VLBI in the service of geodesy 1968–2000: An Onsala perspective

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Very-Long-Baseline Interferometry (VLBI) has been used at the Onsala Space Observatory since 1968. In this paper we summarize the geodetic application of VLBI in terms of the observations so far obtained and the main geodetic results. Estimated time series of intercontinental as well as European baseline lengths are presented. The present facilities include the 20 m radome enclosed radio telescope, several continuously operating GPS receivers, a 21/31 GHz microwave radiometer for studies of the atmospheric excess propagation path due to water vapour, and a gravimetry foundation anchored in the solid granite rock in a laboratory environment. Geodetic VLBI continues to play an important role for the maintenance of the International Terrestrial Reference Frame (ITRF). The international CORE programme has the goal to continuously measure the earth rotation parameters. Over long time scales nutation and UT1 are not possible to estimate reliably from techniques using satellites in orbits around the earth.

1. Introduction

In the sixties and seventies first models for contemporary plate motion were developed, based on geological records of over 10^6 years (Minster & Jordan, 1978). In parallel space geodetic techniques were developed to measure the actual contemporary plate motion directly. Among these techniques were laser ranging to artificial satellites and the moon and the geodetic use of VLBI. Besides the formulation of the primary goal of global geodetic measurements, further goals like the measurement of earth rotation parameters and tidal phenomena were formulated already in the beginning of the development of the space geodetic techniques.

2. The Mark–I period

The first VLBI experiment at Onsala was performed in April 1968 as a combined geodesy/astronomy session. In the following ten years Mark–I data were acquired in many experiments. The observed reproducibility of Mark–I estimates of baseline lengths was of the order of a few tens of centimetres and the estimates of the earth orientation parameters were consistent with the models available at the time (Ryan *et al.*, 1986). The main drawback of the Mark–I system was its sensitivity to the radio wave delay caused by the ionosphere. This was soon realized and the development of the dual-frequency Mark–III system at Haystack Observatory and at NASA, GSFC, in the US was going on in parallel with the Mark–I observations during the seventies.

3. The beginning of Mark–III and detection of plate motion

The Mark–III recording system was installed at Onsala in late 1979 when a first experiment was performed. However, the first successful experiment was carried out in July 1980, followed by two week of continuous VLBI in September and October the same year during the so called MERIT short campaign. The accuracy of baseline estimates improved dramatically by the transition from Mark–I to Mark–III. The MARK–III system was described by Clark *et al.* (1985) and the first evidence for contemporary plate motion between North America and Europe was presented by Herring *et al.* (1986a). The nutation model was found to be in disagreement with the VLBI results (Herring *et al.*, 1986b) and has thereafter been revisited several times, see, *e.g.* Herring *et al.* (1991).

4. Mobile VLBI and GPS applications

Mobile VLBI terminals were developed in the US for densification of VLBI networks in areas such as Alaska and California. Two mobile VLBI campaigns were carried out in Europe in 1989 and 1992. The measurements including Tromsø have been published by Zarraoa *et al.* (1995). The mobile VLBI technique was however rather costly and later when the GPS satellite constellation provided full coverage during 1993 mobile VLBI experiments were no longer regarded to be worth the cost. For example, approximately three years of continuous GPS data from the Swedish GPS network (SWEPOS) was enough in order to detect the post-glacial uplift signal (BIFROST Project, 1996).

