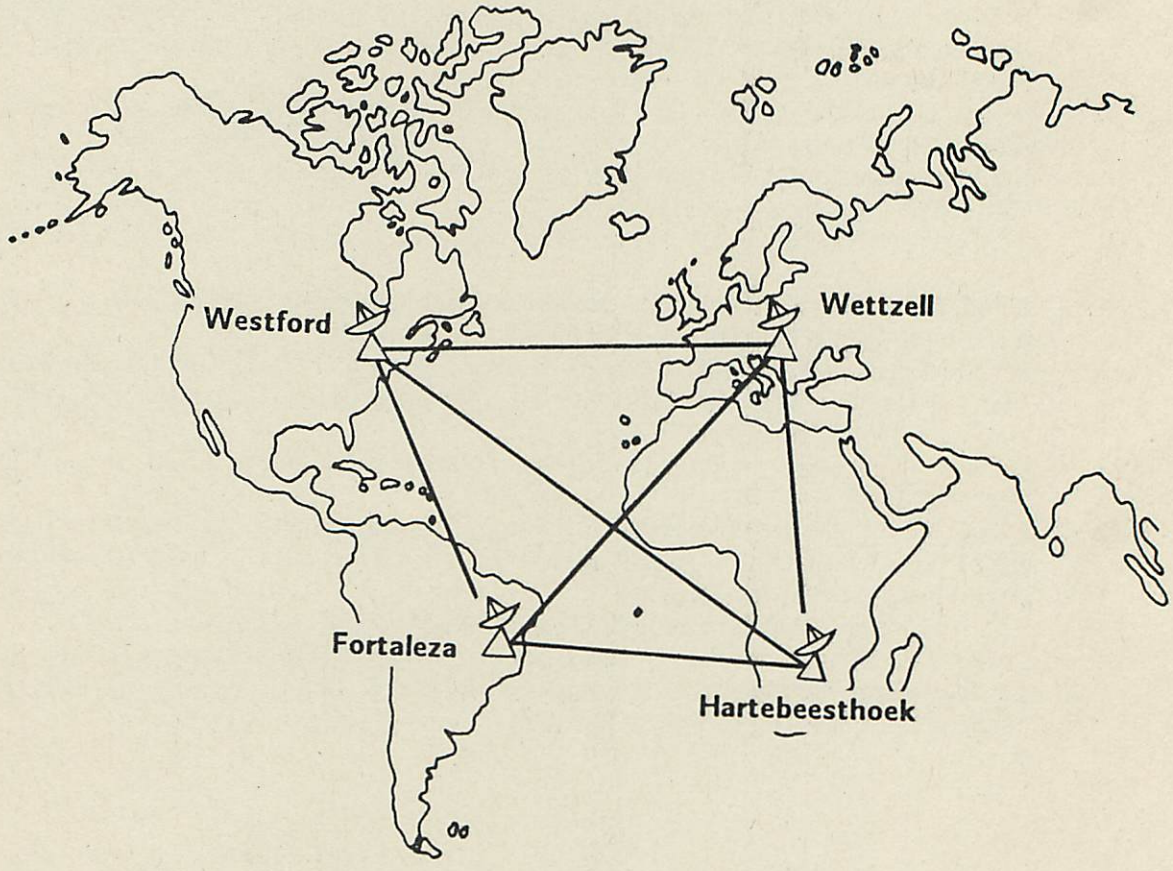


Fig. 1, The current IRIS-S network

The IRIS-S data forms the backbone of the VLBI database at the Geodetic Institute. Until now approximately 60 experiments were observed with a network of stations which is grouped around the Wettzell - Westford - HartRAO (Hartebeesthoek Radio Astronomy Observatory, South Africa) baseline triangle. Since early 1986 when HartRAO was first equipped with a hydrogen maser frequency standard and a Mark III data acquisition terminal the IRIS-S network was scheduled to observe for two months each year in the beginning and regularly in monthly intervals from late 1989. The network first consisted of the stations Wettzell, HartRAO, Westford and Richmond with Onsala and Fort Davis participating in a few experiments (Carter et al., 1987). In the meantime, several changes were necessary: Mojave replaced Fort Davis and was closed eventually, Santiago (Chile) was excluded again after 10 months of participation for financial reasons and Fortaleza (Brazil) started operation in July 1993. Today the network is formed by the stations of Wettzell, HartRAO, Westford and Fortaleza (Fig. 1).

The observing sessions have a duration of 24 hours each and since 1992 the schedules have been prepared with an automatic scheduling program (Autosked) developed at the Geodetic Institute (Steufmehl, 1991).

2. Data Analysis

2.1. Data preparation

The data analysis at the Geodetic Institute is performed with the Calc/Solve/Globl software package developed at the NASA Goddard Space Flight Center in cooperation with a number of other institutions (Caprette et al., 1990). The raw data from the correlator runs through a series of programs which create a database for each experiment, calculate the theoretical delays for linearization and compute contributions and corrections on the basis of the IERS 1989 standards (McCarthy et al., 1989) together with the partial derivatives for the least squares adjustments.

Delay ambiguities originating from the bandwidth synthesis method (Rogers, 1970) are eliminated with the Solve program and the databases are calibrated for ionospheric and tropospheric refraction effects using on-site surface meteorological data before the least squares adjustments are tackled.

2.2. VLBI Analysis Strategies

The least squares adjustments of VLBI experiments can be divided into two groups of estimation strategies. The first one is the separate treatment of individual experiments; the second one is the combined processing of a number of experiments in one single least squares adjustment, a so-called "batch" solution. If the data includes virtually all of the VLBI experiments performed globally over a period of several years, the solution is called a "global" solution.

The geometric time delay τ of signals arriving at two radio telescopes is to first order a function of the baseline vector $\mathbf{b}$ connecting the two telescopes, the unit vector in the direction of the radio source $\mathbf{k}$, the rotation matrix for polar motion W (wobble), the diurnal spin matrix S, and the nutation and precession matrices N and P relating the Earth-fixed and the celestial reference system. In addition to the geometric contributions the observed delay is affected by the relative behaviour of the station clocks τ_{Clock} and the excess path delays caused by atmospheric refraction τ_{Atm}.

$$\tau = -\frac{1}{c} \mathbf{b}\, WSNP\, \mathbf{k} + \tau_{Clock} + \tau_{Atm} \cdots \qquad (1)$$

c is the velocity of light and the negative sign reflects the conventions used in defining τ and $\mathbf{b}$.

The delay and delay rate observables of a single VLBI session with typically 100 to 200 observations per baseline generally are not sufficient to reliably estimate all the parameters on which the observables depend. Although radio source positions and station coordinates can be estimated with the observations of a single experiment the resulting accuracy is still far away from the

potential of a greater number of observations gathered with large observing networks over a longer time span.

Separate solutions of individual experiments are basically needed only when the databases are prepared from correlator output in order to check the quality of the data and to determine the apriori weights of the observations. Only for special purpose experiments it may be advisable to treat each experiment separately.

When a sufficient number of experiments has been gathered a combined least squares adjustment of all observations can be performed running a batch solution. Clock and atmosphere parameters are always treated as arc parameters, i.e. within the batch solution they are estimated for each experiment independently. Radio source positions are truly global parameters which are, in the absence of proper motion, constant for all experiments, i.e. only one pair of source coordinates is estimated for each source.

Station coordinates can be treated in two different ways, either as arc parameters or as global parameters. Arc parameters mean that new sets of station coordinates are estimated for each experiment while global parameters are a single set of coordinates which are estimated using all experiments in a batch run. In the first case the solution does not significantly differ from a series of single solutions except that the information of the radio source positions is carried from one experiment to the next. In addition, such a treatment does not permit to estimate earth orientation parameters simultaneously; these parameters have to be introduced as apriori information. The advantage of this type of solution is that the resulting time series of individual baseline lengths can be analyzed in more detail. In addition, no apriori information of the station drift behaviour is needed.

In the case of global station coordinates the geological history of the station and the time span which is covered by the batch solution determine how the station movements have to be modeled. If the period is short (less than 2 years) and there are only motions to be expected which are smaller than the uncertainties of the station coordinate determinations, station displacements can be either neglected or introduced from a model like NUVEL-1 (Argus and Gordon, 1991). If longer time spans are available drift parameters dx/dt, dy/dt, dz/dt can be estimated together with the individual station coordinates. Depending on the purpose of the solution special constraints have to be applied for the station drift parameters. For a more thorough discussion on these topics see e.g. Ma et al. (1990).

2.3. Analysis of the IRIS-S Experiments

The ideas expressed above are used in the analysis of the IRIS-S observing programme at the Geodetic Institute in Bonn. The data analysis of the IRIS-S experiments starts with a detailed pre-analysis of each individual experiment. In general, the atmospheric excess path delay is estimated as a piece-wise linear function with one offset parameter and an additional rate parameter every three hours for each station. Only if station logs indicate a rapidly changing climatic environment shorter intervals are chosen. A method used earlier which consisted of selecting the rate change epochs in accord with variations in the surface meteorological data, thus aiming at a small number of parameters (Nothnagel, 1991), has not proven to be significantly better than the automated selection at reasonable intervals. The introduction of intervals shorter than three hours on average changed the estimated parameters and the RMS errors only marginally (see also Ryan et al., 1991).

The parametrization of the station clocks mainly with second order polynomial is done in a more conservative fashion. Only if the residuals show distinguished variations additional parameters are introduced preferentially as additional rate changes. We believe that a smaller number of clock parameters as compared to a stochastic treatment of the clocks does not weaken sub-diurnal signals in the Earth orientation parameters.

With its long north-south and east-west extensions covering stations in both hemispheres the IRIS-S network possesses an ideal geometry for the estimation of Earth orientation parameters and radio source positions. A sufficient number of IRIS-S experiments can, therefore, serve as the foundation for an independent determination of station coordinates, radio source positions and Earth orientation parameters. By now 42 IRIS-S databases in monthly intervals including 32 radio sources were combined in a batch solution spanning a period from December 1989 to June 1993.

In the batch solution the coordinates of Wettzell are kept fixed while station positions are estimated for all other stations. The first experiment of the series (Dec 21, 1989) is used as a reference for the determination of the Earth orientation parameters, i.e. pole components and UT1 are fixed at the USNO Rapid Service values (IERS Bulletin A) and the nutation angles are calculated according to the IAU 1980 nutation theory (Wahr, 1981).

In respect to the continental drift history the IRIS-S stations can be divided into three groups. Santiago and Fortaleza have observed for too short a period to detect any significant motion. Wettzell, Westford and Richmond have shown relative drifts which agree with the NNR-NUVEL-1 model to within 1 mm in the north and east components while HartRAO and Mojave disagree at a 6 to 8 mm/year level (Ryan et al., 1993). Taking these peculiarities into account the motions of the stations are parametrized as follows: Wettzell, Westford and Richmond move according to NNR-NUVEL-1; Santiago and Fortaleza are supposed to have zero motion and horizontal drift components are estimated for HartRAO and Mojave. Vertical drifts for these stations are constrained to zero since the network and the duration of the series are not considered sufficient for a reliable estimation of height variations at these stations.

3. Results

The formal errors of the radio source positions versus declination are depicted in figure 1. The sources cover a range in declination from -77° to +81°. The average formal error is 0.20 mas in Right Ascension (* $\cos\delta$) ranging from 0.07 to 0.77 mas. The higher errors are mainly due to the small number of observations of these sources. The average formal error in declination is 0.30 mas varying from 0.17 to 1.07 mas. Figure 2 depicts the individual errors together with the respective number of observations. In order to better understand these results it is important to note that until June 1992 the selection of sources was restricted to -30° in declination due to the visibility limitations of the northern stations. Only with the advent of a second station in the southern hemisphere a few sources further south were included. At present the southern sky is surveyed to find more candidate sources for the geodetic schedules.

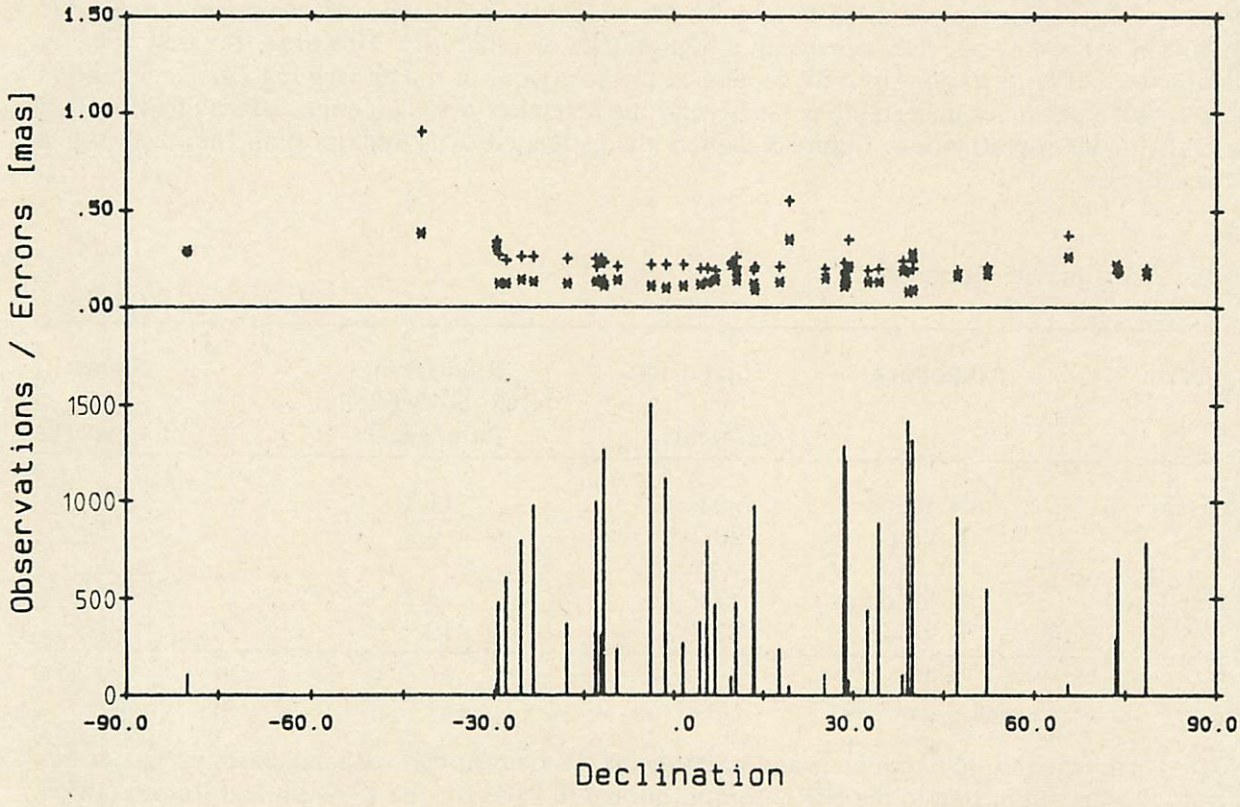


Fig. 2, Formel errors in Right Ascension (*) and Declination (+) versus Declination (top part) together with the respective number of observations (bottom part)

The station coordinates relative to Wettzell are listed in table 1. The average formal errors are in the range of ±1 cm. The errors of Fortaleza are much larger since so far it has only participated once.

Table 1, Estimated Positions (Reference Date Jan 01, 1988)

Station	X [m] Sigma [m]	Y [m] Sigma [m]	Z [m] Sigma [m]
Wettzell	4075540.0480	931735.1200 Reference	4801629.2800
Mojave	-2356170.9549 0.0069	-4646755.8316 0.0087	3668470.6349 0.0121
Richmond	961258.0902 0.0069	-5674090.0133 0.0058	2740533.8021 0.0091
HartRAO	5085442.8352 0.0131	2668263.2626 0.0112	-2768697.1728 0.0110
Westford	1492206.6987 0.0064	-4458130.4731 0.0038	4296015.5237 0.0077
Santiago	1769692.9189 0.0136	-5044504.4164 0.0156	-3468435.0509 0.0111
Fortaleza	4985369.9462 0.0525	-3955020.2049 0.0399	-428472.4129 0.0163

The drift components of Mojave and HartRAO are listed in table 2 together with the differences to the NNR-NUVEL-1 model which show quite significant deviations. Test computations with a modified Earth orientation series have shown that the north velocity components are stable to within 1.5 mm/year, thus providing a high degree of reliability. However, the east velocity components of both stations heavily depend on the behaviour of the underlying Earth orientation series which produces uncertainties far beyond the formal errors. The implications of this effect are still under investigation. Figure 3 depicts the estimated drift vectors with their one sigma error ellipses.

Table 2, Estimated Velocities

Station	Component	Total drift [mm/year]	Relative to NNR-NUVEL-1 [mm/year]	Sigma [mm/year]
Mojave	N Veloc.	-0.6	11.7	1.7
	E Veloc.	-20.2	-7.5	1.3
HartRAO	N Veloc.	17.7	-3.3	2.8
	E Veloc.	32.3	10.7	3.7

The Earth orientation parameters and nutation offsets determined with databases up to December 1992 were submitted to the IERS Central Bureau in Paris for the 1992 Annual Report (IERS, 1993). The average formal errors and the RMS differences relative to the IERS combined solution

are listed in table 3. The numbers agree well with those submitted by other institutions. In the Y pole component the agreement is even better which can be attributed to the favorable geometry of the network for the determination of this component.

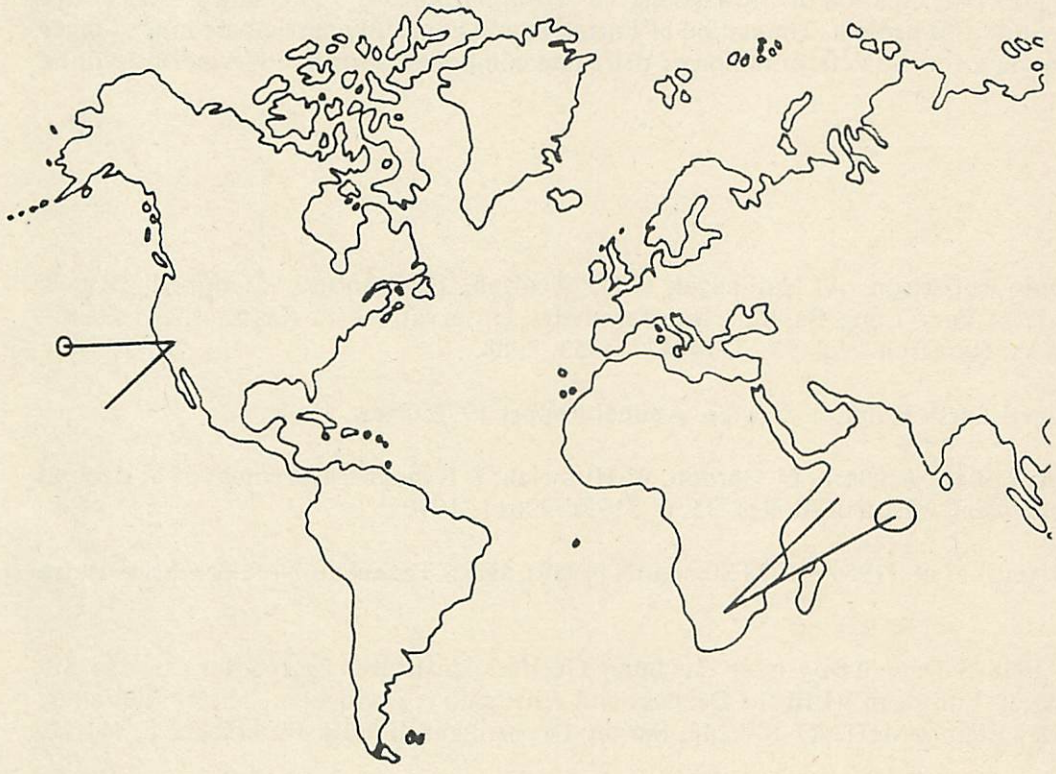


Fig. 3, Estimated horizontal displacement vectors with error ellipses and NNR-NUVEL-1 model vectors

Table 3, Earth Orientation Parameters from IRIS-S Experiments

	x_p [mas]	y_p [mas]	UT1 [ms]	ψ [mas]	ε [mas]
Average Formal Errors	0.37	0.28	0.020	0.52	0.24
RMS Differences wrt. IERS	0.45	0.36	0.042	0.78	0.28

4. Conclusions

The IRIS-S network is now well established. With stations in both hemispheres and long baselines in east-west as well as in north-south direction it provides a favorable geometry for the determination of reliable and consistent Earth orientation parameters, station coordinates and radio source positions. The strategy chosen for the analysis of the IRIS-S data aims at an optimal parameter selection avoiding too many adjustable parameters on the one side and too heavy constraints on the other. Restricting the input data just to IRIS-S experiments and using the procedures presented we produced homogenous and significant results.

Unfortunately, the participation of Santiago had to be discontinued too soon and no drift rates can be derived within this project. The station of Fortaleza will hopefully participate much longer so that sufficient data for the determination of drift rate components for South America will be available.

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VLBI and GPS Measurements of the Fennoscandian Uplift

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Abstract. We are investigating the post-glacial rebound in Fennoscandia. Ten years of observations between Wettzell and Onsala have shown the potential of using VLBI on a regional scale. The addition of a new VLBI station at Ny Ålesund, Spitzbergen and the possible use of more accurate "mobile" VLBI will add new information. In order to make a more dense geodetic network a permanent GPS network (SWEPOS) has been established. Presently, GPS receivers have been installed at 19 sites in Sweden. Similar networks are being built in Norway and Finland. An independent GPS campaign was performed within the DOSE program in August 1993. Besides the permanent Swedish GPS network and the global GPS tracking network eight Finnish stations, one Russian, and one Swedish site were added. Results from VLBI measurements are discussed and preliminary results from the permanent Swedish GPS network are shown. The results obtained from a "standard" analysis of the data from the permanent GPS network in Sweden show repeatabilities in baseline length on the order of 1.5 mm + 2.2 ppb and a factor of 4 worse for the vertical component.

1. Introduction

Over the last decade space techniques such as Very-Long-Baseline Interferometry (VLBI) and Satellite-Laser-Ranging (SLR) have been used in order to monitor Earth rotation, polar motion, and global plate tectonics. The new challenge is to separate global and regional phenomena. One such example of regional crustal deformation is the uplift in Fennoscandia following the last deglaciation period.

The last million years of the Earth's history has been characterized by a series of glacial cycles, each with a duration of approximately 100 kyr [*Shackleton*, 1967]. In turn, each cycle has been characterized by a slow glaciation phase, followed by a much more rapid deglaciation. The last glacial maximum occurred about 20 kyr ago, with much of the ice subsequently dissipating in just 10–15 kyr [*Denton and Hughes*, 1981]. The last deglaciation was so recent and so massive that the Earth presently remains in a state of isostatic disequilibrium. The term post-glacial rebound is normally used to describe the adjustment when the Earth returns to a state of equilibrium.

In a long term program many organizations are building up a network integrating a variety of different techniques such as VLBI, SLR, gravimetry, and the use of the Global Positioning System (GPS). In addition to the already existing European VLBI sites a new station is being built at Ny Ålesund, Spitzbergen. Furthermore, a number of sites have been visited by a mobile VLBI station. Plans about additional sites are being investigated. A more dense geodetic network has been accomplished by the establishment of permanent GPS stations in Norway and Sweden. Also Finland is planning a permanent GPS network and several sites have been monumented. A GPS campaign was run in August 1993, making use of monumented sites which have not yet been occupied by a GPS receiver.

In this paper, we will first describe the VLBI and GPS networks and the expected accuracy, then present preliminary results from a few weeks of operation of the Swedish GPS network. Finally, we will give the conclusions and discuss the geophysical applications of this study.

2. The Growth and Use of the European VLBI network

The existing global and regional VLBI networks are not of sufficiently small scale in order to allow for detailed studies of the post-glacial rebound presently occurring in the northern part of Europe and in North America. They can, however, provide important results for specific baselines. There are two major arguments for incorporating VLBI data in post-glacial rebound studies. VLBI data give: (1) very accurate rate estimates for particular baselines, and (2) independent results to guard against unmodeled errors affecting the results of GPS networks.

Let us now concentrate on the European VLBI network and the post-glacial rebound in Fennoscandia. The most often measured baseline in Europe is the one between Onsala and Wettzell. The demonstrated repeatability of the baseline length estimates is about, or just below, 4 mm [*Elgered and Davis*, 1993]. However, the present data acquired over approximately 10 years cannot yet be used to claim a detected motion. Depending on the analysis method rate estimates typically vary between 0 and -1 mm/year even though the formal one-sigma error of this rate is of the order of 0.2 mm/year.

Given that the accuracy of the fixed station VLBI has been significantly better than has mobile VLBI it is clear that the existing, relatively small amount of, mobile VLBI data at Metsähovi, Tromsö, and Trysil are of little use in studies of postglacial rebound.

The future operation of the Ny Ålesund VLBI station on Spitzbergen is, however, an interesting addition to the European network. We note, however, that at least several years of observations are needed before a rate estimate with an accuracy in the range of sub-mm/year is available.

3. The permanent Swedish GPS network (SWEPOS)

A permanent network of GPS receivers have been established in Sweden by the National Land Survey of Sweden and the Onsala Space Observatory. The location of the sites are found in Figure 1. The GPS network has been established in order to make the geodetic network within Sweden more dense and supply other user groups with data. The monuments are three meter high concrete pillars build on solid rock (Figure 2) with an internal control system to keep the temperature stable. There are three different GPS receiver types in the network, namely 15 TurboRogues, 3 Ashtech P12, and 1 Rogue SNR-800. Every station will be equipped with uninterruptable power supplies (UPS) and PC computers. The data are automatically transferred once per day via telephone modems to an operation center and are stored on disk as well as on DAT tapes. The data formats are both raw binary and compressed RINEX data. The present sample rate is 30 seconds which will be changed to 15 or sometimes even 5 or 1 seconds depending on the demands from groups involved in other applications of GPS. All data are examined and analyzed within a day or two after the actual collection of the data. For the standard analysis we use GIPSY Release 2 [*Lichten and Border*, 1987], developed at Jet Propulsion Laboratory (JPL), on HP-workstations. The Bernese Software version 3.4 [*Rothacher et al.*, 1990] is available for independent checks of the solutions.

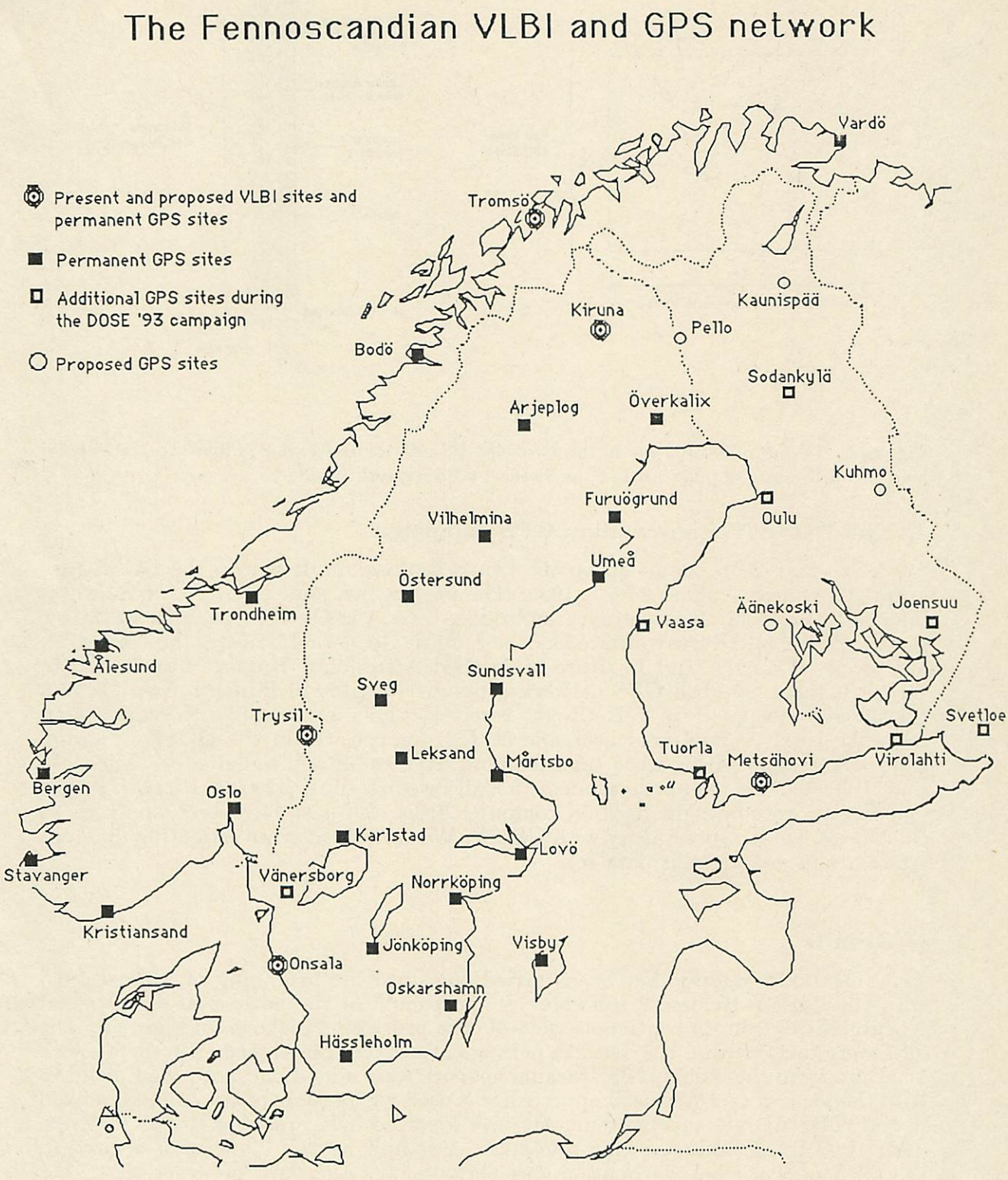


Figure 1. The Fennoscandian VLBI and GPS network

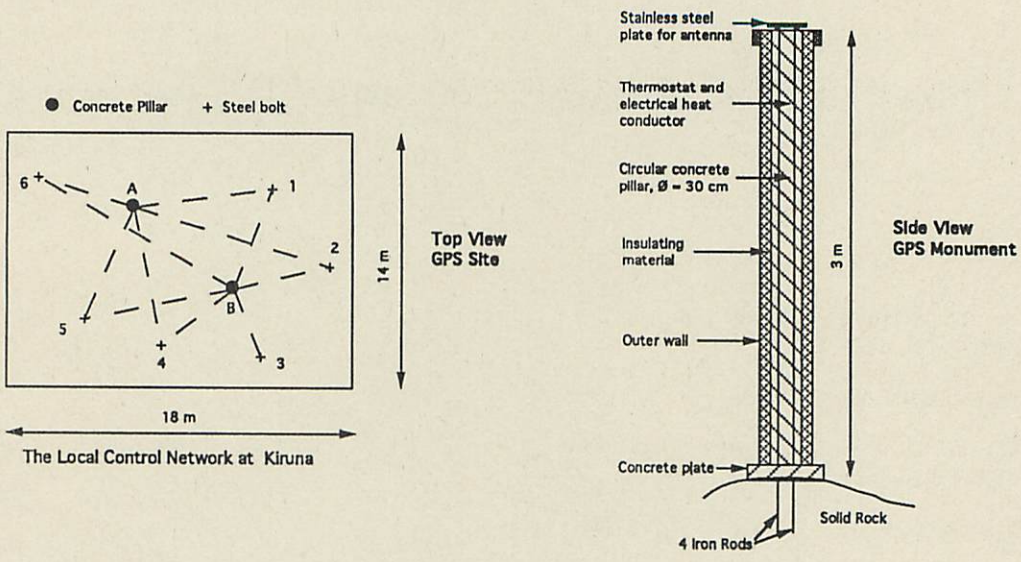


Figure 2. Layout of Kiruna site in the Swedish GPS network (left). A,B: Pillars. 1-6: Reference markers. Schematic of pillar used in the Swedish GPS network (right).

4. The DOSE/Fennoscandian GPS campaign

The first GPS campaign on the Fennoscandian uplift within the DOSE program was run on August 24–27, 1993. The project is a joint effort of the Smithsonian Astrophysical Observatory, Cambridge, USA, the Onsala Space Observatory, the National Land Survey of Sweden, the Finnish Geodetic Institute, the University of Toronto, Canada, and Institute of Applied Astronomy, Russia. In addition to the permanent Swedish GPS network a number of sites in Finland, Sweden, and Russia were occupied by TurboRogue receivers. This was possible through a loan from the receiver pool held available at JPL for use within the DOSE program. Data were collected for more than four full days at all additional sites. The data were collected via telephone modems for all Swedish sites. The data from Finland and Russia were brought back on computer disks. All data have been analyzed at the Onsala Space Observatory with GIPSY. We are currently investigating different strategies to analyze this data set.

5. Results

The daily analysis has been carried out since the beginning of August 1993 with the GIPSY Release 2 software. A "snapshot" of the horizontal and vertical repeatabilities from 14 continuous days of data processing is shown in Figure 3. The data were taken within the Swedish permanent network on August 28 to September 10. Data from the global GPS tracking network were added and processed together with the local data. A fiducial approach was used where some of the sites were fixed in the ITRF'91 reference system. All data reported here are from Rogue receivers which had full P-code tracking available. A sample rate of 30 seconds is used in the GPS network but decimation was performed in the data preprocessing. For this data set we decimated the data to an effective sample rate of 600 seconds. All data above 15 degrees in elevation angle were used and no serious problems with neither satellites nor receivers have been detected. However, we followed the suggestion from the IGS processing centers about removing certain satellites from the solutions during a few days of the reported data set. Adjusting straight lines to

the repeatabilities in Figure 3 indicates long term repeatabilities on the order of 1 mm + 2 ppb and 3 mm + 10 ppb for the baseline length and the vertical component, respectively. These results were achieved without attempting any bias-fixing due to the fact that the software is not yet ready for dealing with such an extensive data set. The repeatabilities and estimated length vectors agree well with those obtained using earlier data [*Johansson et al.*, 1992; *Johansson et al.*, 1993].

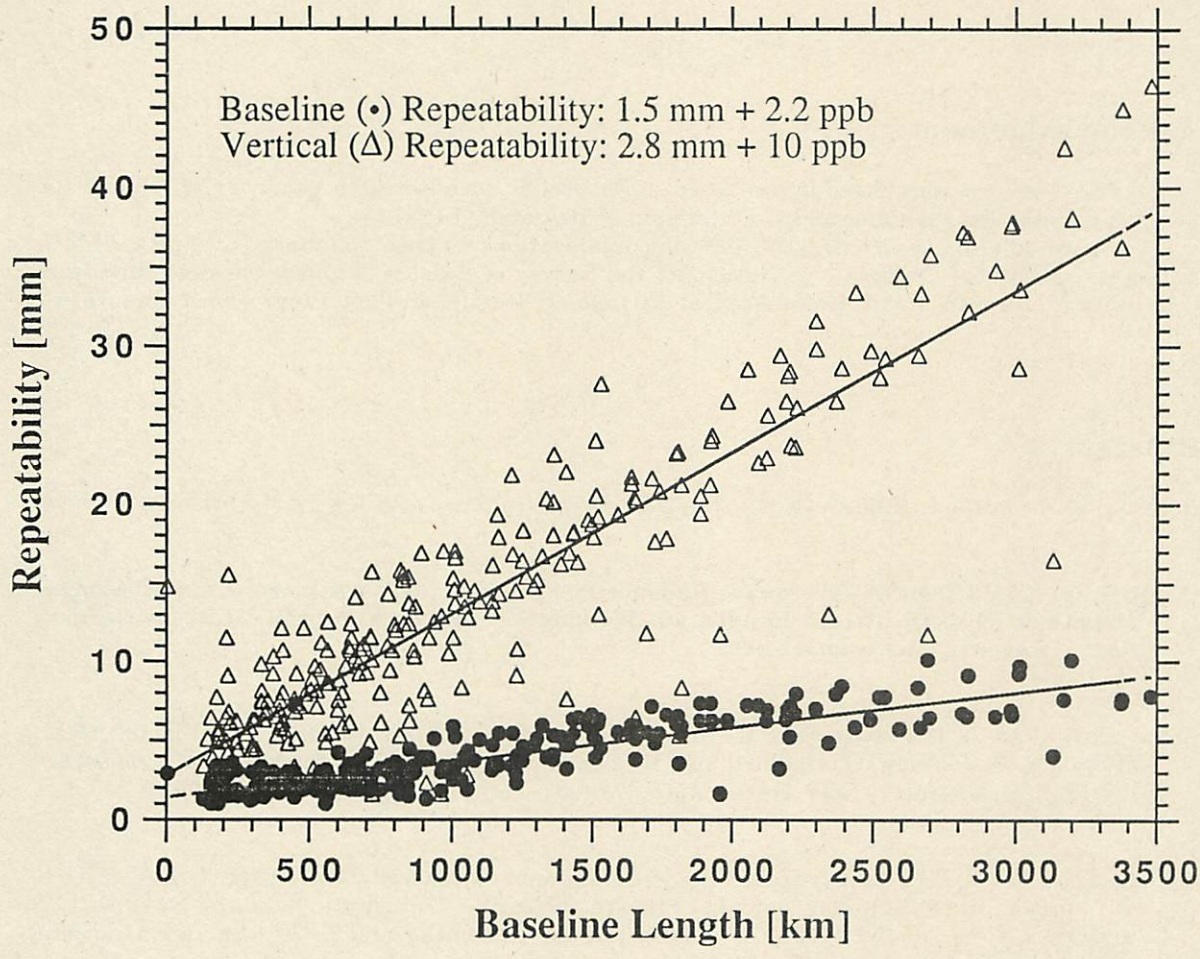


Figure 3. Repeatability for the baseline length and the vertical component as a function of baseline length.

6. Conclusions and future work

The SWEPOS network is a permanent installation which will bring new raw data continuously. The data have to be processed and stored on a daily basis. We are currently investigating different methods of which strategy that should be used for this analysis. Furthermore, we are separately studying the influence of possible sources of error on our results. Example of such studies are multipath, propagation delay due to atmospheric water vapor [*Elgered and Davis*, 1993], and ocean loading effects.

We are planning to repeat the Fennoscandian GPS campaign at least once per year for the next coming years. The long term goal is of course to have permanent receivers on all sites.

The results reported during preliminary studies and the initial measurements in the permanent Swedish GPS network imply that the accuracy of the estimates of

relative position will be about 3 mm for the horizontal component and 13 mm for the vertical, ignoring baseline-length dependencies. Since the network is operating continuously we will obtain daily estimates of relative position. A preliminary calculation shows that after 5 years of observations our rate uncertainties will be 0.3 mm/year horizontal and 1.2 mm/year vertical [*Johansson et al.*, 1993].

The rate uncertainties above can be compared with Figure 4, which provides predictions, based on a standard Earth model and ice history, of the horizontal and vertical deformations rates due to isostatic adjustment along a profile from Luleå, Sweden, to Wettzell, Germany [*Mitrovica et al.*, 1993].

Acknowledgements

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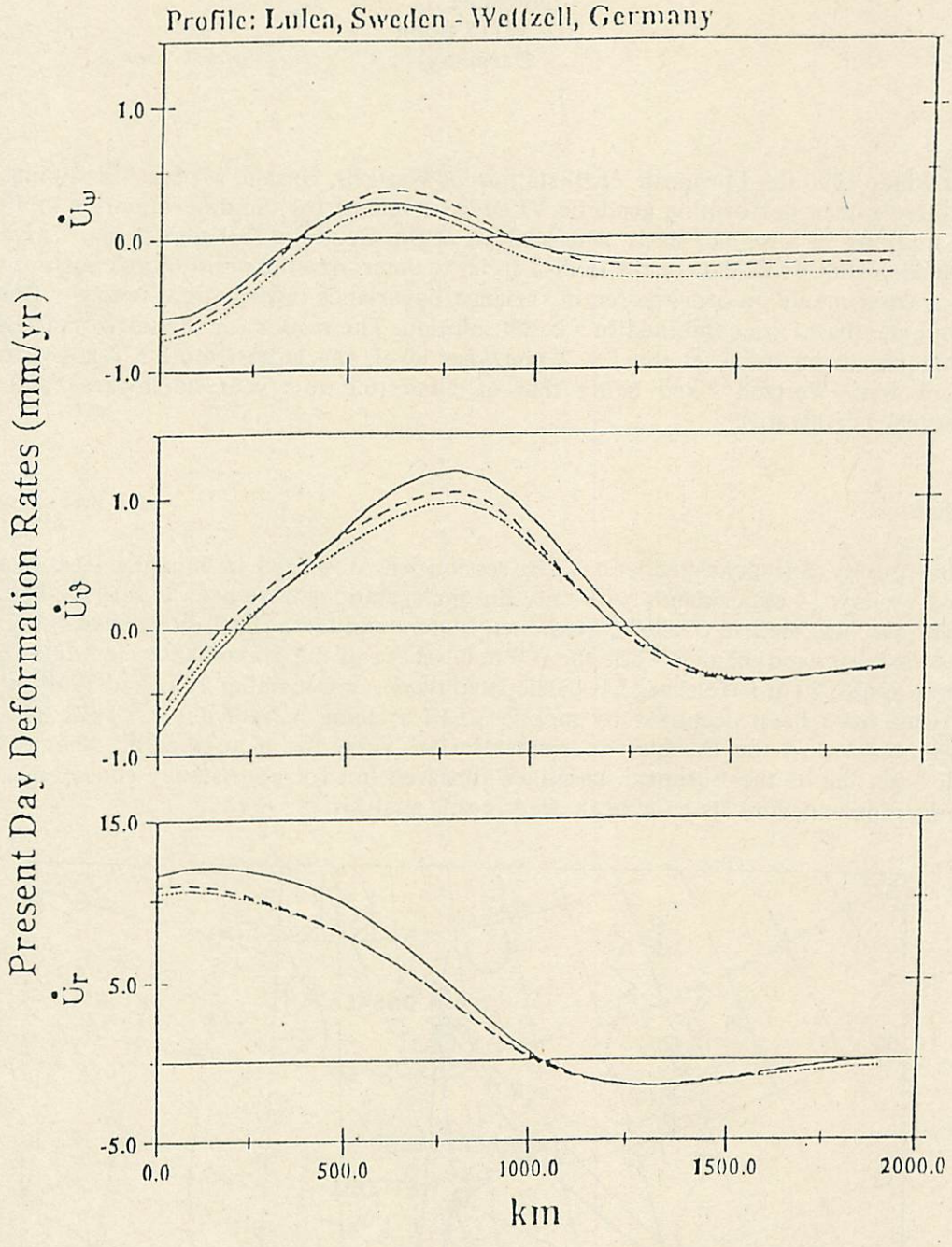


Figure 4. The present day three-dimensional velocity computed along a great circle profile from Luleå (about 10 km north of Furuögrund), Sweden to Wettzell, Germany. The top, middle, and bottom frames of the figure refer to the three components of velocity in the local cartesian reference frame. These are, respectively, $\dot{U}_\Psi$ (local east), $\dot{U}_\vartheta$ (local south), and $\dot{U}_\Gamma$ (local up, or radial). All calculations were performed using the standard Earth model, and the Pleistocene ice loading history adapted from ICE-3G deglaciation chronology. The different lines on each frame are distinguished on the basis of the representation of the ocean load adopted in the calculations. From *Mitrovica et al.*, 1993.

European Baseline Rate Determinations with VLBI

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Abstract. Since 1990 the European VLBI stations of Wettzell, Onsala, Madrid, Medicina, Matera and Noto have been performing geodetic VLBI experiments for the determination of European tectonic motions on a regular basis. The analysis at the Geodetic Institute of the University of Bonn is made using VLBI data of the IRIS-S series to determine the radio source positions for the European experiments. In order to retain variance/covariance information, both the IRIS-S and the Europe databases are combined in a batch solution. The results for the horizontal drift rates are considered to be stable at the 1 - 2 mm/year level, the largest motion relative to NNR-NUVEL-1 with Wettzell fixed being that of Noto (6.0 mm/year northward) and Matera (6.5 mm/year northward).

1 Introduction

The first purely European geodetic VLBI session was observed in January 1990 (Campbell, 1991) and by now 14 experiments with only European stations have been observed. The stations at Wettzell, Onsala, Madrid (DSS65), Medicina, Matera and Noto form the core of the European VLBI network for geodynamics while the 100 m telescope of the Max-Planck-Institute for Radio Astronomy (MPIfR) at Effelsberg has particpated twice, in December 1991 and 1992. A number of platforms have been occupied by mobile VLBI systems in recent years with two mobile sessions embedded in the Europe experiment series. There are a number of other sessions in which at least one of the European baselines appeared but for consistency considerations only genuine Europe experiments have been used in this analysis.

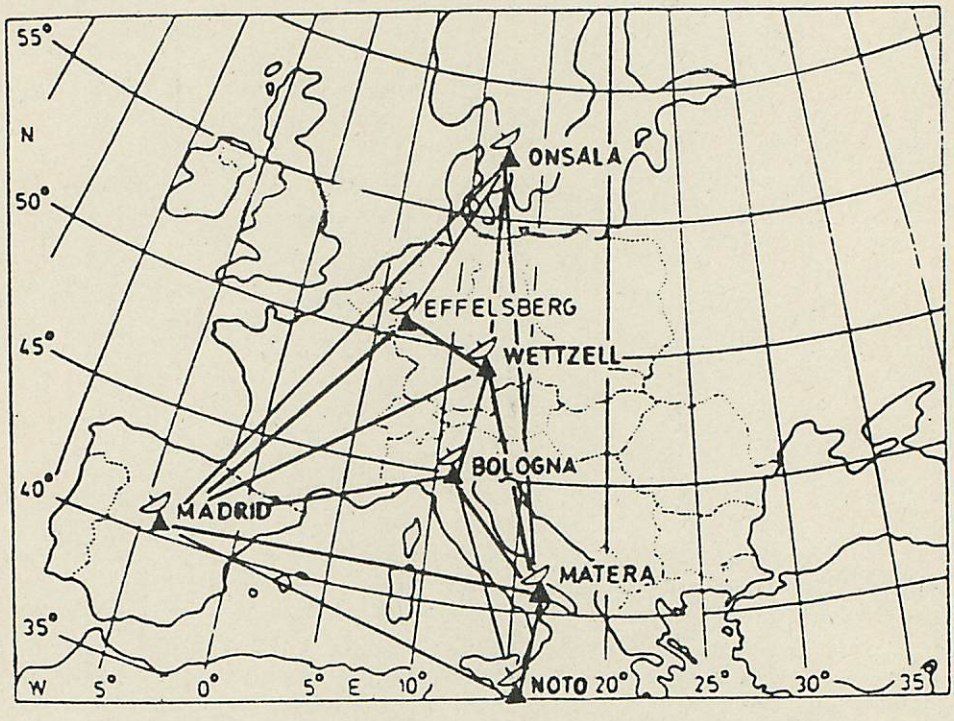


Fig. 1, The European Geodetic Fixed Station VLBI Network

2 Data Analysis

The data analysis of the European experiments was performed with the CALC/SOLVE/GLOBL software package (Caprette et al., 1990) on the basis of the IERS 1989 standards (McCarthy et al., 1989). For the determination of the radio source positions all 14 databases of the Europe experiments were combined in a batch solution with 42 databases of the IRIS-S series which are regularly analysed at the Geodetic Institute in Bonn (Nothnagel, 1993, this volume). Thirty-two of the radio sources observed by the European network are also observed with the IRIS-S network as compared to 9 sources which are observed only in the Europe experiments. This ratio provides a reasonable overlap for a reliable adjustment of the European experiments.

The IRIS-S databases used span a period from December 1989 to June 1993 and include the stations Wettzell, Westford, Richmond, Mojave, Hartebeesthoek, Santiago and Fortaleza. In the batch solution the coordinates of Wettzell were kept fixed at the ITRF 1992 values (IERS, 1993) while station positions were estimated for all other stations. The motions of the stations were parametrised as described in the companion paper by Nothnagel (this volume): Wettzell, Westford and Richmond move according to NNR-NUVEL-1; Santiago and Fortaleza are supposed to have zero motion and horizontal drift components are estimated for Hartebeesthoek and Mojave.

In the batch solution the coordinates of all European stations (except Wettzell) were treated as arc parameter, i.e. new station coordinates were estimated for each session. In order to avoid singularities the Earth orientation parameters had to be kept fixed using the US Naval Observatory (USNO) Rapid Service EOP series which is published in daily intervals (IERS Bulletin A). Nutation offsets were estimated in all experiments. The atmospheric excess path delay was estimated as a piece-wise linear function with one offset parameter and an additional rate parameter every three hours for each station. The parametrization of the station clocks was done in a conservative fashion mainly using second order polynomials.

3 Results

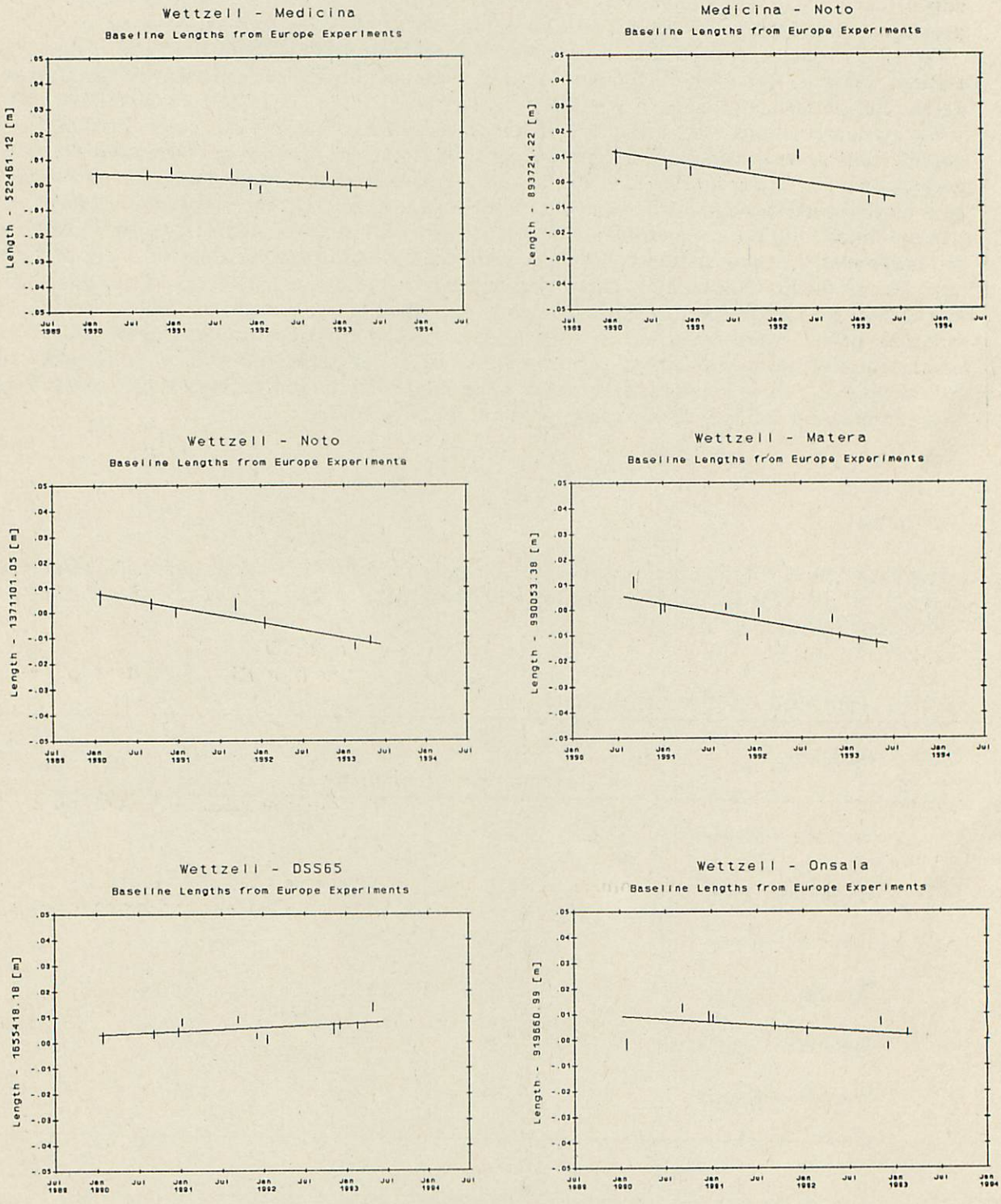
In a first type of solution individual baseline lengths for each experiment were calculated from the sets of coordinates. Table 1 lists some of the estimated baseline length rates within the European network:

Table 1, Estimated Baseline Length Rates

Baseline	Rate [mm/year]	Sigma [mm/year]	WRMS [mm]
Wettzell - Medicina	-1.6	±0.7	2.0
Medicina - Noto	-5.3	±1.6	4.4
Wettzell - Noto	-6.0	±0.9	2.3
Wettzell - Matera	-6.5	±1.6	3.8
Wettzell - Madrid	1.4	±1.1	3.0
Wettzell - Onsala	-2.4	±1.5	4.0

The closure of the rates of the Wettzell - Medicina - Noto baselines which are more or less oriented in the same direction fits very well. The respective weighted RMS scatter about the straight line fits of all baselines express the superior quality of the Europe-only experiments.

However, the rate of -2.4 mm/year for the Wettzell - Onsala baseline raises some questions since such a drift has not been detected when using different series of experiments with longer observing periods (Ryan et al., 1993). Figures 2 to 7 depict the evolution of the baselines shown in table 1.



Figures 2 -7, Baseline length determinations

As mentioned earlier the 100 m telescope of the MPIfR at Effelsberg so far has participated only twice in the European experiments. The two sets of coordinates with a time base of one year agree at the level of 1.7 mm in the east and 4.5 mm in the north component. The formal errors in each solution are about ±1 mm in both components. The two determinations of the baseline between Wettzell and Effelsberg with a length of 457 km agree at the level of 4 mm which underlines the excellent repeatability. The agreement of the relative height component is about an order of magnitude worse (36 mm). The formal errors of this component (±3-5 mm), however, do not reflect the weakness of this determination. Nevertheless, these first epoch measurements form a very promising basis for a continuous monitoring of the central European tectonic stability.

A second type of VLBI batch solution permits to estimate station coordinates and drift rate components for each station (dx/dt, dy/dt and dz/dt) simultaneously. At present this type of solution is in preparation.

4 Conclusion

After more than 3 years of observations with purely European network configurations the results start to become very stable. The uncertainties of the drift rates are at the level of 1 to 2 mm/year and the scatter of the baseline length determinations from individual experiments is less than 5 mm. The quality of the data should soon permit the determination of displacement vectors for each station.

With the support of the EC and the indispensable efforts of the individual groups at the observatories in the participating countries the aim of millimeter accuracy in the displacement rates and directions can soon be achieved with the 6 core European observatories. Densification with other stations, even if they observe only on an annual basis, and further extensions to the east and north are valuable additions to the existing network.

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ANALYSIS OF THE EUROPEAN MOBILE VLBI CAMPAIGNS

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Abstract

Since 1989 several mobile VLBI campaigns have been carried out in Europe as the joint effort of several Institutions. 13 sites have been occupied during these campaigns. Two of these, the Norwegian stations of Tromsø and Trysil, have been revisited. In particular Trysil has been the winter site for MV-2 during 1992 and 1993. The VLBI Analysis group of the Geodetic Institute of the Norwegian Mapping Authority has analyzed the entire set of data using the software package OCCAM V3.2. Each experiment has been processed with several strategies in order to obtain the best possible solutions. In this paper we present the main results of this work and the conclusions that can be drawn from our current experience with the mobile VLBI data.

Introduction

Several institutions in Europe, listed in Table 1, have collaborated with the United States National Oceanographic and Atmospheric Administration in the organization and observation of mobile VLBI campaigns in Europe. The main objectives of these campaigns were the densification of the geodetic VLBI network in Europe and the study of interesting geological sites, including the north of Africa.

The 1989 campaign with the MV-3 mobile system and the extended use of the MV-2 system since 1991, have produced first epoch measurements for several stations in central Europe plus two rather interesting geological places, Iceland and the Azores (Portugal). Moreover, the two Norwegian sites at Tromsø and Trysil have been reobserved, so first analysis of repeatabilities in time can be obtained. Unfortunately, due to political instabilities in the area, it was considered unsafe to observe the planned African station.

Mobile campaigns

In 1989 the MV-3 mobile system was brought to Europe for a summer campaign in which six sites were observed: Hohenbünstorf (Germany), Metsahovi (Finland),

Tromsø (Norway), Carnousty (UK) and Brest and Grasse (France).

In the autumn of 1991, the MV-2 system was moved to Europe for an extended stay. The Norwegian Mapping Authority was responsible for the winter season observations in Trysil. The 1992 summer campaign through Europe included sites at Toulouse (France), Azores Islands (Portugal), Hohenpeissenberg, Kirschberg and Karlsburg (Germany), Høfn (Iceland) and again Tromsø (Norway). In March 1993 a new series of observations was performed at Trysil.

Figure 1 illustrates the location of the mobile and fixed VLBI sites in Europe after these campaigns. Table 2 collects the dates and networks observed with each mobile site.

Institution	Country
Geodetic Institute of Finland	Finland
Institut Geographique National	France
Institut für Angewandte Geodäsie	Germany
Ocean Survey	Great Britain
Iceland Geodetic Institute	Iceland
Statens kartverk (Norwegian Mapping Authority)	Norway
Chalmers University of Technology	Sweden

Table 1. Participant Institutions in the European mobile VLBI campaigns

Data Analysis

We have analyzed the mobile VLBI experiments using the software package OCCAM V3.2 (a status report on the package can be found elsewhere in this proceedings). Each experiment has been analyzed following a common strategy. Wettzell was observed in most of the sessions, so it was a straightforward decision to use it as reference station when possible.

Two different kinds of parametrizations have been applied to the analysis:

A. Wettzell as reference station and the a-priori Earth Orientation Parameters given by the IERS Bulletin B values to fix the reference frame. If Wettzell data were not available, other station was taken as reference.

B. An internal definition of the reference frame, by fixing the direction between Wettzell and a second station, plus the height component of a third station. The three stations determining the reference were selected for each site, considering the networks observed. This was only used when three or more stations were available in addition to the mobile site.

In both cases we have also estimated nutation offsets. In order to have a better knowledge on the possible influence of the tropospheric models, we have used both Davis' model (Davis, 1985) and Lanyi's model (Lanyi, 1984) in different runs to check their influence on the analysis.

The analysis was done with a Kalman Filter technique where tropospheric corrections and clock offsets have been considered random walk stochastic processes. The power spectral densities of the white noises associated with the random walk precesses have been estimated from the data sets themselves (Zarraoa, 1992).

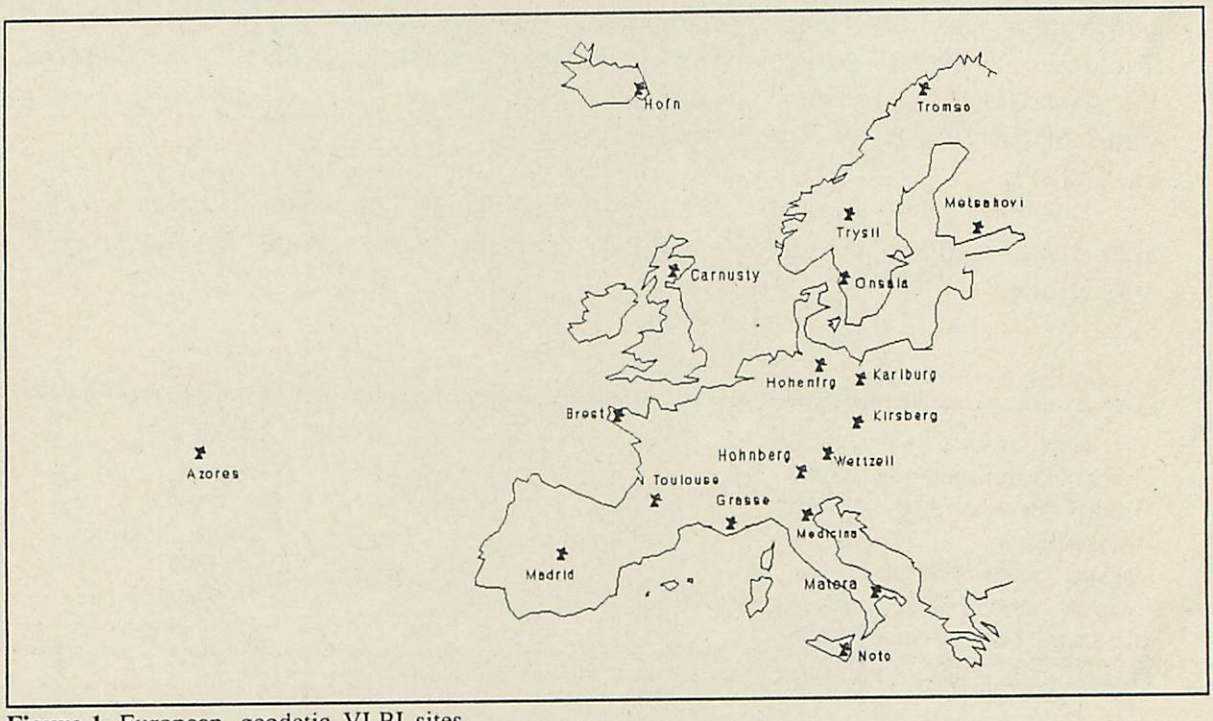


Figure 1. European geodetic VLBI sites.

Results

Table 3 presents the estimated coordinates of the mobile sites in a Cartesian reference frame referred to the a-priori Wettzell coordinates. The vertical component (radial) is also shown. These values have been computed as the mean of one single value for each experiment. The formal errors of the mean have not been corrected by the post-fit chi-square factor, except when this was bigger than 1.

In table 3 we also include the repeatabilities of the estimates as computed including the results for all the four possible strategies followed in each experiment, so they reflect also the internal consistency of the experiments, as well as the repeatability in time. Because of this, some formal errors bigger than the corresponding repeatabilities may be found in tables 3 and 4.

Table 4 collects the baseline length values from the mobile sites to the rest of the sites along with the repeatabilities of the results.

The significance of the numbers in tables 3 and 4 can be assessed by considering the details of the individual analyses of each session. This will also illustrate the kind of problems found during the analysis.

