VLBI: A Fascinating Technique for Geodesy and Astrometry

Annual Conference

Satellite methods and position determination in modern surveying and navigation

Wroclaw, June 2-3, 2011

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TECHNISCHE UNIVERSITÄT WIEN
Vienna University of Technology

VLBI: A Fascinating Technique for Geodesy and Astrometry

I. VERY LONG BASELINE INTERFEROMETRY – PRINCIPLE

II. VLBI PRODUCTS

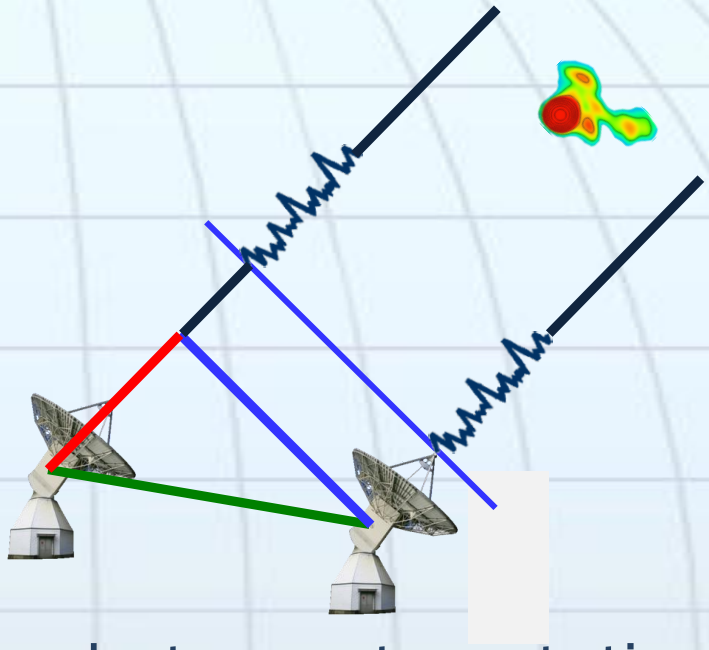
III. MEETING TODAY‘S CHALLENGES

IV. VLBI2010

V. NEW PERSPECTIVES

The principle of VLBI

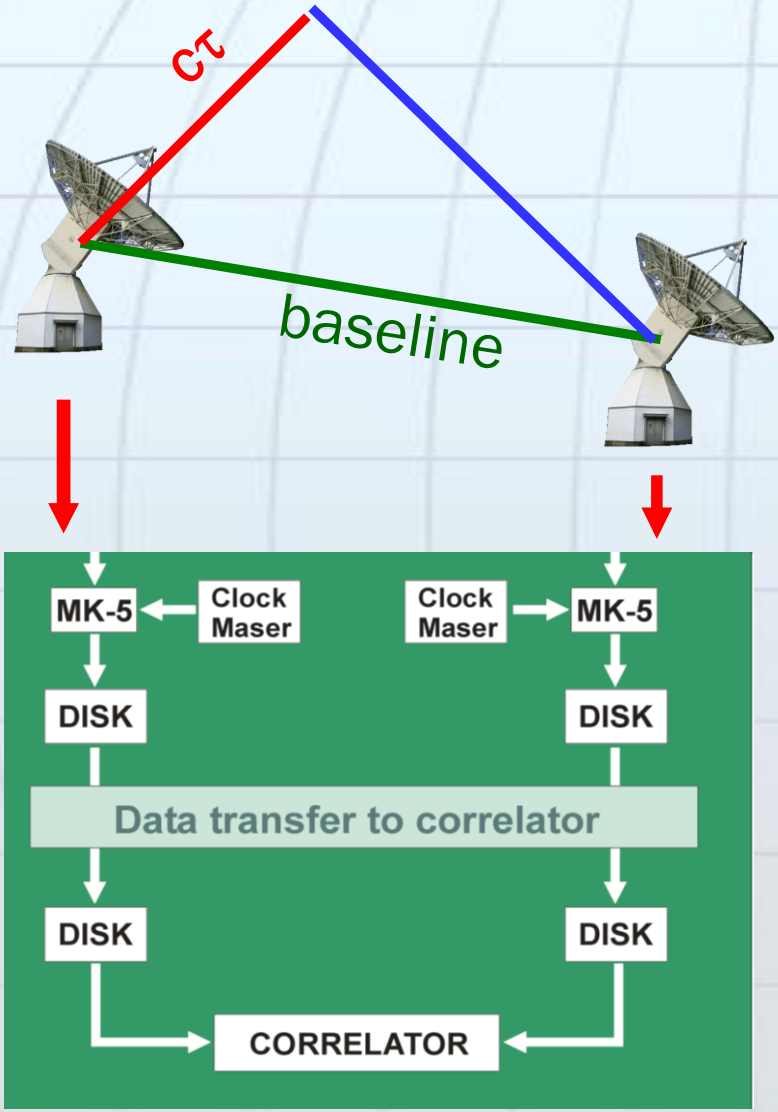
$$\tau = -\frac{1}{c}\mathbf{b}WSNP\mathbf{k}$$



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

VLBI observing system



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

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

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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 (currently applying for membership)

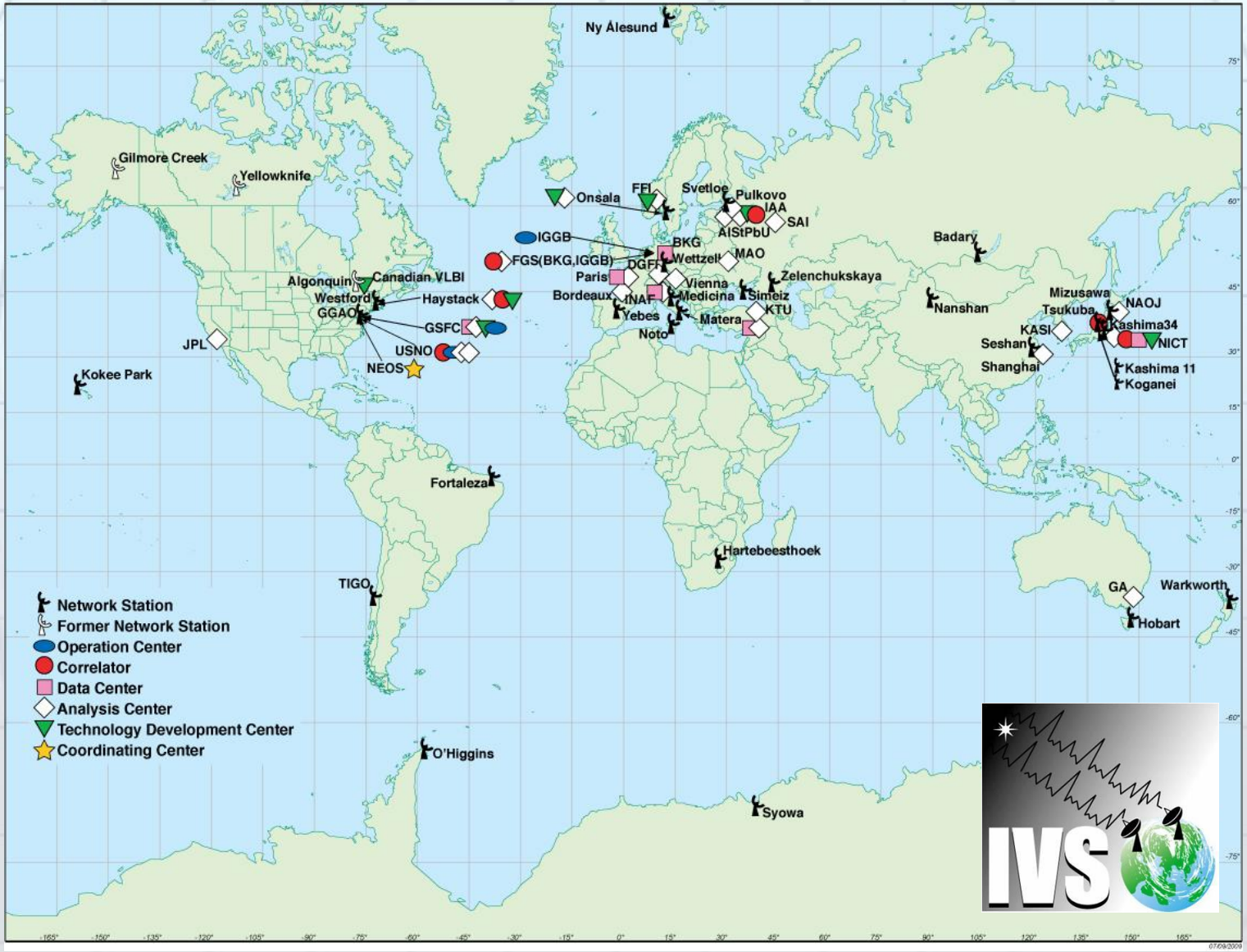
IVS goals:

- 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

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
- 81 Permanent Components supported by >40 institutions in >20 countries
- ~270 Associate Members

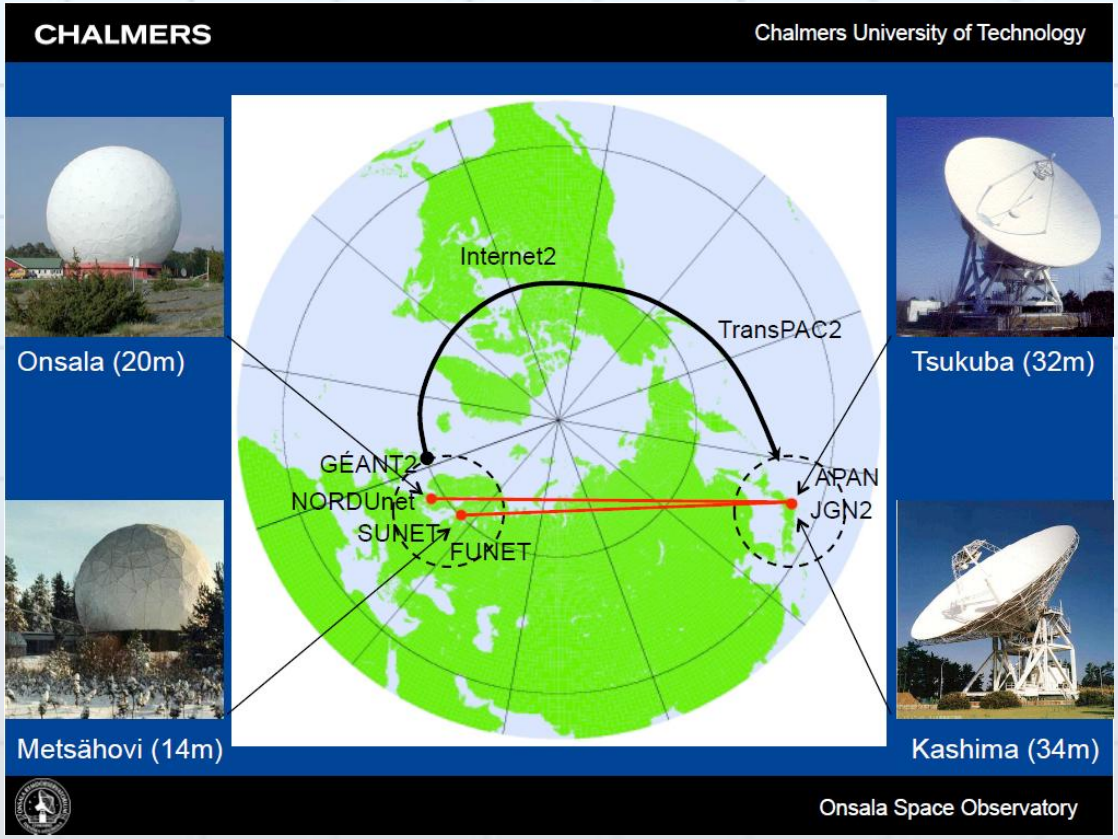
IVS Components



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 4‘ after last scan
[Matsuzaka et al., 2008]



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

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VLBI product: CRF

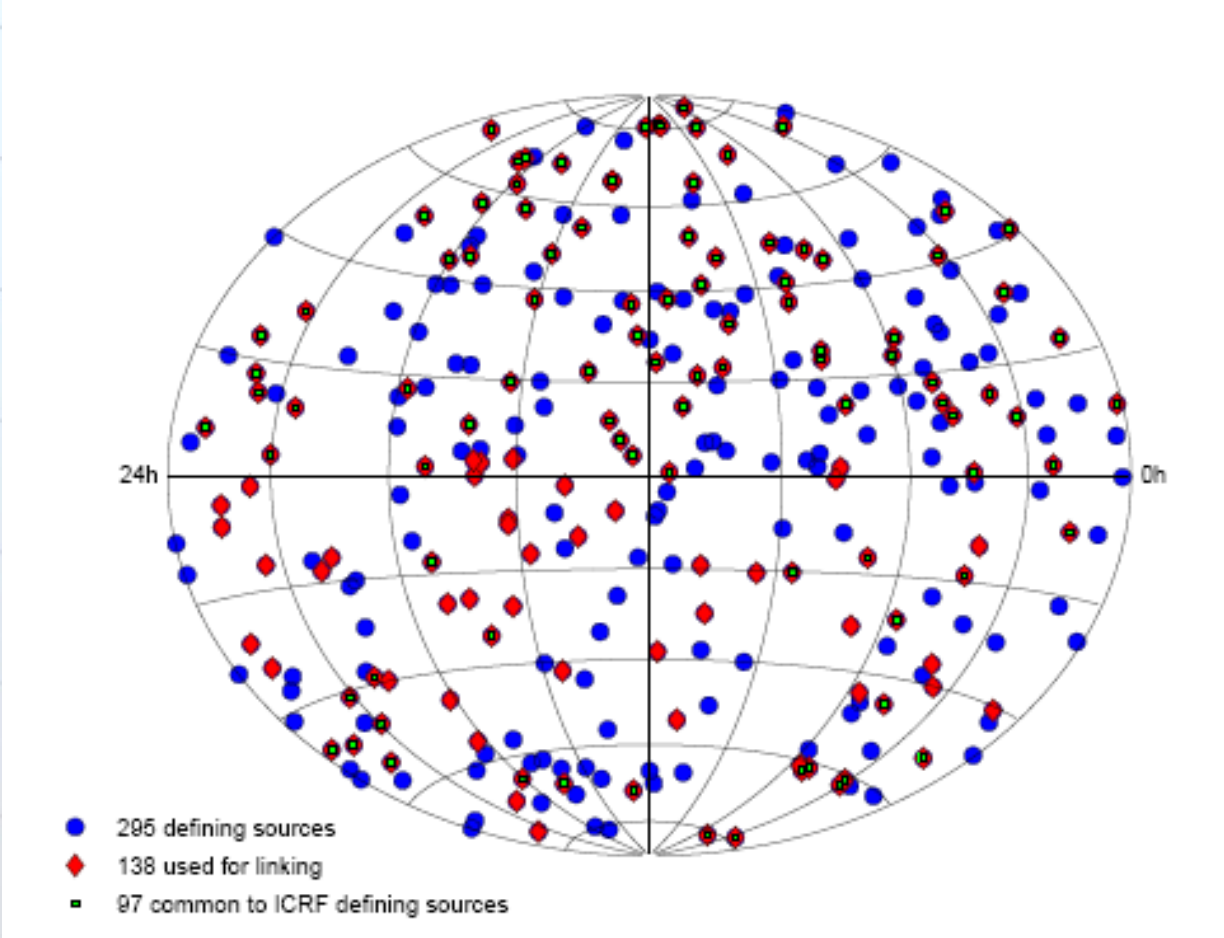
- ICRF2

since 08/2009

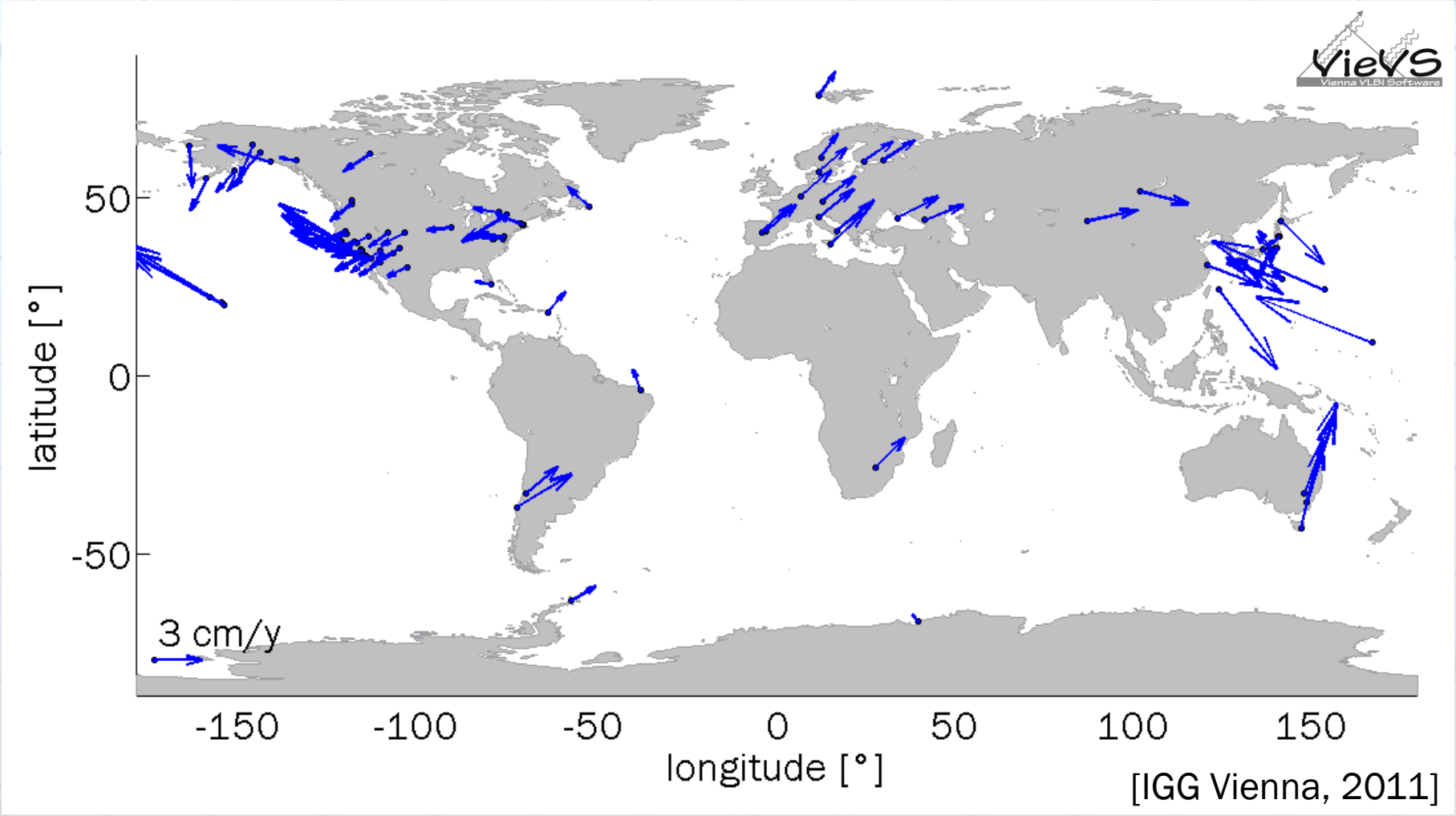
Sources:

total:	3414
defining:	295
linking:	138

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

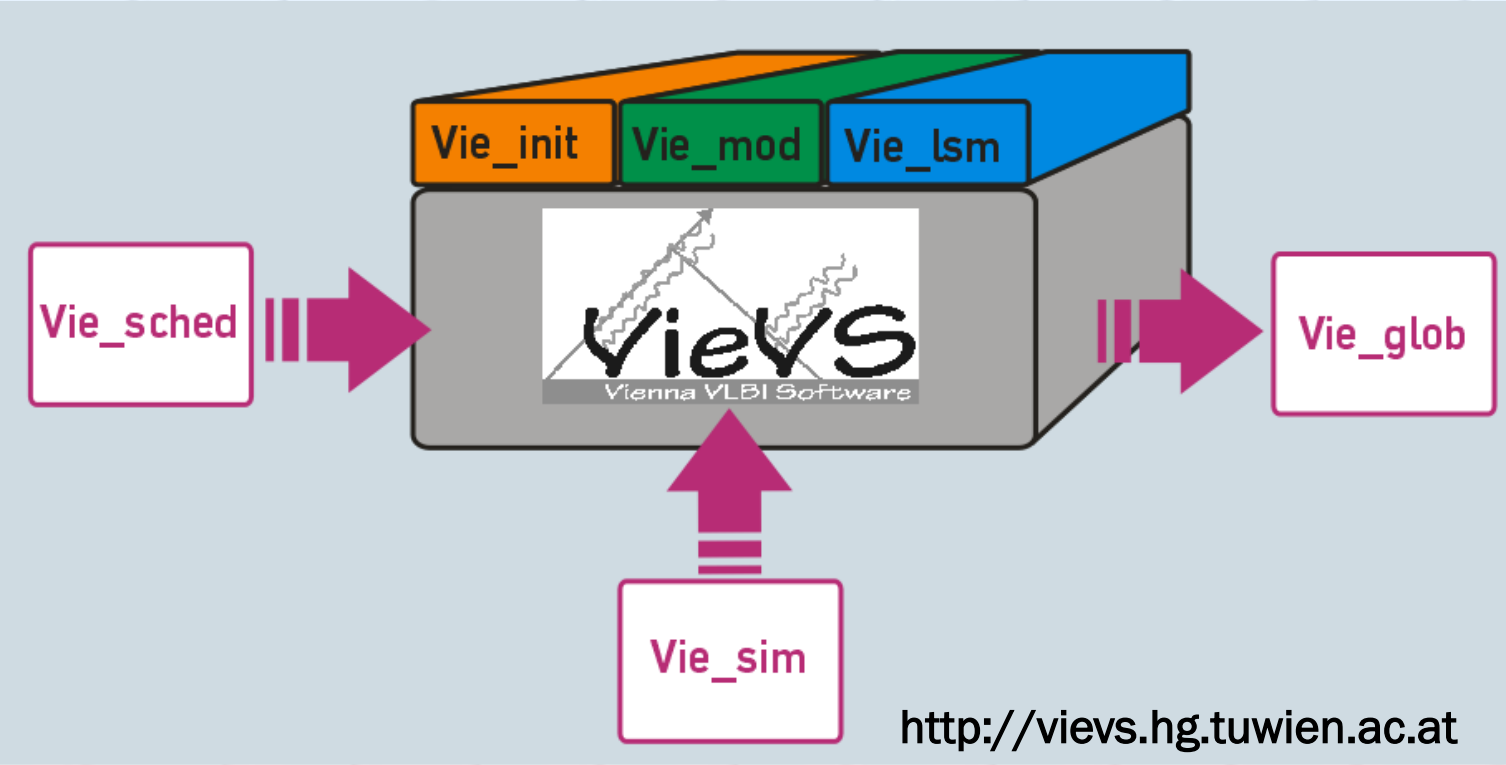


VLBI product: Station velocities



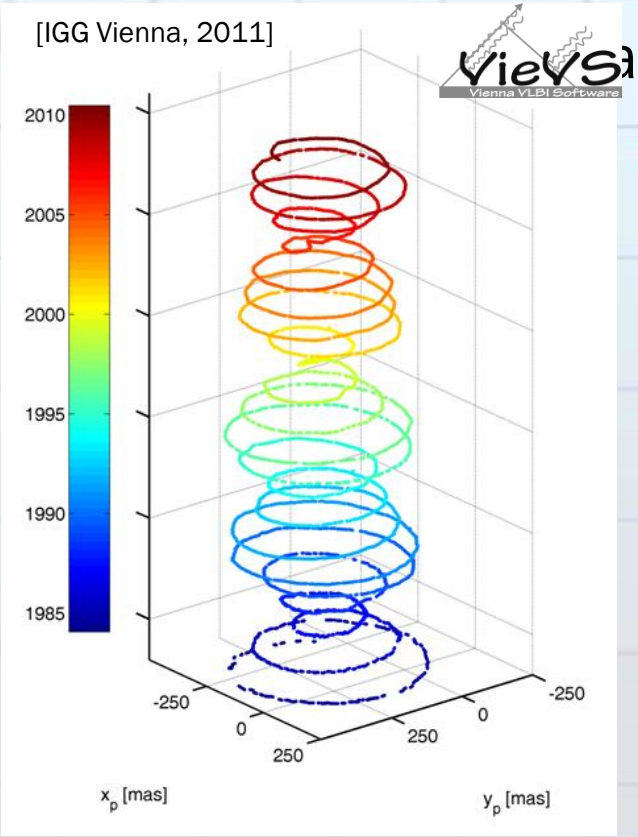
Vienna VLBI Software (VieVS)

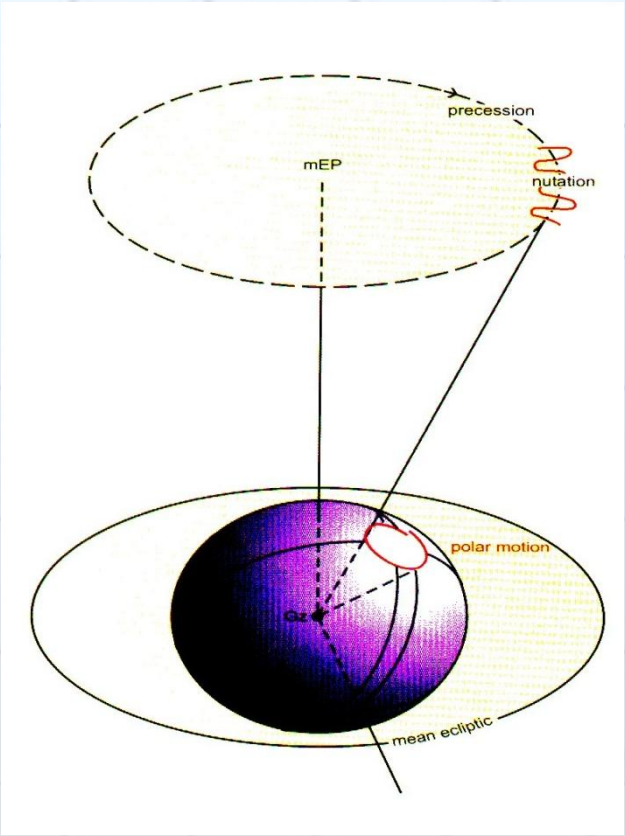
- Developed at IGG Vienna since 2008
- Written in MATLAB
- Easy to use through graphical user interfaces



VLBI product: EOP

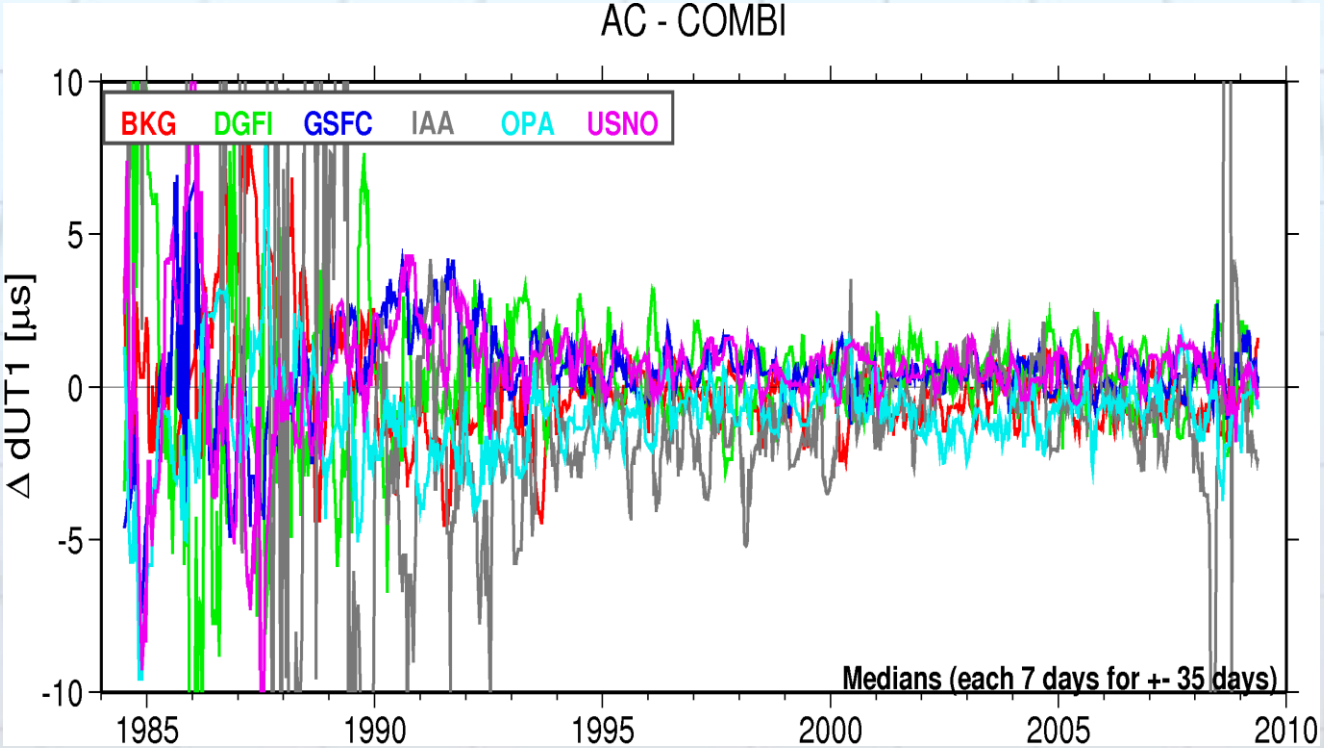
- Earth rotation parameters x_{pole}, y_{pole}, dUT1
- Pre ameters





VLBI product: EOP

- Combined EOP are regular IVS products



UT1-UTC residuals
[A. Nothnagel, IVS Analysis Coordinator, 2011 http://vlbi.geod.uni-bonn.de/IVS-AC]

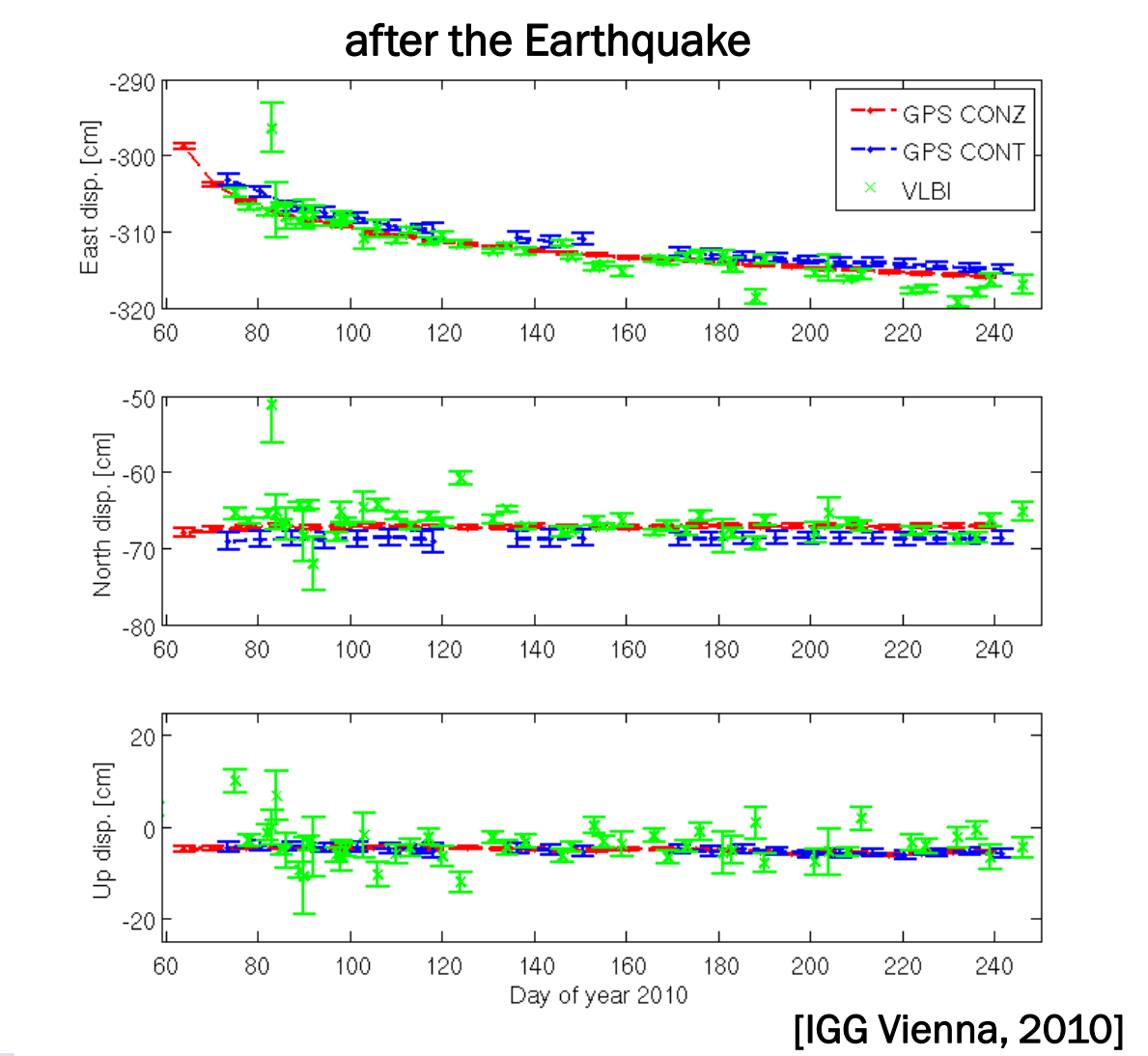
- Complete set of EOP
  - $d\psi$, $d\varepsilon$
  - x_p ,y_p
  - UT1-UTC
- Combined solution from 6 Analysis Centers
- 20-30% improvement
  - accuracy
  - robustness
- R1 & R4 since 2002

VLBI product: Station motions

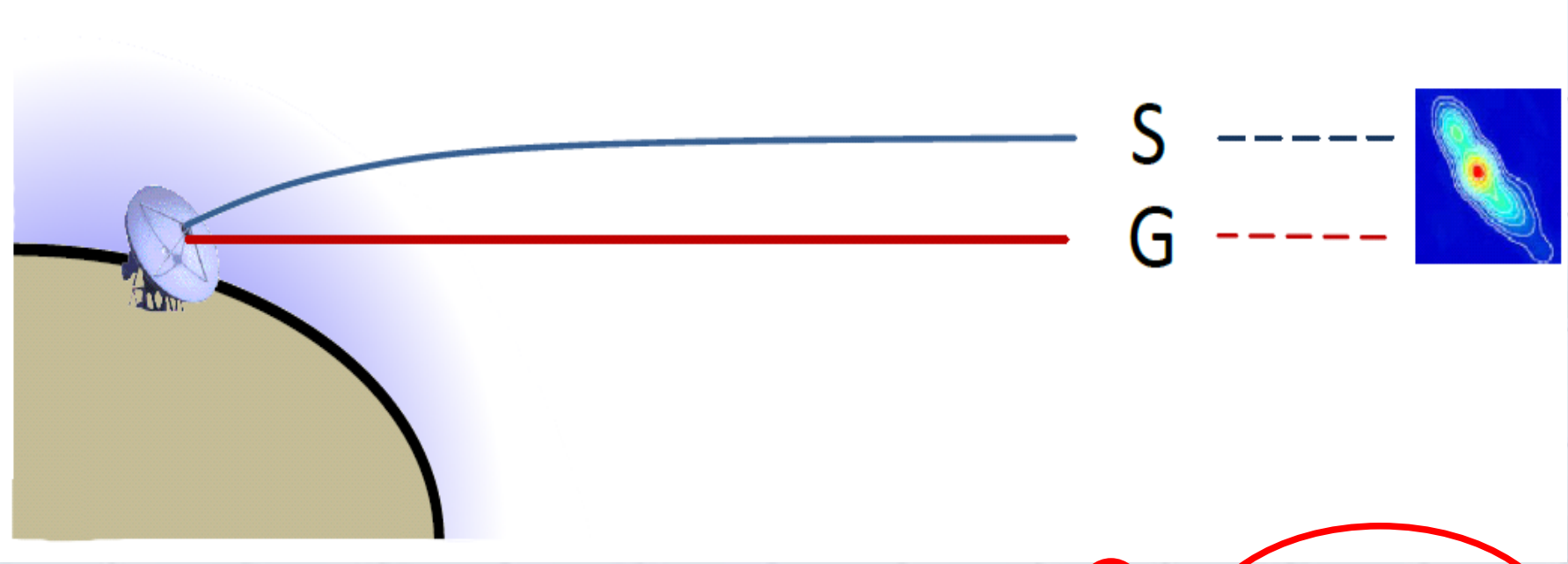
- Displacement of the TIGO radio telescope in Concepción caused by the magnitude 8.8 Earthquake on Feb 27, 2010.