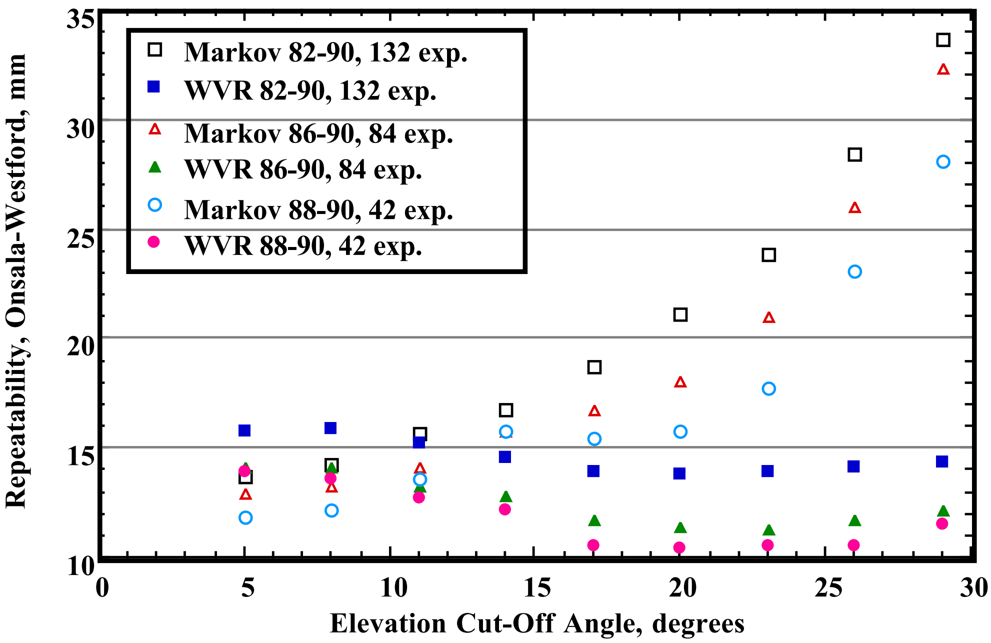

FIGURE 1. The repeatability of the estimated baseline lengths for different elevation cut-off angles using either the VLBI data themselves or external WVR data for the atmospheric correction in the analysis (from Elgered & Davis, 1993).

5. The atmosphere — the main error source?

During the eighties a large effort was made to use water-vapour radiometers (WVRs) to supply corrections for the propagation delay caused by atmospheric water vapour (Elgered *et al.*, 1991). The method of elevation cut-off tests was used to show the difficulty of designing the optimum schedule for geodetic VLBI (see Figure 1).

The basic problem is that if external WVR data are to be used no observations shall be

TABLE 1. Geodetic "Milestones" at the Onsala Space Observatory

Year	Event
1968	First geodetic VLBI experiment across the Atlantic Ocean (Mark-I)
1979	First VLBI Mark-III experiment
1980	Water Vapour Radiometer (WVR) installed
1982	7 more video-converters installed implying a total of 14
1985	Contemporary plate motion detected with VLBI
1986	First GPS experiment with receiver at Onsala (the Iceland campaign)
1986	Cooled FET amplifiers in the VLBI X-band receiver
1987	Both S- and X-band in the 20 m telescope, S-band also uses cooled FET
1987	Start of permanent tracking GPS receiver
1988	First GPS measured local "footprint" around the VLBI antenna
1990	High density Mark-III VLBI recording installed
1992	Drive system of 20 m VLBI antenna upgraded
1992	WVR upgraded, faster slewing, more stable hot loads
1993	First absolute gravimetry measurement
1993	Start of the continuously operating GPS network in Sweden (SWEPOS)
1996	Detection of land uplift in Fennoscandia using GPS
1996	Monitoring system for vertical motions of the VLBI concrete foundation installed
1997	First Mark-IV VLBI experiment
1999	European COST Action starts using GPS data in climate and meteorology
2000	International CORE project with Onsala participation

acquired say below 20 degrees. On the other hand, if no external data are available low elevation observations are needed in order to be able to use the VLBI data themselves to estimate the effect. Later results using antennas with fast slewing and including a relatively large amount of low elevation observations gave comparable results in terms of reproducibility of estimated baseline lengths whether WVR or GPS data were used as an external calibration or not (Emardson *et al.*, 1999). Present research concerning the atmospheric effects is further discussed in Section 8.

6. Establishment of footprints and studies of antenna foundation stability

When GPS became useful for geodetic positioning we established footprints around the 20 m antenna (Johansson, 1992). This work has continued and the latest work has involved the mounting of GPS antennas on the radio telescope itself (Bergstrand *et al.*, 2000). In order to study the vertical motions of the concrete foundation a height monitoring system based on an invar rod has been installed (Elgered & Haas, 1999).

