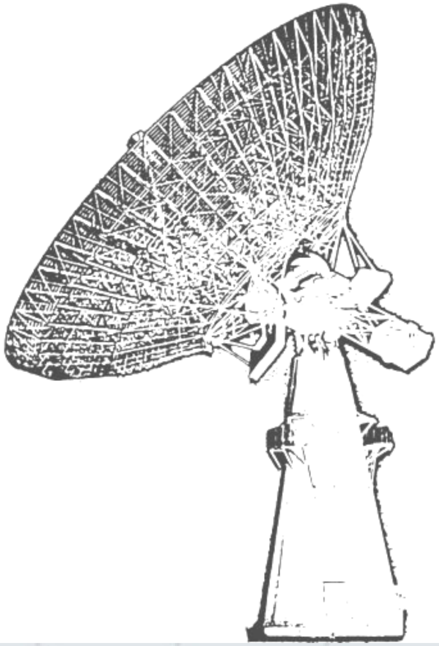
• History of VLBI
• the IVS, and
• the next generation of VLBI



H. Schuh, L. Plank

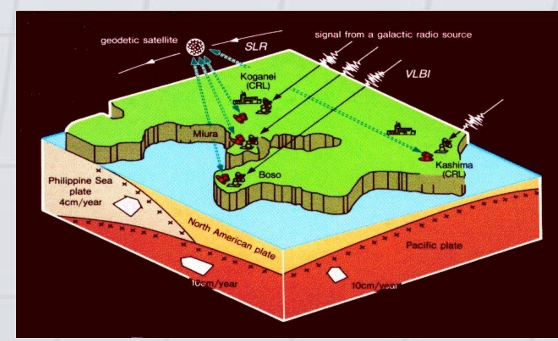
Evolution of VLBI

- 60ies:
  - First realization 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)

- 70ies:
  - Witte (1971) describes VLBI in German journal (ZfV)
  - Shapiro et al. (1972, 1973, 1974): first astronomic/ geodetic VLBI experiments
  - Univ. Bonn: Witte, Seeber, Campbell and Brosche are working on VLBI (Campbell und Witte, 1978, Campbell, 1979)
  - since 1977 support from DFG
  - Collaboration with MPIfR
  - MK-2 system (accuracy 0.2-0.3 m)

Max-Planck-Institut für Radioastronomie

- 80ies:
  - First boost of VLBI
  - Development of the MK-3 system (accuracy 2-3 cm)
    → factor 10!
  - Installation of international observing programs (e.g NASA Crustal Dynamics Project)



VLBI in the 80ies

- In Germany:
  - Use of RT Effelsberg and Werthoven for single VLBI experiments
  - Construction of the 20m-radiotelescope at the fundamental station* Wettzell (1983)

Effelsberg 100m; HG-Exkursion 2008

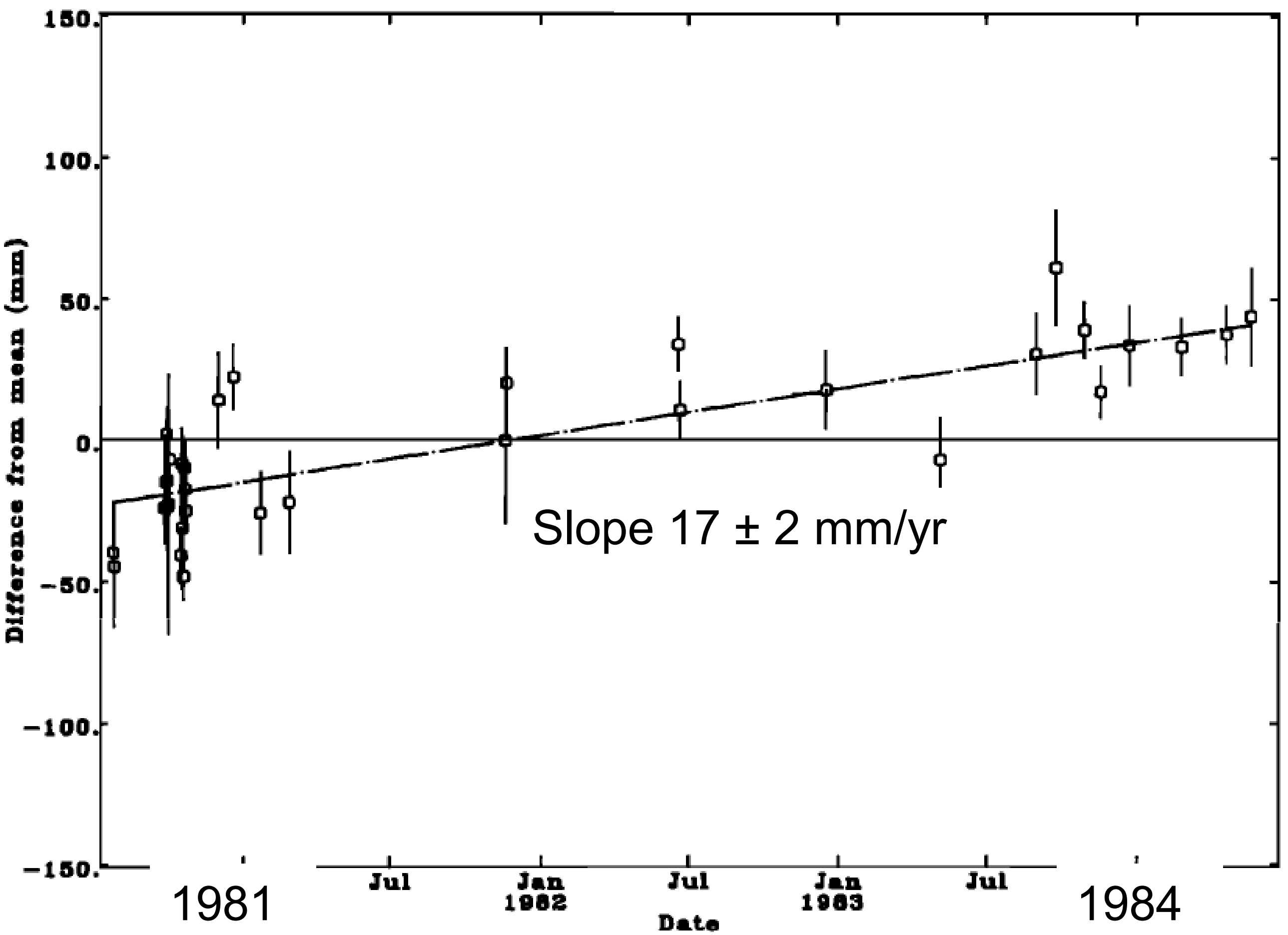
Wettzell 20m

* More techniques at the same place

VLBI in the 80ies

- **First measured proof of tectonic plate motion (middle of the 80ies)**
  before: estimates based on geological data only

Haystack , Massachusetts – Onsala, SWE



Herring et al., 1986:

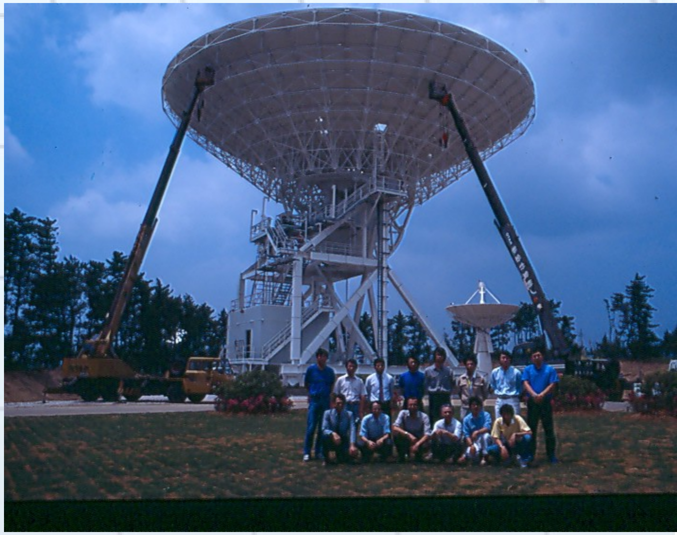
"Evidence for Contemporary Plate Motion"

Improved accuracy:
1980 : 100 ps (= 30 mm)
1990 : 30 ps (= 10 mm)
2000 : 10 ps (= 3 mm)

VLBI in the 90ies

- Improvement of global VLBI measurements (Japan, China, Australia, South-America)

Hobart (26 m)



Kashima (34 m)

Shanghai (26 m)

Tidbinbilla (70 m)

Fortaleza (14 m)

VLBI in den 90ies

- Improvement of global VLBI measurements (Japan, China, Australia, South-America)
- 9m-Radiotelescope O'Higgins (DLR, IfaG) since 1992

O'Higgins
(9m)

VLBI in the 90ies

- Improvement of global VLBI measurements (Japan, China, Australia, South-America)
- 9m-Radiotelescope O'Higgins (DLR, IfaG) since 1992
- Budget problems of NASA
- 01.03.1999: Formation of the IVS (*International VLBI Service for Geodesy and Astrometry*)

http://ivscc.gsfc.nasa.gov/

IVS - International VLBI Service for Geodesy and Astrometry

Astrometry	….	Surveying of the sky
Geodesy	….	Surveying of the Earth

IVS is a Service of

- **IAG** - International Association of Geodesy
- **IAU** - International Astronomical Union
- **WDS** - World Data System