Mobile site / Equipment	Date	Equip.	Network
HOHENFRG (Germany)	21 June 1989	MV-3	Wettzell-Noto-Westford-Richmond-Mojave
	23 June 1989		Wettzell-Noto
	24 June 1989		Wettzell-Noto
	25 June 1989		Wettzell-Noto
	26 June 1989		Wettzell-Noto-Westford-Richmond-Mojave
METSHOVI (Finland)	5 July 1989		Wettzell-Onsala
	6 July 1989		Wettzell-Onsala-Westford-Richmond-Mojave
	8 July 1989		Wettzell-Onsala
	9 July 1989		Wettzell-Onsala
	11 July 1989		Wettzell-Onsala-Westford-Richmond-Mojave
CARNUSTY (UK)	18 Aug. 1989	MV-3	Wettzell
	19 Aug. 1989		Wettzell
	20 Aug. 1989		Wettzell-Westford-Richmond-Mojave
	22 Aug. 1989		Wettzell
BREST (France)	30 Aug. 1989	MV-3	Wettzell-Noto-Westford-Richmond-Mojave
	1 Sep. 1989		Wettzell-Noto
	2 Sep. 1989		Wettzell-Noto
	4 Sep. 1989		Wettzell-Onsala-Noto-Westford-Mojave
GRASSE (France)	12 Sep. 1989	MV-3	Wettzell-Noto
	13 Sep. 1989		Wettzell-Noto
	14 Sep. 1989		Wettzell-Westford-Richmond-Mojave
	16 Sep. 1989		Wettzell
TOULOUSE (France)	10 May 1992	MV-2	Wettzell
	11 May 1992		Wettzell-Westford-Mojave
	12 May 1992		Madrid-Medicina-Matera
AZORES (Portugal)	29 May 1992	MV-2	Wettzell-Westford-Richmond
	30 May 1992		Wettzell-Westford-Richmond
	1 June 1992		Wettzell-Westford-Mojave
	2 June 1992		Wettzell-Westford-Richmond
HOHNBERG (Germany)	15 June 1992	MV-2	Wettzell-Westford-Gilcreek
	17 June 1992		Wettzell
	18 June 1992		Wettzell
KIRSBERG (Germany)	25 June 1992	MV-2	Wettzell-Onsala
	26 June 1992		Wettzell-Onsala
	28 June 1992		Wettzell-Onsala
KARLBURG (Germany)	6 July 1992	MV-2	Wettzell-Onsala-Westford-Mojave
	7 July 1992		Onsala-Madrid-Medicina-Matera
HOFN (Iceland)	20 July 1992	MV-2	Wettzell-Onsala-Westford-Gilcreek
	22 July 1992		Richmond
	26 July 1992		Wettzell-Onsala-Westford-Gilcreek
	27 July 1992		Wettzell-Onsala-Westford-Gilcreek
TROMSO (Norway)	30 July 1989	MV-3	Wettzell-Onsala
	31 July 1989		Wettzell-Onsala-Westford-Richmond-Mojave
	1 Aug. 1989		Wettzell-Onsala
	2 Aug. 1989		Wettzell-Onsala
	25 Aug. 1992	MV-2	Wettzell-Onsala-Westford
	26 Aug. 1992		Wettzell-Onsala-Westford-Gilcreek
	28 Aug. 1992		Wettzell-Onsala-Westford-Gilcreek
	29 Aug. 1992		Wettzell-Onsala-Westford-Gilcreek
TRYSIL (Norway)	8 Nov. 1991	MV-2	Wettzell-Westford-Gilcreek
	15 Nov. 1991		Wettzell-Westford-Gilcreek
	14 Dec. 1991		Wettzell-Westford-Gilcreek
	20 Dec. 1991		Wettzell-Westford-Gilcreek
	7 Feb. 1992		Westford-Gilcreek
	21 Feb. 1992		Wettzell-Westford-Gilcreek
	13 Mar. 1992		Wettzell-Westford-Gilcreek
	20 Mar. 1992		Wettzell-Westford-Gilcreek
	8 Mar. 1993		Wettzell-Onsala-Westford-Gilcreek-NRAO85 3
	15 Mar. 1993		Wettzell-Westford-Gilcreek-NRAO85 3
	22 Mar. 1993		Wettzell-Westford-Gilcreek-NRAO85 3

Table 2. Experiments observed in the European mobile VLBI campaigns

Station	X-component Sigma (Repeat.)	Y-component Sigma (Repeat.)	Z-component Sigma (Repeat.)	Vertical comp. Sigma (Repeat.)
Wettzell Reference	4075540124.0	931735156.0	4801629190.0	
Hohenfrg	3778215078.8 6.4 (11.8)	698644665.1 1.7 (5.6)	5074053419.2 6.9 (13.3)	6364670584.0 8.6 (17.4)
Metshovi	2890652974.6 7.8 (14.0)	1310295234.2 9.2 (17.9)	5513958555.5 14.5 (25.2)	6362113420.4 16.7 (29.0)
Carnusty	3526416574.1 8.5 (11.4)	-171421197.0 5.7 (7.6)	5294098693.2 12.0 (14.5)	6363370184.6 14.4 (15.7)
Brest	4228877296.7 13.7 (27.8)	-333104193.7 3.1 (5.6)	4747180823.6 12.8 (21.7)	6366324481.9 18.1 (28.8)
Grasse	4581697870.1 5.6 (6.3)	556125634.8 5.0 (8.8)	4389351270.1 5.6 (5.4)	6369272773.9 7.8 (7.2)
Azores	4552174762.5 7.5 (16.5)	-2186664820.2 3.7 (5.5)	3882779634.8 6.6 (13.2)	6370225725.8 9.8 (18.2)
Toulouse	4627950220.0 20.8 (28.4)	119843548.7 4.4 (6.2)	4372862859.5 24.4 (34.5)	6368219162.7 31.8 (44.3)
Hohnberg	4213687458.6 11.9 (7.6)	820422842.2 3.0 (2.3)	4702784087.0 12.9 (13.5)	6367451119.1 17.5 (14.9)
Kirsberg	3879830959.1 4.2 (5.3)	987963226.2 2.6 (3.4)	4948713216.0 7.3 (9.4)	6365447517.8 8.0 (10.4)
Karlburg	3653204457.4 7.0 (9.3)	884427588.7 1.8 (2.5)	5135731991.1 19.2 (25.4)	6364264161.7 9.0 (17.5)
Hofn	2679650425.4 7.4 (11.0)	-727916507.9 4.9 (9.8)	5722807067.3 13.3 (13.2)	6360889055.6 14.9 (12.6)
Tromso	2102904280.4 4.5 (13.1)	721602490.0 6.8 (16.2)	5958201150.3 8.6 (20.8)	6359487206.0 9.3 (22.3)
Trysil	2988029362.0 2.7 (9.6)	655957020.9 2.8 (10.1)	5578668931.1 5.0 (13.9)	6362400965.0 7.4 (16.3)

Table 3. Estimated coordinates for the mobile VLBI sites with their formal errors and the repeatabilities in brackets. All values are in millimetres.

HOHENFRG (Hohenbünstorf)

The results for this station can be considered good. The overall repeatability of all the parameters are smaller than the 1-sigma formal errors of the individual results, which are comparable with those of the fixed stations.

It is interesting to note that the first session observed, 1989 June 21, produced serious ill-conditioned matrix problems in the Kalman filter, which were somehow related to Westford. Further investigation will be required on the source of such a problem. Our practical approach was to drop Westford from the analysis, but it still gives results differing from the trend of the other experiments.

METSHOVI (Metsahovi)

The analysis of the Metsahovi data has produced significantly poorer results than Hohenfrg. The repeatabilities were in general consistent with the formal errors, except for the y component, where the scatter was twice as large as that shown by the formal errors. But the formal errors themselves were extremely high, particularly for the vertical component, compared with the fixed stations.

Baseline	Length	Repeat.
HOHENFRG MOJAVE	8257097593.6+/- 3.9	19.8
HOHENFRG NOTO	1825225881.1+/- 3.6	6.3
HOHENFRG RICHMOND	7347945846.8+/- 7.0	18.4
HOHENFRG WESTFORD	5694164283.2+/- 5.2	12.0
HOHENFRG WETTZELL	465777116.1+/- 1.1	3.4
METSHOVI MOJAVE	8149935228.4+/- 19.6	9.1
METSHOVI ONSALA	784441965.7+/- 4.3	8.1
METSHOVI RICHMOND	7758613760.5+/- 16.6	21.8
METSHOVI WESTFORD	6059189116.6+/- 6.0	12.2
METSHOVI WETTZELL	1433414949.2+/- 2.3	4.6
CARNUSTY WETTZELL	1327033090.9+/- 5.5	9.0
CARNUSTY WESTFORD	4848716971.0+/- 9.8	9.0
CARNUSTY RICHMOND	6586356817.8+/- 12.3	11.5
CARNUSTY MOJAVE	7568098993.4+/- 15.2	16.1
BREST WETTZELL	1275263011.0+/- 3.1	6.1
BREST WESTFORD	4970790348.1+/- 9.2	5.2
BREST RICHMOND	6574959754.9+/- 24.6	7.1
BREST NOTO	2029686999.4+/- 4.6	8.8
BREST ONSALA	1480502022.1+/- 6.1	1.8
BREST MOJAVE	7945694729.6+/- 14.2	8.1
GRASSE WETTZELL	753160844.9+/- 2.5	4.5
GRASSE NOTO	1024494289.2+/- 4.0	2.7
GRASSE WESTFORD	5890367633.4+/- 12.5	6.6
GRASSE RICHMOND	7392007165.8+/- 18.0	12.4
GRASSE MOJAVE	8701934635.6+/- 17.7	23.8
AZORES WETTZELL	3285708979.1+/- 3.1	5.5
AZORES WESTFORD	3833239421.2+/- 3.3	5.3
AZORES RICHMOND	5134349274.3+/- 4.9	8.7
AZORES MOJAVE	7336430744.9+/- 11.9	9.4
TOULOUSE WETTZELL	1071524832.7+/- 3.5	2.4
TOULOUSE WESTFORD	5549471949.0+/- 9.9	2.3
TOULOUSE MOJAVE	8484962328.2+/- 14.3	18.6
TOULOUSE MADRID	588518725.3+/- 5.8	0.7
TOULOUSE MATERA	1295572692.4+/- 6.6	2.7
HOHNBERG WETTZELL	203089812.0+/- 2.9	2.6
HOHNBERG WESTFORD	5952734125.6+/- 13.3	6.8
HOHNBERG GILCREEK	6962098319.8+/- 15.6	12.8
KIRSBERG WETTZELL	251191926.3+/- 2.9	3.7
KIRSBERG ONSALA	704561010.5+/- 3.1	4.0
KARLBURG ONSALA	394283786.4+/- 12.0	8.7
KARLBURG WETTZELL	540583115.3+/- 4.4	8.7
KARLBURG WESTFORD	5823912971.2+/- 14.1	8.8
KARLBURG MOJAVE	8298158786.3+/- 20.1	15.9
KARLBURG MATERA	1497018356.3+/- 11.1	5.2
KARLBURG MEDICINA	1060755441.5+/- 9.7	4.8
KARLBURG MADRID	2005730990.9+/- 10.0	5.3
HOFN WETTZELL	2356166457.2+/- 3.6	3.7
HOFN WESTFORD	4166563735.1+/- 6.0	9.2
HOFN GILCREEK	5014113212.0+/- 6.6	9.0
HOFN ONSALA	1640016189.6+/- 3.2	2.5
HOFN RICHMOND	6025898970.0+/- 60.4	3.4
TROMSO WETTZELL	2296324587.5+/- 3.7	8.6
TROMSO ONSALA	1406156768.7+/- 3.2	8.0
TROMSO WESTFORD	5474070419.9+/- 15.7	32.6
TROMSO RICHMOND	7249939449.0+/- 14.9	8.0
TROMSO GILCREEK	4898530406.3+/- 7.5	10.3
TROMSO MOJAVE	7344759283.0+/- 16.1	2.9
TRYSIL WETTZELL	1364743199.5+/- 1.5	4.7
TRYSIL WESTFORD	5480563542.3+/- 5.3	15.8
TRYSIL GILCREEK	5678966122.7+/- 5.2	20.0
TRYSIL ONSALA	449292378.8+/- 3.7	2.8
TRYSIL NRAO85 3	6185201834.6+/- 10.6	20.6

Table 4. Baseline lengths, formal errors and repeatabilities with the mobile VLBI stations

Three of the observing sessions included only Wettzell and Onsala in addition to Metsahovi. One of them produced results inconsistent with the rest of the experiments, which may be caused by a rotation of the reference system.

One of the experiments of the IRIS schedule (89 July 11) was considerably noisier than the others, and small changes in the a-priori conditions produced large variations in results. We have kept what we considered the best solutions of the experiment in the final results presented here.

CARNUSTY (Carnousty)

The main concern with Carnousty was that three of the four sessions observed contained only the Carnousty-Wettzell baseline. This could affect the significance of the estimated coordinates. However, the results were quite consistent in both baselines and coordinates with repeatabilities at the formal error level or lower, although the formal errors are higher than, for instance, Hohenfrg.

The experiment of 1989 August 20 showed a remarkable influence of the tropospheric model used, with differences in all intercontinental baseline lengths of 2 to 3 cm. This is the biggest difference we have found from the use of the two tropospheric models.

BREST

The results at Brest are strongly influenced by the different network observed on each date and their incidence on the determination of the reference system.

The components show large values for the repeatabilities, up to 3 cm. in the vertical component. This is roughly twice as much as the results of the other stations. The baselines show relatively high scatter but much less than the deviation of the components. We attribute most of the differences in coordinates to small rotations of the reference frame.

GRASSE

When only European stations (Wettzell and Noto) are considered along with Grasse, the repeatability is very good, only 7 mm. in the vertical component. However, the IRIS session (1989 Sep. 14) was considerably noisier and the results in the components shifts relatively to the others.

TOULOUSE

The three experiments observed at Toulouse correspond to completely different networks, so the results are difficult to compare. We have made no effort to link the results of the two networks, so big differences are found in the estimated coordinates.

The results show relatively large formal errors for Toulouse for all the sessions.

AZORES

This site has produced some of the best results for a single epoch occupation. This is a direct consequence of the uniformity of the observational network, and also of the advantageous location of the station, in the middle of the network.

The repeatabilities are at the formal error level, which was reasonably good for all components. All baselines show a repeatability at the 1.5 parts per billion level with 3 or 4 sessions.

HOHNBERG (Hohenpeissenberg)

Hohnberg participated in only three experiments, two of which only with Wettzell. The results look very good, with small formal errors and good repeatabilities, due to the short baseline (200 Km.).

KIRSBERG (Kirschberg)

This site observed three sessions along with Wettzell and Onsala. The relatively short baselines produced a good repeatability for all components and lengths.

KARLBURG (Karlsburg)

The Karlsburg site was occupied in two sessions with completely different networks. The only link between them, apart from Karlsburg itself, was Onsala. The coordinates differ from one solution to the other and, of more concern, the baseline length estimate to Onsala changed by 1.5 cm between both sessions.

HOFN (Høfn)

The experiments at Høfn have been analyzed with special care because of two reasons, the geological interest of the site and the numerous difficulties found during the analysis. The data had lower quality than the rest of the experiments, so a detailed editing and reweighing had to be done. The final results show a very good appearance, both in formal errors and in repeatabilities, but the dependance of the results on the editing and reweighing, forces us to be cautious with respect to them.

There are not clear reasons for the poor quality found as most of the weak data came from stations traditionally very good like Onsala or Gilcreek, and they had to be reweighed in order to obtain better results.

TROMSO (Tromsø)

The situation in Tromsø is very similar to Høfn, with the exception that it is not clear the reason why the results show their large scatter. This is especially true for the coordinates, which show repeatabilities larger than the corresponding one-sigma formal errors. In the case of the lengths, the results for 1992 present better agreement, which makes us think that the scatter in the coordinates come from a weak definition of the reference system. In 1989, both coordinates and baseline lengths show large scatter.

Figures 2 and 3 show the results for the vertical component of Tromsø and of the baseline Tromsø-Westford, where the commented effects can be seen. The estimated rate between Tromsø and Westford is 22.2 mm/year. In the plots the two results coming from each of the two parametrizations described above as A and B are shown where possible. They correspond to the almost superimposed errorbars, where the A comes left of the B and has a larger error bar.

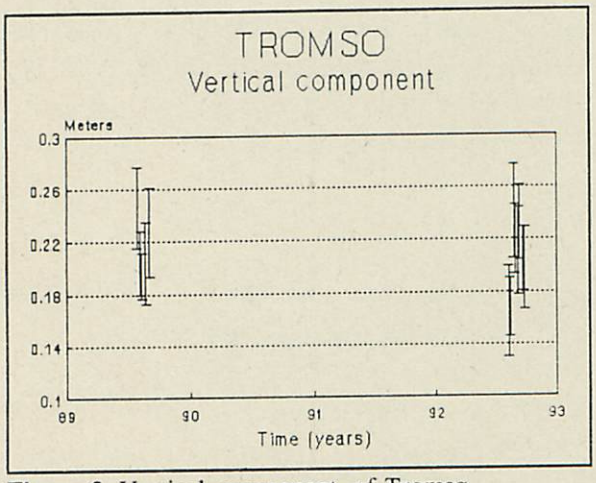


Figure 2. Vertical component of Tromsø

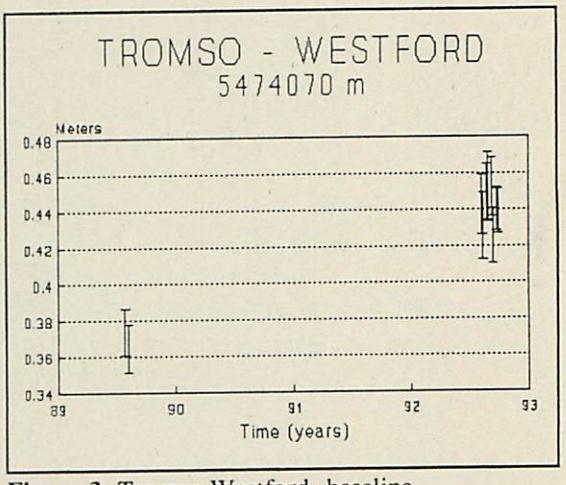


Figure 3. Tromsø-Westford baseline

TRYSIL

Trysil is the most extensively observed mobile site in Europe. A total of 11 sessions have been carried out with MV-2 between November of 1991 and March 1993. This corresponds to one and a half years of data.

The observing network has been quite consistent, by always tagging along Trysil to scheduled IRIS experiments. This makes all the experiments directly comparable with one single exception, where Wettzell did not observe. From the other ten sessions, one has produced significantly different results from the rest, with no apparent reason for that behaviour, so it was dropped from the repeatability results shown in table 3.

The results are very good for coordinates and lengths, with the smallest formal errors of all mobile sites, as can be expected from the larger amount of data, but also with fairly good repeatabilities.

Figure 4 shows the vertical component of Trysil for each experiment. The same comment made for Tromsø regarding parametrizations A and B is valid for this plot. It is clear that the overall noise of the individual estimates is too large to allow any conclusion on the evolution or trend of the station from such a short time span.

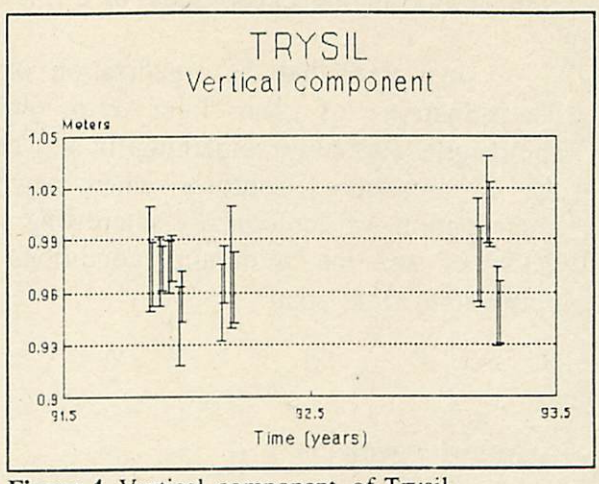


Figure 4. Vertical component of Trysil.

Discussion

Although the quality of the results largely varies from site to site, the general comment is clearly positive. The results are consistent at the centimetre level for single epoch occupations, which is within the initial expectations of the campaigns.

The variety of situations found during the analysis allows us to stress some points with respect to the design of the observing sessions.

1. Occupations with few experiments and different networks have produced results of low value as a first epoch measurement.

2. Sites scheduled in reduced networks with one or two fixed European stations have produced good and consistent results but to link them properly to a global framework could be difficult.

3. Stations observing with a consistent well-defined network have produced in general very good results, which will stand as valuable first epoch data for future comparisons when new occupations have been done.

The most interesting tests on the capabilities of reoccupation for geodesy and geodynamics are illustrated by the Tromsø and Trysil sites.

Tromsø is an example of reoccupation after a relatively long time span has passed. Disregarding some of the problems already commented above, it shows the difficulty to obtain reliable results with sparse reoccupations. Apart from the few really valuable epochs available, there is always the concern about systematic errors between epochs, either because of the eccentricity measurements or the use of different equipment.

Trysil could be considered as a relatively regular observing site, with approximately 2 to 3 time windows per year. With this kind of campaigns it is possible to produce reliable information about geophysical phenomena in relatively short time spans. For instance, results with an uncertainty as large as 3 cm, would produce significant information about rates at the 1 cm/year level (1-sigma of 2 mm/year) in approximately 5 years. This will mean that possible vertical rates produced by post glacial rebound could be detected at this station within 3 or 4 years from now, which is

comparable to the capabilities of a fixed station.

It is clear that the organization of mobile campaigns is difficult and costly, so the determination of clear long term objectives would be very important for future campaigns. Probably something in between the examples of Tromsø and Trysil could be the "compromise" solution when new geophysical information is pursued. Yearly reoccupation of geologically interesting sites with a proper scheduling of the observing networks are the minimum conditions to obtain some significant results within a reasonable time span.

Acknowledgements

This work would not have been possible without the combined efforts of a lot of individuals and Institutions, which made possible the coordination, observation and correlation of the European mobile VLBI campaigns. We wish to thank all of them for their very successful job.

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Geodynamical and astronomical models in VLBI and the question of parameterization of the Earth's rotation

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Abstract

VLBI data analysis requires numerous models to describe the signal propagation from the extragalactic radiosource to the receiving antenna on Earth's crust and further to the data recorder as well as models for position and motion of emitting source and receiving radio telescope. So relativistic, astronomical, geodynamical, atmospheric, technical, ... models are needed. This paper concentrates on periodic astronomical and geodynamical models. It is intended to give a short review of the influences on rotation and deformation of the Earth and to show which models are included in the VLBI data processing software CALC/SOLVE.
In the second part of this paper an alternative concept using only three parameters to parameterize the Earth's rotation is described and first results are presented.

Part I : Geodynamical and astronomical models

1 Introduction

In VLBI radio telescopes on the solid crust of the Earth receive the radiation of extragalactic radiosources. Group delay observations with high precision allow the study of geodetic and geodynamic phenomena, for example tectonic plate motion and variation in Earth rotation. The theoretical model for the observed delay used in data processing includes for example models for signal propagation from the extragalactic radio sources to the receiving radio telescopes on the Earth's crust and models for the motion of the receiving stations. Latter include models for Earth's rotation in the quasi-inertial reference system of radio sources and models for site displacements. The behaviour of the Earth in a celestial reference system [CRS] is modeled by astronomical models and the deformation of the Earth by geodynamical models. These models cannot be strictly separated because they are not independent from each other, so care must be taken when solving for parameters of connected models. Commonly VLBI software follows the IERS-standards but there are some phenomena which should be included in the future in order to increase the accuracy of this space geodetic technique.

2 Rotation and deformation

This paper concentrates on periodic geodynamical and astronomical models for deformation and rotation of the Earth. Both have to great parts the same reasons, they depend on the effects of lunisolar gravitational attraction on the solid Earth, the oceans and the atmosphere.

2.1 Earth rotation

The rotation of the terrestrial reference system [TRS] in the celestial reference system [CRS] is described by the Earth rotation parameters [ERP]. Conceptionally a rotation of two systems with coincident origin can be described by three parameters only. However, historically five parameters are used : the nutation angles ψ and ϵ, the Greenwich Apparent Siderial Time [GAST] to describe the Earth's siderial rotation, and the parameters Xp and Yp to describe polar motion. By analysis of VLBI data we are able to estimate all five parameters connecting TRS and CRS. VLBI is the only space geodetic technique which can provide results for all five parameters.

2.2 Influences on Earth rotation

The rotation of the Earth, and with it the Earth rotation parameters, is not constant. It varies because of the response of the Earth to external torques form extra terrestrial bodies, because of the response of the Earth to internal mass redistribution form surface and internal loads and because of exchanges of angular momentum between solid Earth and fluid elements. Lunisolar gravitational attraction acts on the Earth's equatorial bulge and forces the Earth to react as a gyro and perform precession and nutation. Lunisolar gravitational attraction is the reason for solid Earth tides and ocean tides and one reason for polar motion, too. Earth tides and ocean tides influence polar motion and the siderial rotation of the Earth. Variation of atmospheric angular momentum [AAM] has a strong influence on polar motion and siderial rotation of the Earth. Besides these, ocean currents and Earth's deformation due to other physical effects influence polar motion and the Earth's siderial rotation, too.

2.3 Influences on Earth deformation

Lunisolar gravitational attraction raises tides in solid Earth, ocean and atmosphere. Ocean loading due to ocean tides and ocean pressure due to ocean currents deform the Earth. Concerning atmosphere, loading processes due to atmospheric tides and atmospheric currents deform the Earth. The varying orientation of the Earth's rotation vector leads to a deformation via pole tide. Besides these effects there are other phenomena like plate tectonics, volcanism, Earth quakes, glacial rebound, snow load, groundwater variation, ... , which cause deformations of the Earth.

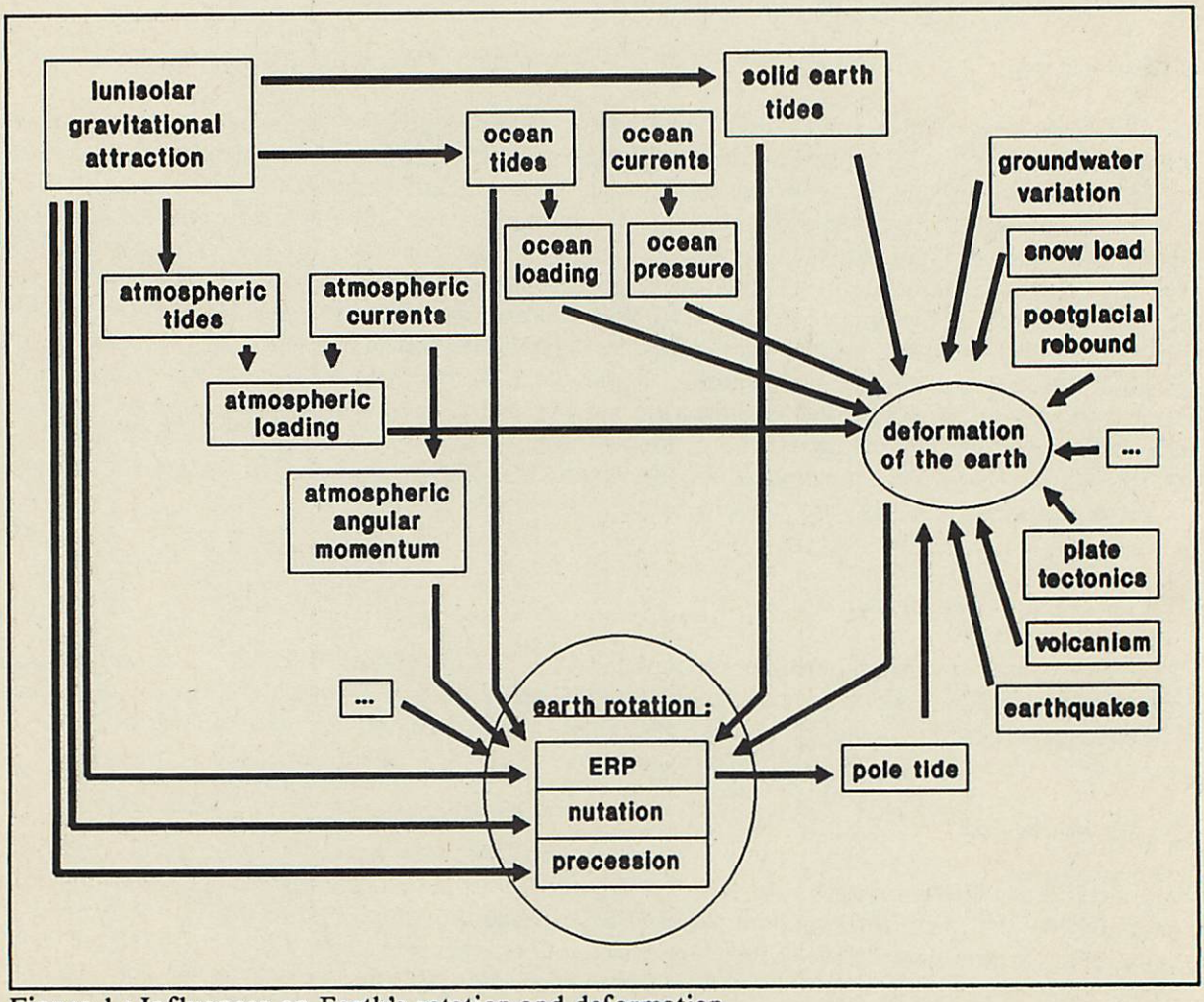


Figure 1 : Influences on Earth's rotation and deformation

3 Modeling in VLBI software

At the Geodetic Institute of the University of Bonn (GIUB) VLBI data analysis routinely is performed with the CALC/SOLVE software. In the next paragraph the geodynamical and astronomical models included in CALC/SOLVE and the effects not yet included in CALC/SOLVE will be described.

3.1 Effects included in CALC/SOLVE

3.1.1 Influences on Earth's rotation

a) Model of precession

The gravitational forces of sun and moon act on the equatorial bulge of the Earth and force the Earth to behave like a gyro. The Earth precesses. By the model of Newcomb (1895) parameters are calculated to transform from the catalog system of radio sources to the mean equatorial system of date. The precession period is about 26000 years as seen from the CRS which corresponds to a retrograde frequency of -1 cycle per siderial day [cpsd] as seen from TRS.

b) Model of nutation

The model of nutation describes the small deviations from the precession cone. Nutation angles are used to transform from true to mean equatorial system. Wahr's model (1980) is based on the model by Kinoshita (1977) for a rigid Earth and includes non-rigid corrections. The Earth model used is model 1066A by Gilbert and Dziewonski. The nutation values by Wahr are not computed for the axis of rotation of the Earth but for the so called "celestial ephemeries pole" [CEP] which describes a Tisserand figure axis which should have no diurnal or quasi-diurnal motion either in CRS or TRS. The periods of Wahr's model of nutation are between 5 days and 18.6 years as seen from CRS which corresponds to periods of about 1 day as seen from TRS. Nutation has retrograde frequencies of about -1 ± 1/(5 days to 18.6 years) cpsd as seen from TRS. Influences on the nutation angles by planets are not included in Wahr's nutation model. Kinoshita (1990) showed for a rigid Earth model that some planetary terms of nutation reach 0.1 mas and several reach 0.005 mas.

c) Solid Earth tidal variation in Earth's rotation

Tidal deformation of the Earth influences its siderial rotation. The influences are calculated by models of Yoder (1981) and Dickman (1991) for periods between 5 and 18.3 years as seen from the TRS and have amplitudes that amount to an influence on UT1 of 170 ms in total.

3.1.2 Influences on Earth deformation :

a) Model of Earth tides

Gravitational attraction deforms the solid Earth to which the VLBI radio telescopes are bound to. The effect of the tidal potential on the Earth is scaled by Love numbers. The Earth tide model by Wahr (1981) uses the same Earth model as the model of nutation, 1066A by Gilbert and Dziewonski. The Earth tides have retrograde frequencies and periods between 1/3 day and ∞ as seen from TRS.

b) Model for ocean loading

The oceans move periodically because of lunisolar gravitational attraction. The effect of ocean tide potential on the deformation of the Earth is again scaled, this time by loading numbers. Based on the ocean tide model by Schwiderski (1983), Scherneck (1983) modeled the loading effects for a spheroidal Earth model. Ocean loading has the same periodic behaviour as ocean tides and can amount to ± 8 cm for island sites and ± 3 cm for inland stations. The ocean loading model has retrograde frequencies and periods between 1/2 day and 1/2 year as seen from TRS. Although ocean loading is implemented in VLBI data analysis software CALC/SOLVE it is not used as default but only as an option in the data analysis.

c) Pole tide

Polar motion leads to elastic deformation of the Earth. Again this effect of an additional potential is scaled by Love numbers. The model by Wahr (1985) uses the same Earth model as the model of nutation and the Earth tide model. The influence of pole tide is about 2 cm.

3.2 Effects not yet included in CALC/SOLVE :

3.2.1 Influences on Earth's rotation :

a) Ocean tidal variation in the Earth's rotation

Analogous to the influence of solid Earth tides on Earth's rotation, the ocean tides affect the Earth's rotation, too. Brosche (1991) and Wünsch (1992) calculate effects from ocean tides on the Earth's siderial rotation and polar motion. The periods are between 1/2 day and 183 days as seen from TRS with a total influence of about 1.5 ms on UT1 and 1 mas on polar motion.

b) Atmospheric angular momentum influence on ERP :

Atmosphere excites the Earth's rotation via exchange of angular momentum. AAM exchange is thought to be the main driving agent for the prograde Chandler wobble. It varies because of changing winds and changing distribution of atmospheric mass. Wind terms of AAM influence the Earth's siderial rotation while pressure terms of AAM influence polar motion. The total AAM is computed from meteorological data by weather forecasting centers in Europe, Japan and the US. Spectral analysis of AAM data shows periods of ~14 days, ~40-50 days, ~1/2 year, ~1 year and longperiodic fluctuations. Comparisons of Earth rotation values with AAM data show strong correlations. AAM effects on ERP cannot be modeled but must be calculated from meteorological data and can then be applied in the data analysis.

3.2.2 Influences on Earth deformation :

a) Atmospheric loading

Time varying atmospheric currents and atmospheric tides due to lunisolar gravitational attraction induce crustal deformation of the Earth. A simple model by Rabbel and Schuh (1986) based on a spheroidal Earth model includes only the instantaneous and the average pressure at a site. The contribution to Earth deformation may be up to 2 cm. The effects have to be calculated from meteorological data and can then be applied in the data analysis.

b) Groundwater variation and snow load

The influences of these effects are thought to be of minor importance. They have a quasi-periodic behaviour with a period of about 1 year and contribute to Earth deformation at a level of 0.5 to 5 mm.

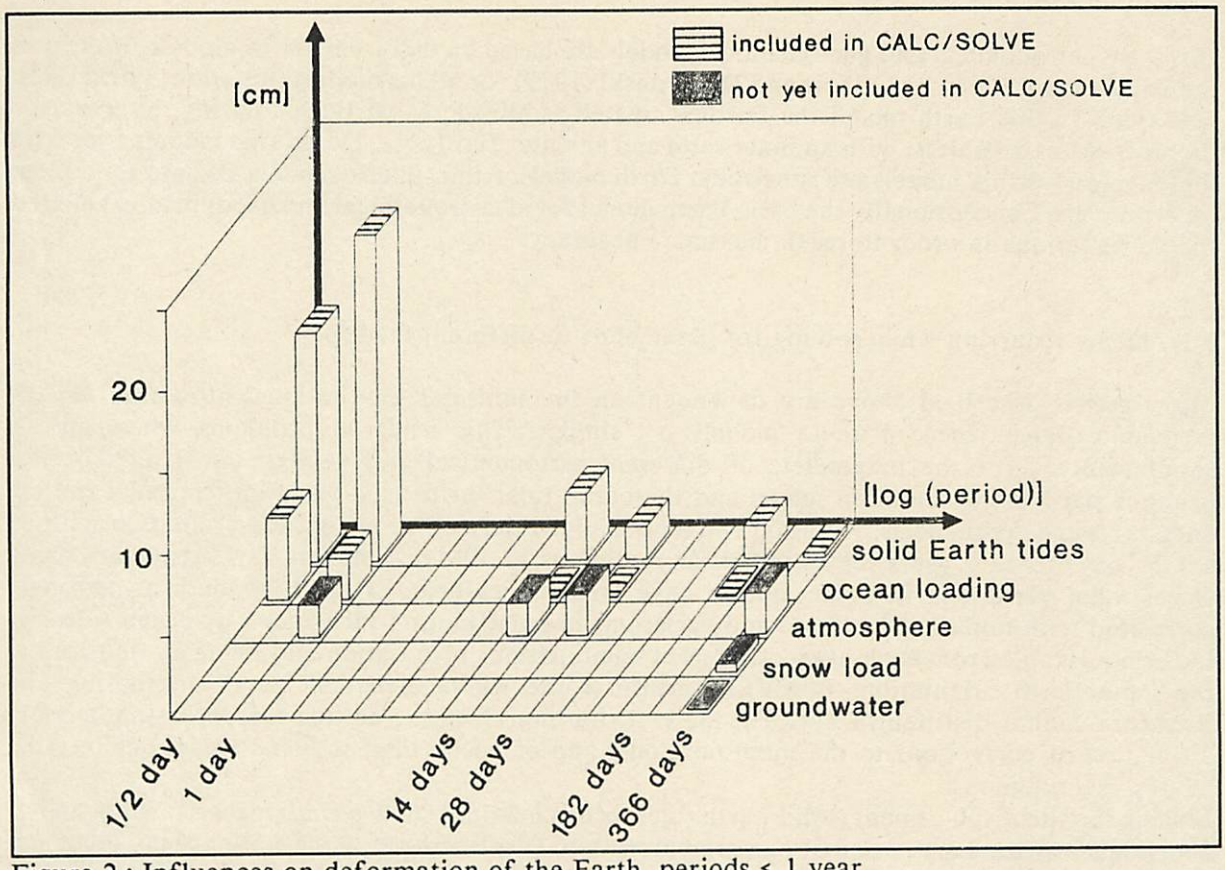


Figure 2 : Influences on deformation of the Earth, periods ≤ 1 year

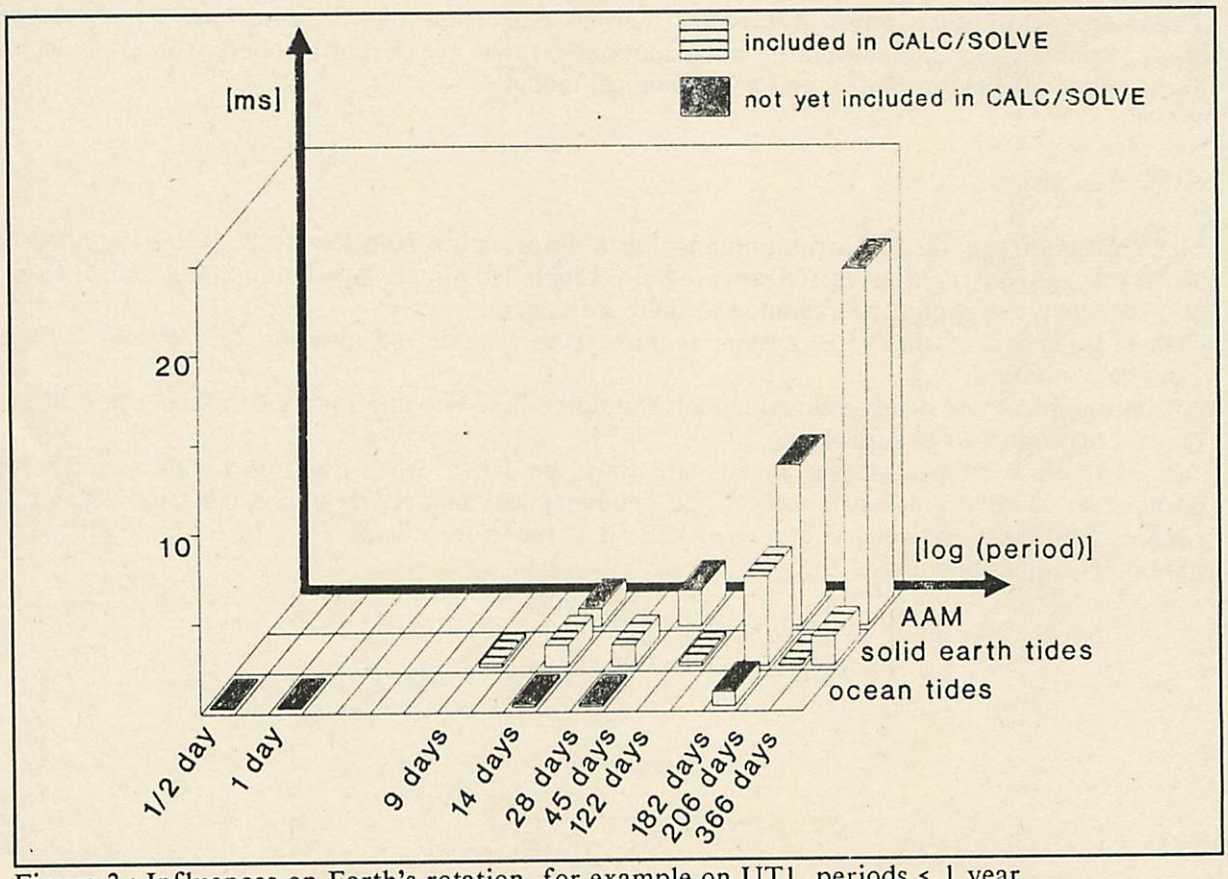


Figure 3 : Influences on Earth's rotation, for example on UT1, periods ≤ 1 year

4 Earth models used in rotation and deformation models

Different astronomical and geodynamical models are based on different Earth models. Wahr uses the Earth model 1066a by Gilbert and Dziewonski (1975) for all his models (nutation, Earth tides, pole tide). In this Earth model the Earth is treated as elliptical, elastical, rotating, hydroelastic prepressed but oceanless, with an inner solid and an outer fluid core. Ocean tide models and, with these, ocean loading models use spheroidal Earth models. Atmospheric models also use spheroidal Earth models. Conceptionally the basic Earth model for all astronomical and geodynamical models should be unique in order to reach maximum accuracy.

5 Problems occurring when solving for parameters of different models

Most models described above are dependent on the lunisolar gravitational attraction. So the frequency dependence of these models is similar. This leads to problems when solving simultaneously for the parameters of different astronomical and geodynamical models. For example parts of the nutation model and the ocean tidal influenced variations in polar motion have the same frequencies. Nutation conventionally is defined as retrograde oscillation with -1 ± 1/(5 days to 18.6 years) cpsd and polar motion as oscillations outside this frequency band. Ocean tidal variations in polar motion have frequencies near -1 cpsd, so they are strongly correlated with nutation. Nutation and variations in polar motion influenced by ocean tides are indistinguishable from each other. Different combinations of nutation and polar motion lead to the same Earth orientation. But VLBI measures the whole effect of Earth orientation and therefore cannot distinguish between the contributing effects. For this reason a simultaneous estimation of corrections to the nutation model and of ocean tidal induced variations in polar motion is ambiguous.
Models for site displacement (solid Earth tides, ocean loading) show a similar the same frequency dependence as the Earth orientation parameters, too. Displacement of the stations may influence the estimated rotation parameters and vice versa. Any rotation variation could be represented by displacements of sites.
There are even other physical effects (thermal expansion of the antennas, variations of atmospheric angular momentum on polar motion, ...) that are partially coherent in frequencies with some of the astronomical and geodynamical models.

6 Conclusions

Most of the effects on Earth rotation and Earth deformation mentioned above are included in VLBI software CALC/SOLVE. Others are not yet included but are large enough to be considered, so VLBI software should be extended to these influences.
Todays precision of the VLBI system requires a new model of nutation that should include planetary nutation.
All astronomical and geodynamical models should be based on a unique Earth model in order to reach a maximum of accuracy.
As seen from the paragraphs ahead care must be taken when solving simultaneously for parameters of different astronomical and geodynamical models in VLBI data analysis. VLBI cannot distinguish between coherent effects. It is therefore not possible to estimate all model parameters simultaneously.

Part II : Question of parameterization of the Earth's rotation

1 Conventional concept of parameterization of the Earth's rotation

Historically the transformation between TRS and CRS uses the five parameters mentioned above, but conceptionally only three parameters are necessary for a rotation of two systems with coincident origins. In VLBI experiments all five Earth orientation parameters may be estimated. Conventionally for a 24 hour VLBI experiment one set of mean values of the five parameters is estimated. Estimating polar motion at shorter intervals leads to strong correlations with nutation estimates.

2 Polar motion and nutation

Polar motion is the terrestrial location of the CEP while the nutation parameters are used to describe the celestial location of the CEP. The direction of the CEP does not coincide with the direction of the rotation axis which is used in dynamical approaches of polar motion. They differ by a maximum of 1.5 mas in both components (ref. Brzezinski/Capitaine 1992). The CEP was chosen as reference in the 1980 nutation model in order to have a point that has no diurnal or quasi-diurnal motion with respect to either TRS or CRS. However, this is not fully possible because polar motion and nutation are not independent of each other. Long periodic motions in nutation appear as short periodic motions in polar motion and vice versa. The relationship between polar motion and nutation is :

$$\Delta x_p = - \Delta\psi \sin(\epsilon_0)\cos(GAST) - \Delta\epsilon \sin(GAST)$$

$$\Delta y_p = - \Delta\psi \sin(\epsilon_0)\sin(GAST) + \Delta\epsilon \cos(GAST)$$

$$\Delta\psi \sin(\epsilon) = - \Delta x_p \cos(GAST) - \Delta y_p \sin(GAST)$$

$$\Delta\epsilon = - \Delta x_p \sin(GAST) + \Delta y_p \cos(GAST)$$

3 Alternative concept of parameterization of the Earth's rotation

An alternative concept (ref. B. Richter 1992, personal communication) for the kinematic rotation between TRS and CRS is to use only three parameters. Richter proposes to use the matrix of rotation between TRS and CRS composed of two apriori rotation matrices left and right of a residual rotation matrix. The precession/nutation model should be taken as one apriori rotation matrix and no corrections should be estimated to it. The other apriori rotation matrix should consist of a model for polar motion and siderial rotation. The residual rotation matrix in the middle between these two apriori matrices should consist of rotations with three new cardanic Earth orientation angles α, β, γ. These three residual parameters should be estimated more often than once in 24 hours, for example a new set of parameters every 1-2 hours. They will include a diurnal motion which is composed by errors in the nutation model and other influences on daily and subdaily timescale, for example ocean tidal variations. Moritz/Mueller (1988) pointed out that errors in the model of nutation will show as daily artifacts in polar motion. The splitting up of the whole effect into influencing parts, as far as possible, must be done in a second step.

4 Plots of estimates of the alternative concept

For two successive IRIS VLBI experiments the alternative parameterization has been performed. Every hour a new set of the three residual parameters has been estimated. The results for the two successive days are plotted below.

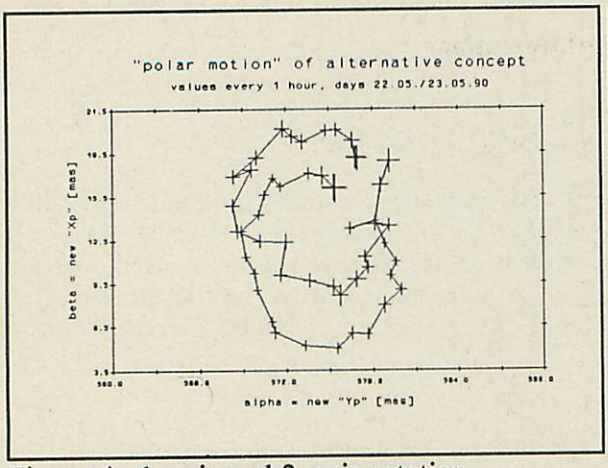


Figure 4 : 1-axis and 2-axis rotation

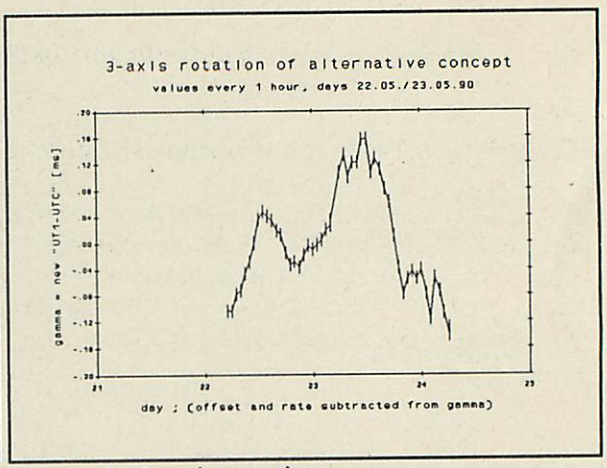


Figure 5 : 3-axis rotation

In polar motion a large diurnal variation of about 20 mas is clearly visible. This is the effect of a superposition of errors in the model of nutation and other daily and subdaily influences (ocean tides, atmospheric influences, ...) on polar motion.

5 Conclusion

The alternative concept for the parameterization of the Earth's rotation is a rigorous approach. It avoids the dependency of nutation and polar motion and the correlations between their estimates. From this point of view it is more strict than the concept used up to now. But the avoidance of dependence between the parameters is accompanied by an increasing total number of parameters because every 1-2 hours a new set of parameters has to be estimated. This might give problems with the observation to parameter ratio. The problem of separating the whole effect of Earth rotation into its contributing influences is not solved by this strategy either.

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An Expert System for the Selection of Parameters in SOLVE[1]

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Summary: The concept of an expert system for processing Very Long Baseline Interferometry (VLBI) data was first presented by the author in 1991. It is an intelligent knowledge-based assistant for the MarkIII Data Analysis System and supports and guides the analysts to make the data analysis faster even if it is done by less experienced analysts. A PC-based prototype of the expert system for the selection of parameters in the least squares fit program SOLVE has been realized. It is called VLBIXPS(P) and uses Prolog to represent rule-based knowledge. The formalization of knowledge and the structure of the rules are shown.

1. Introduction

The concept of an expert system (XPS) for the MarkIII Data Analysis System ('CALC/SOLVE') (Ryan et al., 1980) was presented at the last European VLBI Meeting in Dwingeloo, 1991 (Schuh, 1993). This XPS for one of the most widely used VLBI software is going to be developed in a research project at the University of Bonn as a knowledge-based assistant for supporting an analyst who has already a good basic knowledge. The XPS guides and controls the operations done by the analyst and does all necessary checks if possible automatically. It gives detailed explanations to the analyst (decision support system) in particular when he/she has to choose between different options or has to select specific models or parameters. When failures or problems in the process of data analysis have occurred it should advise the analyst how to overcome the problem (diagnostic system). The system contains a flexible and extensible knowledge base. In the future an extended version of the XPS shall be developed as instruction system for newcomers and the system can also be extended to cover other aspects of the VLBI process. The first version of the expert system runs in parallel on a separate personal computer but it could also be implemented as a kind of shell with all other (existing) programmes integrated. In the first case the XPS is independent but its use is more elaborate because there is no direct data flow between the existing programmes and the knowledge-based software. In the latter case the direct data flow exists, but the additional software parts are not completely independent of the individual programmes which could cause problems in particular if failures and interrupts occur. From the very beginning the new know-

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ledge-based software has been designed to be transferable to other VLBI software packages like OCCAM (developed at the Universities of Bonn and Madrid) or MASTERFIT/MODEST (developed at Jet Propulsion Laboratory (JPL), Pasadena) because the procedure of data analysis is very similar in all VLBI analysis programmes.

2. Design of an expert system for the MKIII data analysis system

The name of the expert system for the MarkIII Data Analysis System ('CALC/SOLVE') is **VLBIXPS**. In the first phase of the project, the general concept and design of a knowledge-based assistant have been completed. By looking at the work which the analyst usually does during the course of data analysis using the MkIII Data Analysis System, we found that almost all of the analyst's tasks can be supported by an XPS. This is shown by the additional blocks in the flow chart of the standard MkIII Data Analysis System in fig. 1. The additional knowledge-based software ammendments for the different steps are explained in more detail by Schuh (1993). It is obvious that not all of those tasks really need an expert system like solution. Some of them can be achieved by a comfortable user interface as well or by additional algorithms or crosschecks programmed within the existing software. Some other tasks could be achieved by using 'classical' programming methods but the use of AI languages will accelerate and fascilitate the realization.

3. Knowledge acquisition, formalization of knowledge and knowledge representation for VLBPXPS(P)

In the second phase of the project an exemplary PC-based prototype VLBIXPS(P) of an expert system for the selection of parameters in SOLVE(P) has been realized using Prolog to represent rule-based knowledge. It supports the current version of the program SOLVE as part of the MarkIII Data Analysis System which is presently implemented at the Geodetic Institute of the University of Bonn (GIUB). The flexible knowledge-base allows an easy transition to any new version of the MkIII Data Analysis System. The implementation of such new version of the VLBI software on a new HP workstation at GIUB has been finished in March 1993.

The program SOLVE(P) is used at the end of VLBI data processing for the least squares fit, i.e. for solving the unknown parameters such as baseline components or Earth rotation parameters (ERPs). Concerning the rules which have to be considered when the solve-for parameters are selected there is a difference between

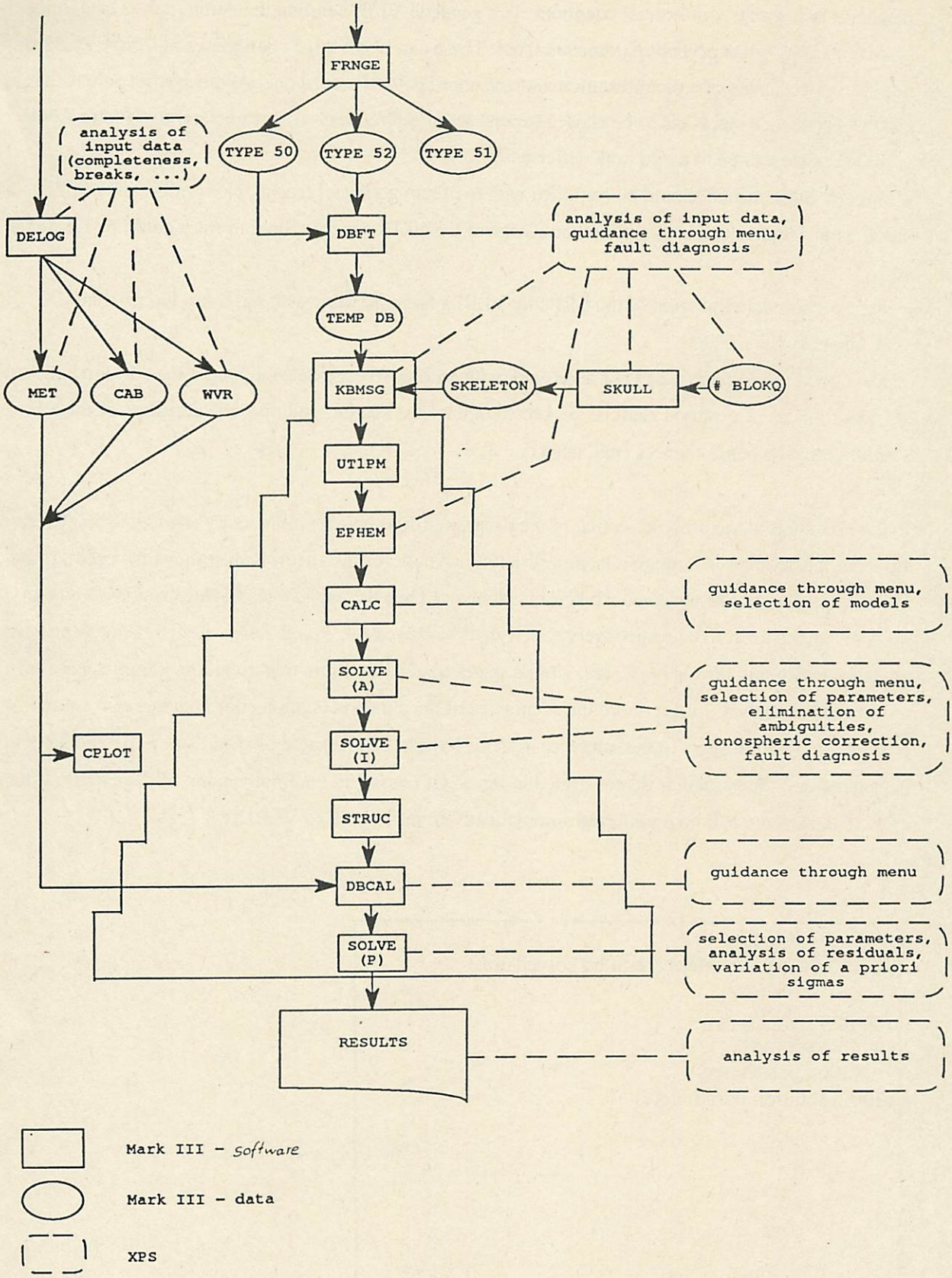


Fig. 1: Flow chart of the standard MarkIII Data Analysis System and all tasks which could be supported by an expert system

- **'strict rules'** which must be complied with; strict rules are necessary for instance to avoid rank deficiencies in the matrix of normal equations. In a geodetic VLBI solution the datum has to be defined by keeping at least 6 independent parameters fixed. These can be all three coordinates of a first VLBI station, two coordinates of a second station and one coordinate of a third one. Another strict rule is that at least one reference clock has to be chosen (or one set of reference clock parameters) to which all other parameters are related to avoid rank deficiencies.
- **'smooth rules'** which should be complied with to obtain good and reasonable results. Smooth rules are based on experience and background knowledge of the VLBI experts. Smooth rules could be for instance:

  'for a precise determination of the ERPs by VLBI a large network with baselines longer than xx kilometers is needed',

  'for a good determination of UT1 a network with an East-West extension longer than xx km is needed'

  'if coordinates of a station shall be kept fixed in the least squares solution, the accuracy of the a priori values must be better then xx centimeters'.

In the execution of the present version of the program it first obtains all facts by asking the analyst questions he has to answer through a menue system. Facts are for instance which stations took part at the VLBI session and have observed which radio sources. Then the analyst has to enter which parameters he/she wants to keep fixed respectively which shall be solved for. Fig. 2 shows such a page of the user interface which is followed by several similar pages to get all information about the parameterization chosen by the analyst. Furthermore the accuracies of the a prioris (station coordinates, radio source positions, ...) with respect to the reference systems have to be estimated or read from a file and have to be entered into the system as demonstrated in fig. 3. Of course, in the final version of the expert system most of these facts will be transferred automatically from SOLVE to VLBIXPS.

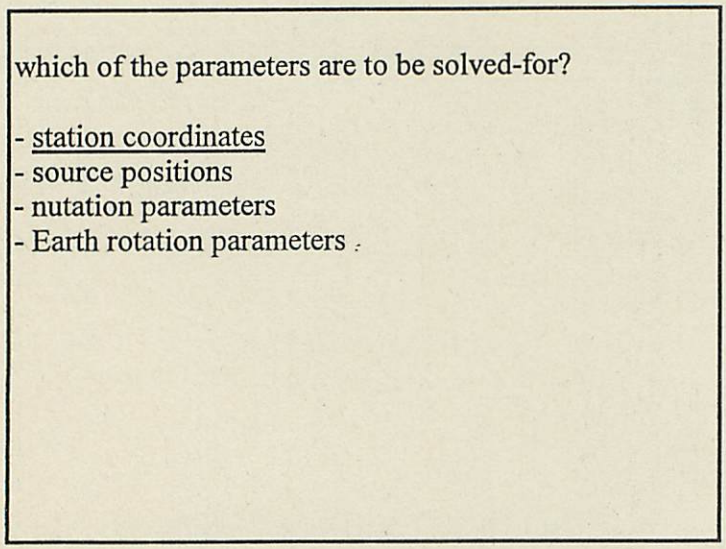


Fig. 2: Selection of parameters

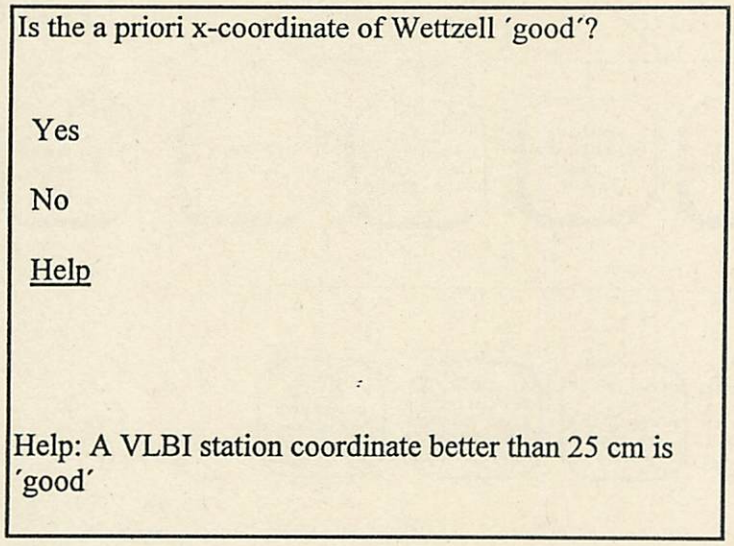


Fig.3: A priori accuracies are entered

Having obtained all facts the XPS starts with the inference process. Fig. 4 shows a typical decision-tree (AND/OR-tree) which is used by the Prolog inference machine in VLBIXPS(P) to check whether the station coordinates can be solved for as selected by the analyst. The inference machine goes through the rules of the decision-tree in a predefined order, i.e. from left to right and from top to the bottom to come to a conclusion. In the example presented here the ERPs are to be solved for additionally to several station coordinates. The system has to check all rules which must be complied with for the datum definition (third level from top of the decision-tree in fig. 4). According to the 'smooth rules' explained above it might also warn the analyst if the ERPs are to be determined from a local or regional VLBI network (see on bottom right of the decision-tree). Then the system would tell him/her about the poor quality of the ERPs to be expected.

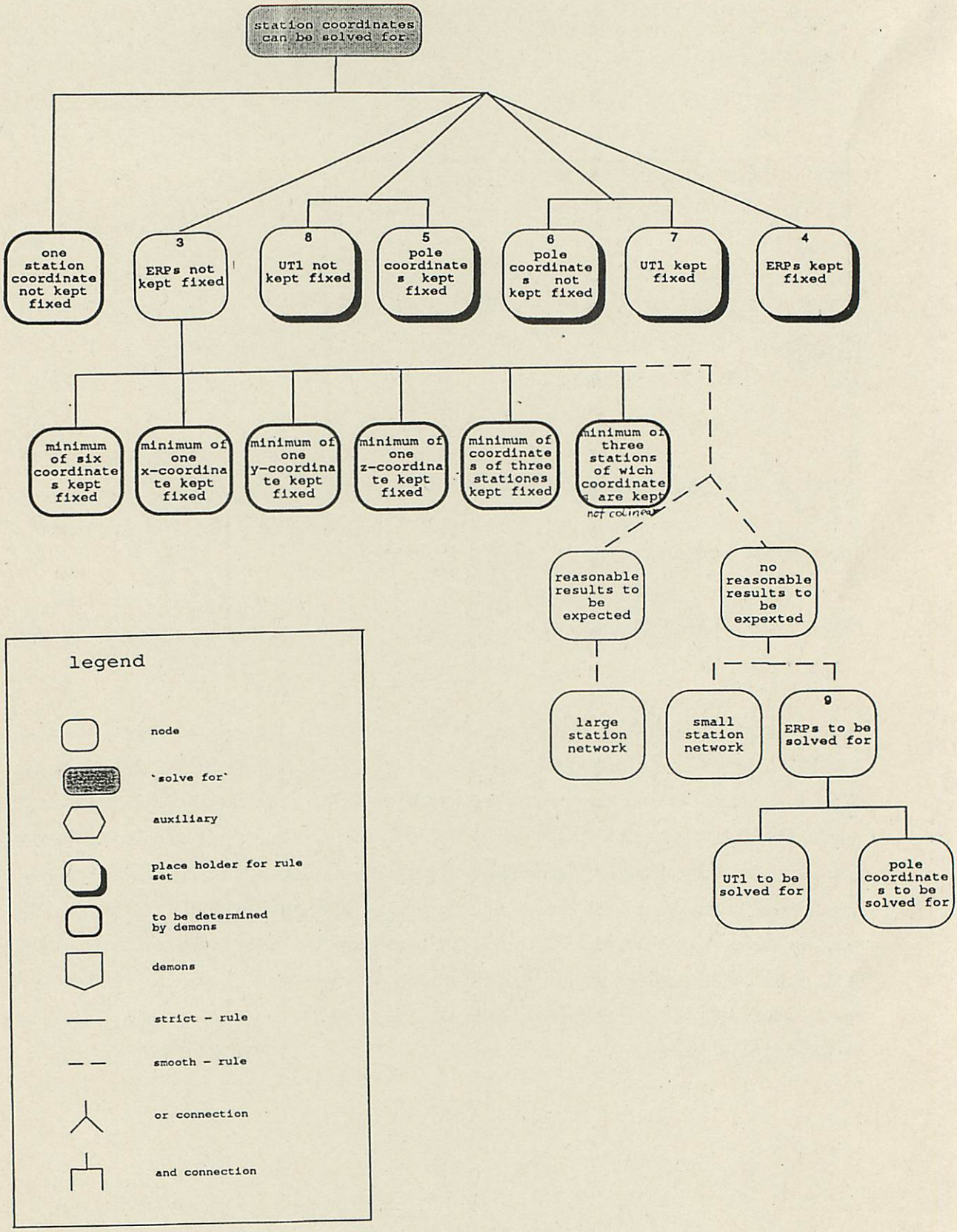


Fig. 4: Decision-tree in VLBIXPS(P)

The parameterization as proposed by the system is shown and compared with the selection done by the analyst (fig. 5). Finally VLBIXPS(P) lists all rules which have been used to obtain the proposed parameterization. In the example (fig. 6) the expert system explains why at least 6 station coordinates and at least one x-coordinate, one y-coordinate and one z-coordinate have to be kept fixed. Thus the program will provide means for education and training of unexperienced analysts. All further details on the acquisition and formalization of knowledge and its representation by rules are described by Jäger, 1992.

coordinates to be kept fixed	XPS	analyst
Wettzell		
x-coordinate	*	*
y-coordinate	*	*
z-coordinate	*	*
Richmond		
x-coordinate	*	*
y-coordinate	*	
z-coordinate	*	

Fig. 5: Parameterization proposed by the expert system

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REASONS

...