7. Onsala milestones and statistics

Before we summarize the present status and future possibilities it may be interesting to look back at the events and to present some statics of the geodetic VLBI activities at Onsala. Table 1 lists geodetic milestones and major events related to the space geodesy research involving both VLBI and the Global Positioning System (GPS) activities at the observatory. The number of experiments per year has been rather constant if we exclude the years of 1989 and 1992 when mobile VLBI campaigns were carried out in Europe and the year of 1994 which included the two week long CONT–94 experiment, see Figure 2. The number of observed sources per experiment has significantly increased over the years. A typical number was 100–200 for the early Mark-III experiments whereas it is 313 in the CORE 3002 experiment in August 2000. Measurements of one transatlantic and one European baseline are shown in Figure 3. Results from geodetic VLBI in Europe are summarized by Haas *et al.* (2000) and shown in Figure 4.

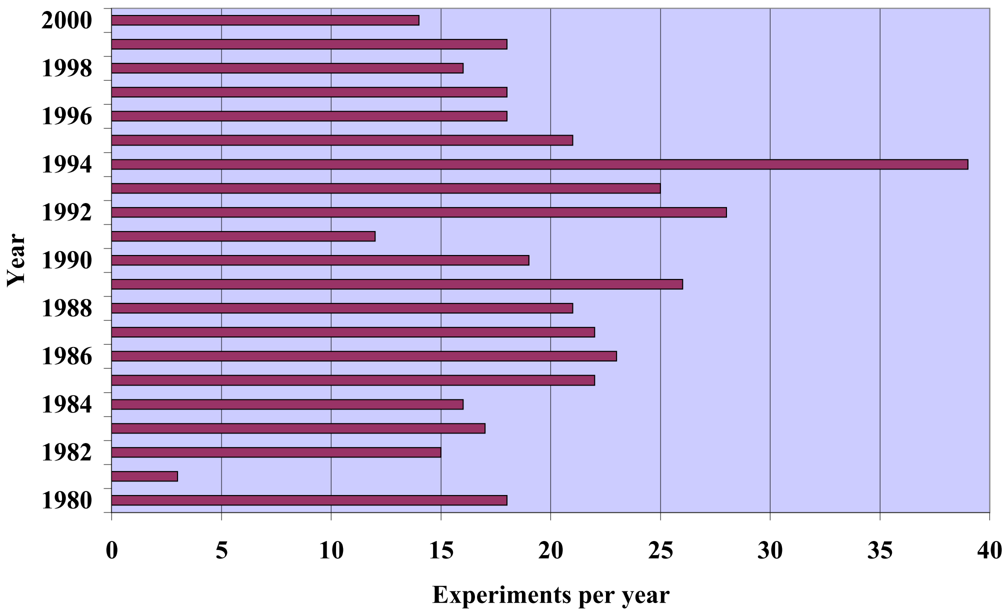

FIGURE 2. Number of geodetic VLBI experiments per year at Onsala.