Displacement of TIGO Concepción

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



Tropospheric delay



$$D_L = 10^{-6} \int N(s) ds + [S - G]$$

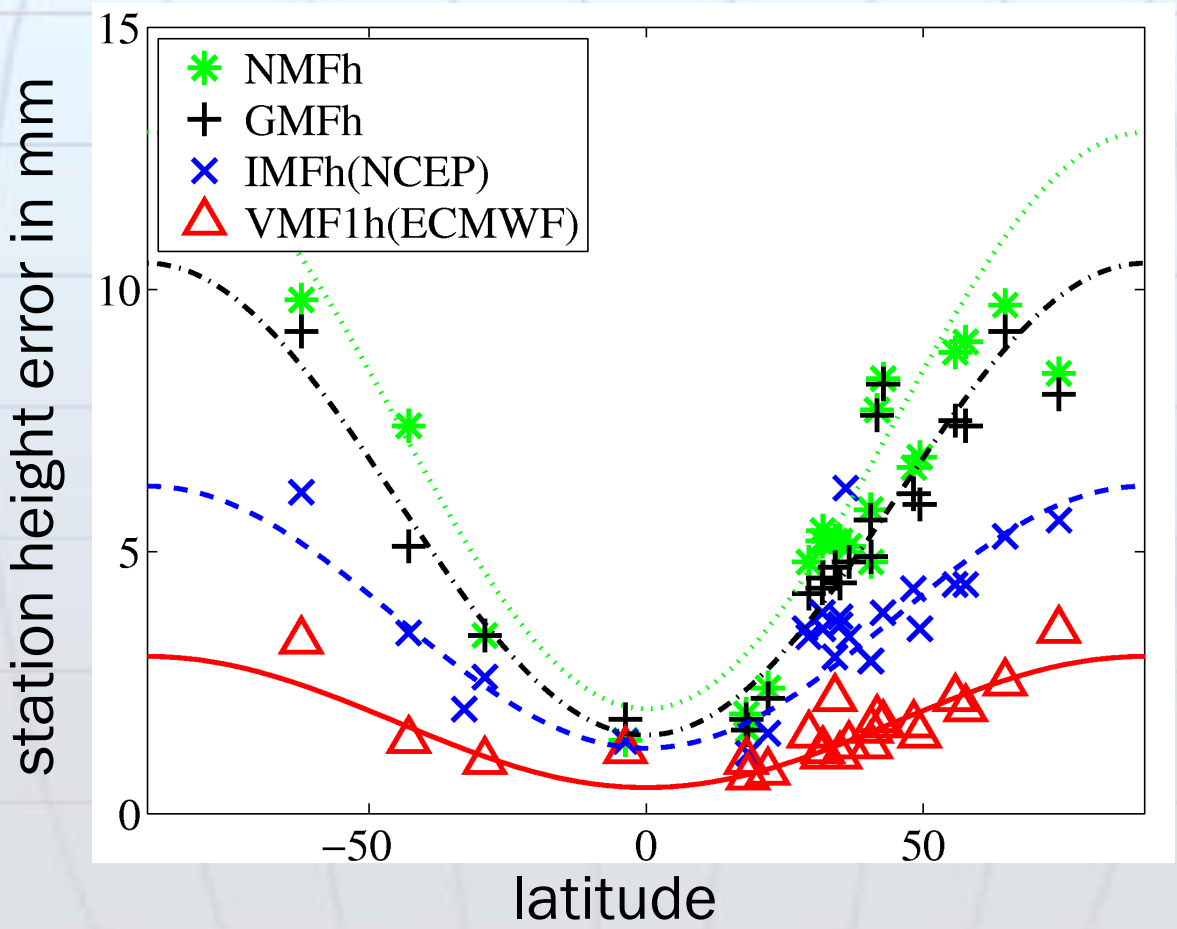
$$N = k_1 \rho + k'_2 \frac{e}{T} + k_3 \frac{e}{T^2}$$

Hydrostatic

Wet

Vienna Mapping Functions (VMF)

- Böhm et al., 2006
- Comparison with radiosonde data



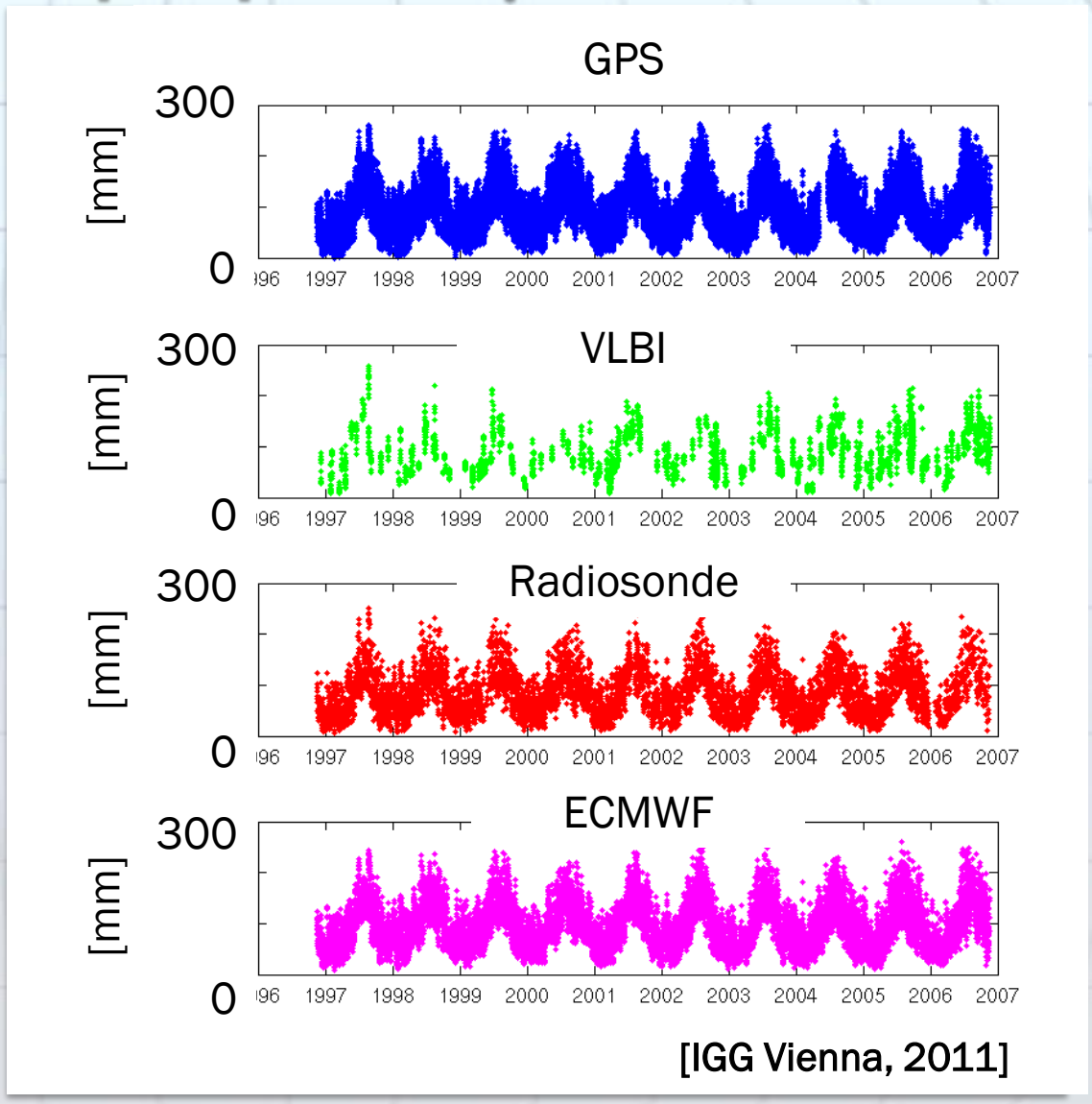
[Niell, 2006]

VLBI product: Tropospheric parameters

- Zenith wet delays (ZWD)

  at Onsala (SWE)

  1996-2007

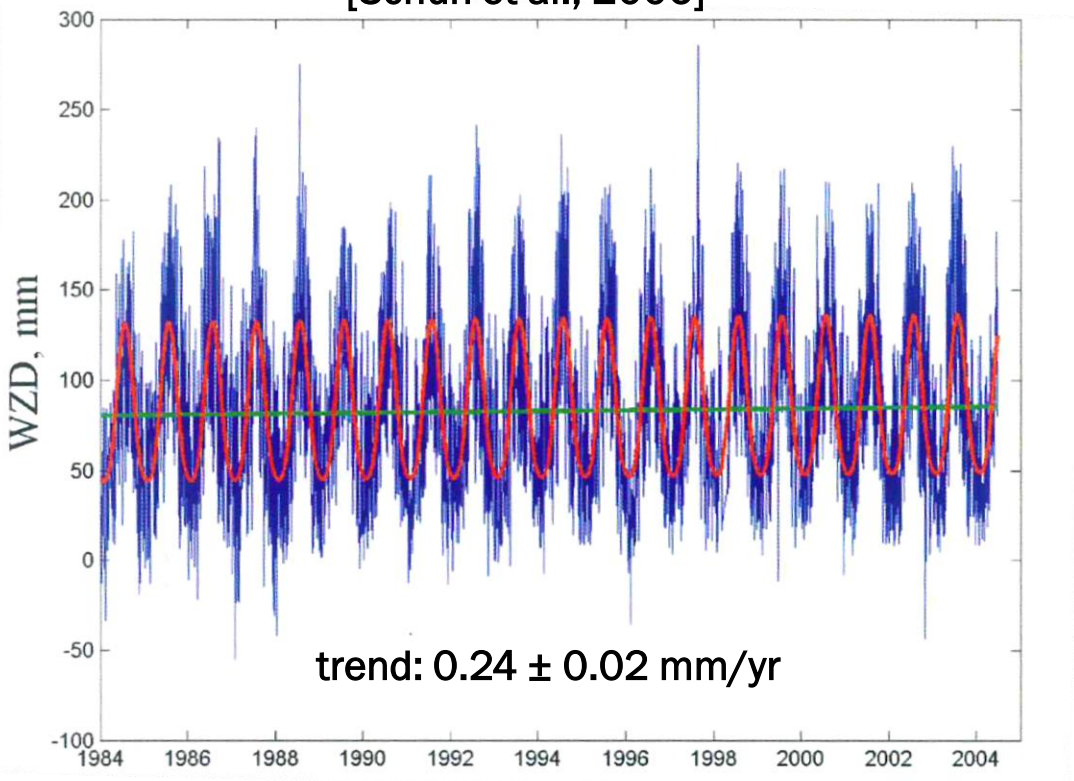


Climate studies using VLBI

- 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

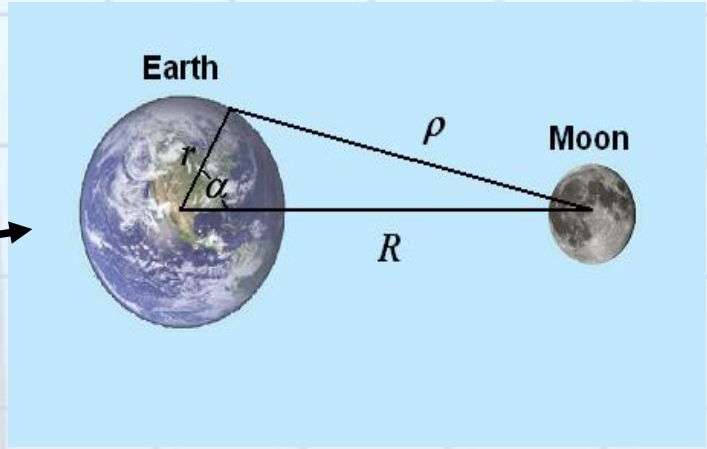
[Schuh et al., 2006]

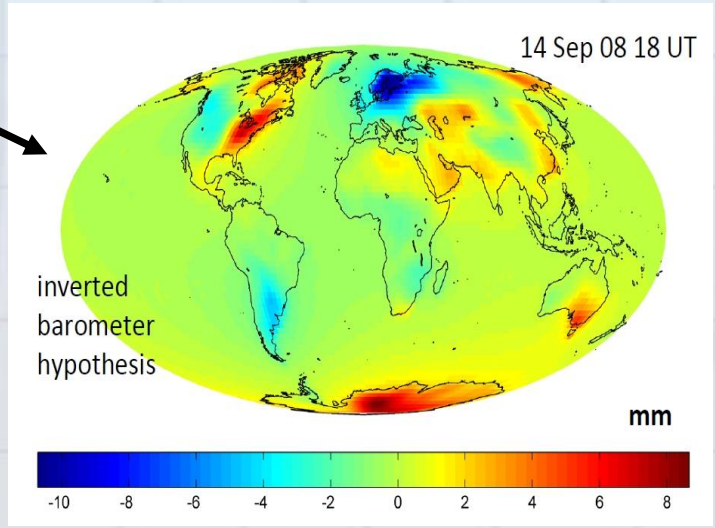


Wet zenith delays (blue) at Wettzell from VLBI obtained at IGG, annual and semiannual signal (red), linear trend (green).

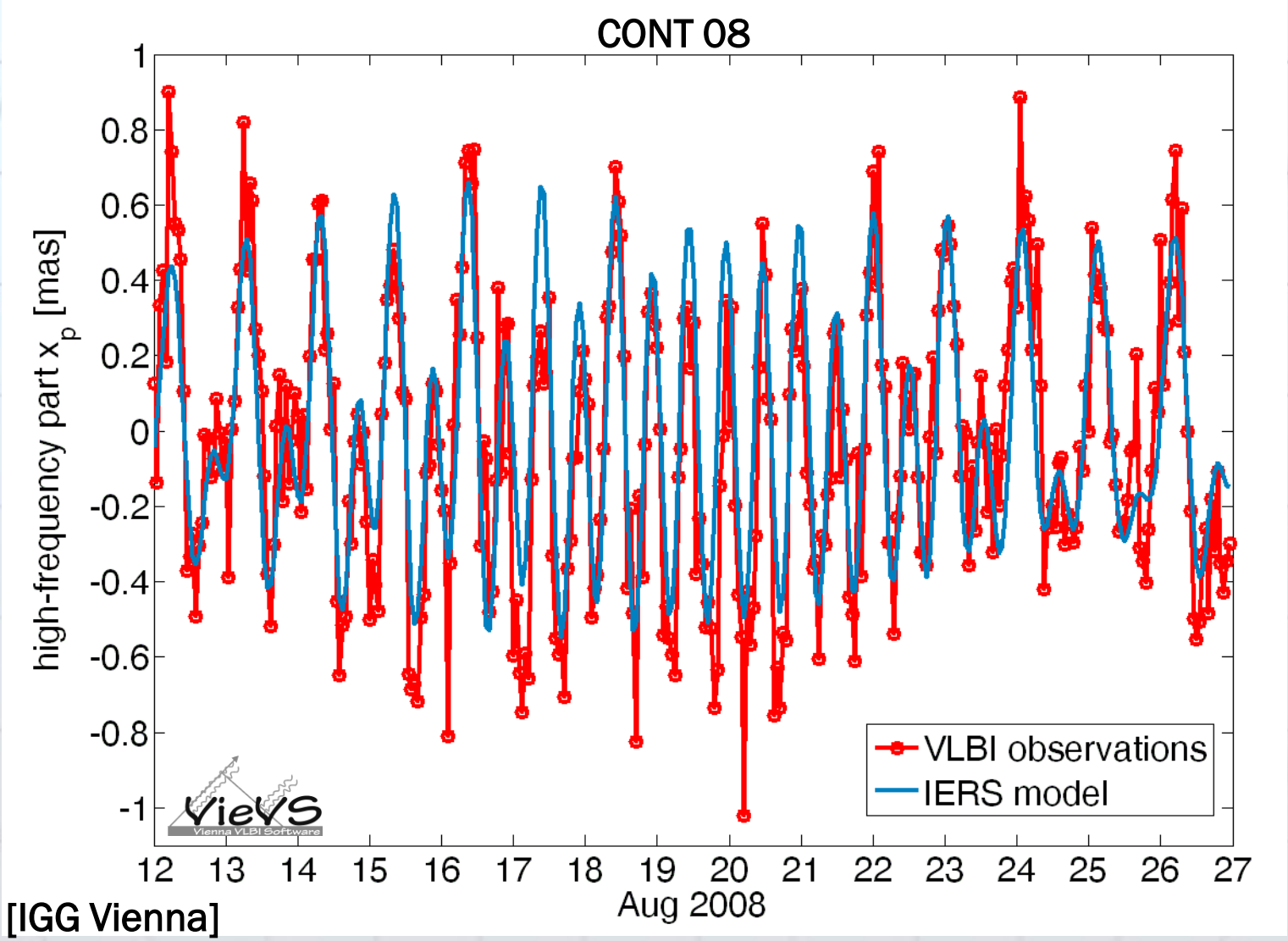
VLBI product: Tides & loading effects

- Deformations of the Earth's surface are caused by tides and different loading effects:
  - Solid Earth tides
  - Ocean loading
  - Atmospheric loading
  - Pole tide
- These effects must be taken into account in VLBI data analysis.
- This also means it is possible to use VLBI to study these effects.