IF a minimum of six station coordinates are kept fixed
IF a minimum of one x-coord. is kept fixed
IF a minimum of one y-coord. is kept fixed
IF a minimum of one z-coord. is kept fixed

...
...
THEN ERP can be solved for
```

Fig. 6: Sample of rules and the conclusion applied by the expert system

4. Plans for the future

In the next phase of the project the present expert system for SOLVE will be extended to cover several additional tasks. These are for instance:

- explanations of data entry, guidance through the menues,
- ambiguity elimination by a planning system with algorithms (computation of ambiguity spacing) and constraints (the sum of the ambiguity levels within each triangle should be zero),
- fault diagnosis (diagnostic system) by giving not only computer-relevant explanations but VLBI-specific reasons as shown by Schuh (1993),
- analysis of the residuals
  * searching for outliers,
  * analyzing station-dependent variations of the residuals,
  * analyzing variations of the residuals with respect to variations of meteorological data,
  * analyzing source-dependent variations of residuals,
- choosing a priori sigmas (planning system).
- Analysis of results by check of plausibility: are solved-for parameters reasonable, too big, ...? (consultation system),
- hints, what to check and in case of problems, reference where to enter again into the programme flow.

In the future the realization of other parts of VLBIXPS and the full integration into the HP environment is planned. The transfer to other VLBI software packages shall be supported as well as the extension of the system to other tasks within the VLBI process. There are several other software programmes which also need the expertise of highly qualified scientists and engineers. These are for instance scheduling of observing sessions and the correlation of the raw data and fringe search. The processing of GPS-observations in the stationary mode, i.e. for geodetic application, has many similarities with geodetic VLBI. Thus, several of the ideas which are behind VLBIXPS will be tranferable to GPS data processing, too.

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The ERS/VLBI Station O'Higgins in Antarctica

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Abstract: The antarctic ERS/VLBI-Station O'Higgins performed the first successful geodetic VLBI experiments during the burst in January/February 1993. The facility is introduced and the first results are presented.

1 History of the ERS/VLBI-Station O'Higgins

Within the ERS-project of ESA the Federal Republic of Germany contributed a ground station for the reception of the radar images of the SAR instrument. Due to the limited space for data storage on the satellite and an optimal use of taking data, the ground stations had to be close to the areas where the images are taken. German research activities in Antarctica are concentrated, besides others, with respect to the ratio of ice in the Weddell Sea. ERS-1 with its SAR instrument offers the capability of weather and daylight independent images for the antarctic region.

Accidently, the frequencies in S- and X-band used for the satellite downlink correspond to those which are used in geodetic VLBI experiments. This coincidence lead to the idea to use the telescope also for VLBI observations.

The final location of the telescope was, therefore, selected with respect to both, the ERS-1 satellite and the VLBI requirements. The main motivation for the VLBI activities is the determination of the continental drift of the sixth continent with respect to the three neighbor continents, South America, Africa and Australia. For geodynamical investigations the telescope had to be founded on rocks, which are at least temporarily ice free. A new foundation of a further German station in Antarctica was not considered due to ecological and economical reasons. The operation of the station was also planned to be periodically and not continuously. The Chilean military base O'Higgins at 63°19'S and 57°54'W outside the polar circle situated on a small 150 x 200m island about 70m off the antarctic peninsula was chosen to host the German ERS/VLBI-Station. In summertime this island is snow and ice free for about six weeks and offered a chance to build the fundament of the radio telescope on solid rocks.

The project was carried out by the Institute for Applied Geodesy (IfAG) in Frankfurt, the German Aerospace Establishment (DLR) in Oberpfaffenhofen and the Alfred-Wegener-Institute for Polar and Marine Research (AWI) in Bremerhaven under guidance of IfAG. The German Federal Ministry of Research and Technology (BMFT) financed the 25 million DM project.

In only three antarctic summers the location was explored (1988/89), the groundwork and foundation were done (1989/90), the radio telescope was assembled and the station was built (1990/91). The first SAR image of ERS-1 were received successfully on October 9th, 1991. The first VLBI experiments were performed during January/February 1992.

On January 29th, 1993, the ERS/VLBI-Station was officially inaugurated by the German embassador in Chile and the attendance of high ranking officials of Chile and Germany.

2 Equipment of the ERS/VLBI-Station

The German part of the station consists of the 9 meter radio telescope, 12 working and living containers, energy generators with fuel containers and sea water de-salination installation for drinking-water supply.

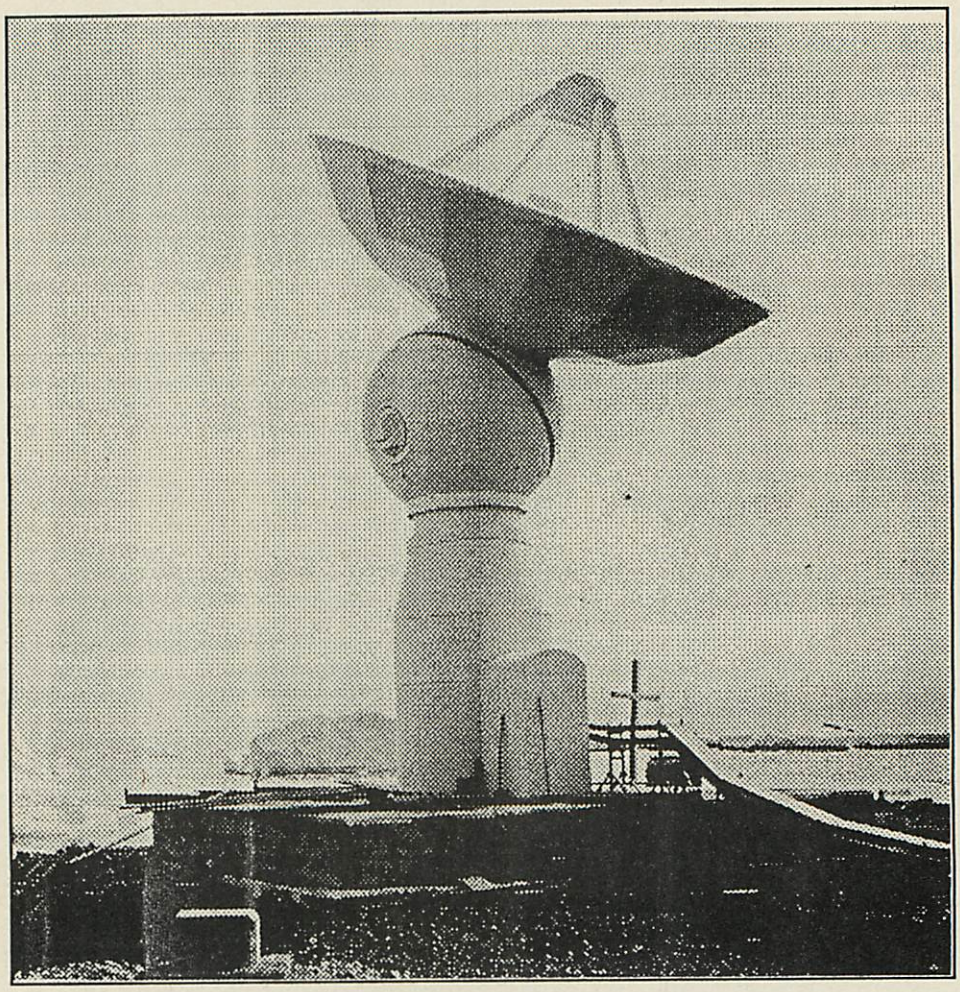


Fig. 1, The new landmark at the Antarctic Peninsula: The antenna of the ERS/VLBI-Station O'Higgins.

2.1 The Radio Telescope

The radio telescope is a new landmark on the Antarctic Peninsula. Due to its location in one of the most stormy regions on Earth the construction was planned to resist wind speeds of 300 km/h. The body of the 9 meter main dish is completely covered to avoid icing of the antenna. The dish is heatable which enables reception during snowfall. The design of the antenna avoided the opposite angle of the H-atoms in the H_2O molecule in order to prevent ice forming at the construction.

The radio telescope was planned following the Cassegrain principle in coaxial arrangement of main reflector, subreflector and feed: A parallel wave front is first reflected at the parabolic main reflector and then from the subreflector into the feed at a secondary focal plane. The S/X-band reception feed is the interface between the photons in space and the electrons in conductors. Waveguides conduct the received energy to the low noise amplifiers.

The steering of the axes of the telescope corresponds to that of a normal azimuth/elevation control. Wire wrap limitations permit to cover an azimuth range of -270° to +270° and an elevation range of 0° to +90°. Unlike normal to azimuth/elevation constructions, the elevation axis is constructed as an oblique axis. Two obliquely mounted halfs of a spheroid are turned against each other. Each direction above horizon can be pointed at.

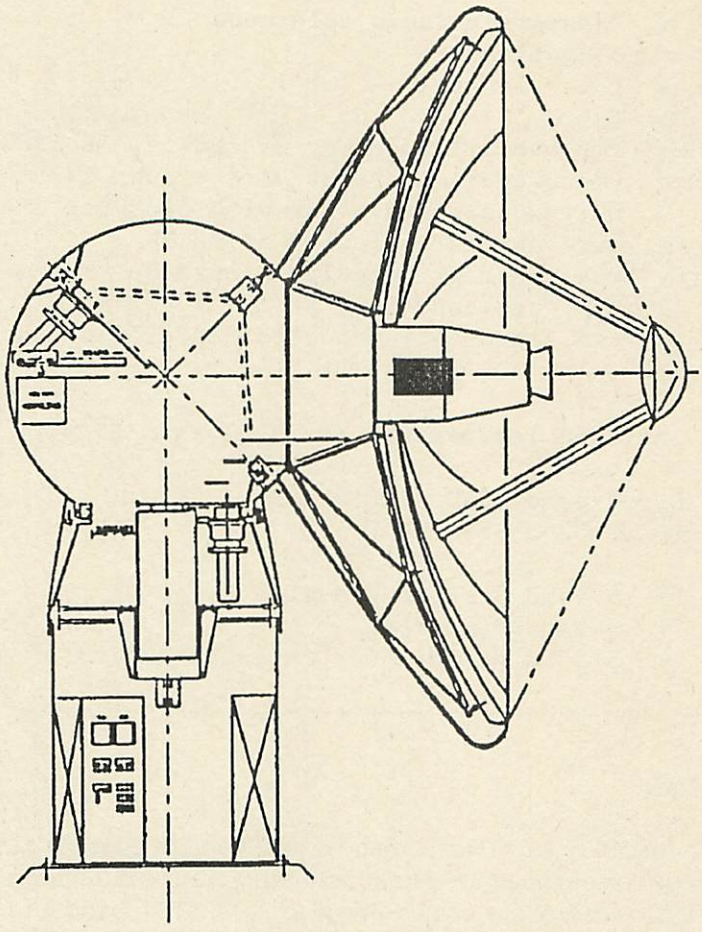


Fig. 2, Schematic drawing of the radio telescope with a fixed and a movable hemisphere. All sensitive parts are mounted inside. The box in the feed cone indicates the VLBI receiver.

The advantage of the Cassegrain arrangement and the special oblique axis is, that all the electronic and high frequency parts which are sensitive to the adverse weather conditions were mounted in the protected and air-conditioned interior of the antenna. In addition, the spheroid has an ideal aerodynamic form.

For satellite tracking the cone of silence is important, in which a satellite cannot be tracked overhead due to the necessary fast azimuth movements at 90° elevation. The construction of the antenna offers to tilt the azimuth axis with a turnable wedge. This feature enables the tracking of overhead passes of satellites.

Owing to its double function as a satellite ground station and as an instrument for faint radio reception the ERS/VLBI-Station possesses two different high frequencies systems. The radiation of the quasars used by VLBI consists of undefined noise and is about 10000-times weaker than the well defined signals of the satellites. Hence the requirements for the receiving components are more stringent on the VLBI side.

Antenna Receiving System for VLBI at O'Higgins

9 m	Cassegrain radio telescope
1.38 m	subreflector
3.6 m	focal length
0.40	f/D
< ±0.50 mm	rms overall accuracy of the main reflector surface
< ±0.25 mm	rms overall accuracy of the subreflector surface
	Oblique-azimuth mount with crossing axes
11 deg/s	max. angular velocity azimuth
5 deg/s	max. angular velocity elevation
	S/X dual band feed
	two stage helium cooled HEMT low-noise amplifier

Antenna Performance for VLBI at O'Higgins

6300 Jy	X-band SEFD single dish
10..12000 Jy	X-band SEFD VLBI
12400 Jy	S-band SEFD single dish
12..18000 Jy	S-band SEFD VLBI
	S-band performance is still under investigation

2.2 The Signal Path

The sky frequencies of 8.0 to 8.6 GHz (X-band) and 2.0 to 2.3 GHz (S-band) enter the S/X dual band feed, in which the frequencies are separated in different conductors. The low noise HEMT amplifiers of the VLBI receiver are cooled down to 20 K at X-band and 50 K at S-band with compressed Helium to reduce the self generated electric noise of the electronic devices. The sky frequencies are amplified by about +30 dB when a mixer generates the intermediate frequencies (I.F.) in the range of 0 to 500 MHz using a local oscillator frequency of 8080 MHz for X-band and 2020 MHz for S-band. The I.F. reaches the VLBI-operation container at the station through two different coaxial cables for X and S-band.

The I.F. channels are linked to VLBA upconverter module in the VLBI container and are upconverted from 0-500 MHz to the range of about 500-1000 MHz using a 479.9 MHz local oscillator. The subsequent VLBA I.F. distributor distributes the I.F. to 14 baseband converters. In geodetic observation mode C, 2 MHz wide frequency bands are separated by different local oscillator frequencies of the I.F. spectrum. The upper 2 MHz sidebands are the analog output of the 14 baseband converters and the input for the sampler which digitizes the spectrum of the sidebands. The formatter adds a time information and parity bits to the data stream. The digital data of 14 parallel tracks are recorded on one inch magnetic tapes at the VLBA recorder.

For the frequency bandwidth synthesis method to work it is necessary to make use a phase calibration signal, which is introduced as 1 MHz pulses into the signal path just before the low noise amplifiers. The phase calibration signal is a reference signal to reconstruct the coherence in the 14 channels at the correlation. Variations in the cable lengths from the phase cal ground unit to the phase cal antenna unit are measured by the cable delay calibration system.

All local oscillators (receiver, upconverter, 14 baseband converters, sampler, formatter, phasecal unit, delaycal unit) are phase locked to the highly stable reference frequency of 5 MHz of the H-maser. The reference frequency of the maser itself is phase locked to the resonance frequency of H-atoms of 1.4 GHz. The stimulated H-atoms transmit their photons for a short moment under extremely highly stable environmental conditions (temperature constance better 0.01°C, 1000-times attenuation of the magnetic field of the Earth, vacuum better than 10^{-6} mbar). The 5 MHz is the mixing result of the natural H-atom frequency and one phase locked TXCO-oscillator.

2.3 The VLBI Container

The VLBI container houses the geodetic VLBA data acquisition rack, the VLBA recorder, the time and frequency rack, the H-maser EFOS-11, the NASA Field System control computer and an air-conditioner.
The time and frequency system of the ERS/VLBI-Station consists of three independent clocks, a Cesium standard, a GPS time receiver and a H-maser. Universal time is generated by the Cesium clock and the GPS time receiver is used to determine the local clock offsets. A station monitor computer controls the equipment.

The central control unit for VLBI experiments is the Field System PC486. The operating system VENIX is a real time unix derivative, which allows to give priorities to special processes. The Field System software allows to control and to monitor the antenna movements, almost all settings in the data acquisition rack, in the recorder and the receiver conditions of the front end. It communicates with the station monitor computer, which is used to monitor the clocks and to administrate meteorological data from the weather station.

Data Acquisition and Timing System for VLBI at O'Higgins

- VLBA Data Acquisition Rack with 14 baseband converters (Interferometrics)
- VLBA Recorder (Interferometrics)
- PC486 VLBI MkIV Field System Computer (NASA-GSFC)

- H-Maser EFOS-11 (OCN)
- Cesium clock (HP)
- GPS-Timereceiver (Navstar)
- Station Timing Monitor Computer and Distribution Amplifier (G.f.S.-EDV)

In the office container exists the satellite telephone and fax device. Most of the communication during the operation is done via satellite fax. VLBI schedules travel on floppy disks with the operator. Communication by fax to the civilization is rather important due to the fact of weather dependent short wave radio news and no television reception.

3 Operation of the ERS/VLBI-Station

The ERS/VLBI-Station is operated by DLR for SAR data reception, while the geodetic use of the station is under the responsibility of IfAG. Up to now two VLBI campaigns per year are planned. Each campaign consists of four to six VLBI experiments. The operation lifetime for O'Higgins is expected to be at least 10 years.
The operational staff consists of two operation engineers, who are doing either satellite data acquisition (DLR) or VLBI experiments (IfAG) and one infrastructure engineer, who is responsible for energy and water supply as well as for antenna maintenance.

The transportation of the operators from Punta Arenas (Chile) via King George Island to O'Higgins is organized with the support of the Chilean Antarctic Institute (INACH), the Chilean Air Force (FACH) and the Chilean Navy (Armada). The transfer is dependent on the actual weather conditions and the military operation schedules. Delays of up to 15 days may happen.

The station itself incorporates twelve 20 ft. containers for working and living: 2 containers for satellite data acquisition, 1 container for VLBI operation, 1 workshop and storage container, 1 office container, 3 containers with 2 beds each, 1 container as bathroom, 1 container as kitchen

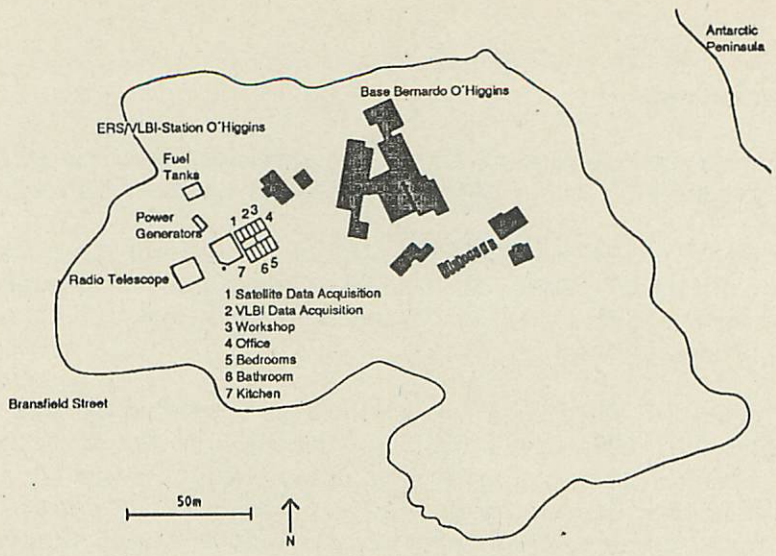


Fig. 3, Map of the island of O'Higgins. The dotted buildings belong to the Chilean base, the white belong to the German station.

and 2 containers as corridor to link all the other containers together. (Further accommodation exists at the Chilean base.) Besides the radio telescope and the 12 living containers the ERS/VLBI-Station includes the essential container for three power generators plus 3 containers for fuel. Two energy generators are identical, one of them is sufficient to drive the antenna and the station. The third generator is smaller in dimension and for emergencies. Another container hosts the desalination device for drinking-water production. Alternatively the drinking-water supply can be realized by melting ice and snow. This is done by the Chilean soldiers to supply the base.

During the absence of the operators all generators are shut off. Then the minimal power supply from the Chilean generators enables the continuous heating of the environment of sensitive electronic devices and the power supply of the station clocks. The maser is shut down, only the vacuum pumps are running. This avoids an unknown status of the maser in case of a power failure longer than the capacity of the batteries.

4 Results of the first three VLBI campaigns at O'Higgins

After the successful transfer of the running H-maser from Europe to Antarctica, the installation of the modules of the data acquisition rack and the installation of a preliminary computer control system for the new VLBA equipment the first VLBI experiments were performed during the antarctic summer in January/February 1992. As a result of the experiments of the first campaign fringes were only found in one X-band and one S-band channel. This was caused by an technical problem which was not considered during the early operation of the station: the phaselock system of the receiver local oscillator locked on 2015 MHz instead of 2020 Mhz. The geodetic results derived from the two channels had only meter-accuracy but provided some apriori coordinates for O'Higgins in the International Terrestrial Reference Frame (ITRF).

The second campaign was carried out in the Antarctic winter in May/June 1992. A power failure during the absence had caused an offset of the cesium clock. In addition, the preamplifier of the GPS antenna was found completely destroyed by corrosion. Hence the time offset to the other stations had to stay undetermined for the correlation. Several runs at the correlator did not show fringes and the attempt to recover the clock offset by extrapolation from the clock behaviour of the third campaign failed.

The experience with the weather dependency of the second campaign lead to a double scheduling for the third series of O'Higgins experiments. For each scheduled experiment an alternative date existed, which will be used only if the first date could not be served. The third campaign was organized in January/February 1993 with double schedules but no alternative date had to be used.

The O'Higgins experiments were executed in a network of stations belonging to four continents: Santiago (Chile), Hartebeesthoek (South Africa), Hobart (Australia), Tidbinbilla (DSS45) (Australia) and O'Higgins (Antarctica). The schedules were prepared by NASA Goddard Space Flight Center for the so-called POLAR-S and SURVEY-S experiment. NOAA's Geoscience Laboratory signed responsible for the Southern Hemisphere Survey (SHS) experiment and the US Naval Research Laboratory scheduled a Southern Reference (SOREF) experiment. The goals of the POLAR-S and SHS experiments were the determination of baselines and coordinates of O'Higgins, while the SOREF (Southern Reference) and SURVEY-S experiments were dedicated to improve and extend the radio source catalog with sources in the deep south.

25.01.1993	SHS-38	O'Higgins,	Hobart,	HartRAO,	Santiago	
27.01.1993	SURVEY-S1	O'Higgins,	Hobart,	HartRAO,	Santiago	
01.02.1993	SOREF-5	O'Higgins,		HartRAO,	Santiago,	DSS45
04.02.1993	SHS-39	O'Higgins,	Hobart,	HartRAO,	Santiago	
10.02.1993	POLAR-S1	O'Higgins,	Hobart,	HartRAO,	Santiago,	DSS45

Tab. 1, VLBI Experiments with O'Higgins

The correlation of the experiments was performed at the correlator of the United States Naval Observatory (USNO) and for the first time all experiments showed fringes in all 14 channels. The results of the correlation showed also minor problems which require some 'fine tuning' of the equipment. Current problems are temperature control of the receiver box, phasecal phase variations and variations in the cable delay measurements.

4.1 Data Analysis

The processing of the VLBI experiments which is presented here was done with the CALC/SOLVE program on the HP9000/720 at the VLBI computing center of the Geodetic Institute of the University of Bonn. The individual experiments were first parametrized running single independent least squares adjustments in order to find the most appropriate model for the behaviour of the station clocks and the local atmospheres. In these solutions the data was checked for obvious deficiencies. Subsequently the parametrizations of the preprocessed experiments were stored in databases.

In a second analysis step the independent experiments were combined in two different batch solutions. Since the O'Higgins experiments alone were not sufficient to reliably estimate all geometric parameters, a series of 41 IRIS-S (International Radio Interferometric Surveying - South) experiments which are regularly analyzed at the Geodetic Institute of the University of Bonn (Nothnagel, 1993, this volume) served as the frame for the determination of the O'Higgins coordinates.

In the standard IRIS-S parametrization Wettzell serves as reference station in the ITRF-92 while all other station coordinates including those of Santiago and HartRAO are estimated. Wettzell moves according to NNR-NUVEL-1 (Argus et al., 1991), Santiago is supposed to have zero motion in its short participation period and the horizontal motion of HartRAO is estimated.

Two different batch solutions were computed which determined the O'Higgins coordinates relative to HartRAO and Santiago based on their locations within the IRIS-S series which closely relates to the International Terrestrial Reference Frame 1992 (ITRF-92). The coordinates of DSS45 and Hobart were estimated in both solutions. In order to permit easy comparisons with other solutions the coordinates and baselines presented here refer to January 1st, 1993.

In the first batch solution the coordinates of O'Higgins were treated as arc parameters, i.e. one

triple of station coordinates was estimated with the data of each individual experiment. This solution is useful to analyze the quality of the individual experiments, which depend on the schedule used and on the conditions at the site.

The second batch solution (batch-93) used the information of all experiments to determine one triple of station coordinates for O'Higgins as global parameters. The advantage of this strategy is that the information of all experiments is used together and the results are stabilized.

Station Solution	Date 1993	X [m+mm]	Scaled Sigma [mm]	Y [m+mm]	Scaled Sigma [mm]	Z [m+mm]	Scaled Sigma [mm]
O'Higgins		1525832		-2432463		-5676174	
SHS-38	25	1093.39	17.16	757.75	18.63	641.85	28.93
SURVEY-S1	27	1062.82	21.49	696.71	23.00	534.12	48.85
SOREF-5	32	977.99	37.46	644.51	49.06	338.51	115.71
SHS-39	35	1061.72	15.98	687.14	18.89	441.20	31.34
POLAR-S1	41	1075.97	13.86	725.50	14.89	542.40	14.68
batch-93		1074.03	14.44	722.50	14.91	541.64	13.80

Table 2, Coordinates from different solutions

Table 2 shows the estimated coordinates referred to the ITRF-92 via the adopted coordinates of Wettzell. Figure 4 depicts the results of the different estimates for the O'Higgins coordinates in a topocentric system (north, east components).

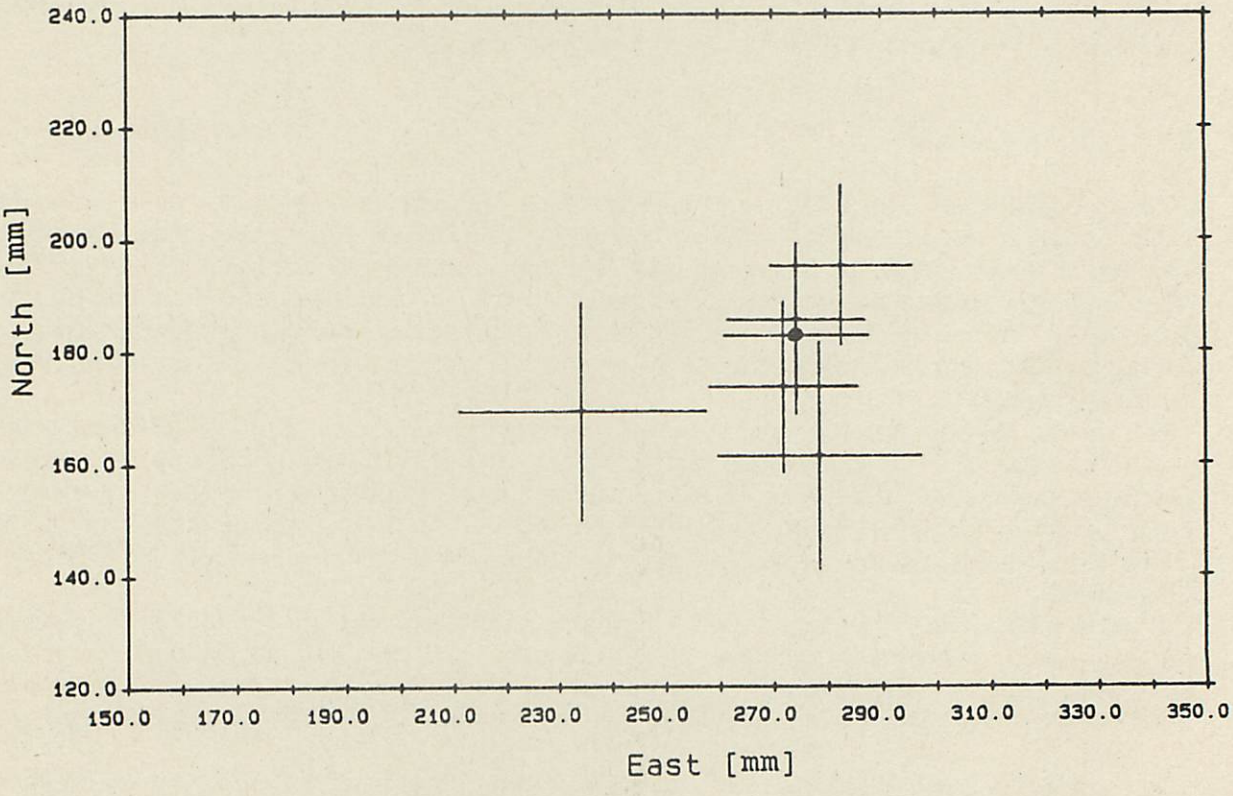


Fig. 4, Horizontal positions in a topocentric system from different experiments. The global topocentric position is marked with a ●

The best agreement of the global O'Higgins coordinates (from batch-93) with those where they were computed as arc parameters is found with the results of the POLAR-S1 experiment. This can be explained by the number of successful (used) observations. Due to the unknown performance of the O'Higgins radio telescope the schedules for most experiments were prepared using relatively long scan lengths in order to acquire a sufficient signal level. Therefore, the resulting numbers of observations in most sessions were rather small.

Table 3 shows the estimated baseline lengths to O'Higgins of the two batch solutions and the baselines in the southern VLBI network of the complete batch solution. In the batch-93 solution the maximum scaled sigma of the baselines is 12 mm while the scaled sigmas of the individual experiments are higher.

Baselines		Experiment	Day in 1993	Length [m+mm]	Scaled Sigma [mm]	used obs.	total obs.	used/tot. [%]
O'Higgins	HartRAO			6865978				
		SHS-38	25	754.11	17.52	31	35	88.6
		SURVEY-S1	27	678.97	28.83	23	83	27.7
		SOREF-5	32	601.34	68.61	49	72	68.1
		SHS-39	35	633.08	19.50	19	36	52.8
		POLAR-S1	41	697.05	10.16	69	72	95.8
		batch-93		**695.56**	**8.87**	**191**	**298**	**64.1**
	Santiago			3428751				
		SHS-38	25	815.65	11.98	45	55	81.8
		SURVEY-S1	27	794.95	25.53	25	97	25.8
		SOREF-5	32	714.80	40.97	51	81	63.0
		SHS-39	35	742.49	11.98	31	53	58.5
		POLAR-S1	41	777.41	6.74	73	102	71.6
		batch-93		**779.98**	**5.77**	**225**	**388**	**58.0**
	Hobart			7509970				
		SHS-38	25	510.92	22.09	35	40	87.5
		SOREF-5	32	296.97	74.09	28	38	73.7
		SHS-39	35	404.82	22.01	21	37	56.8
		POLAR-S1	41	458.90	11.69	46	56	82.1
		batch-93		**457.56**	**11.22**	**130**	**171**	**76.0**
	DSS45			8124908				
		SURVEY-S1	27	594.40	32.26	51	86	59.3
		POLAR-S1	41	624.26	12.29	51	63	81.0
		batch-93		**622.95**	**11.84**	**102**	**149**	**68.5**

Table 3, Baseline lengths from different solutions

Figures 5 and 6 depict the results for the O'Higgins - HartRAO and O'Higgins -Santiago baselines from the different sessions. Again a clear deviation from the averages is obvious for the SOREF experiment.

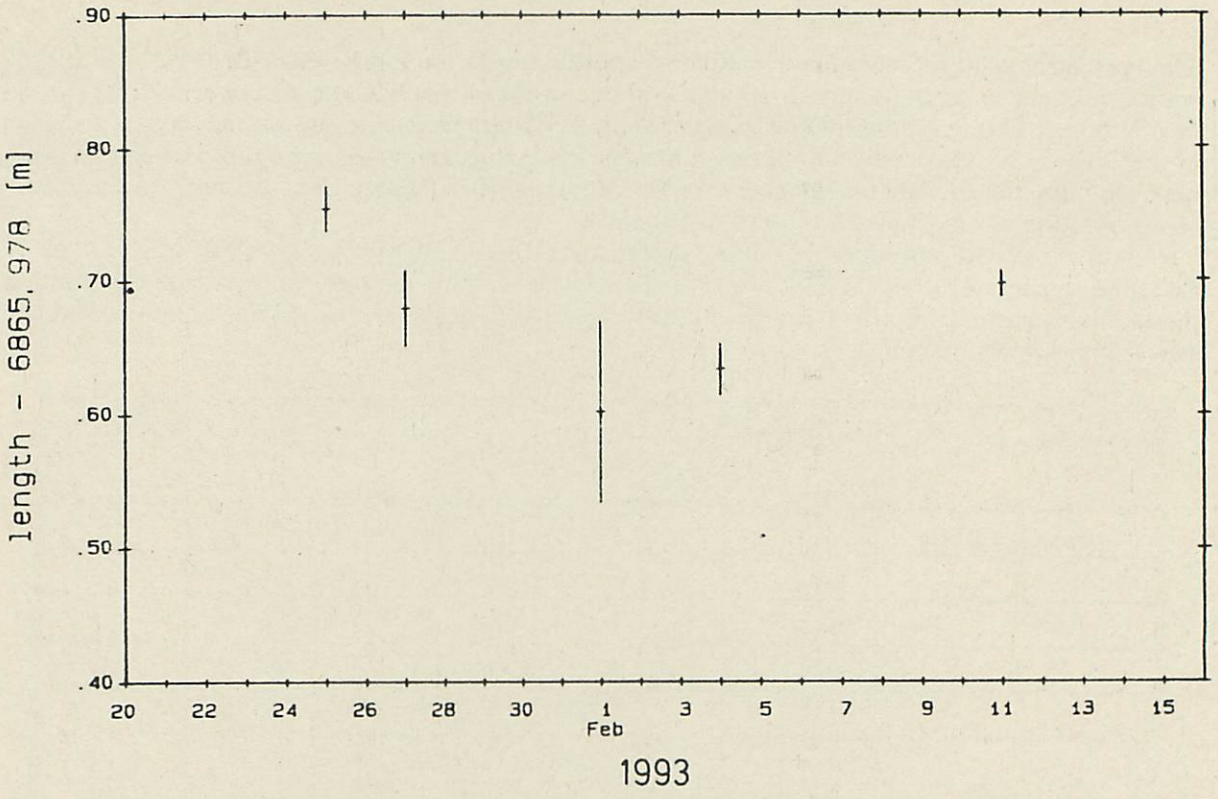


Fig. 5, O'Higgins - HartRAO baseline lengths from different experiments

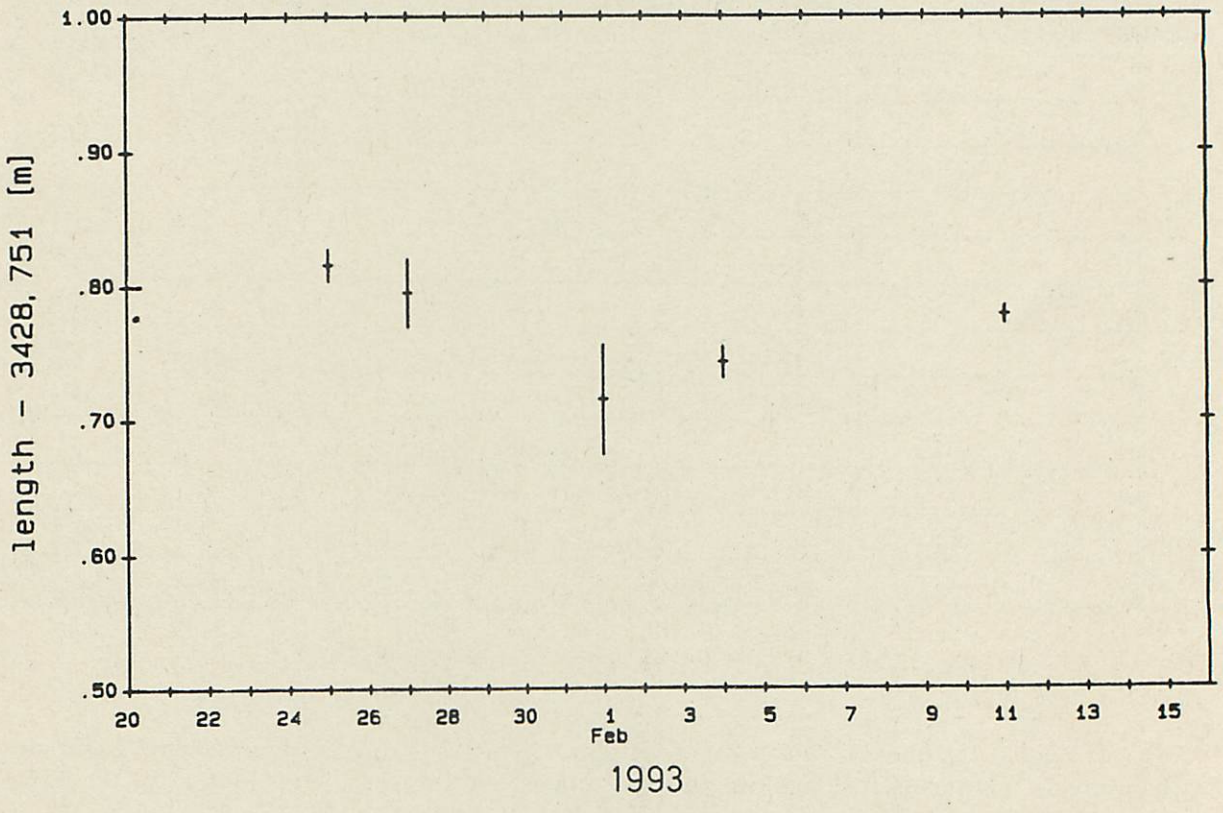


Fig. 6, O'Higgins - Santiago baseline lengths from individual experiments

5 Conclusion and Outlook

The ERS/VLBI-Station O'Higgins is the first VLBI station on the Antarctic continent, which will regularly participate in VLBI experiments. The results of the first successful campaign demonstrate that the station is almost completely set up for routine VLBI operations. The coordinates and baseline lengths presented here have the character of a first epoch measurement for studies of tectonic motions of the Antarctic peninsula.

The station plays an important role for global change studies due to its location at the edge of the ice. In addition to tectonic motions strong vertical and horizontal movements are to be expected by an uplift of the crust due to the remove of ice masses.

In order to extend the knowledge of the vertical changes of O'Higgins IfAG will equip the site with a tide gauge. Gravitational measurements at O'Higgins are under discussion as well as the installation of a permanent GPS receiver. From the geodetic point of view O'Higgins will be the reference point for many other geodetic explorations and activities on the last unknown continent.

6 References

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Microwave Radiometry for Correction of Atmospheric Path-Length Variations in VLBI: Recent Results

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Abstract. We have evaluated the impact on the repeatability of estimated baseline lengths by using a Water-Vapor Radiometer (WVR) to derive corrections for the excess propagation path caused by atmospheric water vapor (called the wet delay). The results are compared with those obtained from the "standard" Kalman filter method for estimation of atmospheric corrections. For recent, presumably more accurate, VLBI data we find that the repeatability is improved by the use of WVR data from the Onsala site, if observations below 15°–20° are not used in the analysis. For the standard Kalman-filter VLBI solution we find that low elevation observations are necessary in order to obtain a repeatability comparable to that obtained when using WVR data and ignoring the low elevation observations.

1. Introduction

The use of water-vapor radiometers (WVRs) in geodetic Very-Long-Baseline Interferometry (VLBI) was foreseen before the Mark-III data acquisition system was in operation [*Shapiro*, 1976]. Since then much effort has been spent on implementing this method as an operational part of the geodetic VLBI network (see, *e.g.*, *Resch et al.*, [1985]). However, even if WVR data have been useful in the characterization of wet delay variations and the evaluation of the performance of different estimation techniques of the wet delay, the hoped large improvement in accuracy of the estimated geodetic parameters has not yet been realized. Rather, the results obtained when using WVR data have been very similar to those using estimation techniques [*Elgered et al.*, 1991; *Kuehn et al.*, 1991].

We have continued to assess the influence of the wet delay on the accuracy of geodetic VLBI by including also more recent data in the analysis under the assumption that the atmospheric errors are now relatively more important compared to other instrumental errors of the Mark-III system and thereby making it easier to study their influence.

2. Measuring vs. Estimating the Wet Propagation Delay

One possible method to handle the wet delay is to measure it *a priori* with a sufficient accuracy so that further estimation of atmospheric delays are not necessary. The opposite procedure is to estimate the wet delay (or even the entire delay) during the experiment using the VLBI data themselves. In the first case we will obtain smaller formal errors in the geodetic parameters but will be sensitive to errors in the *a priori* values. This problem is avoided if the atmospheric delay is estimated but is paid for in terms of larger uncertainties in the geodetic parameters. A detailed discussion of this subject has been given by *Herring* [1986]. The lack of large improvements in the VLBI accuracy when using the WVR method is a consequence of the errors in the derived wet delays being in the order of a centimeter in the zenith direction.

3. The VLBI Data

In the analysis we want to apply atmospheric corrections derived from microwave radiometer data and compare the results with those obtained using the standard Kalman filter method. Let us first give a brief history of the available WVR data.

The WVR was taken into operation during the first successful geodetic Mark-III experiment at Onsala in July 1980. In April 1988 the pointing system of the WVR was modified to use a mirror for the control of the elevation angle, previously accomplished by tilting the whole instrument. We believe that this change improved the stability of the reference temperature load which was cooled in a dewar filled with liquid nitrogen. During the time period 1980–1990 the WVR could be operated in two modes either using the liquid nitrogen reference or using a heated reference load.

In October 1990 the WVR was taken out of operation to upgrade the data acquisition and control system. Also the liquid nitrogen loads were replaced by more accurate actively controlled hot reference loads. This work was finished in February, 1992, when the WVR was again taken into operation. In this analysis we will only use data from the 1980–1990 time period and except for a couple of experiments all the WVR data were obtained in the "cold" mode.

Between July 1980 and October 1990, 205 geodetic VLBI experiments have been scheduled to involve Onsala. Due to strong winds (which prevented us from operating the 25 meter antenna used for S-band before March 1987), or problems with the hardware, such as the antenna drive, the H-maser, and the Mark-III terminal, 14 of these were never carried out, or gave only a few hours of recorded data of acceptable quality. Another 6 experiments are ignored in this analysis due to logistical problems in the data handling. The WVR data was too sparsely sampled during 7 experiments of the short MERIT campaign in October, 1980, and another 7 experiments were ignored because of heavy rain during a major part of the experiment implying that the WVR data are useless. The WVR was malfunctioning during 4 otherwise successful experiments.

Thus we have 167 experiments for use in this analysis, having reasonably good quality and coverage of VLBI as well as WVR data. It should be pointed out that even though 20% of the experiments are not used in the analysis the operational reliability has improved with time. When we look at the statistics for the 1987–1990 period only 10% of the experiments cannot be used due to reasons mentioned above. The distribution of the experiments is presented in Figure 1 for baseline lengths successfully estimated more than 20 times.

All experiments used the Mark-III data acquisition system with the standard geodetic S/X-band frequency setup with 2 MHz windows spanning 360 MHz at X-band and 85 MHz at S-band. After the spring of 1982 there are 8 X-band windows and 6 at S-band (before 4 and 3, respectively).

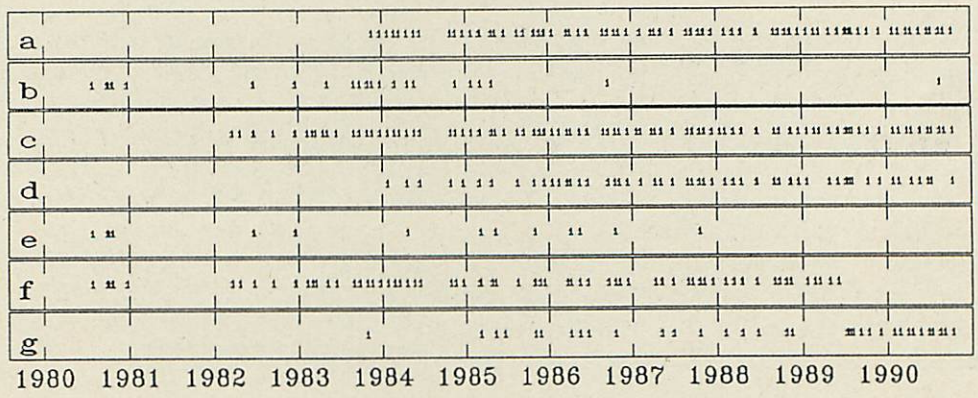


Figure 1. The temporal distribution of the baselines analyzed. Only baselines measured more than 20 times are included in the analysis. From the top Onsala to: (a) Wettzell, 920 km, 117 experiments; (b) Haystack, 5600 km, 31 experiments; (c) Westford, 5601 km, 132 experiments; (d) Richmond, 7307 km, 57 experiments; (e) Owens Valley, 7914 km, 27 experiments; (f) GRAS (Fort Davis), 7941 km, 87 experiments; (g) Mojave, 8021 km, 35 experiments.

4. Results

The analysis is carried out for two different sets of solutions. First we use the "standard" Kalman filter solution for clocks and atmospheres at the different sites [*Herring et al.*, 1990]. In order to study the importance of low elevation angle observations we performed nine different solutions for every experiment each with a different elevation cut-off angle for the Onsala observations.

Thereafter, we performed nine other solutions, the only difference from the original being that instead of estimating the wet delay variations at the Onsala site with the Kalman filter we apply the wet delay values derived from WVR data and make no further adjustment of the delay due to the neutral atmosphere.

We evaluate the solutions based on the obtained weighted root-mean-square (wrms) repeatability of the estimated baseline lengths. We concentrate on recent data and will not discuss the results for the Onsala–Haystack and Onsala–Owens Valley baselines because they are not significantly different from previous analysis [*Elgered et al.*, 1991]. Figures 2–5 show the results of the elevation cut-off tests and the time series with the best repeatability for the Markov case and the WVR case. Below we comment on the results obtained for each baseline:

Wettzell (Figure 2)
The formal one-sigma uncertainty of the estimated baseline lengths and the repeatability improve with time regardless of which method is used for the atmospheric corrections at Onsala. It is seen that the short time repeatability is much better than that over longer time scales. One example of this is the relatively small scatter obtained for the estimated baseline lengths from the ten experiments during July and August, 1989. The WRMS scatter about the mean is 2.1 mm for the Markov solution and 1.4 mm for the WVR solution. This is a remarkable improvement given that a WVR was used only at one end of the baseline. However, we could only speculate about the possible additional improvement if a second WVR would have been used at Wettzell because we do not know how variable that atmosphere actually was during these experiments.

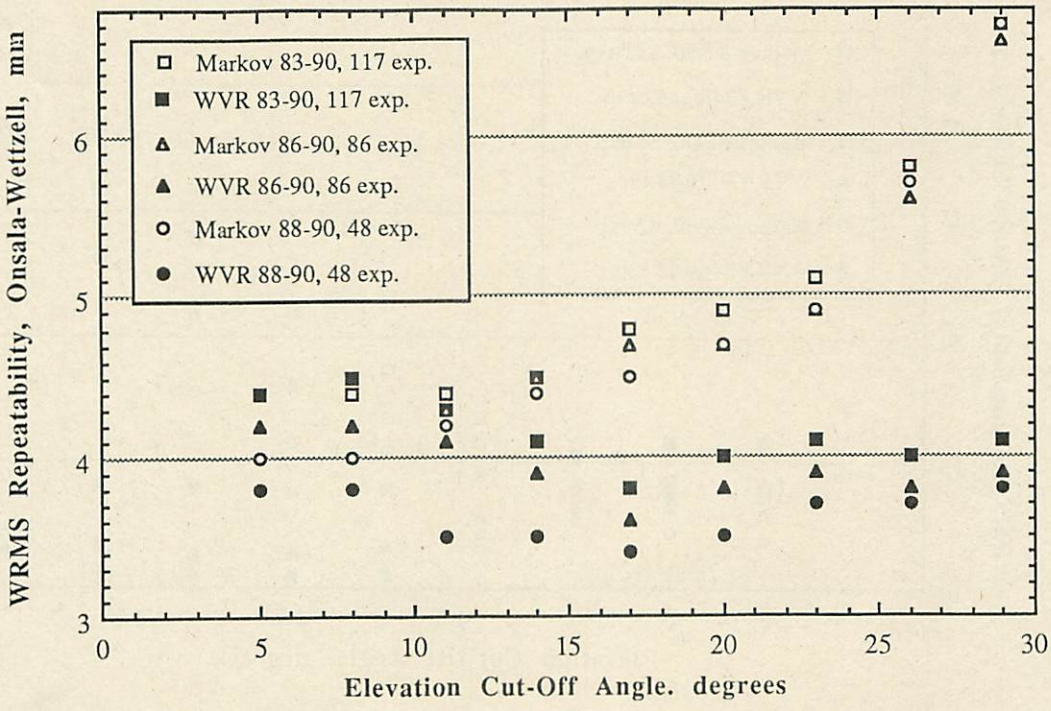


Figure 2a. Repeatability obtained for the Onsala–Wettzell baseline versus the elevation cut-off angle.

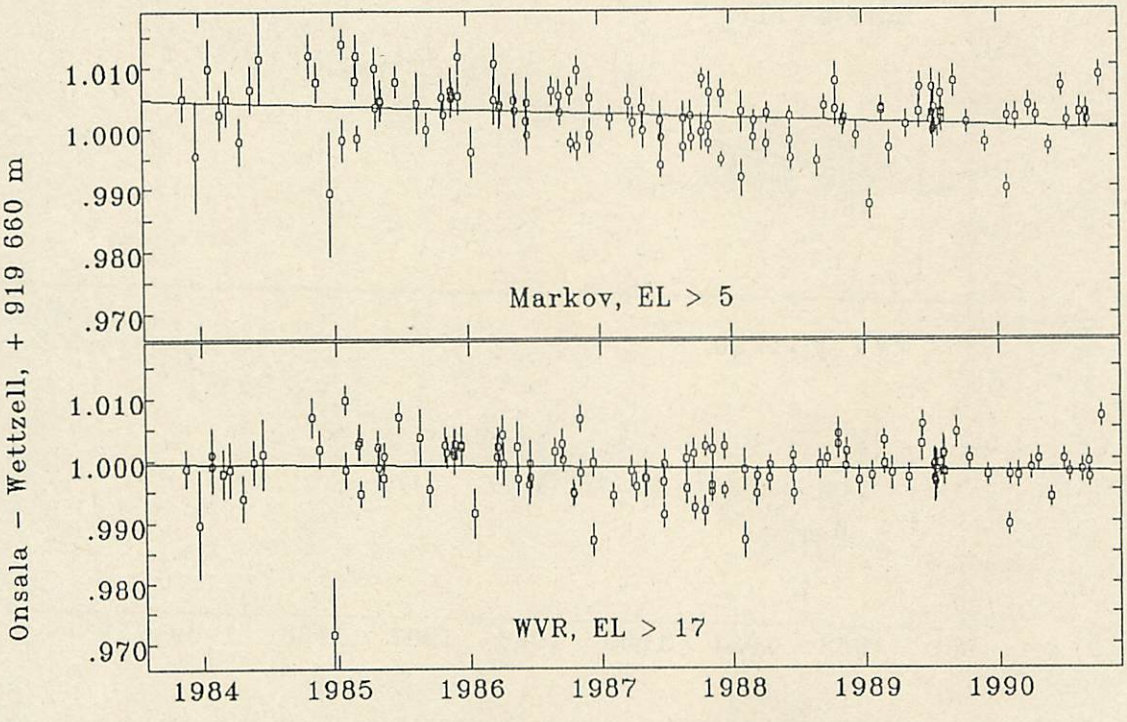


Figure 2b. Time series of estimated baseline lengths for the "best" elevation cut-off angles when using the Markov process or WVR data for the wet delay correction.

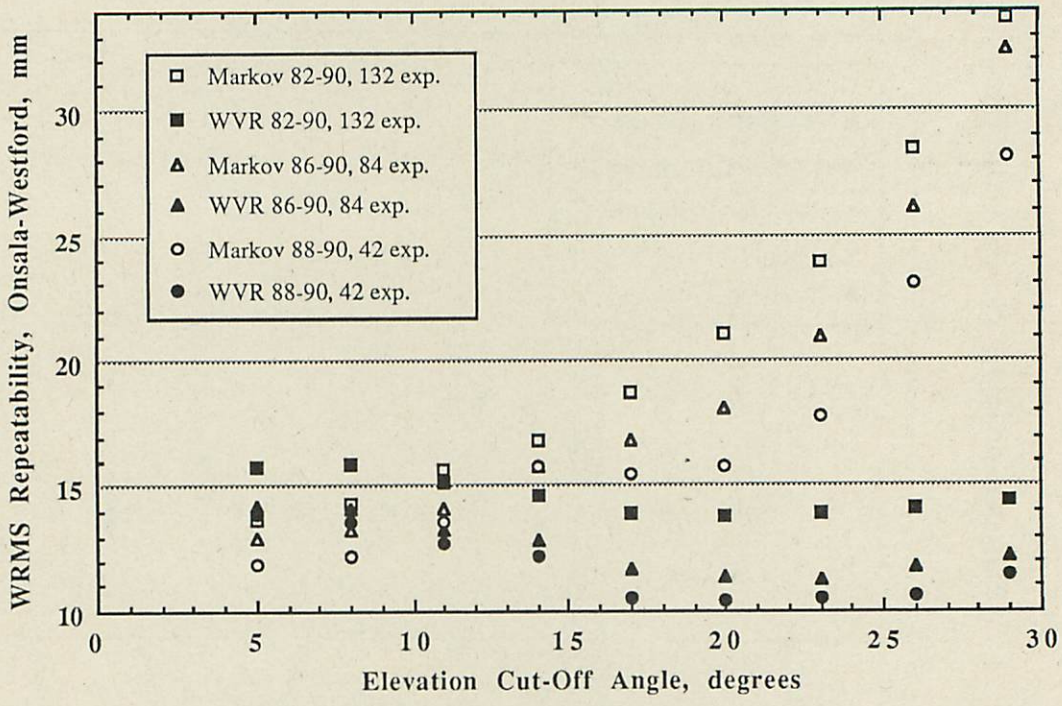


Figure 3a. Repeatability obtained for the Onsala–Westford baseline versus the elevation cut-off angle.

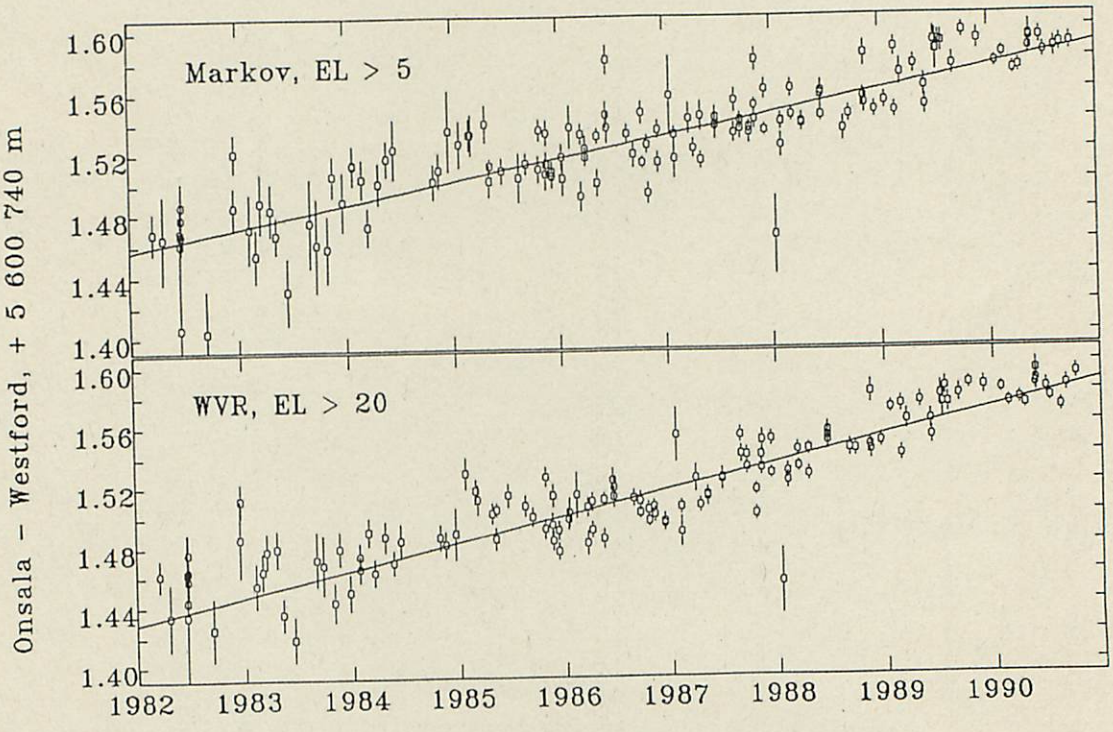


Figure 3b. Time series of estimated baseline lengths for the "best" elevation cut-off angles when using the Markov process or WVR data for the wet delay correction.

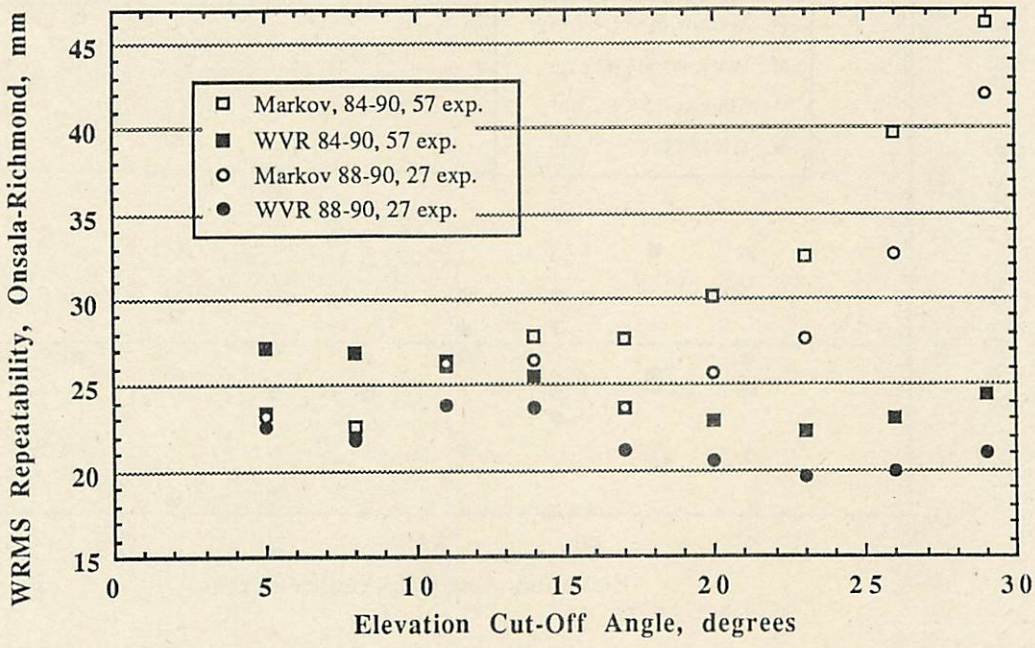


Figure 4a. Repeatability obtained for the Onsala–Richmond baseline versus the elevation cut-off angle.

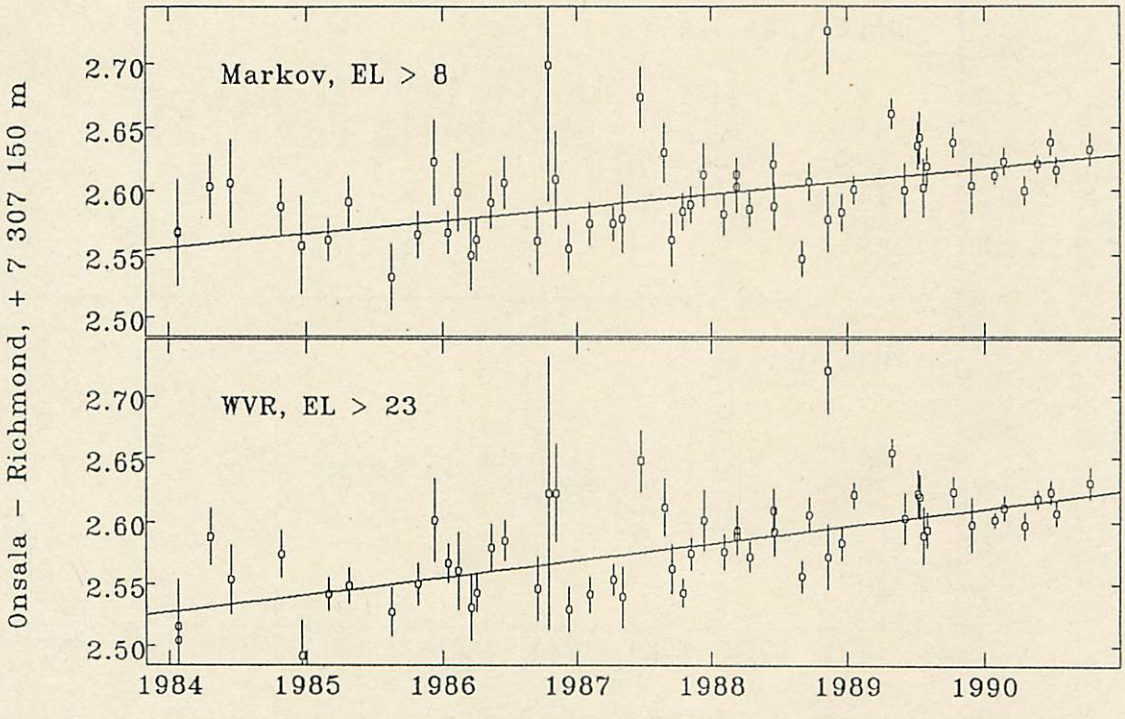


Figure 4b. Time series of estimated baseline lengths for the "best" elevation cut-off angles when using the Markov process or WVR data for the wet delay correction.

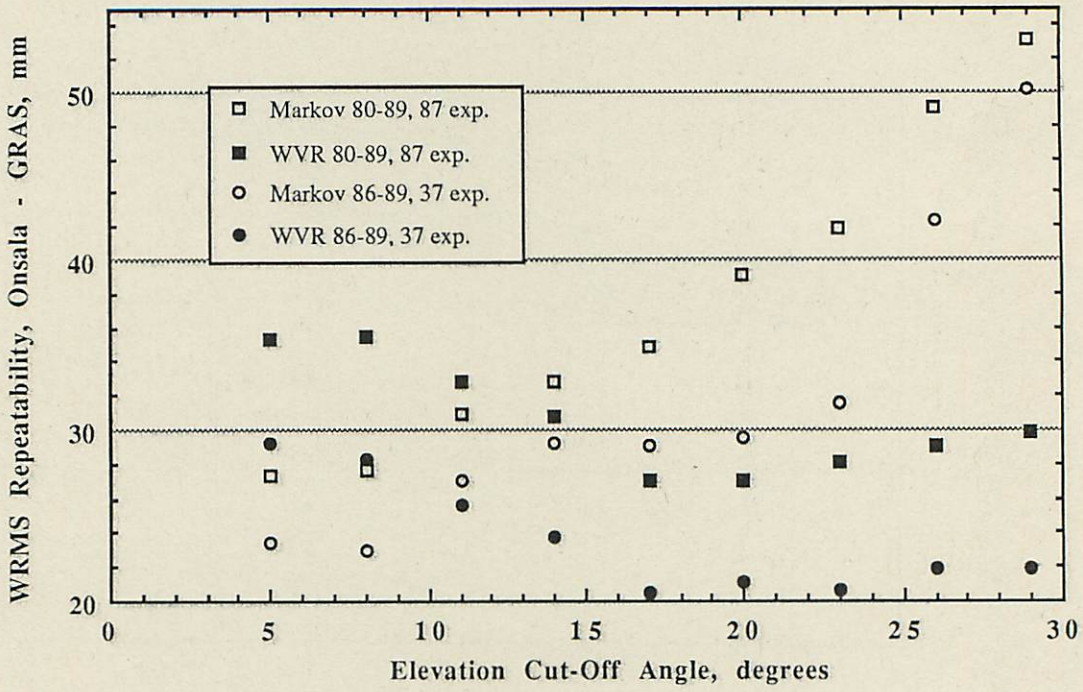


Figure 5a. Repeatability obtained for the Onsala–GRAS (Fort Davis) baseline versus the elevation cut-off angle.

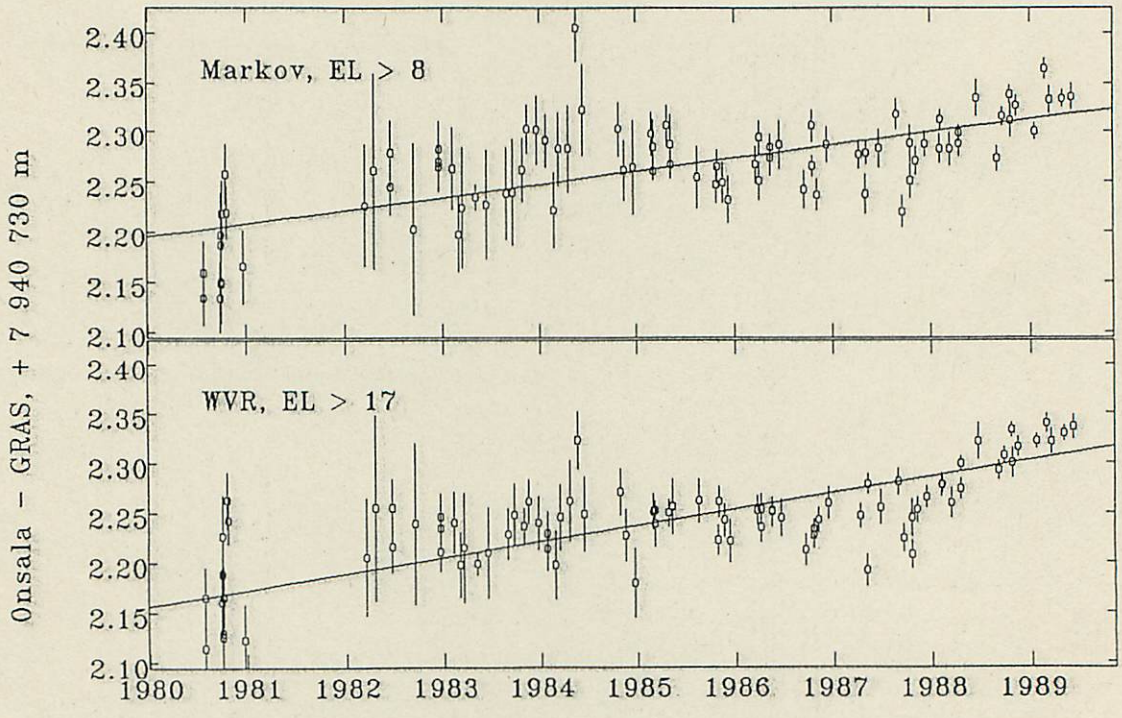


Figure 5b. Time series of estimated baseline lengths for the "best" elevation cut-off angles when using the Markov process or WVR data for the wet delay correction.

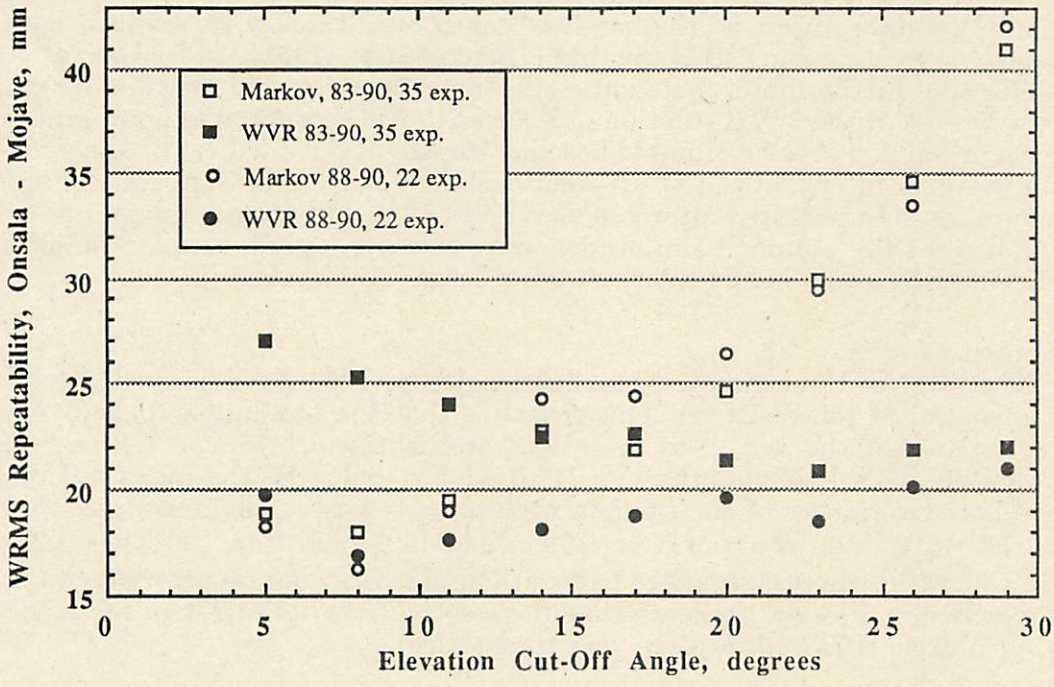


Figure 6a. Repeatability obtained for the Onsala–Mojave baseline versus the elevation cut-off angle.

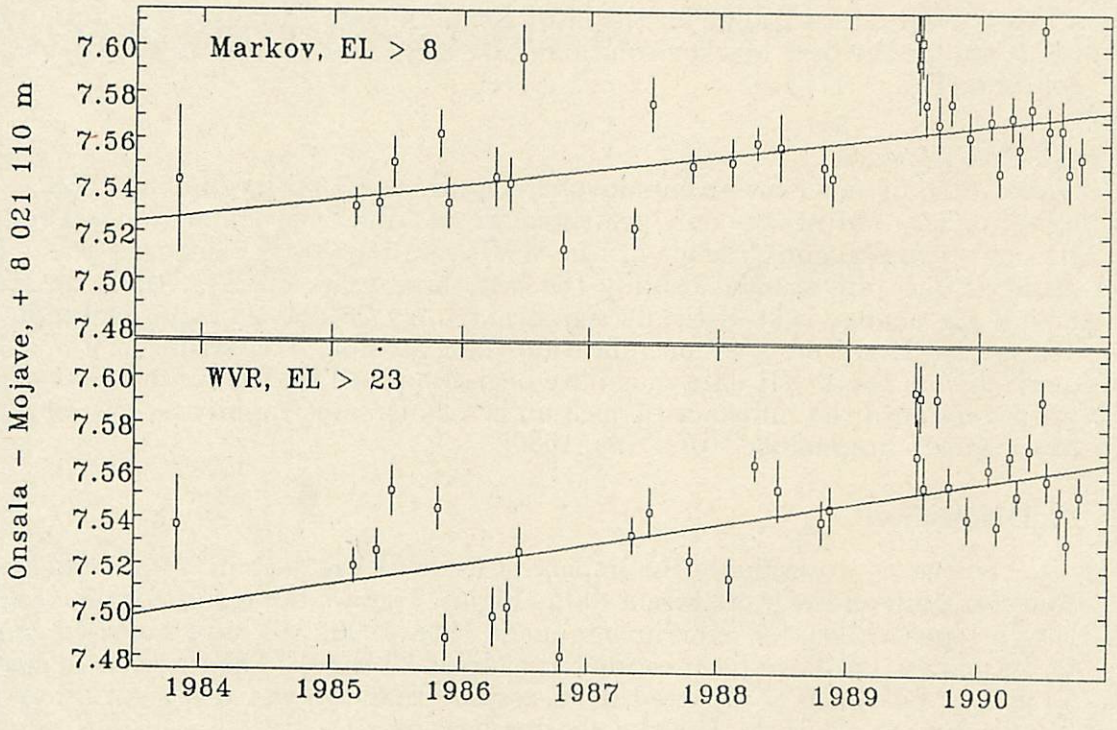


Figure 6b. Time series of estimated baseline lengths for the "best" elevation cut-off angles when using the Markov process or WVR data for the wet delay correction.

Westford (Figure 3)
This baseline is more than six times longer than that to Wettzell and is, therefore, more affected by atmospheric errors [*Davis et al.*, 1985]. Already in the previous evaluation of WVR data for atmospheric corrections in VLBI it was noted that the WVR data improved the baseline length repeatability for the last couple of years (Aug. 86 to June 88 at the time) [*Elgered et al.*, 1991]. This observation still holds and, furthermore, systematic effects in the estimated baseline lengths are clearly seen in the WVR solution in Figure 2b. We estimated annual components of the residuals of the estimated baseline lengths about the best fit slope for both the Kalman filter and the WVR solutions using the entire data set in Figure 2b as well as data acquired after January 1st of 1986 and after January 1st of 1988. In all cases the obtained amplitudes were, however, only a couple of millimeters and improvements in the wrms were not large ($\leq$ 0.5 mm).

Richmond (Figure 4)
The scatter in the estimated baseline lengths to Richmond is much larger than that obtained for Westford. One reason is that the baseline is longer. Another reason is that the wet delay variations at Richmond are expected to be much larger compared to the other VLBI sites. For example, the mean value of the estimated variances of the random walk process—using the delay rate residuals of the VLBI data [*Herring et al.*, 1990; MacMillan and Ray, 1991]—is 0.83 ps^2/s at Richmond whereas it is 0.14 ps^2/s at Onsala. Also radiosonde data from West Palm Beach, Florida, indicate that the wet delay variations here are large (see, *e.g.*, *Elgered* [1993] for a three year time series).

GRAS, Fort Davis (Figure 5)
The VLBI position of GRAS has previously been reported to show systematic variations at the centimeter level. The Onsala–GRAS data are rather noisy before 1986 but also for this baseline the scatter improves with time. Unfortunately, the last experiment involving Onsala and GRAS was carried out in June 1989 (the antenna was "decommissioned" soon after) so there are not enough experiments for a separate analysis of 1988–1990 data. We note, however, that the WRMS scatter about a best fit line for the last 22 experiments (August 1987–June 1989) is 22 mm for the best Markov solution (EL. $>$ 8°) and 16 mm for the best WVR solution (EL. $>$ 17°)

Mojave (Figure 6)
There are only few experiments involving Onsala and Mojave before 1986 so the elevation cut-off tests are only presented for two different time periods. The "optimum" elevation cut-off angle for the WVR solutions is very different depending on if all data are studied or only the last three years of data. It is questionable if the change is statistically significant (only 33 and 22 experiments in the solutions). However, it is an indication than possible bias errors in wet delays derived from the WVR data may have been improved for the more recent experiments because the influence of such an error increases rapidly as low elevation observations are included [*Herring*, 1986].

5. Discussion

Let us try to evaluate the impact of using WVR data in VLBI analysis by concentrating on the more recent data. Figure 7 shows the results of the baseline length repeatability for experiments made 1988–1990. We have included results for baselines that have been estimated at least 20 times. The increase in scatter for longer baselines is expected if we assume that the wet delay variations are a main source of error. For the shorter baselines the WVR solutions offer an improved repeatability if low elevation observations are ignored in the analysis

compared to the standard case using the Kalman filter to estimate a Markov process where low elevation observations are needed in order to obtain the best repeatability. When the WVR data are used the best cut-off angle is in the range 15–20°.

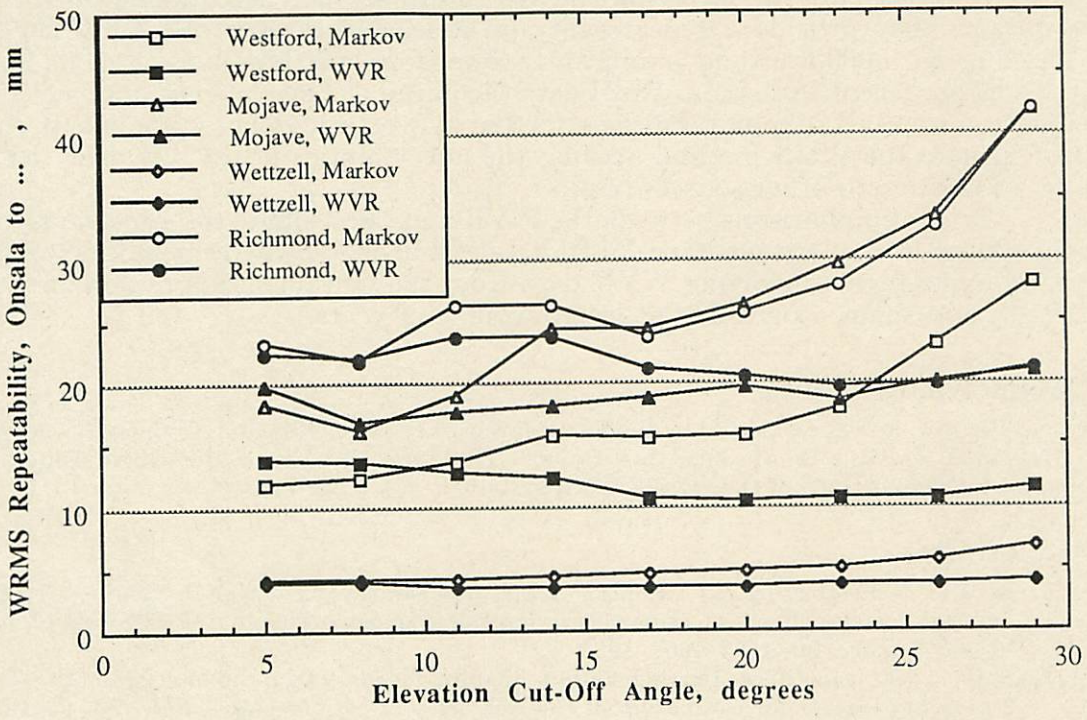


Figure 7. Repeatability obtained for the baselines measured more than 20 times during the period 1988–1990 versus the elevation cut-off angle.

It is possible that the lack of a pronounced minimum of the scatter at a similar elevation cut-off angle for the longer baselines is due to the geometry. When the low elevation observations are ignored at Onsala it is a larger percentage of these that are between Onsala and the sites far away.

Because of the very different optimum elevation cut-off angles obtained for the two cases of using a Kalman filter or the WVR it impossible to schedule an optimum geodetic VLBI experiment. When a WVR is available valuable observing time is lost by performing low elevation observations. On the other hand, if WVR data are strongly affected by rain, or simply just not of acceptable quality, the low elevation observations are extremely important for the necessary estimation of the wet delay variations. One consequence of this is that we do not know what the best repeatability using the WVR method could have been if only sources above say an elevation angle of 15° were observed during an entire 24 hour experiment.

In order to reduce the conflict whether or not to schedule low elevation observations to a VLBI site where a WVR is available it is still important to reduce bias type errors associated with the WVR method. We believe that the three most important are: (1) hydrostatic mapping function errors [*Davis et al.*, 1985] which may be partly responsible for such systematic effects as seen in the WVR solution Onsala–Westford (Figure 3b), (2) instrumental errors of the WVR, and (3) bias errors of the attenuation coefficients for water vapor [*Waters*, 1976; *Liebe*, 1992] used to derive the relation between WVR measured emissions and the wet delay [*Johansson et al.*, 1993].

6. Conclusions and Future work

The use of microwave radiometry for correction of the wet propagation delay ought to be seriously considered at a couple of additional VLBI sites. Even if future units are not operationally reliable to the level so that low elevation observations can be avoided already in the scheduling we have shown that the method of microwave radiometry is useful. In spite of the fact that 10–30% of the successful observations involving the WVR site are not used in the best WVR solutions they provide a repeatability of at least the same order for the long baselines ($>$ 6000 km) and significantly lower for short baselines ($<$ 6000 km).

More recent wide band VLBI data (acquired at Onsala since January 1992) and an improved mapping function for the hydrostatic delay will make it easier to evaluate the WVR method because the uncertainties in the wet delay will be larger relative to other sources of error.

Future comparisons between the WVR and the Kalman filter methods using these new, even more accurate, VLBI data will be made when the number of wide band experiments involving WVR data from the Onsala site is reasonable large ($\gtrsim 20$) and spans a period of at least a couple of years.

Acknowledgements

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The Use of Structure Functions for Characterization of Variations in the Wet Delay

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Abstract

The water vapour radiometer (WVR) at the Onsala Space Observatory has been used to measure the temporal variations in the wet delay. The estimates of the so called "structure functions" differs significantly from what is proposed by a commonly used model in the range from ten to one hundred minutes. The absolute value of the structure function was strongly dependent on how the liquid water content was handled. These measurements will be followed by more systematical investigations using different techniques.

1. Introduction

The variations in the wet delay are considered one of the main error sources in geodetic Very-Long-Baseline Interferometry (VLBI) measurements. The variations are in general solved for by estimating the delay from the VLBI data themselves but it is also possible to use an independent measurement technique such as microwave radiometry (see *Elgered and Davis* [1993]).

If the wet delay is to be estimated from the VLBI data themselves some constraints have to be applied to get acceptable variations. In solutions using Kalman filters made by *Herring et al.* [1990] the estimates of geodetic quantities did not vary much with different power spectral densities of the random walk process used to estimate the wet delay. Despite this, simulations made by *Treuhaft* [1992] show that if the fluctuations follow the Kolmogorov model (see below), the choise of model parameters will influence the RMS of the estimated geodetic quantities.

WVRs can measure the fluctuations in the wet delay over a wide range of time lags and directions and thus contribute to the modelling of the fluctuations.

2. Turbulence : The Kolmogorov Model

The (one dimensional) spatial structure function D_q of a quantity q is defined as

$$D_q(R) \stackrel{\text{def}}{=} < [q(r+R) - q(r)]^2 > \qquad (1)$$

where r and R are position coordinates. For a given spatial separation R the value of $D_q(R)$ is not influenced by variations of much longer wavelengths than R. In contrast to the definition of correlation this definition does not contain any dependence on the expectation value of the process. This is an advantage when the process measured is neither isotropic nor stationary. (See *Tatarskii* [1971] for more details on the statistical properties of structure functions).

In deriving an expression for the structure function for the wind speed Kolmogorov made several assumptions [*Tatarskii*, 1971]:

1. Kinetic energy is injected at relatively long wavelengths.
2. The kinetic energy is transferred to successively smaller and smaller eddies with neglible losses while the turbulence can be preserved.
