Geodetic and astrometric Very Long Baseline Interferometry (VLBI) - the IVS and its future perspectives

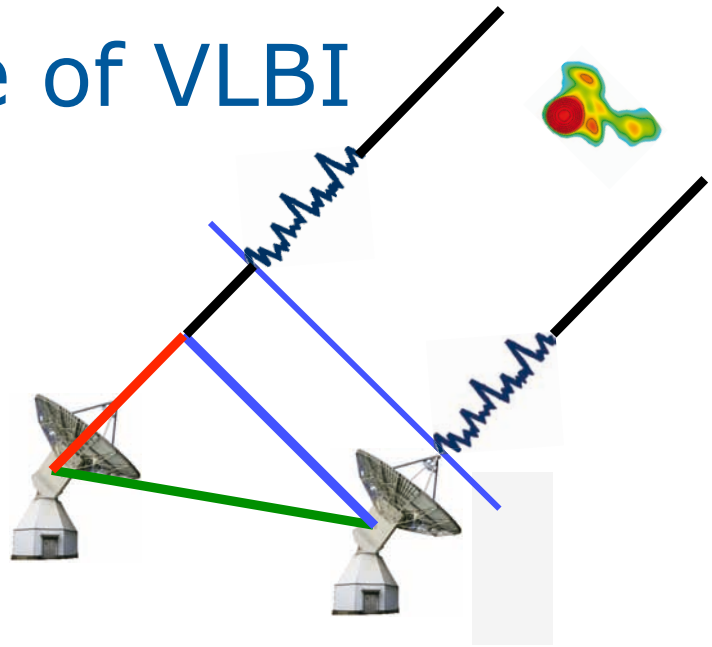
EGU and IVS Training School on VLBI for Geodesy and Astrometry

Aalto University, Espoo, Finland
2nd of March, 2013

Harald Schuh

The principle of VLBI

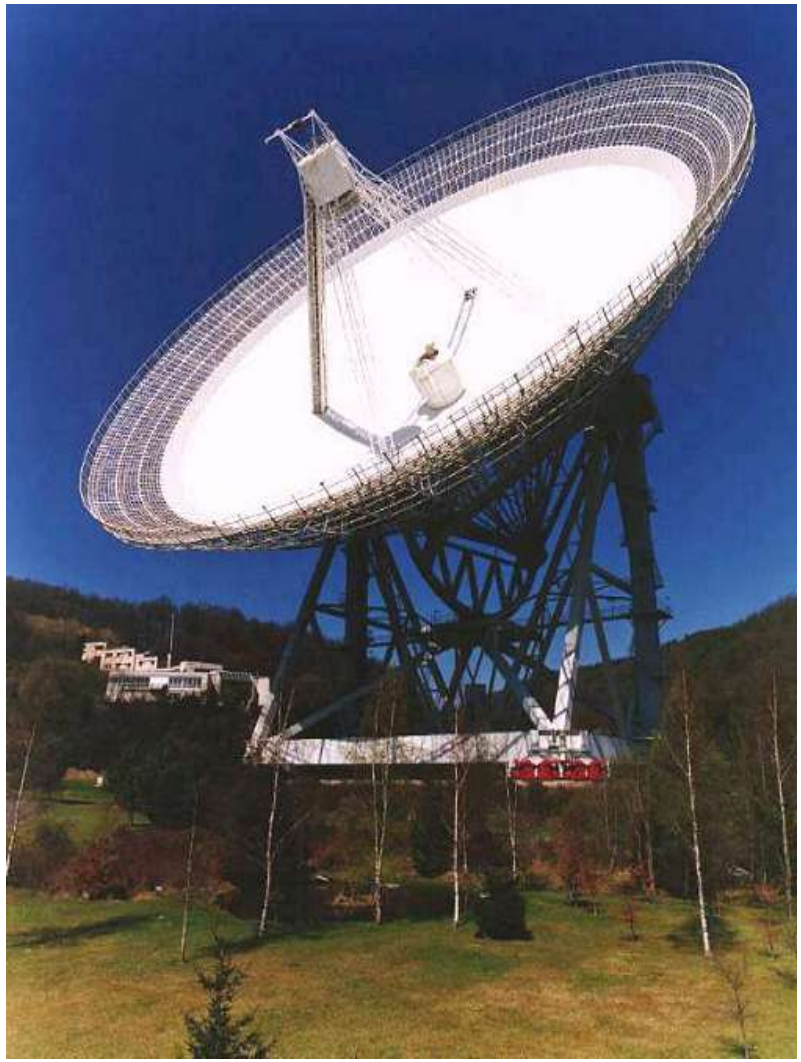
$$\tau = -\frac{1}{c}\mathbf{b}WSNP\mathbf{k}$$



EOP – Earth Orientation Parameters

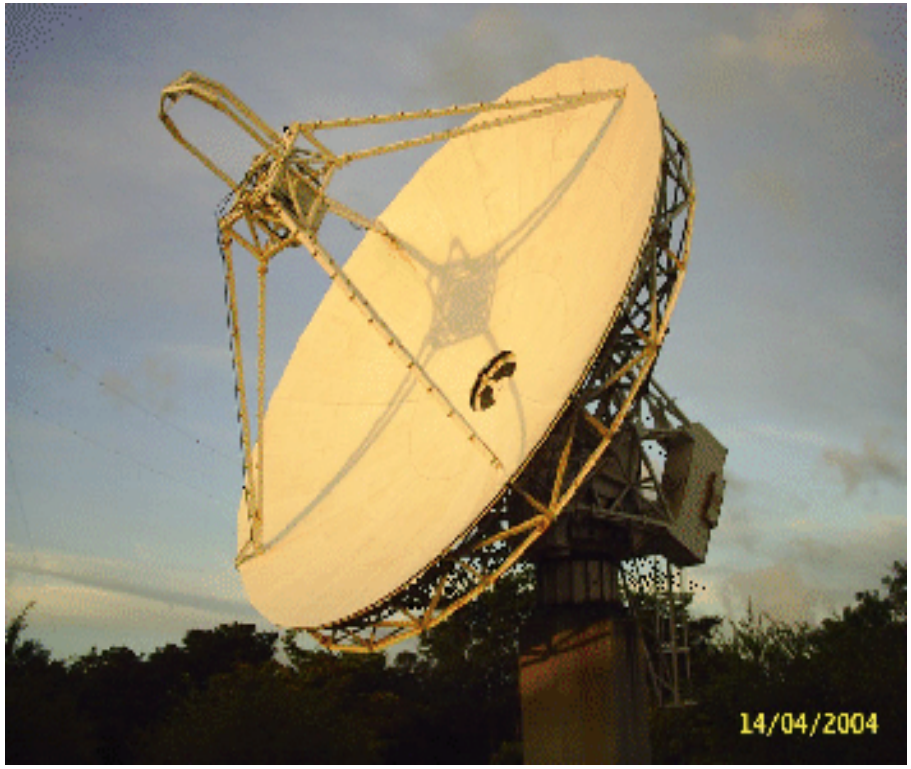
- **b** baseline vector between two stations
- **k** unit vector to radio source
- *W* rotation matrix for polar motion
- *S* diurnal spin matrix
- *N* nutation matrix
- *P* precession matrix

Effelsberg (100 m)

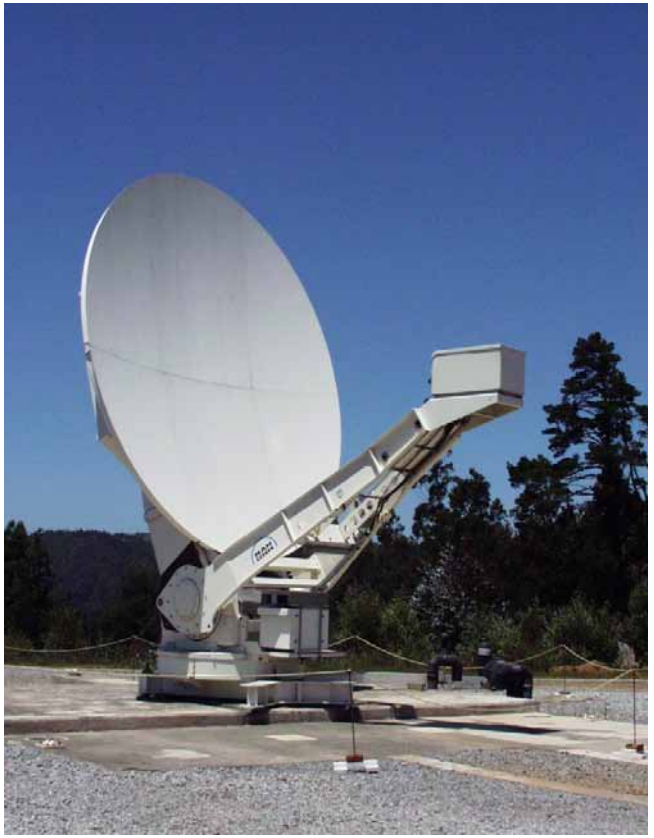


Wettzell (20 m)

VLBI in South America



Fortaleza (14.2 m)
(Brazil)



TIGO (6m)
(Concepción, Chile)

Kashima (34 m)

Shanghai (25 m)

『 e-VLBI 技術 』をご見学

VLBI in the Nordic Countries

Ny-Ålesund (20m), NOR

Onsala Space Observatory (20m), SWE

Metsähovi Radio Observatory (14m), FIN

VLBI2010: Origins, Status and Future

I. VERY LONG BASELINE INTERFEROMETRY – PRINCIPLE

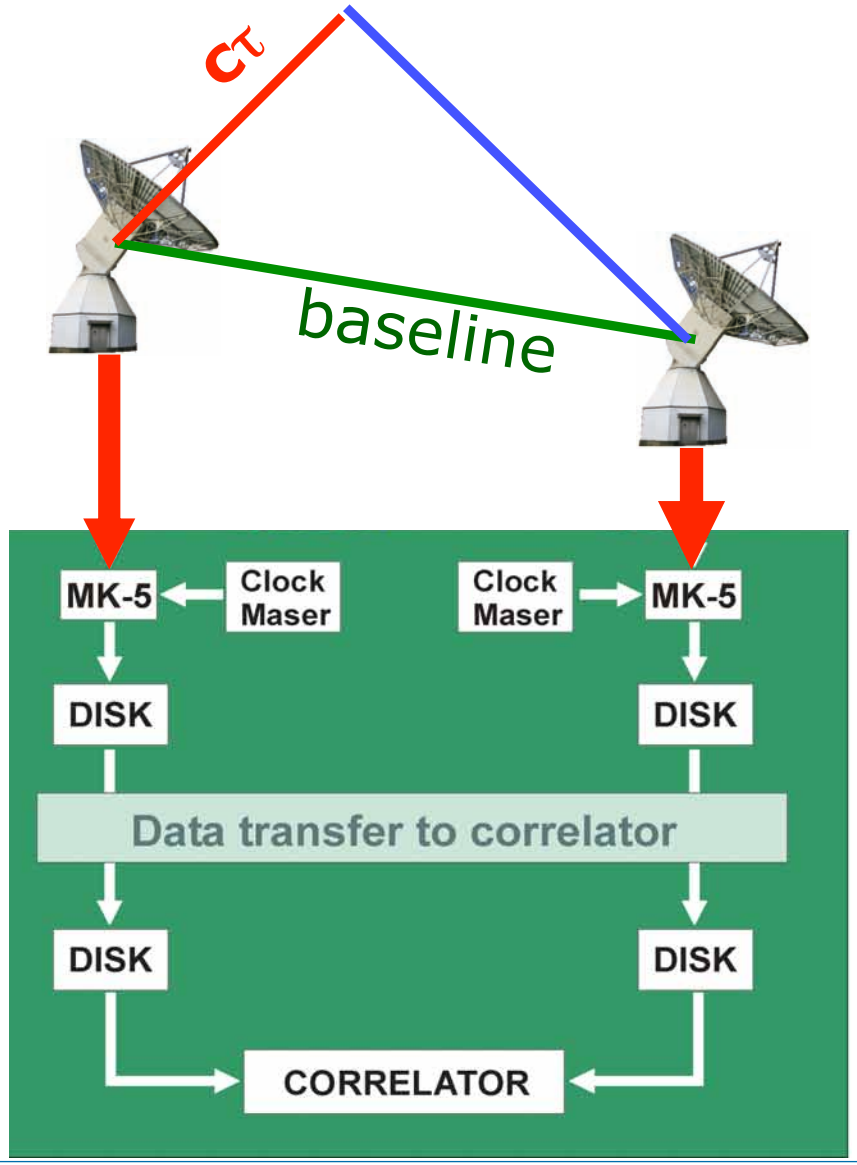
II. VLBI PRODUCTS

III. MEETING TODAY'S CHALLENGES

IV. VLBI2010

V. NEW PERSPECTIVES

VLBI observing system



- Radio signals of quasars or radio galaxies
  - 8 channels X-Band
  - 6 channels S-Band
  - Data stream 1Gbit/sec
  - Time & Frequency
    - ($DF/F \sim 10^{-15}$@50min)
  - Data recording
    - Harddisk (MK-5)
    - e-transfer
- Correlation
  - σ_t ~ 10 to 30 psec

Strengths of VLBI

Very Long Baseline Interferometry (VLBI) plays a fundamental role for the realization and maintenance of the global reference frames and for the determination of the EOP:

- VLBI allows observation of quasars which realize the **CRF**
- VLBI provides complete set of **EOP** and is unique for the determination of DUT1 and long-term nutation
- VLBI provides precisely the length of intercontinental baselines, which strongly support the realization and maintenance of the **TRF** with a stable scale

International VLBI Service for Geodesy and Astrometry - IVS

IVS is a service of

- **IAG** – International Association of Geodesy
- **IAU** – International Astronomical Union
- **WDS –** World Data System (membership approved in June 2012)

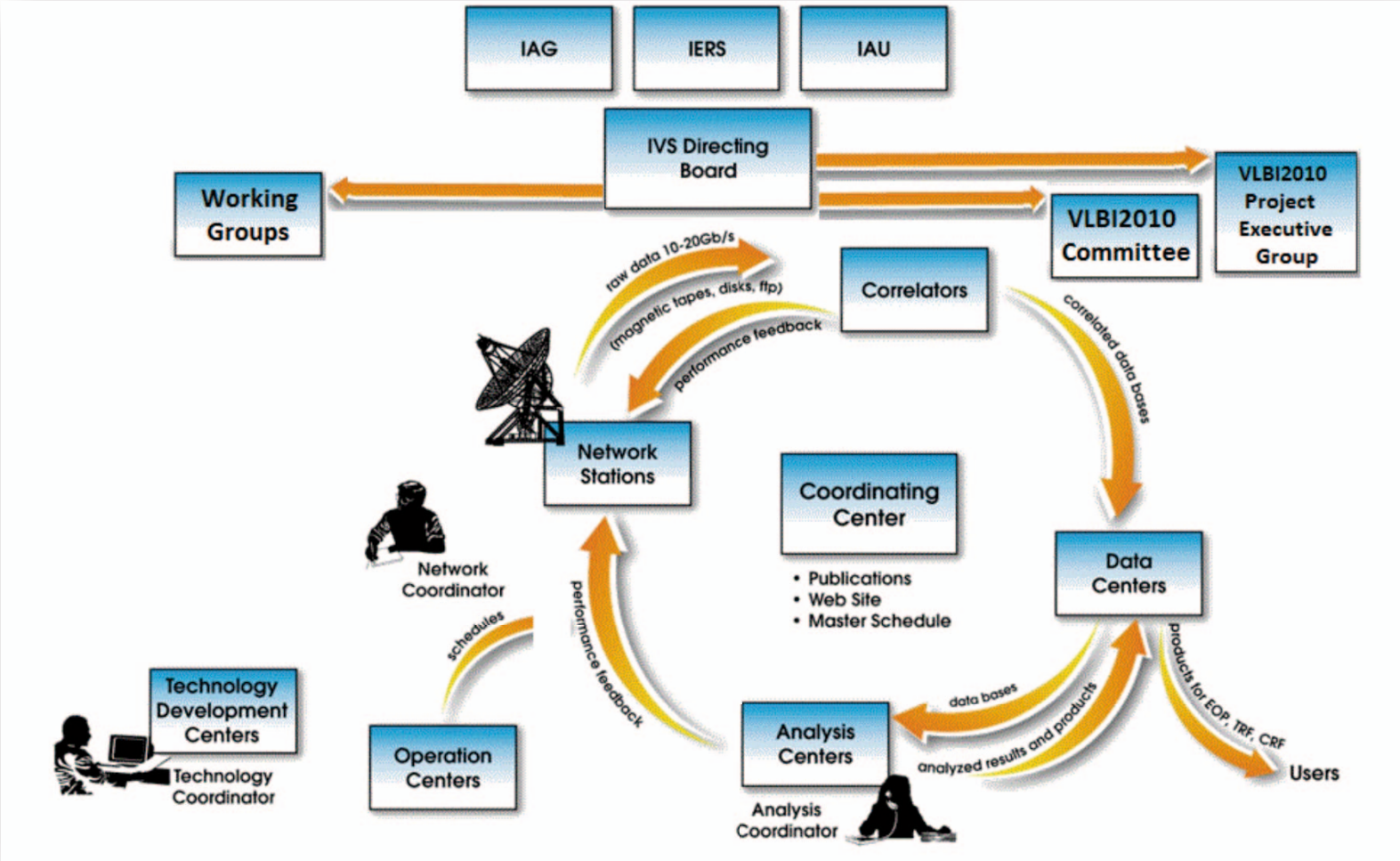
IVS goals:

- To provide a service to support geodetic, geophysical and astrometric research and operational activities
- To promote research and development in the VLBI technique
- To interact with the community of users of VLBI products and to integrate VLBI into a global Earth observing system (i.e. GGOS)

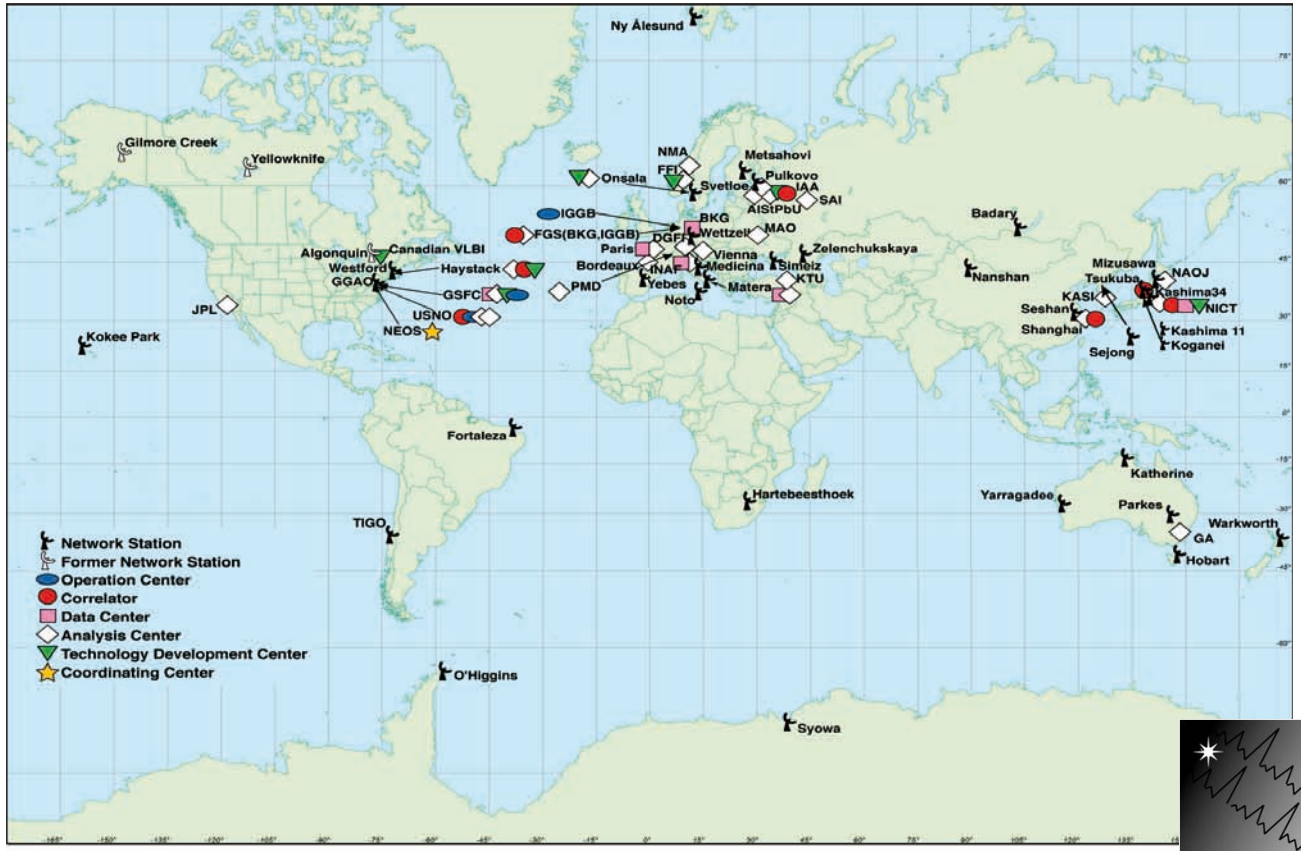
Main tasks of the IVS are: coordinate VLBI components, guarantee provision of products for CRF, TRF, and EOP