VLBI observes subdaily ERP



[IGG Vienna]

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)

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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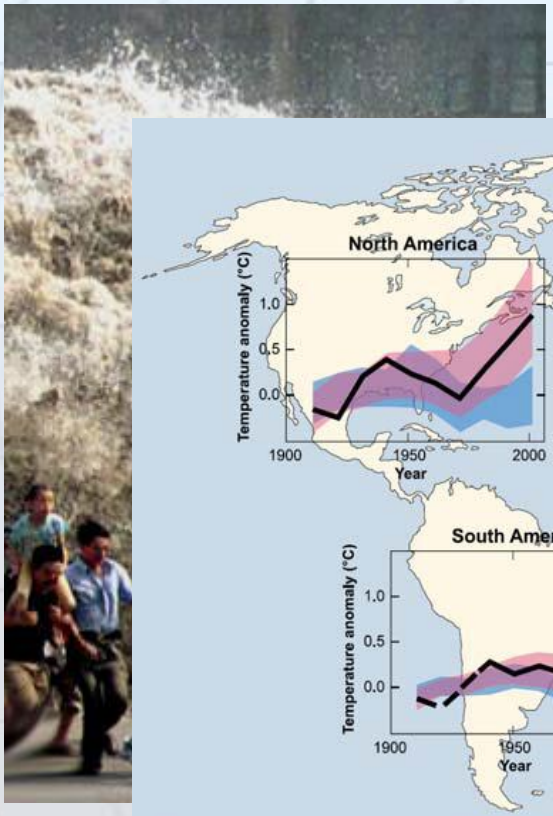
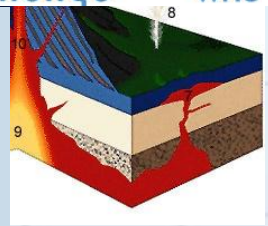
New challenges in geoscience

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

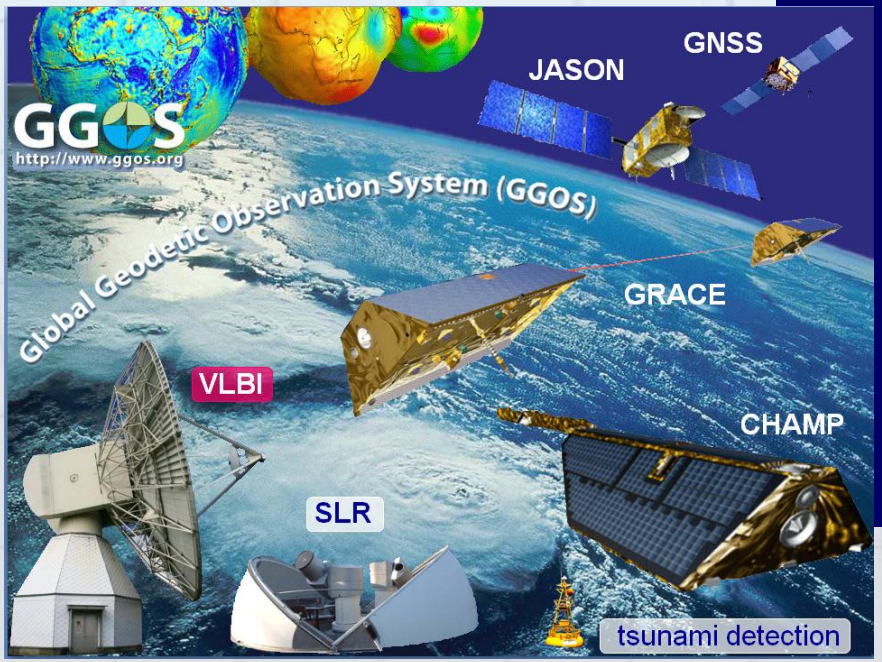


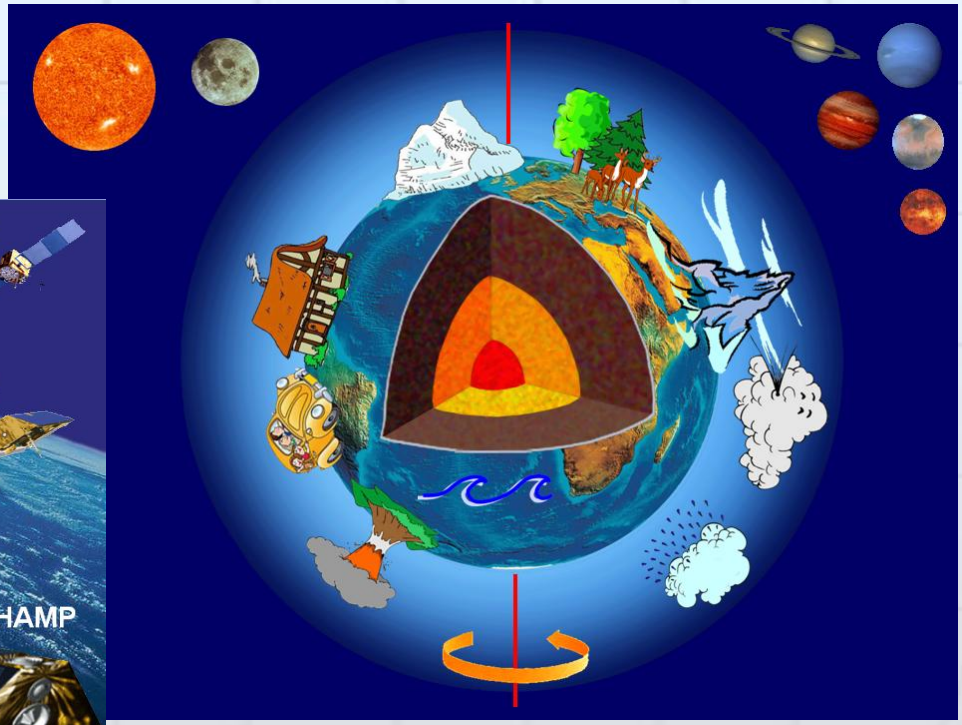
ipcc
INTERGOVERNMENTAL PANEL ON climate change
WMO UNEP



Approaches

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



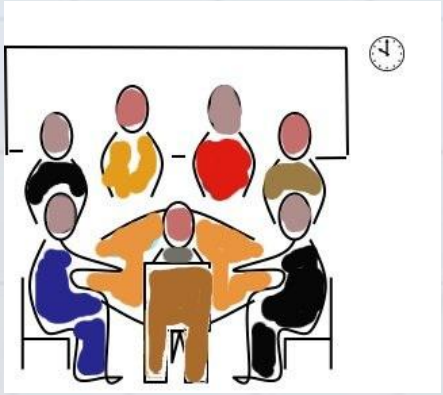


VLBI2010: why do we need it?

- Aging systems
- New technology
- New requirements
- 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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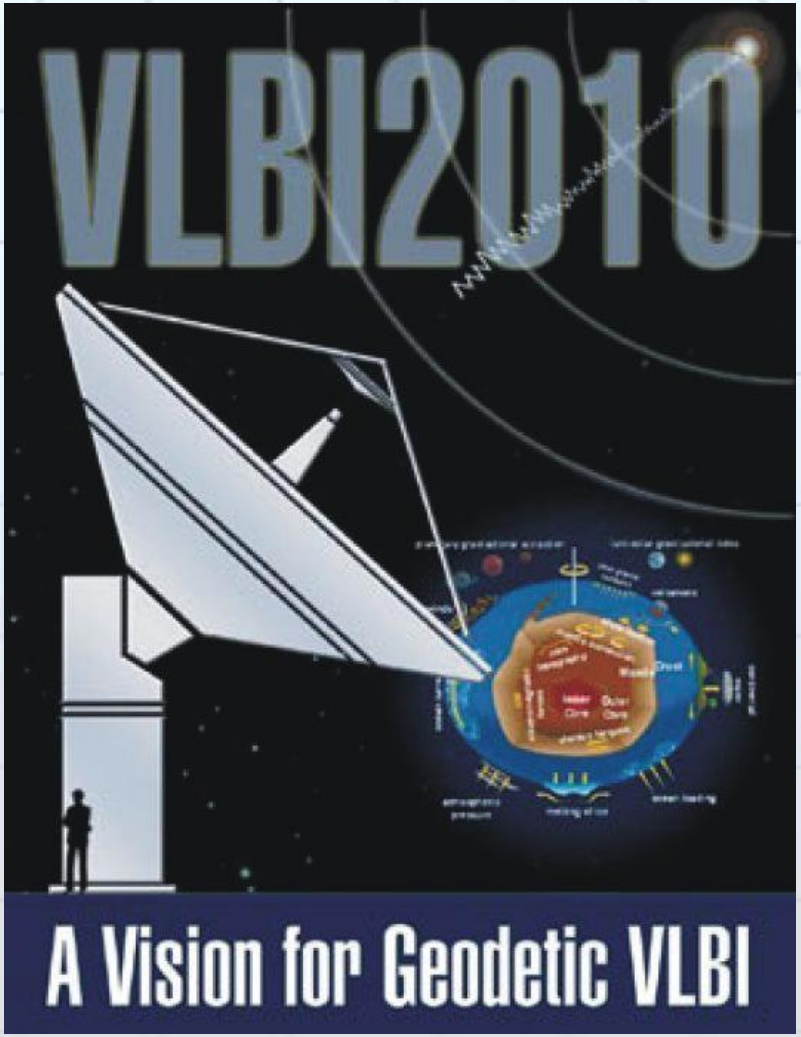
WG 3 report



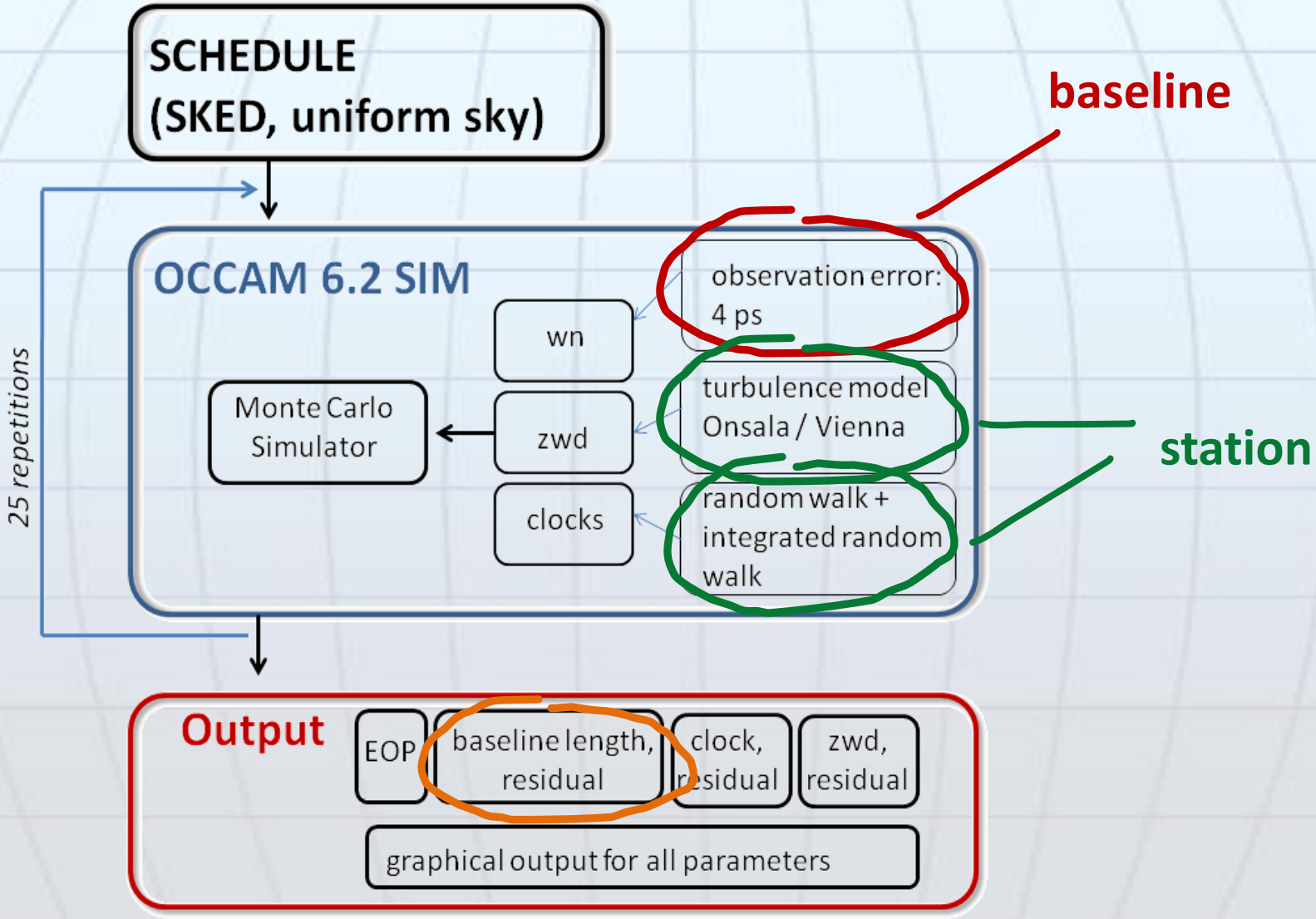
http://ivscc.gsfc.nasa.gov/about/wg/wg3/IVS_WG3_report_050916.pdf

VLBI2010 – goals and strategies

- criteria
  - **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

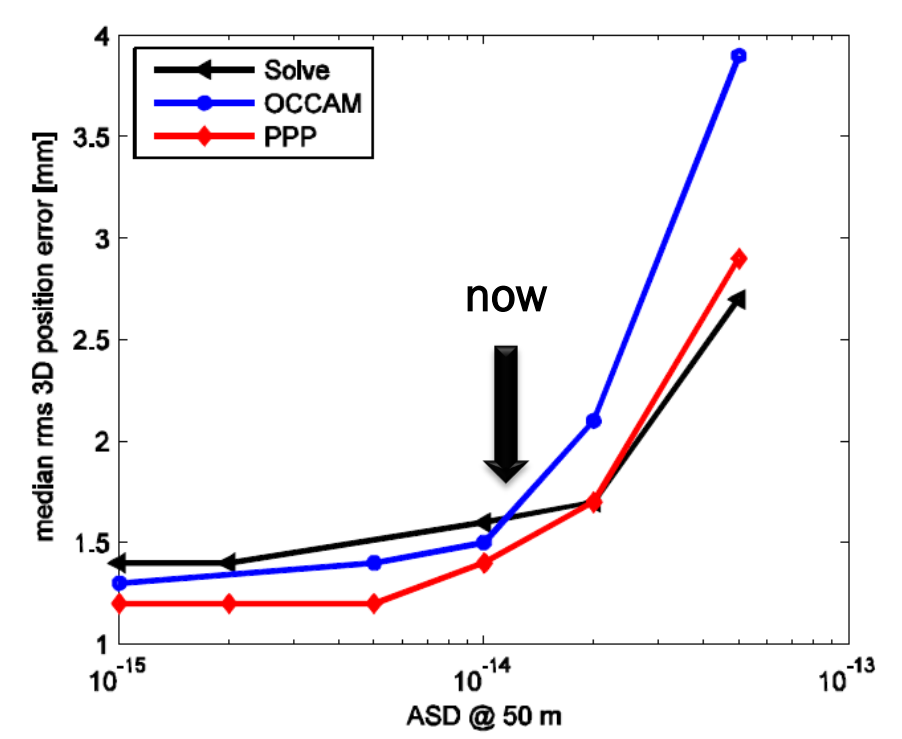
- strategies
  - reduce random and systematic errors of delay observables
  - improve geographic distribution of antennas
  - increase number of observations
  - develop new observing strategies

VLBI2010 – Monte Carlo simulations

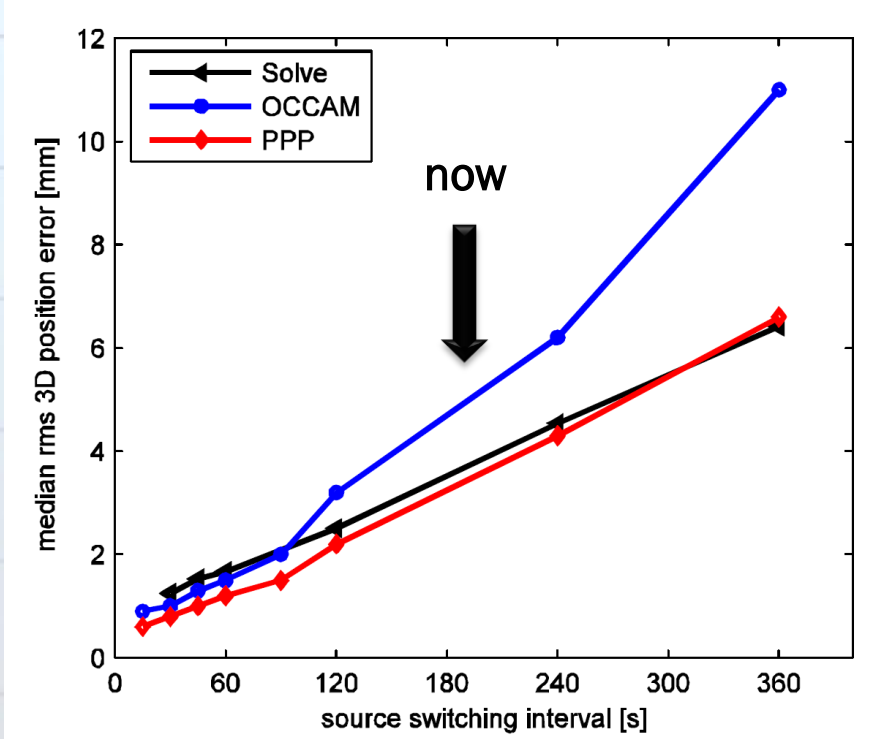


VLBI2010 – simulation results

clock stability



source switching interval

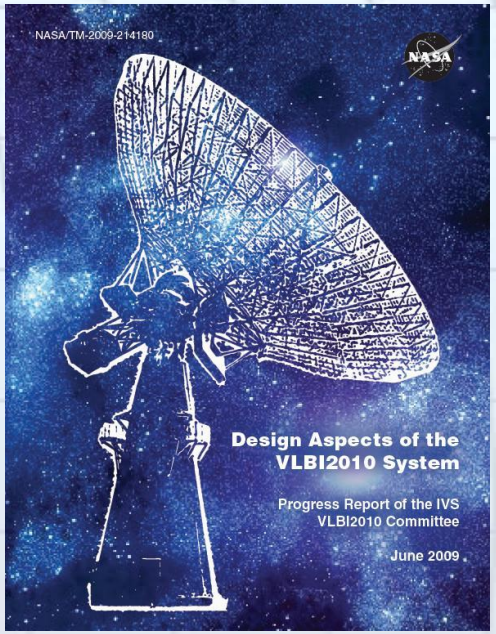


Progress Report of the IVS VLBI2010 Committee, 2009
ftp://ivscc.gsfc.nasa.gov/pub/misc/V2C/PR-V2C_090417.pdf

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, 256 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