3. In this decaying process the original direction disappears and the turbulence becomes locally isotropic in subregions.

From the laws of fluid mechanics and under the assumption that the water molecules are transported by this turbulent motion, the structure function of the wet refractivity, D_χ, can be derived from the above assumptions. It becomes [*Tatarskii*, 1971]

$$D_\chi(R) = C_\chi^2 \cdot R^{2/3} \tag{2}$$

where χ is the wet refractivity and C_χ is a constant. The structure function of the wet delay, τ, for two sites a distance R apart can then be derived [*Treuhaft and Lanyi*, 1987]:

$$D_{\tau,\theta,\phi}(R) = \frac{1}{\sin\theta^2} \int_0^h \int_0^h dz dz' \cdot (C_\chi^2([R^2 + 2(z-z')\,R\,\cot\theta\,\cos\phi + (\frac{z-z'}{\sin\theta})^2]^{1/3}) - C_\chi^2(|z-z'|/\sin\theta)^{2/3}) \tag{3}$$

where θ and ϕ are the elevation and azimuth angles of the observation (ϕ is relative to the vector from site 1 to site 2), and h is the effective height of the troposphere. Equation (2) is expected to be valid for distances from centimeters to a few kilometers where the statistical behaviour is expected to be isotropic, but *Treuhaft and Lanyi* [1987] used (2) also for larger distances since good agreement with some experiments has been obtained.

The temporal structure function $D_{\tau,\theta,\phi}(T)$ of the wet delay at a single site can be derived from (2) assuming "frozen flow"; that the turbulent spatial structure is flowing over a site with a constant wind speed v. In (2) R is replaced by $v \cdot T$, where T is the time difference between two observations. The parameter ϕ is now the azimuth angle of the observation relative to the wind direction.

Figure 1 shows the temporal structure function according to equation (2) for different angles using "standard parameters" $h = 2000$ m, $v = 10$ m/s and $C_\chi = 1.2 \cdot 10^{-7} \mathrm{m}^{-1/3}$. These values are used in later comparisons with measured curves. For short time lags the curves has a power law index of 5/3 and for longer time lags an index of 2/3. It is also seen from Figure 1 that the variations are expected to be smaller along the wind direction than in a direction perpendicular to it for short time lags.

2. WVR Measurements

Dedicated measurements have been made with the Water Vapour Radiometer (WVR) at the Onsala Space Observatory to obtain temporal structure functions. The WVR measures the emission from the atmosphere at 21.0 and 31.4 GHz. The use of two channels enables us to separate the contributions from water vapour and liquid water using the fact that the attenuation from the liquid water is proportional to the frequency squared. This is valid when the drop sizes are much smaller than the wavelength.

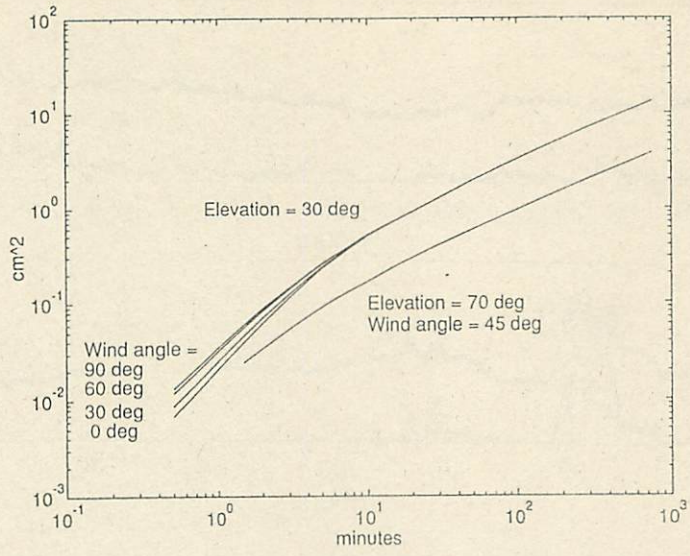


Figure 1. Wet delay temporal structure functions in different directions calculated from the Kolmogorov model and frosen flow hypothesis using standard parameters (see text).

The first procedure used consists of 90 s cycles with measurements in azimuth 0°and elevation 30°, 41.8°, and 70 °followed by azimuth 270°and elevation 70°, 41.8°, and 30°. These six directions form a so called "tip curve" (scans with different elevation angles and then different numbers of air masses). After nine cycles the "gain" (the conversion factor between measured voltages and corresponding temperatures) was measured using microwave loads at known temperatures. These WVR data may, therefore, be used to study both the azimuth end elevation angle dependence of the structure function.

The second procedure has higher resolution in azimuth. It has 60 second cycles with measurements in elevation 30°and azimuth 0°, 30°, 60°, 90°, and 120°. Every third scan was a tip curve from azimuth 120°and elevation 30°, 41.8°, 70°, 110°, 138.2°and 150°. Tip curves are used to get corrections for losses and reflections in the waveguides to the reference loads of the WVR. Every 12th minute a calibration was made. (See *Elgered* [1993] for details on WVR calibration and error sources.)

More frequent measurements than one per minute in each direction are probably less useful because then the white noise from the instrument is expected to be of the same order as the atmospheric variations.

Six measurement periods using these procedures have been made. Figure 2 shows examples the zenith wet delays from two of these periods, one (top) using the first procedure, and another (bottom) using the second procedure.

3. Data Analysis and Results

Three types of outlying data points were removed before the structure functions were calculated:

1. When the sun passed in the vicinity of the WVR beam in any of the directions. This caused a very characteristic peak in the data.
2. Data points where the calculated integrated liquid water content exceeded a certain value. For a large liquid water content big drops are more common which

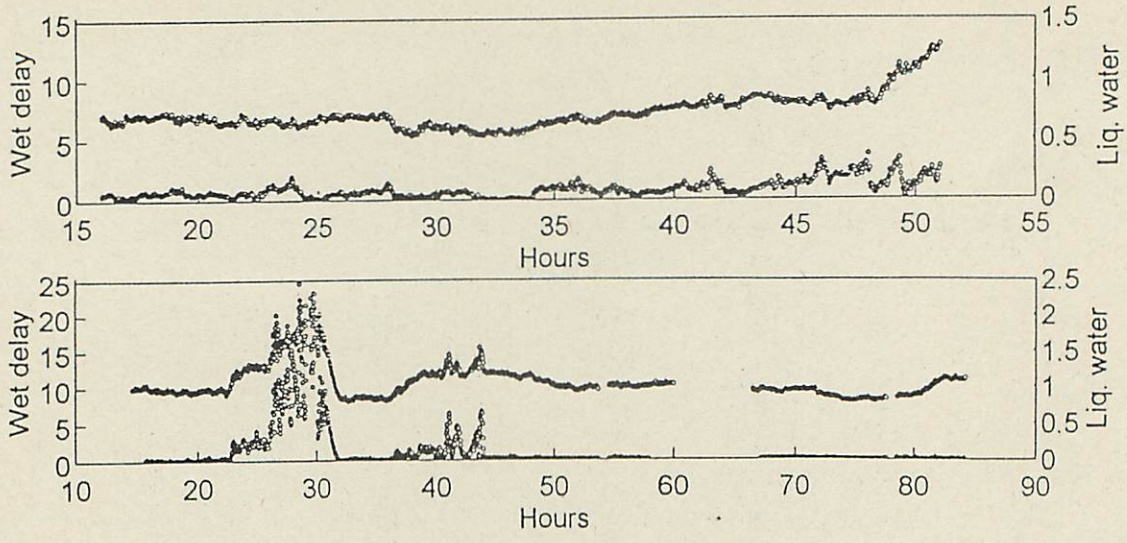


Figure 2. The zenith wet delay in cm from December 9–11 1992 (upper graph) and June 26–29 1993 (lower graph). The lower curves in each graph are the liquid water content in mm.

leads to an overestimated delay. The normally used maximum content (W_{max}) was chosen to 0.3 mm.

3. Data points that differs more than the standard deviation, σ, times a certain number from the other points in a 20 minutes window around the point. They are supposed to be caused by errors in the WVR data collecting system. The default value was 3σ.

Each WVR pointing direction were analysed separately to get the directional dependence of the structure function. All pairs of points in a data set were analysed for the different time lags available in the data set. The estimated variance of the white noise of the instrument, 0.014 cm^2 was then subtracted. Other measurement noises (e.g. the "algorithm error", the offset caused by unusual temperature and humidity height profiles) were assumed to have long enough time constants or small enough not to have a significant effect on the calculations.

The resulting structure functions for the two data sets shown above are presented in Figure 3 together with theoretical calculations using the "standard model".

The shape of the curves for short time lags (1 to 5 minutes) depends very much on the estimate variance of the white noise. On the other hand, for long time lags (longer than one tenth of the time span of the data set) the sizes of passing regions with more water vapour will cause characteristic signatures in the structure function. Therefore curves presented here has been cut off at time lags of 7.5 hours.

In the area from ten to one hundred minutes, where the estimates were expected to be more reliable, the logaritmic plots show straight lines with slope close to one, indicating nearly linear functions of time. This is in accordance with an earlier analysis of WVR data [*Elgered et al.*, 1990]. Standard values in the model predicts a transition towards a power law index close to 2/3 at one hundred minutes.

In order to investigate the effect of the above mentioned removal of points, the data set from June 26–29 was analysed with different W_{max} and different numbers of σ of a point to be considered an outlier. The result was that when the numbers of sigmas were increased the curves for short time lags became noisier but for longer time

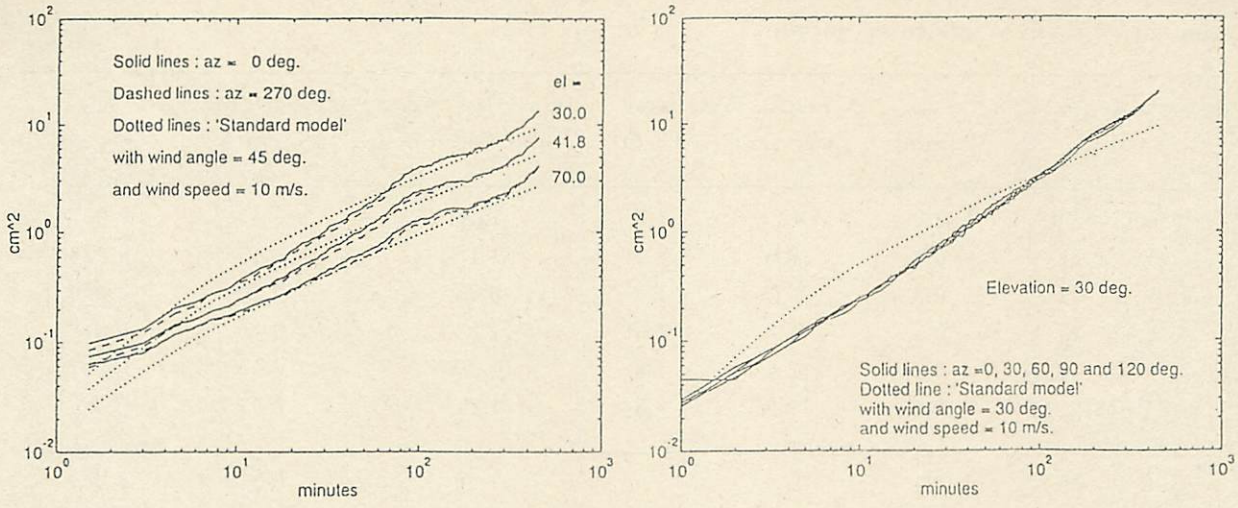


Figure 3. Temporal structure functions from December 9–11 1992 (left) and June 26–29 1993 (right).

lags the curves were unchanged. Changing W_{max} appered to raise or lower the whole curve. Curves with different W_{max} are shown in Figure 4.

In Table 1 the calculated power law indices for all the curves in the area 90 to 100 minutes are shown. Also shown are the values at 95 minutes for the structure function of the zenith delays and the corresponding power spectral density, Φ_r, at 95 minutes (assuming random walk processes). These calculations use the data with $W_{max} = 0.3$ mm. Also shown in Table 1 are the same calculations done on the data set from June 26–29 with different W_{max}.

An attempt to see a correlation between an azimuthal separation of the functions and the measured surface wind directions was made. The data set from August 12–18 was divided up into seven pieces with fairly constant wind directions and speeds which

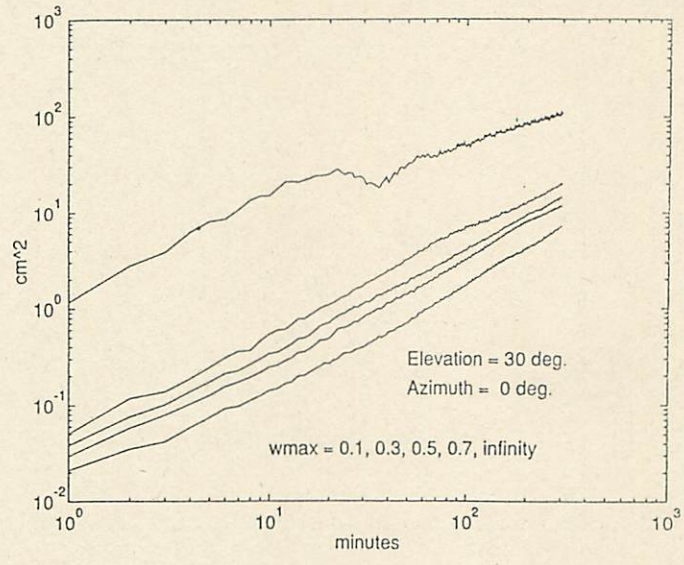


Figure 4. Temporal structure functions from June 26–29 1993 using different maximum liquid water content starting with 0.1 mm (bottom curve).

Table 1. Power law indices and absolute values of the measured structure functions and their corresponding power spectral densities. In the lower part the influence of the maximum liquid water content on these estimates are shown.

Data Set	W_{max} [mm]	Zenith Wet Delay mean [cm]	σ [cm]	Power law index @90–100 min	$D_{z\tau}$(95 min) [cm^2]	Φ_r [ps^2/s]
December 9–11	0.3	7.2	1.3	1.16	0.35	0.068
June 17–21	0.3	10.0	2.2	1.13	0.45	0.088
June 22–24	0.3	8.7	1.0	0.78	0.36	0.070
June 26–29	0.3	9.9	1.3	1.03	0.40	0.078
August 4–6	0.3	12.1	1.8	1.20	0.50	0.097
August 12–18	0.3	10.9	3.8	1.21	0.51	0.099
June 26–29	0.1			1.20	0.31	0.060
June 26–29	0.3			1.03	0.40	0.078
June 26–29	0.5			1.03	0.45	0.088
June 26–29	0.7			1.09	0.50	0.097
June 26–29	∞			(0.16)[1]	(1.14)[1]	(0.222)[1]

[1] The values varied very much between different directions

were analysed separately. The expected lower values for the structure function along the measured wind direction than perpendicular were not detected. A simple analysis of one year's radiosonde data taken at Gothenburg/Landvetter airport showed that the average wind direction within 3000 metres above the surface was 16°off the average surface wind direction. This indicates that the frozen flow model might be too simple.

For longer time lags (from 12 hours) the zenith delay structure functions are easily obtained from radiosondes. Figure 5 shows yearly averaged zenith delay structure functions from Gothenburg/Landvetter airport combined with one winter and one summer measurement from the WVR.

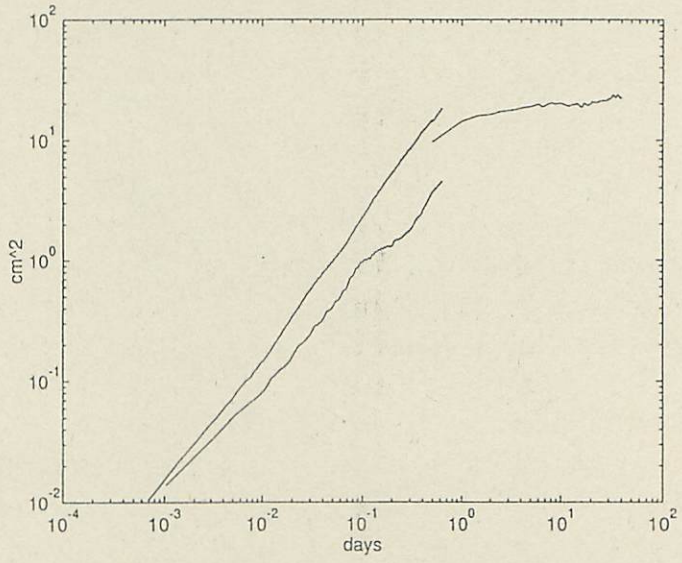


Figure 5. Temporal structure functions from December 9–11 1992 (lower left), August 12–18 1993 (upper left) and from one year's radiosonde data (right).

As expected the curve from one year of radiosonde data appears between the two (extreme) WVR curves for time lags of 12 hours.

4. Discussion and Conclusions

These very preliminary results show that it is of great importance how the data taken during large amounts of liquid water is handled. We note also that the behaviour in the region from 10 to 100 minutes is more linear than expected from the standard model.

More systematic investigations will be made using dedicated WVR procedures, analysis of old WVR measurements, analysis of radiosonde data from different sites, and measurements with airborne metereorological sensors.

Since there seems to be systematic differences in wind direction between different heights, another topic for further work might be the inference of more realistic wind conditions into the Kolmogorov turbulence equations instead of the frozen flow hypothesis.

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COMPARISON OF IONOSPHERIC DELAYS OBTAINED FROM S-X VLBI EXPERIMENTS AND GPS OBSERVATIONS

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ABSTRACT

GPS observations gathered during S-X VLBI experiments have been analyzed to extract the ionospheric delay along the signal path of the VLBI observations. These GPS-based delays have been compared with those obtained from S-X VLBI observations, with the rms of the differences less than 0.1 nanoseconds. In order to check the use of dual GPS data for the ionospheric calibration of single frequency VLBI observations, the baseline lengths estimated using dual VLBI data have been compared with those estimated from single band VLBI data calibrated with the GPS-based ionospheric delays. The differences between both results for European baselines were in the order of 3-5 parts per 10^9.

1. INTRODUCTION

Radio signals crossing the ionosphere suffer a delay that is proportional to the ionospheric Total Electron Content (TEC) along the path and to the inverse of the frequency squared. Being frequency dependent, this delay can be calibrated using dual frequency observations. This is the standard procedure in geodetic Very Long Baseline Interferometry (VLBI) and Global Positioning System (GPS).

However, there are applications in which the use of two frequencies is not possible due to the type of observation or to the available equipment, as in some astrometric VLBI experiments. In this case external ionospheric information is needed for the calibration of the observations.

Some techniques that can be used for ionospheric calibration are the Faraday rotation of geostationary satellite signals, ionospheric models based on ionosonde data, etc. In general, the information provided by these methods is limited in their spatial distribution or their precision is insufficient.

Dual frequency GPS observations can also be used to extract ionospheric delays. This has the advantage that the frequencies used are closer to those used in VLBI. Moreover, they can provide more precise ionospheric calibrations and better spatial coverage.

In this paper we present ionospheric delays for geodetic VLBI observations computed using GPS data and we compare them with the ionospheric delays obtained from dual VLBI data calibrations. For these comparisons, we have analyzed dual GPS data gathered at three European VLBI stations during S-X geodetic VLBI experiments.

2. ESTIMATION OF THE TEC

The main source of error in the estimation of the TEC using dual frequency observations is produced by frequency dependent instrumental delays in the GPS satellites and receiving systems. In the case of the VLBI, the receiver instrumental delay for each station is not distinguishable from a clock bias, so it is neglected in the geodetic analysis. The GPS case is more complicated because we should also consider one term for each satellite.

In the estimation of the TEC from GPS data we have used phase and pseudorange observations. We have estimated, with a method based on Kalman filtering, the instrumental differential biases for each GPS receiver and satellite, assumed constant during each experiment (Sardón and Wanninger, 1993). Once these biases have been removed, we obtain for each observation time, the TEC corresponding to the different GPS observation paths. For more details see (Sardón 1993).

3. EXPERIMENTS

We have analyzed dual GPS data gathered at the European VLBI stations of Madrid (Spain), Onsala (Sweden) and Wettzell (Germany) during five NASA Crustal Dynamics Project VLBI experiments (24 hours each) that appear on table I. All stations were equipped with ROGUE GPS receivers (Onsala from May 1991) located few hundred meters apart from the VLBI antennas.

GPS observations below 10 degrees elevation were neglected to reduce the effect of

multipath errors and to avoid the mismodeling of the function that maps the vertical TEC to slant TEC at low elevations.

DATE	VLBI EXPERIMENT	GPS DATA
September 5/6, 1990	90 EUROPE 2	Madrid Onsala Wettzell
December 20/21, 1990	90 EUROPE 3	Madrid Onsala Wettzell
January 6/7, 1991	91 EUROPE 1	Madrid Onsala
December 1/2, 1991	91 EUROPE 3	Madrid Onsala Wettzell
January 14/15, 1992	92 EUROPE 1	Madrid Onsala Wettzell

TABLE I: Geodetic VLBI experiments.

4. VLBI AND GPS IONOSPHERIC DELAYS

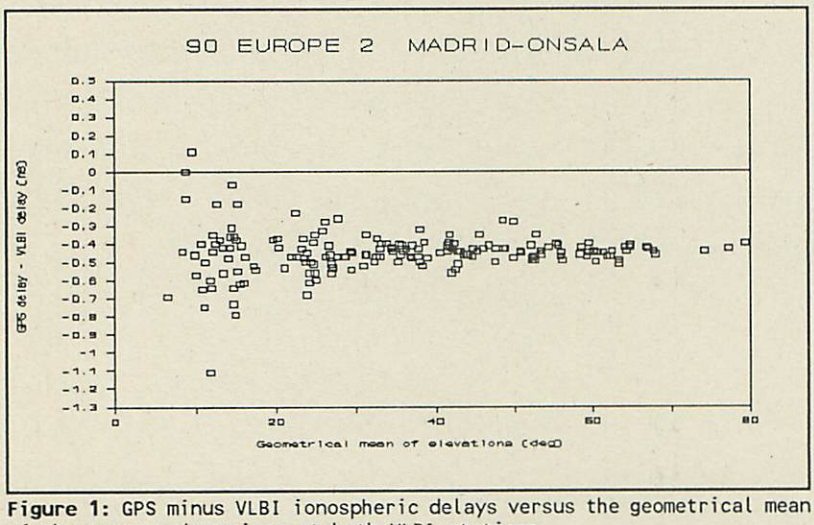


Figure 1: GPS minus VLBI ionospheric delays versus the geometrical mean of the source elevations at both VLBI stations.

Using the TEC obtained from GPS observations, we have predicted the TEC in the direction of the VLBI observations. The ionospheric delay assigned to each VLBI baseline was computed as the difference between the ionospheric delay corresponding to each station in the baseline. The GPS ionospheric delays are compared with the VLBI ionospheric delays obtained for each baseline from the S and X band observations.

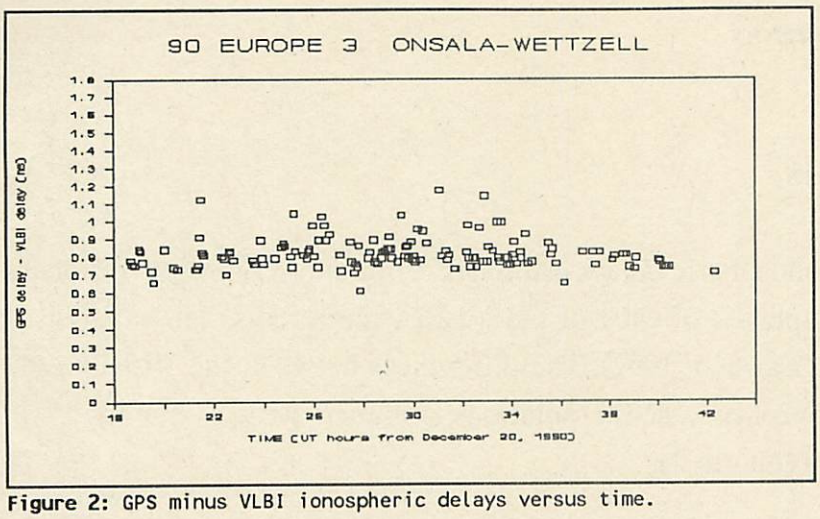


Figure 2: GPS minus VLBI ionospheric delays versus time.

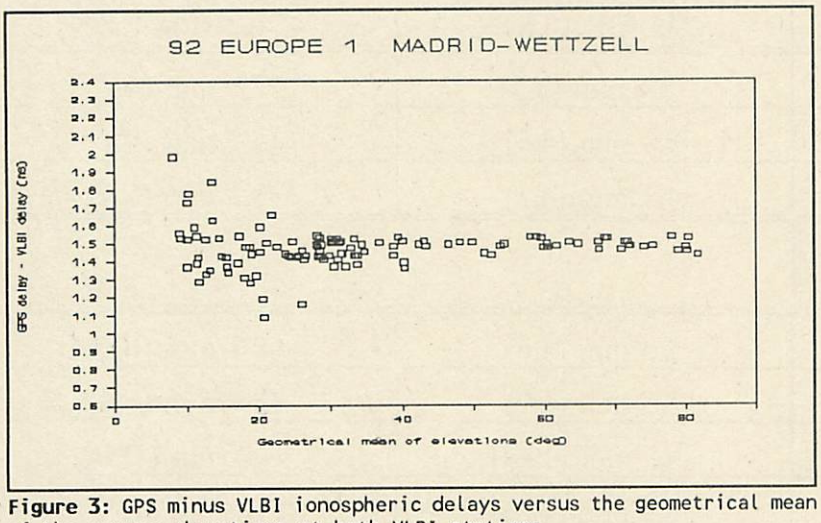


Figure 3: GPS minus VLBI ionospheric delays versus the geometrical mean of the source elevations at both VLBI stations.

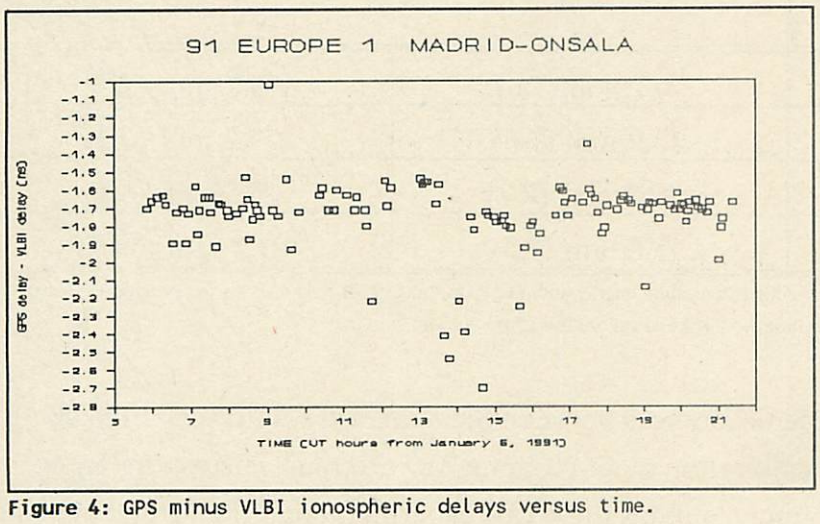


Figure 4: GPS minus VLBI ionospheric delays versus time.

Figures 1 to 4 show some examples of the differences (in nanoseconds) between the VLBI ionospheric delays and the GPS ionospheric delays, as a function of time and as a function of the geometrical mean of the elevations at both VLBI stations in the baseline.

In these figures we see that the difference between the VLBI and GPS ionospheric delays is basically a constant term, which corresponds to uncalibrated instrumental biases in the VLBI stations, plus a superimposed noise. For all the analyzed experiments, the standard deviation of the differences between both ionospheric delays was in the order of 0.1 nanoseconds. For the experiment 91 EUROPE 1, there were no GPS data from Onsala from 13:00 to 17:00 so the prediction was based on GPS data far away in time, producing the increase of noise that can be seen in figure 4. Figures 1 and 3 show that most part of the noise is produced by the low eleva-

tions used in the geodetic VLBI experiments, down to 5 degrees, where the GPS data is grossly affected by systematic errors.

5. VLBI BASELINE LENGTHS

In order to check the ionospheric delays estimated from dual GPS observations, we have introduced them in the analysis of each of the VLBI experiments. This analysis has been done with OCCAM 3.0. (Zarraoa, 1992). The differences between the VLBI baseline lengths obtained with this approach and the solutions obtained with a standard VLBI analysis are shown in table II (column 2).

WETTZELL-ONSALA 919 km	GPS IONOSPHERIC CALIBRATION	NO IONOSPHERIC CALIBRATION
Sep. 5/6, 90 (2.5)	-0.4 mm (3.7)	22.7 mm (4.2)
Dec. 20/21, 90 (3.1)	9.3 mm (4.4)	19.7 mm (4.4)
Jan. 14/15, 92 (2.0)	4.1 mm (4.5)	38.2 mm (7.0)
WETTZELL-MADRID 1655 km		
Sep. 5/6, 90 (2.7)	2.3 mm (4.6)	68.1 mm (6.1)
Dec. 20/21, 90 (4.0)	5.5 mm (6.9)	18.4 mm (6.6)
Dec. 1/2, 91 (4.6)	-0.5 mm (19.8)	93.0 mm (15.7)
Jan. 14/15, 92 (2.9)	6.5 mm (6.3)	70.6 mm (13.1)
MADRID-ONSALA 2205 km		
Sep. 5/6, 90 (3.4)	-0.7 mm (5.6)	74.1 mm (7.1)
Dec. 20/21, 90 (4.6)	13.9 mm (7.6)	29.2 mm (7.3)
Jan. 6/7, 91 (4.4)	-19.2 mm (7.7)	26.5 mm (6.9)
Jan. 14/15, 92 (3.2)	15.0 mm (7.2)	91.5 mm (14.0)

Table II: Differences (millimeters) between the VLBI baseline lengths obtained with dual VLBI data and those obtained: a) using GPS-based ionospheric delays (2nd column), b) without ionospheric calibration (3rd column).

This table also shows the differences between the standard solution and the solution obtained with no ionospheric calibration at all (column 3), with their corresponding formal errors in brackets. The first column contains the VLBI experiment and the formal errors for

the standard VLBI solution.

It must be pointed out that, in general, the differences corresponding to the no ionospheric calibration are one order of magnitude larger than with GPS ionospheric calibration. In the case of the GPS ionospheric calibration, the differences are about 3-5 parts per 10^9 and most of them are within their formal errors. The formal errors from the GPS ionospheric calibration (column 2) are larger than those for the standard VLBI (column 1), due to our present limitation in modeling the ionosphere at low elevations.

6. CONCLUSIONS

In this paper we have compared the ionospheric delays obtained from dual GPS data and from S-X VLBI observations.

The differences between both ionospheric delays show a rms in the order of 0.1 nanoseconds at X band. The rms decreases significantly when no low elevation VLBI observations are used, which confirms the accuracy that can be obtained with GPS derived ionospheric calibrations for single frequency VLBI experiments.

We have also compared the baseline lengths estimated using dual VLBI data with those obtained from single band VLBI plus the GPS-based ionospheric delays. The differences between both results for European baselines were around 3-5 parts per 10^9.

We have applied our method to the calibration of geodetic VLBI experiments in order to test its performance against already calibrated data. But clearly, the use of GPS ionospheric calibrations will be more useful for other types of VLBI experiments where only one frequency is available.

ACKNOWLEDGEMENTS

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THE CNES VLBI SOFT-CORRELATOR

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ABSTRACT

A real need for correlators with increased versatility has been shown in some experiments such as CLUSTER, VLBI on PULSARS, HUYGENS-CASSINI. The main desired possibilities are data processing before correlation and multi level correlation. All these features are easier to implement in software than in hardware, so it was decided to develop a so-called VLBI SOFT-CORRELATOR at CNES Toulouse. This system is presently able to process VLBI data in the markII format. The design makes extensive use of parallel transputer technology and associated software.

At the present time, the system is able to correlate 1 second of data in 2.5 seconds with gating facilities for one baseline. An environement written in turboC enables the use of the system in a batch mode.

1) Introduction

The choice of the computer technology is a key factor in the issue of a soft-correlator. The major technicals constraints are a data transfer rate from the tape recorder to the computer and a huge need of computing power. So we decided to build a computer with a parallel transputer technology rather than a workstation since parallel computer can be easily extended. Moreover, transputers allow the use of occam language specially suited to implement code on various network configuration. Details on the technical solution will be found in section 2.

First, an electronic interface is needed to send the data from the video tape recorder to the parallel computer. The data have to be transferred at a nominal rate of 500Kbytes/s directly to a hard disk. This is describe in section 3.

Then, the data must be formated on the disk in order to put the bits in a proper time position. This operation is actually done in 2 seconds for 1 second of data on a single processor. This is describe in section 4.

Finally, the data are processed and correlated with a multi processors application. For that purpose a concept of module was developped. A module is a piece of software able to do some proccess independantly and concurrently with other modules. We will present briefly the available modules in section 5.

2) Technical choices

Technically, the two major constraints to build such a system are the minimum data transfert rate of 500Kbytes.s-1, due to the tape recorder, and the huge need of computing power. Also, the system has to be easily extendable to follow subsequent improvements such as the addition of baselines or the change of recorder type. All theses reasons drove us to choose the transputer technology in conjontion with OCCAM language.

Transputer is a brick designed to build parallel computer. It is a quite powerful processor credited with 30Mips (peak), our tests give about 0.7 time the power given by a Sun sparcstationII. Moreover it has four bidirectional communication links, each at 2.3Mbytes/s rate, ready to connect either processors between them or externals devices with an appropriate interface. Theses links are managed by a special part so that the central processor is not affected by the data flow. The architecture is RISC like with very little register to allow a quick task commutation. This is very important when one implement concurrent process on a single processor. An internal task scheduler is provided also to improve task commutation.

OCCAM is a language specially suited for transputer, its main characteritic is the possibility to write concurrent process which can exchange data through logical channels. The very important fact is that an application written in OCCAM for one transputer can be easily placed on many transputer with little change in sources. Indeed, sources are mainly splited in two parts: the files *.occ which contains process, then the files *.pgm which contains the placing of the previous process and channels. Theses channels can be placed either logically inside processors or on the physicals links between processors.

3) The data acquisition

3.1 The system:

The figure I shows the block diagram of a versatile data acquisition system. The markII specificity, and difficulty, is the non synchronisation between the video track used for the astrodata and the audio track used for the time tags. When one gets a date on the audio track one can be confident about the date of the video data at a tenth of a second. This fact drive us to a 'a posteriori' date determination done by soft with the formater application. So, our markII interface is only able to enable the acquisition when the date given by the audio track is equal to a date given by the operator. This is done by some logical standard devices. The interface also contains a FIFO memory we will discuss in the next paragraph.

A C011 inmos circuitry is used to interface the transputer link, this device send or receive the data in a byte format, so a serial parallel conversion has to be done before. At this stage, it is helpful to consider that the less significant bit should be the oldest one since in occam the first byte in an array is the less significant one in the retype integer, indeed, many assembler instruction such as bit shift are done on integer.

The performance of this interface is about 1.7Mbytes/s rate. The actual performance of the Data acquisition system depends on the transputer capability to perform concurrently the acquisition and the data management.

3.2 The software application:

It is a two-processor application which puts the video data bit stream from the tape to the SCSI hard disk. First the operator has to set the tape recorder in read state on a position on the tape a little before the date of begin of acquisition. That date is provided to the computer which sends it to the transputer interface. The interface is continuously making a comparison between the date coming from the audio track and the date sent by the computer at a precision of one second. When these dates are equal the interface enables the video acquisition. As we said before the audio and the video track are not synchronous and the comparison is made with the audio track, so the real start of acquisition on the video data is not well known to within some frame, but we trust that the mistake cannot exceed a fraction of second.

The acquisition is done buffer by buffer. The processor works on two buffers at the same time, i.e. in parallel, one receives the video data meanwhile the other sends the data to the SCSI processor. At the end of this operation the two buffers are swapped for the desired number of buffers. Since the task scheduler manages the parallelisation some delay may occur in the acquisition process, and also during commutations at the end of the buffer filling, so the interface has to keep some bytes in a FIFO memory. The commutation time is quite short, some microseconds, and the overlapping of the two process is large so a common 1Kilo FIFO is sufficient. The size of the buffer has to be large enough to allow a quick write on disk, we chose a 1Mbytes size. This choice imposes a resolution of amount of data to be acquired of 4" because two buffers have to be processed sequentially in each loop.

The performance of this application is about 1.1Mbytes/s rate continous, with a 1.2Gbytes maxtor hard disk. This is quite sufficient for the 500Kbytes/s used by a markII application.

4) The formater application

The data written on the disk by the acquisition application are not correctly formated and they have to be prepared before correlation. This is done by the formater application. In MarkII standard, the data are formated on station by means of special bit sequences which are introduced inside the astrodata bitstream. These sequences are used to know the time position of each sample, considering that one sample is one bit. A 24 bits sequence determine the begin of frame (called BOF) it is just followed by its number and a parity bit. The first task to be accomplished by the formater is to find a BOF, this BOF should be with a small number to indicate that we are near the begin of the desired second. This operation can take some time because a large amount of data have to be processed in a bit format, this is not the case later because the distance between two BOF is known within some bytes. From one BOF number to the next one, the continuity is checked in order to ensure the time continuity. When the formater find a bad number or a bad BOF or no BOF at all it looks to the next one again, first in a small window then in a large one. The process is stopped when a certain quantity of bad cases is found. Different strategy can be applied, so the program is quite complex. When a frame is found to be bad, for example in case of uncertainty on the BOF position, all the frame is set to zero, because the correlator don't process long zero bit stream (more than 32 bit at zero).

The frame should contain 30 synchronisation words (called SYNC) separated by 256 bytes. They are used to check the time continuity inside the frame. These SYNC are sought in a window, in the case of a bad position the bytes are moved in the proper place.

All the actions done by the formater are reported in a journal so that the operator can check the data quality. Many things can be said about the MarkII system working.

The time to process 1 second of data is largely dependent on the quality of these data, but typically one can say that less than 2 seconds are necessary including disk access. Parallelisation could be used to be able to process in real time. The next generation of transputer (T9000) will allow real time formating.

5) The correlation applications

5.1 The modularity

The main purpose of our soft correlator is to provide some tools to enable the operator to process and correlate the data at his own convenience. At the same time one must be aware that the real demand for computation power is at this stage. These two facts imply the use of modularity. Indeed, if each tool is independant from each other it will be easier to build an application in a parallel mode and meanwhile to place each tool on different processor to improve efficiency. We must consider also the fact that if the applications have to be various, the tools to be used will be more or less the same. These tools will be called modules.

Let us look the now available modules in matter of pre-processing :

GATE : this tool is used to avoid correlation in some periodic areas defined by the user with the 3 followings numbers: wideness, periodicity, position of the first gate.

SHIFT : this tool is able to shift the data in time on left (to the old time) or on right (to the new time).

ADDER : this tool adds data from n input and sends the result to one output. Input and output have to be both on 8 bits.

ROUND : this tool rounds the data from 8 bits/sample to 4,2 or 1 bit.

FIL18xxx : this tool is able to operate a digital filtering on a 1 bit/sample data input and sends the result on a 8 bits/sample. The used algorithm is a finite impulse response filter one, so that the data are convolved with a mask of various size either in integer or in real number. This is the most demanding computation tool, typically some tens of seconds to process 1" of data. This software tool is used for evaluation. A hardware digital filter is under way.

For the correlation we developed the following modules:

FCOR1Sx : correl one baseline 1 bit/sample data input with a sine model computed on 1,2,4 or 8 bits. In fact these four correlators are different and those with the 1 or 2 bits sine are particulary optimized in matter of speed.

FCOR2Sx : correl one baseline 2 bit/sample data input with a sine model computed on 2 or 4 bits. In fact two differents correlator.

FCOR4S4 : correl one baseline 4 bit/sample data input with a sine model computed on 4 bits.

FCOR8S8 : correl one baseline 8 bit/sample data input with a sine model computed on 8 bits.

Some other modules are necessary to allow the realisation of an application, for exemple:

RSSB : The correlator needs what we call a buffer which is a certain amount of data for which some parameter are constant in the model such as the delay, the frequency rate and the phase rate. These buffers are prepared by this tool.

SEGDUP : this tool is used to copy the data from one input to many outputs.

Many more modules have been developed for exemple to manage the SCSI disk, or to multiplex the data when we have to place many channels on one physical link, or to send the result to the PC host computer and so on. This will be described in a user guide (in preparation).

The data are going from one module to an other through channels which are specified as DATA channels. A special protocol has been defined to standardize the data format between modules. To improve performance in communication the size of the smallest amount of data travelling must be at least some hundreds bytes. So we defined a 'segment' notion which is a packet of 240 integers. When the full segment is null we send only a special tag. Also, at the end of the process, the data channels send a special tag to stop the module.

Most of these modules have to get some information to initialize the processing. Again we need some new modules to manage the information propagation over the transputer network. These modules are called secondary module, in opposition with primary modules which are processing the data. Since the amount of information is not so high, in comparison with data, and to simplify the general organization we send all the information to all the primary modules with appropriate tag. Each primary module is able to check the tag and to keep only his necessary information. Informations are travelling on what we defined as INFO channels. Some special secundary modules send all the information to the network, they are working in sequence because they have to access the host computer for reading the information files.

When all modules have the necessary information, they check the consistency of the data stream. In the case of a mistake in the building of a new application, for exemple bad number of bit per sample, the application sends a message to the user. This facility is particulary useful because it is very difficult to locate such a mistake on a network. It hasn't been possible to inform the user during the compilation.

5.2 The applications

Four applications already exist, they are implemented on a 10-transputer network which resides on two PC boards B008. These boards allow wire connection or soft configurable connection via a link crossbar, so that before running an application one has to set up the connection with an appropriate transputer tool.

CORGAT : This application is able to correlate one baseline of formated data with gating facilities. The gating is applied on one antenna. The number of lags is settable up to 512. This application uses only 3 transputers. It takes 11 seconds to process 1 second of data per baseline.

CORPARG : Same facilities as CORGAT but running on 10 transputers so that it takes 2.5 second to process 1 second of data per baseline. In fact only 3 transputers are used to correlate the data, the others are used for data management the hard disk, the PC host and so on.

COR3GAT : this application is able to perform 3 different gatings and 3 correlations at the same time.

B8R16C22 : this application is able to perform 8 bands digital filtering with shift and gate on two data stream in order to dedisperse the pulsar signal (Petit et al, 1993). Figure II describes this application. The number of coefficients is 16 and they are real. Two correlation are performed at the same time, one on 1 bit and one on two bits resolution.

6) The environment

An environment, running on the PC host computer, was writen in TurboC in order to manage all the system, his main functions are described below.

Management of the SCSI hard disk:

The Transputer developpement system doesn't provide operating system or file system services, so we have to manage directly the data on the SCSI disk. This is also an advantage in matter of performance because we don't allow fragmentation in the file adressing. On the other side we are not compatible with any other standard.

Management of the PC files needed by the different applications:

Each application needs various information which have to be send to his different modules. These information have to be put in various files in specific format. The environment guide the operator to fill these files through various 'menu'.

Management of the application execution:

Before running an application the environment check the validity of the demand and inform the operator if needed, then it configures the network in accordance with the specified application. The operator has the possibility to run the system in a batch mode with a file command in which the result file name are settable.

7) Conclusion

Now, a soft-correlator is operational at CNES Toulouse. Although the gating facilities is the only one fully available now, many other process can be implemented. It has been made in such a way, that it should not be very difficult to create a specific application using the existing modules. The next available facility is the digital filtering of data before correlation. We are confident that the system is versatile enough to enable all kind of further improvement.

We hope that this new tool will be of use in some new VLBI applications, as it is shown already in the case of the pulsars processing.

ACKNOLEDGEMENTS

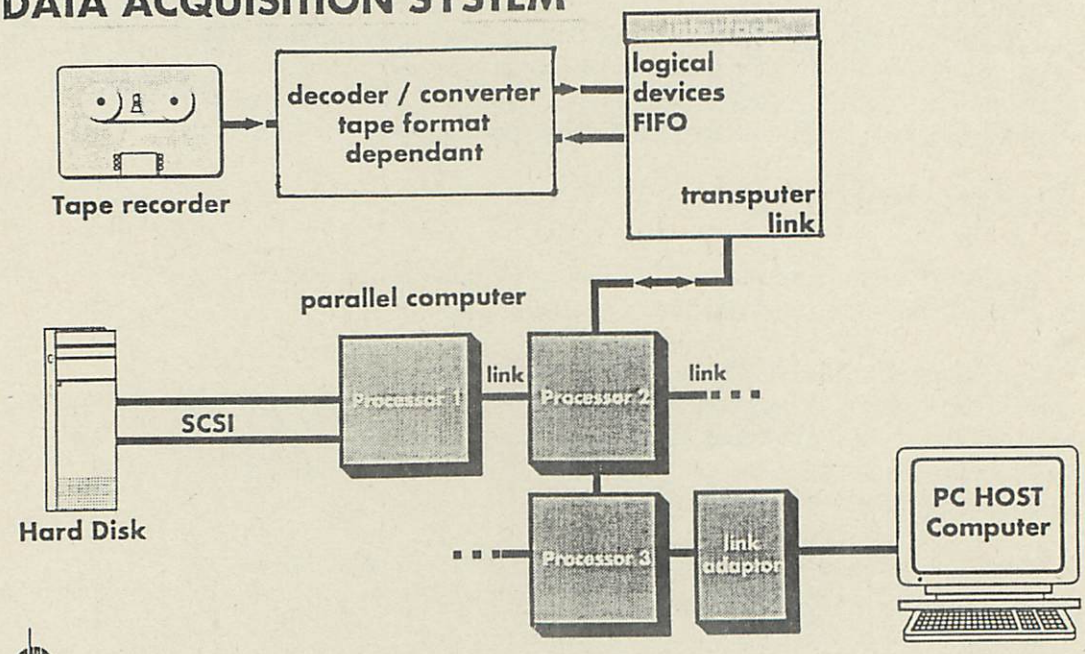
We thank D.Fort (Caltech) for his contribution to the video markII decoder. We are indebted to B. Darchy, G.Daigne, D. Graham and R.Bösel for their help in the development stage.
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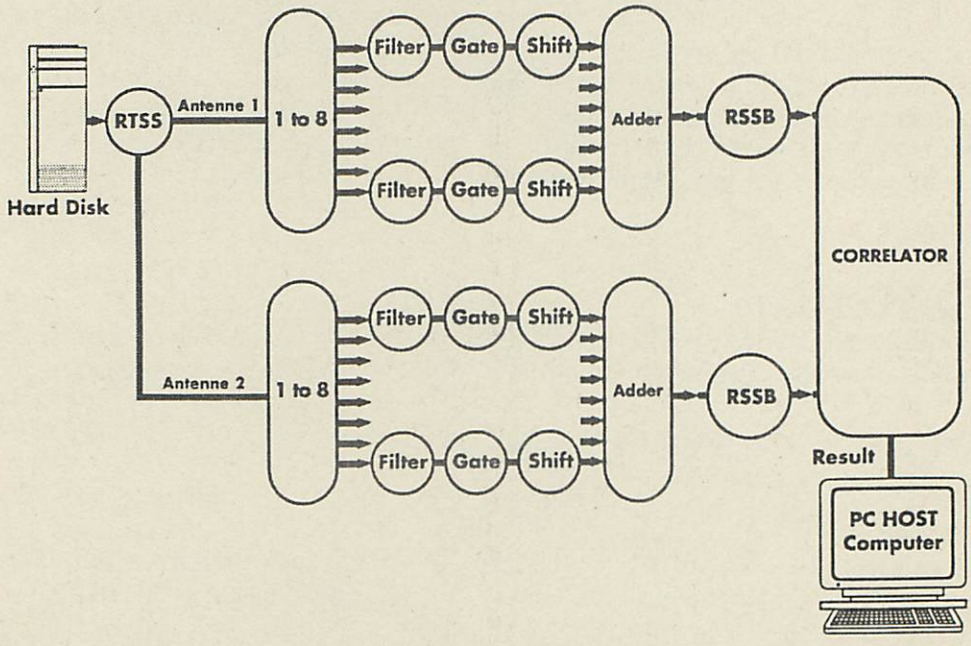
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FIG I **DATA ACQUISITION SYSTEM**



cnes
AGENCE FRANÇAISE DE L'ESPACE

FIG II **PROCESS DIAGRAM FOR PULSAR**



cnes
AGENCE FRANÇAISE DE L'ESPACE

VALIDATION OF THE CNES VLBI CORRELATOR AND ITS USE FOR MILLISECOND PULSAR ASTROMETRY

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1 Introduction

A new VLBI correlator has been developed at the Centre National d'Etudes Spatiales (CNES) in Toulouse, France. The design is based on a high speed interface to a computer disk and on parallel computing (Fayard et al., 1993). So far one interface has been developed, which allows to process VLBI data in the MarkII format.

The validation of this correlator was carried out by comparing its results with those obtained by using other VLBI correlators. This is presented in section 2. We then discuss in section 3 one application made possible by the design of this new correlator. In processing millisecond pulsar VLBI data, it is possible to remove the dispersion of the signal and to gate the data before correlation. This facilitates the detection of the pulsar signal and should help in determining VLBI positions of pulsars, which have important astrometric applications.

2 Validation of the correlator output

The correlator computes, for each integration interval, the complex correlation function for a given number of lags. Each value is phase shifted to account for the average effect of the discrete delay tracking over the integration interval (fractional bitshift correction). After an optional coherent addition over a number of consecutive intervals, the complex correlation sums are passed to the fringe fitting program, which has been adapted from PHASOR, the CIT/JPL MarkII fringe fitting routine (CIT, 1988).

In the fringe fitting program, the complex correlation sums are Fourier transformed from the lag domain to the baseband frequency domain. In the standard set-up, data from nine lags provide four estimates of the cross-power spectrum. Such data for a number of integration intervals (forming a section)

are used to estimate the set of parameters (amplitude, delay, phase rate, phase at mean time) that produce the best fit (in the least squares sense) of the data to the theoretical formula (Moran, 1976). The values of the estimated residual phase and phase rate are then added to the model to provide estimates of the total phase and phase rate, for the mean time of the section. The adopted convention for a baseline AB is that the value of the observables for the date t corresponds to the signal reaching station A at date t.

Similar processing can be done with data correlated on the CIT/JPL Block0 and BlockII systems. For Block0 data, the fringe fitting routine PHASOR is used, while for BlockII data the routine is BWSFIT (Fort, 1993). Data from several MarkII experiments have been processed with the CNES correlator, and with Block0 and/or BlockII. All experiments are at L band (1662.99 MHz), with baselines between Effelsberg (Germany), DSS63 · (Spain), Westerbork (The Netherlands), Medicina (Italy), Bear Lakes (Russia) and Kashima (Japan). In the baselines to Kashima, delays of up to 10 ms and rates up to 1.9×10^{-6} were found. Comparisons between the total phase and phase rate produced by the different correlators have been carried out, and are reported in tables 1 and 2.

It emerges from the comparisons that the phase and phase rate observables generated by the CNES correlator agree with those produced by other MarkII correlators to within measurement noise. The constant phase difference of -0.25 cycle, which is visible in the results, is thought to originate from the different realization of the fringe stopping, and will eventually be included in the phase model.

3 Application to millisecond pulsar VLBI data

Millisecond pulsars provide a direct way to link the extragalactic celestial reference frame with the dynamical reference frame of the solar system, by comparing astrometric positions of pulsars obtained in the former frame with VLBI, and in the latter with timing observations. Millisecond pulsars are weak sources for VLBI but, noting that their signals are regularly spaced in time and dispersed by the interstellar medium, it is possible to gain significant Signal to Noise Ratio (SNR) by gating and dedispersing the VLBI data before correlation. This scheme has been tested on a limited amount of data (Petit et al., 1990).

The CNES system allows such processing to be carried out on a significant amount of data in a reasonable time duration. The dedispersion is realized by digital filtering a number of narrow bands in the recorded bandpass, aligning the filtered data and adding them to perform the correlation (Figure 1). The gating window can be specified with one microsecond resolution, and its position and period are determined a priori from the timing observations of the pulsar. Preliminary tests indicate that such processing allows a net gain in SNR, by a factor of 3. It is thus possible to detect the pulsar in more scans and with less sensitive baselines than would be achievable otherwise.

A 5-station 12-hour experiment was carried out on June 16, 1992 with the European VLBI Network in order to obtain the position of PSR1937+214 relative to nearby quasars. It will be processed using the proposed scheme with the CNES system.

4 Conclusion

A new VLBI correlator is now operational at CNES. It can process VLBI data in the MarkII format, and the phase and phase rate observables that can be formed from its cross correlation sums have been shown to agree with those obtained from independant processing on other systems.

The software implementation of the system is not designed to process massive amounts of data, but it allows special treatments to be performed on the data and is quite flexible in accomodating new data formats. One present application is to perform dedispersion and gating of millisecond pulsar VLBI data in order to improve the detection of the signal. Application of this technique to one full-scale VLBI experiment on PSR1937+214 is under way.

Acknowledgements

We thank the team in charge of the Block0 correlator at Medicina for its assistance. We are indebted to a number of people at CIT/JPL: T. Rogstad for running the BlockII correlator, D. Fort and S. Lowe for introduction to the fringe fitting of BlockII data.

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Tables 1 and 2:

Comparison of CNES and BlockII/Block0 from MarkII data taken at 1.66 GHz: Difference between total phases (cycles) and total phase rates (ps/s).

Scan 1 (3 minutes on 3C454.3):

Baseline code	Phase diff wrt BlockII/Block0	Sigma (cy.)	Rate diff wrt BlockII/Block0	Sigma (ps/s)
EW	-0.247/-0.247	0.003	-0.02/-0.01	0.06
EK	-0.258	0.016	1.3	0.5
WK	-0.256	0.07	1.5	1.2
BK	-0.253	0.07	0.8	1.1
EB	-0.257	0.002	-0.08	0.05
WB	-0.260	0.006	-0.09	0.10

Scan 2 (3 minutes on 1923+210):

Baseline code	Phase diff wrt BlockII/Block0	Sigma (cy.)	Rate diff wrt BlockII/Block0	Sigma (ps/s)
EW	-0.248	0.004	0.01	0.1
EM	-0.252	0.003	0.3	0.2
EL	-0.246	0.01	0.07	0.1
EB	-0.248	0.003	-0.18	0.15
EM(*)	/-0.252	0.003		

(*) This scan is from a different experiment

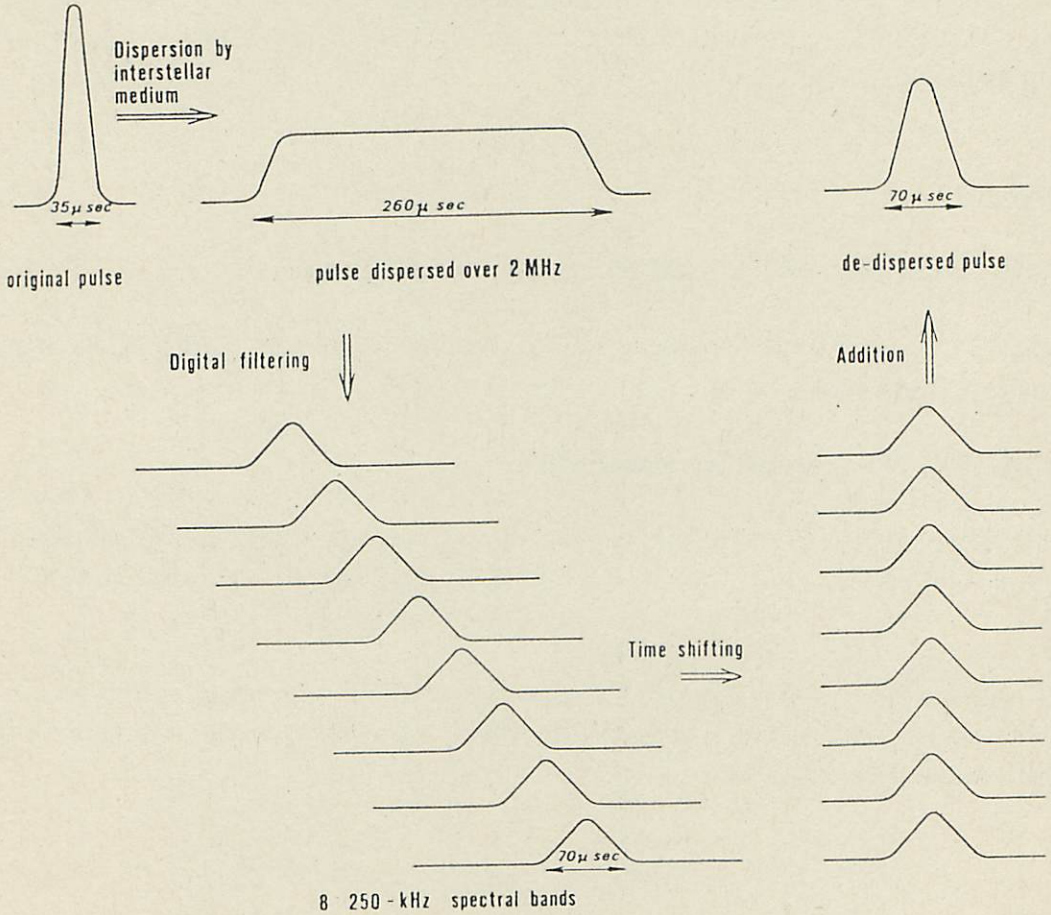


Figure 1 De-dispersion of the pulsar signal

A SENSITIVITY ANALYSIS FOR ORBIT DETERMINATION OF SPACE VERY LONG BASELINE INTERFEROMETRY SATELLITES FOR INTERCONNECTION OF REFERENCE FRAMES

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ABSTRACT