- IVS inauguration was on March 1, 1999
- IVS 10th Anniversary event on March 25, 2009
- 83 Permanent Components supported by >40 institutions in >20 countries
- ~280 Associate Members

IVS Components



IVS Components (Status June 2012)



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VLBI product: CRF

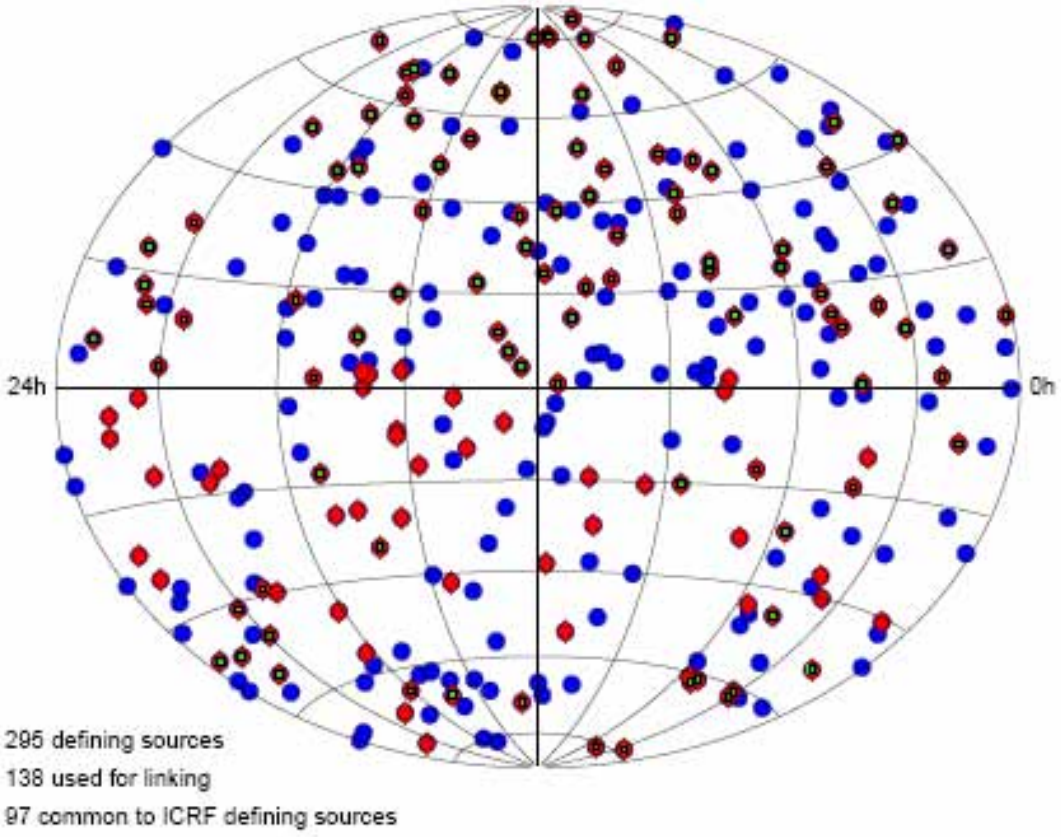
- ICRF2

Adopted by IAU (2009)
Resolution B3

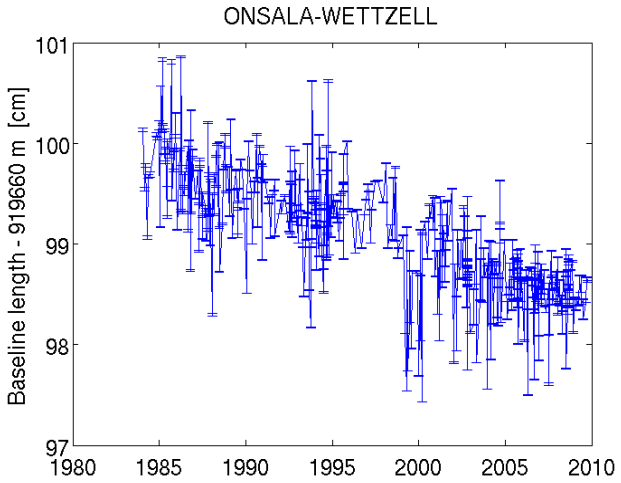
Sources:

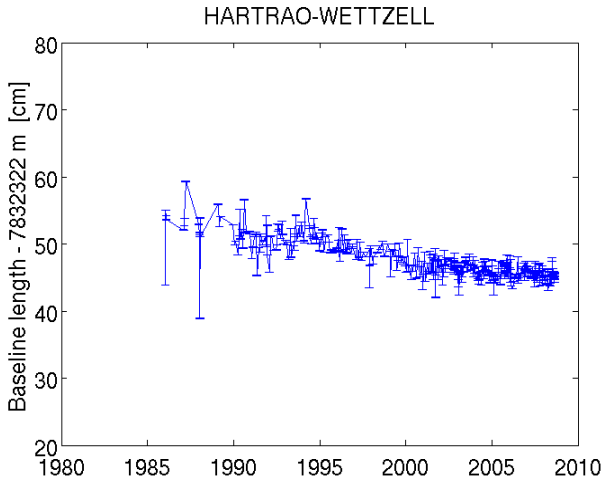
total:	3414
defining:	295
linking:	138

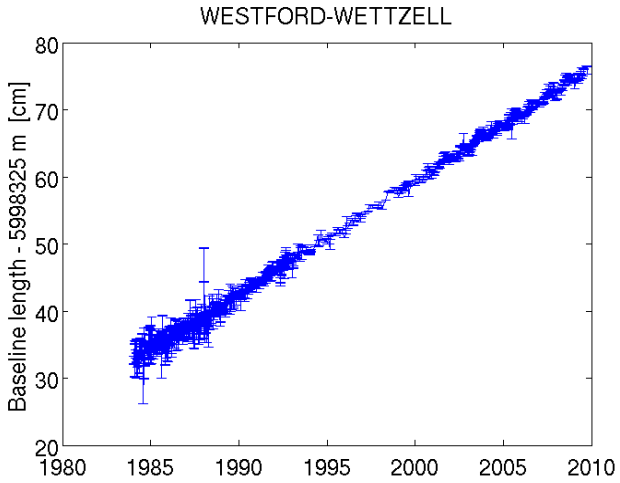
Fey et al., 2009:
IERS Technical Note 35
IERS/IVS Working group
*chaired by **C. Ma***

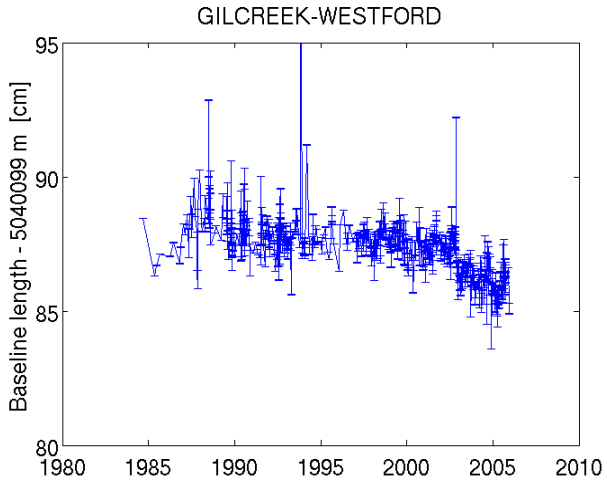


VLBI product: baseline lengths and the TRF

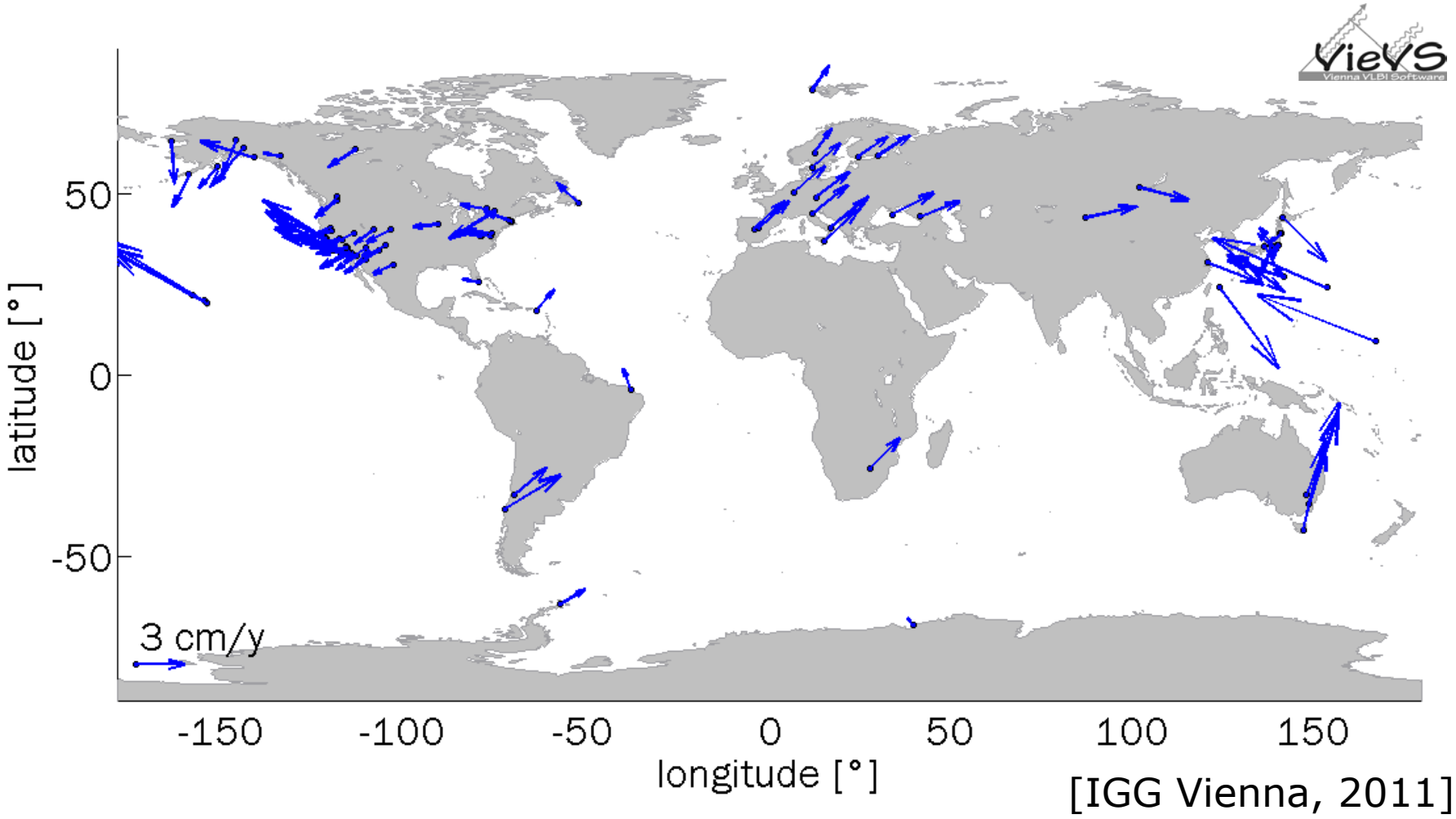








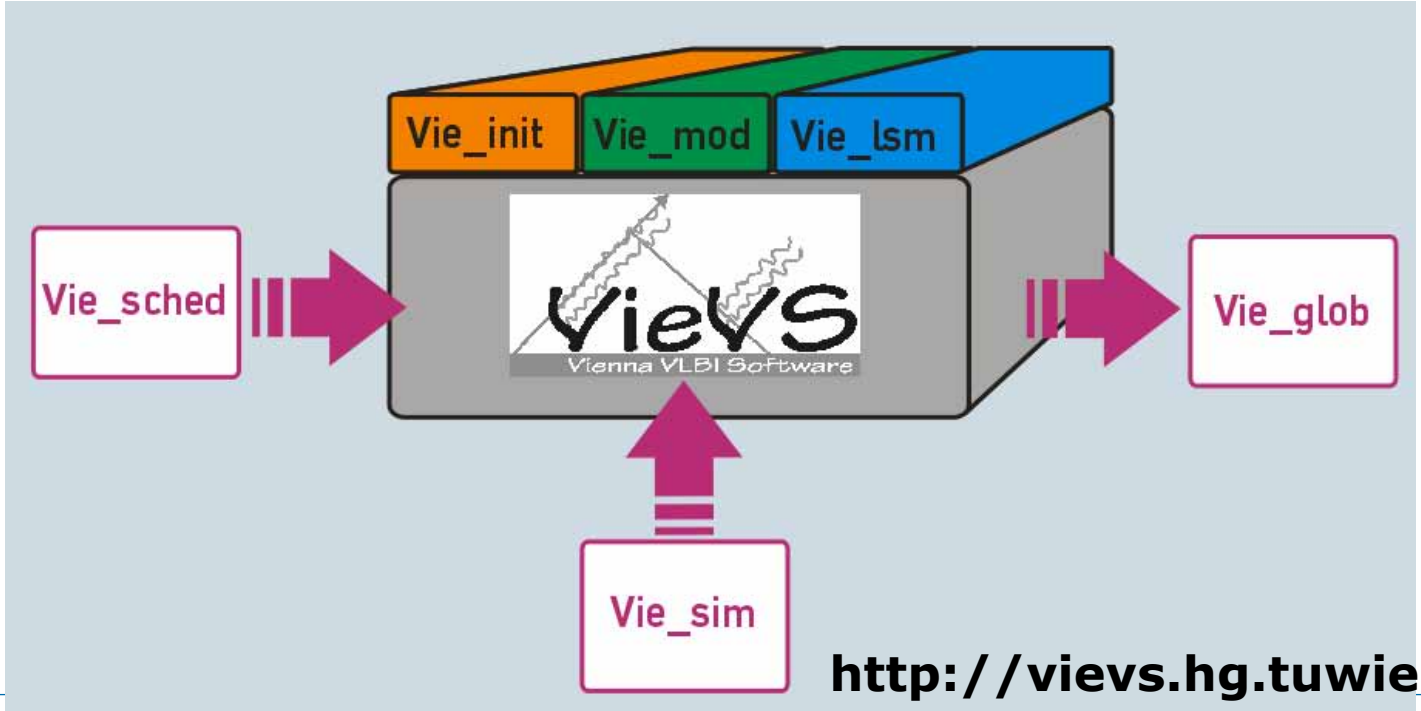
VLBI product: Station velocities



[IGG Vienna, 2011]

Vienna VLBI Software (VieVS)

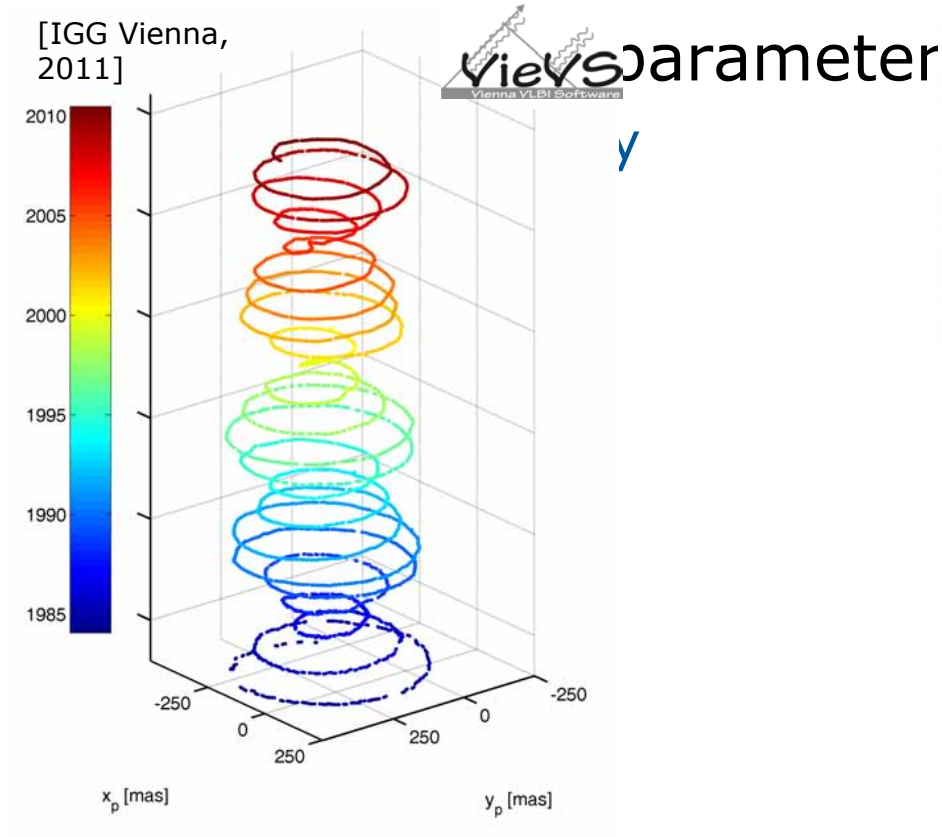
- Developed at TU Vienna since 2008, now as a joint effort of TU Vienna and GFZ/Potsdam
- Written in MATLAB
- Easy to use through graphical user interfaces



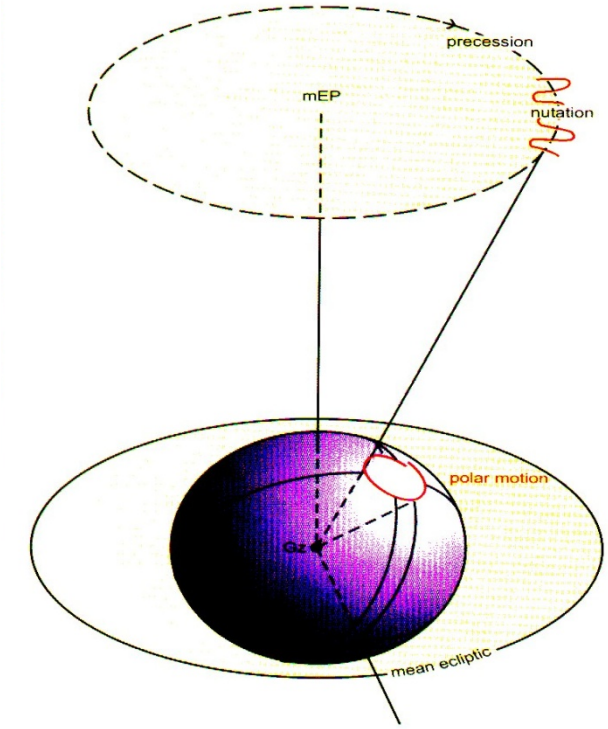
http://vievs.hg.tuwien.ac.at

VLBI product: Earth Orientation Parameters (EOP)

- Earth rotation parameters x_{pole}, y_{pole}, dUT1
- Pre [IGG Vienna, 2011] parameter