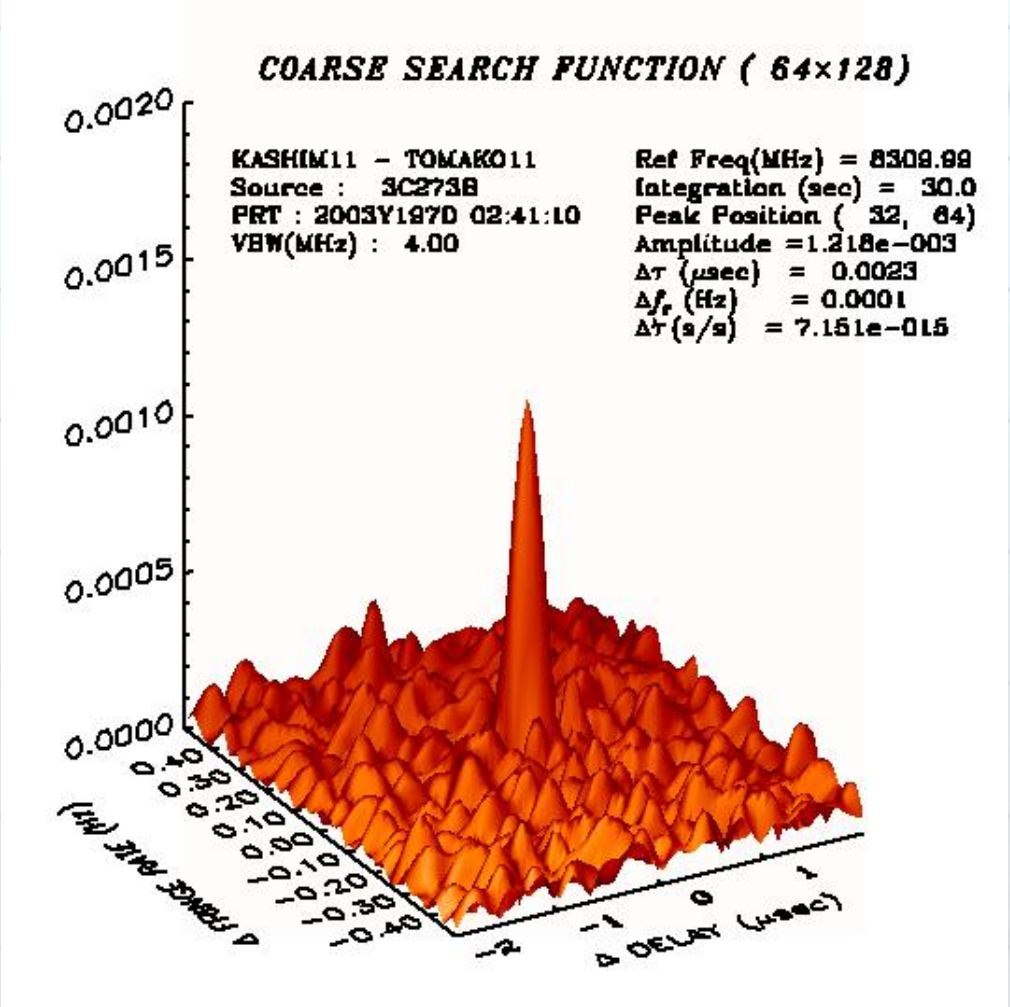
VLBI2010 – a completely new generation of VLBI hardware and software

VLBI2010 also includes

- software correlation

VLBI correlation in the future

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



[T. Hobiger]

VLBI2010 – a completely new generation of VLBI hardware and software

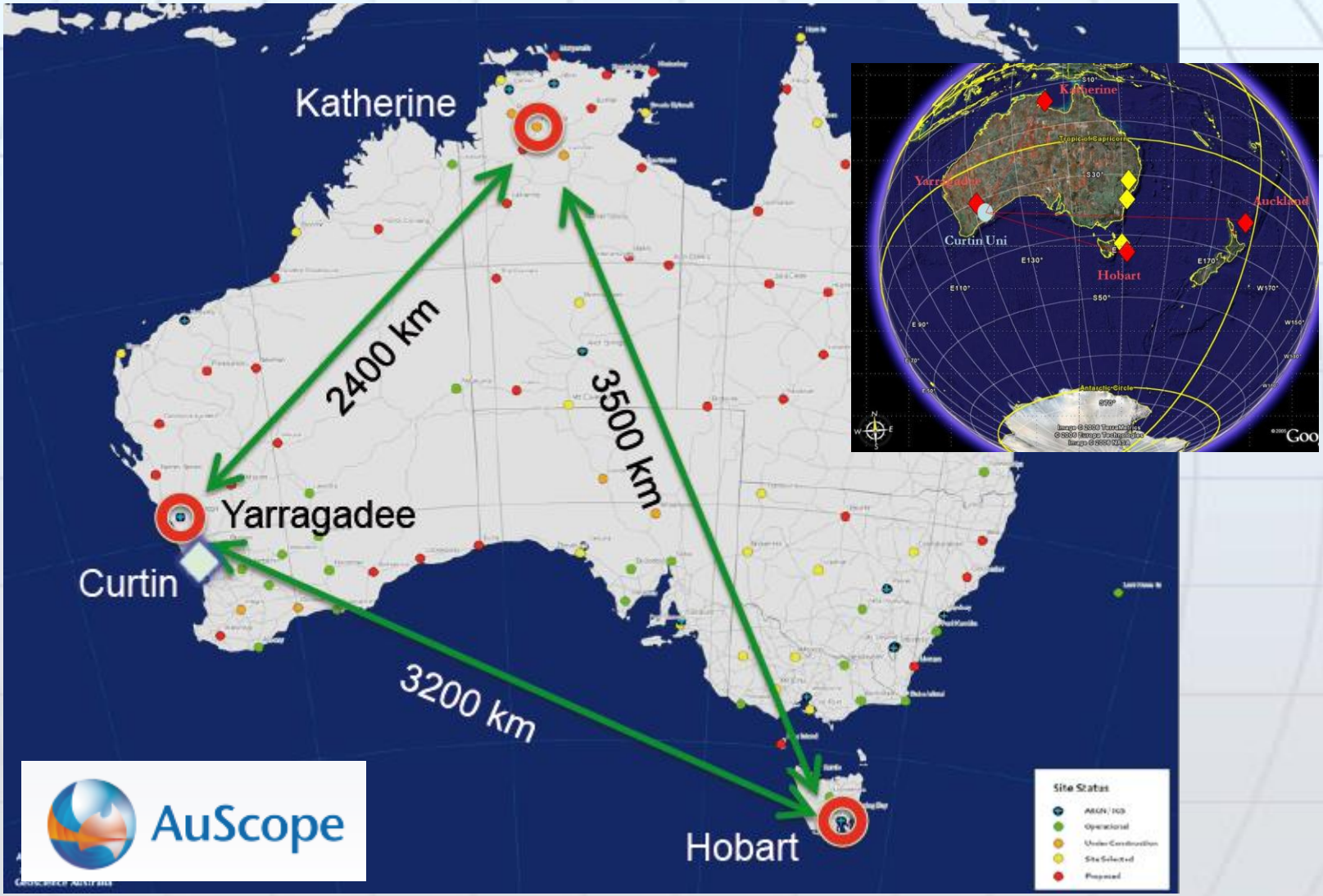
VLBI2010 also includes

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

1st VLBI2010 antenna: Hobart (AUS)

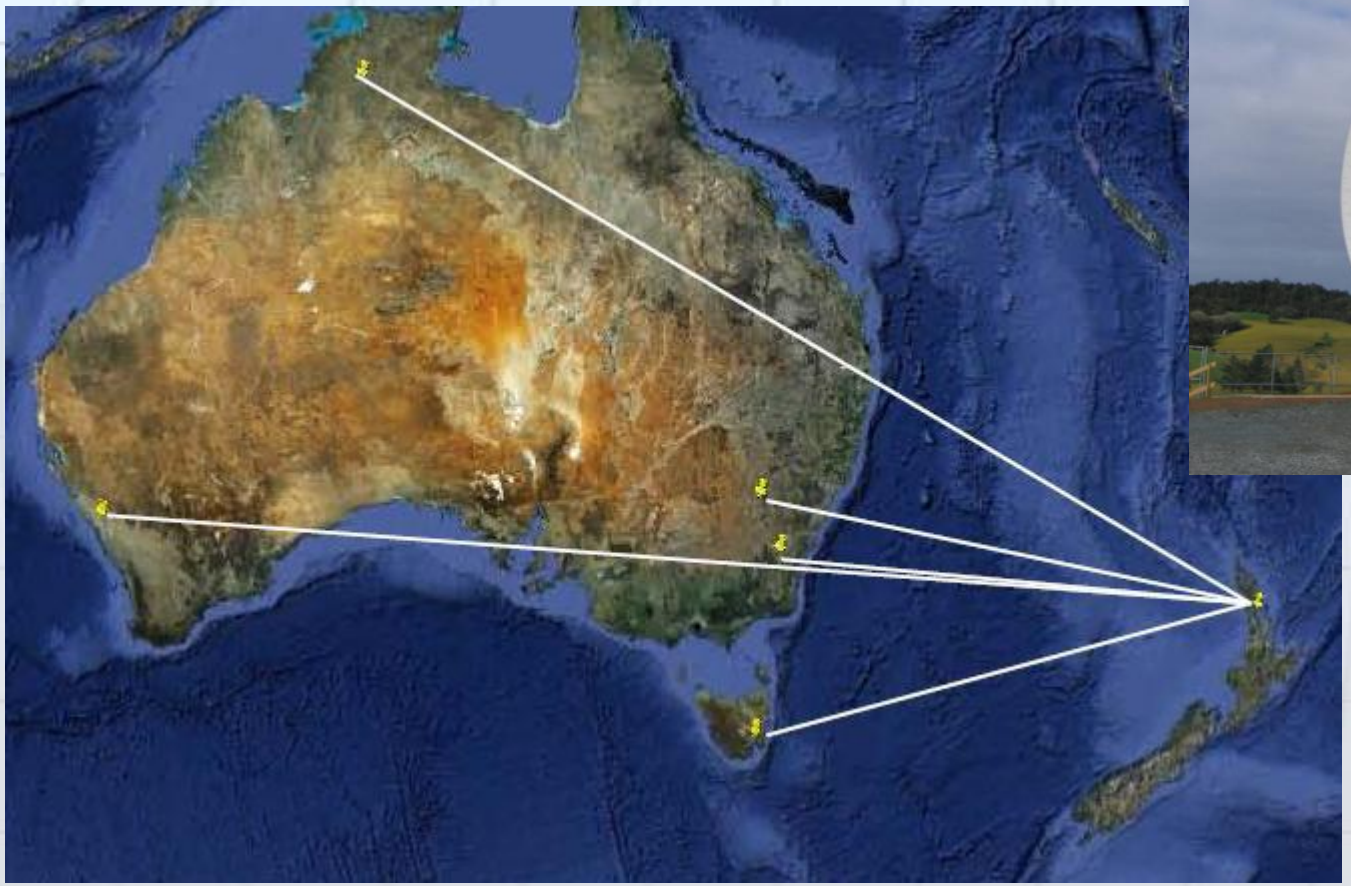
Dedication of the 1st VLBI2010 antenna by the Governor of Tasmania; Feb-09-2010; Mt. Pleasant Observatory, TAS, AUS

New VLBI2010 antennas: AuScope (AUS)



New VLBI2010 antenna: AUT (NZL)

- Auckland



AUT UNIVERSITY
TE WĀNANGA ARONUI O TAMAKI MAKAU RAU

New VLBI2010 antennas: China

New VLBI2010 antennas: RAEGE

RED ATLÁNTICA DE ESTACIONES GEODINÁMICAS Y ESPACIALES (RAEGE)

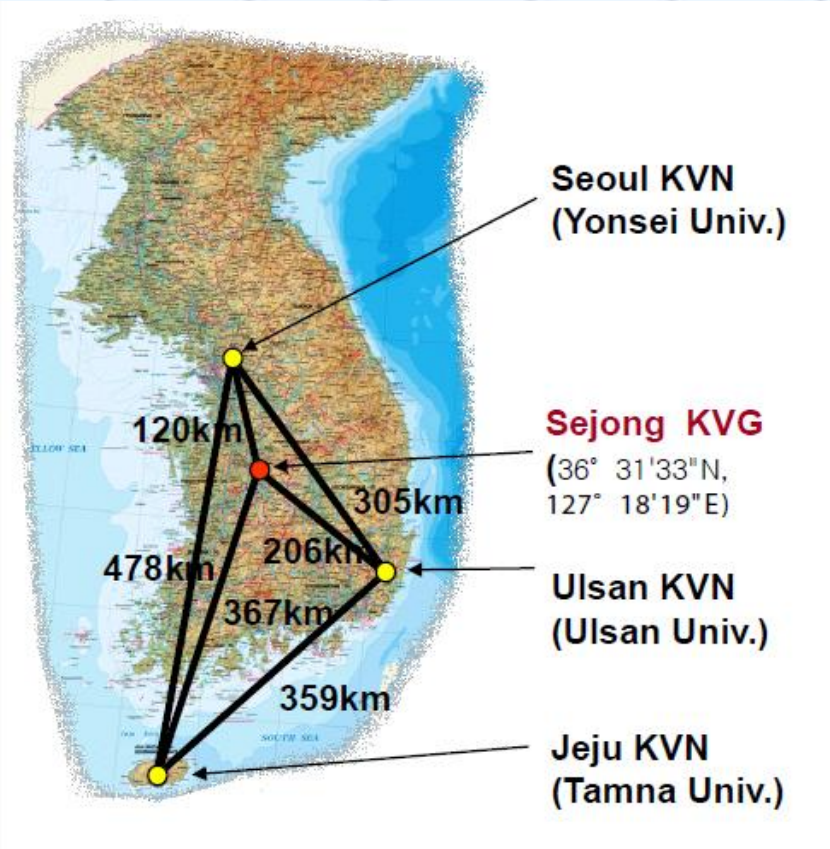
4 new VLBI 2010 antennas (of TTW type)

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)

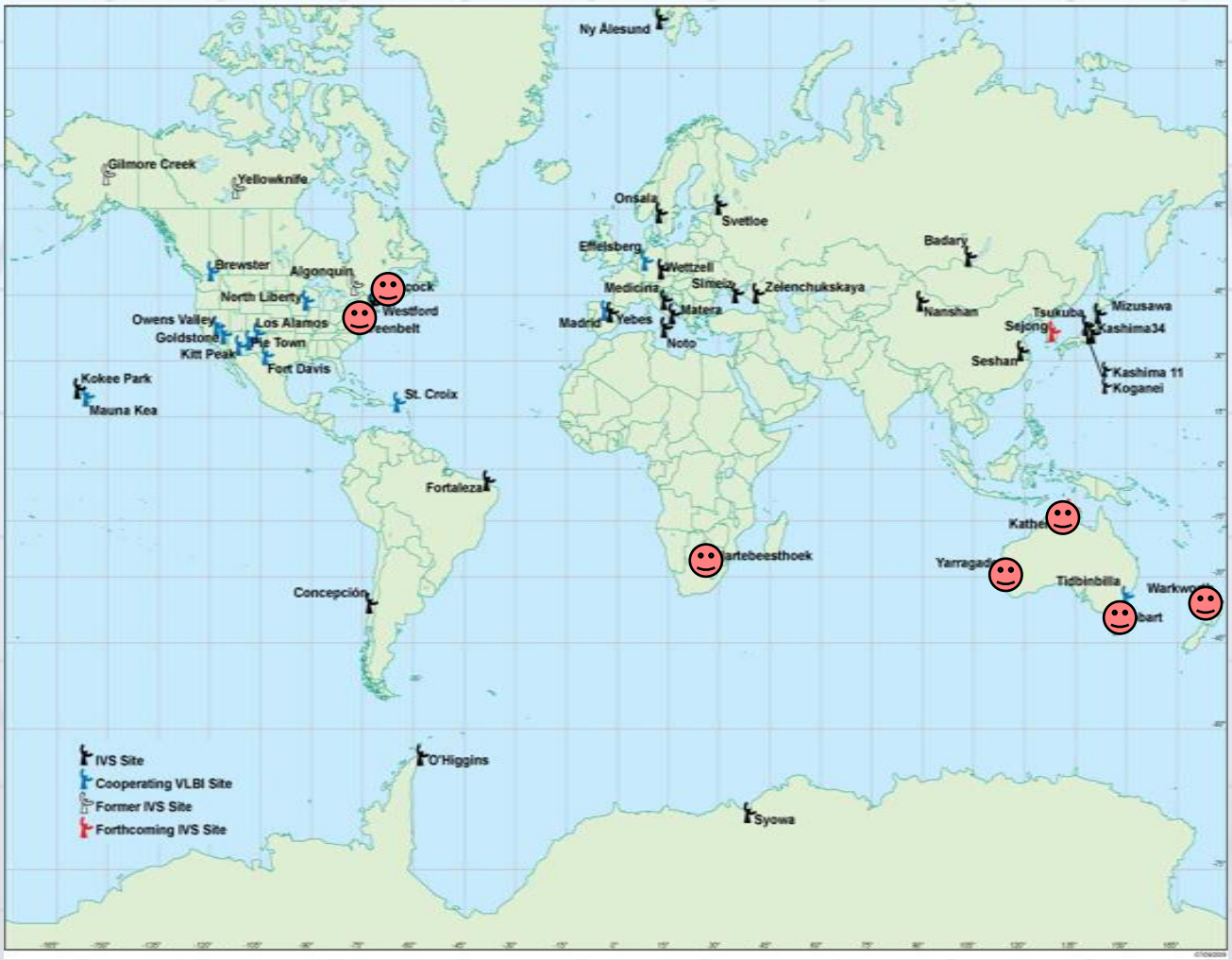
- Partly for geodesy



New VLBI2010 antennas: TTW

- Twin Telescope Wettzell (GER), Vertex Antennas

VLBI2010 Network in 2011



[Hase et al., 2011]