The emerging space geodetic technique of Space Very Long Baseline Interferometry (Space VLBI) will become a reality in the near future, with the launching of the two proposed satellites - RADIOASTRON and VSOP. This unique technique will, for the first time, provide a direct interconnection between the kinematic Conventional Inertial reference System (CIS), the dynamic CIS, and the Conventional Terrestrial reference System (CTS). The estimability and sensitivity analysis and feasibility studies for geodetic and geodynamic applications of Space VLBI have been carried out by Adam (1990) and Kulkarni (1992a), and the application to satellite dynamics has been investigated by Fejes and Mihaly(1991). As a next step, sensitivity analysis for the satellite orbit has been carried out. The sensitivity of the orbital elements to observing configuration, to errors in other geodetic parameters, and to solar radiation pressure is investigated. A comparison of the results obtained for the sensitivity of the orbits of the two proposed Space VLBI satellites has been presented. The results of these numerical investigations and the conclusions drawn have been discussed with reference to their significance for the unification of reference frames using Space VLBI technique, and the possible combination of Space VLBI data with data from other geodetic satellites like the LAser GEOdynamic Satellite - LAGEOS II.

1. INTRODUCTION

The technique of geodetic Very Long Baseline Interferometry (VLBI), established in 1967, has been routinely used since then for very precise geodetic and geodynamic applications, including determination of station positions and Earth Rotation Parameters (ERP's). The emerging technique of Space VLBI is an extension of the existing ground VLBI to space, which will provide longer baselines and higher resolution for astronomic and astrometric applications, and will make the VLBI observables sensitive to the gravity field of the Earth. This unique technique will, for the first time, provide a direct interconnection between the kinematic Conventional Inertial reference System (CIS), the dynamic CIS, and the Conventional Terrestrial reference System (CTS). Thus, Space VLBI observables have some important potential applications in geodesy and geodynamics. The estimability and sensitivity analysis and feasibility studies for this purpose have been carried out by Adam (1990) and Kulkarni(1992a). The aim of this research work has been to investigate the sensitivity of the Space VLBI satellite orbit to the observing configuration, the accuracy of other geodetic parameters and the prominant systematic effect - the solar radiation pressure. The conclusions drawn from the results obtained have been discussed with reference to the application of Space VLBI for interconnection of reference frames, and for orbit determination of other geodetic satellites like the LAser GEOdymanic Satellite LAGEOS II.

2. REFERENCE FRAMES FOR GEODESY AND GEODYNAMICS

With the high level of accuracy achievable today in most geodetic and geodynamic tasks, it is most important and equally difficult to precisely define, monitor and interconnect the different reference frames involved. Only two basic reference coordinate systems are required for geodesy and geodynamics - the CIS and the CTS (see Mueller (1988)). The kinematic CIS is defined through the coordinates of the extra-galactic radio sources observed by VLBI, the dynamic CIS is defined by the orbit of the Earth-orbiting satellites, and the CTS is defined by the precise positions of a set of geodetic ground stations. The CIS and CTS are related through the precession, nutation and ERP's - the polar motion and Earth's rotational rate. These reference frames are presently monitored by the International Earth Rotation Service (IERS) through precise space geodetic observations at collocated stations. The unique technique of Space VLBI

will, for the first time, provide a direct interconnection between these three reference frames (see Adam(1989); Fejes et .al(1989)).

3. THE SPACE VLBI TECHNIQUE

The geodetic VLBI technique has the capability to yield estimates of the length of baselines extending to thousands of km to cm level accuracy, by simultaneous observations of radio signals from extra-galactic sources. Space VLBI, as the name suggests, is an extension of ground VLBI to space, where at least one of the co-observing antennas is mounted on an Earth-orbiting satellite. Thus, the Space VLBI technique yields two new type of observables: the ground-to-space and the space-to-space VLBI observables, which possess certain unique characteristics (see Kulkarni (1992a, pp.11-13)). The technique has several important potential applications in astronomy, astrometry, astrophysics, geodesy and geodynamics, including unification of reference frames and Earth's gravity field estimation. Two Space VLBI missions will be launched in the 1990's: VSOP of Japan (see VLBI (1993)), and RADIOASTRON of Russia (see RADIOASTRON (1993)), thus making this unique type of data available for numerous scientific investigations.

4. ORBIT DETERMINATION FOR SPACE VLBI SATELLITES

One of the most challenging tasks in implementation of Space VLBI applications in various fields is the precise orbit determination for the satellite. Several simulation studies related to this task have been carried out, the requirements of orbit determination accuracy for various applications have been estimated, different proposals for orbit tracking: e.g. PRARE, LASER ranging, GPS, VLBI tracking data, etc. have been investigated, and different orbit determination software have been developed/used (see, for example, Mihaly (1989); Konopliv (1989); Borza et al. (1990)). Due to the high accuracy required in the geodetic applications like interconnection of reference frames and gravity field estimation, the orbit accuracy requirements will also be very stringent. For certain astrometric applications also, a decimetre-level or better accuracy is required, as pointed out by Bartel (1989). An important and well known problem affecting the orbit determination of all Earth-orbiting satellites is the non-separability of the longitude of the ascending node of the satellite (Ω) and the ERP: UT1-UTC. However, as Space VLBI may not be used as a stand-alone technique for geodetic tasks, but as an add-on technique to the existing geodetic systems, we propose that the ERP: rotational rate of the Earth, or (UT1-UTC) can be fixed from the ground-to-ground VLBI data, also obtained during Space VLBI observations, and this can be input to the orbit determination processing, in order to separate it from Ω. With this technique, it should be possible to use Space VLBI data in orbit determination of other geodetic satellites like the LAser GEOdynamic Satellite: LAGEOS II.

5. SENSITIVITY ANALYSIS FOR SPACE VLBI SATELLITES

A detailed sensitivity analysis to investigate the sensitivity of Space VLBI observables to estimation of geodetic parameters, with emphasis on the ERP's, has been reported by Kulkarni (1992a, 1992b) and Kulkarni et al.(1993). As a next step for implementation of Space VLBI for astrometric, geodetic and geodynamic applications, the sensitivity of the orbits of the two Space VLBI satellites: RADIOASTRON and VSOP to the observing configuration: the observing ground stations and the radio sources observed, to errors in other geodetic parameters: the station positions, clock errors, radio source positions, and the ERP's, and to the prominant systematic effect: solar radiation pressure, has been investigated here. The Space VLBI dedicated software SGOFAKE developed at the Satellite Geodetic Observatory, Hungary (for details, see Fejes et al. (1991)) has been used for these numerical investigations. The software simulates the "ideal" orbit and the orbit burdened with the errors assigned, using simplified models for orbit determination, and computes the estimated orbit errors as differences between the two, averaged over the observation period. The a priori errors assigned to the different geodetic parameters are listed in Table 1(a), and the information related to the orbits of the two satellites is given in Table 1(b). The observing ground stations used in the simulation are shown in Figure 1. The total orbit arc used in this simulation is 45 hours, which is estimated to be the optimum observation span for geodetic parameter estimation from Space VLBI observations, as reported by Kulkarni (1992a, pp. 71-87). No errors were assigned to the tracking data, as the errors assigned to the parameters propagate to the observations.

6. RESULTS,CONCLUSIONS AND RECOMMENDATIONS

The estimated averaged orbit errors (root mean square, along-track, across-track and radial errors) for the different cases are plotted in Figures 2(a),(b) - 9(a),(b). From the results obtained for analysing the sensitivity of the orbit to number of observing stations, plotted in Figures 3(a) and 3(b), it can be seen that a total of 6 VLBI tracking stations and one telemetry station may be sufficient for the purpose of orbit determination of VSOP satellite to decimeter level accuracy. From the results obtained for the RADIOASTRON satellite, it may be concluded that such configuration may not be sufficient for that satellite, but due to the software limitation, only maximum of 6 stations could be used in the simulation, hence further investigations are necessary. However, in practice, an observing network of 6 stations may be more realistic, as it may be difficult to have more than 6 large telescopes co-observing the satellite continuously. The importance of very accurate a priori information on all other parameters, especially the semi major axis (a), and the longitude of the ascending node (Ω) can be clearly seen from the results. From the results plotted in Figures 3(a) and 3(b), it can be concluded that the semi-major axis should be known to a very high level of accuracy - probably better than 10 cm; however, this may not be so difficult, as the semi-major axis of the LAser GEOdynamic Satellite (LAGEOS) is estimated to drift by only few mm over one week arc, as reported by Ambrosius et al. (1988). The importance of fixing the longitude of the ascending node of the satellite (Ω) to an accuracy of better than 1 arc second is indicated by the results given in Figures 4(a) and 4(b). As discussed widely in geodetic literature, the problem of non-separability of Ω from the ERP: (UT1-UTC), or the rotational rate of the Earth, affects the orbit determination accuracy of all Earth-orbiting satellites. However, for Space VLBI, this problem can be solved by fixing the (UT1-UTC) through the ground-to-ground VLBI observations, which are also obtained in the Space VLBI technique, and this a priori information can be used in orbit determination, to estimate the Ω accurately. Due to this unique property of the Space VLBI data, it should be possible to use it in orbit determination of other geodetic satellites like LAGEOS II. The effect of errors in the radio source position, station position, polar motion, and clocks, plotted in Figures 5(a) and 5(b) - 8(a) and 8(b) indicate that the present level of accuracy of estimation of these parameters is sufficient for precise orbit determination. The results of orbit sensitivity to error in solar radiation pressure, plotted in Figures 9(a) and 9(b) indicate the importance of accurately modelling the solar radiation pressure effect on the satellite. Hence, a complex model for the area-to-mass ratio of the satellite needs to be designed and used in orbit determination. The relative magnitudes of the results obtained for the two satellites is of more significance than the numbers themselves, as it gives a direct comparison between the two satellites. It shows that a 1 metre level orbit for VSOP should not be difficult to achieve, however, for RADIOASTRON, a 10 metre level orbit seems to be more realistic, using only VLBI tracking data. This may be explained by the fact that the semi-major axis of VSOP orbit is much smaller compared to that of RADIOASTRON, and also the orbit period of VSOP is nearly one-fourth that of RADIOASTRON, thus in the same time period, VSOP would have completed nearly four times the number of complete orbit revolutions that of RADIOASTRON, thus yielding much more information for orbit determination. However, with various other orbit tracking and determination techniques being considered for these satellites, like on-board GPS receivers, PRARE system, etc., it should be possible to obtain more precise orbits.

The investigations related to the geodetic and geodynamic applications of Space VLBI clearly indicate that this new technique has the potential for some important applications in these fields, which needs to be exploited. For this purpose, the following areas should be investigated further:

(i) Implementation of Space VLBI data processing option in the NASA geodetic software GEODYN.

(ii) A detailed orbit sensitivity analysis using GEODYN or similar software.

(iii) Combination of delay and delay rate Space VLBI observations for geodetic parameter estimation.

(iii) Combination of data from ground VLBI and Space VLBI, and also from other space geodetic techniques for geodetic parameter estimation.

(iv) Analytical studies related to the estimability of geodetic parameters from Space VLBI.

(v) Dedicated Space VLBI observations for geodetic and geodynamic applications, when the Space VLBI missions become operational.

(vi) Potential applications of space-to-space Space VLBI data, using two or more Space VLBI satellites.

(vii) Use of Space VLBI data in orbit determination of other geodetic satellites like the LAGEOS II

7. ACKNOWLEDGEMENTS

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These investigations are founded upon the research work done by the authors at the Department of Geodetic Science and Surveying of The Ohio State University, Columbus, USA, during 1989-1992, under the guidance of Prof. Ivan I. Mueller and Prof. Burkhard Schaffrin, whose valuable contribution is gratefully acknowledged. This work is also a contribution to the Special Study Group 2.109 of the International Association of Geodesy on "Application of Space VLBI in the field of Astrometry and Geodynamics".

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Table 1(a). Errors Assigned to Parameters for Sensitivity Analysis

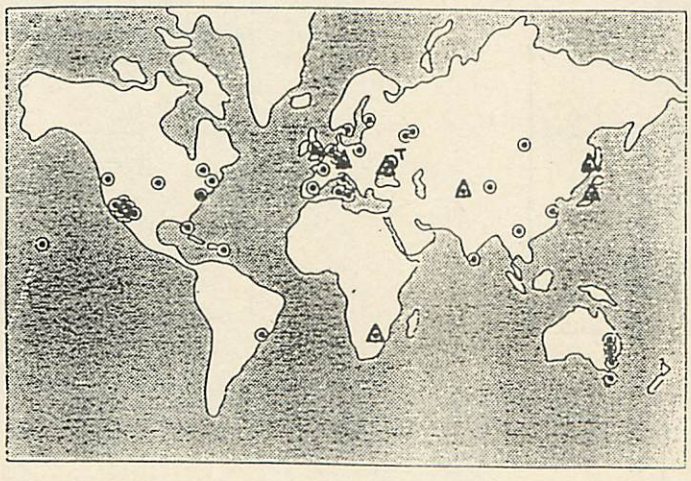
No.	Parameter	A priori Error Assigned
1	Semi-major axis (a)	10 cm
2	Eccentricity (e)	0.000005
3	Inclination (i)	1 arc second
4	Argument of perigee (ω)	1 arc second
5	Long. of Ascending Node (Ω)	1 arc second
6	Mean Anomaly (M)	1 arc second
7	Station Coordinates	3 cm
8	Radio Source Coordinates	1 milli arc second (mas)
9	Polar Motion Componants	1 milli arc second (3 cm)
10	.Clock Drift	0.1 micro second

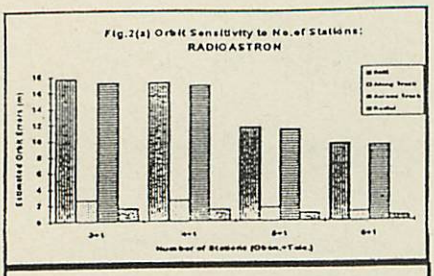
Table 1(b). Orbital Elements of Satellites Used for Sensitivity Analysis

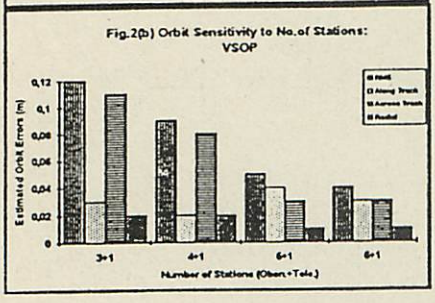
No.	Orbital Element	RADIOASTRON	VSOP
1	Semi-major Axis (a)	41500 Km	16878 Km
2	Eccentricity (e)	0.82	0.562999
3	Inclination (i)	65^0	31^0
4	Argument of Perigee (ω)	310^0	0^0
5	Longitude of Ascending Node (Ω)	$27^0.5$	90^0
6	Mean Anomaly (M)	0^0	0^0
7	Period (T)	23 Hours (approx.)	6 Hours (approx.)

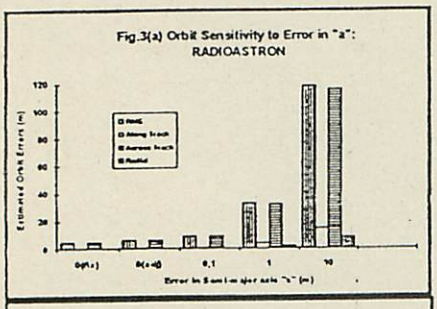
Fig. 1 Ground Stations Used for Sensitivity Analysis

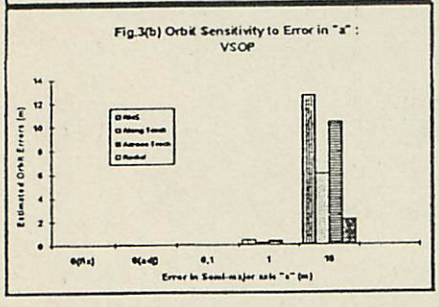
⊙ : VLBI Stations
△ : VLBI Stations Used in Simulation
⊙T : Telemetry Station Used in Simulation

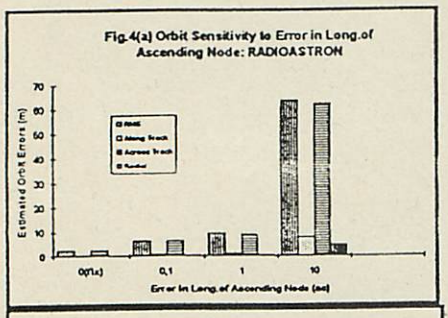


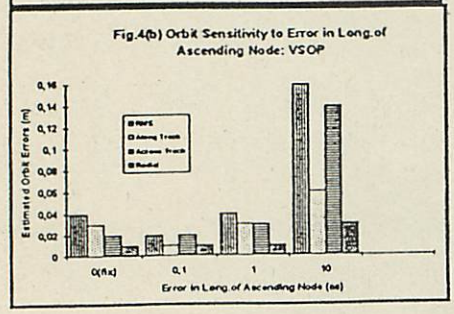

Fig.2(a) Orbit Sensitivity to No.of Stations: RADIOASTRON
Estimated Orbit Errors (m)
RMS
Along Track
Across Track
Radial
3+1
4+1
6+1
6+1
Number of Stations (Obsn.+Tele.)

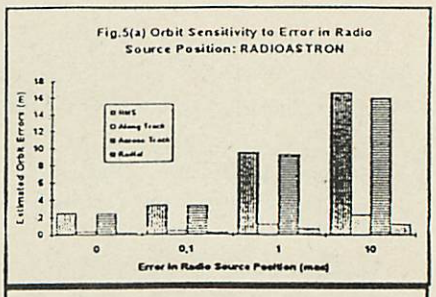

Fig.2(b) Orbit Sensitivity to No.of Stations: VSOP
Estimated Orbit Errors (m)
RMS
Along Track
Across Track
Radial
3+1
4+1
6+1
6+1
Number of Stations (Obsn.+Tele.)

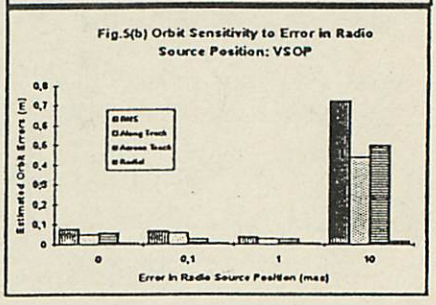

Fig.3(a) Orbit Sensitivity to Error in "a": RADIOASTRON
Estimated Orbit Errors (m)
RMS
Along Track
Across Track
Radial
0(fix)
0(adj)
0,1
1
10
Error in Semi-major axis "a" (m)

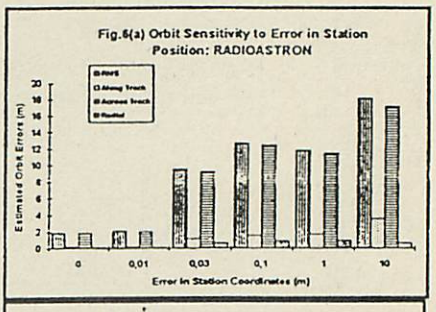

Fig.3(b) Orbit Sensitivity to Error in "a": VSOP
Estimated Orbit Errors (m)
RMS
Along Track
Across Track
Radial
0(fix)
0(adj)
0,1
1
10
Error in Semi-major axis "a" (m)

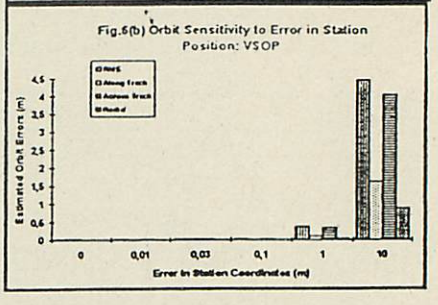

Fig.4(a) Orbit Sensitivity to Error in Long.of Ascending Node: RADIOASTRON
Estimated Orbit Errors (m)
RMS
Along Track
Across Track
Radial
0(fix)
0,1
1
10
Error in Long.of Ascending Node (as)

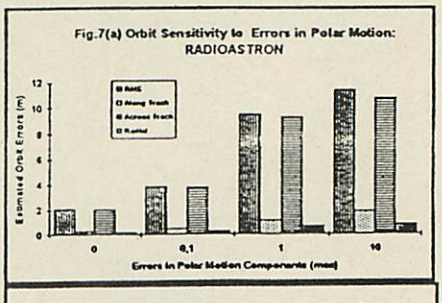

Fig.4(b) Orbit Sensitivity to Error in Long.of Ascending Node: VSOP
Estimated Orbit Errors (m)
RMS
Along Track
Across Track
Radial
0(fix)
0,1
1
10
Error in Long.of Ascending Node (as)

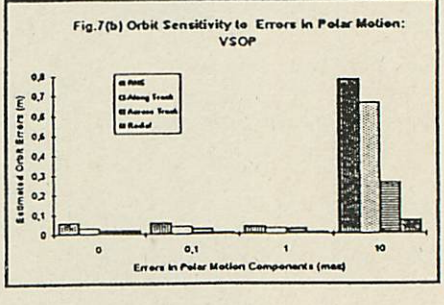

Fig.5(a) Orbit Sensitivity to Error in Radio Source Position: RADIOASTRON
Estimated Orbit Errors (m)
RMS
Along Track
Across Track
Radial
0
0,1
1
10
Error in Radio Source Position (mas)

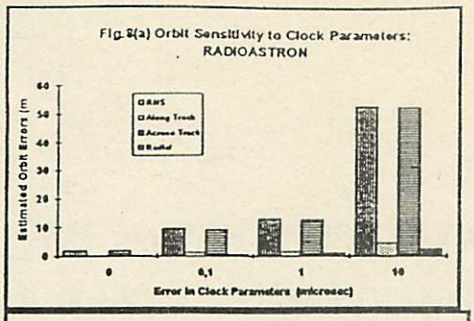

Fig.5(b) Orbit Sensitivity to Error in Radio Source Position: VSOP
Estimated Orbit Errors (m)
RMS
Along Track
Across Track
Radial
0
0,1
1
10
Error in Radio Source Position (mas)

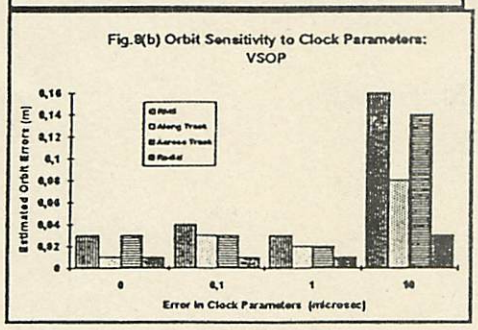

Fig.6(a) Orbit Sensitivity to Error in Station Position: RADIOASTRON
Estimated Orbit Errors (m)
RMS
Along Track
Across Track
Radial
0
0,01
0,03
0,1
1
10
Error in Station Coordinates (m)

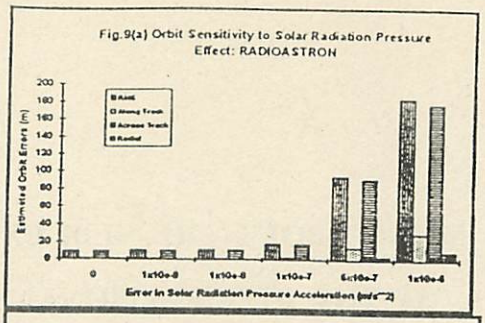

Fig.6(b) Orbit Sensitivity to Error in Station Position: VSOP
Estimated Orbit Errors (m)
RMS
Along Track
Across Track
Radial
0
0,01
0,03
0,1
1
10
Error in Station Coordinates (m)

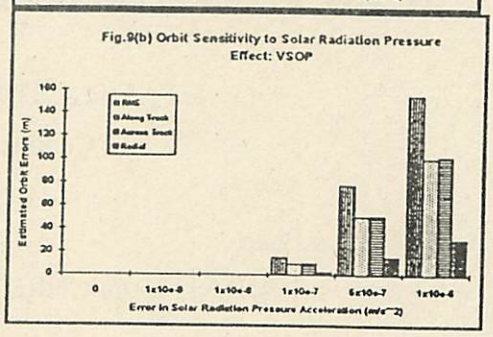

Fig.7(a) Orbit Sensitivity to Errors in Polar Motion: RADIOASTRON
Estimated Orbit Errors (m)
RMS
Along Track
Across Track
Radial
0
0,1
1
10
Errors in Polar Motion Components (mas)


Fig.7(b) Orbit Sensitivity to Errors in Polar Motion: VSOP
Estimated Orbit Errors (m)
RMS
Along Track
Across Track
Radial
0
0,1
1
10
Errors in Polar Motion Components (mas)


Fig.8(a) Orbit Sensitivity to Clock Parameters:
RADIOASTRON
Estimated Orbit Errors (m
Error in Clock Parameters (microsec)


Fig.8(b) Orbit Sensitivity to Clock Parameters:
VSOP
Estimated Orbit Errors (m)
Error in Clock Parameters (microsec)


Fig.9(a) Orbit Sensitivity to Solar Radiation Pressure
Effect: RADIOASTRON
Estimated Orbit Errors (m)


Fig.9(b) Orbit Sensitivity to Solar Radiation Pressure
Effect: VSOP
Estimated Orbit Errors (m)

9th Working Meeting on European VLBI for Geodesy and Astrometry
Bad Neuenahr (Germany), 1993 September 30 and October 1

MORE ABOUT THE VLBI EXTRAGALACTIC REFERENCE FRAME OF THE INTERNATIONAL EARTH ROTATION SERVICE (IERS)

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Central Bureau of IERS

1- Observatorio de La Plata
2- Observatoire de Paris/URA1125 du CNRS

INTRODUCTION

The mission of IERS is to maintain a comprehensive reference system for application in global geodynamics, in space navigation and orbit maintenance, and in astronomy. Its operation is based on VLBI observation and analysis, in conjunction with satellite geodesy techniques: LLR, GPS, SLR. The IERS celestial reference frame (ICRF) is established on the extragalactic compact radio sources observed in the VLBI programs participating to IERS. The time series of Earth Orientation Parameters (EOP) provide a permanent accurate tie between the IERS Terrestrial Reference Frame and the IERS Celestial Reference Frame.

PHYSICAL PROPERTIES OF THE FIDUCIAL OBJECTS

The IERS Celestial Reference Frame (ICRF) is based on the positions of compact extragalactic objects measured by VLBI. It is maintained on the basis of the analyses of several observation programs for the study of Earth rotation, crustal deformations, astrometry, and for deep space navigation. Its latest realization (504 objects, see Figure 1), is a combination of the individual frames obtained by five groups, GIUB, GSFC, JPL, NOAA, and USNO (Charlot (ed.) 1993). The observations analysed by these groups come from various networks: the International Radio Interferometric Surveying program (IRIS), the NASA Crustal Dynamic Project (CDP), the Navy VLBI Network (NAVNET), the Naval Research Laboratory (NRL), and the Deep Space Network. The implementation of the ICRF is described in the 1992 IERS Annual report, part II-2.

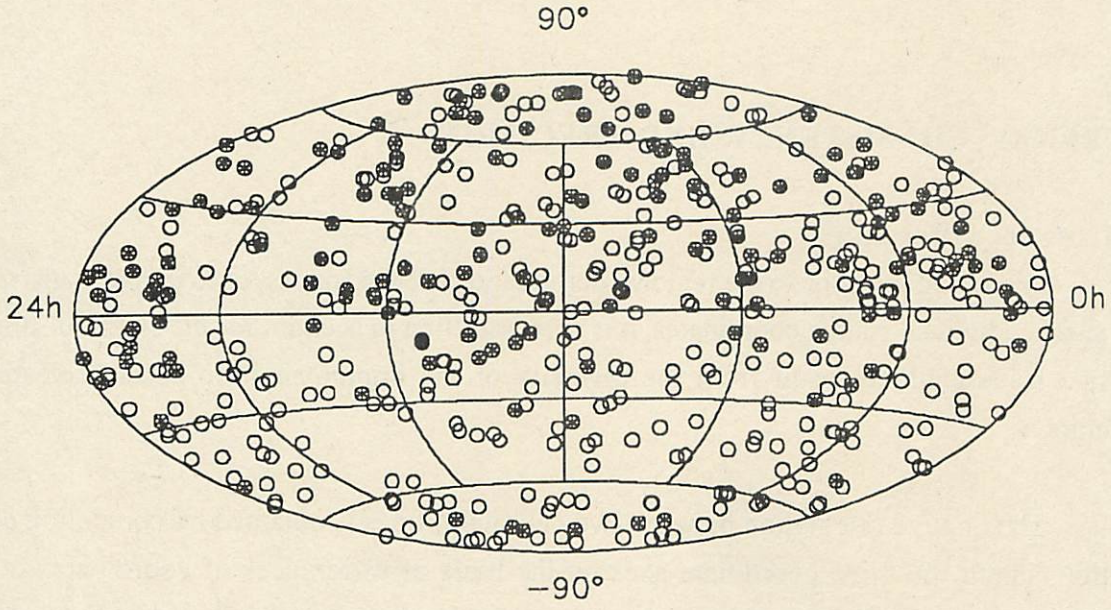


Figure 1. Sky distribution of the 504 radiosources of RSC(IERS) 93 C 01. Filled circles represent the 158 sources with formal uncertainties smaller than 0.00025".

The physical properties of the ICRF objects and the precision of their coordinates in the IERS System are summarized in Table 1, which is based on sky surveys by Preston *et al.* (1985) and Véron and Véron (1989). 67% of the optical counterparts of IERS sources are quasars (ref.: Véron and Véron). The listed flux is the total flux at 2.7 GHz given by Preston *et al.* The redshifts are taken from Véron and Véron; they span the interval 0.1-2.5 quite evenly. The spectral indices are defined (by Preston *et al.*) between 2.7 and 5.0 GHz. The distribution in optical magnitudes (from Véron and Véron) has a peak around the 18th magnitude. A part of the IERS sources has been mapped at S and X bands (e.g. Charlot 1990).

Table 1. The IERS Celestial Reference Frame, RSC(IERS) 93 C 01: 504 objects.

Type of object	%	Total flux (Jansky)	%	Redshift	%	Precision (0.001")	%
Quasars	67	0 - 1	36	0 - 1	48	<0.5	61
Galaxies	7	1 - 2	40	1 - 2	35	0.5< <1.0	16
Bl Lac	12	2 - 4	16	2 - 3	13	1.0< <2.0	10
Other	14	>4	8	3 - 4	4	>2	13

INTERNAL CONSISTENCY AND PRECISION

Systematic differences

In order to investigate the regional deformations of the frames, or to derive statistical properties of the individual source coordinates, it is necessary first to account for the slight misalignment of the two frames which result from the diversity of the implementation of the celestial system definitions.

The relative orientation between two celestial frames is obtained by computing differential rotations about the three coordinate axes on the basis of differences of coordinates of common objects. A source common to the two frames and in the direction of unit vector $\vec{D}$ has two sets of coordinates, one in frame 1 and one in frame 2. If there exists no relative deformations between the frames, and then that they only differ by a rotation, the transformation between the two celestial reference frames can be written as:

$$\vec{D}_2 = M \vec{D}_1 \qquad (1)$$

where the rotation matrix M is

$$M = \begin{vmatrix} 1 & A_3 & -A_2 \\ -A_3 & 1 & A_1 \\ A_2 & -A_1 & 1 \end{vmatrix}$$

A_1, A_2, A_3 are the infinitesimal rotation angles about x,y and z axes respectively. In each frame, the x-axis is in the direction of the origin of right ascensions, the z-axis points to the celestial pole and the y-axis completes a direct triad.

However, various studies have shown that the above model fails to represent adequately the differences that exist between VLBI celestial frames. Starting with the 1992 IERS Annual Report, the classical three rotation-angles model used in the previous realisations has been modified by the inclusion of three auxiliary parameters B_1, B_2, B_3. These parameters intend to absorb some regional deformations, mainly in declination.

If α_{ij}, δ_{ij} are the coordinates of the source j in the frame i, and α_{ic}, δ_{ic} are its coordinates in the combined celestial reference frame, the two equations of observation for the source adopt the form

$$\begin{aligned} & A_1(i)\ tg\ \delta_{ij} \cos\alpha_{ij} + A_2(i)\ tg\ \delta_{ij} \sin\alpha_{ij} - A_3(i) \\ & - B_1(i) \sin\alpha_{ij}/\cos d_{ij} + B_2(i) \cos\alpha_{ij}/\cos\delta_{ij} + \alpha_{jc} = \alpha_{ij} \\ & - A_1(i) \sin\alpha_{ij} + A_2(i) \cos\alpha_{ij} \\ & - B_1(i) \cos\alpha_{ij} \cdot \sin\delta_{ij} - B_2(i) \sin\alpha_{ij} \cdot \sin\delta_{ij} + B_3(i) \cos\delta_{ij} + \delta_{jc} = \delta_{ij} \end{aligned} \qquad (2)$$

where $A_1(i)$, $A_2(i)$, $A_3(i)$ are the rotation angles between the axes of the combined frame and those of the individual frame i, and $B_1(i)$, $B_2(i)$, $B_3(i)$ are the auxiliary parameters attached to the individual frame i.

In comparisons as well as in combinations, the equations are weighted according to formal uncertainties in the individual VLBI reference frames, after applying a lower limit of 0.25 mas.

Precision

The precision of source positions in the VLBI celestial frames is estimated from the least squares adjustment, together with a number of other astronomical and geodetic parameters. The systematic effects of the uneven distribution of observations appear in the covariance matrices but they do not affect the estimated uncertainties. The formal uncertainties on the source coordinates in the catalogs follow a law in N^{α} for numbers of observations N up to a few thousands as shown in Table 2 for the five individual frames.

The decrease of formal uncertainties in most frames is practically proportional to $N^{-0.5}$. The typical uncertainty for 100 observations is of similar size in the two frames, 0.20 mas in $\sigma_{\alpha} \cos\delta$ and 0.25 mas in σ_{δ}.

The five individual frames have been combined with equations (2) in order to derive the new version of the IERS Celestial Reference Frame, RSC(IERS) 93 C 01. For 301 sources having coordinates in at least two individual frames one can derive position uncertainties from the agreement of coordinates in the different frames. The N-dependence of these uncertainties is given in Table 3. The dependence is extremely similar to that in the individual frames, which was not the case prior to the introduction of the B terms in equations (2).

The individual standard errors of the combined coordinates are plotted on Figure 2 as a function of declination

Table 2. Formal uncertainties of source coordinates as a function of their number of observations in the individual frames. $\sigma = \sigma_0 N^{\alpha}$ (Unit for σ : 0.001")

	GIUB		GSFC		JPL	
	$\sigma_\alpha \cos\delta$	$0.8\ N^{-0.3}$	$3.2\ N^{-0.6}$		$1.2\ N^{-0.4}$	
	σ_δ	$0.6\ N^{-0.1}$	$2.6\ N^{-0.5}$		$1.6\ N^{-0.4}$	
N	$\sigma_\alpha \cos\delta$	σ_δ	$\sigma_\alpha \cos\delta$	σ_δ	$\sigma_\alpha \cos\delta$	σ_δ
10 Obs	0.43 ±0.13	0.41 ±0.10	0.83 ±0.14	0.84 ±0.12	0.44 ±0.12	0.56 ±0.12
100 Obs	0.23 ±0.09	0.30 ±0.10	0.22 ±0.06	0.27 ±0.06	0.16 ±0.06	0.20 ±0.06
1000 Obs	0.12 ±0.06	0.22 ±0.09	0.06 ±0.02	0.09 ±0.03	0.06 ±0.03	0.07 ±0.03

	NOAA		USNO	
	$\sigma_\alpha \cos\delta$	$1.2\ N^{-0.4}$	$2.1\ N^{-0.6}$	
	σ_δ	$1.2\ N^{-0.3}$	$2.1\ N^{-0.5}$	
N	$\sigma_\alpha \cos\delta$	σ_δ	$\sigma_\alpha \cos\delta$	σ_δ
10 Obs	0.48 ±0.13	0.53 ±0.16	0.57 ±0.13	0.73 ±0.26
100 Obs	0.19 ±0.07	0.24 ±0.10	0.15 ±0.05	0.25 ±0.12
1000 Obs	0.07 ±0.04	0.11 ±0.06	0.04 ±0.02	0.08 ±0.05

Table 3. Formal uncertainties of coordinates in RSC(IERS) 93 C 01 for sources having coordinates in at least two individual frames.

$\sigma = \sigma_0 N^{\alpha}$ (Unit : 0.001")

	$\sigma_\alpha \cos\delta =$	$1.52\ N^{-0.4}$
	$\sigma_\delta =$	$1.47\ N^{-0.4}$
N	$\sigma_\alpha \cos\delta$	σ_δ
10 Obs	0.58 ±0.14	0.63 ±0.15
100 Obs	0.22 ±0.07	0.27 ±0.09
1000 Obs	0.08 ±0.04	0.12 ±0.05

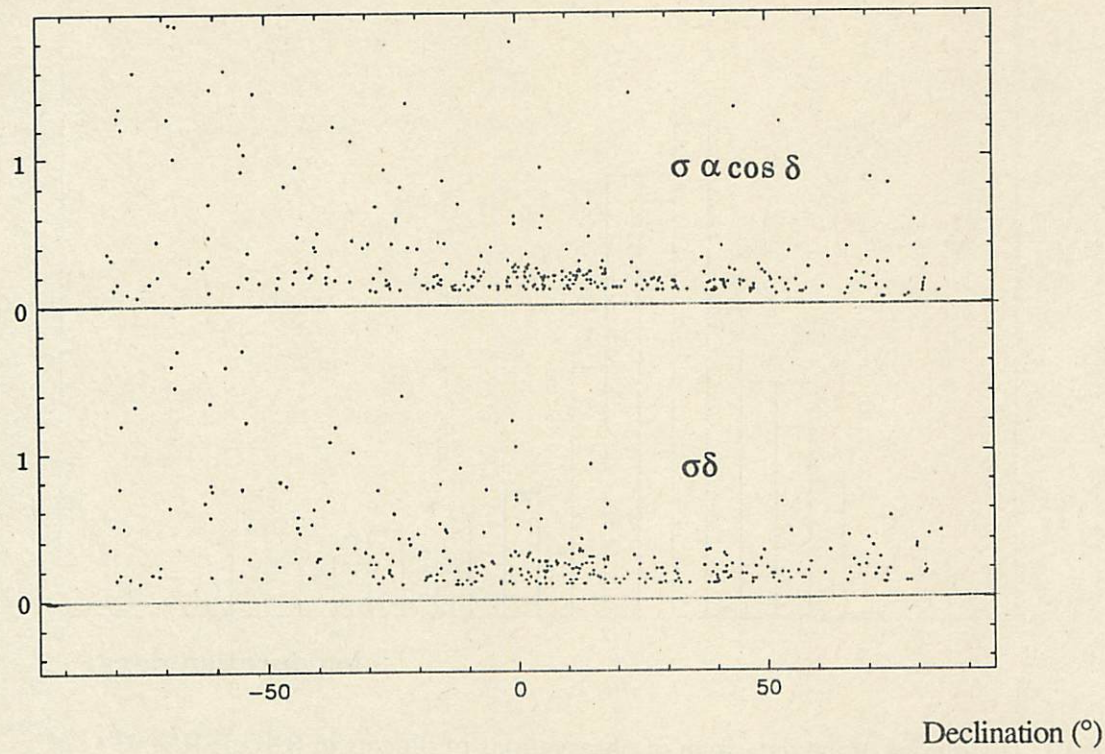


Figure 2. Uncertainty of source coordinates in RSC(IERS) 93 C 01, as a function of declination.

MAINTENANCE OF THE ICRF

The maintenance of the frame has two aspects: the repeated observation of the fiducial objects, and the refinement and extension of the frame, while keeping fixed the System.

Monitoring of the objects

A large number of the fiducial objects for which coordinates are available in the IERS System benefit from a long observational history, as illustrated by Figure 3. Correlatively, the numbers of observations of some objects can be very large (Figure 4). These two characteristics are important factors for the stability of the IERS celestial frame.

Maintenance of the system

The new astrometric techniques and the possibility to reanalyse large numbers of observations whenever necessary raise the question of how one should understand the conventional character of the celestial frame. In practice, it can be understood in two ways:

- the source coordinates themselves are considered conventional, *i.e.*, their numerical values are fixed for some time (years). This is the FKn philosophy;

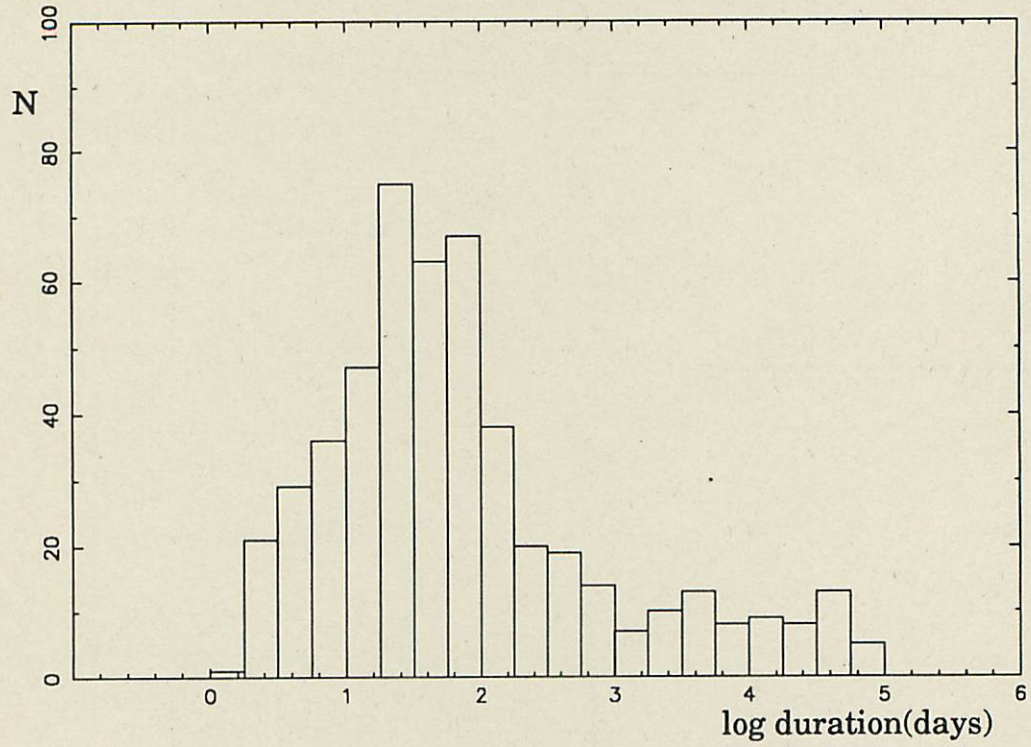


Figure 3. Histogram of the data span of observations of objects in RSC(IERS) 93 C 01
Unit: days (logarithmic scale).

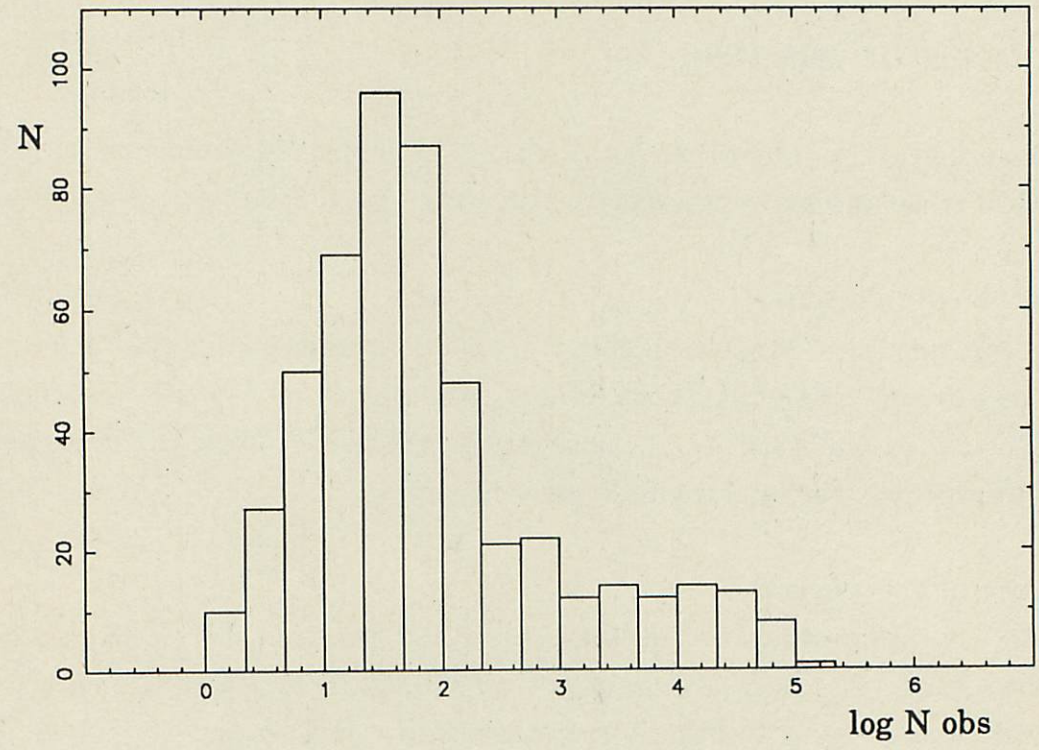


Figure 4. Histogram of the number of observations of objects in RSC(IERS) 93 C 01
Logarithmic scale.

- the axes of the system are considered conventionally as fixed to their initial directions, but improved or additional source coordinates available at the time of analysis are provided to the users; this is required for space navigation, Earth orientation programs, geodetic applications, link of celestial frames, etc. The system maintenance method applied by the IERS is along these lines; such a procedure is made possible by the high model standardization in the operation of IERS, and because the implementation of an extragalactic celestial frame implies much less geophysical and astronomical modeling than does the FK series of catalogues. This approach was also retained in the IAU resolutions on reference systems, adopted in August 1991.

The initial definition of the IERS system and its maintenance process is described by Arias and Feissel (1990). As new information on source positions becomes available, new realizations of the ICRF are introduced, applying a no rotation constraint with respect to the previous realization. In this process the directions of the axes of the frame are maintained and the frame is progressively densified and made more precise. The maintenance of the direction of the axes is based on selected *primary* sources, whose coordinates are stable and consistent.

Table 4 gives the list of the issues of the ICRF since 1988, with the successive rotation angles. The consistency of axes is currently kept within ±0.0001". The improvement in the precision is illustrated by Figure 5, showing the histograms of position uncertainties for the first issue of the ICRF and the most recent one.

Table 4. Relative orientation of the successive realizations of the IERS celestial system. Angles (A_1, A_2, A_3) rotate the realization of year N to that of year N+1.

Name	Label	Nb of objects	A_1	A_2	A_3	Reference
			(0.001")			
RSC(IERS)	88 C 01	228				Arias *et al.*, 1988
			-0.15	-0.24	+0.21	
			±0.10	±0.10	±0.07	
RSC(IERS)	89 C 01	209				IERS, 1989
			+0.00	+0.07	+0.05	
			±0.12	±0.11	±0.10	
RSC(IERS)	90 C 01	228				IERS, 1990
			+0.03	+0.06	+0.00	
			±0.05	±0.04	±0.04	
RSC(IERS)	91 C 01	396				IERS, 1991
			+0.05	+0.03	-0.09	
			±0.09	±0.09	±0.07	
RSC(IERS)	92 C 01	422				IERS, 1992
			0.00	0.00	0.00	
			±0.03	±0.03	±0.02	
RSC(IERS)	93 C 01	504				IERS, 1993

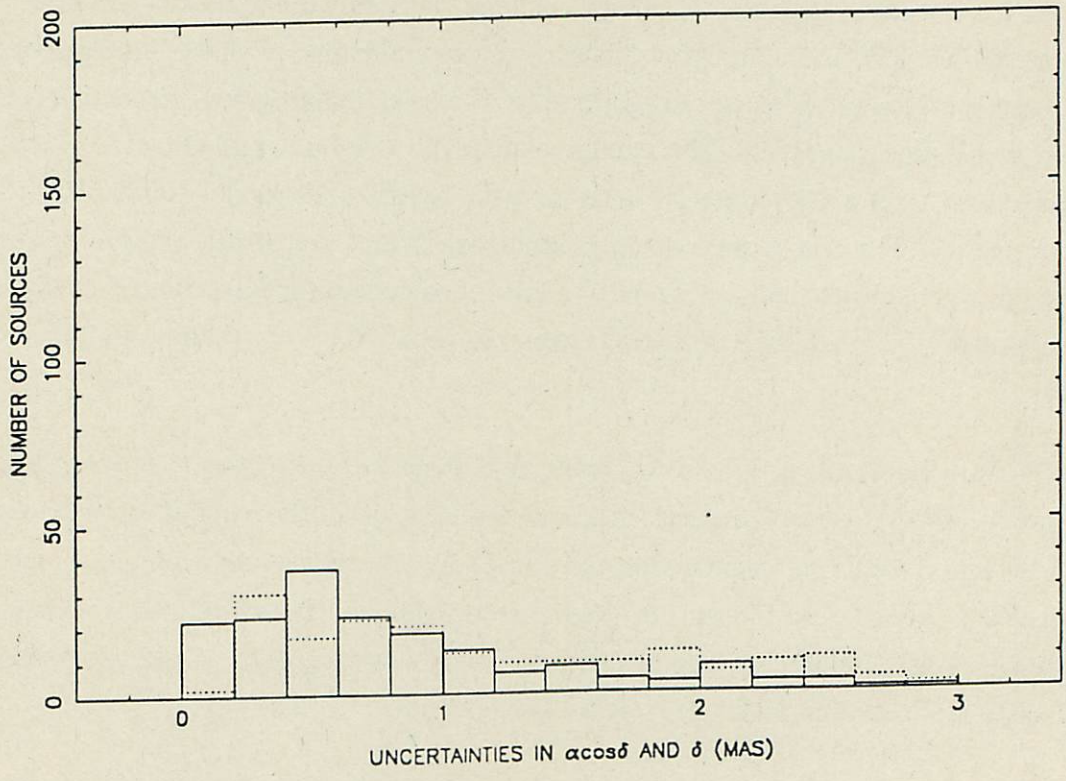


Figure 5a. Distribution of the formal uncertainties in right ascension (full line) and in declination (dashed line) of the source positions in RSC(IERS) 88 C 01. 55 sources with formal uncertainties larger than 0.003" are not shown.

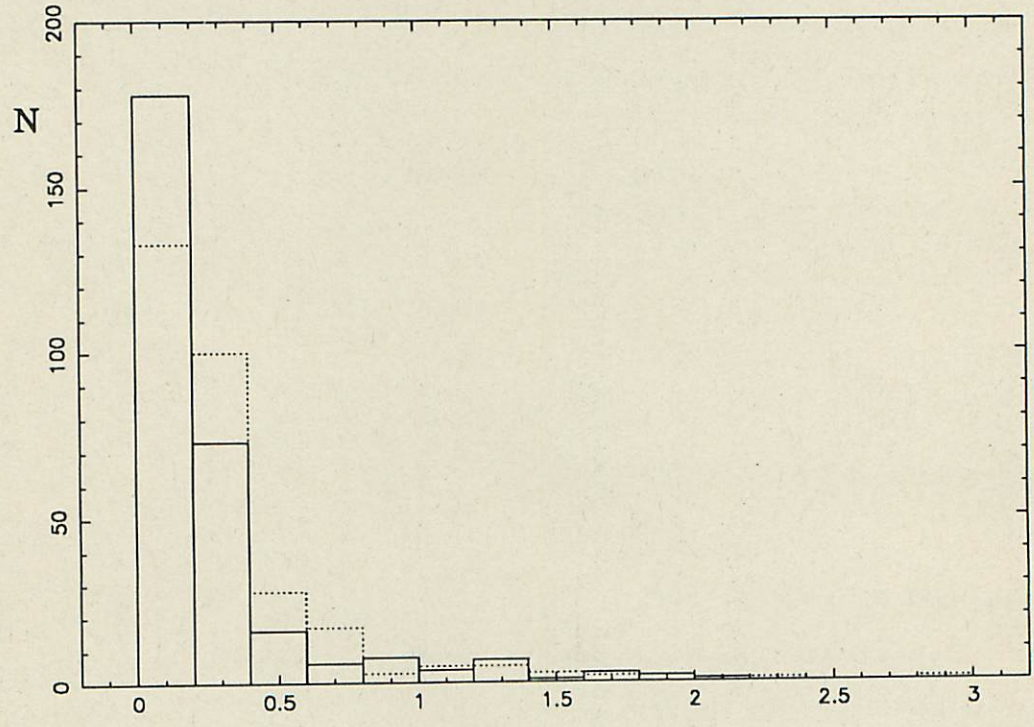


Figure 5b. Distribution of the formal uncertainties in right ascension (full line) and in declination (dashed line) of the source positions in RSC(IERS) 93 C 01. 49 sources with formal uncertainties larger than 0.003" are not shown.

SUMMARY

The International Astronomical Union recommended that efforts be made to elaborate a list of primary radio sources which will define the direction of axes of the primary celestial frame, and a list of secondary sources candidate to become primary in the future. In agreement with these recommendations, and using the wealth of observations accumulated in the Earth rotation and other programs, the International Earth Rotation Service (IERS) regularly evaluates the astrometric quality of VLBI results and implements the IERS celestial system.

The celestial system of the IERS is maintained at the level of 0.0001". The direction of its axes relative to physical directions related to the Earth rotation (mean celestial pole) and orbit (dynamical equinox) are known within ±0.003". Its 1993 realization contains 504 objects in the declination range -82° to +86°, over 300 objects have positions that are known within ±0.0005". Its largest systematic errors are smaller than 0.001".

The contribution of Earth rotation observations to the extragalactic celestial frame includes the monitoring of the radiosources. The data available to IERS in 1993 concern 301 sources monitored in at least two programs of observations. Also available to IERS are 203 objects with coordinates in only one frame (GSFC: 148 objects; JPL: 53 objects; USNO: 2 objects)). The networks are operated in parallel by groups which tend to extend their lists of observed objects both with common and non common sources, in order to perpetuate their celestial references on a sound basis; this results in a progressive improvement in precision and distribution of the global celestial frame.

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A catalogue of phase reference sources.

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Abstract: A catalogue of phase reference sources is described. The positional accuracy of this catalogue is 12 milliarcsec rms.

1 Introduction

For an interferometer with a baseline of a few hundred km, one needs a denser grid of phase calibrators than is available from the VLA calibrator list or VLBI catalogues. In particular, for the MERLIN array at Jodrell Bank, UK, one needs a calibrator within about 3° of the target source (Patnaik et al. 1991). The basic uses of phase reference sources are to be able to coherently integrate the data over several hours to detect weak radio sources and to determine accurate positions of the target sources.

The sources suitable for the above purpose should have a well defined compact component and should be bright enough to be detected with a signal-to-noise ratio of $\geq$10 in a few minutes integration. Only flat spectrum radio sources satisfy these criteria. In order to get a large sample of a few thousand flat spectrum sources we used the Green Bank catalogues at 1.4 and 5 GHz (Condon, Broderick 1985, 1986, Condon, Broderick, Seielstad 1989). The sources were selected using the following criteria: a) flux density at 5 GHz $\geq$200 mJy, b) spectral index flatter than 0.5, c) $\delta \geq 0°$, and d) $\mid b \mid \geq 2.5°$.

2 Observations and results

The observations were made, in three sessions, using the VLA in the A array at 8.4 GHz giving a resolution of 200 milliarcsec (mas). In each of the three observing sessions we observed about 900 sources. Each source was observed for about 2 minutes and a calibrator was observed every 5 minutes. We used the sources from the VLBI catalogue with mas position accuracies as calibrators (Ma et al. 1990) and the positions we determine are with respect to these sources.

We checked a group of sources around 3C345 (1641+399) whose positions are known from the VLBI catalogue. These sources were observed in exactly the same way as other target sources in order to determine the position accuracies. We also reobserved some sources to check the repeatability of the positions. From these observations we find the position errors with respect to the VLBI catalogue are 12 mas rms. Appoximately 80% of the sources observed are found to be suitable for use as calibrators. While these errors are acceptable for an array like MERLIN. These are rather large for astrometric applications. Observations using the VLBA in S/X bands are planned to further improve the positions.

3 Conclusion

We have presented a catalogue of phase reference sources with 12 mas rms position errors. The planned VLBA observations at S/X bands should improve the positions so that the catalogue

may be useful for astrometric applications. Part of this catalogue (Patnaik et al. 1992) is ready for distribution via email (apatnaik@mpifr-bonn.mpg.de).

Acknowledgements

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Differential astrometry on the pair of radiosources 1038+528 A and B.

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Abstract: I present the angular separation between the pair of quasars 1038+528 A and B, at $\lambda = 3.6$ and 13cm, measured with simultaneous VLBI observations in June 1990. Differential astrometric techniques applied to the analysis of this and previous epochs, March 1981 and May 1983, have been used to monitor the angular separation between this pair of quasars at the μas level along a decade. I propose a plausible scenario for the kinematics of the quasars 1038+528 A and B that reproduces the differences between their relative separations measured at the three epochs. The non-secular character of the positional changes attributed to the core of the quasar 1038+528 A rules out the identification with proper motion in this quasar. Further investigations strongly support that they are mainly related to the finite resolution of the interferometer. The exhaustive error analysis made provides an experimental estimate of the stationary character of the core of the quasar 1038+528 A at $\lambda = 3.6$cm, with respect to the more distant reference quasar 1038+528 B, of about $20 \pm 14\mu$as/year.

1 Introduction

A detailed presentation of this pair of quasars can be found elsewhere (Marcaide, 1982; Elósegui, 1991; Rioja, 1993) so I will not reproduce it here. The short angular separation (33") between the pair of quasars 1038+528 A ($z \sim 0.678$) and B ($z \sim 2.296$) transform this pair in an ideal system for application of differential astrometric techniques. At centimeter wavelengths both sources can be simultaneously observed because they lie within the main beam of an antenna. Under these conditions the temporal and spatial dependence of the instrumental and propagation medium contributions to the VLBI observables and phase-delay quantity, very difficult to estimate, show up with approximately the same magnitude in the simultaneous observations of both radiosources. Therefore these individual contributions practically cancel out in the differential magnitudes and the relative separation can be estimated at the μas level.

On March 1981 and May 1983 (Marcaide, 1985; Elósegui, 1991) an intercontinental array of radiotelescopes observed simultaneously the pair of quasars 1038+528 A and B at $\lambda = 3.6$ and 13cm. Several hypothesis were proposed to explain the change in the relative position between this pair of quasars in this two years period, either proper motion of the quasar 1038+528 A or "core-jitter" effects in the core of the same radiosource (Elósegui, 1991). Similar observations were made in June 1990 (Rioja, 1993) whose purpose was to constrain the scope of valid arguments proposed after the analysis of the first two epochs, or to propose new ones. The aim of this project was to provide experimental evidence of the stationary character of the core of the quasar 1038+528 A, according to the standard theory for extragalactic radiosources (Blandford & Königl, 1979), using phase reference techniques with respect to a much more distant reference source.

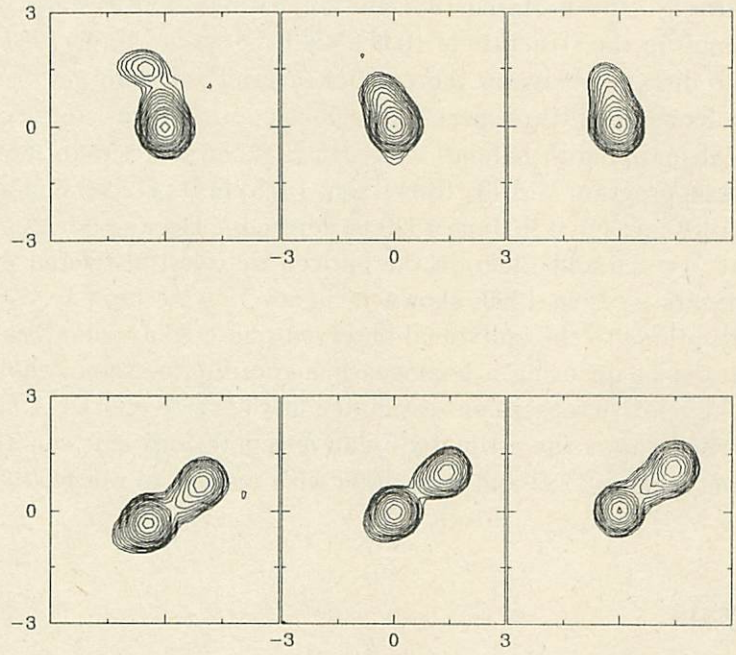


Figure 1: **(top)** From left to right, maps of the quasar 1038+528 A at $\lambda = 3.6$cm in March 1981, May 1983 and June 1990. **(bottom)** From left to right, maps of the quasar 1038+528 B at $\lambda = 3.6$cm in March 1981, May 1983 and June 1990. Units are mas.

Effect	$\Delta\theta$	
	$\lambda = 3.6$cm	$\lambda = 13$cm
EOP	$< 1\mu$as	$< 1\mu$as
Baseline error	$< 3\mu$as	$< 3\mu$as
Reference source position error	$\sim 0.1\mu$as	$\sim 0.1\mu$as
Troposphere	$\sim 1\mu$as	$\sim 1\mu$as
Ionosphere	$\sim 0.2\mu$as	$\sim 3\mu$as
Solar plasma	$\sim 8\mu$as	$\sim 120\mu$as
Calibration	$< 10\mu$as	
Astrometric software	$< 10\mu$as	
Beamwidth-SNR	$\sim 37\mu$as	

Table 1: Compendium of effects considered to estimate the uncertainty in the relative position ($\Delta\theta$) between the quasars 1038+528 A and B in June 1990, at $\lambda = 3.6$ and 13cm.

2 Data analysis

Figure 1 shows the brightness distributions of the radiosources 1038+528 A and B at $\lambda = 3.6$, derived with the Caltech software package (kindly made available by Tim Pearson). According to the maps in figure 1a the inner part of the jet in the structure of 1038+528 A appears closely aligned, oriented towards North, in March 1981 and June 1990. The maps in Figure 1b don't show any relevant changes in the structure of 1038+528 B between March 1981 and May 1983, while in June 1990 the distance between the component and the core has increased and the flux of the former has decreased with respect to previous epochs. Consistent results have been found using independent mapping techniques to reconstruct the structure of both radiosources.

I used the astrometric program VLBI3 (Robertson, 1975) in its G2 version and the differential phase-delay quantities measured in June 1990 to determine the angular separation between 1038+528 A and B, at $\lambda = 3.6$ and 13cm, in the baricentric celestial reference frame J2000.0. The maps of both quasars in June 1990, shown in figure 1, were used to estimate the individual structure contributions to the individual observed phase-delay quantities. The first two epochs had to be reduced again using a homogeneous coordinate-system that would allow a direct comparison of the relative separations estimated at the three epochs (Chopo Ma, private communication). Figure 2 shows the estimated relative separations between 1038+528 A and B, at $\lambda = 3.6$ and 13cm, in May 1983 and June 1990 with respect to March 1981.

3 Error analysis

I have performed an error analysis on the observations made in June 1990 to derive reliable uncertainties in the astrometric estimates. Table 1 lists all the effects considered along with the propagation of the associated uncertainties on the estimated angular separation at this epoch and at $\lambda = 3.6$ and 13cm. I will just briefly mention additional effects considered in this error analysis with respect to the one performed by Elósegui on previous epochs (Elósegui, 1991) in order of decreasing relevance.

- Identification of identical reference points within the structure of each quasar at the three epochs. It depends on the synthesized beamwidth and the signal-to-noise ratio of the map. This effect limits the precision achievable in the knowledge of the relative separation evolution between this particular pair of radiosources.

- Diversity of criteria to choose the reference points.

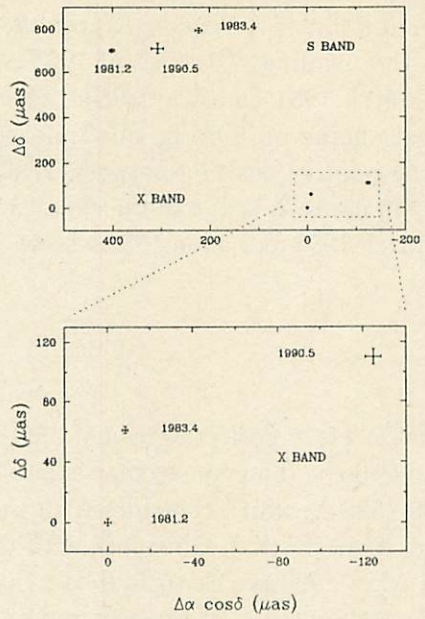


Figure 2: Relative separations between the quasars 1038+528 A and B in May 1983 and June 1990, at $\lambda = 3.6$ and 13cm, with respect to March 1981. Note that the error bars correspond to formal uncertainties. According to our error analysis a reliable estimate of the astrometric uncertainties corresponds to a factor 7 larger. Opacity effects in the core of the quasar 1038+528 A are the responsible for the dependence of the relative position with respect to the observing wavelength (Marcaide, 1982). This effect has also been observed in other sources (Biretta, 1986).

- The bias introduced by the particular software used in the astrometric analysis.
- The particular homogeneous-system, determined by consistent values for telescopes and reference source coordinates and EOP (Earth Orientation Parameteres), used to compare the separations at the three epochs.

A quadratic sum of the uncertainties listed in table 1 provides a realistic uncertainty in the angular separation estimated between 1038+528 A and B. It is 7 times larger than the formal error derived from the statistical fit, at $\lambda = 3.6$cm, at the three epochs.

4 Interpretation

I propose a new scenario to explain the changes in the relative position between 1038+528 A and B measured along a decade of VLBI observations, as shown in figure 2. It considers the effect of structure changes in the reference quasar 1038+528 B, noticeable in figure 1, on the relative separation estimates measured at different epochs. A proper subtraction from the astrometric estimates shown in figure 2 will provide the individual contribution attributed to the quasar 1038+528 A. From the maps in figure 1 and other independent arguments (Rioja, 1993) I propose a secular expansion of the structure of the radiosource 1038+528 B between 1981 and 1990, due to a displacement of the single visible component in the maps at $\lambda = 3.6$cm in figure 1, at a rate equal to 17μas/year ($v = 0.7h^{-1}c$, $0 < h < 1$, $H_0 = 100$Km s^{-1} Mpc^{-1}, $q_0 = 0.5$), along the jet direction opposite to the core. This would translate into a change in the relative position of 1038+528 A with respect to B in May 1983 and June 1990, with respect to March 1981, of about 34 and 170 μas in direction P.A -50^0, respectively. Moreover, it also determines from

purely astrometric arguments a change in the position of the reference point in the radiosource 1038+528 A of 43μas, in direction P.A.25^0, between March 1981 and May 1983. This orientation is perfectly compatible with the bending of the jet of 1038+528 A in the maps at $\lambda = 3.6$cm, shown in figure 1, between March 1981 and May 1983. This bending can be interpreted as a consequence of active processes going on, during this time period, in the core region. Within this scenario the change in the relative position between 1038+528 A and B in June 1990 with respect to March 1981, shown in figure 2, is due to the expansion of the structure of 1038+528 B. The maps of this source in March 1981 and June 1990, shown in figure 1, are also rather similar.

5 Conclusions