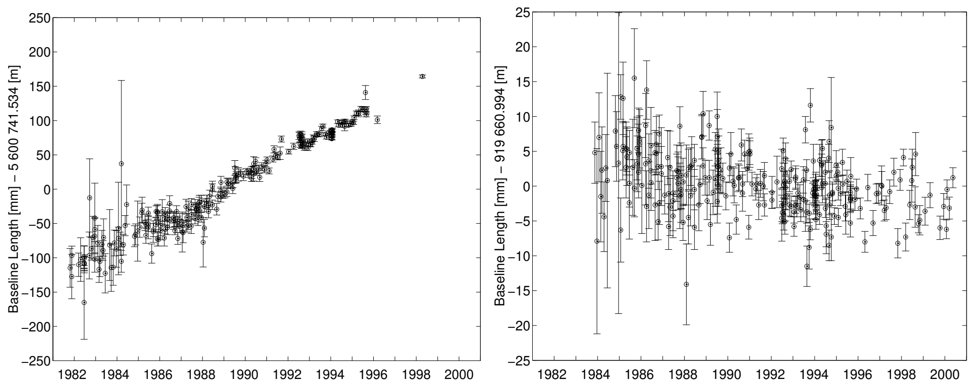

FIGURE 3. Baseline evolution Onsala–Westford (left) and Onsala–Wettzell (right). The best fit linear rates are 17.1±0.2 and −0.4±0.1 mm/yr, and the weighted RMS values, about the best fit straight line, are 8.3 and 3.3 mm, respectively. The uncertainties are one sigma values. Note that the vertical scales differ by a factor of ten (NASA–GSFC 2000).

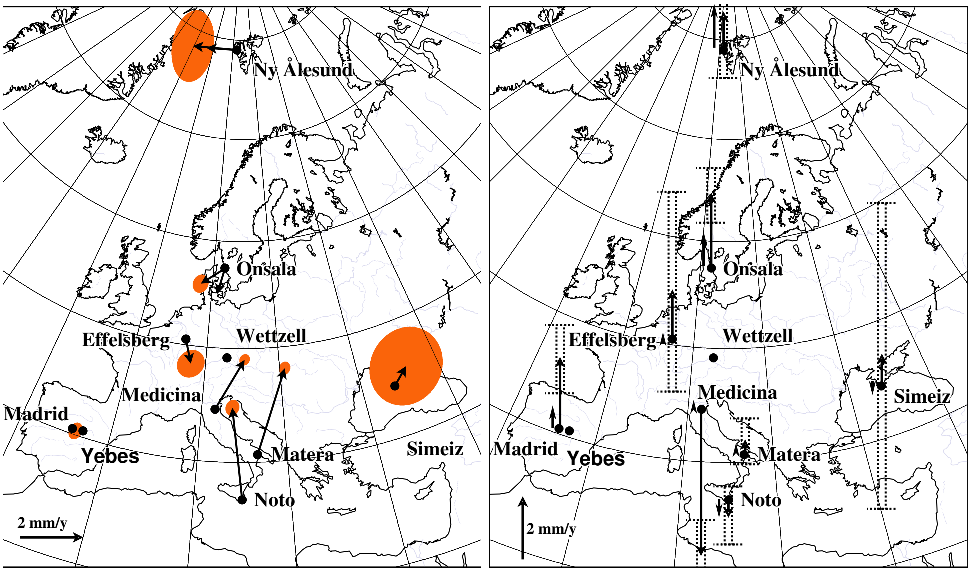

FIGURE 4. Horizontal motions with respect to Wettzell (left) and vertical motions with respect to Wettzell (right): geodetic VLBI observations (vectors with error ellipses or error bars) and predictions due to a post-glacial rebound model (vectors without error ellipses or error bars) (from Haas *et al.*, 2000).

8. Present and future tasks for geodetic VLBI

Geodetic VLBI continues to play an important role for the maintenance of the International Terrestrial Reference Frame (ITRF) (Drewes, 2000). The backbone of the ITRF are permanently operating space geodetic techniques like geodetic VLBI, GPS, SLR, LLR and others. Among those techniques geodetic VLBI uses the most stable instruments which are rather immovable and therefore provide a superior stability and reliability. For example a GPS receiver can easily be removed while this is much more difficult and unlikely for a VLBI telescope. Furthermore geodetic VLBI provides results for station positions and velocities that are independent of satellite orbit errors due to mismodeling of the gravity field. Variations of the geo-centre due to mass changes do not influence the results from geodetic VLBI, especially not the vertical component.

While geodetic VLBI is one of a couple of contributing techniques for the ITRF, although a major one, it is unique to determine and maintain the International Celestial Reference Frame (ICRF). VLBI observation of extragalactic radio sources which are stationary points with todays observational accuracy define the quasi-inertial reference frame which is realized by the ICRF. Todays accuracy of the position of the defining sources of the ICRF is 0.25 milliarcseconds (Ma, 2000).