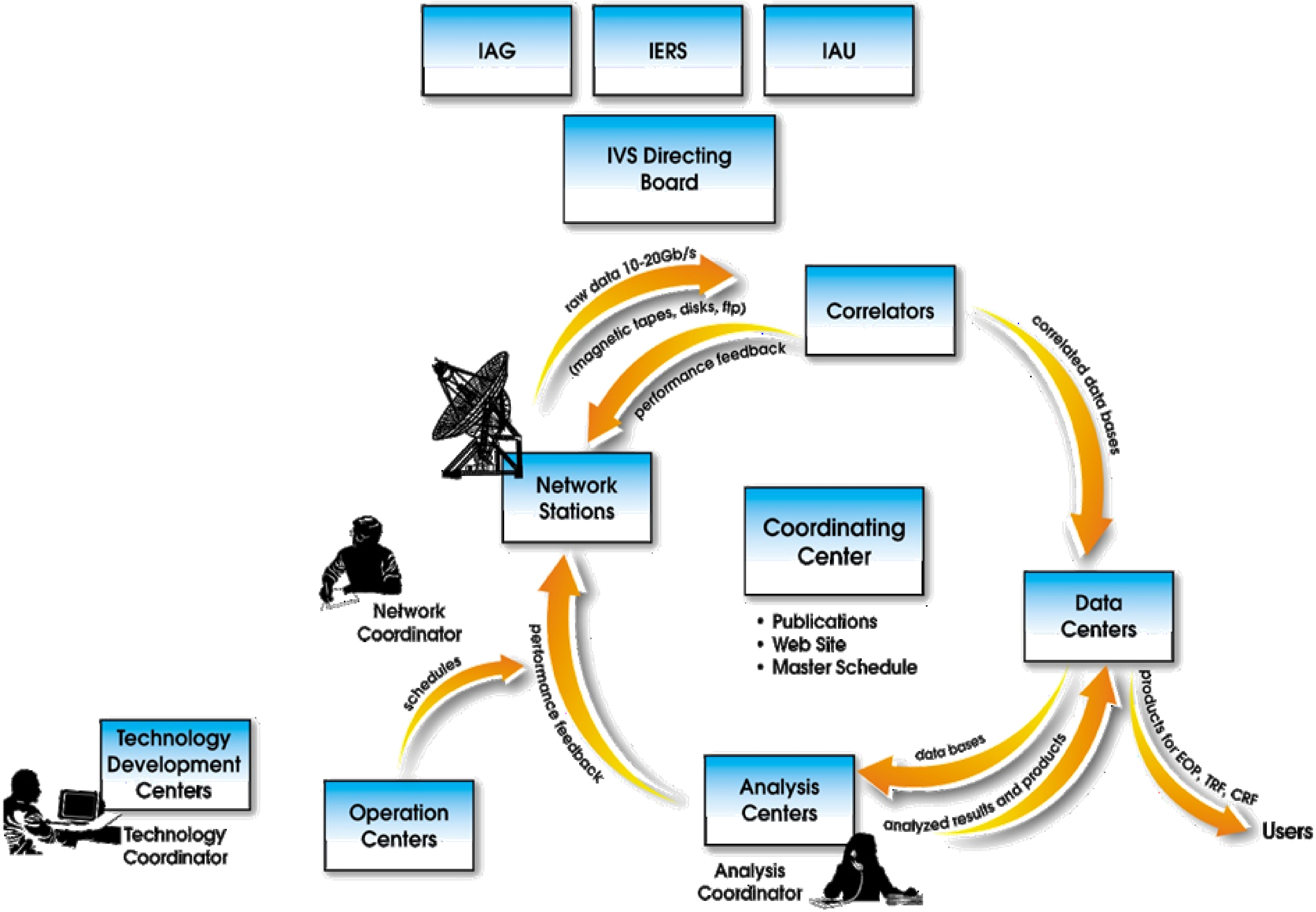
IVS goals:

- To provide a service to support geodetic, geophysical and astrometric research and operational activities → operational
- 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 (GGOS)

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

- IVS inauguration was on March 1st, 1999
- 81 permanent components supported by >40 institutions in >20 countries
- ~270 Associate Members
- \+ 1000 technicians & operators

IVS Structure

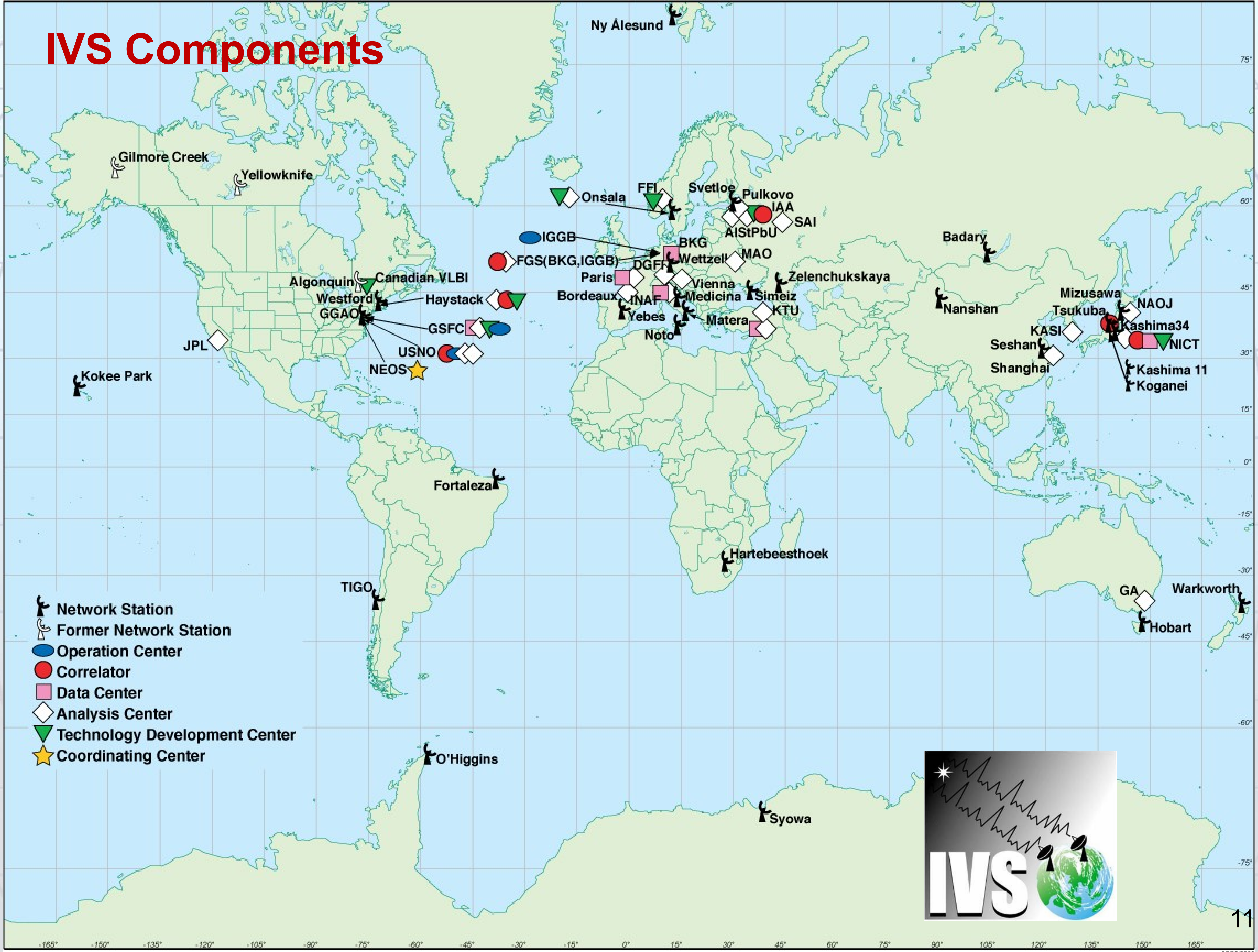


IVS Directing Board

Oct 2010

Position	Name	Affiliation	Country
IAG Representative, Chair	Harald Schuh	Technical University Vienna	Austria
IAU Representative	Patrick Charlot	Bordeaux Observatory	France
IERS Representative	Chopo Ma	NASA Goddard Space Flight Center	USA
Coordinating Center Director	Dirk Behrend	NVI, Inc./Goddard Space Flight Center	USA
Analysis Coordinator	Axel Nothnagel	Institut für Geodäsie und Geoinformation der Universität Bonn	Germany
Technology Coordinator	Alan Whitney	Haystack Observatory	USA
Network Coordinator	Ed Himwich	NVI, Inc./Goddard Space Flight Center	USA
Networks Representative	Gino Tuccari	Istituto di Radioastronomia INAF	Italy
Networks Representative	Hayo Hase	Bundesamt für Kartographie und Geodäsie, TIGO	Germany/Chile
Correlators and Operation Centers Representative	Alessandra Bertarini	IGG Bonn, Max Planck Institute for Radio Astronomy	Germany
Analysis and Data Centers Representative	Oleg Titov	Geoscience Australia	Australia
Technology Development Centers Representative	Rüdiger Haas	Onsala Space Observatory, Chalmers University of Technology	Sweden
At Large Member	Jesús Gómez González	National Geographical Institute of Spain	Spain
At Large Member	Shinobu Kurihara	Geospatial Information Authority of Japan	Japan
At Large Member	Fengchun Shu	Shanghai Astronomical Observatory	China