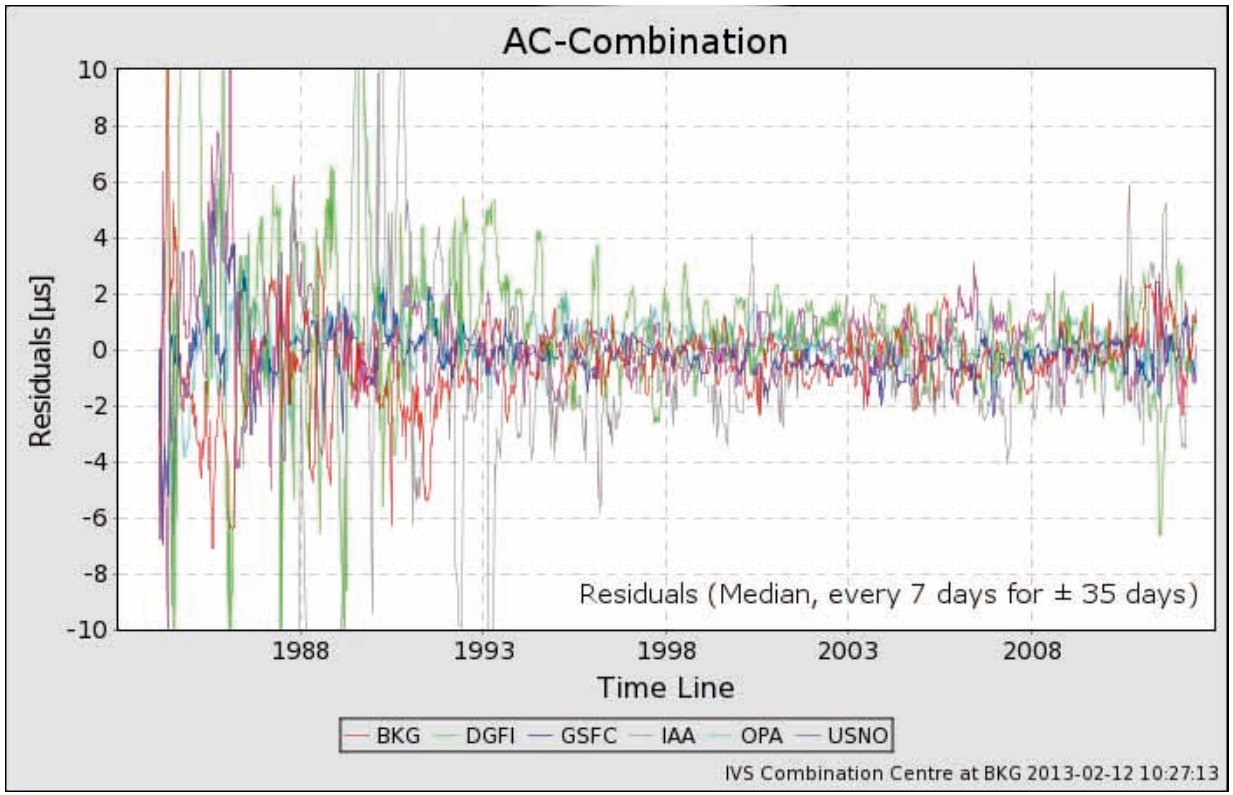


y



VLBI product: EOP

- Combined EOP are regular IVS products



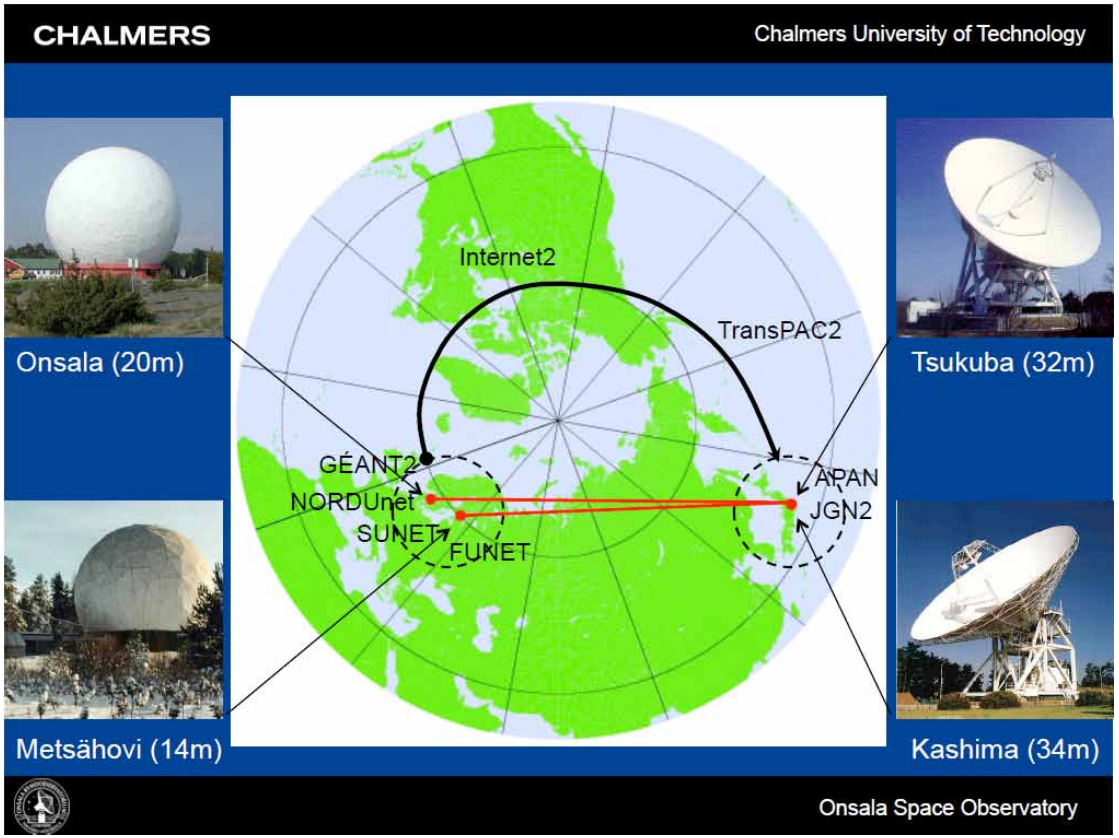
UT1-UTC residuals

[A. Nothnagel, IVS Analysis Coordinator, 2013 http://vlbi.geod.uni-bonn.de/IVS-AC]

- **Complete set of EOP**
  - dX, dY
  - x_p ,y_p
  - UT1-UTC
- **Combined solution from 6 Analysis Centers**
- **20-30% improvement**
  - accuracy
  - robustness
- **R1 & R4 since 2002**

e-VLBI Intensives (1h)

- Ultra-rapid Intensives between Europe and Japan
- Onsala-Tsukuba
  Metsähovi-Kashima
- UT1 turnaround within
  < 30 minutes

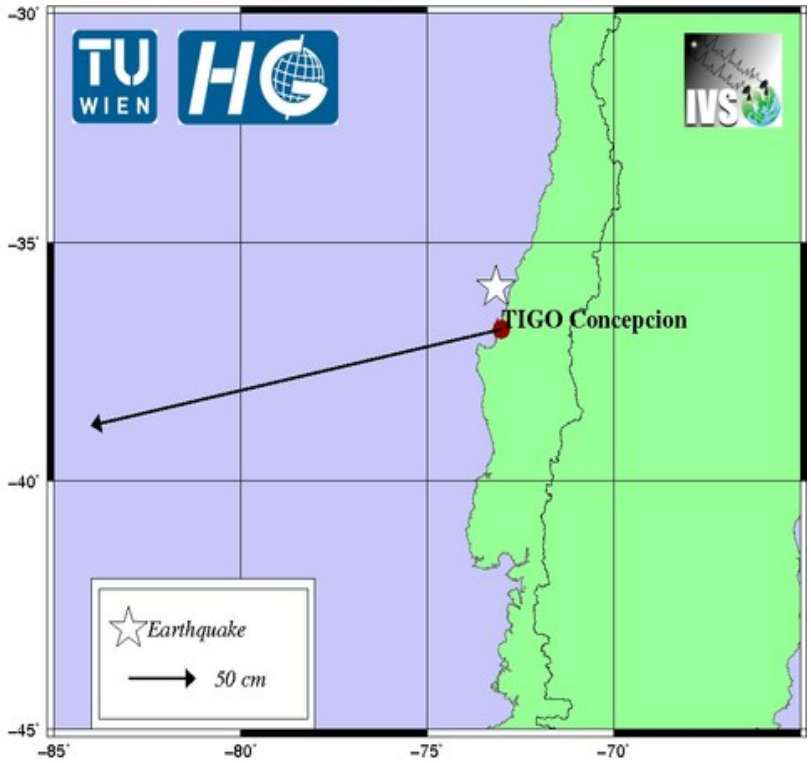


21. Feb. 2008:
Results within 4min after last scan [Matsuzaka et al., 2008]

**[Haas et al., 2011:
Ultra-rapid dUT1-observations with e-VLBI]**

VLBI product: Station motions

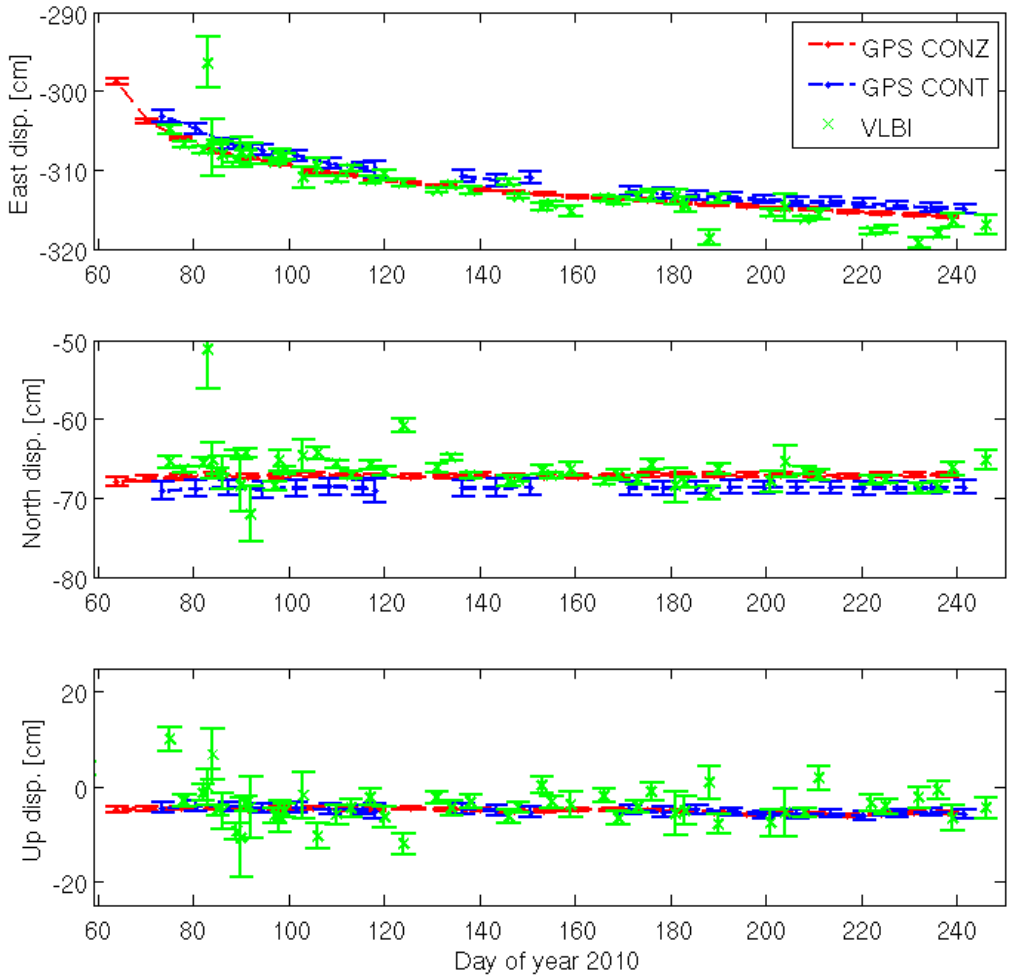
- Displacement of the TIGO radio telescope in Concepción caused by the magnitude 8.8 Earthquake on Feb 27, 2010.



Displacement of TIGO Concepción

- The Earthquake moved Concepción by about 3 m to the west
- Similar results are obtained from GPS measurements

after the Earthquake



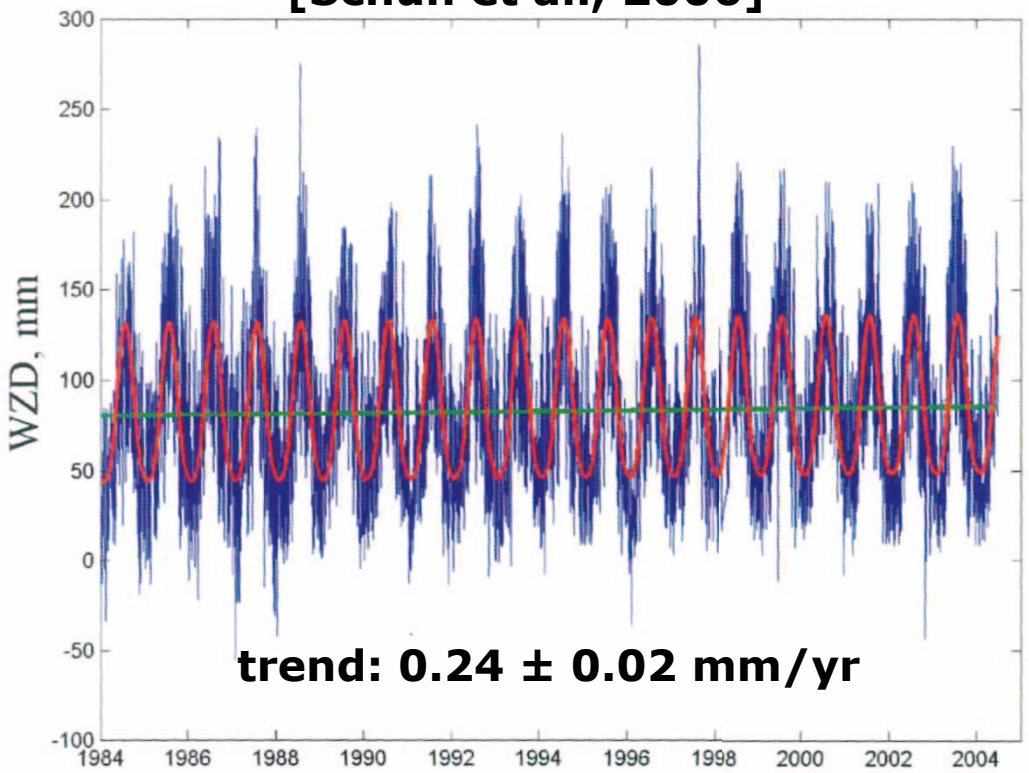
[IGG Vienna, 2010]

Climate studies using VLBI

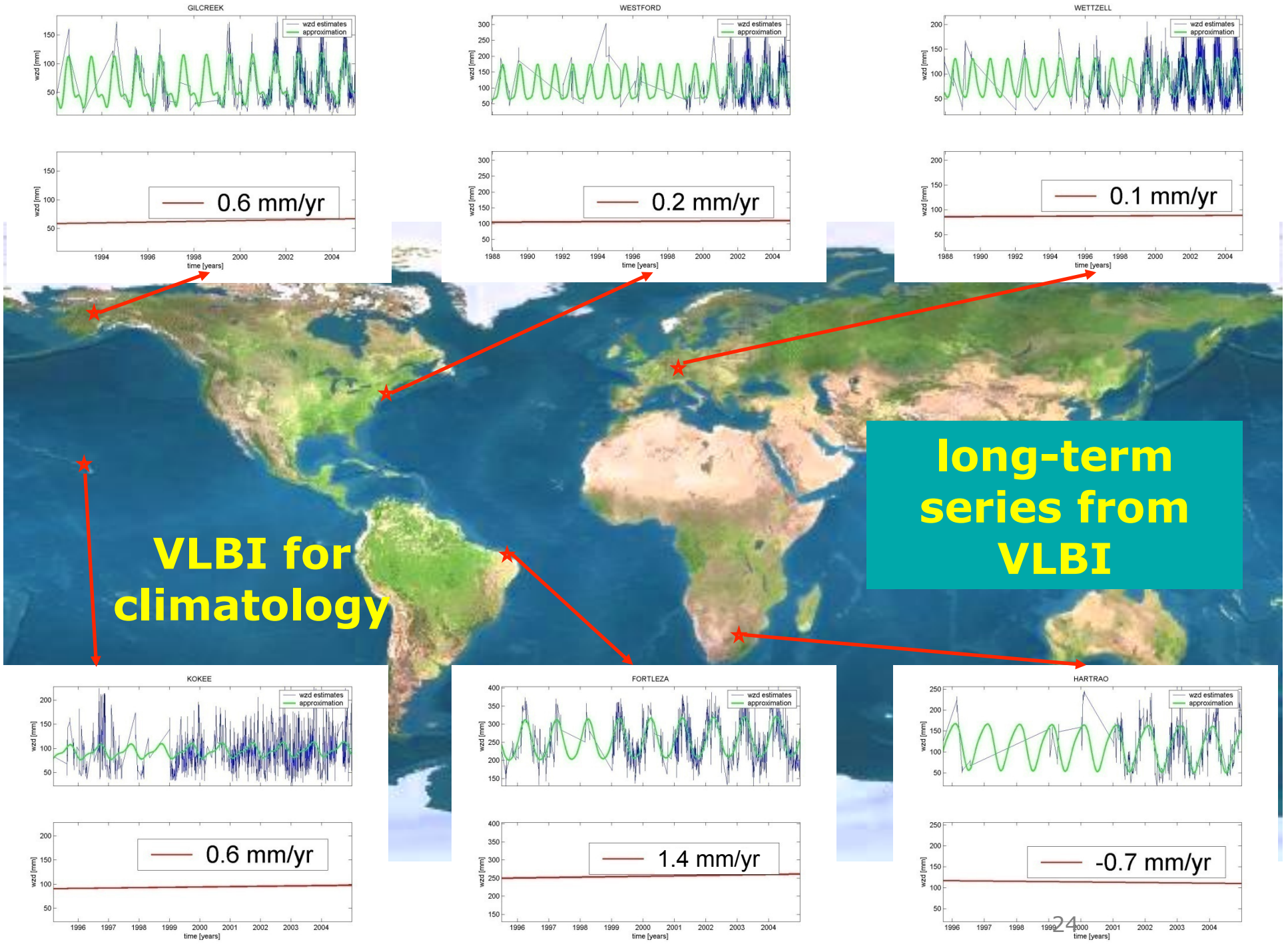
- Long time-series of Zenith Wet Delays (ZWD) can be used for climate studies
- To detect climate change series with high stability are needed

see also: R. Heinkelmann, 2008

[Schuh et al., 2006]



Wet zenith delays (blue) at Wettzell from VLBI obtained at IGG, annual and semiannual signal (red), linear trend (green).