VLBI2010 very fast

radio telescope

twin radio telescope

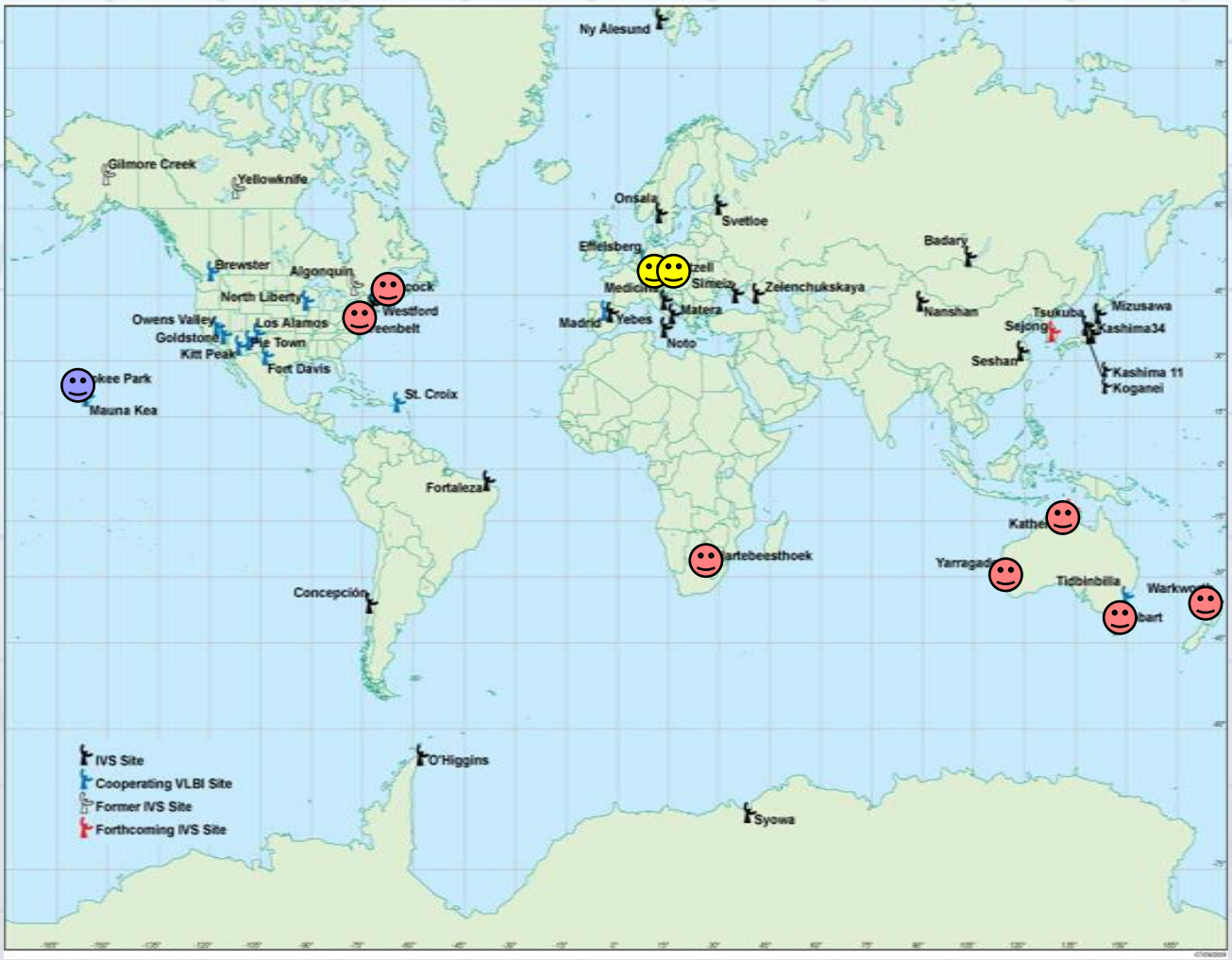
VLBI2010 fast

radio telescope

upgrade legacy

radio telescope

VLBI2010 Network in 2012



[Hase et al., 2011]

VLBI2010 very fast

- radio telescope
- twin radio telescope

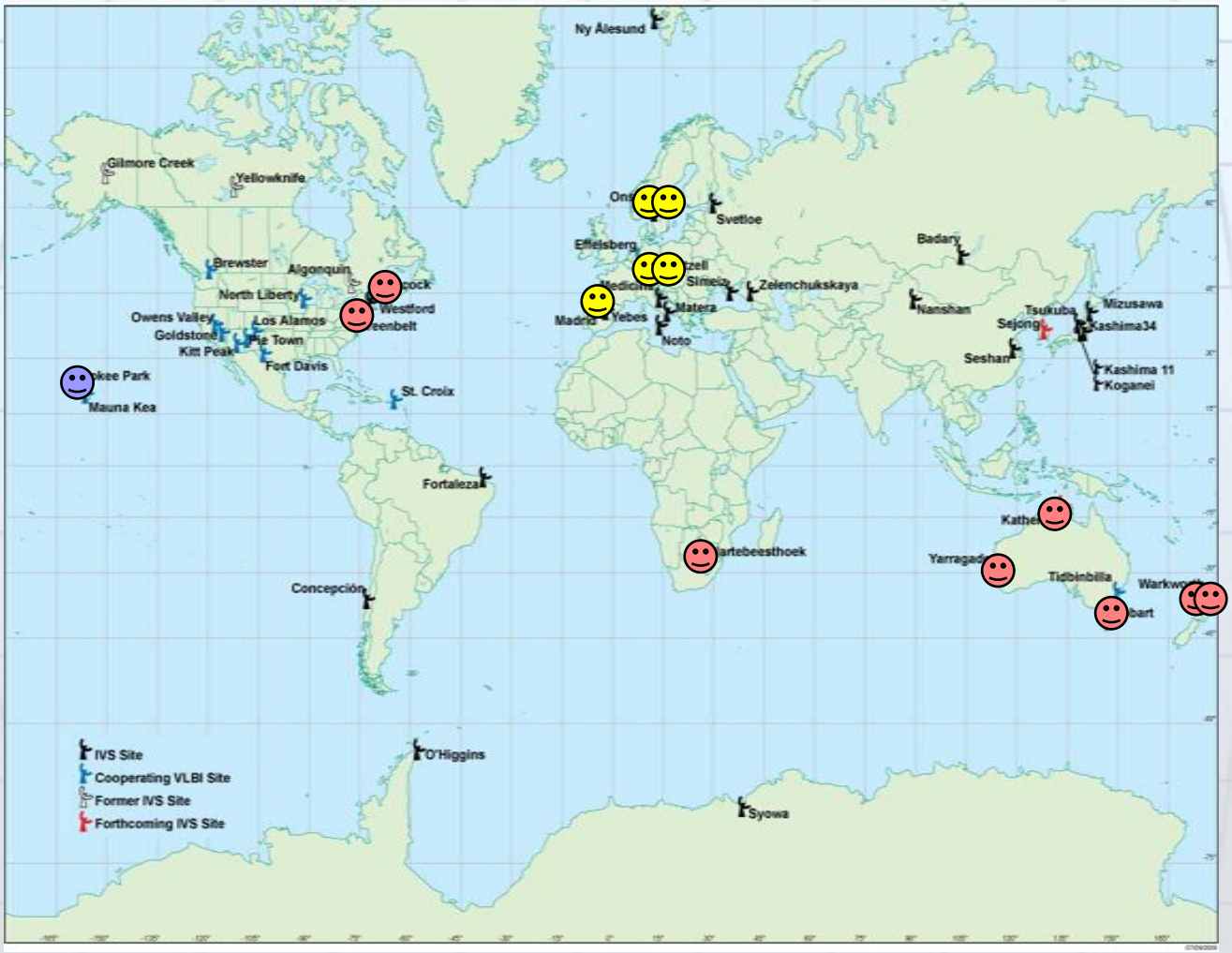
VLBI2010 fast

- radio telescope

upgrade legacy

- radio telescope

VLBI2010 Network in 2013



[Hase et al., 2011]

VLBI2010 very fast

- radio telescope
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VLBI2010 fast

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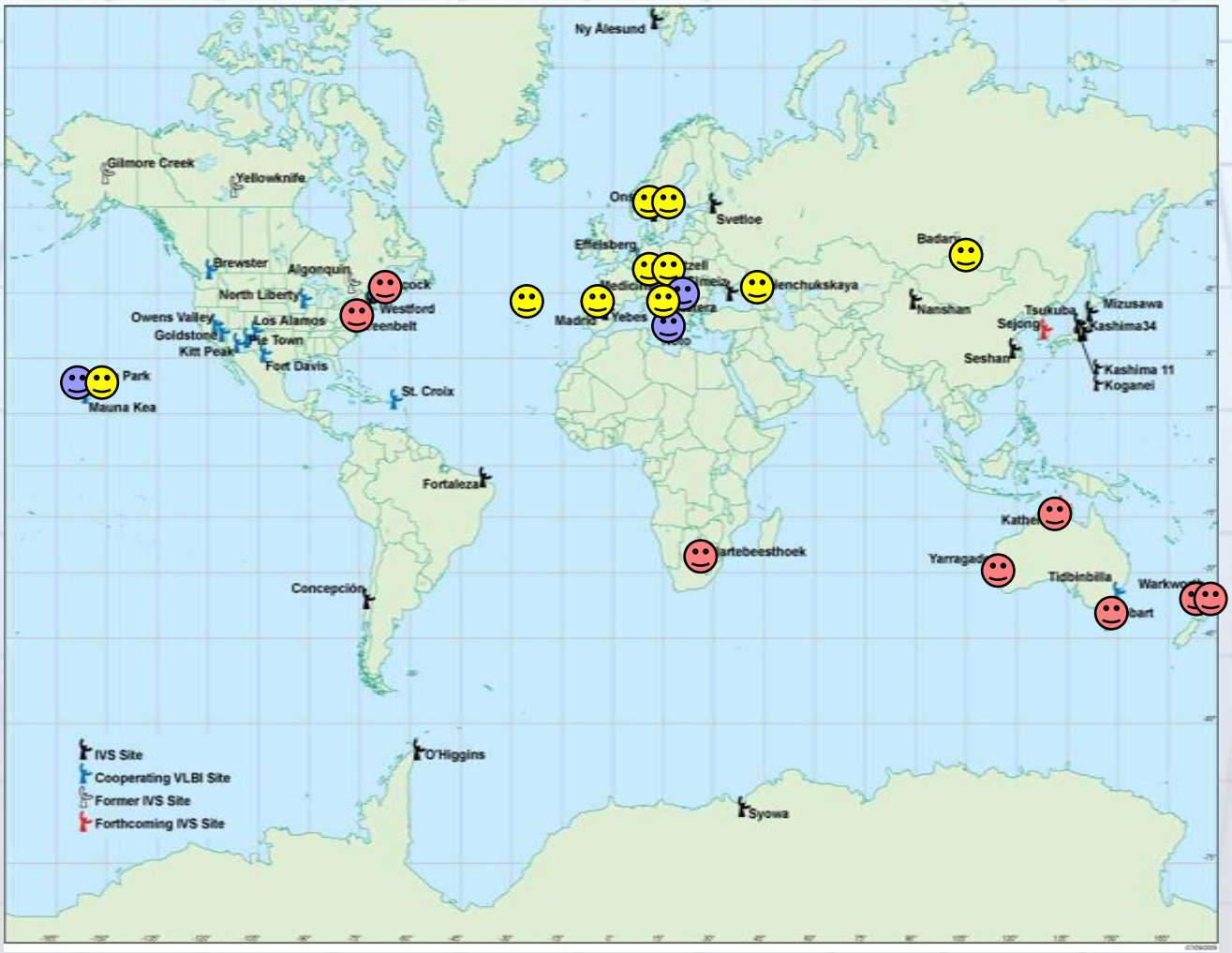
VLBI2010 Network in 2014



[Hase et al., 2011]

VLBI2010 very fast

- radio telescope
- twin radio telescope

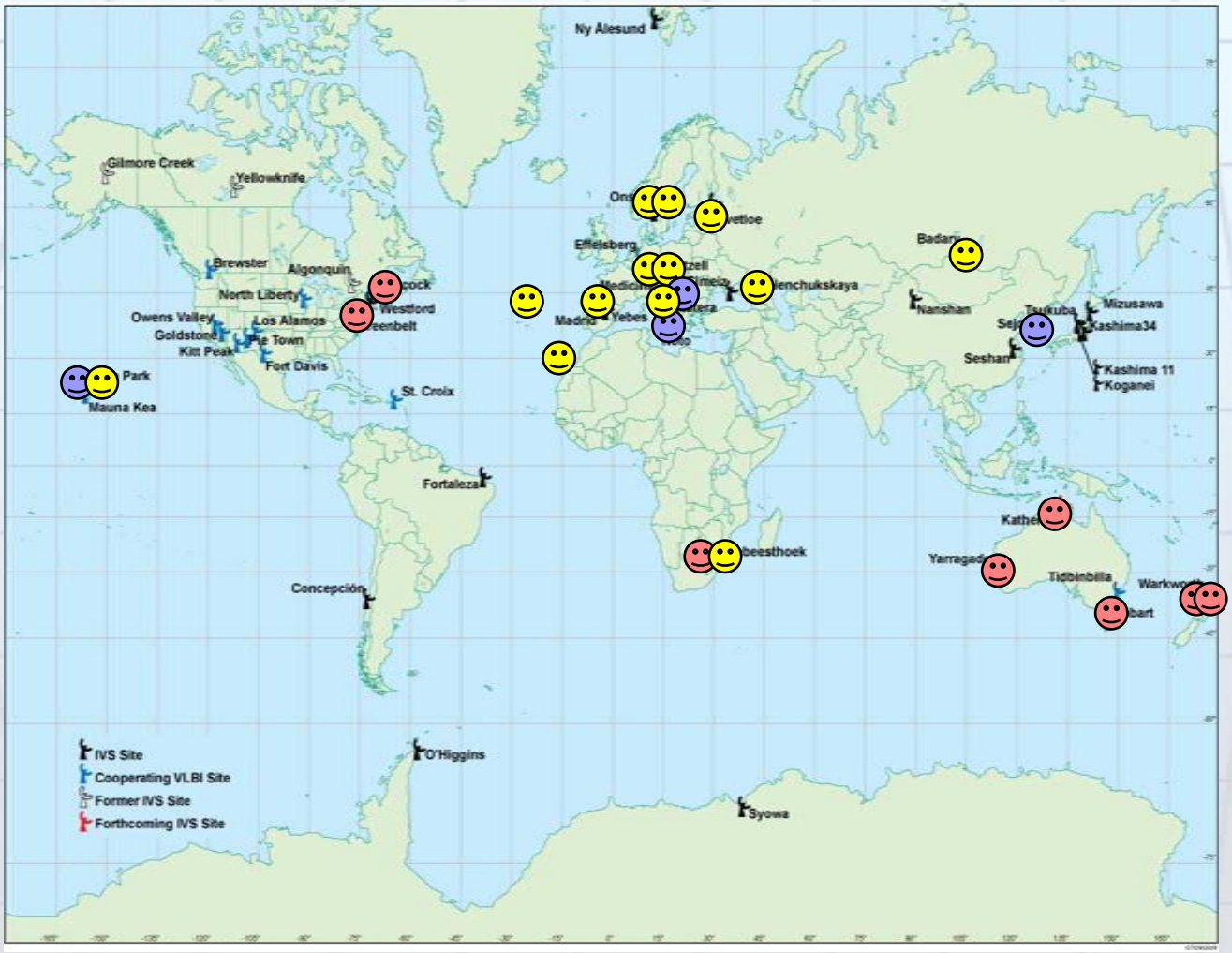
VLBI2010 fast

- radio telescope

upgrade legacy

- radio telescope

VLBI2010 Network in 2015



[Hase et al., 2011]