The scenario presented in section 4 is in perfect agreement with the maps and astrometric results shown in figures 1 and 2, respectively. The non-secular character of the displacement attributed to the reference point in 1038+528 A, which coincides with the core, rules out the hypothesis of proper motion in this quasar. Also, its close alinement with the bending in the jet of 1038+528 A between March 1981 and May 1983 seems to indicate that, due to the finite resolution of the interferometer, it monitors the position of the centroid of the brightness distribution rather than the position of the core of 1038+528 A itself. The position of the centroid is expected to change, for instead, in the early stages of emission of a new component, yet unresolved in the maps, from the core, or due to instabilities in the core region ("core-jitter") (Elósegui, 1991). In this sense these results provide an upper limit to the observed displacements rate of the core of the extragalactic radiosource 1038+528 A, of $20 \pm 14\mu$as/year ($v = 0.4h^{-1}c$, previous values for H_0 and q_0), along a decade of VLBI observations. This work provides experimental evidence of the stationary character of the core of the quasars as assumed in the standard theory for extragalactic radiosources.

Acknowledgements

I am indebted to Jon Marcaide, Pedro Elósegui and Irwin Shapiro for their valuable comments and ideas to carry out this research.

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RADIO SOURCE STRUCTURE AND ITS INFLUENCE ON THE ACCURACY OF GEODETIC VLBI ANALYSIS

Part 1:How do the "pointlike" sources really look like?

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Geodetic measurements in our days determine baselineshifts with a spatial resolution of a few millimeters. The accuracy of baseline determination and measurement of earth rotation parameters has reached a limit where second-order contributions become significant.

In geodesy and for the determination of earth orientation ten to twenty radio sources are regularly observed by VLBI. The ideal observing schedule for geodetic VLBI would use a number of structureless radio sources in all parts of the mutually visible sky with many observations of each source in the course of a day. But most of the celestial radio sources with flux densities higher than 0.5 Jansky exhibit complex and extended spatial structures at the milliarcsecond scale.

The aim of our investigation is to test the commonly used radio sources for their suitability for geodetic measurments which means to monitor source structure and its development in the course of the years and develop an algorythm to correct for source structure effects. Extended structure does not necessarily limit the accuracy of geodetic measurements. If the extended structure is well-known and predictable the determination of the source-structure effects and its proper correction in the analyses can be sufficiently reliable. Our investigations aim to improve the quality of the selected sources concerning geodetic requirements and to prepare for eventual replacements in the current sourcelist.

Investigating this database means collecting knowledge about source-structure developments of about 30 sources. These informations are of enormous interest also in astrophysics. The high duty-cycle of the observations (every month for IRIS-S) allows to study the milliarcsecond structures and their variations simultaneously at two frequencies (8.4 and 2.3 GHz) on short timescales. There's nothing comparable to this amount of data in radio-astronomy. Many "geodetic" sources have

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already been observed in purely astronomical observations but only comparatively few observations exist. The astrophysical merit of this database lies obviously in the monthly persecution of structural changes in extragalactic radio sources over at best 10 years time and the filling of the gaps between high dynamic range observations. The dynamic range we can achieve with geodetic data is limited to 1:50.

1. *Status-report*

From the available geodetic VLBI campaigns we selected fifteen different epochs of IRIS-S (high north-south resolution and almost circular beam for low declination sources) and EUROPE (high sensitivity due to large telescopes) observations (correlated in Bonn) covering a maximum time base of 10 years (1983-1993). Table 1 lists the 29 radio sources which have yet been investigated. Column 1 gives the IAU name, column 2 the common name, column 3 the identification and column 4 the redshift. Column 5 lists the number of images, which means either CLEAN-maps or "modelfits" (a fit of components with gaussian luminosity distribution to the data) (Britzen, 1993 and Schalinski, 1990). The last column describes the by the investigations covered timebase. Only one source out of a sample of 29 sources fulfills the condition of being essentially pointlike at at least one epoch of observation: 0229+131 in May 1988, see figure 1.

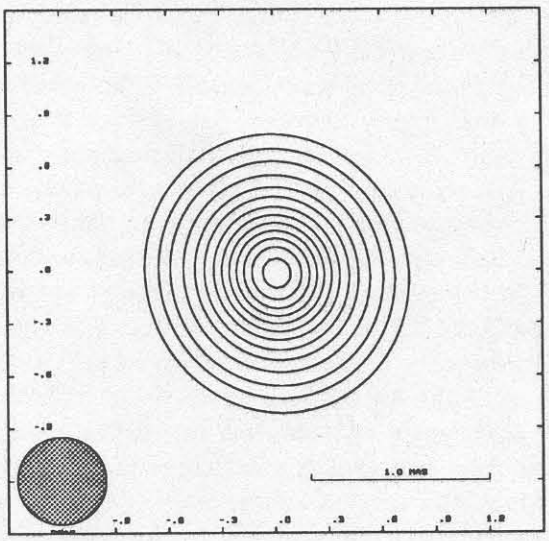


Fig. 1. Modelfit of 0229+131 at 8.4 GHz, May 1988.

Table 1

Investigated Sources and Epochs

IAUName	*Name*	*ID*	*z*	*Images*	*Timebase*
0016+731		QSO	1.76	2(X)	1992.34-1993.01
0106+013		QSO	2.11	1(X)	1988.34
0212+735		OVV	2.37	12(X)	1983.4-1992.34
0229+131		QSO	2.065	15(X)	1988.34-1993.13
0300+470	4C47.08	BL Lac		1(X)	1992.15
0420−014		QSO	0.915	1(X)	1992.15
0454−234		QSO		1(X)	1992.15
0528+134		BL?	2.06	6(X)	1988.34-1993.01
0552+398	DA193	QSO	2.365	5(X)	1988.34-1992.19
0727−115		BL?		3(X)	1992.15-1992.92
0851+202	OJ287	BL Lac	0.31	8(X)	1988.34-1992.92
0923+392	4C39.25	QSO	0.699	9(X)	1988.34-1992.34
1226+023	3C273	QSO	0.158	1(X)	1988.34
1308+326		BL Lac	0.99	1(X)	1992.92
1334−127		QSO	0.541	1(X)	1992.15
1404+286	OQ208	QSO	0.077	4(X)	1988.33-1992.15
1606+106		QSO		3(X)	1992.92-1993.13
1611+343	DA406	QSO	1.401	1(X)	1992.15
1641+399		QSO	0.704	1(X)	1988.34
1739+522		QSO	1.375	4(X)	1992.92-1993.01
1741−038		QSO	1.057	10(S),7(X)	1988.95-1993.01
1803+784		BL Lac	0.68	3(S),11(X)	1983.4-1992.34
2007+777		BL Lac	0.34	2(X)	1992.92-1993.13
2121+053		QSO	1.878	2(X)	1988.95-1992.15
2134+004		QSO	1.936	1(X)	1988.34
2145+067		QSO	0.99	1(S),3(X)	1992.27-1993.01
2200+420	BL Lac	BL Lac	0.07	1(X)	1988.34
2234+282		QSO	0.795	3(X)	1988.95-1992.52
2251+158	3C454.3	QSO	0.859	1(X)	1988.34

2. *Summary of first results*

In the following we present comments and maps on some sources from Table 1.

⋆ **1226+023** (3C273)
This "original" quasar (Unwin in Zensus et al. 1990) reveals a core-jet structure which extends from a radius $\leq$ 1 pc to 40 kpc from the nucleus. At least 5 knots move with superluminal velocities along a curved jet (Zensus et al., 1988). The fast convergence of the mapping-process for this source and the good reproduction of the known components underline the astrophysical potential of the geodetic data.

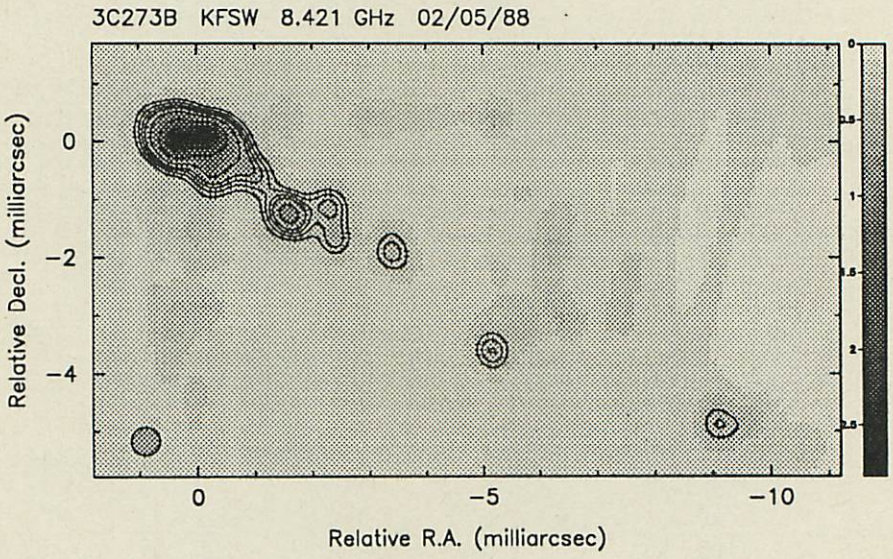


Fig. 2. CLEAN map of 3C273 at 8.4 GHz, May 1988. Contours are 15, 20, 25, 30, 40, 60 and 80% of the peak brightness.

⋆ **0212+735**
This quasar belongs to the "superluminal" sources. 5 GHz observations revealed the existence of at least 3 components in a jet which extends to the east from the core to a distance of approximately 13 mas (Eckart et al. 1987). Our map is in accordance with astronomical observations and investigations of this source. The elongation of the core (seen by Schalinski 1990) as well as the curvature of the jet and the positions of the components can be followed to a distance of about 13 mas from the nucleus.

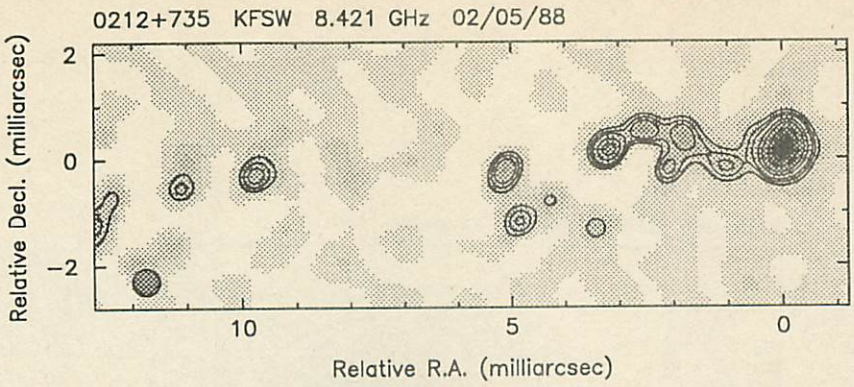


Fig. 3. CLEAN map of 0212+735, May 1988. Contours are 10, 15, 20, 30, 40, 60 and 80 % of the peak brightness.

⋆ 1803+784

The due to the incomplete uv-coverage poor quality of geodetic data (concerning mapping) compared with astronomical data requires a careful calibration with a source whose structure is well-known from high dynamic range observations which is the case e.g. for the blazar 1803+784. For this source informations from nearly all parts of the electromagnetic spectrum exist (from radio to gamma rays). While the structure on the kp-scales is dominated by a north-south structure due to a secondary component 45" south of the core, the mas- and sub-milliarcsecond-structures are dominated by a core-jet structure in east-west direction. A curved jet extends under a position-angle of 261° to a distance of $\sim$ 25 mas. This jet exhibits the coexistence of moving and at least one stationary component. The latter dominates the source-structure at 8.4 GHz and makes this source a useful structure-calibrator and geodetic source since more than ten years now (Witzel et al., 1988).

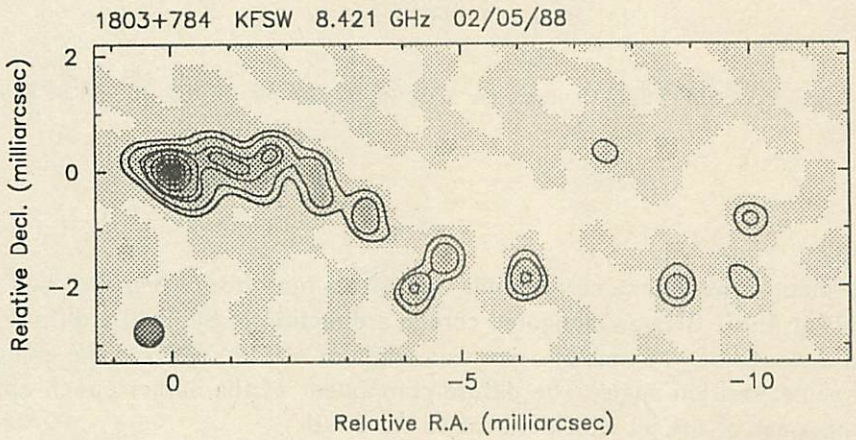


Fig. 4. CLEAN map of 1803+784 at 8.4 GHz. Contours are 5, 10, 20, 25, 40, 60 and 80 % of the peak brightness.

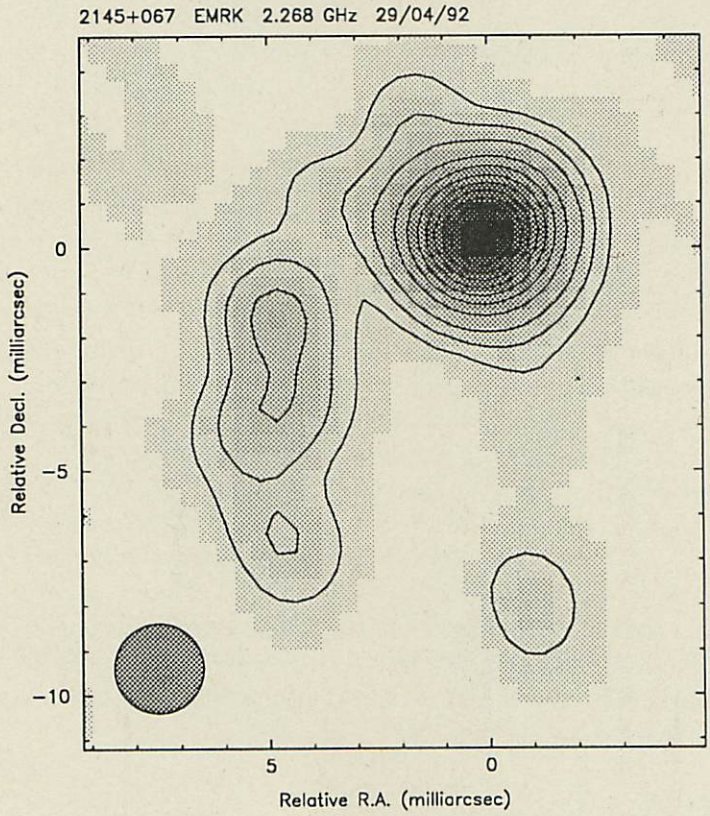


Fig. 5. S-band map of 2145+067. Contours are 2, 5, 10, 20, 30, 40, 50, 60, 70 and 80 % of the peak brightness.

⋆ 2145+067
The S-band map of this source corresponds well with a map from Wehrle et al. (1990) which reveals at 4.991 GHz an elongated core in a direction of 90^o and a diffuse component at a distance of $\sim$ 5 mas at a position angle of $\sim 140^o$. We see the elongated core in the same position-angle. The diffuse component of the earlier epoch appears to be a component of the jet which is bent to the south.

⋆ 2251+158 (3C454.3)
This source shows superluminal motions as well as stationary components. A comparison of our result with a map of I. Pauliny-Toth reveals a good correspondence for this quasar which is of high interest due to its complex and unusual structural changes.

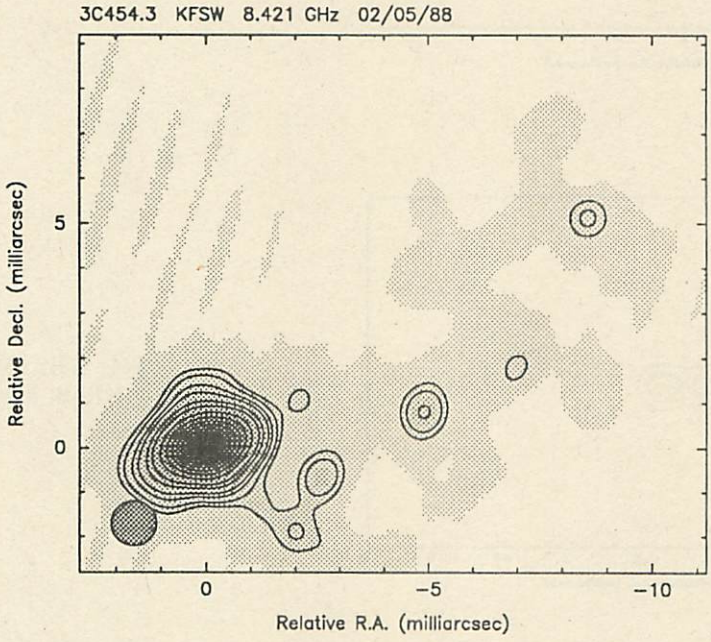
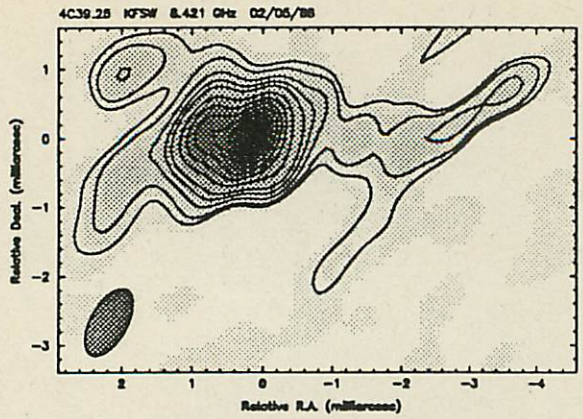


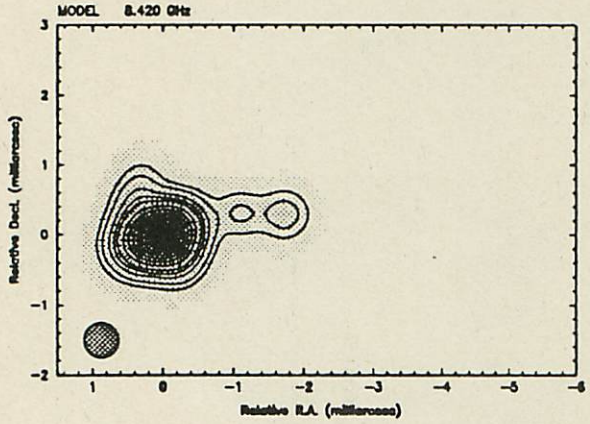
Fig. 6. CLEAN map of 3C454.3, May 1988. Contours are 3.5, 5, 7.5, 10, 15, 20, 30, 40, 50, 60, 70 and 80 % of the peak brightness.

⋆ **0923+392** (4C39.25)

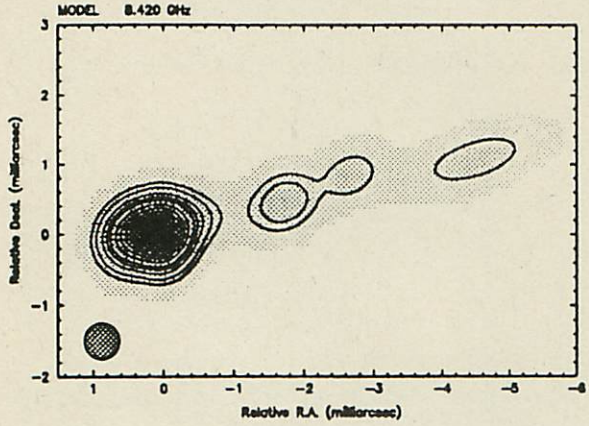
This quasar has been studied with milliarcsecond resolution since the early days of VLBI. Marcaide et al. (1987) showed that none of the known three components has the characteristics usually associated with the cores of compact radio sources. Our 8.4 GHz maps and modelfits show a structure which fits well to the model proposed by Marcaide et al. (1989) of a doubly bent nozzle. Two of the components correspond to these bends, and a third moving component corresponds to a shock travelling down the jet.



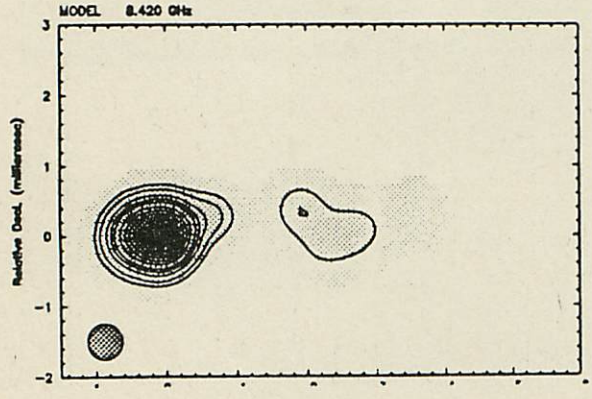
8.4 GHz CLEAN map of 4C39.25 (IRIS, May 1988). FWHM of the restoring beam is 0.5 mas. Contours are 2.5, 5, 10, 15, 20, 30, 40, 50, 60, 70 and 80 % of the peak brightness.



8.4 GHz Modelfit of 4C39.25 (IRIS-S, March 1991).



8.4 GHz Modelfit of 4C39.25 (IRIS-S, September 1991).



8.4 GHz Modelfit of 4C39.25 (IRIS-S, October 1991).

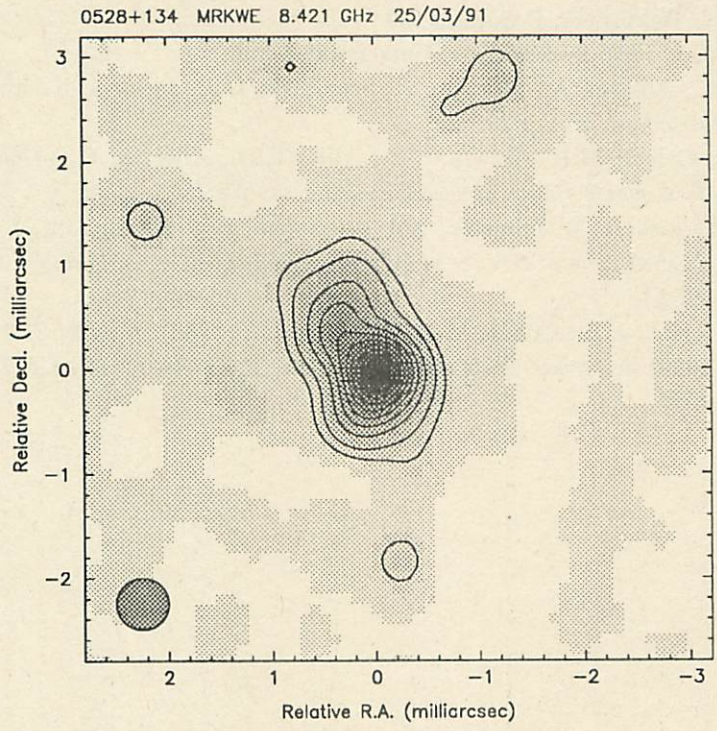


Fig. 8. CLEAN map of 0528+134 at 8.4 GHz. Contours are 5, 10, 20, 30, 40, 50, 60, 70 and 80 % of the peak brightness.

⋆ 0528+134

This source is one of the brightest γ-ray sources in the sky, which makes it particularly interesting for many astronomers. Radio-maps are rare but of great importance to study the physics of such an object. Only one astronomical observation of this source exists but about 60 geodetic observations can be analyzed since this source belongs to the IRIS-S program sources.

Acknowledgements

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Radio source structure and its influence on the accuracy of geodetic VLBI analysis.

Part 2: How to correct for structure effects?

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Abstract: As there is essentially no point like radio source at the milliarcsecond level we need to correct for source structure to reach millimeter accuracy on geodetic parameters. A status report on our source structure software is presented and plans for future developments are exposed.

1 Introduction

At the milliarsecond level, most of the extragalactic radio sources used in geodetic and astrometric experiments have extended structures. It has been shown that effects produced by these structure on the band width synthesis delay are significant (Charlot *et al.* 1988). For a map of 1 mas resolution, a component with 2% intensity located at 10 mas distance from the core affects the delay at the level of 100 ps ($\sim$ 3.5 cm) and a 3% component at the same distance produces effects at the 150 ps ($\sim$ 4.5 cm) level. Therefore for high-precision geodetic VLBI analysis source structure effects must be accounted for.

Although geodetic experiments have a sparse u-v coverage and incomplete calibration information, it has been demonstrated by several VLBI groups that such experiments can provide valuable maps (Charlot 1993, Charlot 1989, Charlot *et al.* 1989, Schalinski *et al.* 1988 a and b, Shaffer *et al.* 1987, Tang *et al.* 1987).

After a short review on the computation of the delay due to source structure, we present the result of tests made to improve the source structure correction-software developed in Bonn. Finally we describe the future plans in order to make this correction available for typical geodetic/astrometric VLBI data analysis.

2 Computation of source structure delay

The effect of source structure on the band width synthesis delay is defined as the fringe phase derivative with respect to angular frequency:

$$\tau_s = \frac{\partial \phi_s}{\partial \omega} \qquad (1)$$

where ϕ_s is the part of fringe phase due to structure effect and ω the observing frequency.

As we are not only interested in phase computation but also in phase variation with respect to frequency, we have expanded equation (1) into two parts and we obtain:

$$\tau_s = \frac{\partial \phi_s}{\partial u}\ \frac{\partial u}{\partial \omega} + \frac{\partial \phi_s}{\partial v}\ \frac{\partial v}{\partial \omega} = \nabla \phi_s\ \frac{B}{\lambda \omega}$$

where $\nabla \phi_s$ is the gradient of phase with respect to (u,v) coordinates and λ the wavelength, B represents the baseline projection onto the plane of sky.

The fringe phase and the derivative of the phase are only functions of the complex visibility function cv(u,v) of the observed source and they are given by:

$$\arctan \phi_s = \frac{Im\ cv(u,v)}{Re\ cv(u,v)}$$

$$\frac{\partial \phi_s}{\partial u} = \frac{\frac{\partial\ Im\ cv(u,v)}{\partial u}\ Re\ cv(u,v) - \frac{\partial\ Re\ cv(u,v)}{\partial u}\ Im\ cv(u,v)}{(Re\ cv(u,v))^2 + (Im\ cv(u,v))^2}$$

with a similar expression for the phase derivative with respect to v.

Finally, the complex visibility function is calculated from the brightness distribution of the source I(x,y) using a two dimensional Fourier Transformation:

$$cv(u,v) = \int\int I(x,y)\ e^{-2\pi\ i\ (ux\ +\ vy)}\ dx\ dy$$

To obtain the delay due to source structure-effects we need the map of delta functions (like those shown in part 1) representing the brightness distribution of the source in the plane of sky (Thomas 1980).

Using this formula the Geodetic Institut of the University of Bonn, jointly with the Max-Planck-Institut für Radioastronomie has developed a software, called 'struc', to compute source structure corrections.

3 Status report on structure correction software 'struc'

First of all we have installed the software STRUC on a work station in order to introduce it into the process of geodetic VLBI analysis, after having tested our computation. The first test consist in checking our results against observed closure quantities.

For source imaging we use the closure phases which are computed by summing the phases around a triangle (ie: a closed loop of baselines). As all effects known today, except source

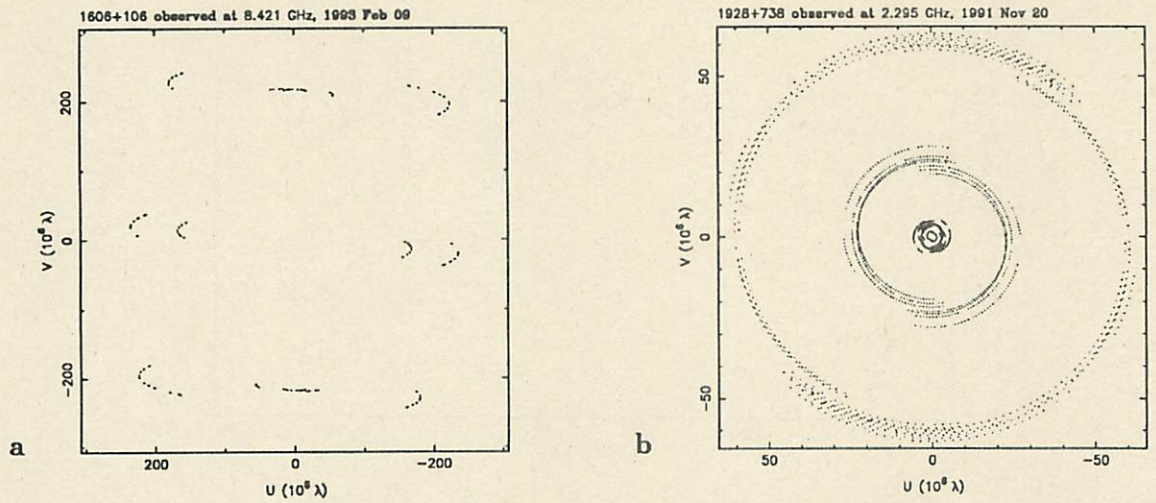


Figure 1: u-v sky coverage **a** for IRIS-S geodetic experiment and **b** for the used observations.

structure effects, are associated with individual antennas, we expect that the non-zero closure quantities are only due to source structure effects (Pearson and Readhead 1984). We have computed the closure phases from the obtained map and compared them with those observed in order to test our computation. Provided that all computations are based on the same experiment and same frequency, the closure phases derived from the map should agree with observed data to within the noise level due to uncertainties in observations and mapping algorithms.

Astrometric observations, performed the 20 november 1991 by the spanish VLBI group on the source 1928+738 at S-band using 7 stations: Effelsberg, Madrid (70m), Haystack and 4 VLBA antennas Fort-Davis, Los Alamos, Kitt Peak, Pietown, are used for the test. We have choose this observations for the sky coverage which is better than for geodetic observations (see fig. 1), and also for the good dynamic range map of 1928+738 at S-band they provide.

Then the bad agreement between observed and computed closure phases obtained first can only be attributed to bugs in the software and not in the poor quality of the map or of the data. Figure 2 show the agreement between computed and measured closure phases after removing some errors in the software.

4 Conclusion

The comparisons between computed and measured closure phases have shown a good agreement and we have to extend this kind of comparisons to the closure delays and closure delay rates in order to improve our software.

The next step would be to introduce the source structure correction in Calc/Solve to be able to analyse in details the influence of source structure on the accuracy of geodetic analysis.

Acknowledgements

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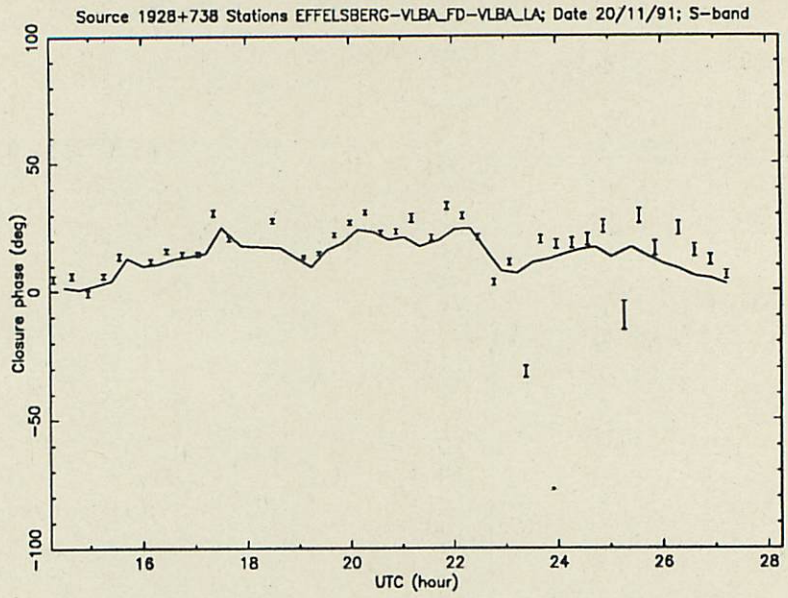


Figure 2: Closure phases with respect to time for the triangle Effelsberg - Fort Davis - Los Alamos. Dots are observed closure phases with their uncertainties and computed closure phases are the continous curves.

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Evidence for Source Structure Effects Caused by the Quasar 3C273 in Geodetic VLBI Data

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Abstract

Analysis of a set of geodetic VLBI experiments conducted by the International Radio Interferometric Surveying and Crustal Dynamics Programs reveals a variation of 1.5 milliarcsecond (mas) in the estimated astrometric position of the quasar 3C273 between 1985 and 1987. Based on dual-frequency (2.3 and 8.4 GHz) hybrid VLBI maps at five epochs, produced from the geodetic experiments themselves, we show that this variation is caused by changes in the extended structure of 3C273 during this period. After modeling the effect of this structure on the Band Width Synthesis delay and delay rate observables, the estimated astrometric position of 3C273 varies by no more than 0.2 mas, and the scatter of the delay residuals on 3C273 is reduced by 8%. This analysis also shows that global astrometry combined with hybrid mapping is able to detect and measure apparent motions of source components with respect to the global astrometric frame, thus providing a way to identify stable components in complex extragalactic radio sources.

1 Introduction

At the milliarcsecond scale, most of the extragalactic radio sources exhibit spatially extended structures that are variable in both time and frequency. Such radio structures set limits on the accuracy of source positions determined with VLBI astrometry unless their effects can be accounted for. Radio source structure effects are modeled by referring the astrometric position of a source to a specific feature of its morphology, generally the source core, after its brightness distribution has been determined. The algorithm to apply such modeling to the Band Width Synthesis (BWS) delays and delay rates observed in VLBI geodesy and astrometry has been described by Charlot (1990a). This algorithm is used below to study the case of the quasar 3C273 whose extended and variable brightness distribution is suspected to cause significant source structure effects (Ma and Shaffer 1991, Herring *et al.* 1991, Jacobs *et al.* 1993). Indeed, these effects may significantly affect the global geodetic and astrometric solutions, because 3C273 was one of the sources most observed by the International Radio Interferometric Surveying (IRIS) network and the Crustal Dynamics Program (CDP) until 1988 for monitoring Earth orientation and plate tectonic motions (e.g. Ma *et al.* 1990).

For the purpose of studying source structure effects caused by 3C273, dual-frequency (8.4 and 2.3 GHz) hybrid VLBI maps of 3C273 at five epochs between May 1985 and March 1987 have been produced (Sect. 2). These maps were made from data of geodetic VLBI experiments conducted by CDP. Section 3 investigates radio source structure effects in selected IRIS and CDP experiments carried out at epochs close to the epochs of our maps. In this analysis, particular attention is paid to the stability with time of the astrometric position of 3C273 and to the magnitude of the post-fit residuals on 3C273. We discuss the improvement in the position stability and the decrease of the post-fit residuals when modeling the structure of 3C273 with the hybrid maps obtained, as well as the ability of global astrometry to detect and measure apparent motions of quasar inner jet components with respect to the global extragalactic frame.

2 Dual-frequency hybrid VLBI maps of 3C273

The VLBI data used to map 3C273 were acquired during five dual-frequency (2.3 and 8.4 GHz) CDP geodetic experiments conducted between 1985.4 and 1987.2 on a North-Pacific network (Mojave, Vandenberg, Hatcreek, Gilcreek, Kauai, Kashima). Such experiments are shown to provide valuable maps despite the limited u-v coverage and the incomplete calibration information (CHARLOT 1990b). These data have been analyzed with the Caltech VLBI package to produce the hybrid maps shown in Fig. 1.

The quasar 3C273 is a typical core-jet radio source with the core D located on the eastern side of the structure and jet components moving away from the core at position angles between $-100°$ and $-130°$ (see Fig. 1). Since 1980, seven superluminal components (C2, C3, C4, C5, C7, C8, C9) with apparent velocities between 0.59 mas/yr and 1.20 mas/yr have been detected with VLBI (UNWIN *et al.* 1985, COHEN *et al.* 1987, ZENSUS *et al.* 1988, 1990, KRICHBAUM *et al.* 1990). The identification of these components in our maps, as well as their proper motions, is discussed by CHARLOT (1992).

At 8.4 GHz, the jet of 3C273 is detected up to $\sim$ 10 mas from the core and its brightest feature is the recently ejected component C8. The first epoch map (1985.37) does not show the weak emission located 6-10 mas from the core because this map has a lower dynamic range. At 2.3 GHz, the structure of 3C273 consists of three emission regions labelled R1, R2 and R3, following the notation of ZENSUS *et al.* (1988). Region R1 is identified with component C2, region R2 contains the components C6, C5, C4 and C3, and region R3 contains the components D, C8 and C7. Comparing flux densities at 2.3 and 8.4 GHz is useful to determine the spectral indices along the jet and to study their variations with time (see CHARLOT 1993).

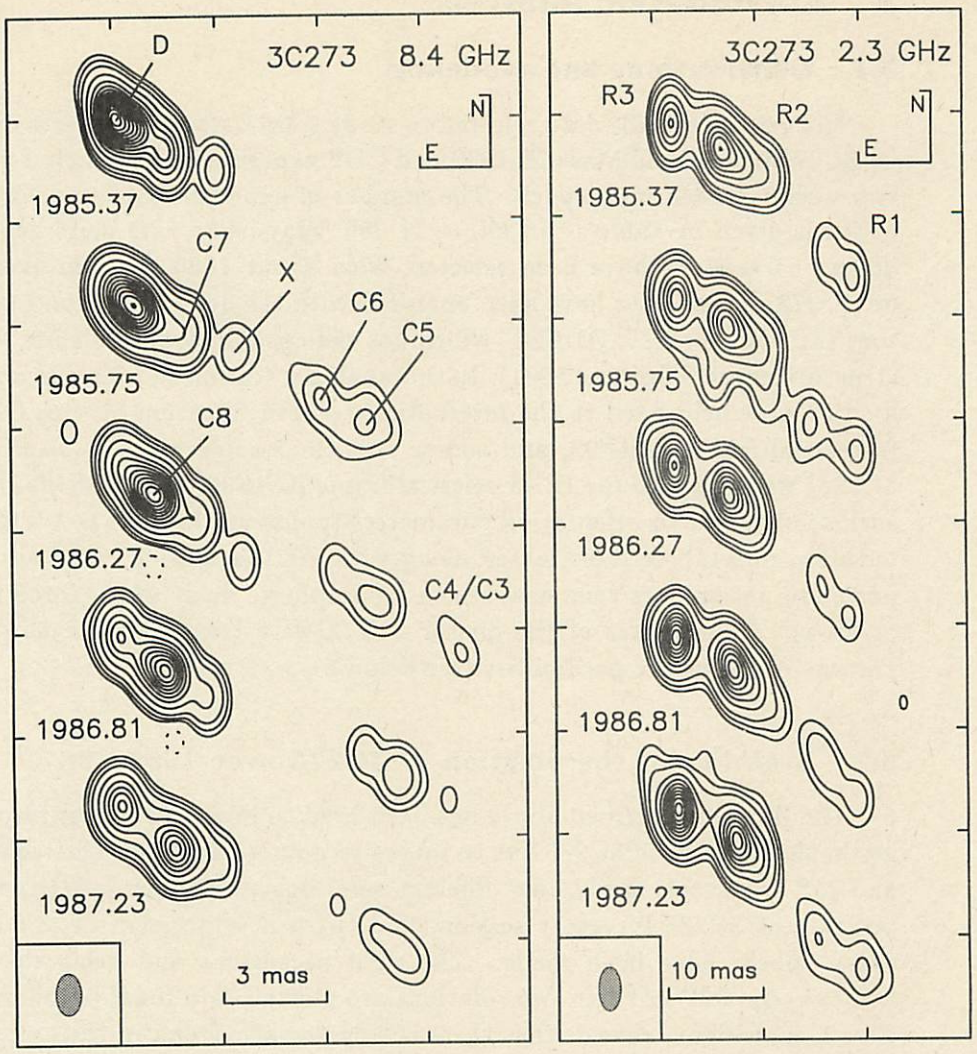


Figure 1: 8.4 and 2.3 GHz hybrid VLBI maps of 3C273 at five epochs. The maps are displaced vertically in time order and are aligned horizontally on the easternmost component D. The beam size is 1.2×0.7 mas with PA $= 0°$ at 8.4 GHz and 4.5×2.2 mas with PA $= 0°$ at 2.3 GHz. Contour levels are drawn at 0.09, 0.18, 0.36, 0.90, 1.8, 2.7, 3.6, 4.5, 5.4, 6.3, 7.2, 8.1, 9.0, 9.9 and 10.8 Jy/beam at 8.4 GHz, and at 0.15, 0.3, 0.6, 1.5, 2.5, 3.5, 4.5, 5.5, 6.5, 7.5, and 8.5 Jy/beam at 2.3 GHz. The peak brightness is 11.4 Jy/beam at 8.4 GHz and 9.0 Jy/beam at 2.3 GHz.

Table 1: Geodetic VLBI data analyzed

Data span	Number of experiments		
	IRIS	CDP	Total
85/05/04 – 85/05/30	6	4	10
85/09/15 – 85/10/15	7	2	9
86/03/25 – 86/04/23	6	4	10
86/10/09 – 86/11/07	6	7	13
87/03/10 – 87/04/08	7	2	9

3 Astrometric analysis

3.1 Observations and modeling

The geodetic VLBI data selected to study source structure effects caused by 3C273 include all Mark III IRIS and CDP experiments conducted within two weeks of each map epoch. The number of experiments found for each epoch is given in Table 1. In all, $\sim$ 27 000 delay-delay rate pairs acquired during 51 sessions have been selected, with about 1600 of them observed on 3C273. These data have been analyzed with the Jet Propulsion Laboratory (JPL) software MODEST, which has the capability of modeling source structure effects (SOVERS 1991). In this analysis, station coordinates and velocities were held fixed to the International Earth Rotation Service (IERS) terrestrial frame ITRF92, and source coordinates (except the position of 3C273) were fixed to the IERS celestial frame ICRF92 (see IERS1993). For each session, Earth orientation parameters (polar motion, UT1−UTC, and nutation offsets) were estimated along with station-specific clock and troposphere parameters (one new zenith tropospheric delay every three hours of data). Coordinates of the quasar 3C273 were treated either as global parameters or as arc parameters (see below).

3.2 Stability of the position of 3C273 over 1985-1987

The dataset described above has been used to investigate possible changes in the position of 3C273 due to source structure variations between 1985 and 1987. For this study, two different solutions which estimate (a) a new position of 3C273 for every session, and (b) a new position of 3C273 for every epoch, have been made. The right ascensions and declinations of 3C273 estimated in these two solutions are plotted as a function of time in Fig. 2. This figure reveals that there is a systematic trend in the estimated positions of 3C273. Both the right ascension and declination of 3C273 are shown to smoothly decrease until 1986.8 and to increase afterwards. This trend is most obvious in solution (b) because uncertainties in the position estimates are smaller. It is likely that this systematic behavior be caused by variations in the 8.4 GHz structure of 3C273. Indeed, the ejection of the bright jet component C8 (see Fig. 1) moves the centroid of the brightness distribution away from the core D, thus causing the right ascension and declination of 3C273 to decrease, consistently with the trend observed until 1986.8 in Fig. 2. After 1986.8, component C8 fades so that the centroid of the structure tends back to the core towards increasing right ascension and declination, also in agreement with the results for epoch 1987.23 in Fig. 2.

To confirm that this behavior is actually due to structure variations, an analysis which model source structure effects in the BWS delays and delay rates observed on 3C273 has been carried out. These effects were calculated for each epoch of data by using the dual-frequency VLBI maps in Fig. 1, with the astrometric position of 3C273 referred to the core D. The results of this analysis are plotted in Fig. 3 in terms of right ascension and declination estimates for two solutions similar to solutions (a) and (b) above. These results indicate that the position of the core of 3C273 is stable with respect to the global astrometric frame, and thus confirm that the systematic trend seen in Fig. 2 is indeed caused by source structure effects. By comparing

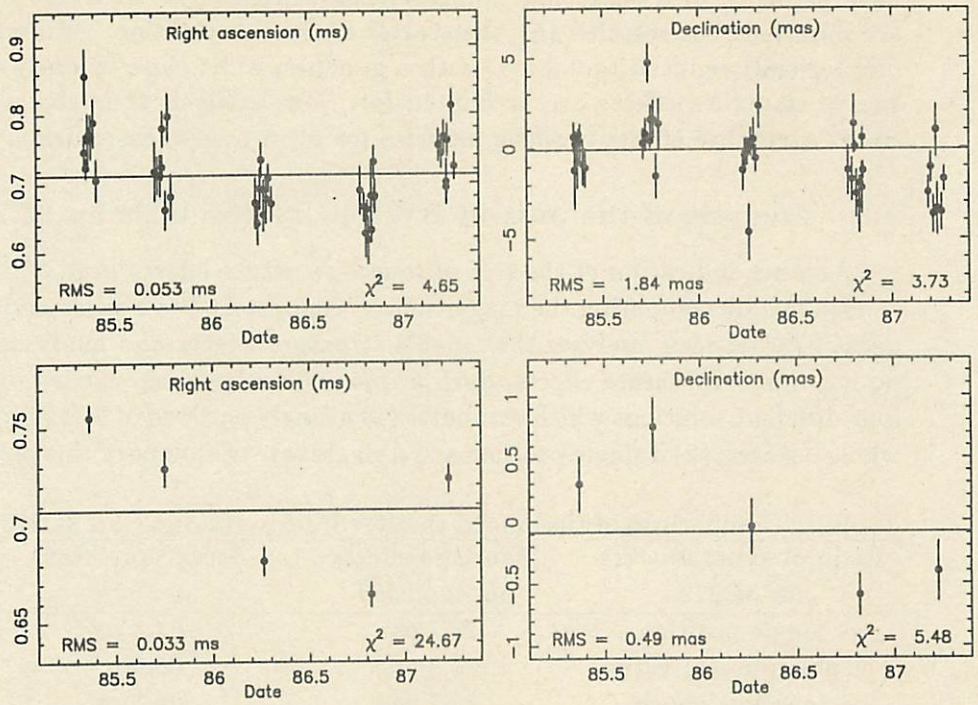


Figure 2: Estimated right ascension and declination of 3C273 as a function of time when source structure effects are not modeled. The top and bottom pictures are for solutions (a) and (b), respectively (see text). In these plots, the zero right ascension and declination refers to the position: α =12 hr 29 min 6.699 s, $\delta = 2^\circ\ 3'\ 8.599''$. The scatter of the positions (rms) and the goodness of fit with respect to the mean position are given at the bottom of each plot.

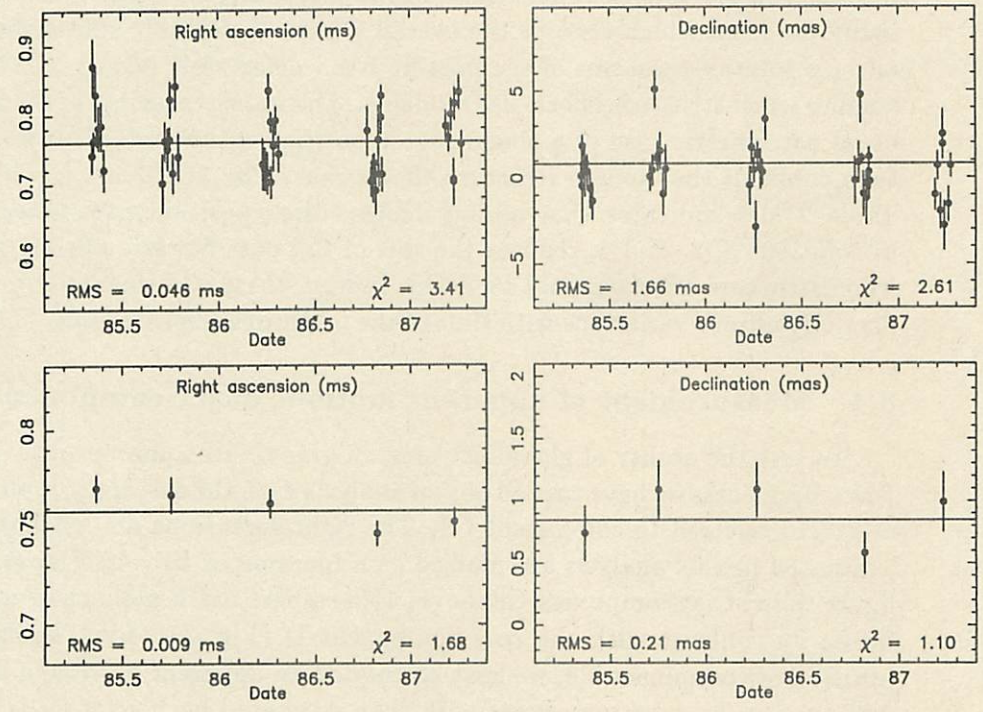


Figure 3: Estimated right ascension and declination of 3C273 as a function of time when source structure effects are modeled with the core D as the astrometric reference point. See Fig. 2 for details.

the scatter (rms) of the individual position estimates in Figs. 2 and 3, we have evidence of a significant improvement when source structure effects are modeled. For solution (b), the scatter of the five positions estimated is dramatically reduced to 0.2 mas with a goodness of fit close to unity when source structure effects are accounted for. Our analysis thus shows that source structure effects must be modeled for ultra-precise astrometry.

3.3 Analysis of the post-fit BWS delay residuals on 3C273

Another indication of the role of source structure effects in 3C273 data is obtained by comparing the magnitude of the post-fit BWS delay residuals on 3C273 between analyses that model structure effects and analyses that do not model structure effects. Such a comparison has been carried out for four different solutions which estimates (1) a single position of 3C273 for the whole dataset; (2) a single position and a single rate of change of this position

Table 2: Comparison of the rms of the BWS delay residuals on 3C273

Estimated parameters for 3C273	Structure effects not modeled	Structure effects modeled
1 single position	72.7 ps	67.0 ps
1 position + 1 rate	71.8 ps	66.9 ps
1 position/epoch	70.7 ps	66.8 ps
1 position/session	69.1 ps	66.0 ps

for the whole dataset; (3) a new position for every epoch; and (4) a new position for every session. Table 2 gives the rms of the post-fit delay residuals on 3C273 for these four solutions. Observations with residuals larger than 2.5 times their uncertainties (~3% of the total number of observations) are not considered in this comparison because some of these observations, generally in the low visibility region of the u-v plane, have structure effects badly modeled which corrupt the overall statistics. Table 2 shows that for all four solutions the rms of the post-fit BWS delay residuals on 3C273 are smaller when structure effects are modeled. The improvement is of 8% in the usual astrometric case of a single source position estimated. This analysis then confirms that source structure effects caused by 3C273 are significant. Table 2 also indicates that adding more source position parameters like in solutions 2, 3, and 4, reduces the rms of the post-fit residuals on 3C273 when structure effects are not modeled. Indeed, these additional parameters partially absorb variations with time of the brightness distribution of 3C273.

3.4 Measurement of apparent motions of jet components

To test the ability of global astrometry to measure apparent motions of jet components, we have carried out an analysis with the astrometric position of 3C273 referred to component C8. The right ascensions and declinations estimated in this analysis are plotted as a function of time in Fig. 4. This figure shows that component C8 moves with respect to the global astrometric frame by contrast with the core component D (Fig. 3). By tracking the position of component C8, we have calculated an apparent motion of 0.84 ± 0.09 mas/yr in good agreement with that estimated by KRICHBAUM *et al.*

(1990) from data at several frequencies (0.76 ± 0.05 mas/yr). This shows that global astrometry has enough accuracy to measure apparent motions of jet components when source structures are accounted for in the theoretical model of the BWS delay. Such studies are useful to identify stable core components in complex extragalactic radio sources.

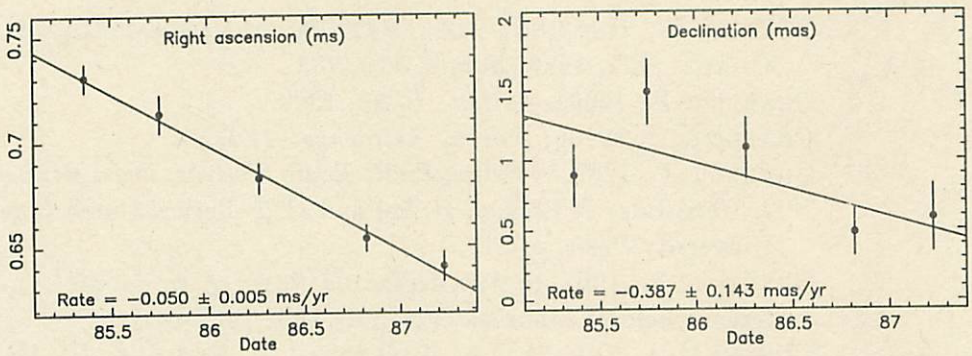


Figure 4: Estimated right ascension and declination of 3C273 as a function of time when source structure effects are modeled with jet component C8 as the astrometric reference point. The rate of change indicated in the bottom of each picture has been calculated by fitting a straight line to the five individual right ascension or declination estimates

4 Conclusion

Analysis of 51 IRIS/CDP geodetic VLBI experiments carried out at five epochs between 1985.4 and 1987.2 shows evidence for source structure effects caused by the quasar 3C273. Such effects produce systematic variations with time in the astrometric position of 3C273. When modeling source structure effects with dual-frequency hybrid VLBI maps at same epochs as our data, these systematic variations disappear and the rms of the post-fit delay residuals on 3C273 becomes 8% smaller. Our analysis also shows that global astrometry can precisely measure superluminal motions in extragalactic radio sources if referring the astrometric source position to moving jet components. In the case of 3C273, the astrometric position is shown to be stable when referred to the source core. The technique presented here can supplement differential VLBI techniques to investigate long term quasar core stability (Bartel *et al.* 1986). In the future, we plan to extend this study by analyzing additional epochs of data on 3C273 and by looking at other sources.

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Standard solution of the 1989 mobile VLBI european campaign

9th Working Meeting on European VLBI for Geodesy and Astrometry

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ABSTRACT

In our Study we have processed the 1989 mobile VLBI european campaign which concerns six new stations in Western Europe. We determined two kinds of solutions :

- A global standard solution (VLBIM89) .

- An experimental solution relative to the determination of the earth rotational parameters.

The results obtained show an internal and external consistency respectively confirmed by the standard deviations of the coordinates (less than one centimeter of the horizontal components and one to two centimeters for the vertical ones) and by a comparative study to solutions found by other groups. Thus, this solutions can be included in the ITRF solution, realization of the international reference frame of the IERS

KEY WORDS : VLBI, terrestrial reference frame, troposphere,

INTRODUCTION

The purpose of the VLBI geodetic experiments is the determination of the station coordinates using a pre-established celestial reference frame. In reality things are less obvious : generally, one determines all parameters during global processing of the observations.

The experiment use the usual geodetic VLBI equipment (data acquisition system MARK III, dual frequency receiver S and X with the hydrogen maser clock).

The data of this campaign are provided by the National Geodetic Survey of the United States. These data are the measures delay and delay rate. The processing of the data was done at IGN using the software Modest of "Jet Propulsion Laboratory" (O.J., Sovers et al, 1991). The solution is obtained by the adjustment of the geometric parameters (the vector linking the two radio-telescopes) to the measured quantities.

DATA

The observed stations network during the 1989 mobile VLBI Euref campaign include new six mobile european stations and six fixed ones - three europeans and three americans.

The lengths of baselines with respect to Wettzell (reference station), vary from 400 km to 9500 km.

A session of observations has an average length of 24 hours. The number of observing stations varies from two to six (table 1).

II- STANDARD GLOBAL SOLUTION

II.1- Choice of adjustment intervals of tropospheric parameters

The usual processing, known in the litterature, adjusts tropospheric parameters on time intervals with variable length sometimes as short as one hour, the case of NGS processing (Abell, MD and al, 1990). In this case, one adjusts on each interval either a constant bias or a linear segment (bias and slope), and can introduce constraints between the parameter values of contignous intervals. This type of adjustment uses an important number of parameters which can bias the solution. To avoid this type of problems during the processing, we tried to reduce the number of parameters to a minimum keeping a physical meaning to the solution. To do this some tests were done as presented in (N. Rebai, 1992).

Finally we chose six hours intervals, limiting the risk of using too many parameters.

II.2- Model Description and computing hypothesis

The final adjustment of the 1989 mobile VLBI european campaign is based on 11778 pairs of delay and delay rates obtained from the observations of the 24 radio-sources. The values of declination and right ascension of the sources are provided by IERS (ICRF 90)

The station coordinates, the clock parameters, and tropospheric parameters are determined in the standard global solution. The others parameters are fixed.

The clock parameters that are adjusted are the same as those used in the preleminary adjustment with two to four clock break by station and by session , except Wettzell which is chosen as reference.

The apriori station coordinates were obtained from the 1989.7 ITRF90 solution.

In our solution, the radio-telescopes coordinates are given in terrestrial reference frame defined as follows :

- the origin is defined by the adoption of the Wettzell station coordinates. This station is chosen arbitrarily and fixed in the global adjustment as it was used for the preliminary solution

- the scale is that of the international system unit "SI" with the choice of the relativistic modelisation in a geocentric system (IERS,1990).

- the orientation is fixed by the adoption of celestial system and IERS rotation parameters of the Earth. These values are the same as those taken in the preliminary solution (N. Rebai and G. Petit, 1991).

- the tropospheric parameters are adjusted for each station by session.

- the nutation model corrections are those published by the IERS

II.3-. Results

The results of the processing of the VLBI campaign data is presented below:

Data of standard global solution	Results delay (ps)	delay rates (fs/s)
Number of parameters adjusted	1305	1305
Percentage of observations excluded	27.7	19
RMS	**89.8**	**78.4**
Chi square	0.92	1.6

The percentage of excluded observations is relatively high for the delay and delay rate and this is due to the transatlantic baselines of IRIS sessions including the mobile stations.

The percentage concerning the sessions dedicated to the mobile VLBI is much smaller indicating good quality measures. The residuals after model adjustments with respect to the measures have normal distribution with RMS of 89.8 ps for the delays and 78.4 fs/s for the delay rates. The residuals of the equivalent delays have an average value of 2.5 cm and are essentially due to the modelisation of the tropospere. The residuals of the delay rates are also dominated by the contribution of the troposphere. The residuals allowed us to reach centimetric accuracy, explained by the standard deviations on the radio-telescopes coordinates (table 2).

The Chi square represents degree of likelihood of the computing hypothesis. If it is close to unity this proves the apriori errors and standard deviation of the coordinates are well estimated. For the delays, the estimator value is close to one and slightly larger for the delay rates. However the delays is the main observable of the VLBI.

II.4- A comparative study

In the goal to evaluate and validate our results, we used a comparative study. The standard global VLBI solution noted (VLBIM89) was compared to two other solutions ITRF90 and NGS. The method of comparison of the two solutions is to consider each solution as a set of coordinates and then compute an adjusted solution to which we compare the two solutions (C. Boucher, 1988). The comparison gives us the residuals and seven parameters (three parameters of translation, three parameters of rotation, and a scale factor).

In all we have done three comparisons between (VLBIM89, ITRF90), (VLBIM89, NGS), and (ITRF90, NGS). From the comparison between VLBIM89 and ITRF90 three important results can be pointed out (table 3) :

- the scale factor is low and to the contrary of the preliminary global solution found in a previous study (N.Rebai, et G. Petit, 1991), but it seems consistent with the ITRF90 solution. This result proves that we have correctly used the relativistic modelisation in a geocentric system.

- The rotation obtained on Z (2.3 mas) can be explained by the inconsistency between the Earth rotation parameters (UT1) and the celestial and

terrestrial systems. This was explained by the IERS annual report for 1989 (Table.II-3, p.II-5).

- the residuals for all stations are low from 1 to 3 cm, except Brest with 7.7 cm (tables.3a, 3b) of the difference. This difference in Brest station can be supported by ITRF90 solution or VLBIM89 solution, because they are compared to the adjusted solution.

To know more about the systematization on Brest station and the rotation on Z, we have done two tests :

- the first consists of comparison of the VLBIM89 and ITRF90 solutions to the NGS solution of the 1989 mobile VLBI european campaign which was carried out by (M.D, Abell, 1990). In fact, this test can prove to us that if the systematization on Z for Brest station will be supported by our solution or by each solution. The results of these comparisons presented in the table below show a relatively important difference on the vertical component of Brest. This difference obtained from the comparison between NGS and ITRF90 is 3 cm and 5 cm between NGS and VLBIM89. So, these results confirm our hypothesis concerning systematization on the vertical component of Brest station, which appears for each solution.

Compared solutions	Residuals on Z for BREST
VLBIM89-ITRF90	7.7 cm
NGS-ITRF90	3 cm
VLBIM89-NGS	5 cm

- the second test is to compute a solution with station coordinates of fixed antenna. The residuals of the solution is 98 ps for delay and 78 fs/s for delay rates. These residuals are not as good as the residuals of the VLBIM89 solution. In fact, when we stopped the rotation of fixed stations we include a systematization effect on the global adjustment, which is absorbed by the adjustment. In this case, we suggest to compute a solution where we resolve the earth rotation parameters to confirm the consistency of our solution with the IERS values.

III-Determination of the Earth rotation parameters

This study completes the first one. We determine the Earth rotation parameters.

III.1- Computing hypothesis

Earth rotation parameters (EOP), as defined in the IERS annuel report (1989), are the parameters that describe the rotation of the International Terrestrial Reference Frame (ITRF) to International Celestial Reference Frame (ICRF) in conjuntion with nutation-precession conventionnel model. These parameters are unforeseeable part of the Earth rotation.

The parameters which will be determined are the position of the pôle (X,Y) in the Celestial system and (UT1-UTC). For our case, we need to know in particular the UT1 variations to verify the consistency of standard global solution VLBIM89 with the IERS.

The computing hypothesis of processing used for this solution (VLBIM89R) are similar to those of the VLBIM89 solution, with all stations fixed (i.e.: no rotation for the terrestrial system).

This determination include only IRIS sessions. The IRIS network contains european and american stations, so we have transatlantic baselines. This network is very usefull in particular for the determination of the Earth rotation parameters. In the case where we have short baselines, the determination of the Earth rotation parameters will not be significant.

III.2- Results

The results of the rotation parameters are presented in (table.6). The variation of UT1 is close to 2.5 mas. This variation is close to the value of the rotation obtained by the comparison between VLBIM89 and ITRF90. This result proves to us a consistency with the apriori value defined by the IERS which is close to 2.1 mas (Annual Report for 1989). This value of 2.1 mas explains in reality the inconsistency between the Earth parameters and celestial and terrestrial systems.

CONCLUSION

The results of the processing of the 1989 mobile VLBI european campaign presented an internal and external consistency.

The residuals of the standard global solution VLBIM89 is 89.8 ps for delay and 78.4 fs/s for delay rates. The standard deviation of the coordinates is close to one centimeter and chi square for the delays is close to unity. These results proves an internal consistency of the standard global solution VLBIM89.

The comparison of our geodetic solution with the ITRF90 solution proves a good accuracy of our results : the standard deviation on the translation component is close to 1 cm and for the residuals maximum value is 7 cm on the vertical component of Brest. For the scale factor there is no significant difference, except a rotation on Z (2.3 mas). This rotation is similar to variations on UT1 (2.5 mas) obtained by VLBIM89R. The value 2.1 explains in fact the inconsistency between the rotation parameters (UT1) and terrestrial and celestial frames (IERS annual report for 1989). This result proves also the internal consistency of our solution VLBIM89.

The comparison between our solution and other solutions: NGS and ITRF90 proves a general systematization on vertical component of Brest station. This systematization can be explained by the bad adjustment of tropospheric parameters or by the insuffisant number of observations. It is very wished to have more observations to understand more this systimatization.

The residuals of all other station coordinates are low and are similar to all solutions. This external consistency proves that the VLBIM89 solution is as good as the ITRF90 and NGS solutions, so it can be included in the ITRF solution, realisation of the International Reference Frame of the IERS.

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Observing session (tu)		Number of stations	Mobile MV3	fixed stations					
from	to			WETTZ	WESTF	MOJAV	RICHM	ONSAL	NOTOP
21/06 18h	22/06 18h	6	HOHEN	X	X	X	X		X
23/06 07h	24/06 07h	3		X					X
24/06 07h	25/06 07h	3		X					X
25/06 10h	26/06 10h	3		X					X
26/06 18h	27/06 18h	6		X	X	X	X		X
								X	
05/07 07h	06/07 07h	3	METSH	X				X	
06/07 07h	07/07 18h	6		X	X	X	X	X	
08/07 07h	09/07 07	3		X				X	
09/07 07h	10/07 07h	3		X				X	
11/07 18h	12/07 18h	6		X	X	X	X		
								X	
30/07 15h	31/07 15h	3	TROMS	X				X	
31/07 18h	01/08 18h	6		X	X	X	X	X	
01/08 20h	02/08 20h	3		X				X	
02/08 20h	03/08 20h	3		X					
18/08 20h	19/08 20h	2	CARNU	X					
19/08 20h	20/08 07h	2		X					
20/08 18h	21/08 18h	5		X	X	X	X		
22/08 07h	23/08 07h	2		X					
30/08 18h	31/08 18h	6	BREST	X	X	X	X		X
01/09 07h	02/09 07h	3		X					X
02/09 07h	03/09 07h	3		X				X	X
04/09 18h	05/09 18h	6		X	X	X			X