GILCREEK
WESTFORD
WETTZELL
wzd estimates
approximation
wzd [mm]
0.6 mm/yr
0.2 mm/yr
0.1 mm/yr
time [years]
VLBI for climatology
long-term series from VLBI
KOKEE
FORTLEZA
HARTRAO
0.6 mm/yr
1.4 mm/yr
-0.7 mm/yr

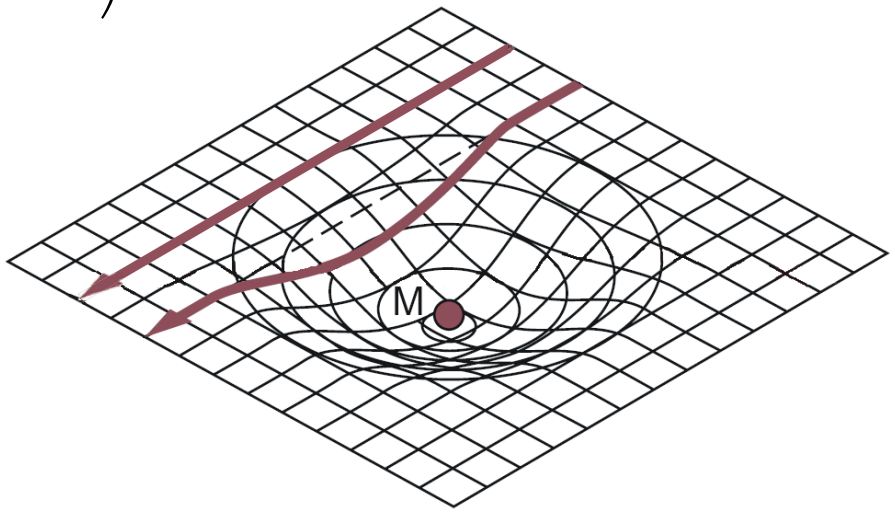
Gravitational time delay

Gravitational delay of n-th solar system body

$$\tau_{g,n} = (1+\gamma)\cdot\frac{GM_n}{c^3}\cdot\ln\left(\frac{\left|\vec{\mathbf{x}}_{1,\mathbf{n}}\right| + \vec{\mathbf{x}}_{1,\mathbf{n}}\cdot\vec{\mathbf{k}}}{\left|\vec{\mathbf{x}}_{2,\mathbf{n}}\right| + \vec{\mathbf{x}}_{2,\mathbf{n}}\cdot\vec{\mathbf{k}}}\right)$$

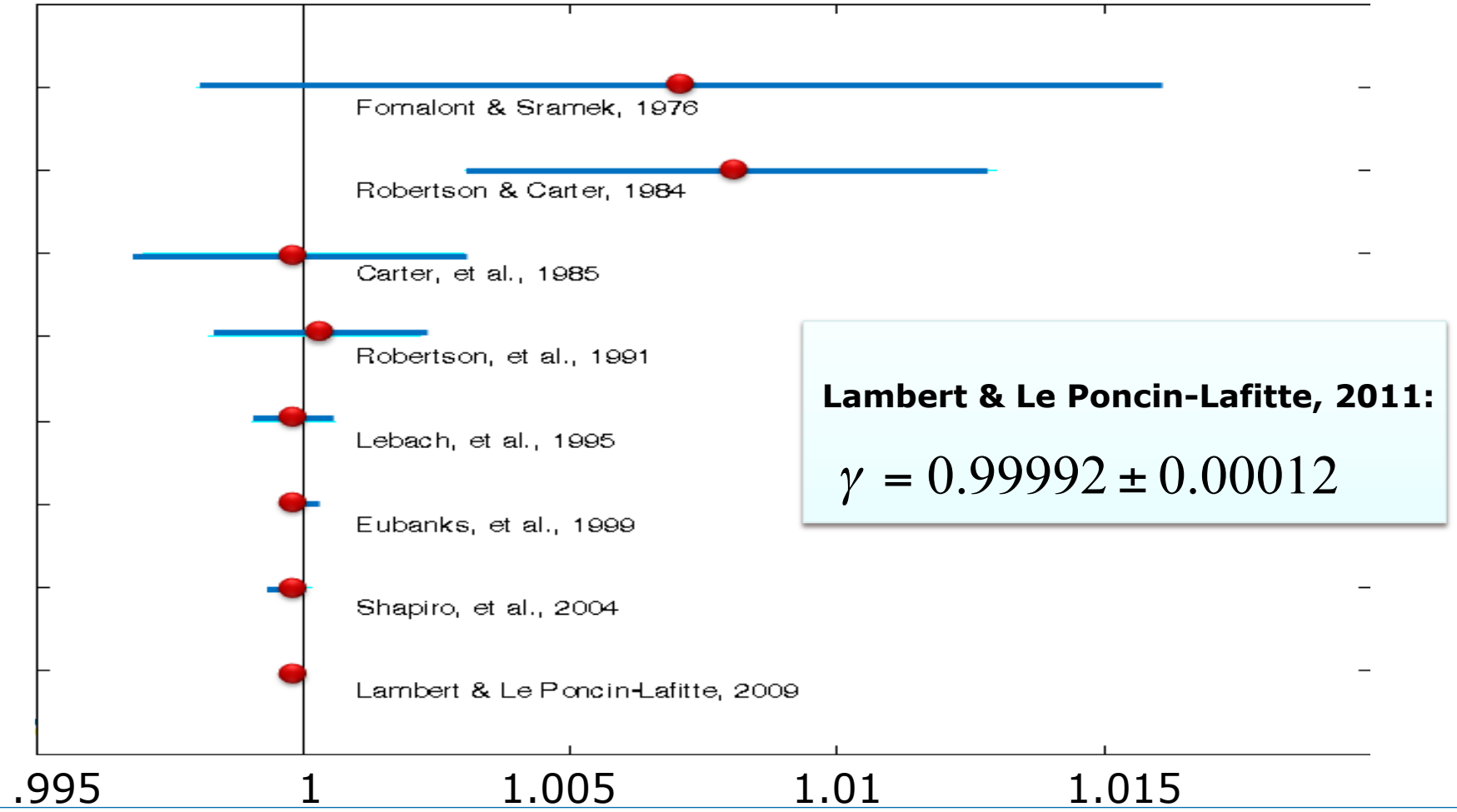
$\vec{x}_{i,n}$ **... position vector of station i w.r.t. center of mass of n-th body**

$\vec{k}$ **... unit vector towards source**



VLBI product: relativistic parameters

γ	„Mass-induced spatial curvature“	≡ 1 (GR)



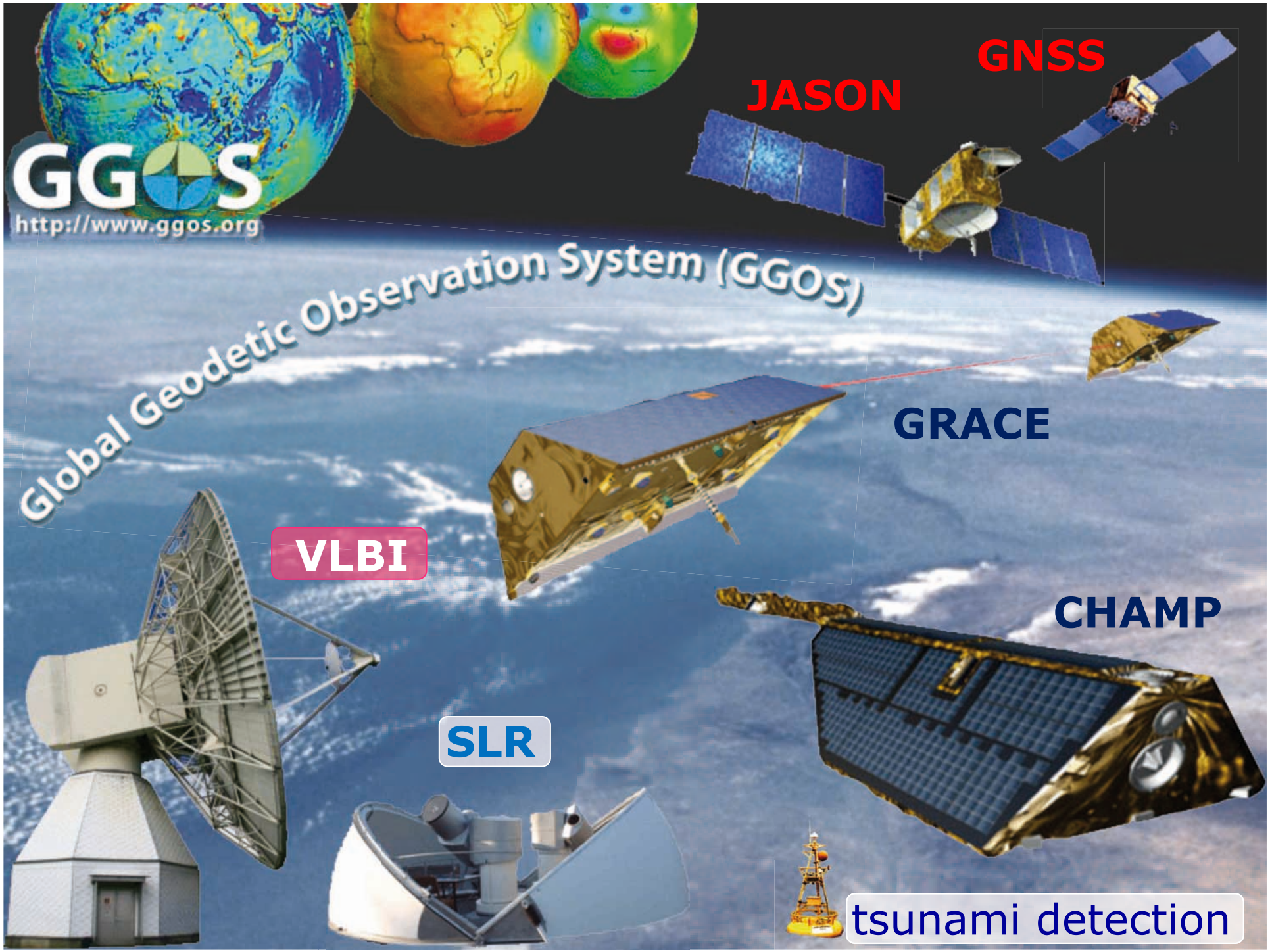
Lambert & Le Poncin-Lafitte, 2011:

$$\gamma = 0.99992 \pm 0.00012$$

VLBI and GGOS

- In the last years GGOS, the Global Geodetic Observing System of the IAG has been implemented.

- All VLBI results are provided to GGOS (via the IVS)


GGOS
http://www.ggos.org
Global Geodetic Observation System (GGOS)
JASON
GNSS
GRACE
CHAMP
VLBI
SLR
tsunami detection

Contribution of VLBI to GGOS

[M. Rothacher]

Parameter Type	VLBI	GNSS	DORIS	SLR	LLR	Altimetry
ICRF (Quasars)	**X**					
Nutation	**X**	(X)		(X)	X	
Polar Motion	X	X	X	X	X	
UT1	**X**					
Length of Day	(X)	X	X	X	X	
ITRF (Stations)	X	X	X	X	X	(X)
Geocenter		X	X	X		X
Gravity Field		X	X	X	(X)	X
Orbits		X	X	X	X	X
LEO Orbits		X	X	X		X
Ionosphere	X	X	X			X
Troposphere	X	X	X			X
Time Freq./Clocks	X	X		(X)		

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Motivation: Monitoring the Earth System

Geometry and Deformation of the Earth

- **Problem and fascination of measuring the Earth:**

Everything is moving !

- **Monitoring today mainly by permanent networks (e.g. ITRF, SIRGAS, EUREF, GEONET, ...)**

- **Examples**
  - Earth rotation
  - Plate motions
  - Earthquakes
  - Solid Earth tides (caused by Sun and Moon)
  - Loading phenomena (ice, ocean, atmosphere)
  - Sea-level change

Continuous monitoring is absolutely crucial !

VLBI2010: why do we need it?

- Aging systems
- Rapid developments in technology
- New requirements on products
- phenomena to be observed have magnitudes of a few millimeters ➡ mm accuracy!
- **VLBI2010:** response of the IVS to significantly improve geodetic VLBI and reach this high level of accuracy
- 2003-2005:

  IVS Working Group 3 „VLBI2010"

  - goals and requirements
  - strategies and recommendations

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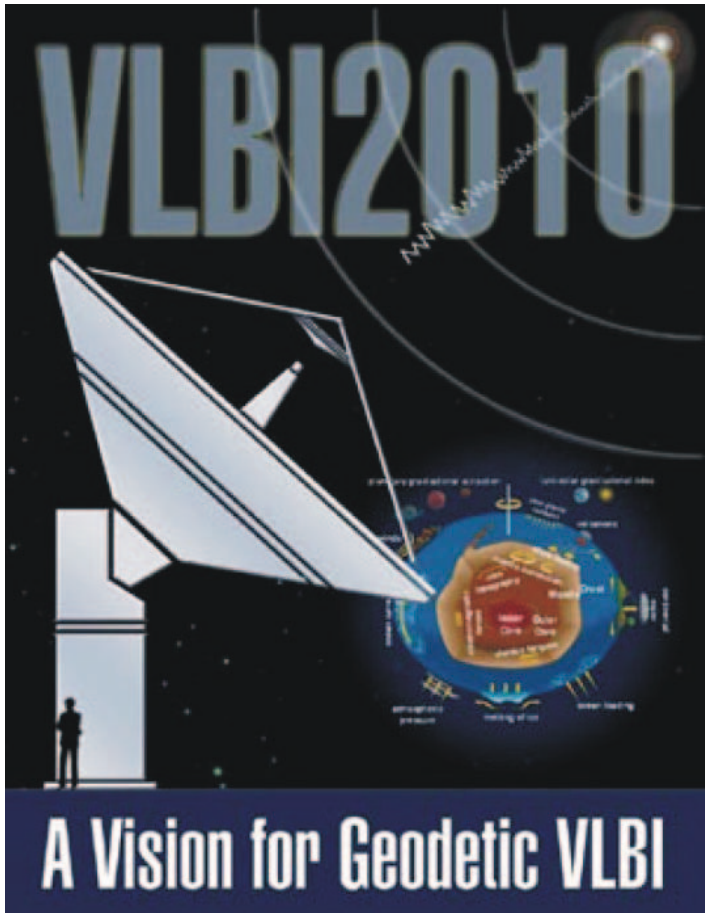
WG 3 report



http://ivscc.gsfc.nasa.gov/about/wg/wg3/IVS_WG3_report_050916.pdf

VLBI2010 – goals and strategies

- goals
  - **1 mm position and 0.1 mm/yr** velocity accuracy on global scales
  - **continuous measurements** (time series of EOPs and baselines)
  - turn around time to initial geodetic results within **less than 24 hours**
  - **low cost** construction and operation

- strategies
  - reduce random and systematic errors of delay observables
  - improve geographic distribution of antennas
  - increase number of observations
  - develop new observing strategies

VLBI2010 – the V2C

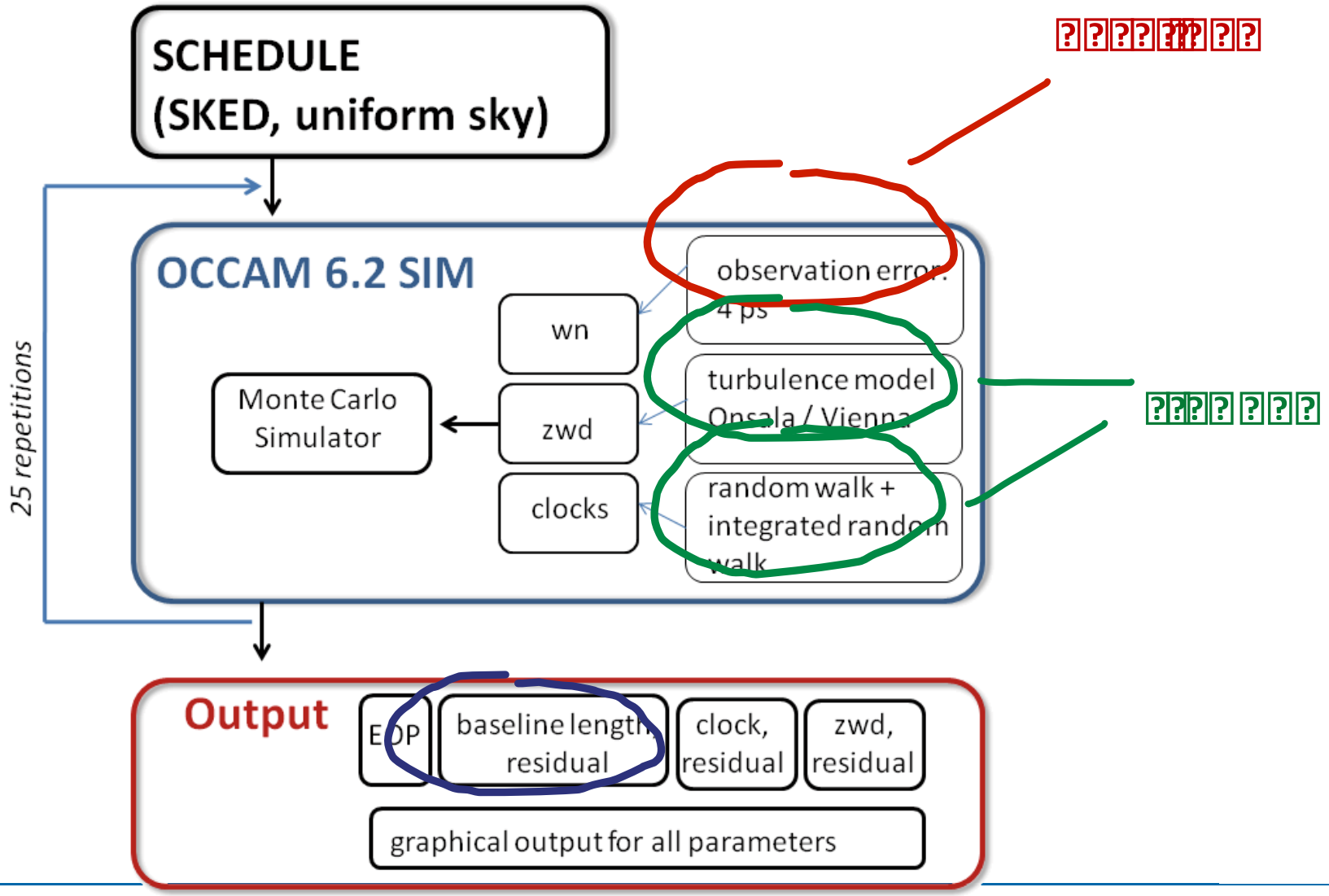
- the **VLBI2010 Committee (V2C)** was established in September 2005

- to encourage the implementation of the recommendations of WG3

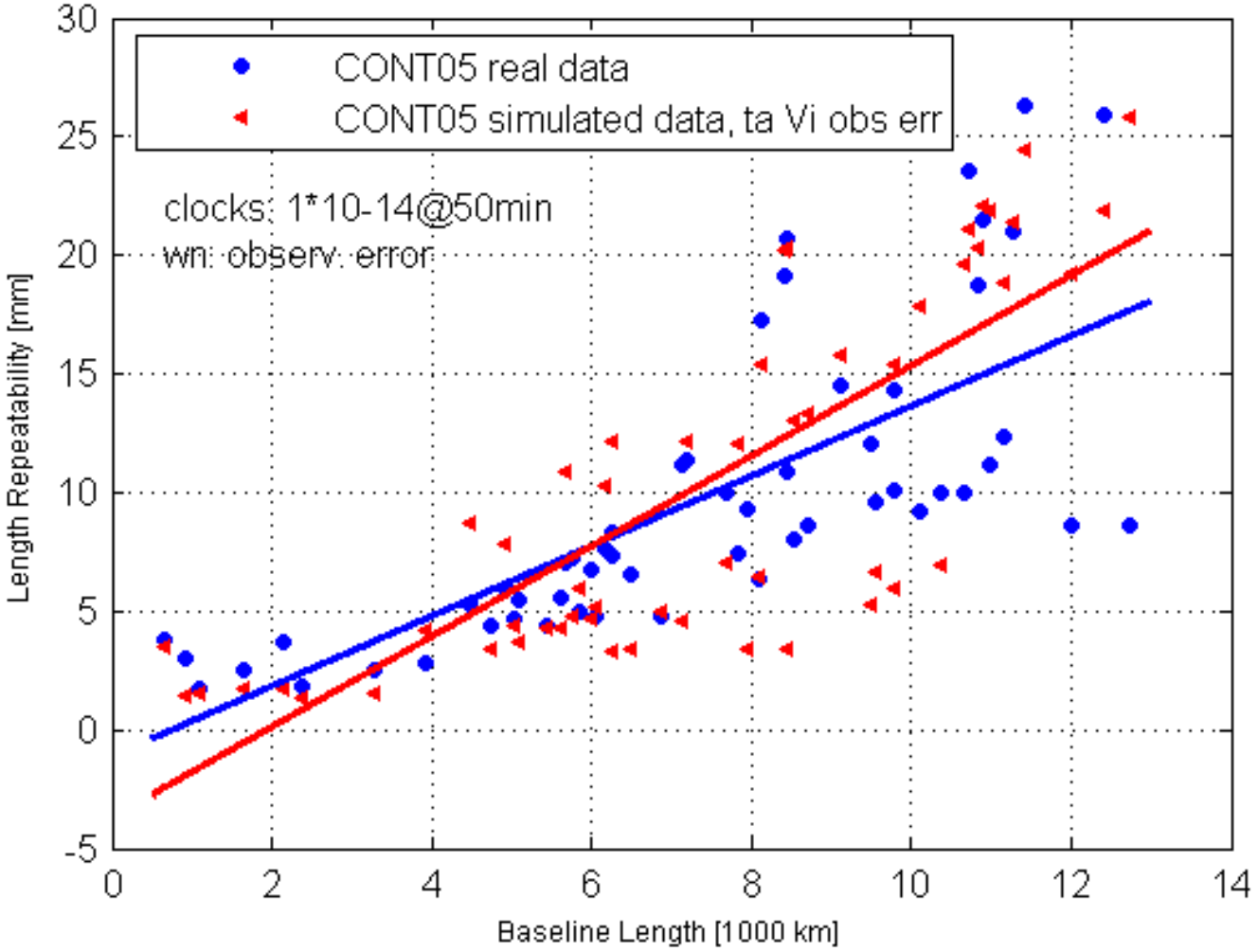
VLBI2010 – V2C activities

- system studies
- Monte Carlo simulations
- development projects
- prototyping

VLBI 2010 Monte Carlo simulations



CONT05: real data versus Monte Carlo simulator



zenith wet delay (zwd)