VLBI2010 very fast

radio telescope

twin radio telescope

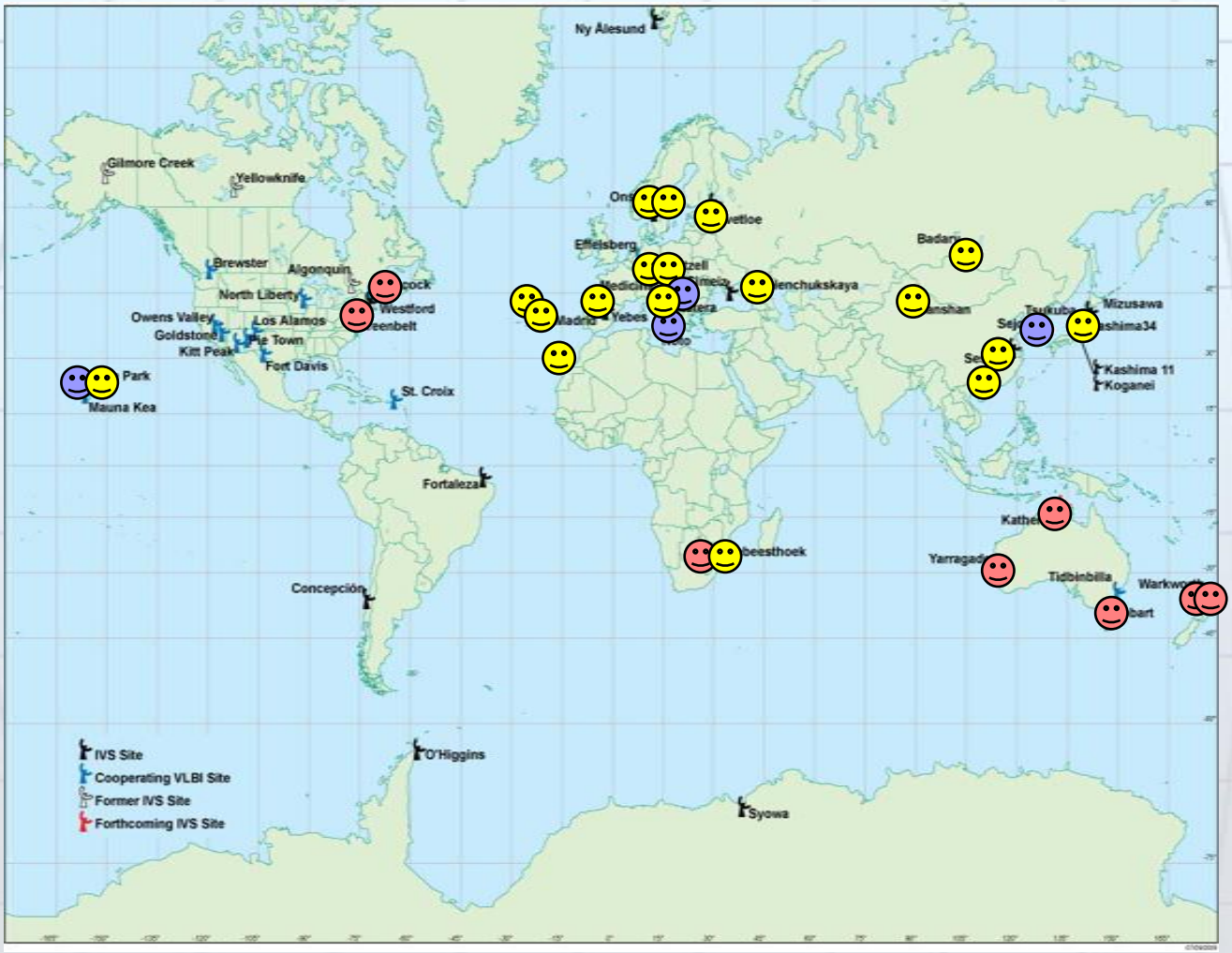
VLBI2010 fast

radio telescope

upgrade legacy

radio telescope

VLBI2010 Network in 2016



VLBI2010 very fast

- radio telescope
- twin radio telescope

VLBI2010 fast

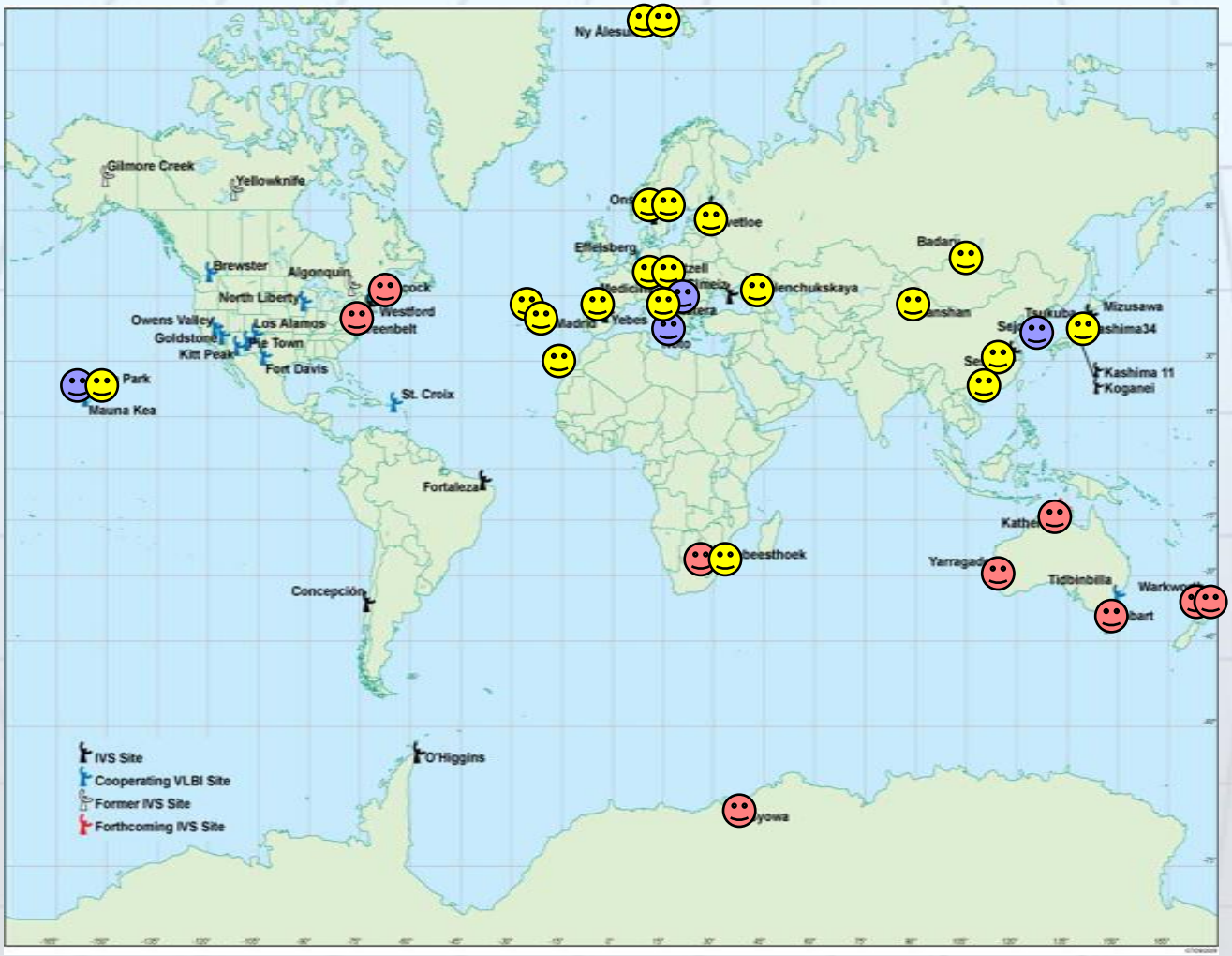
- radio telescope

upgrade legacy

- radio telescope

[Hase et al., 2011]

VLBI2010 Network in 2017



VLBI2010 very fast

- radio telescope
- twin radio telescope

VLBI2010 fast

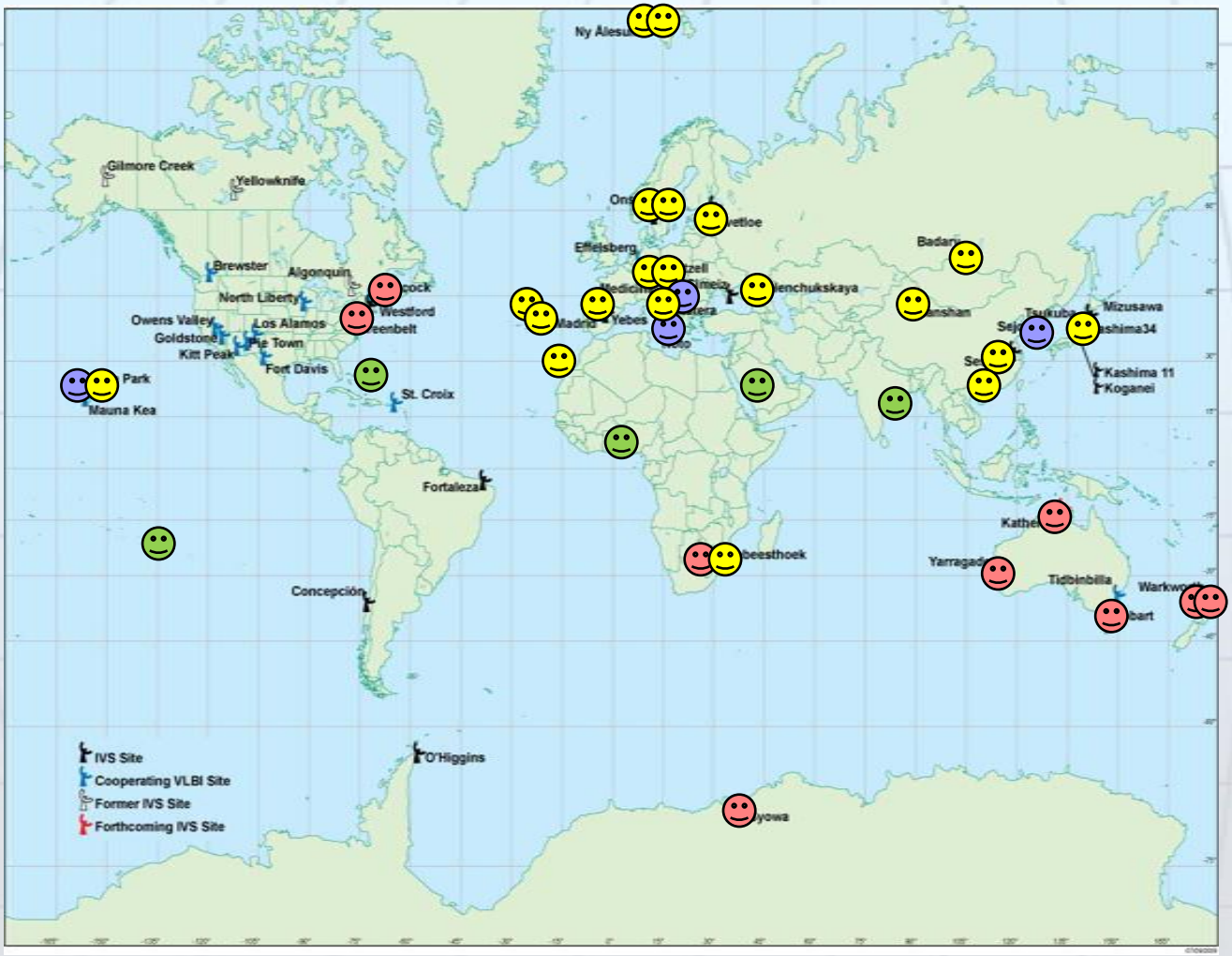
- radio telescope

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]

Conclusions VLBI2010

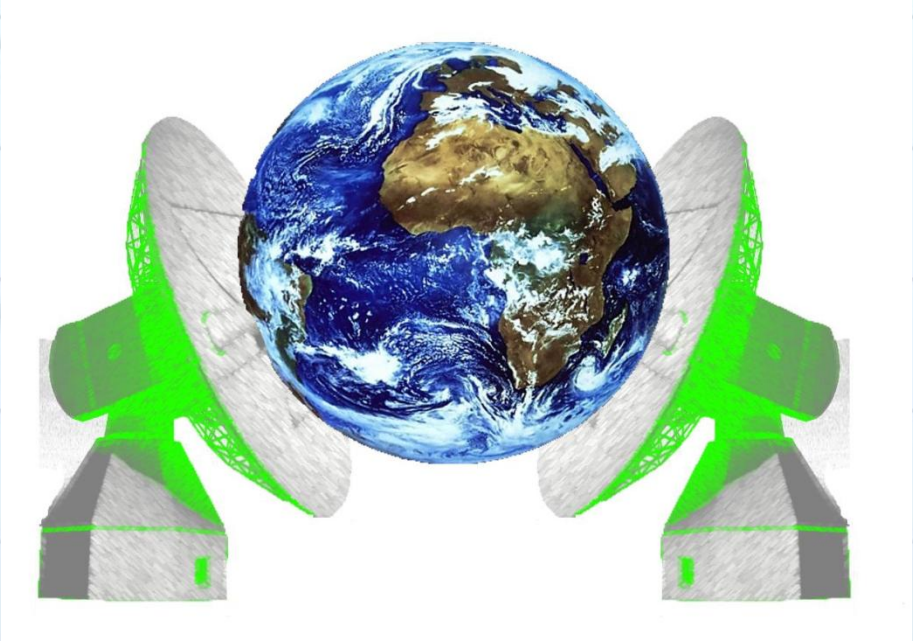
- > 20 new radio telescopes with VLBI2010 compliance should become operational by 2017.
- Additional new stations might join in.
- By 2015 a sufficient number of VLBI2010 compatible radio telescopes will be available for initial VLBI2010 operations.
- The American/Pacific region will lack presence of VLBI2010 network stations.

Concluding remarks

- VLBI plays an important role in geodesy as it provides unique information and allows to investigate a lot of geodynamical and astronomical phenomena

- with VLBI2010 more prosperous decades will follow

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



Thank you for your attention!

harald.schuh@tuwien.ac.at

Development of VLBI in the 60‘s

- First realizations in Canada (Broten et al., 1967) and in the U.S.A. (Bare et al., 1967, Shapiro, 1968)
- MK-1 System (accuracy ~ 0.5 m)

MK-1 System

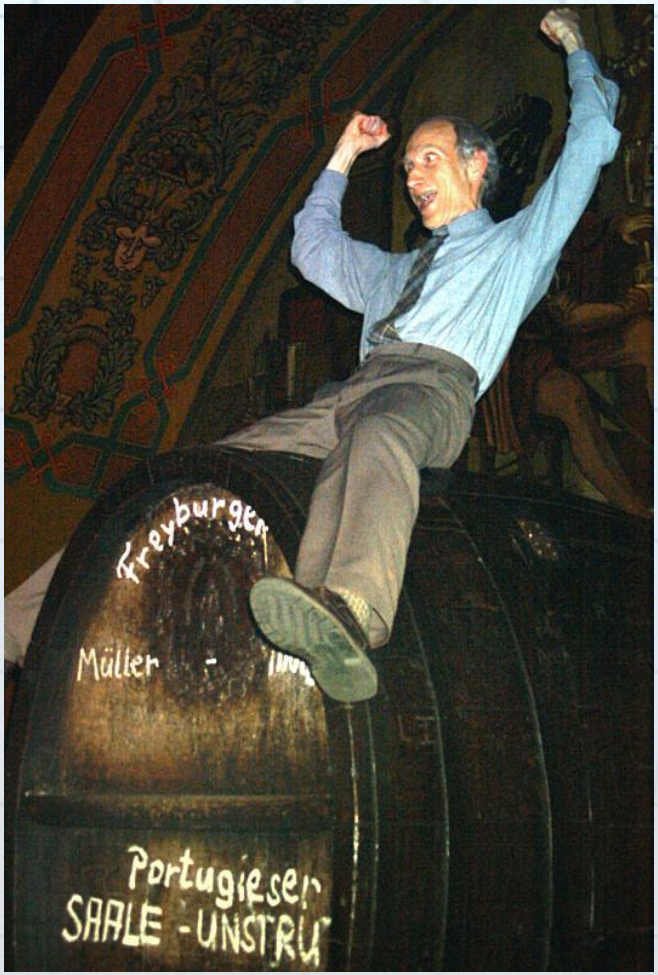
VLBI in the 70‘s

USA:

- Shapiro et al. (1972, 1973, 1974): first astronomical-geodetic VLBI experiments

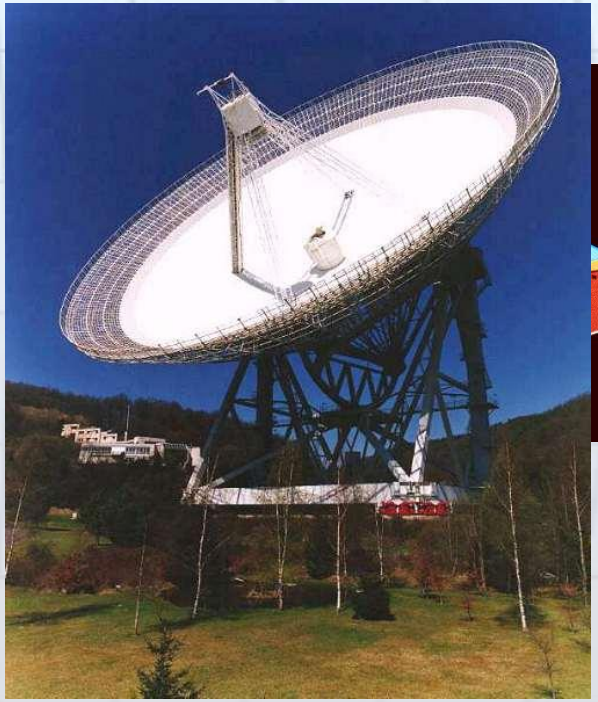
Europe:

- Witte (1971) demonstrates the potential of VLBI
- University of Bonn: Witte, Seeber, Campbell und Brosche work with VLBI (Campbell und Witte, 1978, Campbell, 1979); collaboration with MPIfR
- MK-2 System (accuracy: 0.2-0.3 m)



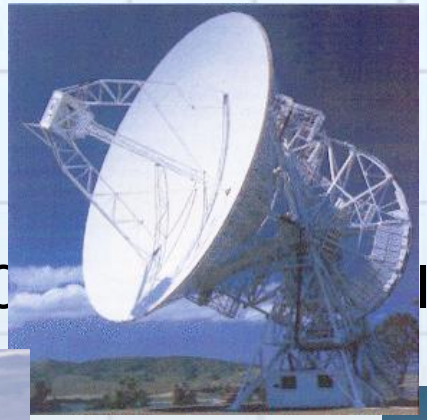
VLBI in the 80‘s

- Development of the MK-3 System (accuracy: 2-3 cm)
- Installation of international observing campaigns (e.g. within NASA Crustal Dynamics Project)
- Radio telescopes in Europe:
  - Onsala Space Observatory (SWE)
  - Effelsberg 100 m (GER)
  - 20 m telescope at the „Fundamentalstation“ Wettzell (GER)
- First metrological proof of plate tectonics
  - Herring et al., 1986
    rate Haystack-Onsala + 17 ± 2 mm/yr



VLBI in the 90‘s

- Extension of the global network (Japan, China, Australia, South-America)



lescope C lfaG), sin

Hobart (26 m)

nd or 94

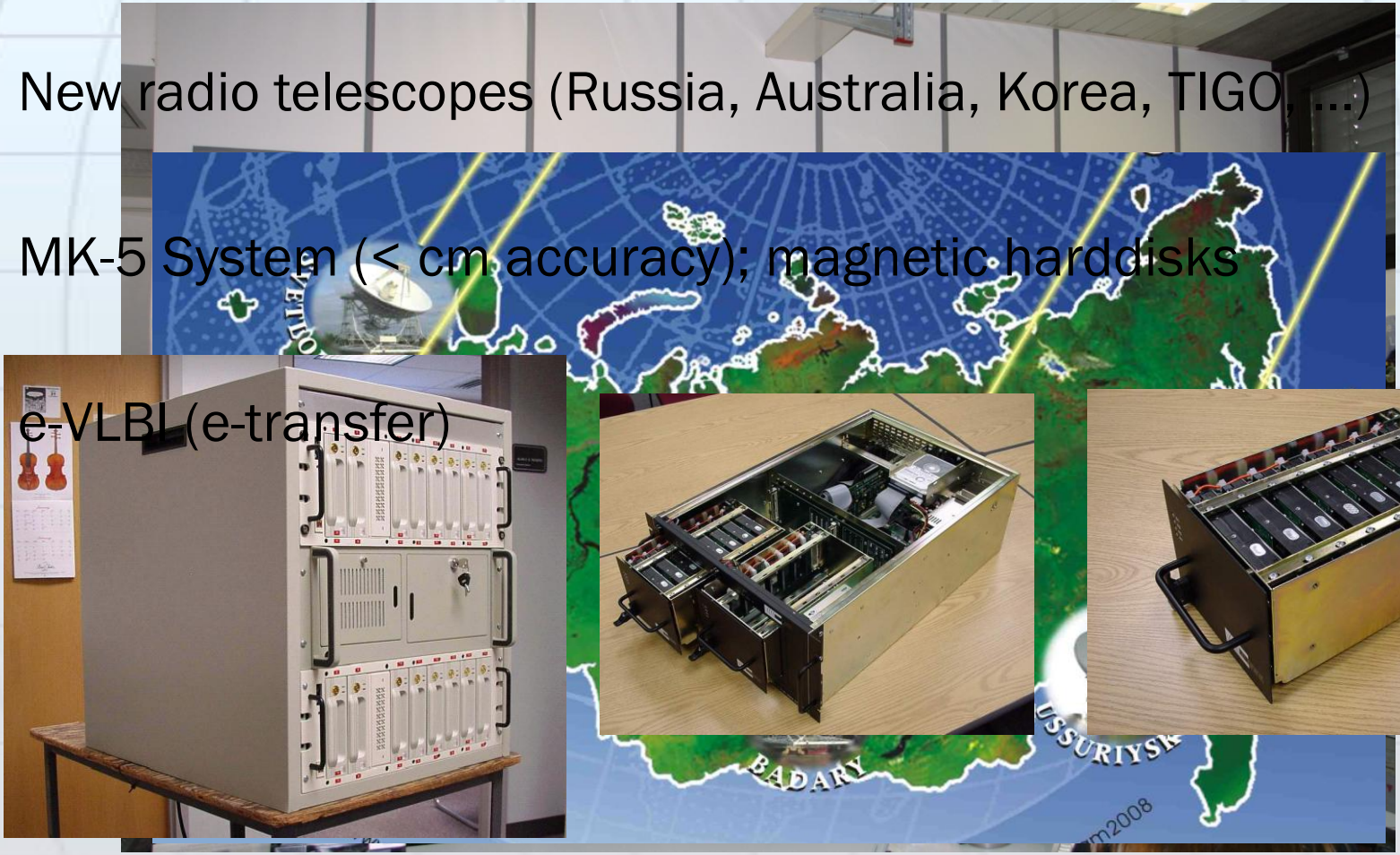
and Astromet

Shanghai (25 m)

Tidbinbilla (70 m)

VLBI in the new century

- MK-4 correlator at MPIfR (fall 2000)
- New radio telescopes (Russia, Australia, Korea, TIGO, ...)
- MK-5 System (< cm accuracy); magnetic harddisks
- e-VLBI (e-transfer)



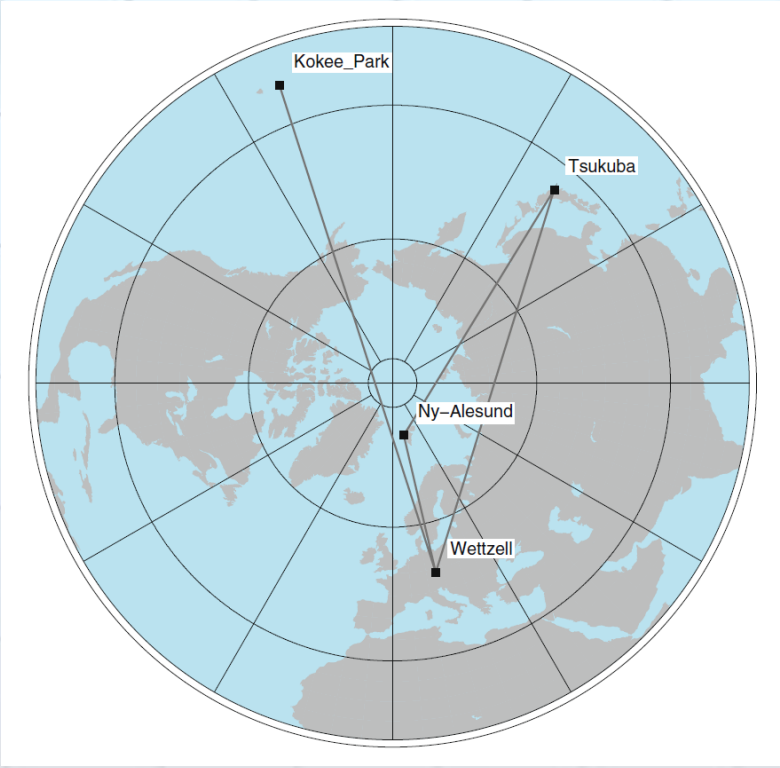
VLBI product: dUT1 from Intensives

- 1 hour sessions carried out every day for determination of Universal Time.