IVS Components



IVS Analysis Centres

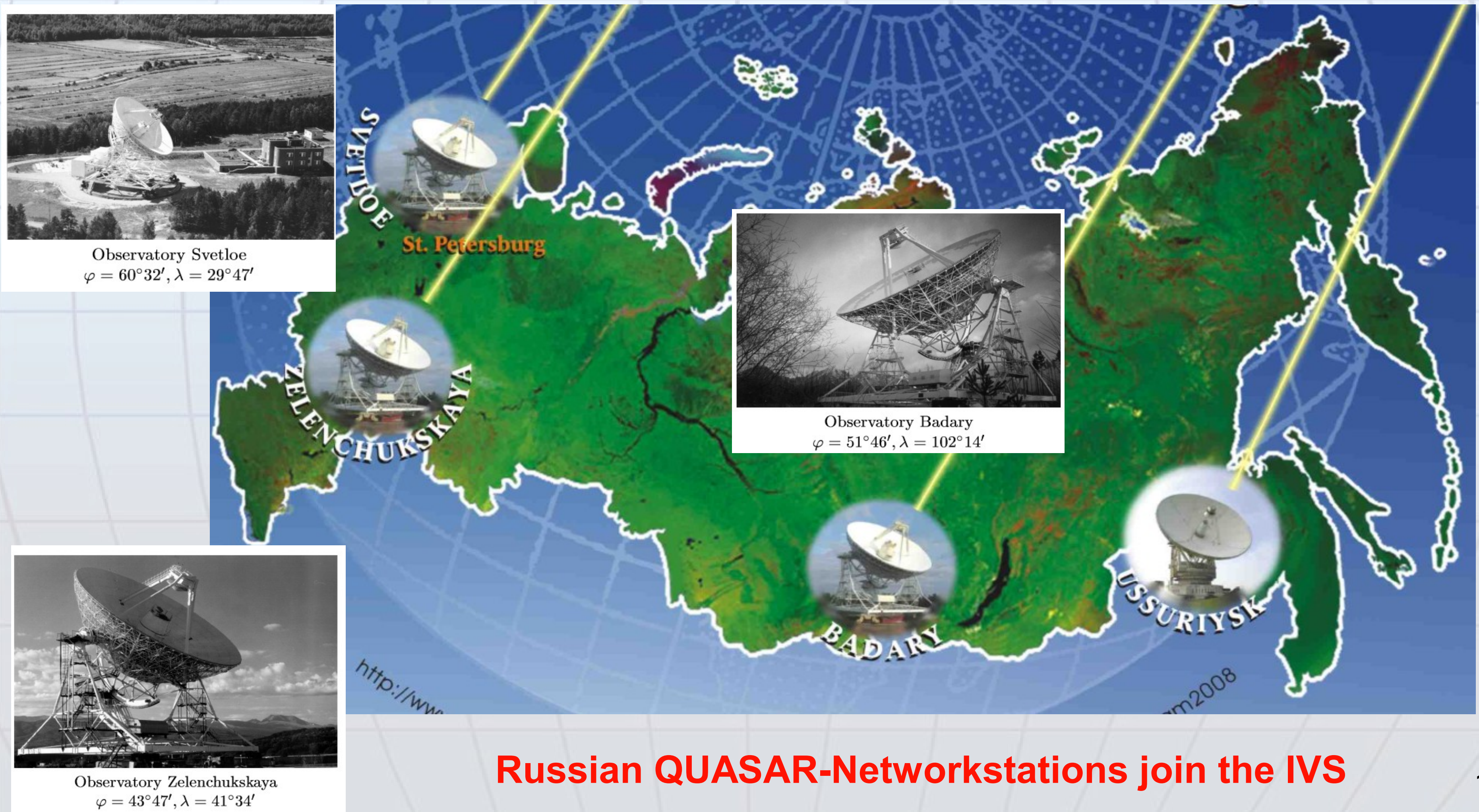
Country	IVS Component Name (link to recent Annual Report)	Type	Primary Contact	Sponsoring Organization	Software
Australia	Geoscience Australia	Full	Olev Titov	Geoscience Australia	
Austria	Institute of Geodesy and Geophysics (IGG)	Assoc	Harald Schuh	Institute of Geodesy and Geophysics (IGG), of the University of Technology Vienna	OCCAM **VieVS**
China	Shanghai Observatory	Full	Jinling Li	Shanghai Observatory, Chinese Academy of Sciences	CALC/SOLVE
France	Observatoire de Paris	Assoc	Anne-Marie Gontier	Observatoire de Paris	GLORIA
France	Observatoire de Bordeaux	Assoc	Patrick Charlot	Observatoire de Bordeaux	MODEST
Germany	DGFI	Full	Robert Heinkelmann	Deutsches Geodätisches Forschungsinstitut	OCCAM
Germany	IGGB-BKG Analysis Center	Full	Axel Nothnagel, Volkmar Thorandt	Institut für Geodäsie und Geoinformation der Universität Bonn and Bundesamt für Kartographie und Geodäsie	CALC/SOLVE
Germany	BKG/DGFI Combination Center	Combi	Wolfgang Schwegmann	Bundesamt für Kartographie und Geodäsie and Deutsches Geodätisches Forschungsinstitut	DOGS
Italy	Italy INAF	Assoc	Monia Negusini	Istituto di Radioastronomia INAF	CALC/SOLVE
Italy	Agenzia Spaziale Italiana	Assoc	Giuseppe Bianco	Centro di Geodesia Spaziale (CGS)	CALC/SOLVE
Japan	National Institute of Information and Communications Technology	Assoc	Yasuhiro Koyama	National Institute of Information and Communications Technology	CALC/SOLVE, vlbest
Japan	National Astronomical Observatory of Japan	Assoc	Seiji Manabe	National Astronomical Observatory of Japan	
Norway	Forsvarets forskningsinstitutt (FFI)	Assoc	Per-Helge Andersen	Norwegian Defence Research Establishment	GEOSAT
Russia	Institute of Applied Astronomy Analysis Center	Full	Elena Skurikhina	Institute of Applied Astronomy	OCCAM
Russia	Astronomical Institute of St.-Petersburg University	Full	Maria Kydryashova	Astronomical Institute of St. Petersburg University	OCCAM
Russia	Pulkovo Observatory	Assoc	Zinovy Malkin	Pulkovo Observatory	OCCAM
Russia	Sternberg Astronomical Institute (SAI)	Assoc	Vladimir Zharov	Lomonosov Moscow State University	ARIADNA
South Korea	KASI	Combi	Jungho Cho	Korea Astronomy and Space Science Institute	CATREF, DOGS
Sweden	Onsala Space Observatory	Assoc	Gunnar Elgered	Chalmers University of Technology	CALC/SOLVE, GLOBK
Turkey	Karadeniz Technical University (KTU)	Assoc	Emine Tanir	Karadeniz Technical University	CALC/SOLVE, GLOBK
Ukraine	Main Astronomical Observatory	Assoc	Sergei Bolotin	Main Astronomical Observatory, National Academy of Sciences, Kiev	SteelBreeze
USA	Goddard Space Flight Center	Full	Chopo Ma	NASA Goddard Space Flight Center	CALC/SOLVE
USA	Haystack Observatory	Assoc	Arthur Niell	Haystack Observatory and NASA Goddard Space Flight Center	SOLVK
USA	U. S. Naval Observatory Analysis Center	Full	Alan Fey	U. S. Naval Observatory	CALC/SOLVE
USA	U. S. Naval Observatory Analysis Center for Source Structure	Assoc	Alan Fey	U. S. Naval Observatory	CALC/SOLVE
USA	Jet Propulsion Laboratory	Assoc	Chris Jacobs	Jet Propulsion Laboratory	MODEST

VLBI in the new century

- MK-4 Correlator at MPIfR, fall 2000 ("the last one with the big tapes")

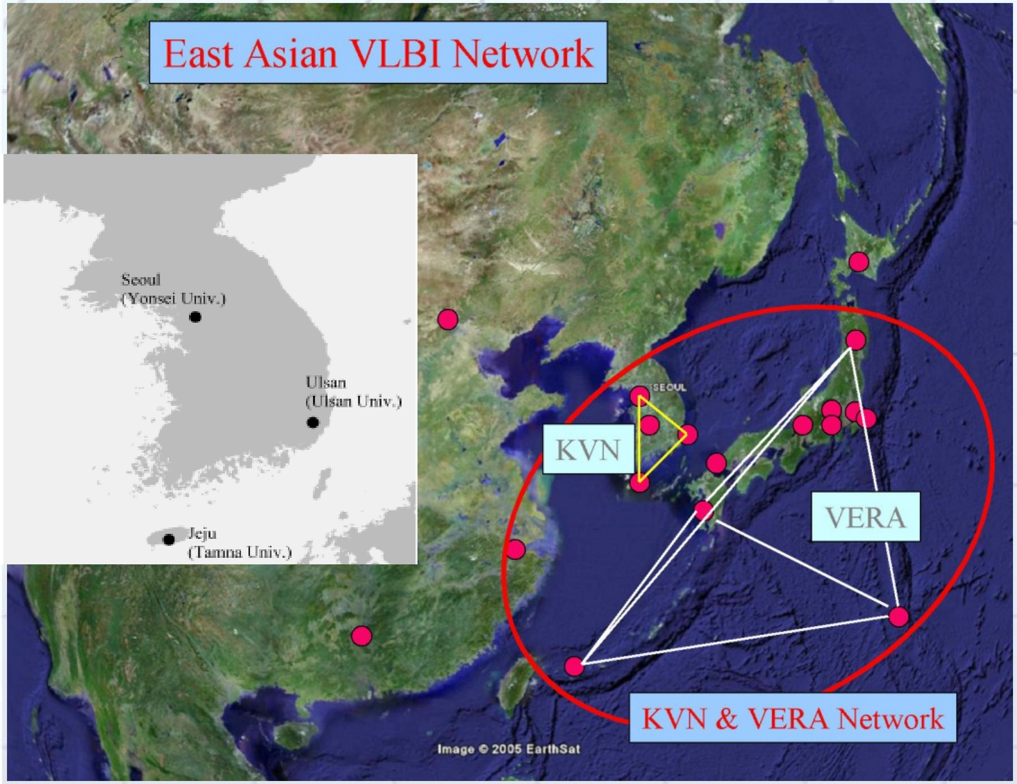
VLBI in the new century

- MK-4 Correlator at MPIfR, fall 2000
- new Radiotelescopes (Russia, Australia, Korea, TIGO, ...)