turb. model Vienna

clocks

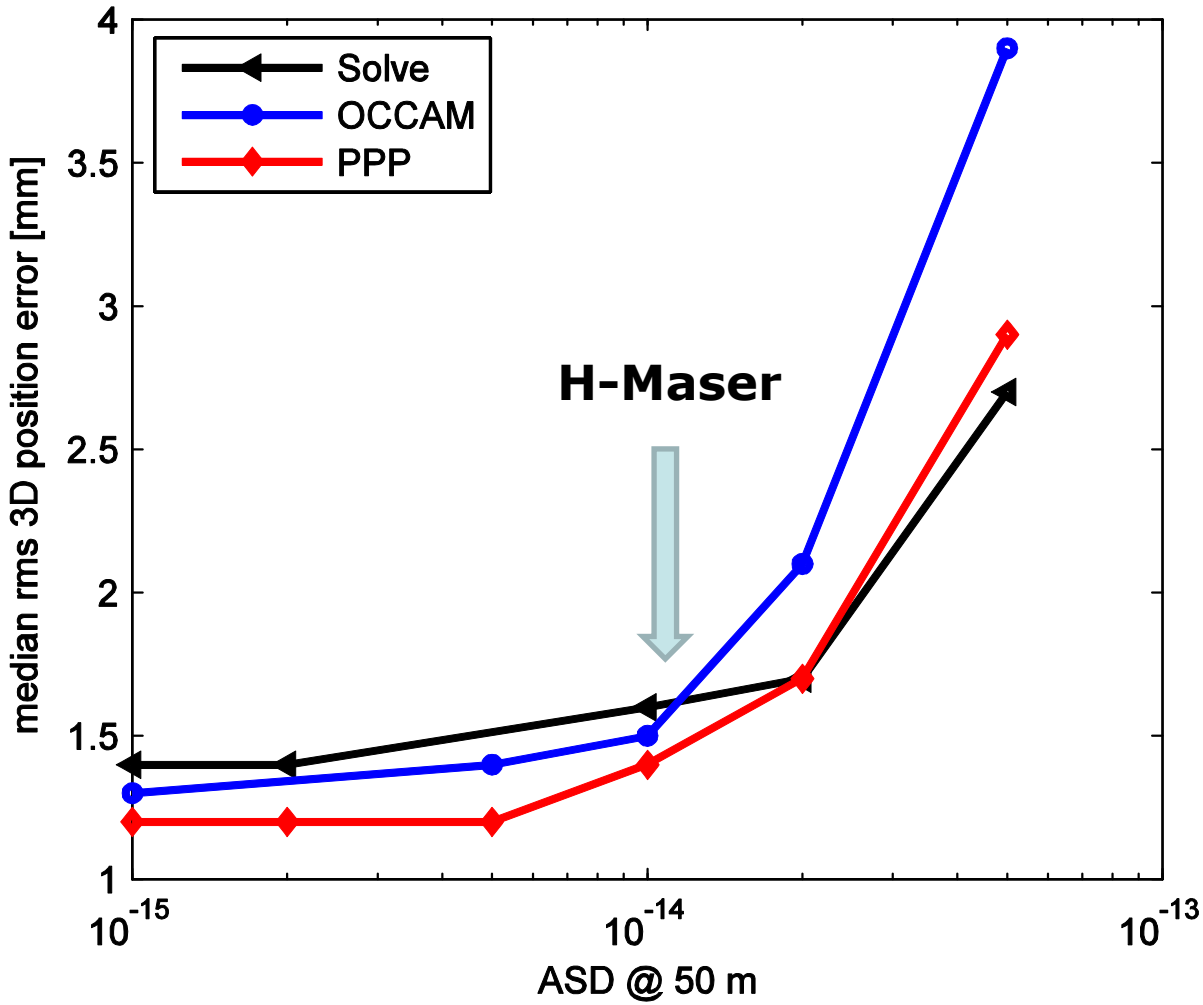
$1 \cdot 10^{-14}$@50min (ASD)

white noise

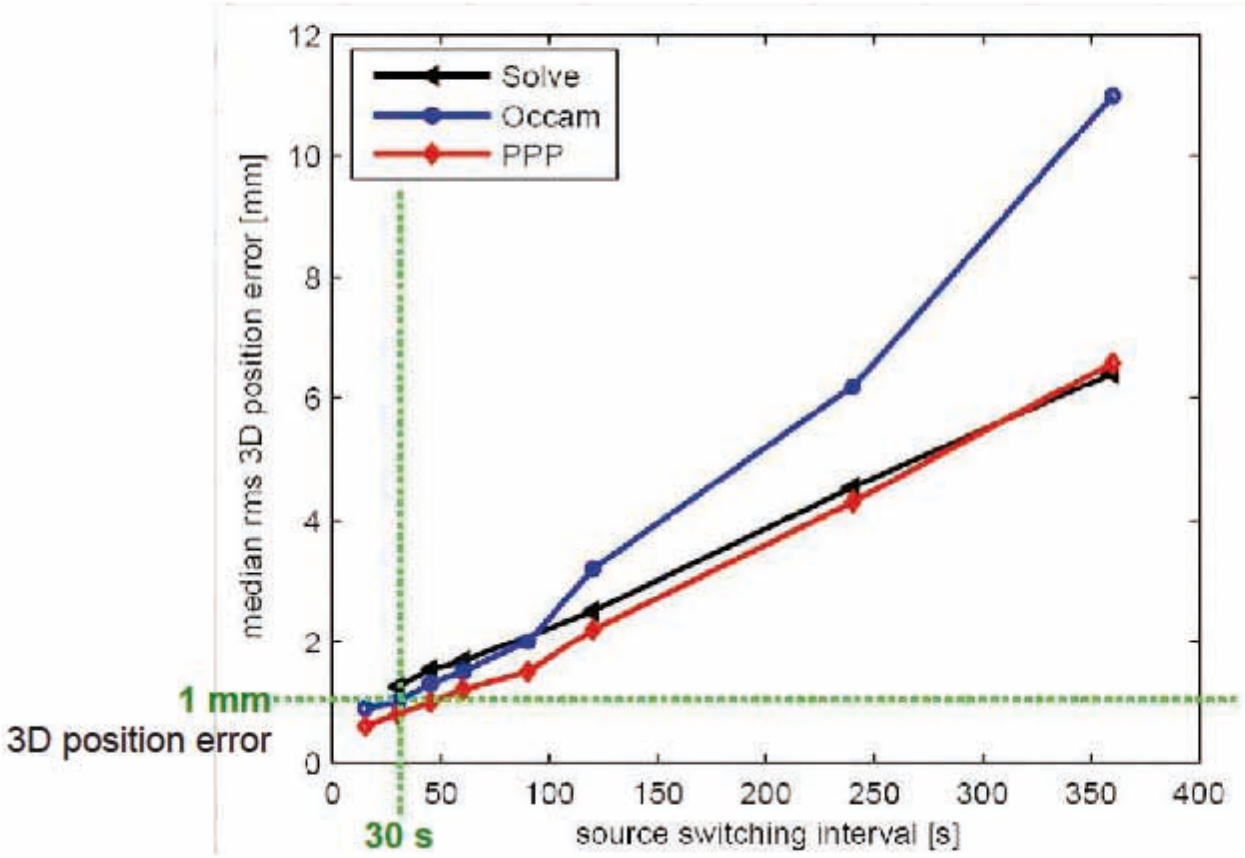
obs. error

- the use of the turbulence model gives a realistic Monte Carlo simulation

Test of different clock performance

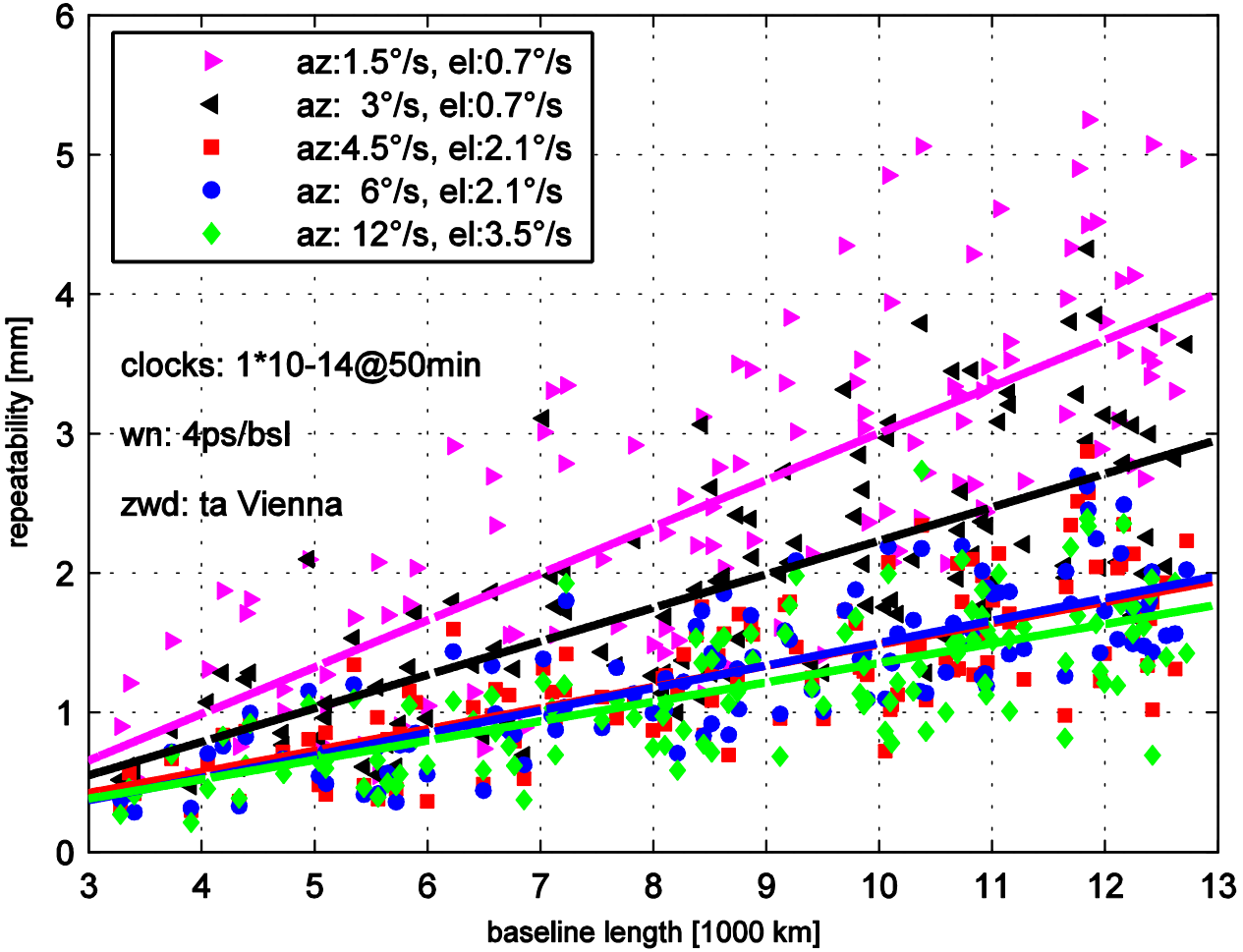


Ex.: Source switching intervals



Slew speed tests using SKED

Baseline length repeatability



zwd:
turbulence
model -Vienna

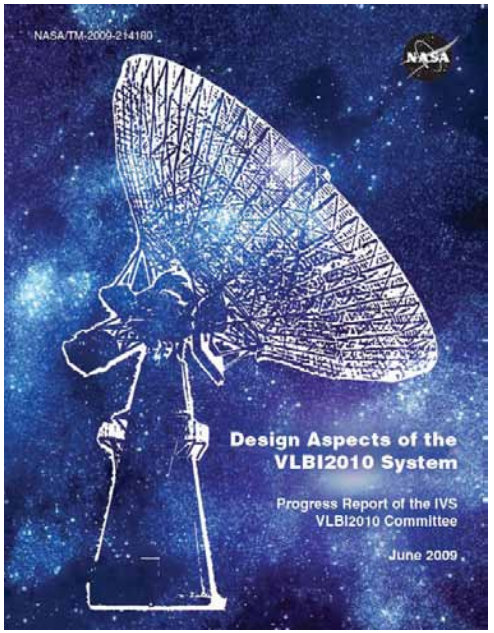
clocks:
$1 \cdot 10^{-14}$@50min

wn: 4psec/bsl

VLBI2010 – V2C Progress Report

- "Design Aspects of the VLBI2010 System"

	Current	VLBI2010
antenna size	5–100 m dish	~ 12 m dish
slew speed	~20–200 deg/min	≥ 360 deg/min
sensitivity	200–15,000 SEFD	≤ 2,500 SEFD
frequency range	S/X band	~2–14 (18) GHz
recording rate	128-512 Mbps	8–16 Gbps
data transfer	usually ship disks, some e-transfer	e-transfer, e-VLBI, ship disks when required



ftp://ivscc.gsfc.nasa.gov/pub/misc/V2C/TM-2009-214180.pdf

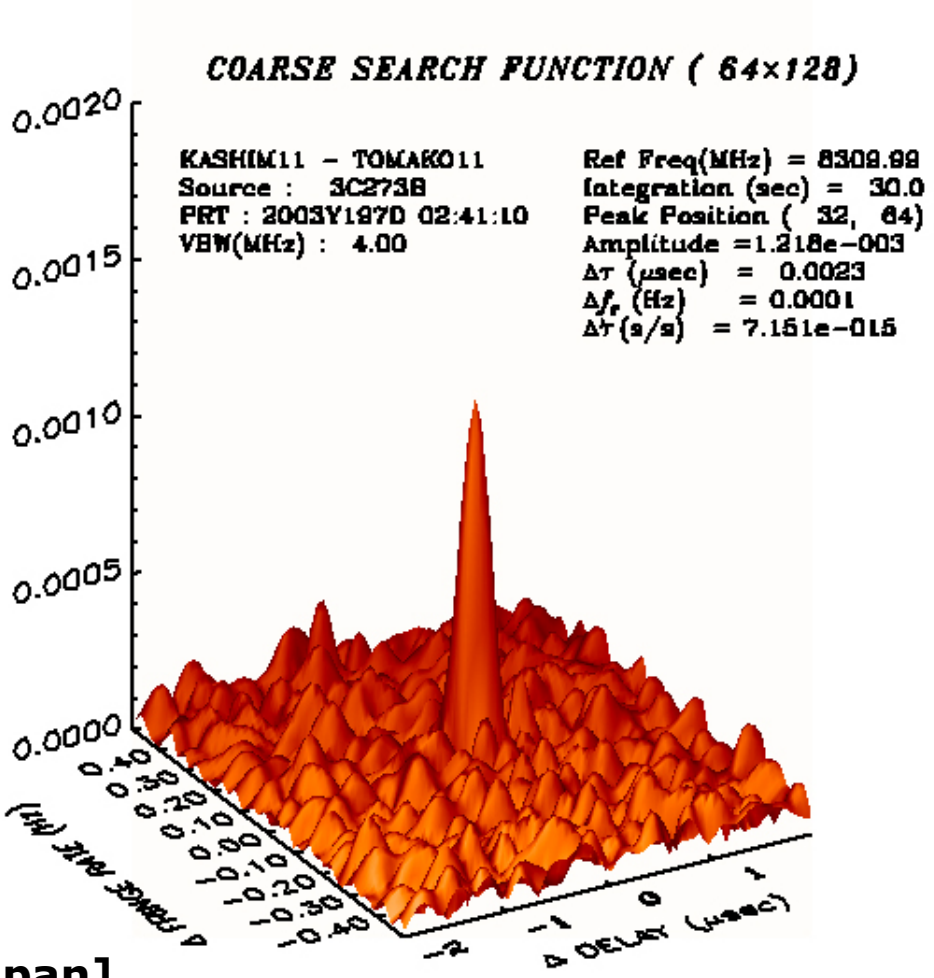
VLBI2010 – a completely new generation of VLBI hardware and software

VLBI2010 also includes

- software correlation

VLBI correlation in the future

- Software correlator
- Use of Graphics processing units (GPU)



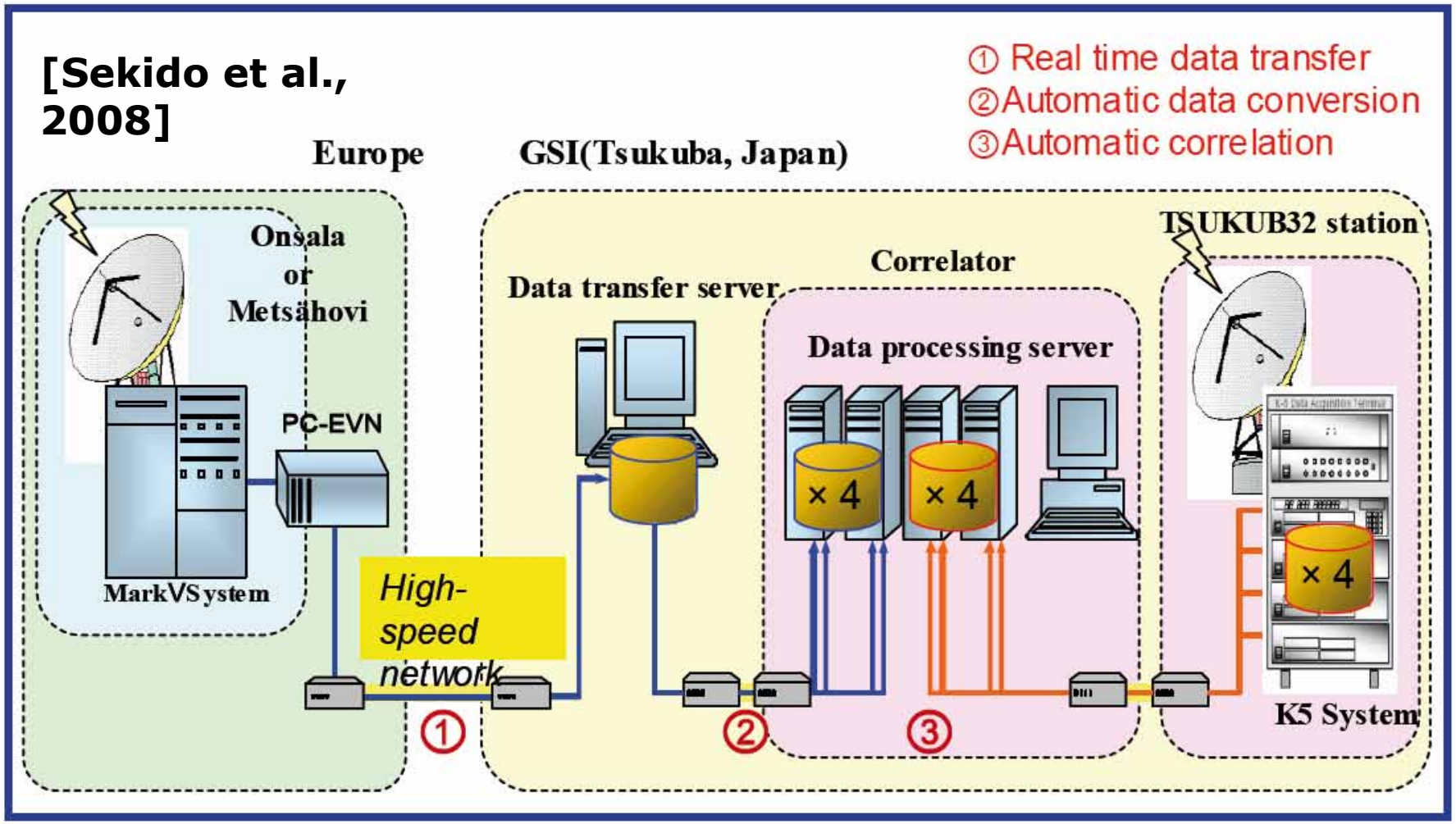
[T. Hobiger, NICT, Japan]