  INT1: Wettzell-Kokee (Mon-Fri)

  INT2: Wettzell-Tsukuba (Sat-Sun)

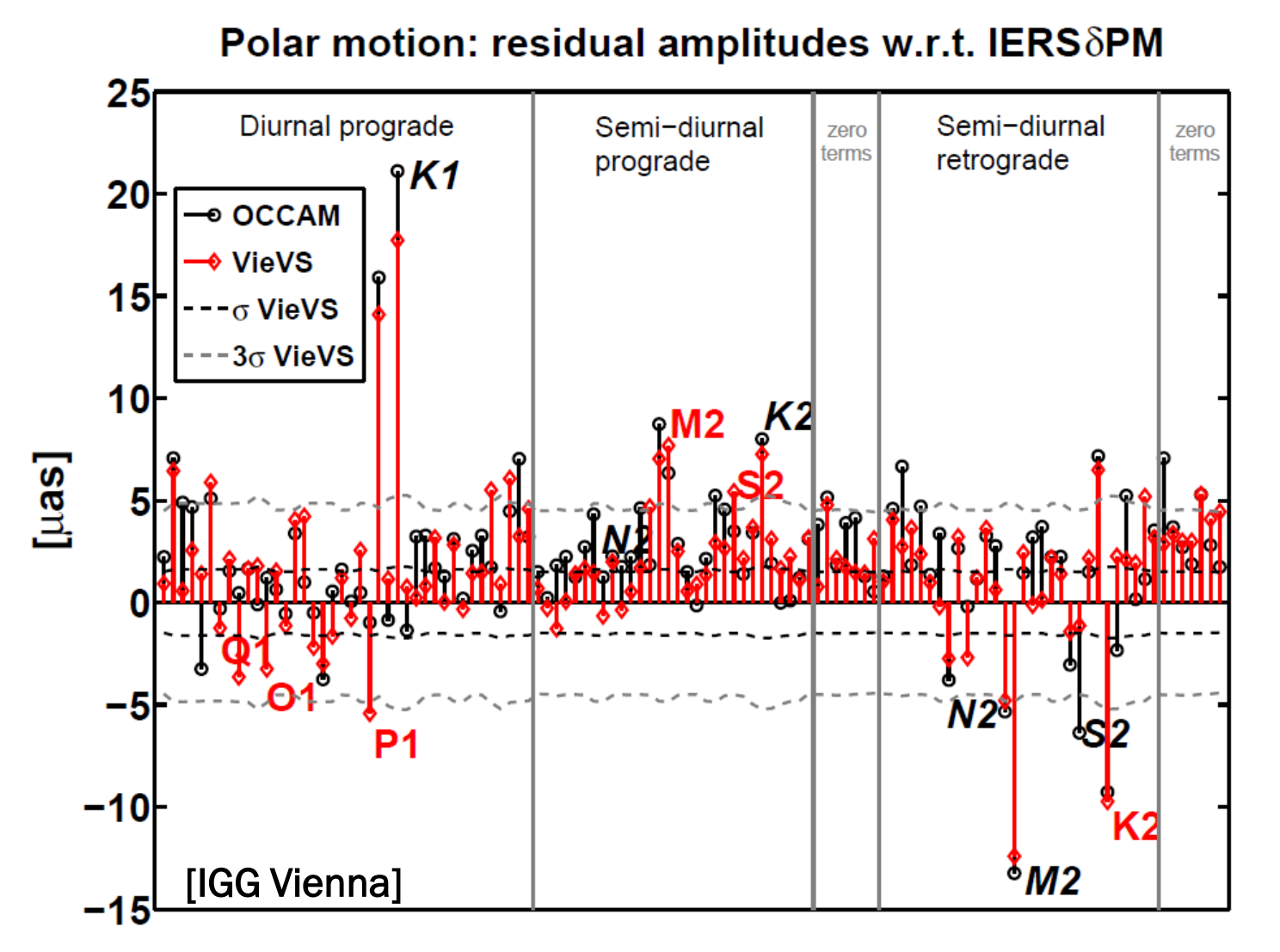
  INT3: Wettzell, Tsukuba,
  Ny-Ålesund (Monday morning)



[Luzum & Nothnagel, 2010]

- Important for EOP prediction;
  especially if data is available in near real-time.

Tidal terms in polar motion



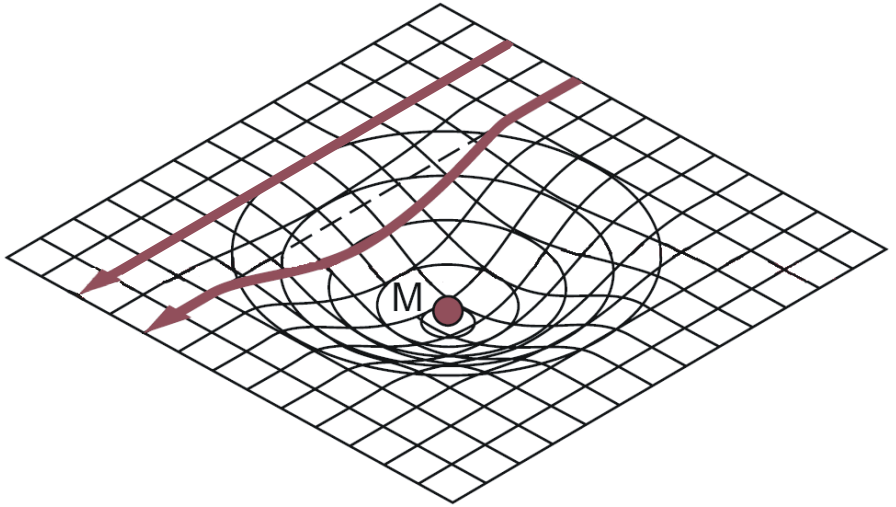
Gravitational time delay

Gravitational delay of n-th solar system body

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

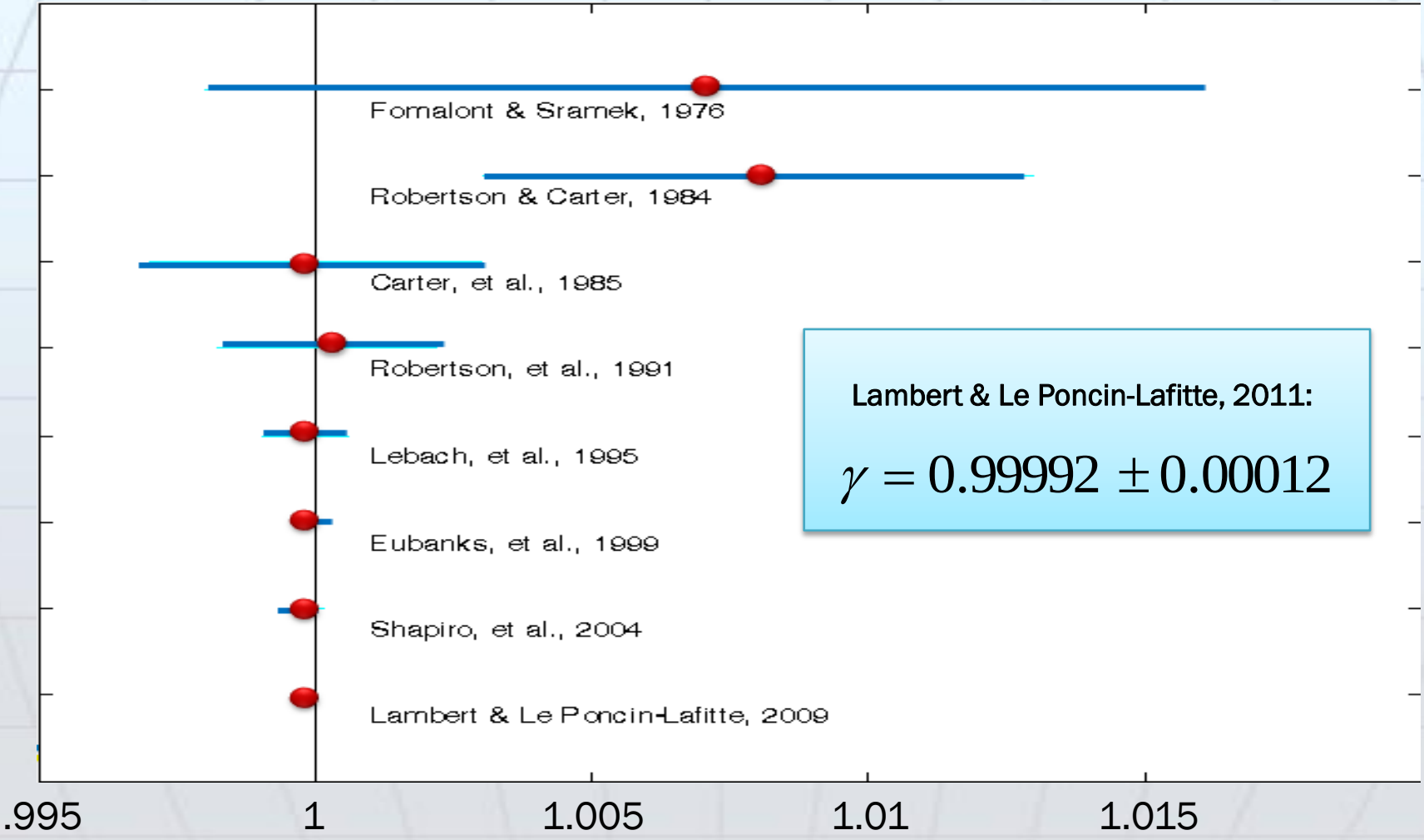
$\vec{x}_{i,n}$ ... position vector of station i w.r.t. center of mass of n-th body

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



VLBI product: relativistic parameters

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



Lambert & Le Poncin-Lafitte, 2011:

$$\gamma = 0.99992 \pm 0.00012$$

VLBI2010 – the V2C

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

- to encourage the implementation of the recommendations of WG3

VLBI2010 – V2C activities

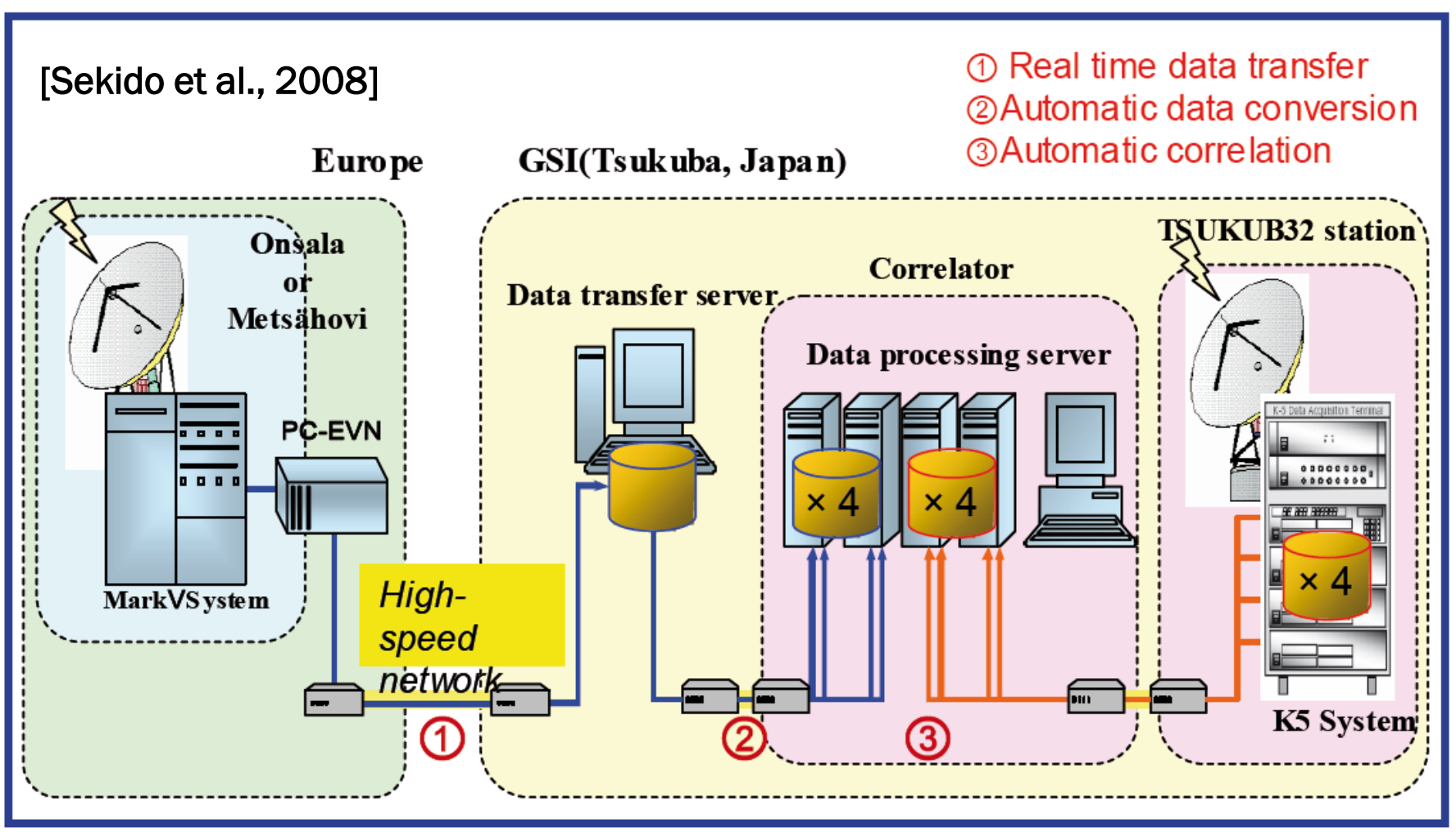
- system studies
- Monte Carlo simulations
- development projects
- prototyping

VLBI2010 – a completely new generation of VLBI hardware and software

VLBI2010 also includes

- software correlation
- automation of data analysis

VLBI analysis automation



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.
  - Final prototypes are in development.

VLBI: A Fascinating Technique for Geodesy and Astrometry

I. VERY LONG BASELINE INTERFEROMETRY – PRINCIPLE

II. VLBI PRODUCTS

III. MEETING TODAY‘S CHALLENGES

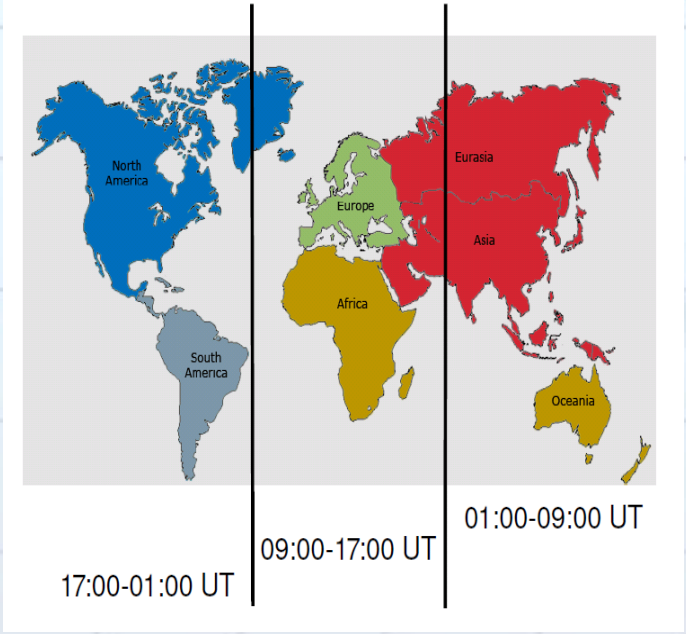
IV. VLBI2010

V. **NEW PERSPECTIVES**

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.

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)
  - e.g. Microsatellites for GNSS Earth Monitoring (MicroGEM)
- **Differential**
  - Quasar –
    - Deep s
    - DSN, Δ
    - NASA,
  - SC – SC
    - multi-f
    - same
    - e.g. SE