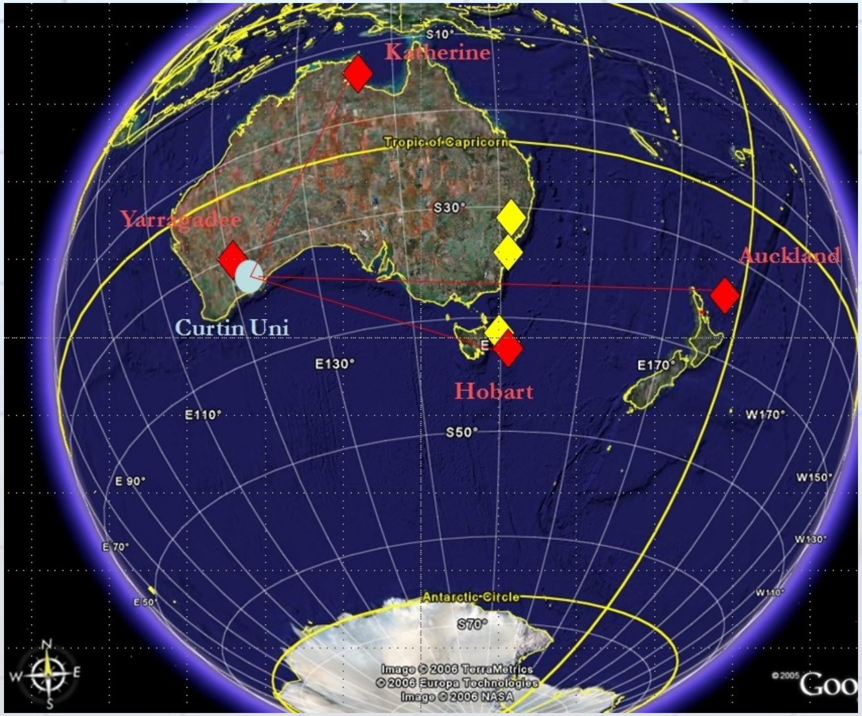


Russian QUASAR-Networkstations join the IVS

Korean VLBI Network (KVN)



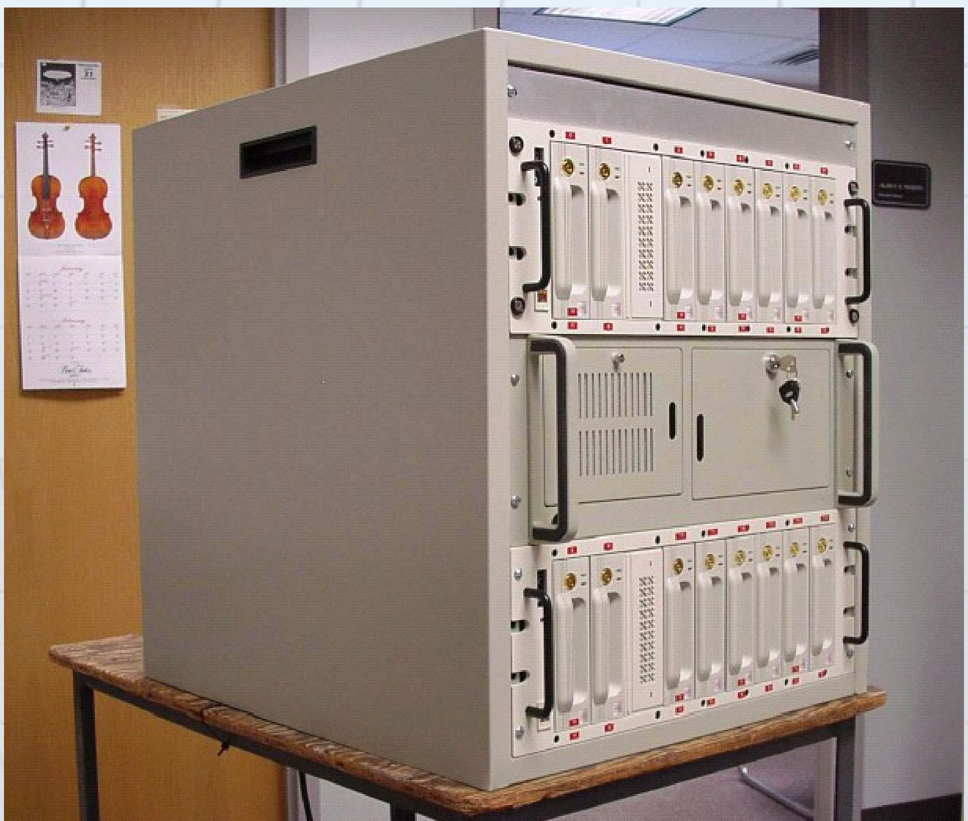
Australia and New Zealand

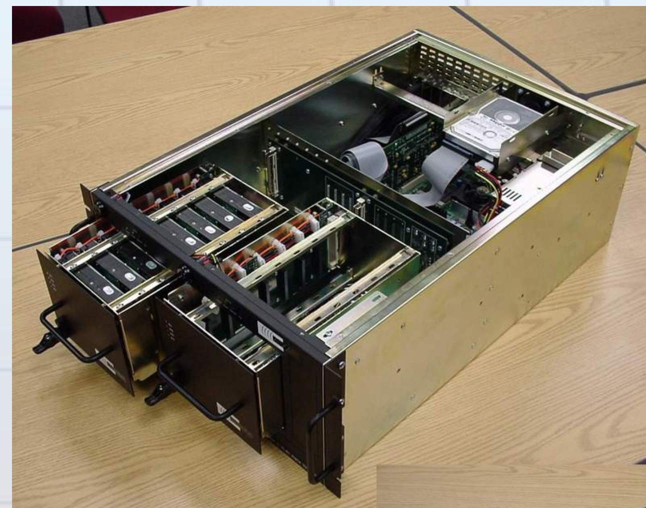


TIGO (6m) @ Concepción, Chile

VLBI in the new century

- MK-4 Correlator at MPIfR, fall 2000
- new Radiotelescopes (Russia, Australia, Korea, TIGO, ...)
- Development of the MK-5 system (sub-cm accuracy), → harddiscs





Alan Whitney (MIT Haystack Observatory)

VLBI in the new century

- MK-4 Correlator at MPIfR, fall 2000
- new Radiotelescopes (Russia, Australia, Korea, TIGO, ...)
- Development of the MK-5 systems (sub-cm accuracy), → hard dics
- e-VLBI
- In the IVS: globally about 80 VLBI groups, 30-40 radiotelescopes for geodetic VLBI, ~ 3,5 days per week; goal is the continuous measurement with sub-mm accuracy in near real time
- Demands for VLBI for the future: VLBI2010

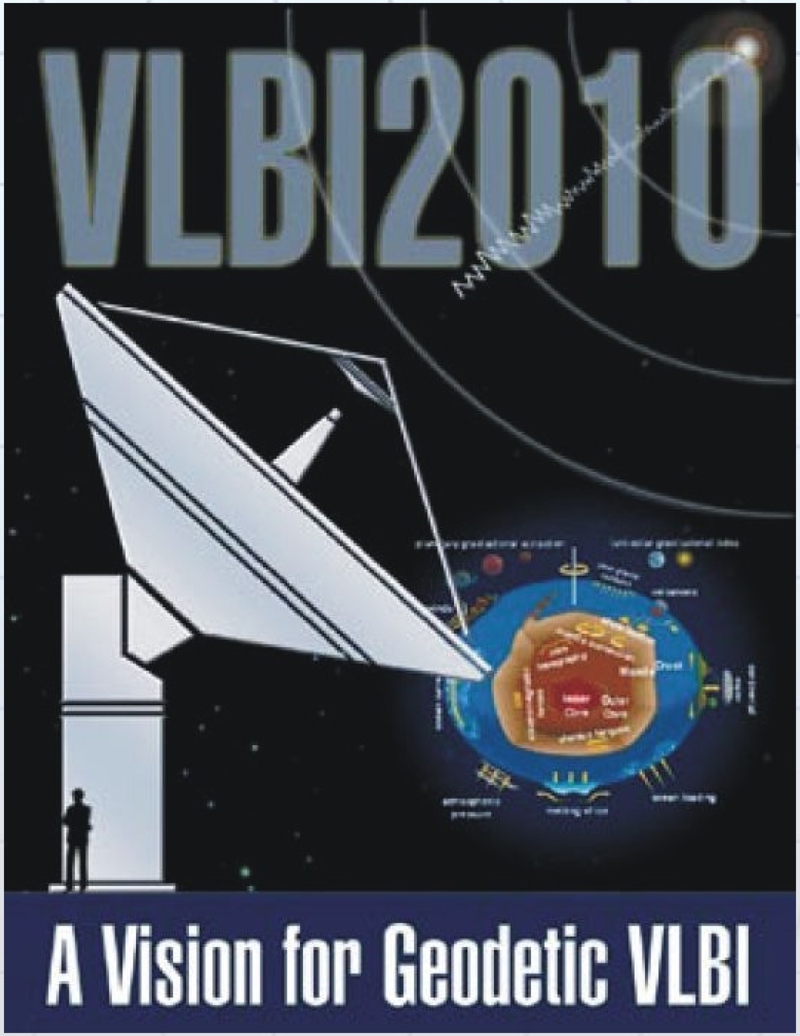
VLBI2010: why do we need it?