VLBI2010 – a completely new generation of VLBI hardware and software

VLBI2010 also includes

- software correlation
- automation of data analysis

VLBI analysis automation



VLBI2010 – a completely new generation of VLBI hardware and software

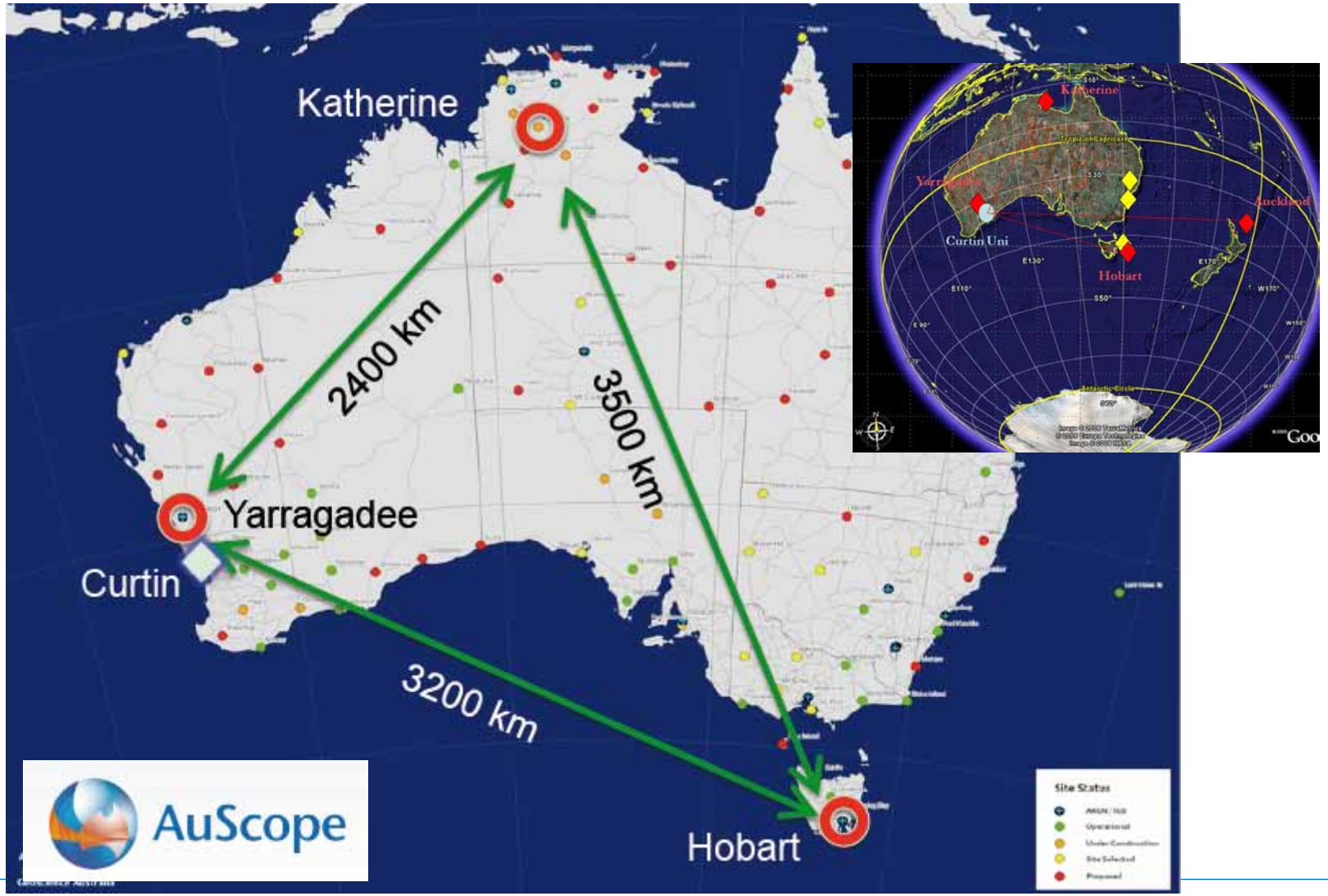
VLBI2010 also includes

- software correlation
- automation of data analysis
- promote e-transfer
- many other aspects…

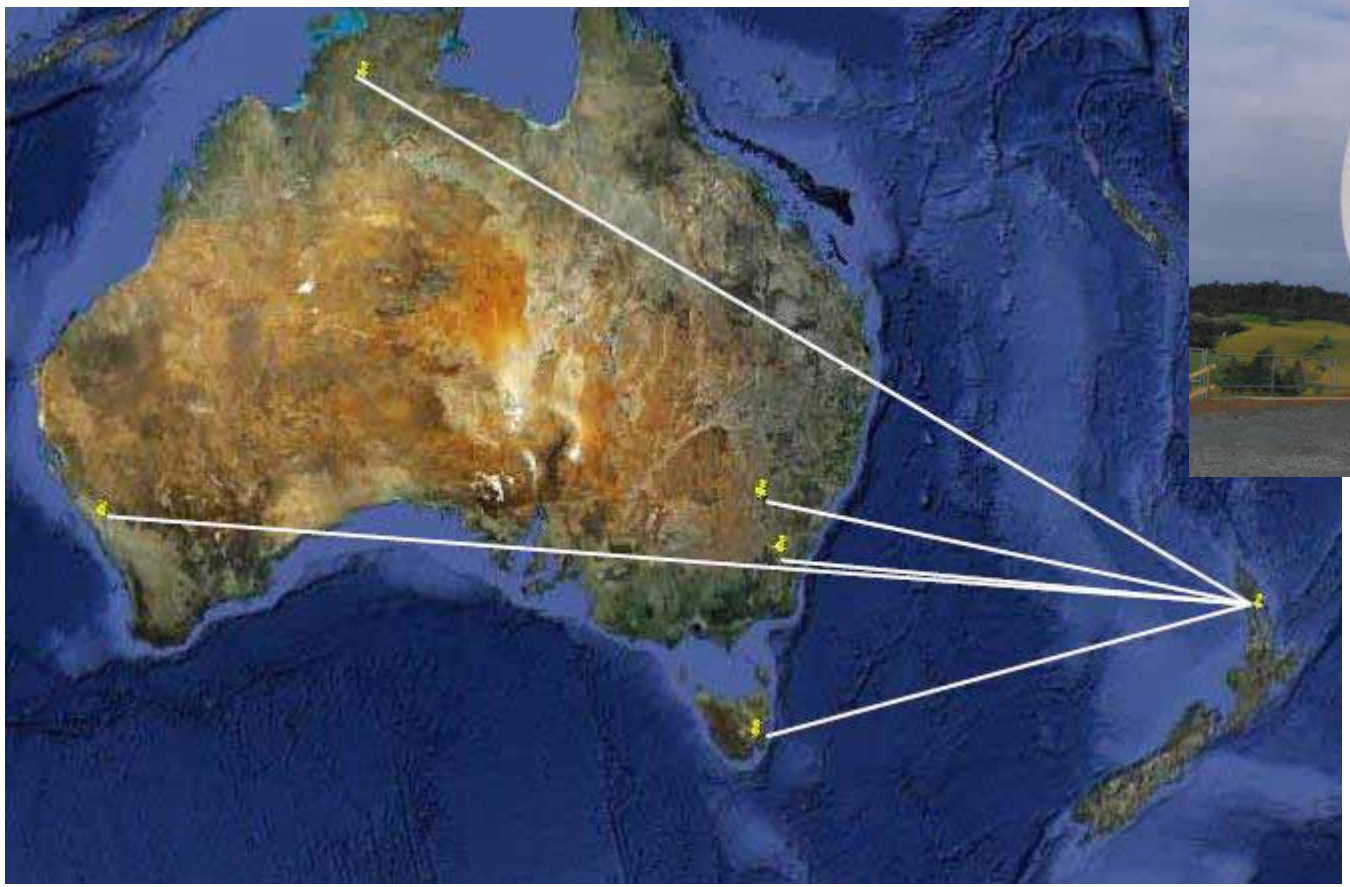
1st VLBI2010 antenna: Hobart (AUS)

Dedication of the 1st VLBI2010 antenna by the Governor of Tasmania; Feb-09-2010; Mt. Pleasant Observatory, TAS, AUS

New VLBI2010 antennas: AuScope



New VLBI2010 antenna: AUT (NZL)

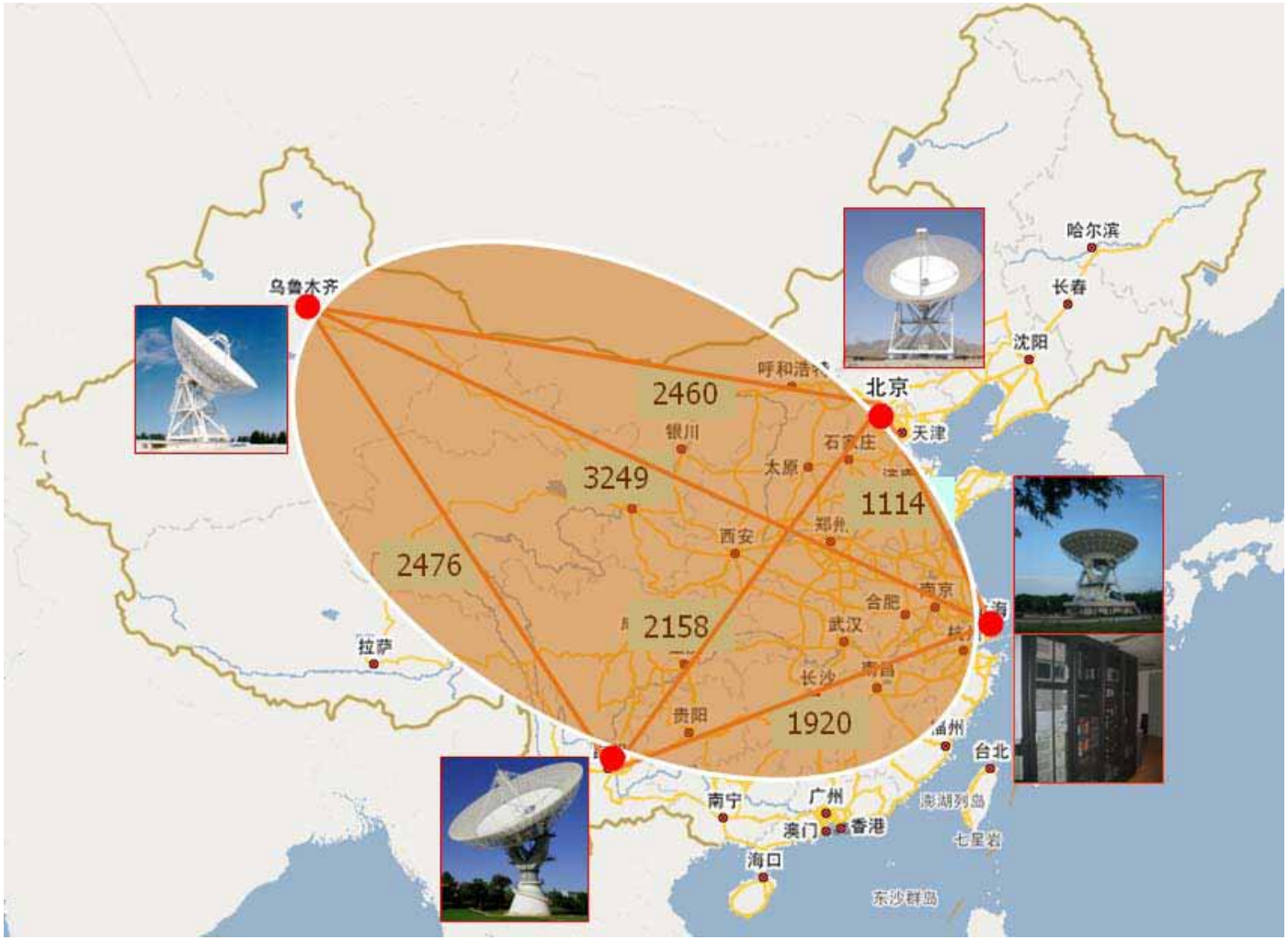


AUT
UNIVERSITY
TE WĀNANGA ARONUI O TAMAKI MAKAU RAU

- Spatial Data Infrastructure

Model of the Australian Spatial Data Infrastructure

New VLBI2010 antennas: China



New VLBI2010 antennas: RAEGE

RED ATLÁNTICA DE ESTACIONES GEODINÁMICAS Y ESPACIALES (RAEGE)

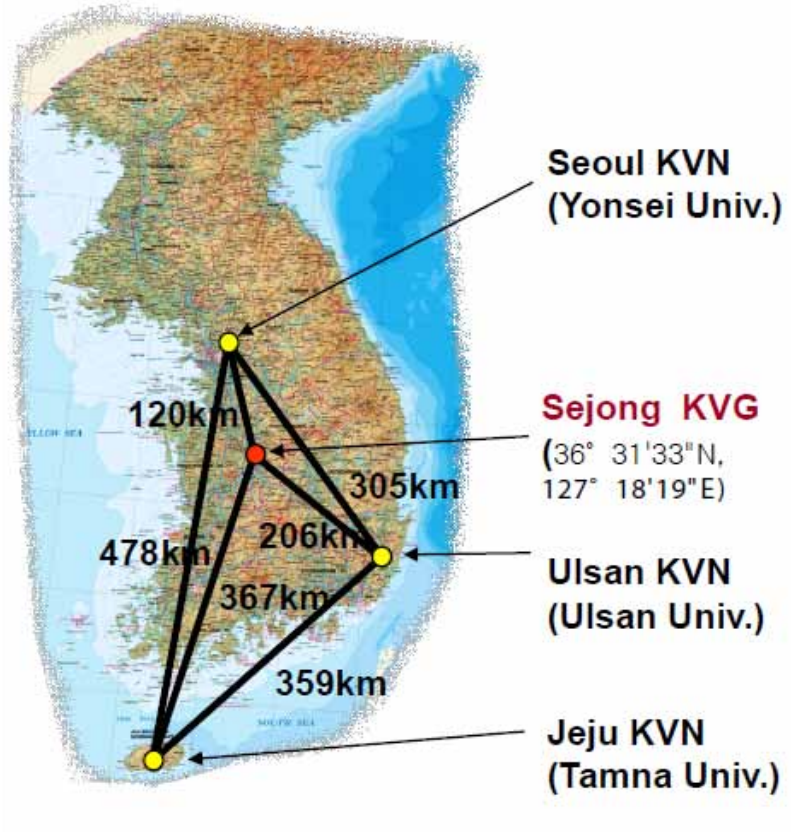
4 new VLBI 2010 antennas (of TTW type)

Baselines:

- Yebes – Canary Islands : 2150 km
- Yebes – Sao Miguel : 2000 km
- Yebes – Flores : 2400 km
- Canary Islands – Flores : 2000 km

Korea VLBI for Geodesy (KVG)

- KVN (Korean VLBI Network) partly for geodesy
- KVG fully for geodesy



New VLBI2010 antennas: TTW

- Twin Telescope Wettzell (GER), two new Vertex antennas

Twin Telescope Wettzell, April 2012

NASA Broadband Delay Proof-of-concept Development Project

- **Purpose**:
  - Prove that Broadband Delay can be used operationally to resolve phase delay.
  - Develop the first generation of VLBI2010 electronics.
  - Gain experience with new VLBI2010 subsystems.
- **Status:**
  - Proof-of-concept tests are ongoing (2013).
  - Final prototypes are in development.

VLBI2010 – Current Status (March 2013)

- **V2PEG (VLBI2010 Project Executive Group)** is in charge of providing strategic leadership to VLBI2010, realization of the concept, contacts on political level, letters of support, visits, consulting etc.
- **Station Survey (questionnaire)** sent to IVS observing stations asking about their future plans
- **VGOS (VLBI2010 Global Observing System)** was launched at the IVS General Assembly in Madrid (March 2012)
- **RFI tests** at the stations
- Tables with **Digital Backend comparisons** and **feed comparisons** have been produced:
  http://www.haystack.mit.edu/workshop/ivtw/2012.12.17_DBE_testing_memo_final.pdf

Status of VLBI2010 in 2013

VLBI2010 Network in 2011

VLBI2010 very fast

- radio telescope
- twin radio telescope

VLBI2010 fast

- radio telescope

upgrade legacy

- radio telescope

[Hase et al., 2011]

VLBI2010 Network in 2012

VLBI2010 very fast

radio telescope

twin radio telescope

VLBI2010 fast

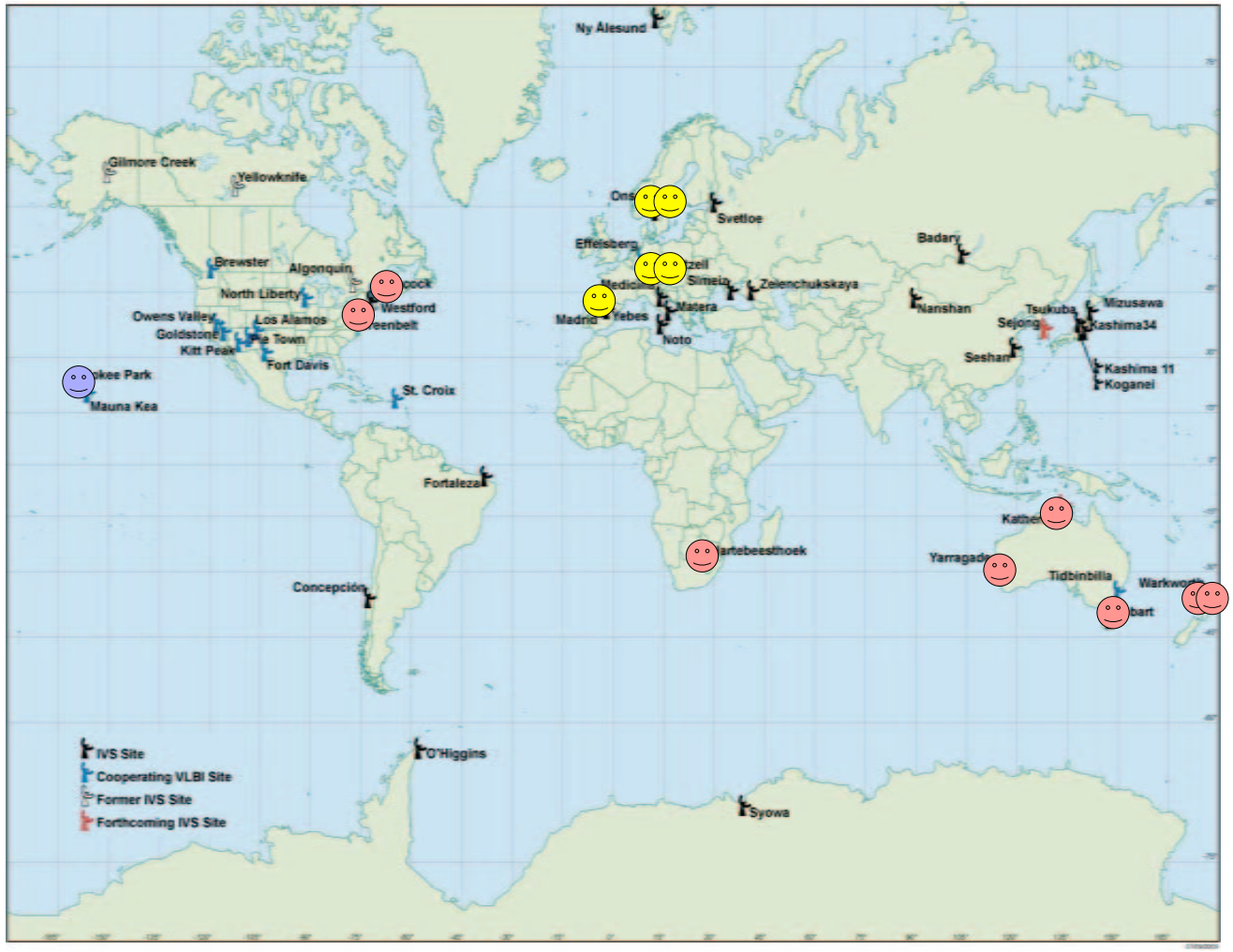
radio telescope

upgrade legacy

radio telescope

[Hase et al., 2011]