The transformation between the two reference frames, the ITRF and the ICRF, is expressed using the so-called earth rotation parameters (ERP). The motion of the earth's rotation axis with respect to the earth's crust is described by the polar motion (PM), the actual rotation angle of the earth by UT1, and the motion of the earth's rotation axis with respect to the inertial frame by the nutations. Geodetic VLBI is the only space geodetic technique that can provide reliable measurements of UT1 and nutations over long periods.

Today the formal uncertainties of UT1 and PM determinations with geodetic VLBI are about 30-40 microarcseconds. These formal uncertainties have to be scaled by a factor of about 2–4 to give the actual uncertainties of todays measurements. Comparison of simultaneous observations in different VLBI networks show that there are systematic differences on the order of 100–150 microarcseconds (MacMillan, 2000). Similar results have been obtained from the analysis of simultaneous GPS subnets corresponding to the VLBI networks. Therefore more investigations are needed to understand the reasons for these differences and to separate the different geophysical effects on the integrated response of the earth that is being monitored with geodetic VLBI by observing ERP.

Thus an international project has been started with the goal to perform Continuous Observations of the Rotation of the earth (CORE) with geodetic VLBI (Vandenberg *et al.*, 2000). Starting during the year 2000 with the transition from the Mark III to the Mark IV technique, the installation of the Mark IV correlators and 2.5 observation days per week, the goal is to reach 6 observation days per week in 2003 utilising different geodetic VLBI networks. The expected uncertainties for PM and UT1 are on the level of 25 milliarcseconds. On the way to this goal a couple of geophysical signals have to be investigated and the geodetic VLBI analysis software has to be completed and extended.

Geodetic VLBI is a useful tool to study solid earth tides since it is purely sensitive to the tidal displacement of the observing stations and is not influenced by tidal variations of the gravity field via satellite orbits. It has been shown by Haas & Schuh (1996) that it is possible to study the resonance effect of the earth's free core. The free core resonance also influences the nutations which are uniquely observed over long periods by geodetic VLBI. Nutation results from geodetic VLBI form the constraints of modern advanced nutation models (Mathews *et al.*, 2000) and the basis of modern advanced solid earth tide models (Mathews, 2000).

Crustal loading effects due to ocean tides and atmospheric pressure variations are another topic that has been and is going to be studied extensively with geodetic VLBI. This includes the primary loading effect by ocean tides (Scherneck *et al.*, 2000), by the atmosphere (VanDam & Herring, 1994), (MacMillan & Gipson 1994), (Haas *et al.*, 1997) and also the secondary effect of crustal loading on the earth's rotation (Scherneck & Haas, 1999).

Besides the deformation effects due to the solid earth tides and the loading by ocean and atmosphere, there are also local effects at the VLBI stations themselves that have to be investigated. VLBI telescopes are large constructions of steel and/or steel reinforced concrete that are deformed by variations in temperature. This effect has to be studied and accounted for in the analysis of geodetic VLBI data. Also possible local site displacements due to ground water variations have to be investigated. These local site effects are of special importance for the maintenance of the ITRF.

Another major signal to be investigated with geodetic VLBI is the atmospheric propagation delay. Starting with relatively simple mapping functions and the assumption of an azimuth independent atmosphere, more advanced mapping functions have been introduced by Niell (1996) and Niell (2000) and more advanced models for the azimuth dependence have been developed by Davis *et al.* (1993) and introduced into the VLBI analysis software by MacMillan (1995). Comparison of tropospheric parameters derived from different independent space geodetic and remote sensing techniques (Gradinarsky *et al.*, 2000) and also comparisons to numerical weather models (Behrend *et al.*, 2000) confirm the importance of geodetic VLBI to study the atmospheric propagation delay.

9. Conclusions

We have tried to summarize the geodetic VLBI activities at the Onsala Space Observatory during the last 30 years. The observed baseline length reproducibilities have improved from the sub-metre range down to a few millimetres for baseline lengths of global scale. We believe that geodetic VLBI will continue to be the fundamental, most accurate technique to observe and realize the earth rotation parameters and the large scale terrestrial reference frame.

Acknowledgments

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