12/09 07h	13/09 07h	3	GRASS	X					X
13/09 07h	14/09 07h	3		X					X
14/09 18h	15/09 18h	5		X	X	X	X		
16/09 07h	17/09 07h	2		X					

Table.1 - Observing sessions of the 1989 mobile VLBI european campaign

VLBI MODEST vlbim89.bin: Station coordinates

Station	x (mm) <XY> Shifts: E (mm) <EN>	y (mm) <YZ> N (mm) <NV>	z (mm) <XZ> V (mm) <EV>	Avg. obs. time	Nob
GRASSE EURA				89/ 9/14 10:18	570 648
	4581700837.1 +- 8.7	556126026.6 +- 2.4	4389354392.2 +- 8.5		
	0.38390	0.40547	0.90342		
	0.8 +- 2.2	96.4 +- 2.6	4353.2 +- 11.9		
	0.08482	0.01929	-0.00041		
BREST EURA				89/ 9/ 2 16: 5	678 790
	4228879976.5 +- 7.3	-333104531.9 +- 2.4	4747184051.2 +- 8.0		
	-0.05468	-0.06137	0.88458		
	-23.0 +- 2.5	21.1 +- 2.6	4205.4 +- 10.5		
	-0.02306	-0.01857	0.15370		
CARNUSTY EURA				89/ 8/21 2:44	353 398
	3526418934.7 +- 11.3	-171421280.0 +- 4.0	5294102445.8 +- 15.0		
	-0.02647	-0.10996	0.92533		
	40.6 +- 4.0	-3.9 +- 3.6	4415.3 +- 18.5		
	-0.20748	-0.25737	0.04470		
TROMSONO EURA				89/ 8/ 1 16: 8	660 686
	2102905608.5 +- 5.7	721602939.1 +- 2.8	5958205225.1 +- 12.1		
	0.43026	0.47364	0.77891		
	1.4 +- 2.5	-5.7 +- 3.3	4237.2 +- 13.0		
	0.14731	-0.13102	-0.08833		
METSHOVI EURA				89/ 7/ 8 16:10	682 890
	2890654802.3 +- 6.2	1310296107.9 +- 3.5	5513962290.9 +- 9.9		
	0.70313	0.76542	0.88248		
	-2.4 +- 2.3	-8.1 +- 2.5	4251.5 +- 11.7		
	0.10919	-0.25540	0.07883		
ONSALA60 EURA				89/ 7/26 2:51	1902 2150
	3370606166.1 +- 3.7	711917405.5 +- 1.5	5349830662.0 +- 4.9		
	0.47426	0.41765	0.85439		
	-3.3 +- 1.3	11.0 +- 1.7	23.8 +- 5.9		
	-0.08682	-0.23477	-0.01394		
HOHENFRG EURA				89/ 6/24 20:40	917 1009
	3778217548.9 +- 6.7	698645165.2 +- 2.2	5074056947.9 +- 8.4		
	0.56220	0.54110	0.91691		
	11.9 +- 1.8	-10.0 +- 2.2	4309.4 +- 10.6		
	-0.04963	-0.14054	0.03737		
MOJAVE12 NOAM				89/ 8/ 2 12:43	1579 1919
	-2356170989.0 +- 4.7	-4646755829.0 +- 6.0	3668470573.6 +- 7.1		
	0.30728	-0.69454	0.21920		
	-85.5 +- 4.3	-6.2 +- 5.0	-40.5 +- 8.1		
	0.74884	0.29608	0.34686		
RICHMOND NOAM				89/ 7/28 8:51	1352 1494
	961258080.2 +- 4.5	-5674090005.5 +- 7.9	2740533734.8 +- 6.9		
	-0.38411	-0.59456	0.70191		
	-63.9 +- 4.1	-2.4 +- 4.9	-46.4 +- 9.5		
	0.60159	0.33804	0.31578		
NOTOP EURA				89/ 8/ 1 2:10	1805 1979
	4934563309.9 +- 3.9	1321201151.5 +- 1.4	3806484366.4 +- 3.7		
	0.69709	0.62711	0.86843		
	-18.9 +- 1.0	14.0 +- 1.5	23.6 +- 5.3		
	-0.05269	0.28049	0.01635		
WESTFORD NOAM				89/ 8/ 2 11:36	1887 2247
	1492206679.3 +- 4.3	-4458130468.2 +- 4.8	4296015461.6 +- 6.6		
	-0.43214	-0.67057	0.79519		
	-50.1 +- 3.7	5.9 +- 3.0	-55.7 +- 7.9		
	0.61600	0.41779	0.48744		

Table.2- Standard Global Solution of the 1989 mobile VLBI european campaign -VLBIM89.

indice	designation	TX sigma TX (m)	TY sigma TY (m)	TZ sigma TZ (m)	D (10^{-6}) sigma D	RX (") sigma RX	RY (") sigma RY	RZ (") sigma RZ
1	VLBIM89	0.002 2 0.012	0.060 2 0.009	-0.009 2 0.010	0.0006 2 0.0009	0.0008 2 0.0004	-0.0006 2 0.0005	-0.0023 2 0.0002

Table.3- Seven transformation parameters and standard deviation (VLBIM89, ITRF90)

- a- For VLBIM89

Indice	Designation	Rejet (1)	Residus cartesiens (syst. equatorial, en m) (VX VY VZ)			Residus normalises (syst. equatorial) (NX NY NZ)			Residus cartesiens (syst. local, en m) (VL VP VH)		
1	10002M003CERGA GR VLBI	1	0.002	0.000	-0.010	0.268	0.159	-1.068	0.000	-0.009	-0.005
2	10004M002BREST VLBI	1	0.009	0.000	0.007	1.114	-0.121	0.881	0.000	-0.002	0.011
3	13296M002BUDDON - VLBI	1	-0.002	0.000	-0.001	-0.171	-0.073	-0.049	0.000	0.001	-0.002
4	10302M002TROMSO VLBI	1	0.001	0.000	0.010	0.203	-0.088	0.812	-0.001	0.002	0.009
5	10503M002METSAHOV VLBI	1	-0.002	-0.002	-0.004	-0.363	-0.494	-0.363	-0.001	0.001	-0.005
6	10402S002ONSALA-R VLBI	1	-0.001	0.000	-0.003	-0.280	0.110	-0.532	0.000	-0.001	-0.003
7	14202M002HOHENBUN VLBI	1	0.000	0.000	0.000	-0.016	-0.024	0.020	0.000	0.000	0.000
8	40405S009GOLDSTON VLBI	1	0.000	0.002	-0.002	-0.041	0.289	-0.333	-0.001	-0.001	-0.003
9	40499S001RICHMOND VLBI	1	0.000	0.003	-0.001	-0.070	0.381	-0.214	0.000	0.000	-0.003
10	12717S001NOTO VLBI	1	0.000	0.000	0.000	-0.106	0.115	-0.117	0.000	0.000	-0.001
11	40440S003WESTFORD VLBI	1	0.000	-0.001	0.006	0.003	-0.259	0.881	0.000	0.004	0.005
12	14201S004WETTZELL VLBI	1	-0.001	-0.001	0.005	-0.057	-0.107	0.592	-0.001	0.004	0.004

b- For ITRF90

Indice	Designation	Rejet (1)	Residus cartesiens (syst. equatorial, en m) (VX VY VZ)			Residus normalises (syst. equatorial) (NX NY NZ)			Residus cartesiens (syst. local, en m) (VL VP VH)		
1	10002M003CERGA GR VLBI	1	-0.003	-0.006	0.012	-0.298	-0.716	1.187	-0.006	0.011	0.005
2	10004M002BREST VLBI	1	-0.050	0.005	-0.058	-2.647	0.443	-2.534	0.001	-0.001	-0.077
3	13296M002BUDDON - VLBI	1	0.008	0.003	0.003	0.358	0.238	0.101	0.003	-0.005	0.007
4	10302M002TROMSO VLBI	1	-0.007	0.004	-0.030	-0.473	0.354	-1.421	0.006	-0.006	-0.030
5	10503M002METSAHOV VLBI	1	0.020	0.024	0.026	1.089	1.731	0.980	0.014	-0.011	0.037
6	10402S002ONSALA-R VLBI	1	0.008	-0.005	0.015	0.771	-0.548	1.277	-0.007	0.002	0.017
7	14202M002HOHENBUN VLBI	1	0.001	0.002	-0.001	0.035	0.146	-0.047	0.002	-0.001	0.000
8	40405S009GOLDSTON VLBI	1	0.000	-0.002	0.002	0.057	-0.337	0.333	0.001	0.001	0.003
9	40499S001RICHMOND VLBI	1	0.001	-0.003	0.002	0.097	-0.381	0.275	0.000	0.001	0.004
10	12717S001NOTO VLBI	1	0.008	-0.008	0.009	0.452	-0.691	0.524	-0.010	0.004	0.010
11	40440S003WESTFORD VLBI	1	0.000	0.003	-0.008	-0.005	0.363	-1.007	0.001	-0.004	-0.007
12	14201S004WETTZELL VLBI	1	0.001	0.001	-0.005	0.057	0.107	-0.592	0.001	-0.004	-0.004

Tables.3a, 3b- Residuals of station coordinates (ITRF90, VLBIM89)

DATE	JD	X Pole m arcsec	Y Pole m arcsec	UT1-UTC m sec
1989/ 6/22	2447699.758	221.5+/- 0.5	391.7+/- 0.5	-376.42+/-0.03
		1.1	0.4	**-0.20**
1989/ 6/27	2447704.759	230.8+/- 0.5	375.9+/- 0.5	-383.83+/-0.02
		0.2	-2.1	**-0.23**
1989/ 7/ 7	2447714.731	247.2+/- 0.5	347.0+/- 0.5	-390.29+/-0.02
		0.3	-2.3	**-0.17**
1989/ 7/12	2447719.777	251.9+/- 0.5	333.3+/- 0.5	-395.63+/-0.02
		-1.6	-1.8	**0.05**
1989/ 8/ 1	2447739.742	260.2+/- 0.4	272.3+/- 0.4	-415.83+/-0.01
		0.5	-1.3	**-0.14**
1989/ 8/21	2447759.778	253.8+/- 0.5	210.6+/- 0.5	-439.09+/-0.02
		-0.3	-1.4	**-0.11**
1989/ 8/31	2447769.781	245.6+/- 0.3	183.1+/- 0.4	-449.18+/-0.02
		-0.5	0.8	**-0.13**
1989/ 9/ 5	2447774.755	235.9+/- 0.5	165.8+/- 0.4	-455.96+/-0.02
		-0.6	-0.9	**-0.12**
1989/ 9/15	2447784.718	212.6+/- 0.6	138.6+/- 0.6	-466.58+/-0.03
		0.5	-2.3	**-0.16**

Table. 6- Earth rotation parameters solution VLBIM89R

The Future of Geodetic VLBI

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Introduction

- first geodetic VLBI experiments in the 70ties (Mark II)
- Mark III for geodetic purposes since 79/80 (in Europe: Onsala, Effelsberg)
- basic procedures unchanged (observation - correlation - data analysis)
  only technology has improved (marginally)
- high costs, time consuming
- today: competition with GPS and other satellite techniques

Has geodetic VLBI still a future?

Yes, but:

1. Improvements of the data analysis software are necessary (improve the current models, consistency of the models, further small effects have to be considered)
2. Improvements of the VLBI data analysis procedure are necessary (AI-methods)
3. New technological developments have to be adopted soon (benefits from rapid progress in computer and communication technologies)
4. Advantages of VLBI have to be made clearer
5. Concentration on main tasks, i.e. reference systems, ... (routine monitoring work to be done by GPS)
6. New research topics

*) Topics 1,2,3 will be discussed in more detail in this presentation

Differences between VLBI and other modern geodetic techniques

Advantages of VLBI

- relation to an inertial reference system
- does not depend on satellites
- all three Earth rotation parameters can be independently monitored without additional constraints
- improvement of the nutation/precession model by VLBI
- radio telescopes are 'stable' instruments and cannot be removed
- results for a period of 15 years available

Disadvantages of VLBI

- high costs
- delay between time of observation and availability of results (one week minimum)
- no homogeneous distribution of stations on the Earth
- radio telescopes can be subject to antenna deformation effects (thermal expansion, wind loading)

Other Differences

- VLBI not related to the center of mass of the Earth
- gives neither direct information about the gravity field of the Earth nor on the kinematics of the Moon (like LLR)

Present status of data analysis software

VLBI: most accurate analysis software, in agreement with IERS Standards, needs still further improvements

SLR/LLR: software almost as good as VLBI software, but 'more problems'

GPS: analysis software still in the developing stage, no agreement with IERS Standards yet, high accuracies are obtained due to the high number of stations and observations (quasi-permanent)

1. Improvements of geodetic VLBI software necessary to obtain 1 mm accuracy

(CALC/SOLVE, OCCAM, MODEST, ...)

- improved models for atmospheric path delay
- daily UT1- and pole variations due to the ocean tides
- ocean loading due to ocean tides
- influences of the ocean currents
- influences of source structure on delay observables
- atmospheric loading
- local station displacements (´antenna deformation´ due to thermal expansion, pillar torsion, etc.)
- improved nutation model
- ....
- (minor bugs in CALC/SOLVE to be eliminated)

General important aspects:

- consistency of basic models important (solid Earth, ocean tides, ...)
- if too many parameters (´empirical models´) are solved for there is a danger that the parameters of one model absorb effects of different origins
- phase connection solutions for long baselines might provide a considerable increase in accuracy

2. Improvements of the VLBI data analysis procedure

- many steps of the data analysis can be supported by use of AI methods
  * improvement of program flow
  * streamlining of SOLVE processing

- more data can be processed faster and more cost efficient
  * faster turn around
  * personnel budgets continue to be cut
  * VLBA data

3. Improvements of the technical process

3.1. Data transmission

New high speed broadband communication networks will soon allow transmission of signals at Gbit/sec

* optical fiber (test installations at 1 Gbit/sec already exist)
* communication satellites (ACTS satellite for 'supercomputing networking applications' at up to 800 Mbit/sec to be launched in 1993)

costs are high but tape transport is not needed any more and network specialists are interested in spectacular applications (up to now mostly transmission of moving images or multidimensional signal processing)

--- **direct transmission** of the received signals from the radio telescopes to the correlator or to a central computer for further processing

3.2. Correlation

Software correlation possible (Petit, 1987, 1993) but needs high computer power (MkIII correlator performance equivalent to 1Gflops/baseline, MkIV 10-100 Gflops/baseline). Present massively parallel computers offer simultaneous high speed processing on up to more than 65000 processors, computer peak performance is already in the range of Gflops, but I/O bottleneck

--- **on line software correlation** can be realized within a few years (allows direct feedback to the stations)

3.3 Data analysis (CALC, MODEST, OCCAM, ...)

Many steps can be parallelised, too.
Tools for parallelising FORTRAN programmes already exist.

--- **global solution** in a few seconds

Remarks: Centers on parallel computing in St. Augustin (GMD) and at the Univ. of Cologne.
Cooperation between VLBI experts and computer specialists will start in Nov. 93,

Conclusions

Considerable acceleration and simplification of the VLBI process is possible.
Quasi **on line monitoring** of the Earth rotation parameters and of geodynamic effects is possible with 1 mm accuracy if all technical improvements are adopted and if the present models for data analysis are improved considerably. Finally, lower total costs can be achieved.

Geodetic VLBI has a future as the most precise observing technique for special applications

More on European Stations Velocity

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Summary. Transatlantic baselines including Onsala, Effelsberg or Wettzell have been observed from long time using VLBI. Some of the transatlantic baselines like Westford Wettzell, or Westford Onsala, are the most observed in the VLBI sample. In the last few years a numbers of new antennas become available for geodetic VLBI in Europe, and then European baselines have been observed regularly. From the beginning of 1990 the european baseline have been observed with properly designed experiments, using only european antennas. In this paper the databases with at least two european baselines have been analysed and combined in a global solve solutions. Different reference systems have been used and different constraints are applied in order to text the quality of the reference system. Using Wettzell as origin of the system and applying Nuvel model, no motions was found at Onsala and Madrid. Noto shows a velocity of 6.7 mm/yr towards North. Matera shows 4.7 mm/yr with similar direction. Medicina shows a very small velocity, 2.3 mm/yr.

Introduction

VLBI technique has been developed very fast in the last decade, both for radioastronomy and geodesy and a large number of stations have been involved in this technique, expecially in the northern hemisphere. The european VLBI for geodesy come into air with some delay in respect to the American counterpart, even if Onsala station was involved in geodetic VLBI from the very beginning and Wettzell from 1984 regularly observes at least one hour a day together with Westford in U.S. But the power of VLBI in measuring regional deformations in Europe could be proved only with an european network observing at regular rate. That became a reality when the DSN antenna near Madrid in Spain was available for geodetic VLBI observations, and more antennas, Medicina (near Bologna, in 1987), Noto (in Sicily, in 1989) and Matera (in southern Italy, in 1990) started geodetic VLBI observations. At this point it is possible to talk of a real european VLBI network, even if its geometry, all stations but Madrid aligned in North - South direction, is not the best. Nevertheless the preliminary results from European experiments are the best ever found in geodetic VLBI. In the future, probably during next year, when more antennas will be available (Seimez in Crimea, Ny-Alesund in Spitzbergen island, and Svetloa near St. Petersburg), the european network will have a stronger configurations both from geodetic and geometric point of view.

The very first VLBI experiments including more than two european baselines were observed during 1988. These experiments, called EATL have been designed for measuring the rate of the enlargement of the Atlantic basin. More EATL experiments have been observed during 1989 including in this case Noto, (Medicina was down for resurfacing) and some others using mobile VLBI. Starting from January 1990 purely european experiments were planned and observed. Stations availability and lack of correlating time have limited in the past the experiments numbers, the regularity in time, and the stations participations. In any case from 1990 to 1993 more than 12 European experiments has been performed, with at least five european stations. Baseline analysis has been performed by different groups, using CALC/SOLVE software (Hase and Tornatore, 1991, Campbell et al.,1992, Campbell et al.,1992, Campbell et al.,1993), and Occam (Zarraoa et al., 1991 and 1993), using a subset of the data now available. Ryan et al, 1993, at the IAG assembly at Wiesbaden presented a paper in which the repeatability of the european stations have been computed using the whole set of databases with at least one european stations in it. Using Wettzell as reference site, and considering the direction Wettzell to Onsala fixed, the position uncertainties was computed for all the european stations. The velocity was also computed for Effelsberg, Matera, Medicina, Noto Madrid and Tromso. The last two stations have the vertical velocity constrained to zero. With this reference system and these constraints an averaged (to all stations, including mobile VLBI sites) positions uncertainties was 47 mm, 8 mm and 9 mm for upper, east and north direction respectively. No motions was found for Madrid, Noto shows

7.9 mm/yr, directions 346 deg., Matera 4.1 mm/yr direction 18 deg. and Medicina 2.3 mm/yr direction 48 deg. A discussion following the presentation of the previous paper suggest to be more conservative in the selections of data bases. In fact there is some indications that so many transatlantic experiment could overtake the quality of the european data, in particular considering that few stations (like Wettzell and Onsala) have hundreds of observations (237 for Onsala and 810 for Wettzell at the end of 1992) and some others like Medicina, Noto, Madrid and Matera have only few tenths, or one or two for mobile sites. Moreover a new observations have been made during 1993, very important for site like Noto and even more for Matera with few observations and not regularly distributed in time. That suggests more investigations on the european data, in order to find out the influence of different reference system and/or constraints on the results, and how the Earth Rotation Parameters (Polar Motion and UT1), affect the results.

Data analysis and results

The analysis started at the Bologna computer, a 9000/380 workstation, but was performed at the VLBI group at Goddard Space Flight Center, because when the new Unix version 9.0 was installed on the Bologna workstation some parts of the batch program refused to run. Then I have used databases installed at Goddard, with no modifications on the single arc (single database). That means autoconstraints for clock and atmosphere with one hour break. The databases selected was that with at least four european station except for mobile experiment, where only three european stations have been used when Noto station was in the experiment. Following that selection criteria 27 databases have been used in the analysis. I have then used EATL experiment excluding the ones using HARTRAO antennas in South Africa, Europe experiments and mobile experiments with Noto. The observations span from december 1988 to April 1993. In the global analysis a cutoff of 7 deg. in elevations was adopted. The reason for that was related to the atmosphere models that are very uncertain under this limit. When applied, the earth rotation file for ERP was er885a and nutation file was nut885a.mod, both coming from the Goddard global solution 885. These two files are computed until the end of 1992, for that when used in processing data, the two 1993 Europe experiments had to be excluded from the solution. Three different set of reference system and constraints have been used in the analysis to test differences. The first selection was: use Nuvel model, consider Wettzell fixed to Nuvel and direction from Wettzell to Onsala fixed. The vertical velocity for Madrid (DSS65 station) constrained to zero. In this case we have computed the position and the velocity for all the fixed european stations. The results for velocity are shown on table 1.

Table 1
No upper velocity for DSS65 (Madrid)

	azimuth deg.	hor. vel. mm/yr	sigma mm/yr	upp. vel. mm/yr	sigma mm/yr
MEDICINA	26	1.9	0.3	1.8	1.3
DSS65	109	0.4	0.6		
ONSALA	176	0.6	0.3	-0.04	0.02
NOTO	345	8.7	0.4	11.5	2.6
MATERA	8	7.1	0.6	14.9	3.2

Using ERP from file

	azimuth deg.	hor. vel. mm/yr	sigma mm/yr	upp. vel. mm/yr	sigma mm/yr
MEDICINA	58	2.3	0.3	-4.3	1.3
DSS65	57	1.4	0.3		
ONSALA	176	0.5	0.3	-0.03	0.02
NOTO	350	6.1	0.5	-4.4	2.0
MATERA	9	4.7	0.7	9.0	3.0

Some comments on the results shown on table 1. The constraints of the upper velocity for DSS65 (Madrid) is two week for the geometry of the network and produce unrealistic upper velocities for Noto and Matera. Comparing the upper part of table 1, with the lower part, when Earth Rotation Parameters came from a file, with their errors, the formal error is similar or worst and horizontal velocity became smaller for Noto and Matera, larger for Medicina and DSS65. In any case the results in the upper component of velocity for Noto and Matera suggest a different constraints.

The second selection change the constraints on the velocity, using a constraints on the formal error on the components of the velocity parameter. In this case the error for the vertical component of the velocity have been fixed to 1 mm/yr (or less), and the error on the others components three times larger than that. This constraints have been applied to Onsala and Madrid, in one case and to Madrid, Matera and Noto in a second attempt. The first attempt gave results almost identical to the ones shown on table 1, then on table two is shown the results applying the constraints on Madrid, Matera and Noto.

Table 2
Constraints on velocity errors for DSS65, MATERA and NOTO

	azimuth deg.	hor. vel. mm/yr	sigma mm/yr	upp. vel. mm/yr	sigma mm/yr
MEDICINA	22	1.6	0.3	-1.8	1.1
DSS65	320	1.1	0.5	0.1	1.0
ONSALA	176	0.5	0.3	-0.04	0.02
NOTO	340	7.5	0.3	0.8	0.9
MATERA	10	6.2	0.5	1.0	0.9

Using ERP from file

	azimuth deg.	hor. vel. mm/yr	sigma mm/yr	upp. vel. mm/yr	sigma mm/yr
MEDICINA	58	2.3	0.3	-4.1	1.2
DSS65	56	1.5	0.3	2.0	0.7
ONSALA	176	0.6	0.3	-0.04	0.02
NOTO	349	6.1	0.5	-1.1	0.5
MATERA	9	4.7	0.6	0.9	1.0

The results on table 2 present lower velocity for Noto and Matera and no upper velocity for any european stations, due to constrants used. The solution using ERP from external file produced the same results as previous selection (table 1), excluding the upper component for the velocity. For that reason it seems the more convincing solution.

The third selection presents more differences from the previous ones, and it was introduced to investigate in a better way a possible relative motion between Onsala, Wettzell and Madrid stations. The Nuvel model was used, the velocity baricenter of Wettzell, Onsala and Madrid was fixed to Nuvel model and a constraints to the upper velocity component error for the same stations, as in the second selection. The results are shown in table 3.

This last reference system, considering the formal errors on velocities, and the upper velocity for some stations, seems not very useful for european stations.

It must be noted that for all the different solutions the positions of the fixed european stations show a formal error less than 5 mm, for the upper component and three to four time less for the North and East component.

Finally a baseline solution was performed. In this case we have used the databases until the end of 1992. In table 4 the rate for baseline length and baseline transverse in respect to Wettzell, were shown with relative formal errors.

Table 3
Constraint on velocity baricenter and velocity error

	azimuth deg.	hor. vel. mm/yr	sigma mm/yr	upp. vel. mm/yr	sigma mm/yr
MEDICINA	36	3.0	0.9	0.3	1.8
WETTZELL	7	1.0	0.7	-0.5	0.8
DSS65	118	2.3	1.7	-0.1	0.8
ONSALA	283	1.9	1.3	0.4	0.8
NOTO	3	9.2	1.1	8.1	3.9
MATERA	19	8.8	1.6	12.0	4.0

Using ERP from file

	azimuth deg.	hor. vel. mm/yr	sigma mm/yr	upp. vel. mm/yr	sigma mm/yr
MEDICINA	55	2.6	0.3	-5.0	1.2
WETTZELL	41	0.4	0.2	-1.6	0.5
DSS65	75	1.6	0.2	1.4	0.6
ONSALA	263	1.5	0.2	-0.6	0.6
NOTO	357	6.2	0.5	-5.4	2.1
MATERA	15	5.3	0.7	7.7	3.0

Table 4

		length rate mm/yr	error mm/yr	Wrms of fit mm	transv. rate mm/yr	error mm/yr	Wrms of fit mm
ONSALA	WETTZELL	-0.8	0.7	3.0	-2.4	0.5	2.3
DSS65	WETTZELL	-0.9	0.9	3.7	-1.8	0.5	2.0
MEDICINA	WETTZELL	-1.9	0.6	2.2	-2.1	0.6	2.1
MATERA	WETTZELL	-4.1	1.9	2.9	-4.3	1.5	2.3
NOTO	WETTZELL	-6.7	1.3	4.4	-1.4	1.4	4.4

The same results are shown in fig. 1, where the baseline evolution is plotted. The results are compatible with what found in the previous analysis.

Conclusion

As shown in the previous sections using different reference systems and constraints the final results are different. Moreover using ERP from file, affect not the formal error, as expected, but the results on the velocity. We can consider that the particular geometry of the network, its dimension and configuration, is particularly sensible to ERP, and as already suggested by Ryan et al. 1993, the real error is larger than the formal error, probably by a factor 1.5. More investigations are needed to fully hunderstand this particular effect. In any case adding to purely European experiments some partially European experiments seems to improve the solutions. From this analysis the best result is that presented in the lower part of table 2, where Medicina has an horizontal velocity of 2.3 mm/yr with an error of 0.3 mm/yr, and azimuth direction 58 deg., DSS65 horizontal velocity of 1.5 mm/yr, error of 0.3 mm/yr, and azimuth direction 56 deg., Matera horizontal velocity of 4.7 mm/yr, with an error of 0.6 mm/yr, and azimuth direction of 9 deg., and Noto horizontal velocity 6.1 mm/yr, with an error of 0.5 mm/yr and azimuth direction of 345 deg. Considering the wrms of fit from the baseline solution (table 4 and fig 1)

the Madrid velocity is probably far more uncertain that what we can suppose from its formal error. In conclusion, more data are needed, possibly spanned more regularly in time, to stabilize the results all over the network.

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Table 1

Investigated Sources and Epochs

IAUName	*Name*	*ID*	*z*	*Images*	*Timebase*
0016+731		QSO	1.76	2(X)	1992.34-1993.01
0106+013		QSO	2.11	1(X)	1988.34
0212+735		OVV	2.37	12(X)	1983.4-1992.34
0229+131		QSO	2.065	15(X)	1988.34-1993.13
0300+470	4C47.08	BL Lac		1(X)	1992.15
0420−014		QSO	0.915	1(X)	1992.15
0454−234		QSO		1(X)	1992.15
0528+134		BL?	2.06	6(X)	1988.34-1993.01
0552+398	DA193	QSO	2.365	5(X)	1988.34-1992.19
0727−115		BL?		3(X)	1992.15-1992.92
0851+202	OJ287	BL Lac	0.31	8(X)	1988.34-1992.92
0923+392	4C39.25	QSO	0.699	9(X)	1988.34-1992.34
1226+023	3C273	QSO	0.158	1(X)	1988.34
1308+326		BL Lac	0.99	1(X)	1992.92
1334−127		QSO	0.541	1(X)	1992.15
1404+286	OQ208	QSO	0.077	4(X)	1988.33-1992.15
1606+106		QSO		3(X)	1992.92-1993.13
1611+343	DA406	QSO	1.401	1(X)	1992.15
1641+399		QSO	0.704	1(X)	1988.34
1739+522		QSO	1.375	4(X)	1992.92-1993.01
1741−038		QSO	1.057	10(S),7(X)	1988.95-1993.01
1803+784		BL Lac	0.68	3(S),11(X)	1983.4-1992.34
2007+777		BL Lac	0.34	2(X)	1992.92-1993.13
2121+053		QSO	1.878	2(X)	1988.95-1992.15
2134+004		QSO	1.936	1(X)	1988.34
2145+067		QSO	0.99	1(S),3(X)	1992.27-1993.01
2200+420	BL Lac	BL Lac	0.07	1(X)	1988.34
2234+282		QSO	0.795	3(X)	1988.95-1992.52
2251+158	3C454.3	QSO	0.859	1(X)	1988.34

2. *Summary of first results*

In the following we present comments and maps on some sources from Table 1.

⋆ **1226+023** (3C273)
This "original" quasar (Unwin in Zensus et al. 1990) reveals a core-jet structure which extends from a radius $\leq$ 1 pc to 40 kpc from the nucleus. At least 5 knots move with superluminal velocities along a curved jet (Zensus et al., 1988). The fast convergence of the mapping-process for this source and the good reproduction of the known components underline the astrophysical potential of the geodetic data.

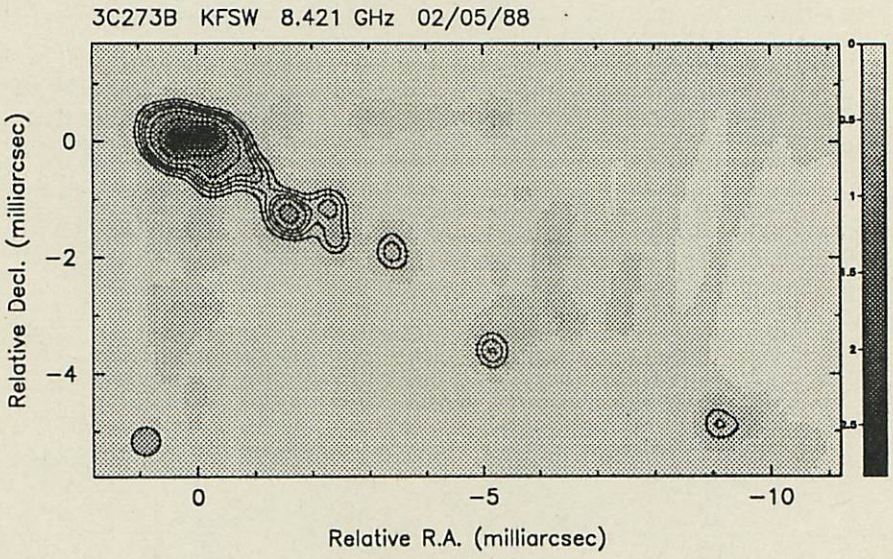


Fig. 2. CLEAN map of 3C273 at 8.4 GHz, May 1988. Contours are 15, 20, 25, 30, 40, 60 and 80% of the peak brightness.

⋆ **0212+735**
This quasar belongs to the "superluminal" sources. 5 GHz observations revealed the existence of at least 3 components in a jet which extends to the east from the core to a distance of approximately 13 mas (Eckart et al. 1987). Our map is in accordance with astronomical observations and investigations of this source. The elongation of the core (seen by Schalinski 1990) as well as the curvature of the jet and the positions of the components can be followed to a distance of about 13 mas from the nucleus.

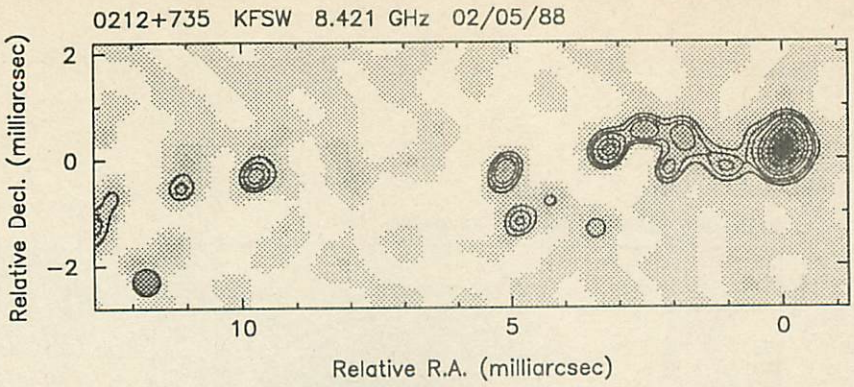


Fig. 3. CLEAN map of 0212+735, May 1988. Contours are 10, 15, 20, 30, 40, 60 and 80 % of the peak brightness.

⋆ 1803+784

The due to the incomplete uv-coverage poor quality of geodetic data (concerning mapping) compared with astronomical data requires a careful calibration with a source whose structure is well-known from high dynamic range observations which is the case e.g. for the blazar 1803+784. For this source informations from nearly all parts of the electromagnetic spectrum exist (from radio to gamma rays). While the structure on the kp-scales is dominated by a north-south structure due to a secondary component 45" south of the core, the mas- and sub-milliarcsecond-structures are dominated by a core-jet structure in east-west direction. A curved jet extends under a position-angle of 261° to a distance of $\sim$ 25 mas. This jet exhibits the coexistence of moving and at least one stationary component. The latter dominates the source-structure at 8.4 GHz and makes this source a useful structure-calibrator and geodetic source since more than ten years now (Witzel et al., 1988).

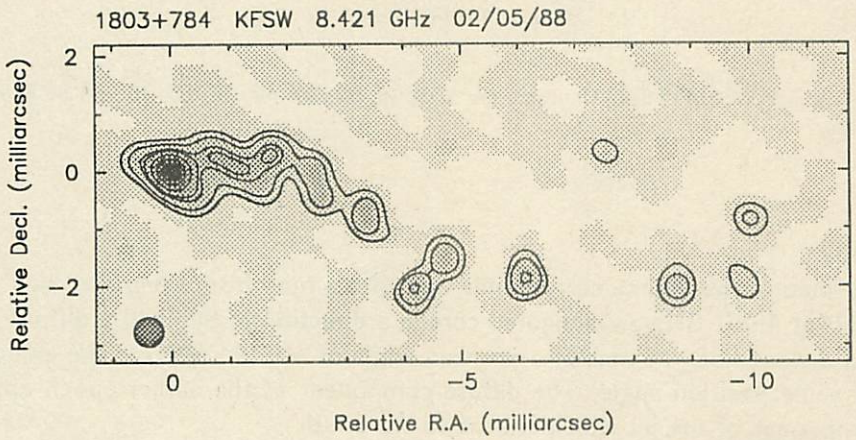


Fig. 4. CLEAN map of 1803+784 at 8.4 GHz. Contours are 5, 10, 20, 25, 40, 60 and 80 % of the peak brightness.

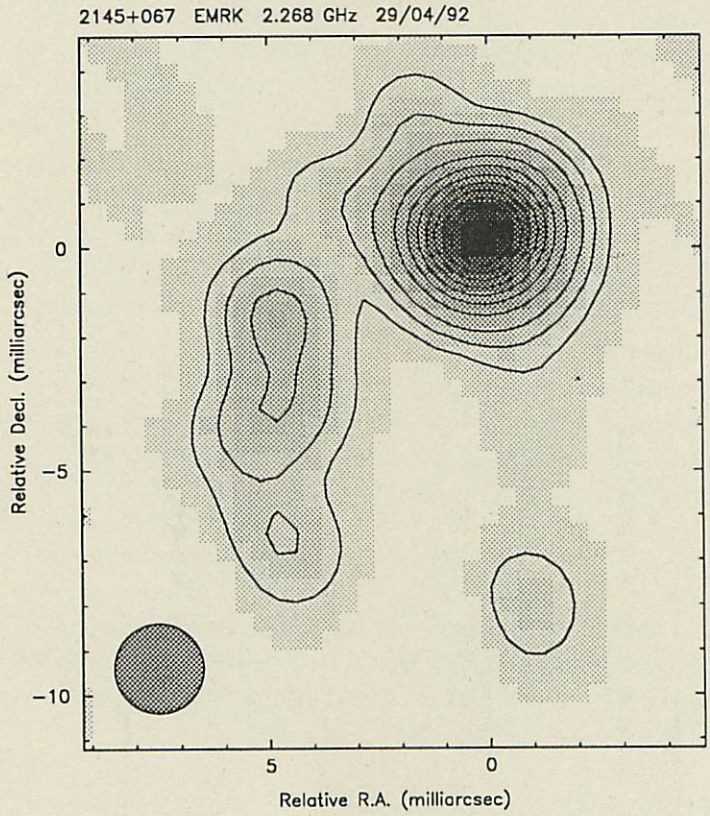


Fig. 5. S-band map of 2145+067. Contours are 2, 5, 10, 20, 30, 40, 50, 60, 70 and 80 % of the peak brightness.

⋆ 2145+067
The S-band map of this source corresponds well with a map from Wehrle et al. (1990) which reveals at 4.991 GHz an elongated core in a direction of 90^o and a diffuse component at a distance of $\sim$ 5 mas at a position angle of $\sim 140^o$. We see the elongated core in the same position-angle. The diffuse component of the earlier epoch appears to be a component of the jet which is bent to the south.

⋆ 2251+158 (3C454.3)
This source shows superluminal motions as well as stationary components. A comparison of our result with a map of I. Pauliny-Toth reveals a good correspondence for this quasar which is of high interest due to its complex and unusual structural changes.

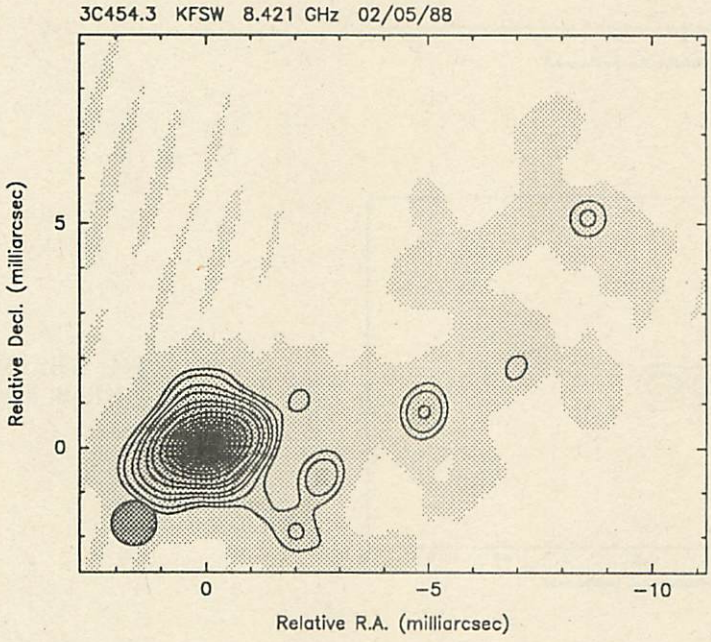
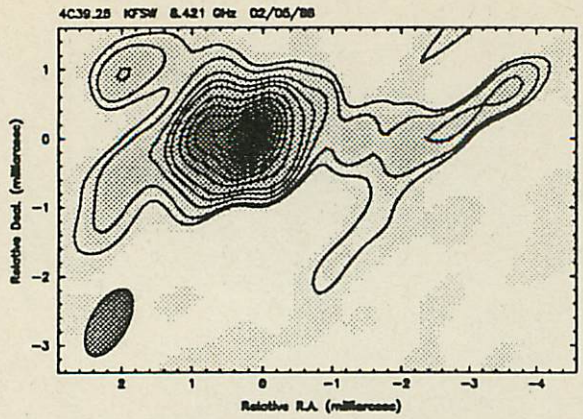


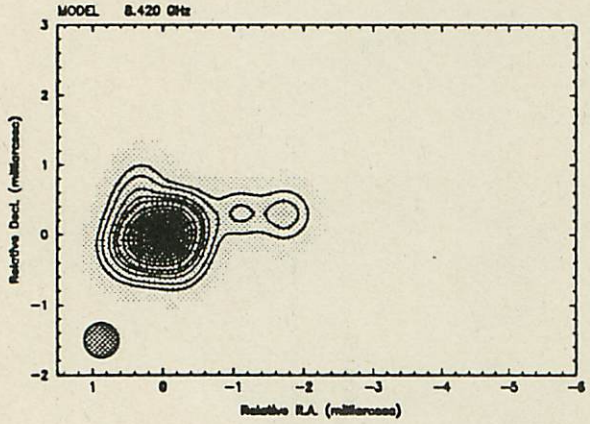
Fig. 6. CLEAN map of 3C454.3, May 1988. Contours are 3.5, 5, 7.5, 10, 15, 20, 30, 40, 50, 60, 70 and 80 % of the peak brightness.

⋆ **0923+392** (4C39.25)

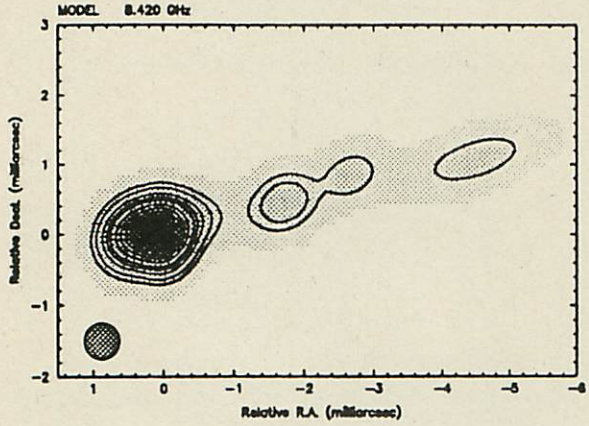
This quasar has been studied with milliarcsecond resolution since the early days of VLBI. Marcaide et al. (1987) showed that none of the known three components has the characteristics usually associated with the cores of compact radio sources. Our 8.4 GHz maps and modelfits show a structure which fits well to the model proposed by Marcaide et al. (1989) of a doubly bent nozzle. Two of the components correspond to these bends, and a third moving component corresponds to a shock travelling down the jet.



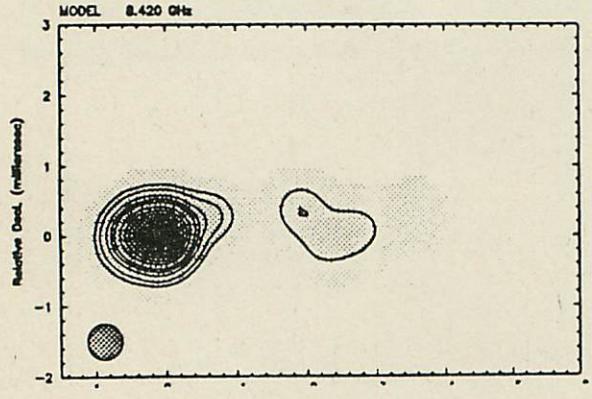
8.4 GHz CLEAN map of 4C39.25 (IRIS, May 1988). FWHM of the restoring beam is 0.5 mas. Contours are 2.5, 5, 10, 15, 20, 30, 40, 50, 60, 70 and 80 % of the peak brightness.



8.4 GHz Modelfit of 4C39.25 (IRIS-S, March 1991).



8.4 GHz Modelfit of 4C39.25 (IRIS-S, September 1991).



8.4 GHz Modelfit of 4C39.25 (IRIS-S, October 1991).

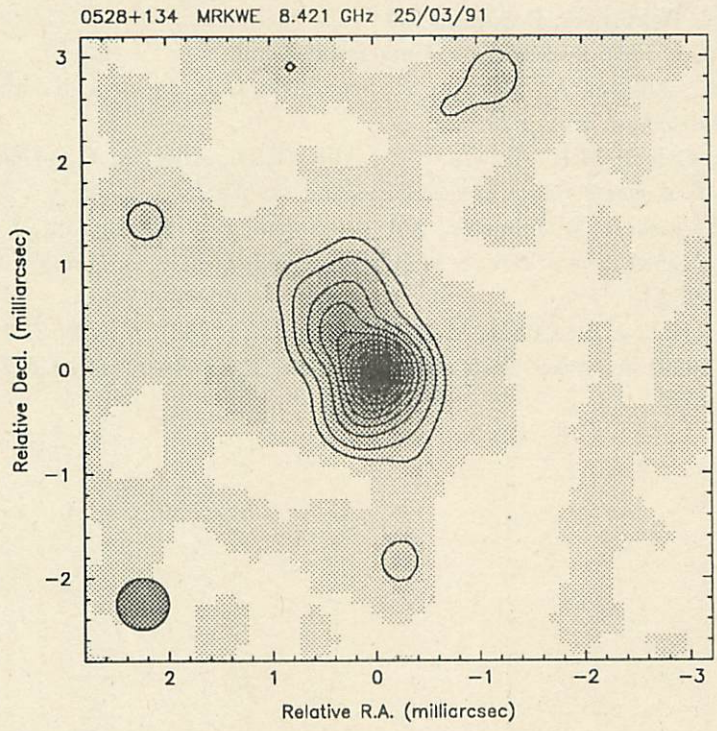


Fig. 8. CLEAN map of 0528+134 at 8.4 GHz. Contours are 5, 10, 20, 30, 40, 50, 60, 70 and 80 % of the peak brightness.

⋆ 0528+134

This source is one of the brightest γ-ray sources in the sky, which makes it particularly interesting for many astronomers. Radio-maps are rare but of great importance to study the physics of such an object. Only one astronomical observation of this source exists but about 60 geodetic observations can be analyzed since this source belongs to the IRIS-S program sources.

Acknowledgements

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Radio source structure and its influence on the accuracy of geodetic VLBI analysis.

Part 2: How to correct for structure effects?

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Abstract: As there is essentially no point like radio source at the milliarcsecond level we need to correct for source structure to reach millimeter accuracy on geodetic parameters. A status report on our source structure software is presented and plans for future developments are exposed.

1 Introduction

At the milliarsecond level, most of the extragalactic radio sources used in geodetic and astrometric experiments have extended structures. It has been shown that effects produced by these structure on the band width synthesis delay are significant (Charlot *et al.* 1988). For a map of 1 mas resolution, a component with 2% intensity located at 10 mas distance from the core affects the delay at the level of 100 ps ($\sim$ 3.5 cm) and a 3% component at the same distance produces effects at the 150 ps ($\sim$ 4.5 cm) level. Therefore for high-precision geodetic VLBI analysis source structure effects must be accounted for.

Although geodetic experiments have a sparse u-v coverage and incomplete calibration information, it has been demonstrated by several VLBI groups that such experiments can provide valuable maps (Charlot 1993, Charlot 1989, Charlot *et al.* 1989, Schalinski *et al.* 1988 a and b, Shaffer *et al.* 1987, Tang *et al.* 1987).

After a short review on the computation of the delay due to source structure, we present the result of tests made to improve the source structure correction-software developed in Bonn. Finally we describe the future plans in order to make this correction available for typical geodetic/astrometric VLBI data analysis.

2 Computation of source structure delay

The effect of source structure on the band width synthesis delay is defined as the fringe phase derivative with respect to angular frequency:

$$\tau_s = \frac{\partial \phi_s}{\partial \omega} \qquad (1)$$

where ϕ_s is the part of fringe phase due to structure effect and ω the observing frequency.

As we are not only interested in phase computation but also in phase variation with respect to frequency, we have expanded equation (1) into two parts and we obtain:

$$\tau_s = \frac{\partial \phi_s}{\partial u}\ \frac{\partial u}{\partial \omega} + \frac{\partial \phi_s}{\partial v}\ \frac{\partial v}{\partial \omega} = \nabla \phi_s\ \frac{B}{\lambda \omega}$$

where $\nabla \phi_s$ is the gradient of phase with respect to (u,v) coordinates and λ the wavelength, B represents the baseline projection onto the plane of sky.

The fringe phase and the derivative of the phase are only functions of the complex visibility function cv(u,v) of the observed source and they are given by:

$$\arctan \phi_s = \frac{Im\ cv(u,v)}{Re\ cv(u,v)}$$

$$\frac{\partial \phi_s}{\partial u} = \frac{\frac{\partial\ Im\ cv(u,v)}{\partial u}\ Re\ cv(u,v) - \frac{\partial\ Re\ cv(u,v)}{\partial u}\ Im\ cv(u,v)}{(Re\ cv(u,v))^2 + (Im\ cv(u,v))^2}$$

with a similar expression for the phase derivative with respect to v.

Finally, the complex visibility function is calculated from the brightness distribution of the source I(x,y) using a two dimensional Fourier Transformation:

$$cv(u,v) = \int\int I(x,y)\ e^{-2\pi\ i\ (ux\ +\ vy)}\ dx\ dy$$

To obtain the delay due to source structure-effects we need the map of delta functions (like those shown in part 1) representing the brightness distribution of the source in the plane of sky (Thomas 1980).

Using this formula the Geodetic Institut of the University of Bonn, jointly with the Max-Planck-Institut für Radioastronomie has developed a software, called 'struc', to compute source structure corrections.

3 Status report on structure correction software 'struc'

First of all we have installed the software STRUC on a work station in order to introduce it into the process of geodetic VLBI analysis, after having tested our computation. The first test consist in checking our results against observed closure quantities.

For source imaging we use the closure phases which are computed by summing the phases around a triangle (ie: a closed loop of baselines). As all effects known today, except source

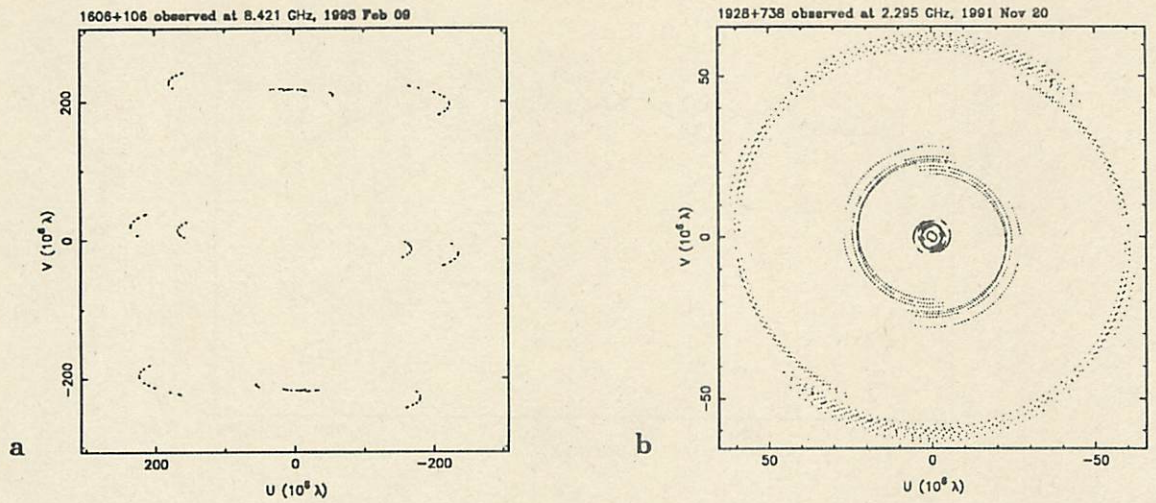


Figure 1: u-v sky coverage **a** for IRIS-S geodetic experiment and **b** for the used observations.

structure effects, are associated with individual antennas, we expect that the non-zero closure quantities are only due to source structure effects (Pearson and Readhead 1984). We have computed the closure phases from the obtained map and compared them with those observed in order to test our computation. Provided that all computations are based on the same experiment and same frequency, the closure phases derived from the map should agree with observed data to within the noise level due to uncertainties in observations and mapping algorithms.

Astrometric observations, performed the 20 november 1991 by the spanish VLBI group on the source 1928+738 at S-band using 7 stations: Effelsberg, Madrid (70m), Haystack and 4 VLBA antennas Fort-Davis, Los Alamos, Kitt Peak, Pietown, are used for the test. We have choose this observations for the sky coverage which is better than for geodetic observations (see fig. 1), and also for the good dynamic range map of 1928+738 at S-band they provide.

Then the bad agreement between observed and computed closure phases obtained first can only be attributed to bugs in the software and not in the poor quality of the map or of the data. Figure 2 show the agreement between computed and measured closure phases after removing some errors in the software.

4 Conclusion

The comparisons between computed and measured closure phases have shown a good agreement and we have to extend this kind of comparisons to the closure delays and closure delay rates in order to improve our software.

The next step would be to introduce the source structure correction in Calc/Solve to be able to analyse in details the influence of source structure on the accuracy of geodetic analysis.

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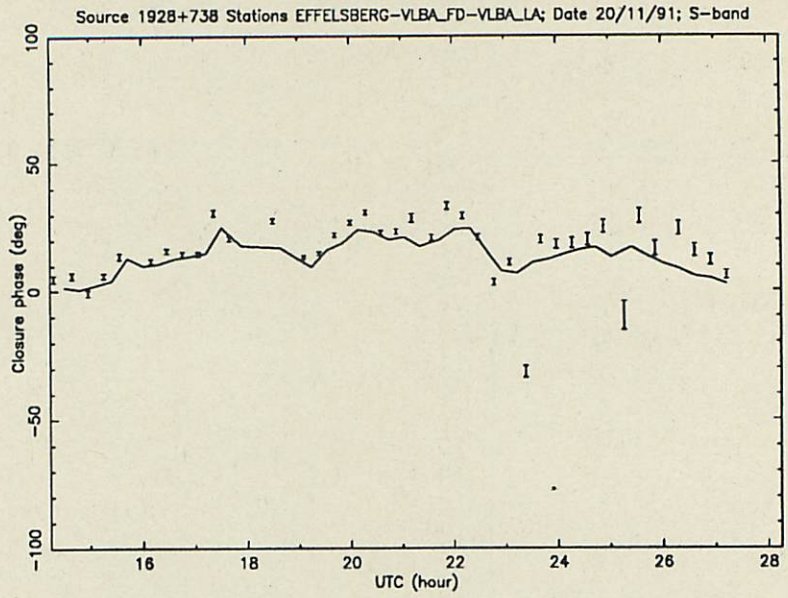


Figure 2: Closure phases with respect to time for the triangle Effelsberg - Fort Davis - Los Alamos. Dots are observed closure phases with their uncertainties and computed closure phases are the continous curves.

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Evidence for Source Structure Effects Caused by the Quasar 3C273 in Geodetic VLBI Data

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Abstract

Analysis of a set of geodetic VLBI experiments conducted by the International Radio Interferometric Surveying and Crustal Dynamics Programs reveals a variation of 1.5 milliarcsecond (mas) in the estimated astrometric position of the quasar 3C273 between 1985 and 1987. Based on dual-frequency (2.3 and 8.4 GHz) hybrid VLBI maps at five epochs, produced from the geodetic experiments themselves, we show that this variation is caused by changes in the extended structure of 3C273 during this period. After modeling the effect of this structure on the Band Width Synthesis delay and delay rate observables, the estimated astrometric position of 3C273 varies by no more than 0.2 mas, and the scatter of the delay residuals on 3C273 is reduced by 8%. This analysis also shows that global astrometry combined with hybrid mapping is able to detect and measure apparent motions of source components with respect to the global astrometric frame, thus providing a way to identify stable components in complex extragalactic radio sources.

1 Introduction

At the milliarcsecond scale, most of the extragalactic radio sources exhibit spatially extended structures that are variable in both time and frequency. Such radio structures set limits on the accuracy of source positions determined with VLBI astrometry unless their effects can be accounted for. Radio source structure effects are modeled by referring the astrometric position of a source to a specific feature of its morphology, generally the source core, after its brightness distribution has been determined. The algorithm to apply such modeling to the Band Width Synthesis (BWS) delays and delay rates observed in VLBI geodesy and astrometry has been described by Charlot (1990a). This algorithm is used below to study the case of the quasar 3C273 whose extended and variable brightness distribution is suspected to cause significant source structure effects (Ma and Shaffer 1991, Herring *et al.* 1991, Jacobs *et al.* 1993). Indeed, these effects may significantly affect the global geodetic and astrometric solutions, because 3C273 was one of the sources most observed by the International Radio Interferometric Surveying (IRIS) network and the Crustal Dynamics Program (CDP) until 1988 for monitoring Earth orientation and plate tectonic motions (e.g. Ma *et al.* 1990).

For the purpose of studying source structure effects caused by 3C273, dual-frequency (8.4 and 2.3 GHz) hybrid VLBI maps of 3C273 at five epochs between May 1985 and March 1987 have been produced (Sect. 2). These maps were made from data of geodetic VLBI experiments conducted by CDP. Section 3 investigates radio source structure effects in selected IRIS and CDP experiments carried out at epochs close to the epochs of our maps. In this analysis, particular attention is paid to the stability with time of the astrometric position of 3C273 and to the magnitude of the post-fit residuals on 3C273. We discuss the improvement in the position stability and the decrease of the post-fit residuals when modeling the structure of 3C273 with the hybrid maps obtained, as well as the ability of global astrometry to detect and measure apparent motions of quasar inner jet components with respect to the global extragalactic frame.

2 Dual-frequency hybrid VLBI maps of 3C273

The VLBI data used to map 3C273 were acquired during five dual-frequency (2.3 and 8.4 GHz) CDP geodetic experiments conducted between 1985.4 and 1987.2 on a North-Pacific network (Mojave, Vandenberg, Hatcreek, Gilcreek, Kauai, Kashima). Such experiments are shown to provide valuable maps despite the limited u-v coverage and the incomplete calibration information (CHARLOT 1990b). These data have been analyzed with the Caltech VLBI package to produce the hybrid maps shown in Fig. 1.

The quasar 3C273 is a typical core-jet radio source with the core D located on the eastern side of the structure and jet components moving away from the core at position angles between $-100°$ and $-130°$ (see Fig. 1). Since 1980, seven superluminal components (C2, C3, C4, C5, C7, C8, C9) with apparent velocities between 0.59 mas/yr and 1.20 mas/yr have been detected with VLBI (UNWIN *et al.* 1985, COHEN *et al.* 1987, ZENSUS *et al.* 1988, 1990, KRICHBAUM *et al.* 1990). The identification of these components in our maps, as well as their proper motions, is discussed by CHARLOT (1992).

At 8.4 GHz, the jet of 3C273 is detected up to $\sim$ 10 mas from the core and its brightest feature is the recently ejected component C8. The first epoch map (1985.37) does not show the weak emission located 6-10 mas from the core because this map has a lower dynamic range. At 2.3 GHz, the structure of 3C273 consists of three emission regions labelled R1, R2 and R3, following the notation of ZENSUS *et al.* (1988). Region R1 is identified with component C2, region R2 contains the components C6, C5, C4 and C3, and region R3 contains the components D, C8 and C7. Comparing flux densities at 2.3 and 8.4 GHz is useful to determine the spectral indices along the jet and to study their variations with time (see CHARLOT 1993).

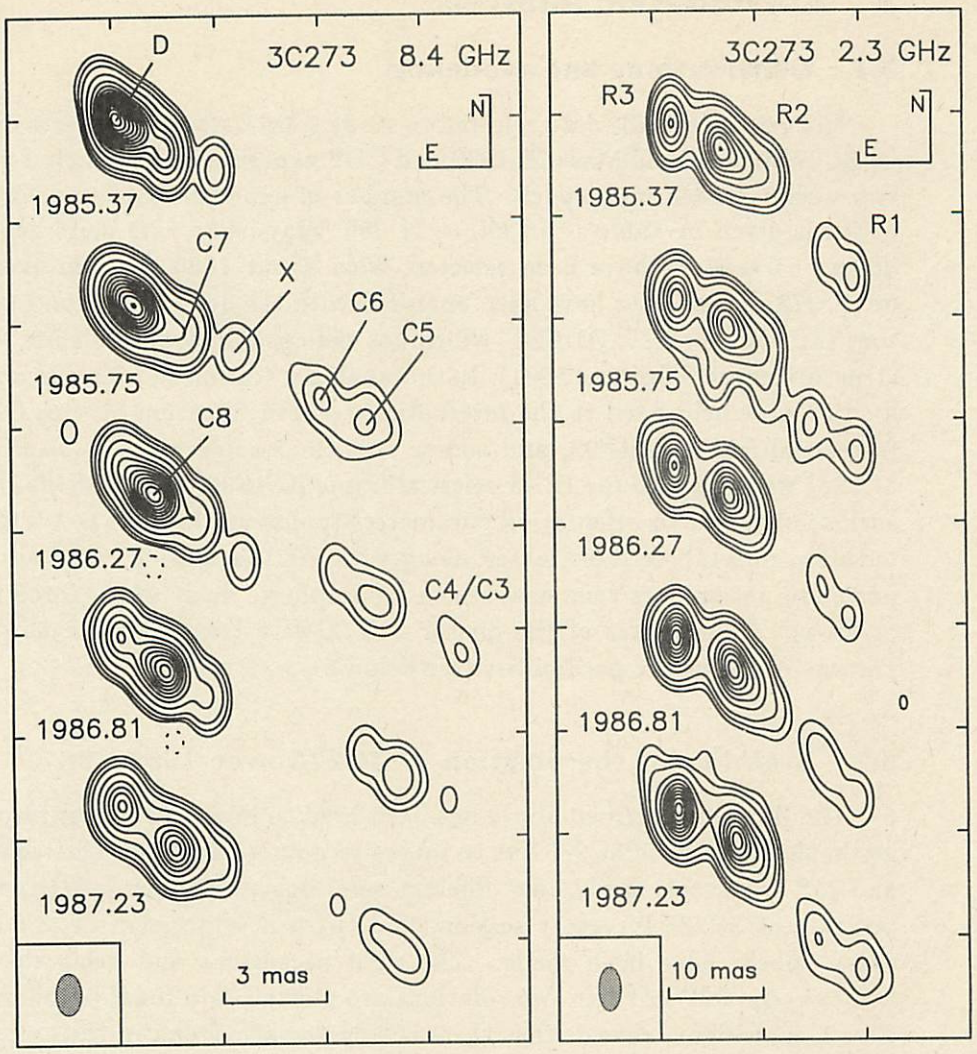


Figure 1: 8.4 and 2.3 GHz hybrid VLBI maps of 3C273 at five epochs. The maps are displaced vertically in time order and are aligned horizontally on the easternmost component D. The beam size is 1.2×0.7 mas with PA $= 0°$ at 8.4 GHz and 4.5×2.2 mas with PA $= 0°$ at 2.3 GHz. Contour levels are drawn at 0.09, 0.18, 0.36, 0.90, 1.8, 2.7, 3.6, 4.5, 5.4, 6.3, 7.2, 8.1, 9.0, 9.9 and 10.8 Jy/beam at 8.4 GHz, and at 0.15, 0.3, 0.6, 1.5, 2.5, 3.5, 4.5, 5.5, 6.5, 7.5, and 8.5 Jy/beam at 2.3 GHz. The peak brightness is 11.4 Jy/beam at 8.4 GHz and 9.0 Jy/beam at 2.3 GHz.

Table 1: Geodetic VLBI data analyzed

Data span	Number of experiments		
	IRIS	CDP	Total
85/05/04 – 85/05/30	6	4	10
85/09/15 – 85/10/15	7	2	9
86/03/25 – 86/04/23	6	4	10
86/10/09 – 86/11/07	6	7	13
87/03/10 – 87/04/08	7	2	9

3 Astrometric analysis

3.1 Observations and modeling

The geodetic VLBI data selected to study source structure effects caused by 3C273 include all Mark III IRIS and CDP experiments conducted within two weeks of each map epoch. The number of experiments found for each epoch is given in Table 1. In all, $\sim$ 27 000 delay-delay rate pairs acquired during 51 sessions have been selected, with about 1600 of them observed on 3C273. These data have been analyzed with the Jet Propulsion Laboratory (JPL) software MODEST, which has the capability of modeling source structure effects (SOVERS 1991). In this analysis, station coordinates and velocities were held fixed to the International Earth Rotation Service (IERS) terrestrial frame ITRF92, and source coordinates (except the position of 3C273) were fixed to the IERS celestial frame ICRF92 (see IERS1993). For each session, Earth orientation parameters (polar motion, UT1−UTC, and nutation offsets) were estimated along with station-specific clock and troposphere parameters (one new zenith tropospheric delay every three hours of data). Coordinates of the quasar 3C273 were treated either as global parameters or as arc parameters (see below).

3.2 Stability of the position of 3C273 over 1985-1987

The dataset described above has been used to investigate possible changes in the position of 3C273 due to source structure variations between 1985 and 1987. For this study, two different solutions which estimate (a) a new position of 3C273 for every session, and (b) a new position of 3C273 for every epoch, have been made. The right ascensions and declinations of 3C273 estimated in these two solutions are plotted as a function of time in Fig. 2. This figure reveals that there is a systematic trend in the estimated positions of 3C273. Both the right ascension and declination of 3C273 are shown to smoothly decrease until 1986.8 and to increase afterwards. This trend is most obvious in solution (b) because uncertainties in the position estimates are smaller. It is likely that this systematic behavior be caused by variations in the 8.4 GHz structure of 3C273. Indeed, the ejection of the bright jet component C8 (see Fig. 1) moves the centroid of the brightness distribution away from the core D, thus causing the right ascension and declination of 3C273 to decrease, consistently with the trend observed until 1986.8 in Fig. 2. After 1986.8, component C8 fades so that the centroid of the structure tends back to the core towards increasing right ascension and declination, also in agreement with the results for epoch 1987.23 in Fig. 2.