VLBI2010 Network in 2013



VLBI2010 very fast

- radio telescope
- twin radio telescope

VLBI2010 fast

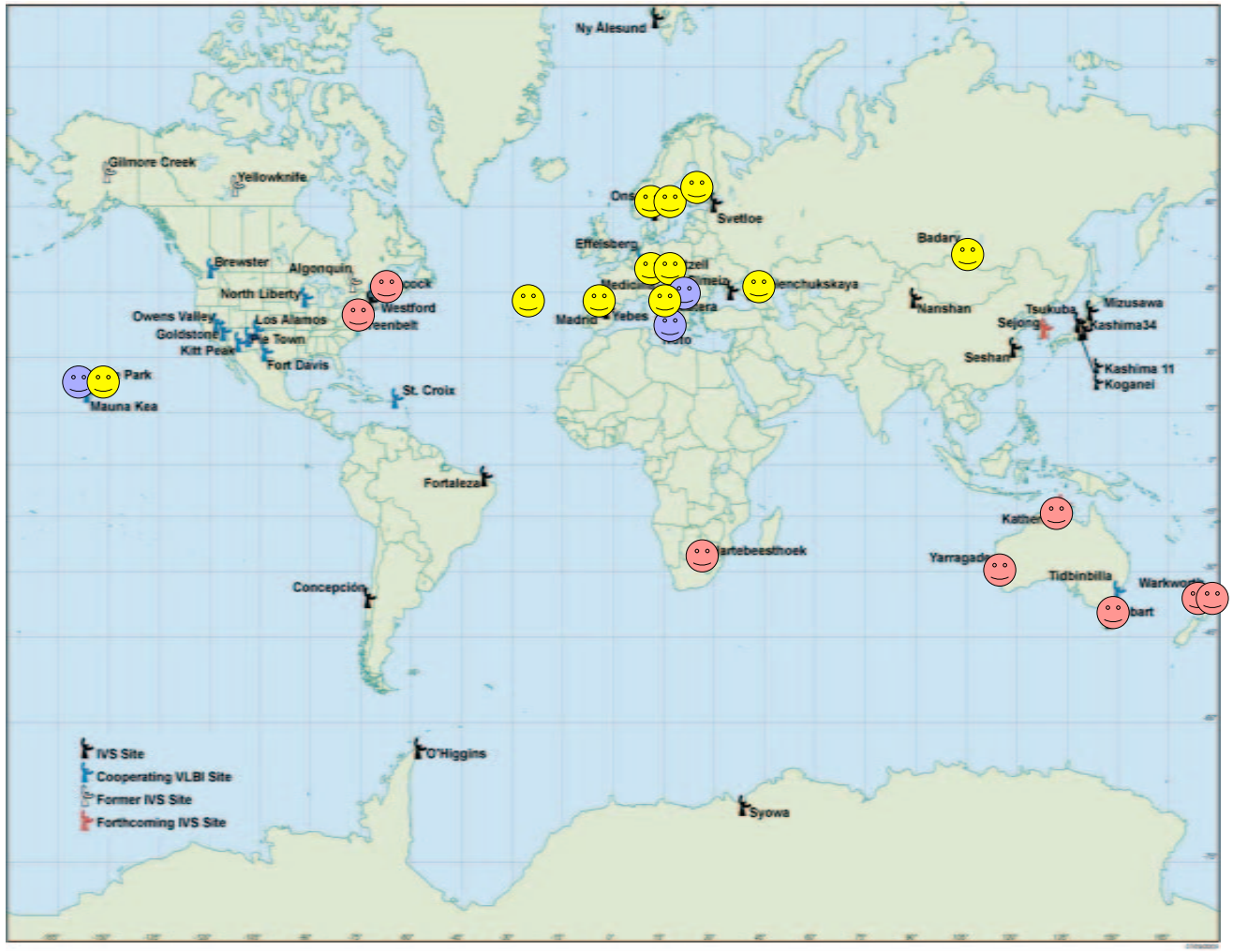
- radio telescope

upgrade legacy

- radio telescope

[Hase et al., 2011]

VLBI2010 Network in 2014



VLBI2010 very fast

radio telescope

twin radio telescope

VLBI2010 fast

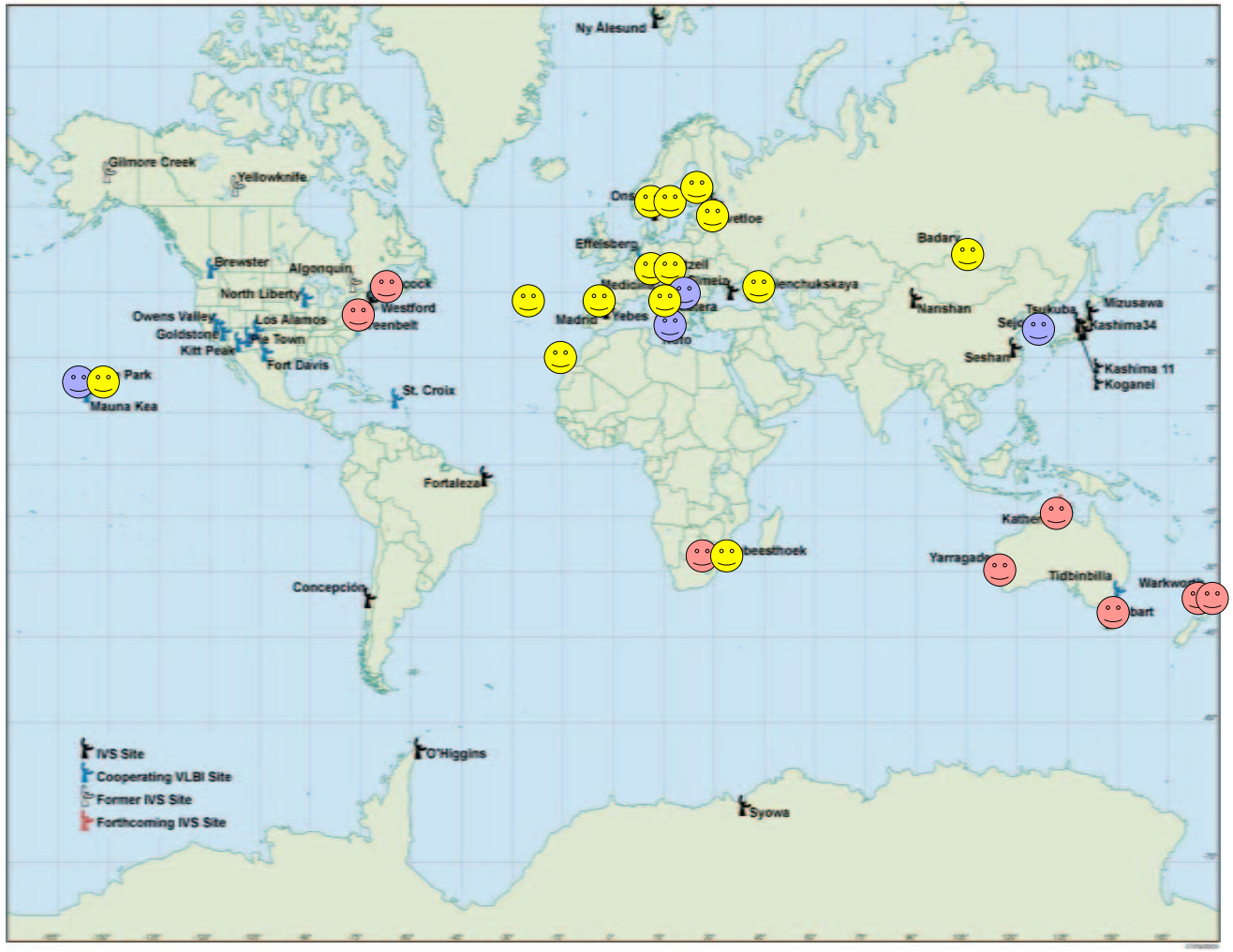
radio telescope

upgrade legacy

radio telescope

[Hase et al., 2011]

VLBI2010 Network in 2015



VLBI2010 very fast

radio telescope

twin radio telescope

VLBI2010 fast

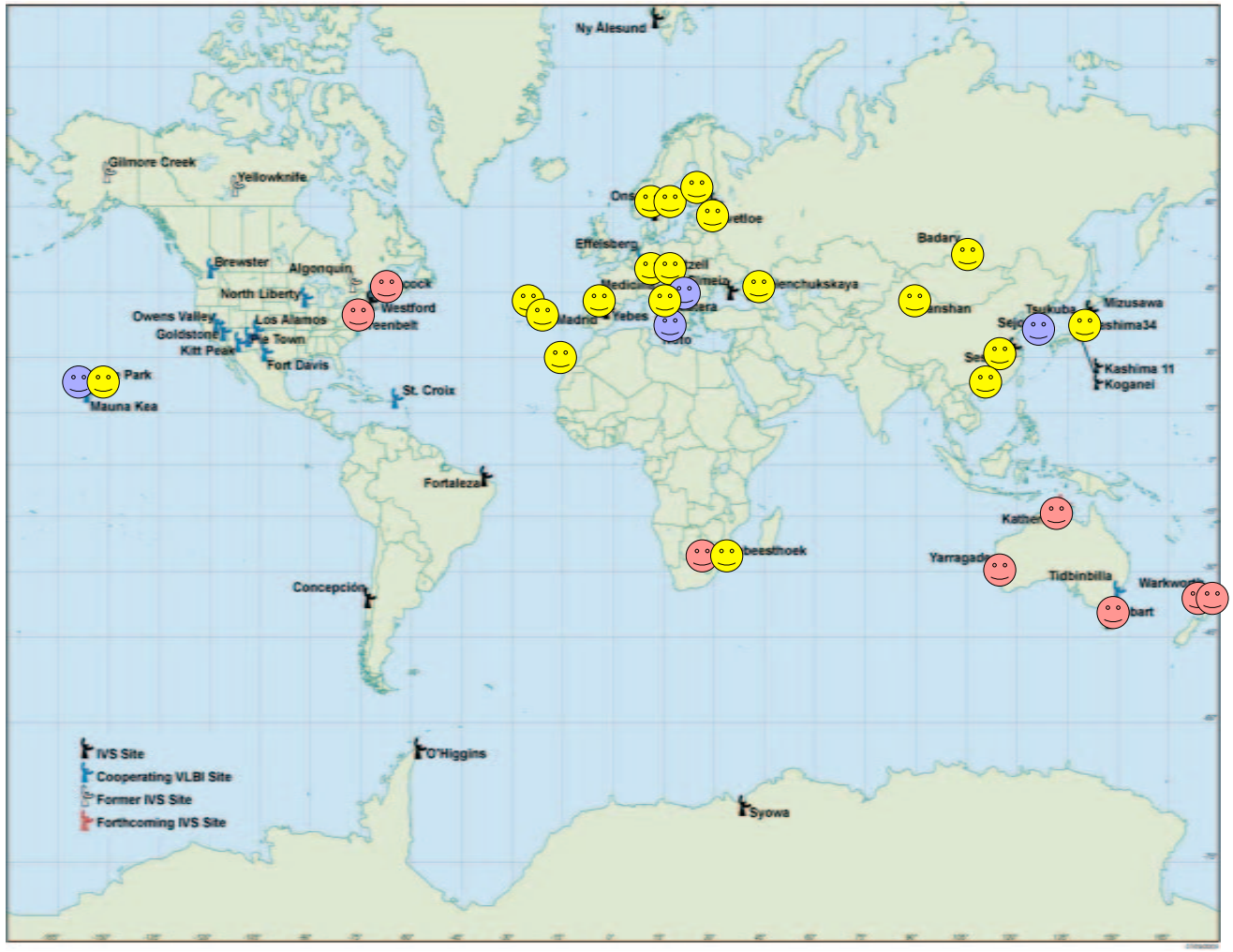
radio telescope

upgrade legacy

radio telescope

[Hase et al., 2011]

VLBI2010 Network in 2016



VLBI2010 very fast

- radio telescope
- twin radio telescope

VLBI2010 fast

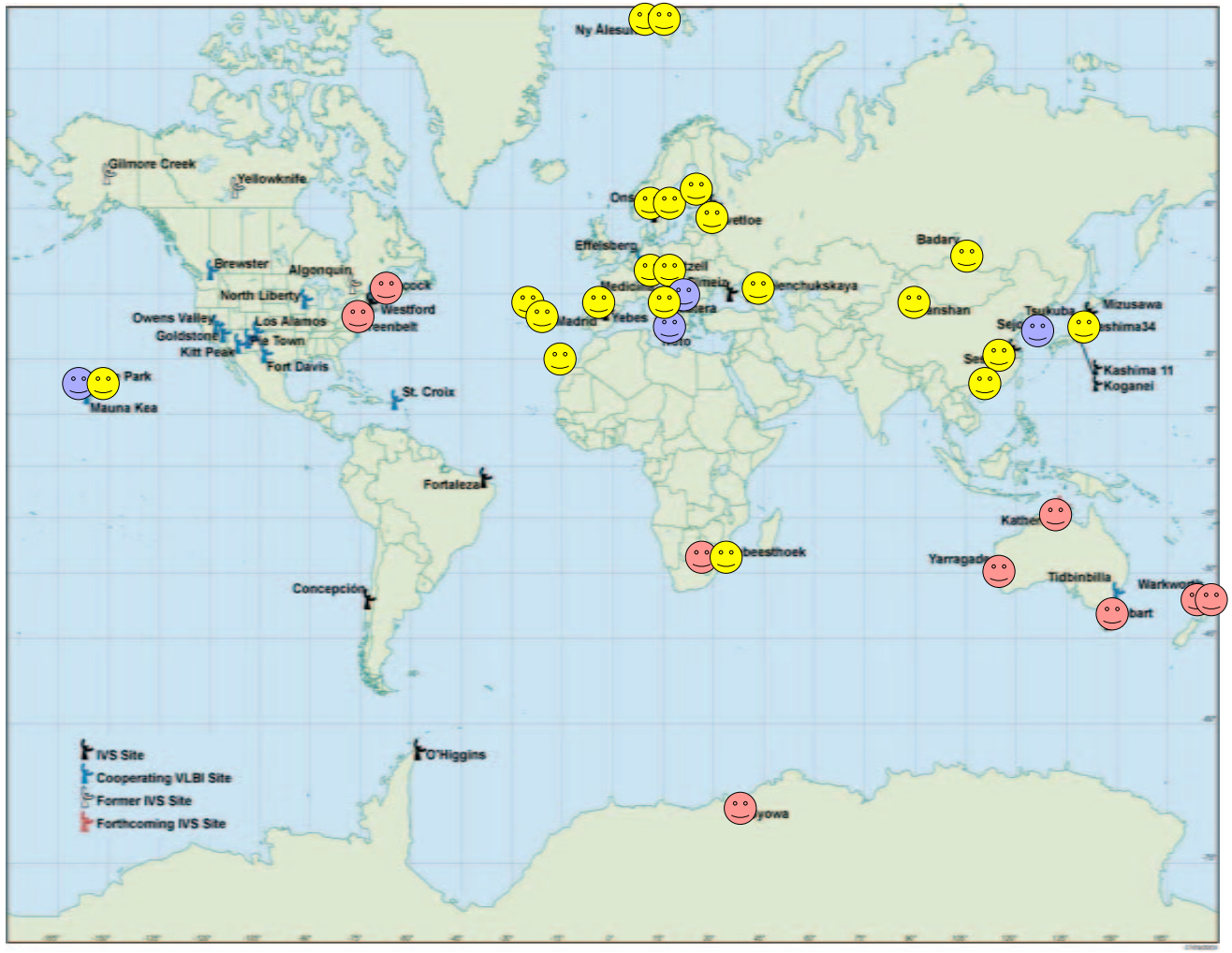
- radio telescope

upgrade legacy

- radio telescope

[Hase et al., 2011]

VLBI2010 Network in 2017



VLBI2010 very fast

radio telescope

twin radio telescope

VLBI2010 fast

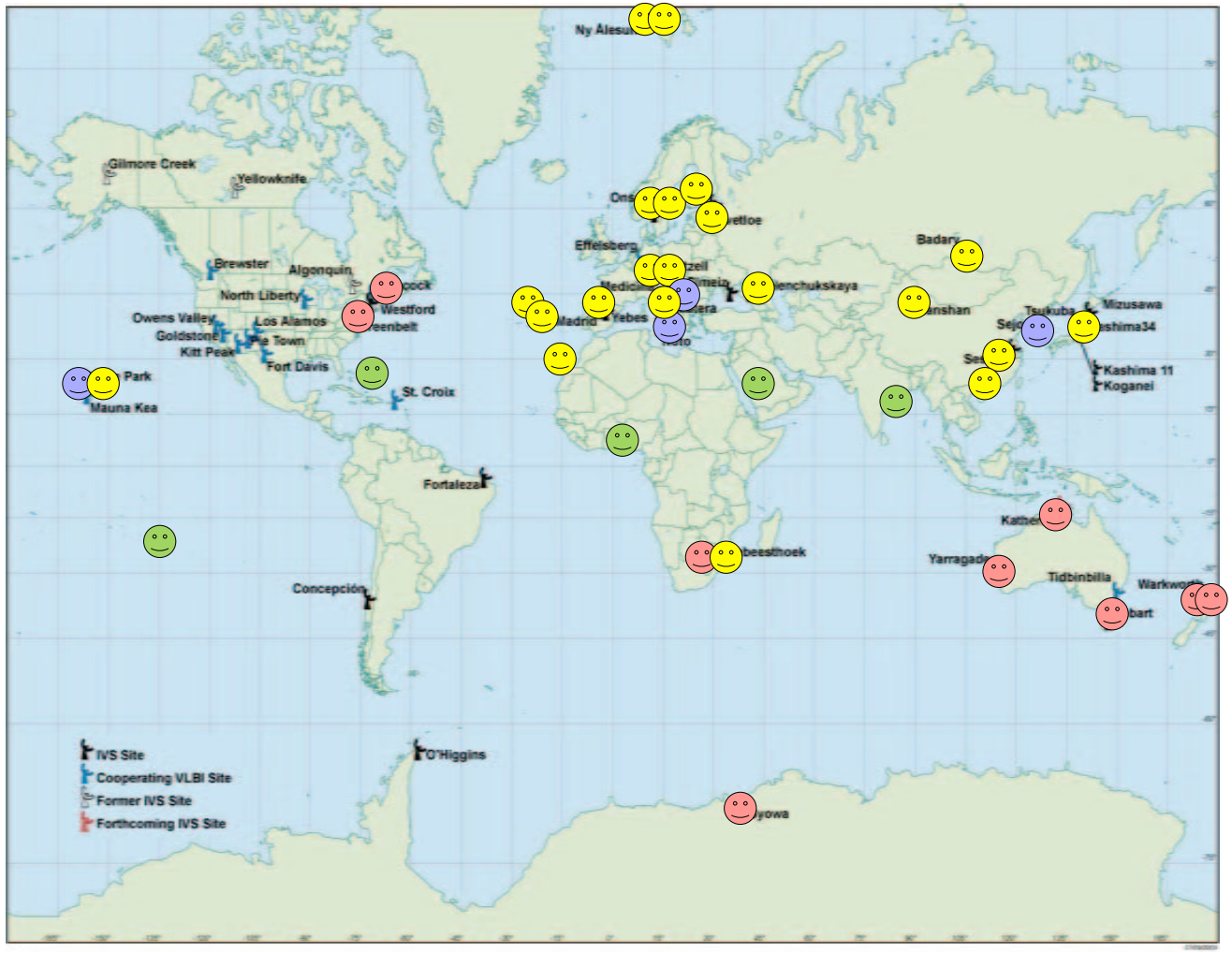
radio telescope

upgrade legacy

radio telescope

[Hase et al., 2011]

VLBI2010 Network in 2017 including potential new sites



VLBI2010 very fast

radio telescope

twin radio telescope

VLBI2010 fast

radio telescope

upgrade legacy

radio telescope

potential new site

radio telescope

[Hase et al., 2011]

VLBI2010: Origins, Status and Future

I. VERY LONG BASELINE INTERFEROMETRY – PRINCIPLE

II. VLBI PRODUCTS

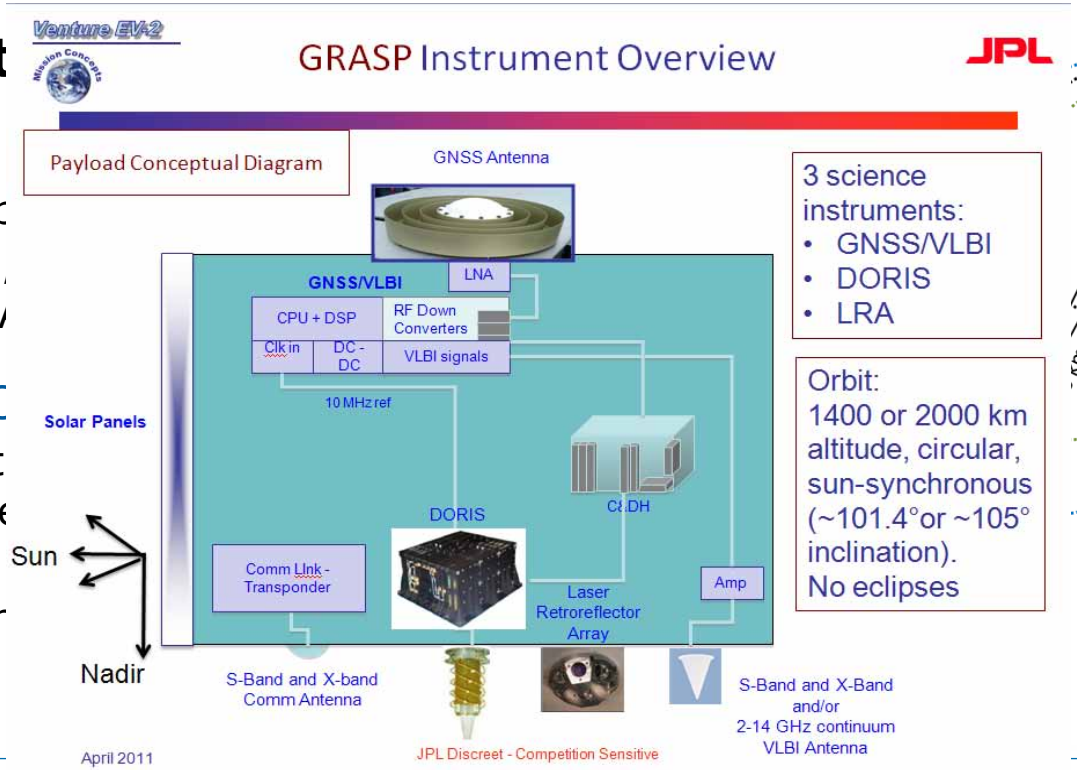
III. MEETING TODAY'S CHALLENGES

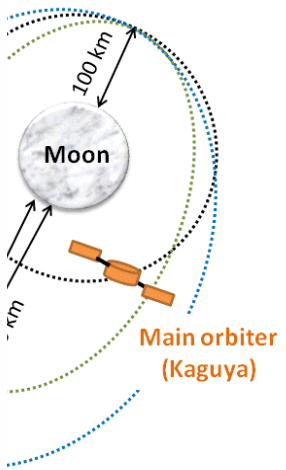
IV. VLBI2010

V. <u>NEW PERSPECTIVES, e.g. VLBI for Space Applications</u>

VLBI for space applications

- **Satellite VLBI**
  - Tracking of GNSS satellites (e.g. Tornatore et al., 2010)
  - e.g. Geodetic Reference Antenna in Space (GRASP) (Y. Bar-Sever), proposal to NASA not accepted but re-submission planned
  - e.g. Microsatellites for GNSS Earth Monitoring (MicroGEM, Nano-X)
- **Different**
  - Quasar
    - Deep
    - DSN
    - NAS
  - SC – SC
    - mult
    - same
    - e.g. Char