- 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

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

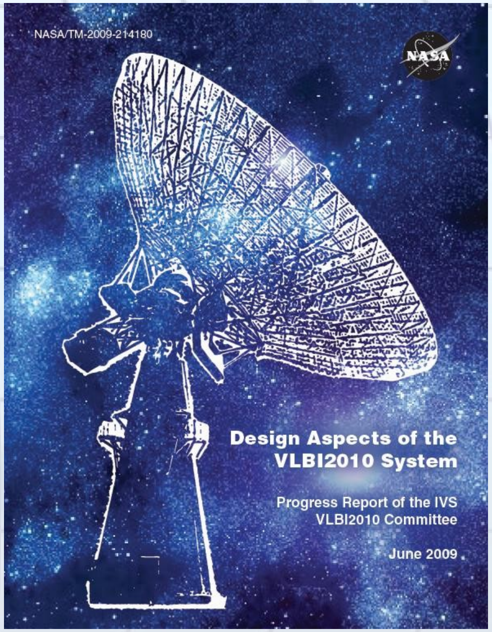
VLBI2010 – V2C activities

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

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

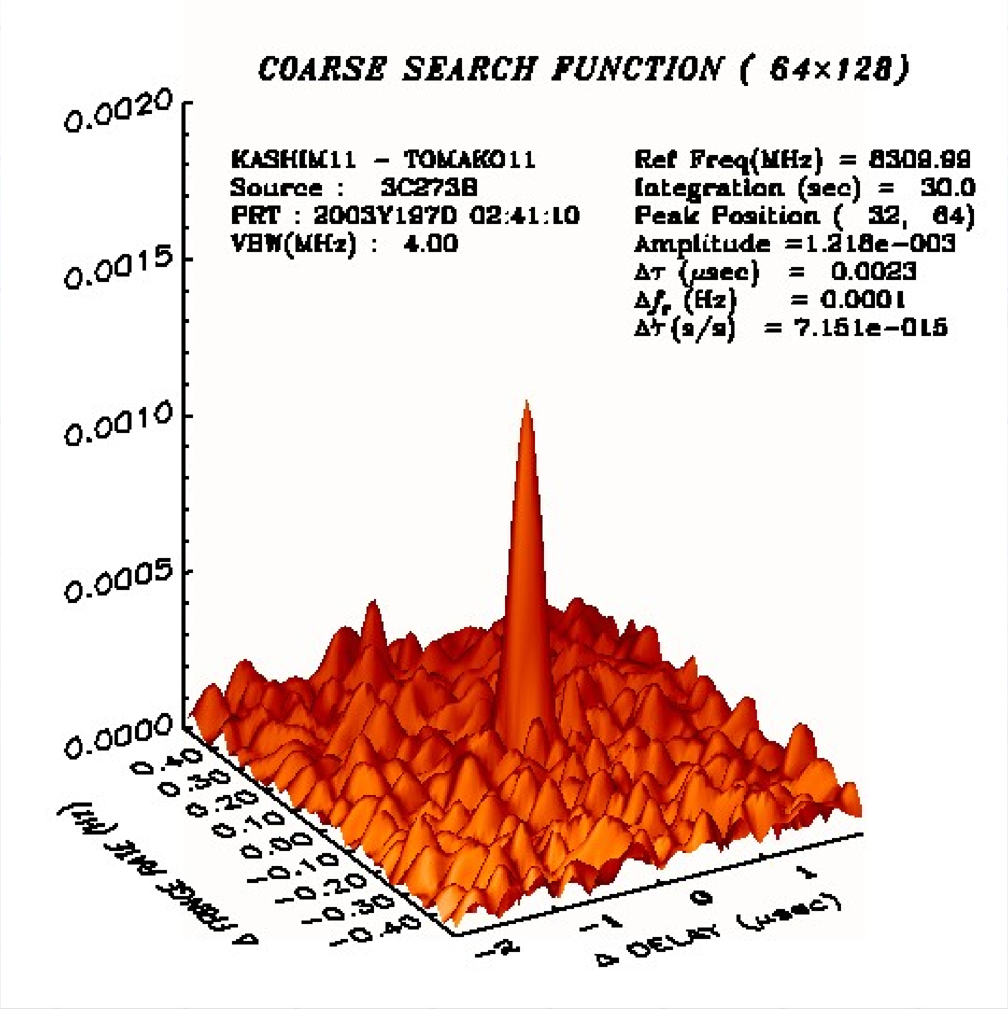
VLBI2010 – a completely new generation of VLBI hardware and software

VLBI2010 also includes

- software correlation

VLBI correlation in the future

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



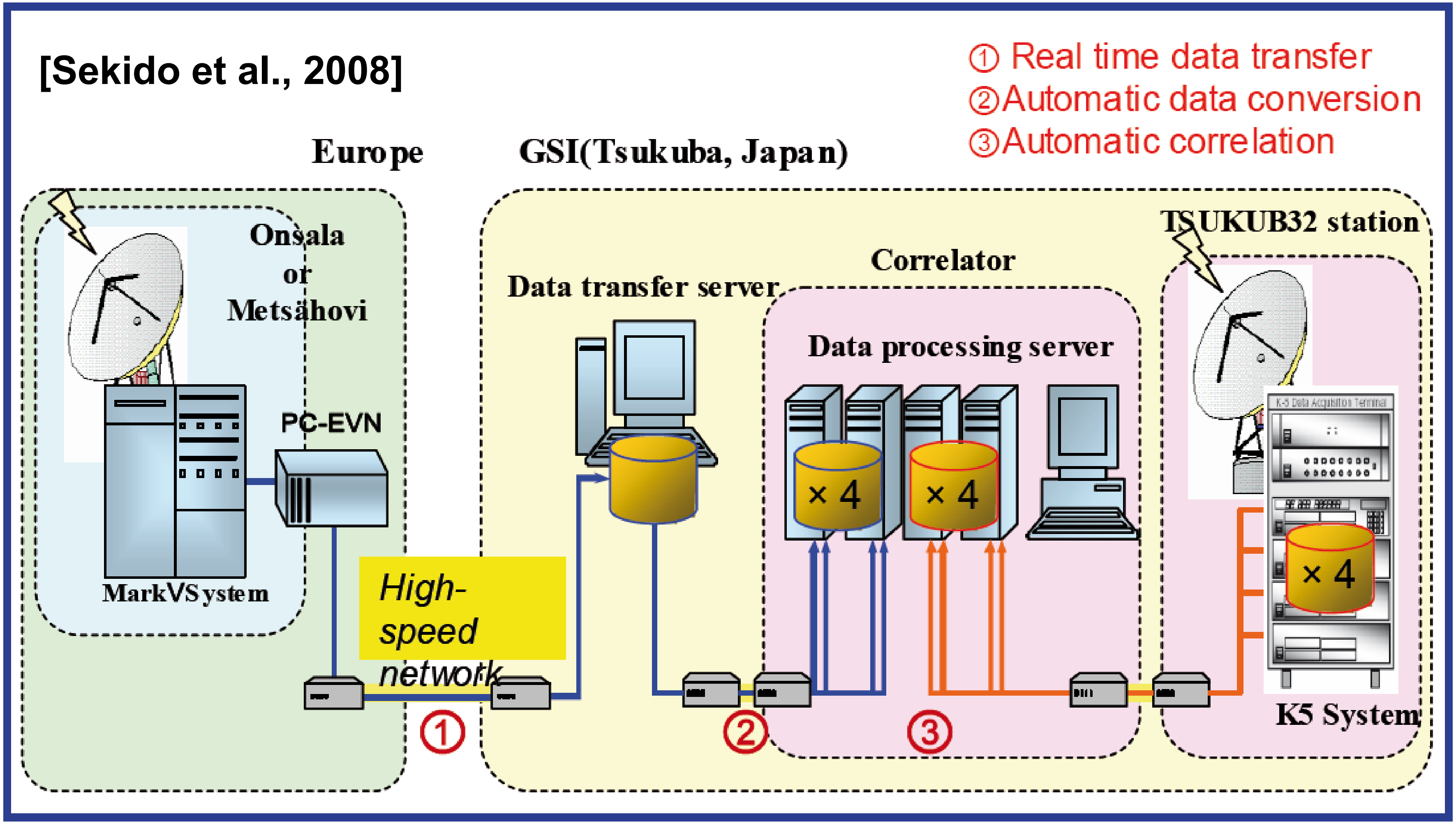
[T. Hobiger, NICT, Japan]