To confirm that this behavior is actually due to structure variations, an analysis which model source structure effects in the BWS delays and delay rates observed on 3C273 has been carried out. These effects were calculated for each epoch of data by using the dual-frequency VLBI maps in Fig. 1, with the astrometric position of 3C273 referred to the core D. The results of this analysis are plotted in Fig. 3 in terms of right ascension and declination estimates for two solutions similar to solutions (a) and (b) above. These results indicate that the position of the core of 3C273 is stable with respect to the global astrometric frame, and thus confirm that the systematic trend seen in Fig. 2 is indeed caused by source structure effects. By comparing

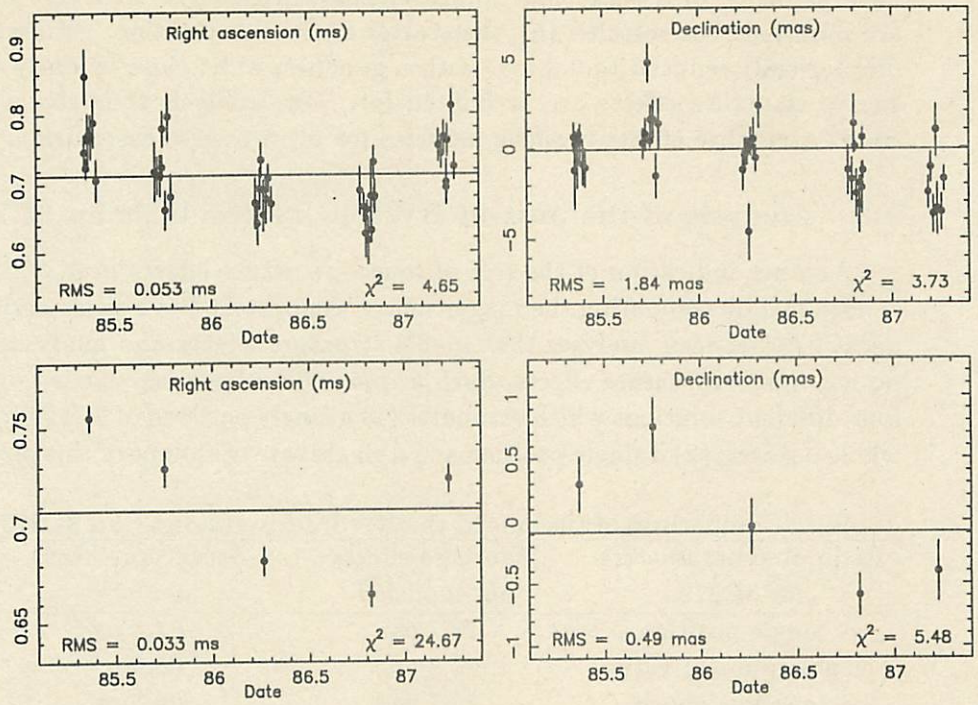


Figure 2: Estimated right ascension and declination of 3C273 as a function of time when source structure effects are not modeled. The top and bottom pictures are for solutions (a) and (b), respectively (see text). In these plots, the zero right ascension and declination refers to the position: α =12 hr 29 min 6.699 s, $\delta = 2^\circ\ 3'\ 8.599''$. The scatter of the positions (rms) and the goodness of fit with respect to the mean position are given at the bottom of each plot.

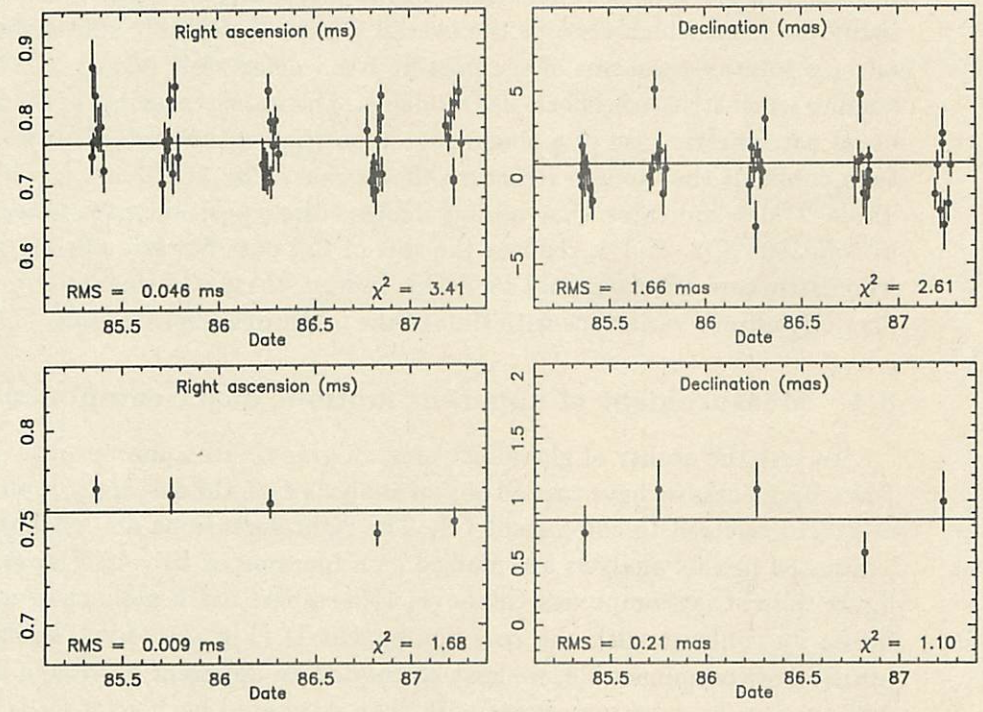


Figure 3: Estimated right ascension and declination of 3C273 as a function of time when source structure effects are modeled with the core D as the astrometric reference point. See Fig. 2 for details.

the scatter (rms) of the individual position estimates in Figs. 2 and 3, we have evidence of a significant improvement when source structure effects are modeled. For solution (b), the scatter of the five positions estimated is dramatically reduced to 0.2 mas with a goodness of fit close to unity when source structure effects are accounted for. Our analysis thus shows that source structure effects must be modeled for ultra-precise astrometry.

3.3 Analysis of the post-fit BWS delay residuals on 3C273

Another indication of the role of source structure effects in 3C273 data is obtained by comparing the magnitude of the post-fit BWS delay residuals on 3C273 between analyses that model structure effects and analyses that do not model structure effects. Such a comparison has been carried out for four different solutions which estimates (1) a single position of 3C273 for the whole dataset; (2) a single position and a single rate of change of this position

Table 2: Comparison of the rms of the BWS delay residuals on 3C273

Estimated parameters for 3C273	Structure effects not modeled	Structure effects modeled
1 single position	72.7 ps	67.0 ps
1 position + 1 rate	71.8 ps	66.9 ps
1 position/epoch	70.7 ps	66.8 ps
1 position/session	69.1 ps	66.0 ps

for the whole dataset; (3) a new position for every epoch; and (4) a new position for every session. Table 2 gives the rms of the post-fit delay residuals on 3C273 for these four solutions. Observations with residuals larger than 2.5 times their uncertainties (~3% of the total number of observations) are not considered in this comparison because some of these observations, generally in the low visibility region of the u-v plane, have structure effects badly modeled which corrupt the overall statistics. Table 2 shows that for all four solutions the rms of the post-fit BWS delay residuals on 3C273 are smaller when structure effects are modeled. The improvement is of 8% in the usual astrometric case of a single source position estimated. This analysis then confirms that source structure effects caused by 3C273 are significant. Table 2 also indicates that adding more source position parameters like in solutions 2, 3, and 4, reduces the rms of the post-fit residuals on 3C273 when structure effects are not modeled. Indeed, these additional parameters partially absorb variations with time of the brightness distribution of 3C273.

3.4 Measurement of apparent motions of jet components

To test the ability of global astrometry to measure apparent motions of jet components, we have carried out an analysis with the astrometric position of 3C273 referred to component C8. The right ascensions and declinations estimated in this analysis are plotted as a function of time in Fig. 4. This figure shows that component C8 moves with respect to the global astrometric frame by contrast with the core component D (Fig. 3). By tracking the position of component C8, we have calculated an apparent motion of 0.84 ± 0.09 mas/yr in good agreement with that estimated by KRICHBAUM *et al.*

(1990) from data at several frequencies (0.76 ± 0.05 mas/yr). This shows that global astrometry has enough accuracy to measure apparent motions of jet components when source structures are accounted for in the theoretical model of the BWS delay. Such studies are useful to identify stable core components in complex extragalactic radio sources.

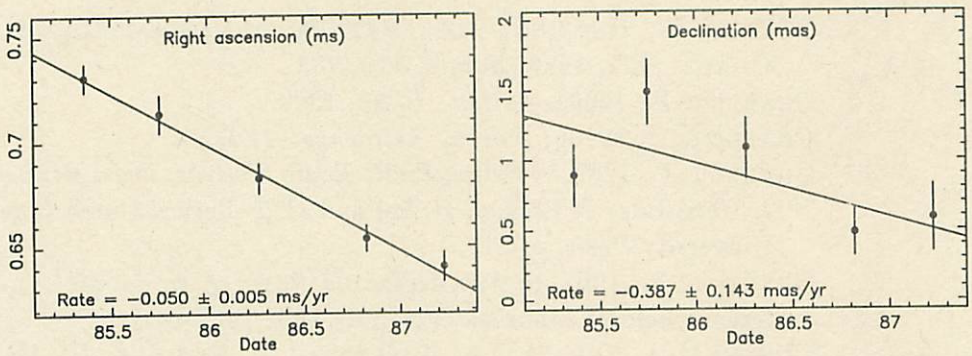


Figure 4: Estimated right ascension and declination of 3C273 as a function of time when source structure effects are modeled with jet component C8 as the astrometric reference point. The rate of change indicated in the bottom of each picture has been calculated by fitting a straight line to the five individual right ascension or declination estimates

4 Conclusion

Analysis of 51 IRIS/CDP geodetic VLBI experiments carried out at five epochs between 1985.4 and 1987.2 shows evidence for source structure effects caused by the quasar 3C273. Such effects produce systematic variations with time in the astrometric position of 3C273. When modeling source structure effects with dual-frequency hybrid VLBI maps at same epochs as our data, these systematic variations disappear and the rms of the post-fit delay residuals on 3C273 becomes 8% smaller. Our analysis also shows that global astrometry can precisely measure superluminal motions in extragalactic radio sources if referring the astrometric source position to moving jet components. In the case of 3C273, the astrometric position is shown to be stable when referred to the source core. The technique presented here can supplement differential VLBI techniques to investigate long term quasar core stability (Bartel *et al.* 1986). In the future, we plan to extend this study by analyzing additional epochs of data on 3C273 and by looking at other sources.

Acknowledgements. The author is indebted to O. J. Sovers for providing the JPL VLBI software MODEST as well as pre-processed data files for the experiments analyzed in this report. He is also grateful to C. Ma for providing the VLBI observations used to map 3C273. The hybrid maps shown here were made with the Caltech VLBI package, mostly written by T. J. Pearson.

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Standard solution of the 1989 mobile VLBI european campaign

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ABSTRACT

In our Study we have processed the 1989 mobile VLBI european campaign which concerns six new stations in Western Europe. We determined two kinds of solutions :

- A global standard solution (VLBIM89) .

- An experimental solution relative to the determination of the earth rotational parameters.

The results obtained show an internal and external consistency respectively confirmed by the standard deviations of the coordinates (less than one centimeter of the horizontal components and one to two centimeters for the vertical ones) and by a comparative study to solutions found by other groups. Thus, this solutions can be included in the ITRF solution, realization of the international reference frame of the IERS

KEY WORDS : VLBI, terrestrial reference frame, troposphere,

INTRODUCTION

The purpose of the VLBI geodetic experiments is the determination of the station coordinates using a pre-established celestial reference frame. In reality things are less obvious : generally, one determines all parameters during global processing of the observations.

The experiment use the usual geodetic VLBI equipment (data acquisition system MARK III, dual frequency receiver S and X with the hydrogen maser clock).

The data of this campaign are provided by the National Geodetic Survey of the United States. These data are the measures delay and delay rate. The processing of the data was done at IGN using the software Modest of "Jet Propulsion Laboratory" (O.J., Sovers et al, 1991). The solution is obtained by the adjustment of the geometric parameters (the vector linking the two radio-telescopes) to the measured quantities.

DATA

The observed stations network during the 1989 mobile VLBI Euref campaign include new six mobile european stations and six fixed ones - three europeans and three americans.

The lengths of baselines with respect to Wettzell (reference station), vary from 400 km to 9500 km.

A session of observations has an average length of 24 hours. The number of observing stations varies from two to six (table 1).

II- STANDARD GLOBAL SOLUTION

II.1- Choice of adjustment intervals of tropospheric parameters

The usual processing, known in the litterature, adjusts tropospheric parameters on time intervals with variable length sometimes as short as one hour, the case of NGS processing (Abell, MD and al, 1990). In this case, one adjusts on each interval either a constant bias or a linear segment (bias and slope), and can introduce constraints between the parameter values of contignous intervals. This type of adjustment uses an important number of parameters which can bias the solution. To avoid this type of problems during the processing, we tried to reduce the number of parameters to a minimum keeping a physical meaning to the solution. To do this some tests were done as presented in (N. Rebai, 1992).

Finally we chose six hours intervals, limiting the risk of using too many parameters.

II.2- Model Description and computing hypothesis

The final adjustment of the 1989 mobile VLBI european campaign is based on 11778 pairs of delay and delay rates obtained from the observations of the 24 radio-sources. The values of declination and right ascension of the sources are provided by IERS (ICRF 90)

The station coordinates, the clock parameters, and tropospheric parameters are determined in the standard global solution. The others parameters are fixed.

The clock parameters that are adjusted are the same as those used in the preleminary adjustment with two to four clock break by station and by session , except Wettzell which is chosen as reference.

The apriori station coordinates were obtained from the 1989.7 ITRF90 solution.

In our solution, the radio-telescopes coordinates are given in terrestrial reference frame defined as follows :

- the origin is defined by the adoption of the Wettzell station coordinates. This station is chosen arbitrarily and fixed in the global adjustment as it was used for the preliminary solution

- the scale is that of the international system unit "SI" with the choice of the relativistic modelisation in a geocentric system (IERS,1990).

- the orientation is fixed by the adoption of celestial system and IERS rotation parameters of the Earth. These values are the same as those taken in the preliminary solution (N. Rebai and G. Petit, 1991).

- the tropospheric parameters are adjusted for each station by session.

- the nutation model corrections are those published by the IERS

II.3-. Results

The results of the processing of the VLBI campaign data is presented below:

Data of standard global solution	Results delay (ps)	delay rates (fs/s)
Number of parameters adjusted	1305	1305
Percentage of observations excluded	27.7	19
RMS	**89.8**	**78.4**
Chi square	0.92	1.6

The percentage of excluded observations is relatively high for the delay and delay rate and this is due to the transatlantic baselines of IRIS sessions including the mobile stations.

The percentage concerning the sessions dedicated to the mobile VLBI is much smaller indicating good quality measures. The residuals after model adjustments with respect to the measures have normal distribution with RMS of 89.8 ps for the delays and 78.4 fs/s for the delay rates. The residuals of the equivalent delays have an average value of 2.5 cm and are essentially due to the modelisation of the tropospere. The residuals of the delay rates are also dominated by the contribution of the troposphere. The residuals allowed us to reach centimetric accuracy, explained by the standard deviations on the radio-telescopes coordinates (table 2).

The Chi square represents degree of likelihood of the computing hypothesis. If it is close to unity this proves the apriori errors and standard deviation of the coordinates are well estimated. For the delays, the estimator value is close to one and slightly larger for the delay rates. However the delays is the main observable of the VLBI.

II.4- A comparative study

In the goal to evaluate and validate our results, we used a comparative study. The standard global VLBI solution noted (VLBIM89) was compared to two other solutions ITRF90 and NGS. The method of comparison of the two solutions is to consider each solution as a set of coordinates and then compute an adjusted solution to which we compare the two solutions (C. Boucher, 1988). The comparison gives us the residuals and seven parameters (three parameters of translation, three parameters of rotation, and a scale factor).

In all we have done three comparisons between (VLBIM89, ITRF90), (VLBIM89, NGS), and (ITRF90, NGS). From the comparison between VLBIM89 and ITRF90 three important results can be pointed out (table 3) :

- the scale factor is low and to the contrary of the preliminary global solution found in a previous study (N.Rebai, et G. Petit, 1991), but it seems consistent with the ITRF90 solution. This result proves that we have correctly used the relativistic modelisation in a geocentric system.

- The rotation obtained on Z (2.3 mas) can be explained by the inconsistency between the Earth rotation parameters (UT1) and the celestial and

terrestrial systems. This was explained by the IERS annual report for 1989 (Table.II-3, p.II-5).

- the residuals for all stations are low from 1 to 3 cm, except Brest with 7.7 cm (tables.3a, 3b) of the difference. This difference in Brest station can be supported by ITRF90 solution or VLBIM89 solution, because they are compared to the adjusted solution.

To know more about the systematization on Brest station and the rotation on Z, we have done two tests :

- the first consists of comparison of the VLBIM89 and ITRF90 solutions to the NGS solution of the 1989 mobile VLBI european campaign which was carried out by (M.D, Abell, 1990). In fact, this test can prove to us that if the systematization on Z for Brest station will be supported by our solution or by each solution. The results of these comparisons presented in the table below show a relatively important difference on the vertical component of Brest. This difference obtained from the comparison between NGS and ITRF90 is 3 cm and 5 cm between NGS and VLBIM89. So, these results confirm our hypothesis concerning systematization on the vertical component of Brest station, which appears for each solution.

Compared solutions	Residuals on Z for BREST
VLBIM89-ITRF90	7.7 cm
NGS-ITRF90	3 cm
VLBIM89-NGS	5 cm

- the second test is to compute a solution with station coordinates of fixed antenna. The residuals of the solution is 98 ps for delay and 78 fs/s for delay rates. These residuals are not as good as the residuals of the VLBIM89 solution. In fact, when we stopped the rotation of fixed stations we include a systematization effect on the global adjustment, which is absorbed by the adjustment. In this case, we suggest to compute a solution where we resolve the earth rotation parameters to confirm the consistency of our solution with the IERS values.

III-Determination of the Earth rotation parameters

This study completes the first one. We determine the Earth rotation parameters.

III.1- Computing hypothesis

Earth rotation parameters (EOP), as defined in the IERS annuel report (1989), are the parameters that describe the rotation of the International Terrestrial Reference Frame (ITRF) to International Celestial Reference Frame (ICRF) in conjuntion with nutation-precession conventionnel model. These parameters are unforeseeable part of the Earth rotation.

The parameters which will be determined are the position of the pôle (X,Y) in the Celestial system and (UT1-UTC). For our case, we need to know in particular the UT1 variations to verify the consistency of standard global solution VLBIM89 with the IERS.

The computing hypothesis of processing used for this solution (VLBIM89R) are similar to those of the VLBIM89 solution, with all stations fixed (i.e.: no rotation for the terrestrial system).

This determination include only IRIS sessions. The IRIS network contains european and american stations, so we have transatlantic baselines. This network is very usefull in particular for the determination of the Earth rotation parameters. In the case where we have short baselines, the determination of the Earth rotation parameters will not be significant.

III.2- Results

The results of the rotation parameters are presented in (table.6). The variation of UT1 is close to 2.5 mas. This variation is close to the value of the rotation obtained by the comparison between VLBIM89 and ITRF90. This result proves to us a consistency with the apriori value defined by the IERS which is close to 2.1 mas (Annual Report for 1989). This value of 2.1 mas explains in reality the inconsistency between the Earth parameters and celestial and terrestrial systems.

CONCLUSION

The results of the processing of the 1989 mobile VLBI european campaign presented an internal and external consistency.

The residuals of the standard global solution VLBIM89 is 89.8 ps for delay and 78.4 fs/s for delay rates. The standard deviation of the coordinates is close to one centimeter and chi square for the delays is close to unity. These results proves an internal consistency of the standard global solution VLBIM89.

The comparison of our geodetic solution with the ITRF90 solution proves a good accuracy of our results : the standard deviation on the translation component is close to 1 cm and for the residuals maximum value is 7 cm on the vertical component of Brest. For the scale factor there is no significant difference, except a rotation on Z (2.3 mas). This rotation is similar to variations on UT1 (2.5 mas) obtained by VLBIM89R. The value 2.1 explains in fact the inconsistency between the rotation parameters (UT1) and terrestrial and celestial frames (IERS annual report for 1989). This result proves also the internal consistency of our solution VLBIM89.

The comparison between our solution and other solutions: NGS and ITRF90 proves a general systematization on vertical component of Brest station. This systematization can be explained by the bad adjustment of tropospheric parameters or by the insuffisant number of observations. It is very wished to have more observations to understand more this systimatization.

The residuals of all other station coordinates are low and are similar to all solutions. This external consistency proves that the VLBIM89 solution is as good as the ITRF90 and NGS solutions, so it can be included in the ITRF solution, realisation of the International Reference Frame of the IERS.

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Observing session (tu)		Number of stations	Mobile MV3	fixed stations					
from	to			WETTZ	WESTF	MOJAV	RICHM	ONSAL	NOTOP
21/06 18h	22/06 18h	6	HOHEN	X	X	X	X		X
23/06 07h	24/06 07h	3		X					X
24/06 07h	25/06 07h	3		X					X
25/06 10h	26/06 10h	3		X					X
26/06 18h	27/06 18h	6		X	X	X	X		X
								X	
05/07 07h	06/07 07h	3	METSH	X				X	
06/07 07h	07/07 18h	6		X	X	X	X	X	
08/07 07h	09/07 07	3		X				X	
09/07 07h	10/07 07h	3		X				X	
11/07 18h	12/07 18h	6		X	X	X	X		
								X	
30/07 15h	31/07 15h	3	TROMS	X				X	
31/07 18h	01/08 18h	6		X	X	X	X	X	
01/08 20h	02/08 20h	3		X				X	
02/08 20h	03/08 20h	3		X					
18/08 20h	19/08 20h	2	CARNU	X					
19/08 20h	20/08 07h	2		X					
20/08 18h	21/08 18h	5		X	X	X	X		
22/08 07h	23/08 07h	2		X					
30/08 18h	31/08 18h	6	BREST	X	X	X	X		X
01/09 07h	02/09 07h	3		X					X
02/09 07h	03/09 07h	3		X				X	X
04/09 18h	05/09 18h	6		X	X	X			X
12/09 07h	13/09 07h	3	GRASS	X					X
13/09 07h	14/09 07h	3		X					X
14/09 18h	15/09 18h	5		X	X	X	X		
16/09 07h	17/09 07h	2		X					

Table.1 - Observing sessions of the 1989 mobile VLBI european campaign

VLBI MODEST vlbim89.bin: Station coordinates

Station	x (mm) <XY> Shifts: E (mm) <EN>	y (mm) <YZ> N (mm) <NV>	z (mm) <XZ> V (mm) <EV>	Avg. obs. time	Nob
GRASSE EURA				89/ 9/14 10:18	570 648
	4581700837.1 +- 8.7	556126026.6 +- 2.4	4389354392.2 +- 8.5		
	0.38390	0.40547	0.90342		
	0.8 +- 2.2	96.4 +- 2.6	4353.2 +- 11.9		
	0.08482	0.01929	-0.00041		
BREST EURA				89/ 9/ 2 16: 5	678 790
	4228879976.5 +- 7.3	-333104531.9 +- 2.4	4747184051.2 +- 8.0		
	-0.05468	-0.06137	0.88458		
	-23.0 +- 2.5	21.1 +- 2.6	4205.4 +- 10.5		
	-0.02306	-0.01857	0.15370		
CARNUSTY EURA				89/ 8/21 2:44	353 398
	3526418934.7 +- 11.3	-171421280.0 +- 4.0	5294102445.8 +- 15.0		
	-0.02647	-0.10996	0.92533		
	40.6 +- 4.0	-3.9 +- 3.6	4415.3 +- 18.5		
	-0.20748	-0.25737	0.04470		
TROMSONO EURA				89/ 8/ 1 16: 8	660 686
	2102905608.5 +- 5.7	721602939.1 +- 2.8	5958205225.1 +- 12.1		
	0.43026	0.47364	0.77891		
	1.4 +- 2.5	-5.7 +- 3.3	4237.2 +- 13.0		
	0.14731	-0.13102	-0.08833		
METSHOVI EURA				89/ 7/ 8 16:10	682 890
	2890654802.3 +- 6.2	1310296107.9 +- 3.5	5513962290.9 +- 9.9		
	0.70313	0.76542	0.88248		
	-2.4 +- 2.3	-8.1 +- 2.5	4251.5 +- 11.7		
	0.10919	-0.25540	0.07883		
ONSALA60 EURA				89/ 7/26 2:51	1902 2150
	3370606166.1 +- 3.7	711917405.5 +- 1.5	5349830662.0 +- 4.9		
	0.47426	0.41765	0.85439		
	-3.3 +- 1.3	11.0 +- 1.7	23.8 +- 5.9		
	-0.08682	-0.23477	-0.01394		
HOHENFRG EURA				89/ 6/24 20:40	917 1009
	3778217548.9 +- 6.7	698645165.2 +- 2.2	5074056947.9 +- 8.4		
	0.56220	0.54110	0.91691		
	11.9 +- 1.8	-10.0 +- 2.2	4309.4 +- 10.6		
	-0.04963	-0.14054	0.03737		
MOJAVE12 NOAM				89/ 8/ 2 12:43	1579 1919
	-2356170989.0 +- 4.7	-4646755829.0 +- 6.0	3668470573.6 +- 7.1		
	0.30728	-0.69454	0.21920		
	-85.5 +- 4.3	-6.2 +- 5.0	-40.5 +- 8.1		
	0.74884	0.29608	0.34686		
RICHMOND NOAM				89/ 7/28 8:51	1352 1494
	961258080.2 +- 4.5	-5674090005.5 +- 7.9	2740533734.8 +- 6.9		
	-0.38411	-0.59456	0.70191		
	-63.9 +- 4.1	-2.4 +- 4.9	-46.4 +- 9.5		
	0.60159	0.33804	0.31578		
NOTOP EURA				89/ 8/ 1 2:10	1805 1979
	4934563309.9 +- 3.9	1321201151.5 +- 1.4	3806484366.4 +- 3.7		
	0.69709	0.62711	0.86843		
	-18.9 +- 1.0	14.0 +- 1.5	23.6 +- 5.3		
	-0.05269	0.28049	0.01635		
WESTFORD NOAM				89/ 8/ 2 11:36	1887 2247
	1492206679.3 +- 4.3	-4458130468.2 +- 4.8	4296015461.6 +- 6.6		
	-0.43214	-0.67057	0.79519		
	-50.1 +- 3.7	5.9 +- 3.0	-55.7 +- 7.9		
	0.61600	0.41779	0.48744		

Table.2- Standard Global Solution of the 1989 mobile VLBI european campaign -VLBIM89.

indice	designation	TX sigma TX (m)	TY sigma TY (m)	TZ sigma TZ (m)	D (10^{-6}) sigma D	RX (") sigma RX	RY (") sigma RY	RZ (") sigma RZ
1	VLBIM89	0.002 2 0.012	0.060 2 0.009	-0.009 2 0.010	0.0006 2 0.0009	0.0008 2 0.0004	-0.0006 2 0.0005	-0.0023 2 0.0002

Table.3- Seven transformation parameters and standard deviation (VLBIM89, ITRF90)

- a- For VLBIM89

Indice	Designation	Rejet (1)	Residus cartesiens (syst. equatorial, en m) (VX VY VZ)			Residus normalises (syst. equatorial) (NX NY NZ)			Residus cartesiens (syst. local, en m) (VL VP VH)		
1	10002M003CERGA GR VLBI	1	0.002	0.000	-0.010	0.268	0.159	-1.068	0.000	-0.009	-0.005
2	10004M002BREST VLBI	1	0.009	0.000	0.007	1.114	-0.121	0.881	0.000	-0.002	0.011
3	13296M002BUDDON - VLBI	1	-0.002	0.000	-0.001	-0.171	-0.073	-0.049	0.000	0.001	-0.002
4	10302M002TROMSO VLBI	1	0.001	0.000	0.010	0.203	-0.088	0.812	-0.001	0.002	0.009
5	10503M002METSAHOV VLBI	1	-0.002	-0.002	-0.004	-0.363	-0.494	-0.363	-0.001	0.001	-0.005
6	10402S002ONSALA-R VLBI	1	-0.001	0.000	-0.003	-0.280	0.110	-0.532	0.000	-0.001	-0.003
7	14202M002HOHENBUN VLBI	1	0.000	0.000	0.000	-0.016	-0.024	0.020	0.000	0.000	0.000
8	40405S009GOLDSTON VLBI	1	0.000	0.002	-0.002	-0.041	0.289	-0.333	-0.001	-0.001	-0.003
9	40499S001RICHMOND VLBI	1	0.000	0.003	-0.001	-0.070	0.381	-0.214	0.000	0.000	-0.003
10	12717S001NOTO VLBI	1	0.000	0.000	0.000	-0.106	0.115	-0.117	0.000	0.000	-0.001
11	40440S003WESTFORD VLBI	1	0.000	-0.001	0.006	0.003	-0.259	0.881	0.000	0.004	0.005
12	14201S004WETTZELL VLBI	1	-0.001	-0.001	0.005	-0.057	-0.107	0.592	-0.001	0.004	0.004

b- For ITRF90

Indice	Designation	Rejet (1)	Residus cartesiens (syst. equatorial, en m) (VX VY VZ)			Residus normalises (syst. equatorial) (NX NY NZ)			Residus cartesiens (syst. local, en m) (VL VP VH)		
1	10002M003CERGA GR VLBI	1	-0.003	-0.006	0.012	-0.298	-0.716	1.187	-0.006	0.011	0.005
2	10004M002BREST VLBI	1	-0.050	0.005	-0.058	-2.647	0.443	-2.534	0.001	-0.001	-0.077
3	13296M002BUDDON - VLBI	1	0.008	0.003	0.003	0.358	0.238	0.101	0.003	-0.005	0.007
4	10302M002TROMSO VLBI	1	-0.007	0.004	-0.030	-0.473	0.354	-1.421	0.006	-0.006	-0.030
5	10503M002METSAHOV VLBI	1	0.020	0.024	0.026	1.089	1.731	0.980	0.014	-0.011	0.037
6	10402S002ONSALA-R VLBI	1	0.008	-0.005	0.015	0.771	-0.548	1.277	-0.007	0.002	0.017
7	14202M002HOHENBUN VLBI	1	0.001	0.002	-0.001	0.035	0.146	-0.047	0.002	-0.001	0.000
8	40405S009GOLDSTON VLBI	1	0.000	-0.002	0.002	0.057	-0.337	0.333	0.001	0.001	0.003
9	40499S001RICHMOND VLBI	1	0.001	-0.003	0.002	0.097	-0.381	0.275	0.000	0.001	0.004
10	12717S001NOTO VLBI	1	0.008	-0.008	0.009	0.452	-0.691	0.524	-0.010	0.004	0.010
11	40440S003WESTFORD VLBI	1	0.000	0.003	-0.008	-0.005	0.363	-1.007	0.001	-0.004	-0.007
12	14201S004WETTZELL VLBI	1	0.001	0.001	-0.005	0.057	0.107	-0.592	0.001	-0.004	-0.004

Tables.3a, 3b- Residuals of station coordinates (ITRF90, VLBIM89)

DATE	JD	X Pole m arcsec	Y Pole m arcsec	UT1-UTC m sec
1989/ 6/22	2447699.758	221.5+/- 0.5	391.7+/- 0.5	-376.42+/-0.03
		1.1	0.4	**-0.20**
1989/ 6/27	2447704.759	230.8+/- 0.5	375.9+/- 0.5	-383.83+/-0.02
		0.2	-2.1	**-0.23**
1989/ 7/ 7	2447714.731	247.2+/- 0.5	347.0+/- 0.5	-390.29+/-0.02
		0.3	-2.3	**-0.17**
1989/ 7/12	2447719.777	251.9+/- 0.5	333.3+/- 0.5	-395.63+/-0.02
		-1.6	-1.8	**0.05**
1989/ 8/ 1	2447739.742	260.2+/- 0.4	272.3+/- 0.4	-415.83+/-0.01
		0.5	-1.3	**-0.14**
1989/ 8/21	2447759.778	253.8+/- 0.5	210.6+/- 0.5	-439.09+/-0.02
		-0.3	-1.4	**-0.11**
1989/ 8/31	2447769.781	245.6+/- 0.3	183.1+/- 0.4	-449.18+/-0.02
		-0.5	0.8	**-0.13**
1989/ 9/ 5	2447774.755	235.9+/- 0.5	165.8+/- 0.4	-455.96+/-0.02
		-0.6	-0.9	**-0.12**
1989/ 9/15	2447784.718	212.6+/- 0.6	138.6+/- 0.6	-466.58+/-0.03
		0.5	-2.3	**-0.16**

Table. 6- Earth rotation parameters solution VLBIM89R

The Future of Geodetic VLBI

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Introduction

- first geodetic VLBI experiments in the 70ties (Mark II)
- Mark III for geodetic purposes since 79/80 (in Europe: Onsala, Effelsberg)
- basic procedures unchanged (observation - correlation - data analysis)
  only technology has improved (marginally)
- high costs, time consuming
- today: competition with GPS and other satellite techniques

Has geodetic VLBI still a future?

Yes, but:

1. Improvements of the data analysis software are necessary (improve the current models, consistency of the models, further small effects have to be considered)
2. Improvements of the VLBI data analysis procedure are necessary (AI-methods)
3. New technological developments have to be adopted soon (benefits from rapid progress in computer and communication technologies)
4. Advantages of VLBI have to be made clearer
5. Concentration on main tasks, i.e. reference systems, ... (routine monitoring work to be done by GPS)
6. New research topics

*) Topics 1,2,3 will be discussed in more detail in this presentation

Differences between VLBI and other modern geodetic techniques

Advantages of VLBI

- relation to an inertial reference system
- does not depend on satellites
- all three Earth rotation parameters can be independently monitored without additional constraints
- improvement of the nutation/precession model by VLBI
- radio telescopes are 'stable' instruments and cannot be removed
- results for a period of 15 years available

Disadvantages of VLBI

- high costs
- delay between time of observation and availability of results (one week minimum)
- no homogeneous distribution of stations on the Earth
- radio telescopes can be subject to antenna deformation effects (thermal expansion, wind loading)

Other Differences

- VLBI not related to the center of mass of the Earth
- gives neither direct information about the gravity field of the Earth nor on the kinematics of the Moon (like LLR)

Present status of data analysis software

VLBI: most accurate analysis software, in agreement with IERS Standards, needs still further improvements

SLR/LLR: software almost as good as VLBI software, but 'more problems'

GPS: analysis software still in the developing stage, no agreement with IERS Standards yet, high accuracies are obtained due to the high number of stations and observations (quasi-permanent)

1. Improvements of geodetic VLBI software necessary to obtain 1 mm accuracy

(CALC/SOLVE, OCCAM, MODEST, ...)

- improved models for atmospheric path delay
- daily UT1- and pole variations due to the ocean tides
- ocean loading due to ocean tides
- influences of the ocean currents
- influences of source structure on delay observables
- atmospheric loading
- local station displacements (´antenna deformation´ due to thermal expansion, pillar torsion, etc.)
- improved nutation model
- ....
- (minor bugs in CALC/SOLVE to be eliminated)

General important aspects:

- consistency of basic models important (solid Earth, ocean tides, ...)
- if too many parameters (´empirical models´) are solved for there is a danger that the parameters of one model absorb effects of different origins
- phase connection solutions for long baselines might provide a considerable increase in accuracy

2. Improvements of the VLBI data analysis procedure

- many steps of the data analysis can be supported by use of AI methods
  * improvement of program flow
  * streamlining of SOLVE processing

- more data can be processed faster and more cost efficient
  * faster turn around
  * personnel budgets continue to be cut
  * VLBA data

3. Improvements of the technical process

3.1. Data transmission

New high speed broadband communication networks will soon allow transmission of signals at Gbit/sec

* optical fiber (test installations at 1 Gbit/sec already exist)
* communication satellites (ACTS satellite for 'supercomputing networking applications' at up to 800 Mbit/sec to be launched in 1993)

costs are high but tape transport is not needed any more and network specialists are interested in spectacular applications (up to now mostly transmission of moving images or multidimensional signal processing)

--- **direct transmission** of the received signals from the radio telescopes to the correlator or to a central computer for further processing

3.2. Correlation

Software correlation possible (Petit, 1987, 1993) but needs high computer power (MkIII correlator performance equivalent to 1Gflops/baseline, MkIV 10-100 Gflops/baseline). Present massively parallel computers offer simultaneous high speed processing on up to more than 65000 processors, computer peak performance is already in the range of Gflops, but I/O bottleneck

--- **on line software correlation** can be realized within a few years (allows direct feedback to the stations)

3.3 Data analysis (CALC, MODEST, OCCAM, ...)

Many steps can be parallelised, too.
Tools for parallelising FORTRAN programmes already exist.

--- **global solution** in a few seconds

Remarks: Centers on parallel computing in St. Augustin (GMD) and at the Univ. of Cologne.
Cooperation between VLBI experts and computer specialists will start in Nov. 93,

Conclusions

Considerable acceleration and simplification of the VLBI process is possible.
Quasi **on line monitoring** of the Earth rotation parameters and of geodynamic effects is possible with 1 mm accuracy if all technical improvements are adopted and if the present models for data analysis are improved considerably. Finally, lower total costs can be achieved.

Geodetic VLBI has a future as the most precise observing technique for special applications

More on European Stations Velocity

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Summary. Transatlantic baselines including Onsala, Effelsberg or Wettzell have been observed from long time using VLBI. Some of the transatlantic baselines like Westford Wettzell, or Westford Onsala, are the most observed in the VLBI sample. In the last few years a numbers of new antennas become available for geodetic VLBI in Europe, and then European baselines have been observed regularly. From the beginning of 1990 the european baseline have been observed with properly designed experiments, using only european antennas. In this paper the databases with at least two european baselines have been analysed and combined in a global solve solutions. Different reference systems have been used and different constraints are applied in order to text the quality of the reference system. Using Wettzell as origin of the system and applying Nuvel model, no motions was found at Onsala and Madrid. Noto shows a velocity of 6.7 mm/yr towards North. Matera shows 4.7 mm/yr with similar direction. Medicina shows a very small velocity, 2.3 mm/yr.

Introduction

VLBI technique has been developed very fast in the last decade, both for radioastronomy and geodesy and a large number of stations have been involved in this technique, expecially in the northern hemisphere. The european VLBI for geodesy come into air with some delay in respect to the American counterpart, even if Onsala station was involved in geodetic VLBI from the very beginning and Wettzell from 1984 regularly observes at least one hour a day together with Westford in U.S. But the power of VLBI in measuring regional deformations in Europe could be proved only with an european network observing at regular rate. That became a reality when the DSN antenna near Madrid in Spain was available for geodetic VLBI observations, and more antennas, Medicina (near Bologna, in 1987), Noto (in Sicily, in 1989) and Matera (in southern Italy, in 1990) started geodetic VLBI observations. At this point it is possible to talk of a real european VLBI network, even if its geometry, all stations but Madrid aligned in North - South direction, is not the best. Nevertheless the preliminary results from European experiments are the best ever found in geodetic VLBI. In the future, probably during next year, when more antennas will be available (Seimez in Crimea, Ny-Alesund in Spitzbergen island, and Svetloa near St. Petersburg), the european network will have a stronger configurations both from geodetic and geometric point of view.

The very first VLBI experiments including more than two european baselines were observed during 1988. These experiments, called EATL have been designed for measuring the rate of the enlargement of the Atlantic basin. More EATL experiments have been observed during 1989 including in this case Noto, (Medicina was down for resurfacing) and some others using mobile VLBI. Starting from January 1990 purely european experiments were planned and observed. Stations availability and lack of correlating time have limited in the past the experiments numbers, the regularity in time, and the stations participations. In any case from 1990 to 1993 more than 12 European experiments has been performed, with at least five european stations. Baseline analysis has been performed by different groups, using CALC/SOLVE software (Hase and Tornatore, 1991, Campbell et al.,1992, Campbell et al.,1992, Campbell et al.,1993), and Occam (Zarraoa et al., 1991 and 1993), using a subset of the data now available. Ryan et al, 1993, at the IAG assembly at Wiesbaden presented a paper in which the repeatability of the european stations have been computed using the whole set of databases with at least one european stations in it. Using Wettzell as reference site, and considering the direction Wettzell to Onsala fixed, the position uncertainties was computed for all the european stations. The velocity was also computed for Effelsberg, Matera, Medicina, Noto Madrid and Tromso. The last two stations have the vertical velocity constrained to zero. With this reference system and these constraints an averaged (to all stations, including mobile VLBI sites) positions uncertainties was 47 mm, 8 mm and 9 mm for upper, east and north direction respectively. No motions was found for Madrid, Noto shows

7.9 mm/yr, directions 346 deg., Matera 4.1 mm/yr direction 18 deg. and Medicina 2.3 mm/yr direction 48 deg. A discussion following the presentation of the previous paper suggest to be more conservative in the selections of data bases. In fact there is some indications that so many transatlantic experiment could overtake the quality of the european data, in particular considering that few stations (like Wettzell and Onsala) have hundreds of observations (237 for Onsala and 810 for Wettzell at the end of 1992) and some others like Medicina, Noto, Madrid and Matera have only few tenths, or one or two for mobile sites. Moreover a new observations have been made during 1993, very important for site like Noto and even more for Matera with few observations and not regularly distributed in time. That suggests more investigations on the european data, in order to find out the influence of different reference system and/or constraints on the results, and how the Earth Rotation Parameters (Polar Motion and UT1), affect the results.

Data analysis and results

The analysis started at the Bologna computer, a 9000/380 workstation, but was performed at the VLBI group at Goddard Space Flight Center, because when the new Unix version 9.0 was installed on the Bologna workstation some parts of the batch program refused to run. Then I have used databases installed at Goddard, with no modifications on the single arc (single database). That means autoconstraints for clock and atmosphere with one hour break. The databases selected was that with at least four european station except for mobile experiment, where only three european stations have been used when Noto station was in the experiment. Following that selection criteria 27 databases have been used in the analysis. I have then used EATL experiment excluding the ones using HARTRAO antennas in South Africa, Europe experiments and mobile experiments with Noto. The observations span from december 1988 to April 1993. In the global analysis a cutoff of 7 deg. in elevations was adopted. The reason for that was related to the atmosphere models that are very uncertain under this limit. When applied, the earth rotation file for ERP was er885a and nutation file was nut885a.mod, both coming from the Goddard global solution 885. These two files are computed until the end of 1992, for that when used in processing data, the two 1993 Europe experiments had to be excluded from the solution. Three different set of reference system and constraints have been used in the analysis to test differences. The first selection was: use Nuvel model, consider Wettzell fixed to Nuvel and direction from Wettzell to Onsala fixed. The vertical velocity for Madrid (DSS65 station) constrained to zero. In this case we have computed the position and the velocity for all the fixed european stations. The results for velocity are shown on table 1.

Table 1
No upper velocity for DSS65 (Madrid)

	azimuth deg.	hor. vel. mm/yr	sigma mm/yr	upp. vel. mm/yr	sigma mm/yr
MEDICINA	26	1.9	0.3	1.8	1.3
DSS65	109	0.4	0.6		
ONSALA	176	0.6	0.3	-0.04	0.02
NOTO	345	8.7	0.4	11.5	2.6
MATERA	8	7.1	0.6	14.9	3.2

Using ERP from file

	azimuth deg.	hor. vel. mm/yr	sigma mm/yr	upp. vel. mm/yr	sigma mm/yr
MEDICINA	58	2.3	0.3	-4.3	1.3
DSS65	57	1.4	0.3		
ONSALA	176	0.5	0.3	-0.03	0.02
NOTO	350	6.1	0.5	-4.4	2.0
MATERA	9	4.7	0.7	9.0	3.0

Some comments on the results shown on table 1. The constraints of the upper velocity for DSS65 (Madrid) is two week for the geometry of the network and produce unrealistic upper velocities for Noto and Matera. Comparing the upper part of table 1, with the lower part, when Earth Rotation Parameters came from a file, with their errors, the formal error is similar or worst and horizontal velocity became smaller for Noto and Matera, larger for Medicina and DSS65. In any case the results in the upper component of velocity for Noto and Matera suggest a different constraints.

The second selection change the constraints on the velocity, using a constraints on the formal error on the components of the velocity parameter. In this case the error for the vertical component of the velocity have been fixed to 1 mm/yr (or less), and the error on the others components three times larger than that. This constraints have been applied to Onsala and Madrid, in one case and to Madrid, Matera and Noto in a second attempt. The first attempt gave results almost identical to the ones shown on table 1, then on table two is shown the results applying the constraints on Madrid, Matera and Noto.

Table 2
Constraints on velocity errors for DSS65, MATERA and NOTO

	azimuth deg.	hor. vel. mm/yr	sigma mm/yr	upp. vel. mm/yr	sigma mm/yr
MEDICINA	22	1.6	0.3	-1.8	1.1
DSS65	320	1.1	0.5	0.1	1.0
ONSALA	176	0.5	0.3	-0.04	0.02
NOTO	340	7.5	0.3	0.8	0.9
MATERA	10	6.2	0.5	1.0	0.9

Using ERP from file

	azimuth deg.	hor. vel. mm/yr	sigma mm/yr	upp. vel. mm/yr	sigma mm/yr
MEDICINA	58	2.3	0.3	-4.1	1.2
DSS65	56	1.5	0.3	2.0	0.7
ONSALA	176	0.6	0.3	-0.04	0.02
NOTO	349	6.1	0.5	-1.1	0.5
MATERA	9	4.7	0.6	0.9	1.0

The results on table 2 present lower velocity for Noto and Matera and no upper velocity for any european stations, due to constrants used. The solution using ERP from external file produced the same results as previous selection (table 1), excluding the upper component for the velocity. For that reason it seems the more convincing solution.

The third selection presents more differences from the previous ones, and it was introduced to investigate in a better way a possible relative motion between Onsala, Wettzell and Madrid stations. The Nuvel model was used, the velocity baricenter of Wettzell, Onsala and Madrid was fixed to Nuvel model and a constraints to the upper velocity component error for the same stations, as in the second selection. The results are shown in table 3.

This last reference system, considering the formal errors on velocities, and the upper velocity for some stations, seems not very useful for european stations.

It must be noted that for all the different solutions the positions of the fixed european stations show a formal error less than 5 mm, for the upper component and three to four time less for the North and East component.

Finally a baseline solution was performed. In this case we have used the databases until the end of 1992. In table 4 the rate for baseline length and baseline transverse in respect to Wettzell, were shown with relative formal errors.

Table 3
Constraint on velocity baricenter and velocity error

	azimuth deg.	hor. vel. mm/yr	sigma mm/yr	upp. vel. mm/yr	sigma mm/yr
MEDICINA	36	3.0	0.9	0.3	1.8
WETTZELL	7	1.0	0.7	-0.5	0.8
DSS65	118	2.3	1.7	-0.1	0.8
ONSALA	283	1.9	1.3	0.4	0.8
NOTO	3	9.2	1.1	8.1	3.9
MATERA	19	8.8	1.6	12.0	4.0

Using ERP from file

	azimuth deg.	hor. vel. mm/yr	sigma mm/yr	upp. vel. mm/yr	sigma mm/yr
MEDICINA	55	2.6	0.3	-5.0	1.2
WETTZELL	41	0.4	0.2	-1.6	0.5
DSS65	75	1.6	0.2	1.4	0.6
ONSALA	263	1.5	0.2	-0.6	0.6
NOTO	357	6.2	0.5	-5.4	2.1
MATERA	15	5.3	0.7	7.7	3.0

Table 4

		length rate mm/yr	error mm/yr	Wrms of fit mm	transv. rate mm/yr	error mm/yr	Wrms of fit mm
ONSALA	WETTZELL	-0.8	0.7	3.0	-2.4	0.5	2.3
DSS65	WETTZELL	-0.9	0.9	3.7	-1.8	0.5	2.0
MEDICINA	WETTZELL	-1.9	0.6	2.2	-2.1	0.6	2.1
MATERA	WETTZELL	-4.1	1.9	2.9	-4.3	1.5	2.3
NOTO	WETTZELL	-6.7	1.3	4.4	-1.4	1.4	4.4

The same results are shown in fig. 1, where the baseline evolution is plotted. The results are compatible with what found in the previous analysis.

Conclusion

As shown in the previous sections using different reference systems and constraints the final results are different. Moreover using ERP from file, affect not the formal error, as expected, but the results on the velocity. We can consider that the particular geometry of the network, its dimension and configuration, is particularly sensible to ERP, and as already suggested by Ryan et al. 1993, the real error is larger than the formal error, probably by a factor 1.5. More investigations are needed to fully hunderstand this particular effect. In any case adding to purely European experiments some partially European experiments seems to improve the solutions. From this analysis the best result is that presented in the lower part of table 2, where Medicina has an horizontal velocity of 2.3 mm/yr with an error of 0.3 mm/yr, and azimuth direction 58 deg., DSS65 horizontal velocity of 1.5 mm/yr, error of 0.3 mm/yr, and azimuth direction 56 deg., Matera horizontal velocity of 4.7 mm/yr, with an error of 0.6 mm/yr, and azimuth direction of 9 deg., and Noto horizontal velocity 6.1 mm/yr, with an error of 0.5 mm/yr and azimuth direction of 345 deg. Considering the wrms of fit from the baseline solution (table 4 and fig 1)

the Madrid velocity is probably far more uncertain that what we can suppose from its formal error. In conclusion, more data are needed, possibly spanned more regularly in time, to stabilize the results all over the network.

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