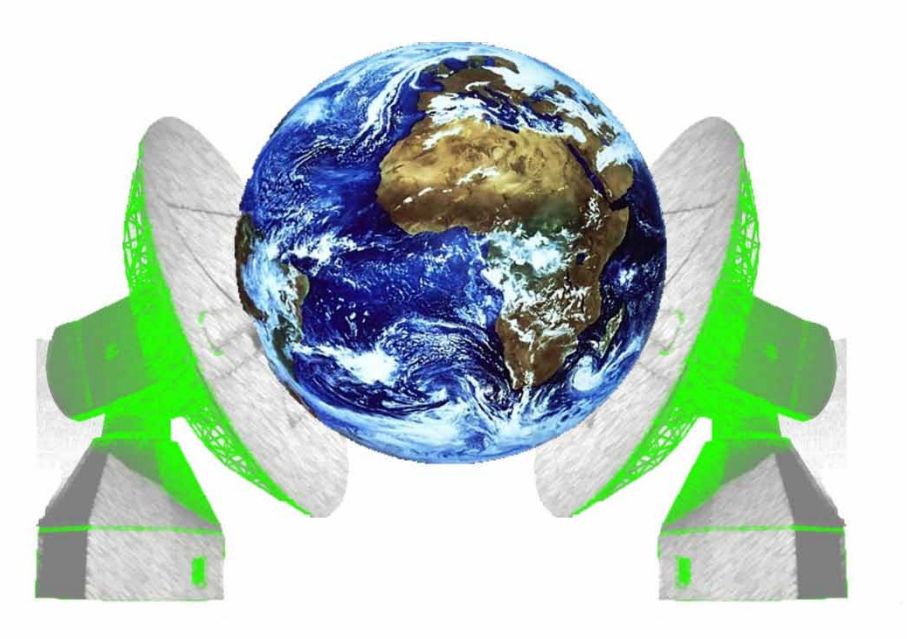
Conclusions VLBI2010 and VGOS

- > 20 new radio telescopes with VLBI2010 compliance should become operational by 2018.
- Additional new stations might join in.
- By 2015 a sufficient number of VLBI2010 compatible radio telescopes will be available for initial VLBI2010 operations.
- NASA proposal for additional 10 antennas

Concluding remarks

- **VLBI plays an important role in geodesy as it provides unique information and allows to investigate a lot of geodynamical astronomical, and physical phenomena**
- **VLBI is essential as a fundamental geodetic technique to link national reference frames with the ITRF and it provides the most precise and stable celestial reference frame (ICRF)**
- **with VLBI2010 and its VGOS (VLBI2010 Global Observing System) more prosperous decades will follow**

"*meeting the requirements of a global society on a changing planet in 2020.*" *[GGOS 2020, Plag & Pearlman, 2009]*

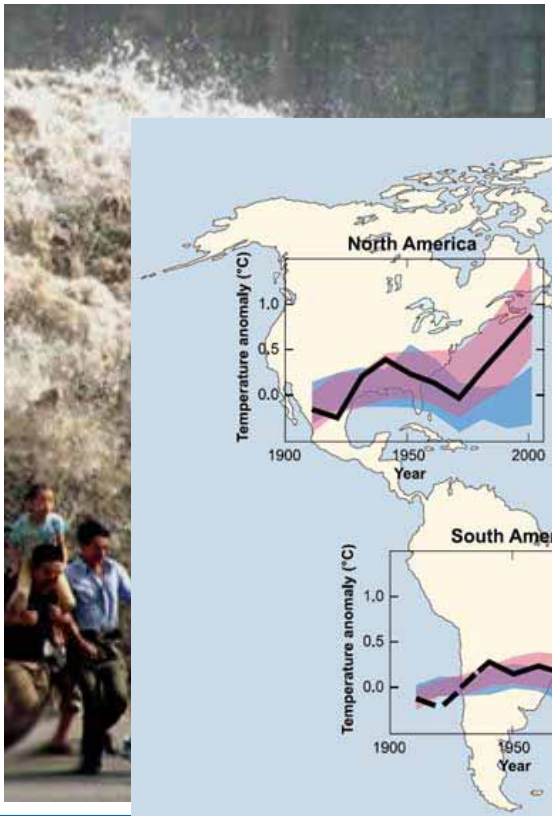


Thank you for your attention!

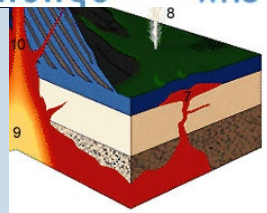
schuh@gfz-potsdam.de

New challenges in geoscience

- Increase of natural disasters
  - Strong demand for prediction and warning
- Global climate change

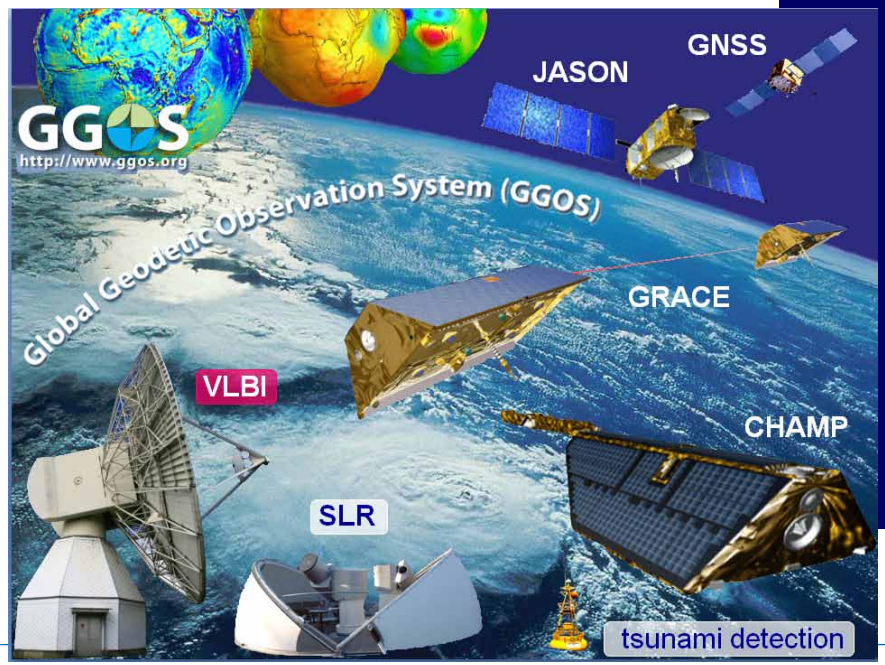


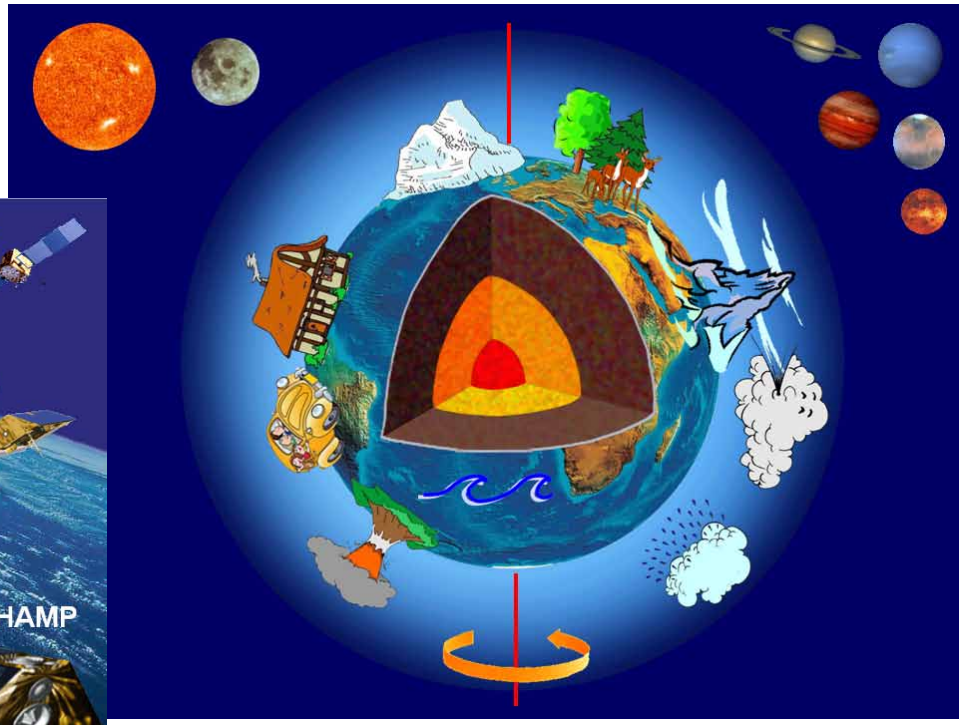
ipcc
INTERGOVERNMENTAL PANEL ON climate change
WMO UNEP



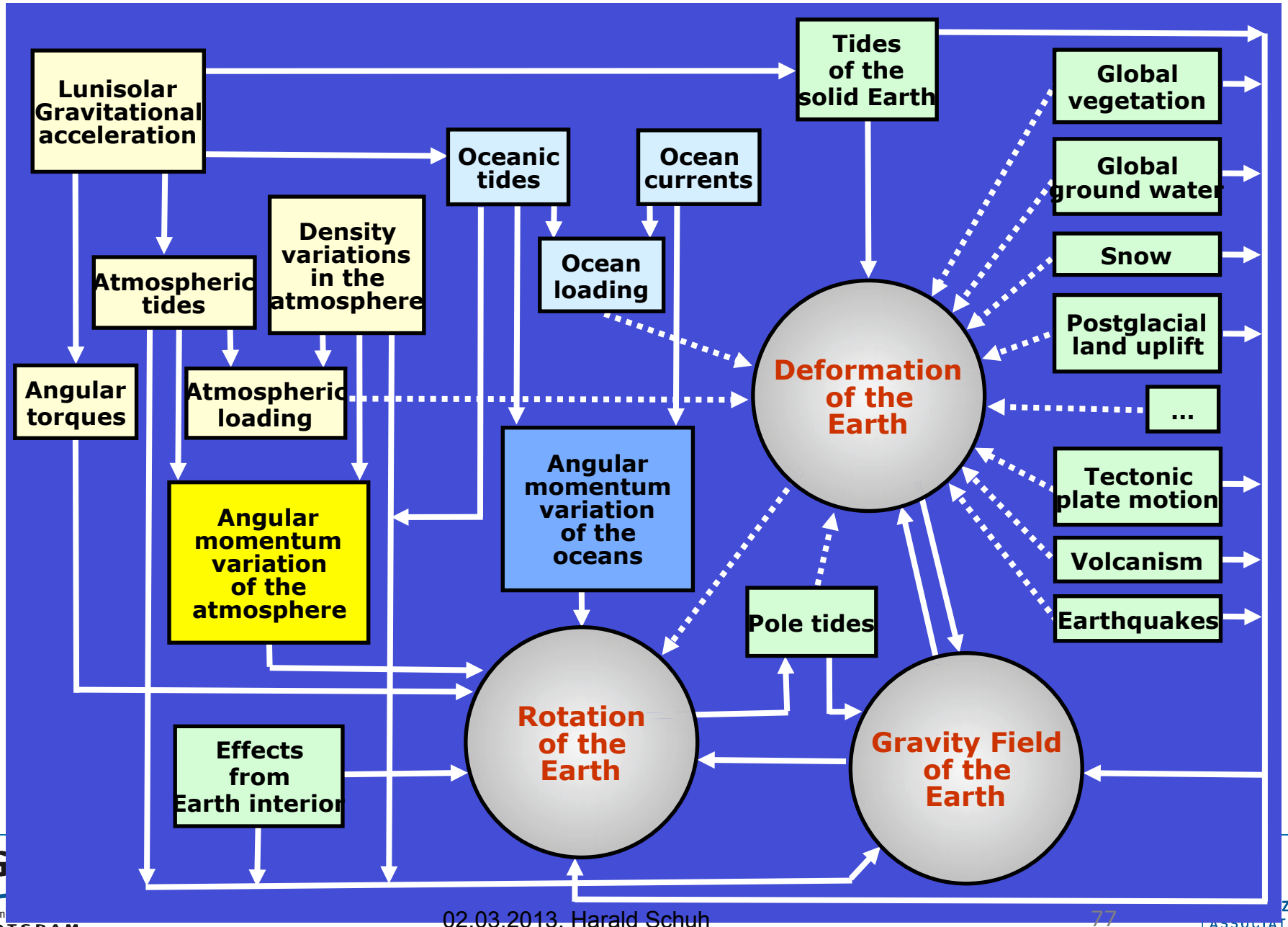
Approaches

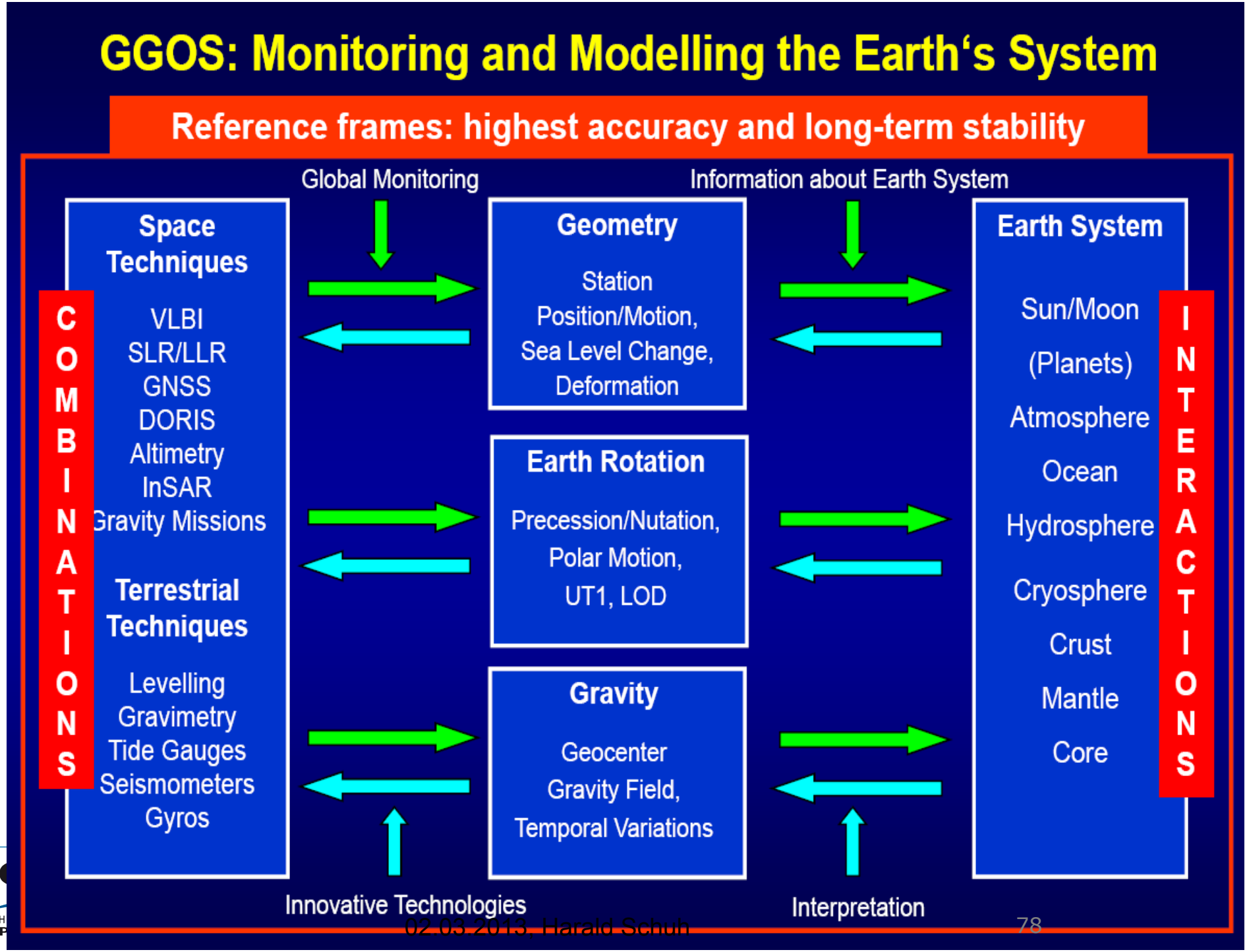
- Combination of all available observations in the sense of GGOS
- Improve our understanding of the ”System Earth“





Model of the Interactions in the Earth System (Schuh, 1995)

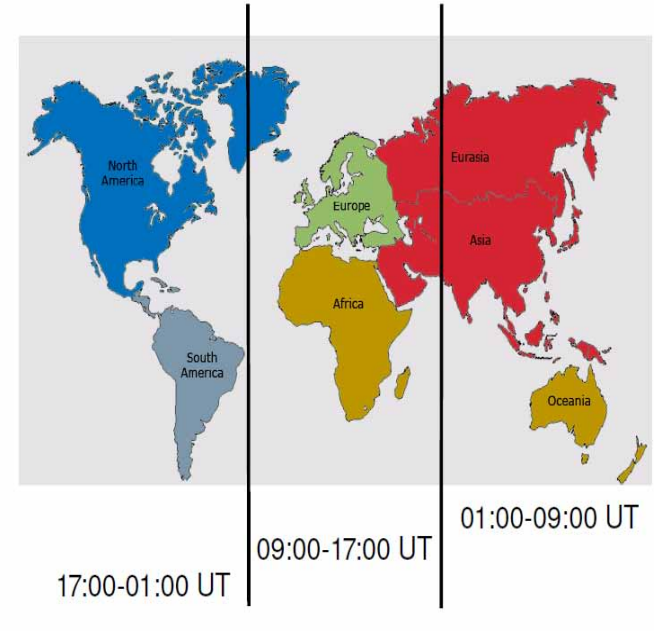



GGOS: Monitoring and Modelling the Earth's System
Reference frames: highest accuracy and long-term stability
Global Monitoring
Information about Earth System
Space Techniques
VLBI
SLR/LLR
GNSS
DORIS
Altimetry
InSAR
Gravity Missions
Terrestrial Techniques
Levelling
Gravimetry
Tide Gauges
Seismometers
Gyros
COMBINATIONS
Geometry
Station Position/Motion, Sea Level Change, Deformation
Earth Rotation
Precession/Nutation, Polar Motion, UT1, LOD
Gravity
Geocenter Gravity Field, Temporal Variations
Earth System
Sun/Moon
(Planets)
Atmosphere
Ocean
Hydrosphere
Cryosphere
Crust
Mantle
Core
INTERACTIONS
Innovative Technologies
Interpretation

Global cooperation within the IVS

- Remote control of VLBI telescopes
  - Future VLBI2010: VLBI observations seven days/week.
  - **Idea:** use remote control of the telescopes. At night a telescope is controlled remotely from another telescope where it is daytime.

  [A. Neidhardt, Wettzell]



- Requirements:
  - ✓ Stable internet connection.
  - ✓ Stable and standardized software for remote control.