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

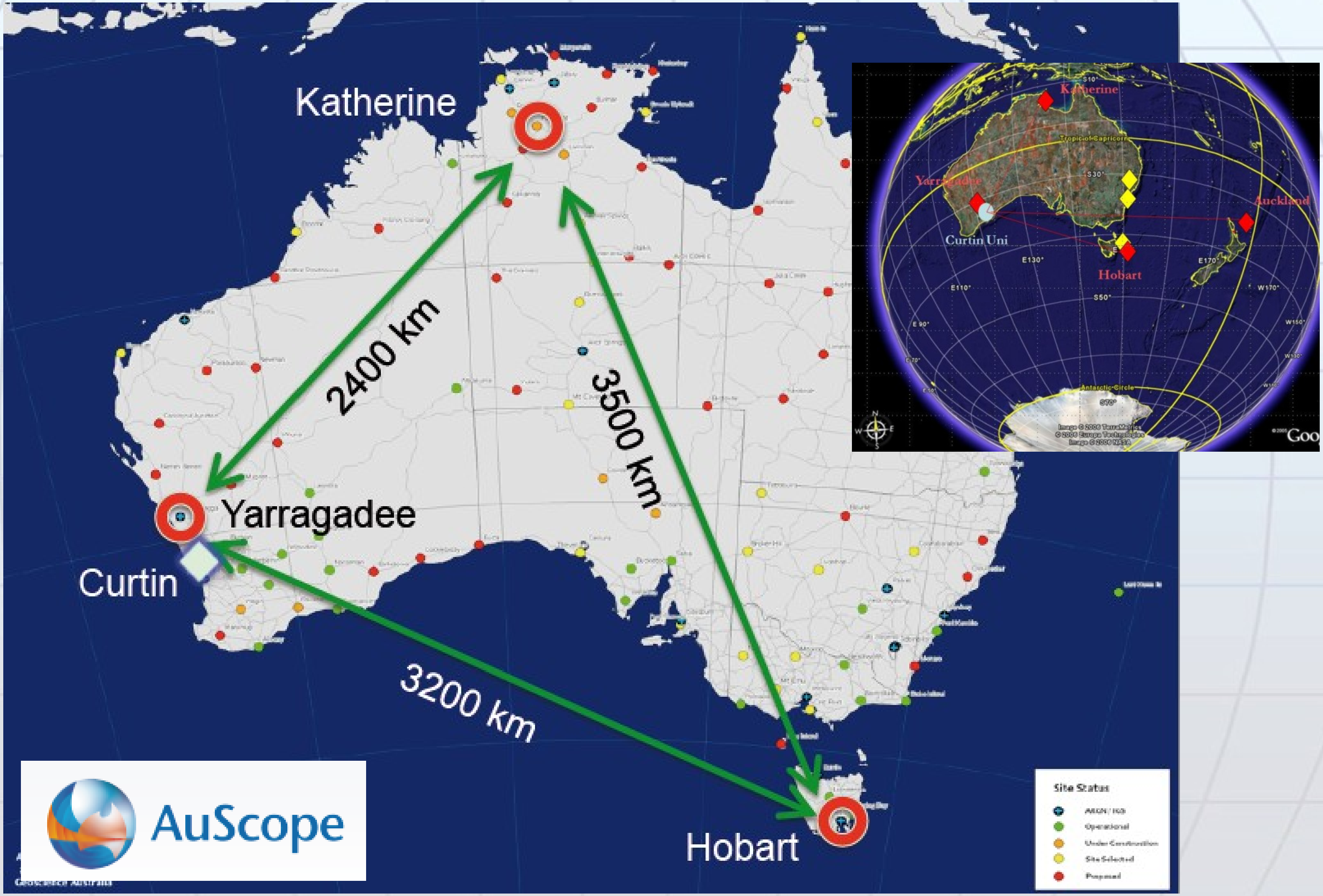
VLBI2010 also includes

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

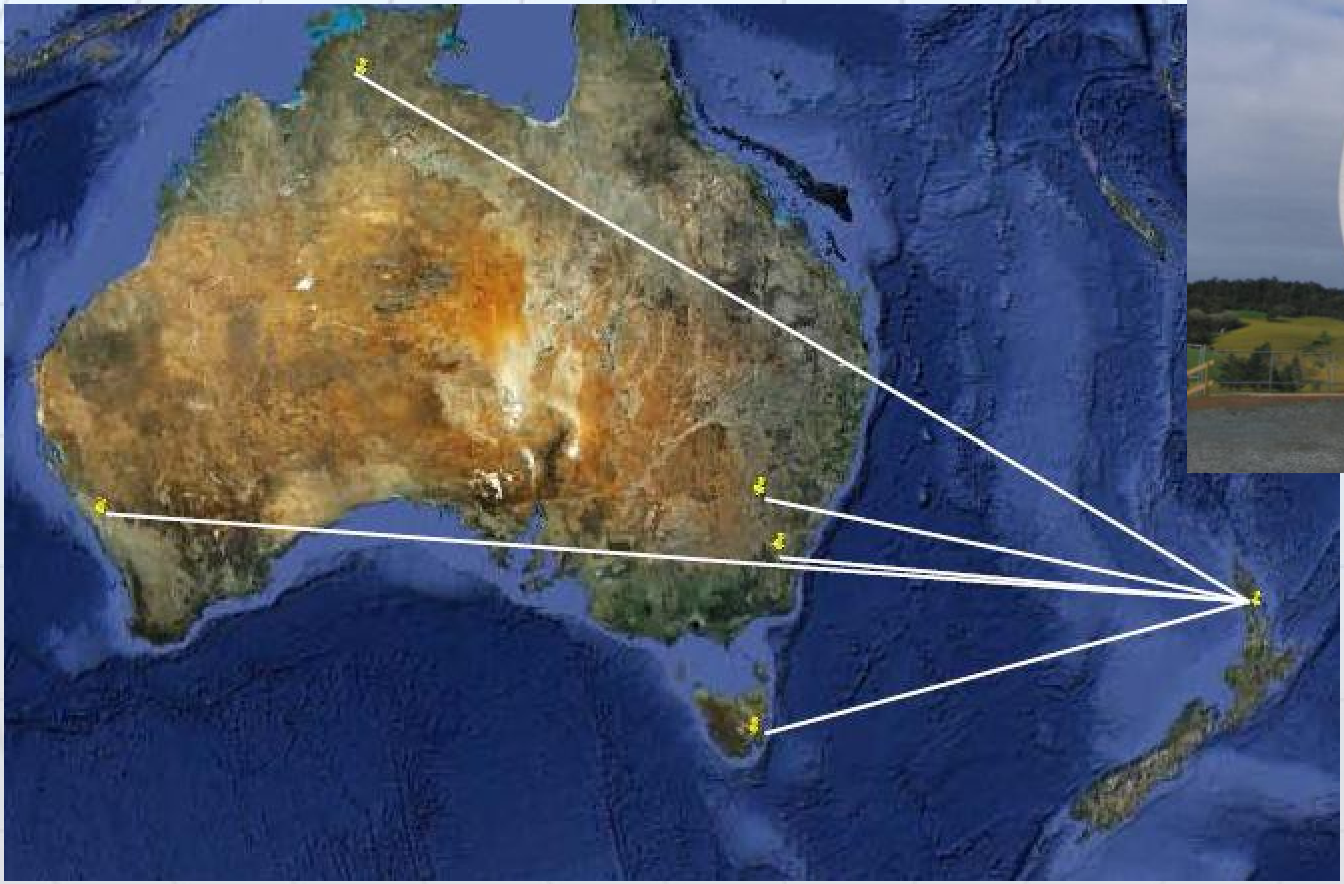
1st VLBI2010 antenna: Hobart (AUS)

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

New VLBI2010 antennas: AuScope (AUS)



New VLBI2010 antenna: AUT (NZL)



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)

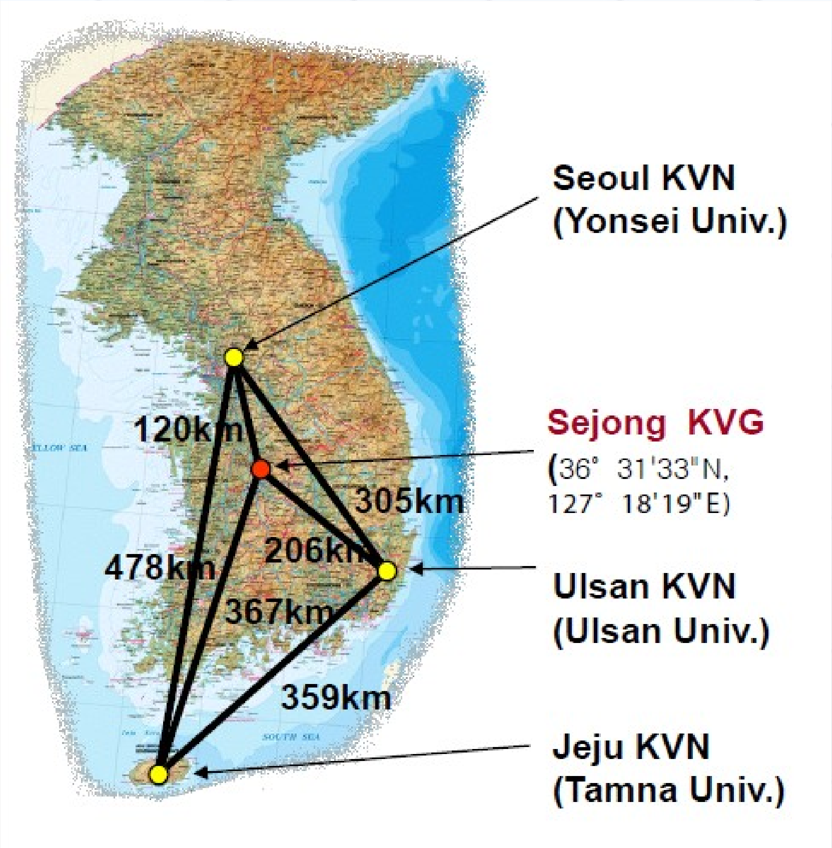
4 new VLBI 2010 antennas (of TTW type)

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



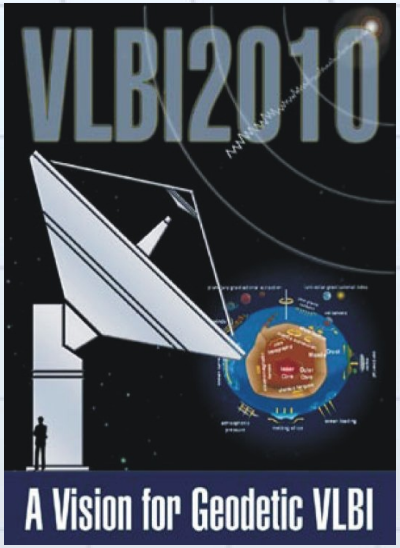
New VLBI2010 antennas: TTW

- Twin Telescope Wettzell (GER), Vertex Antennas

VLBI2010 – Committee (since 2006)

The VLBI2010 Committee got the task to understand the effectiveness of new hardware, software, strategies, etc through the use of combinations of the following approaches:

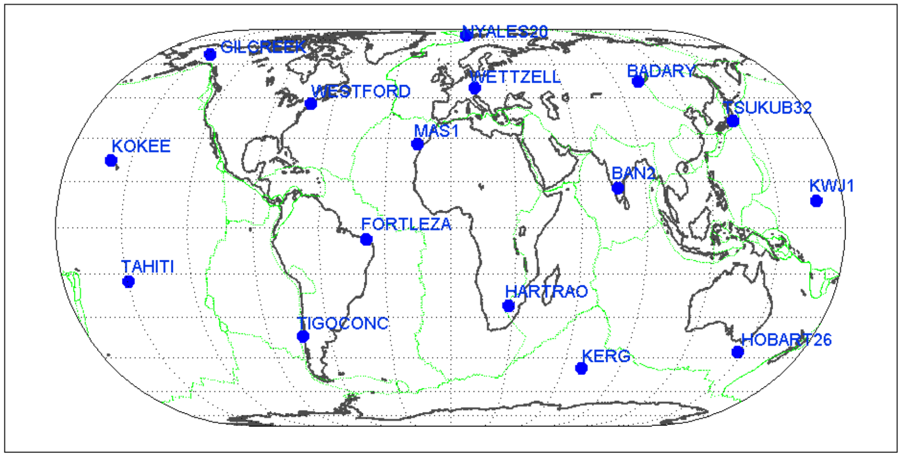
- Analytic studies
- Simulations
- Prototyping
- R&D experiments
- Re-analysis or interpretation of previous campaigns or global data sets
- Inter-technique co-location studies
  → Connection with other techniques (GNSS, SLR, …)



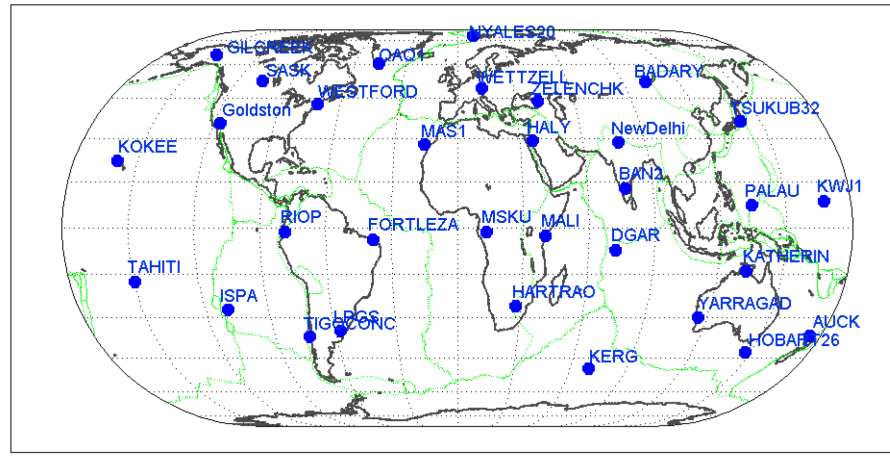
Based on the WG3 report, since 2006 a number of simulations have been performed; particularly at IGG/Vienna and GSFC/NASA.

VLBI2010 – simulation networks

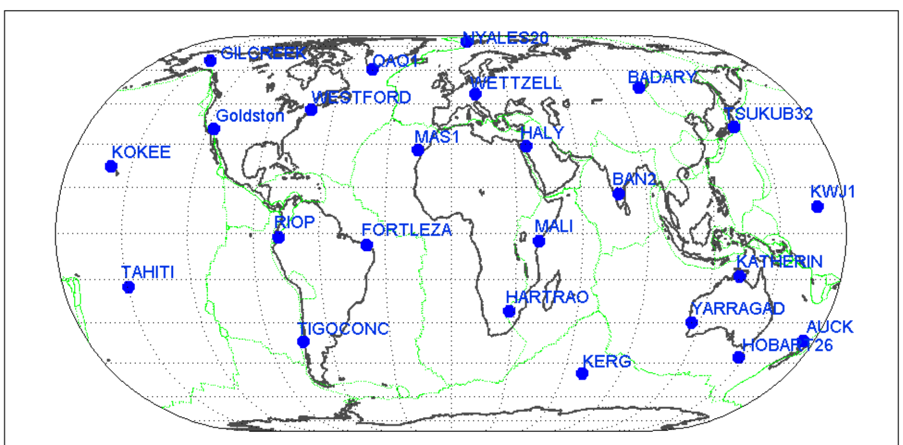
simulation - 16 stns origin(lon,lat) [0 0]



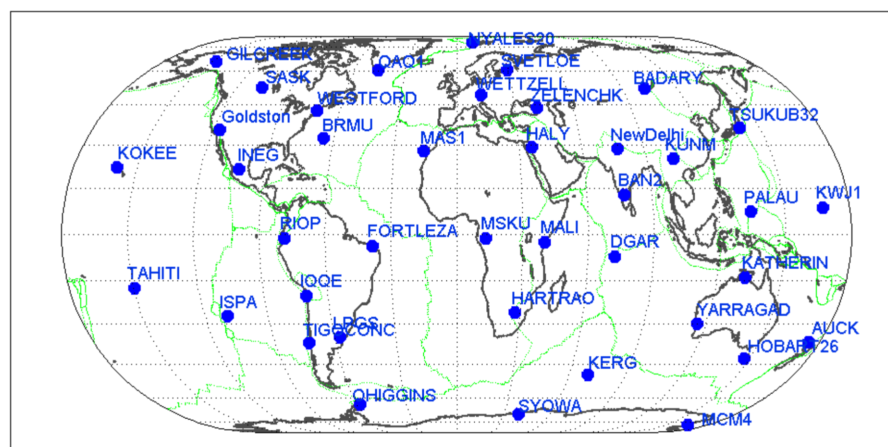
simulation - 32 stns origin(lon,lat) [0 0]



simulation - 24 stns origin(lon,lat) [0 0]



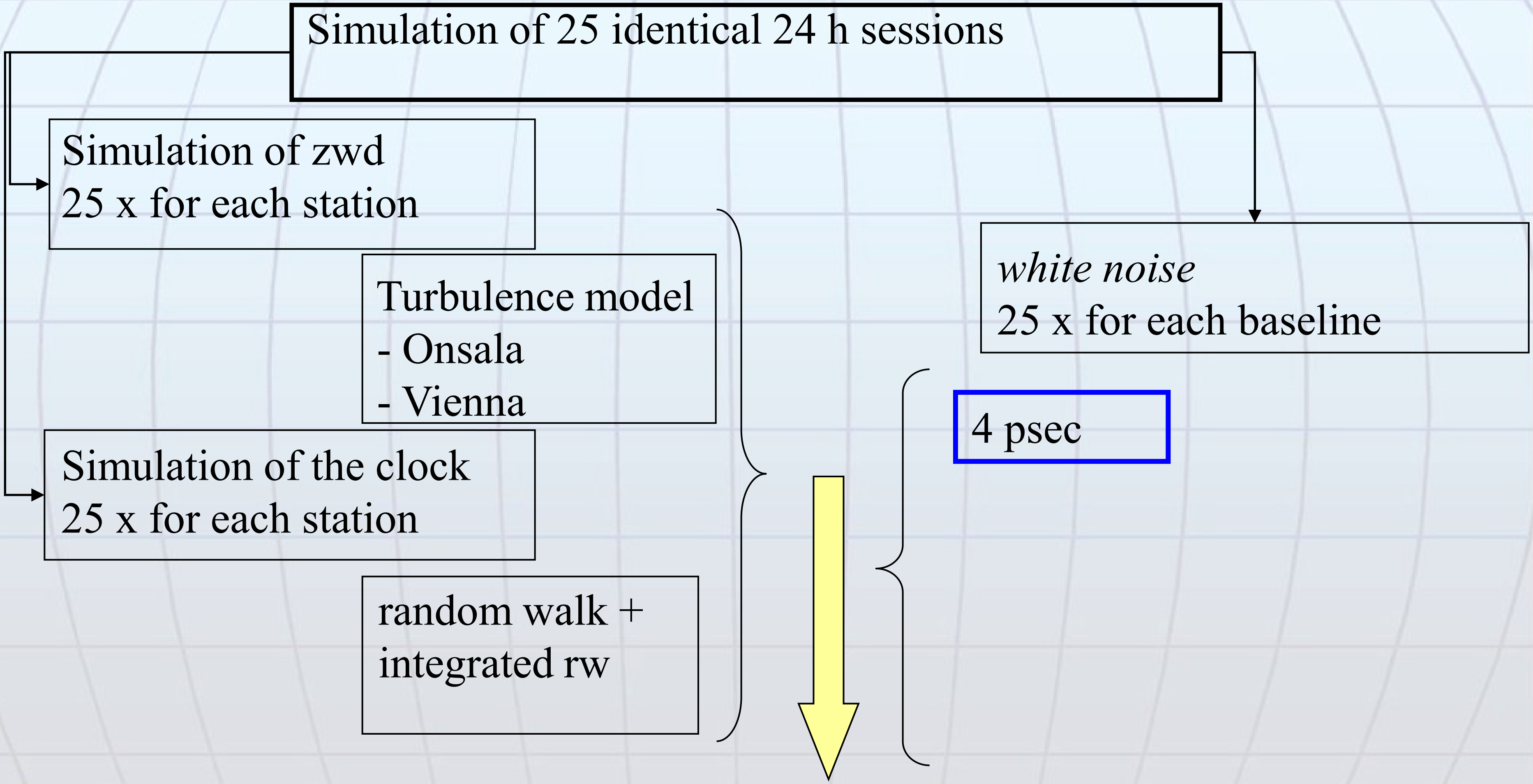
simulation - 40 stns origin(lon,lat) [0 0]



VLBI2010 – Monte Carlo Simulation

3 VLBI software packages

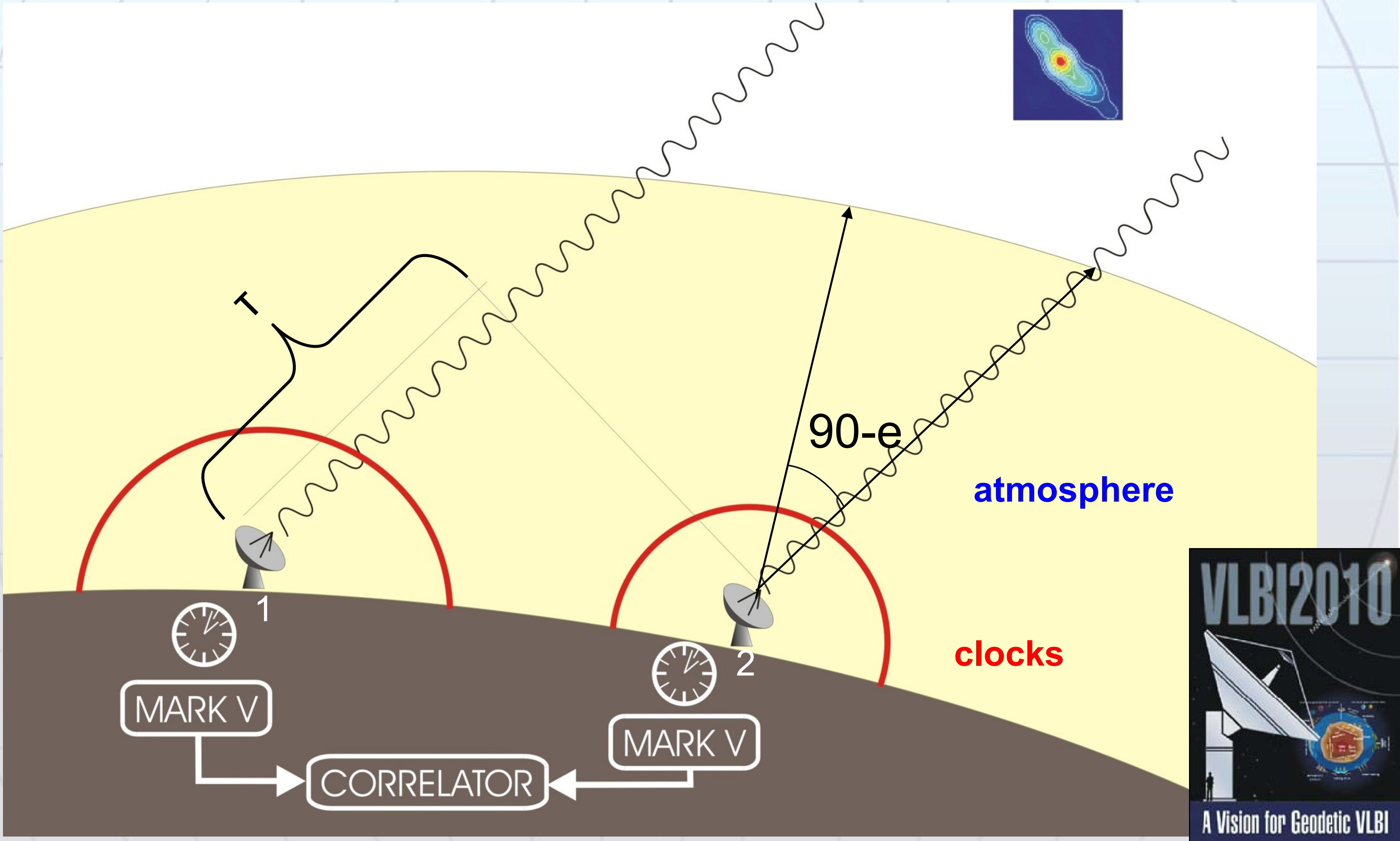
- **OCCAM *(@ IGG Vienna)***
- **Calc/Solve *(@ NVI/GFSC, Washington)***
- **PPP *(@ IGG Vienna)***



OCCAM Kalman Filter, Calc Solve or PPP
Baselinelength repeatabilities
RMS of 3D-station position - median

Monte Carlo simulation

wzd & clocks are stochastic processes → simulate for station 1 and 2



VLBI2010 – Monte-Carlo-Simulation

Simulation des *zenith wet delay*

$$o - c = \left(zwd_2 \cdot mfw_2(e) + cl_2\right) - \left(zwd_1 \cdot mfw_1(e) + cl_1\right) + wn_{Bsl}$$

Turbulenzmodell

- Tobias Nilsson, Onsala Space Observatory (OSO), Sweden
- fast turbulence model (Vienna)

VLBI2010 – Monte-Carlo-Simulation

Simulation der VLBI Uhren

$$o - c = \left(wzd_2 \cdot mfw_2(e) + cl_2\right) - \left(wzd_1 \cdot mfw_1(e) + cl_1\right) + wn_{Bsl}$$

random walk + integrated random walk

Allan-Standard-Deviation von $1 \cdot 10^{-14}$@50min

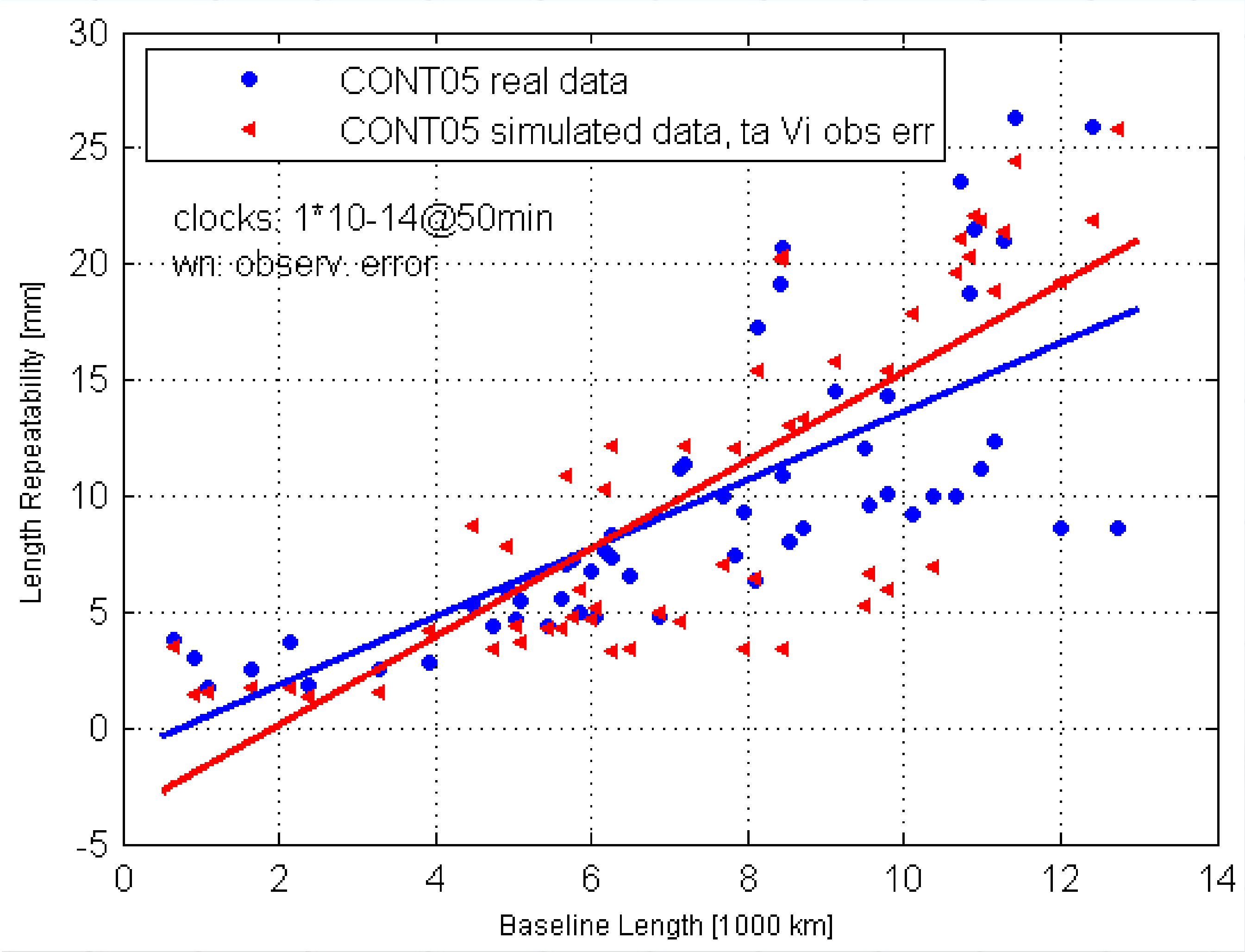
VLBI2010 – Monte-Carlo-Simulation

Simulation des Beobachtungsfehlers

$$o - c = \left(wzd_2 \cdot mfw_2(e) + cl_2\right) - \left(wzd_1 \cdot mfw_1(e) + cl_1\right) + wn_{Bsl}$$

white noise: 4 psec

CONT05: real data vs OCCAM KF (Monte Carlo simulator)



zenith wet delay (zwd)

turb. model Vienna

clocks

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

white noise

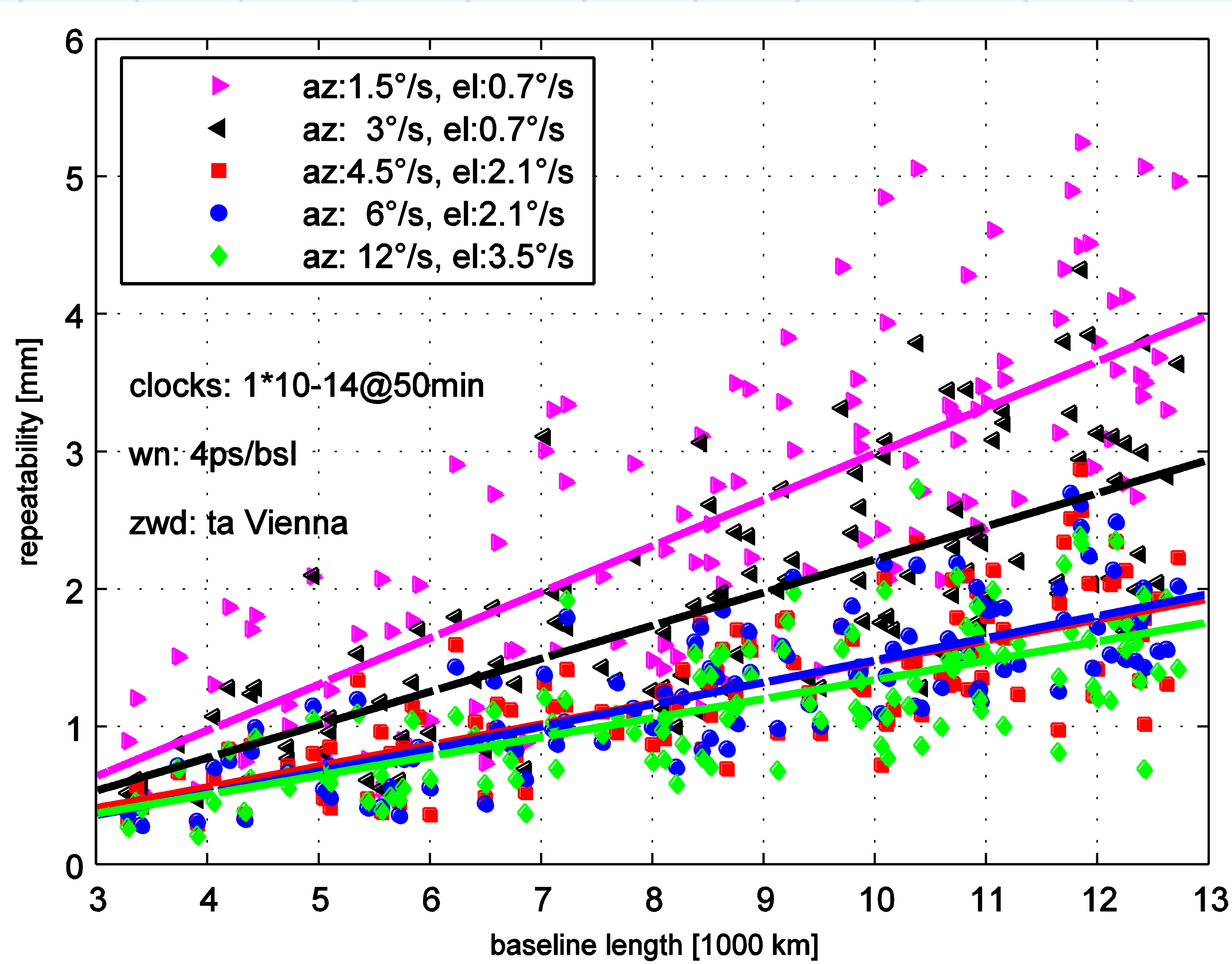
obs. error

- The usage of the turbulence model gives a realistic Monte-Carlo simulation
- The Vienna turbulence model is very fast and hence suitable for simulations

Tests with different slewing speed

Baselinelengths -repeatabilities

Ex.: baseline 1,5 mm → √2 → precision per station = 1mm



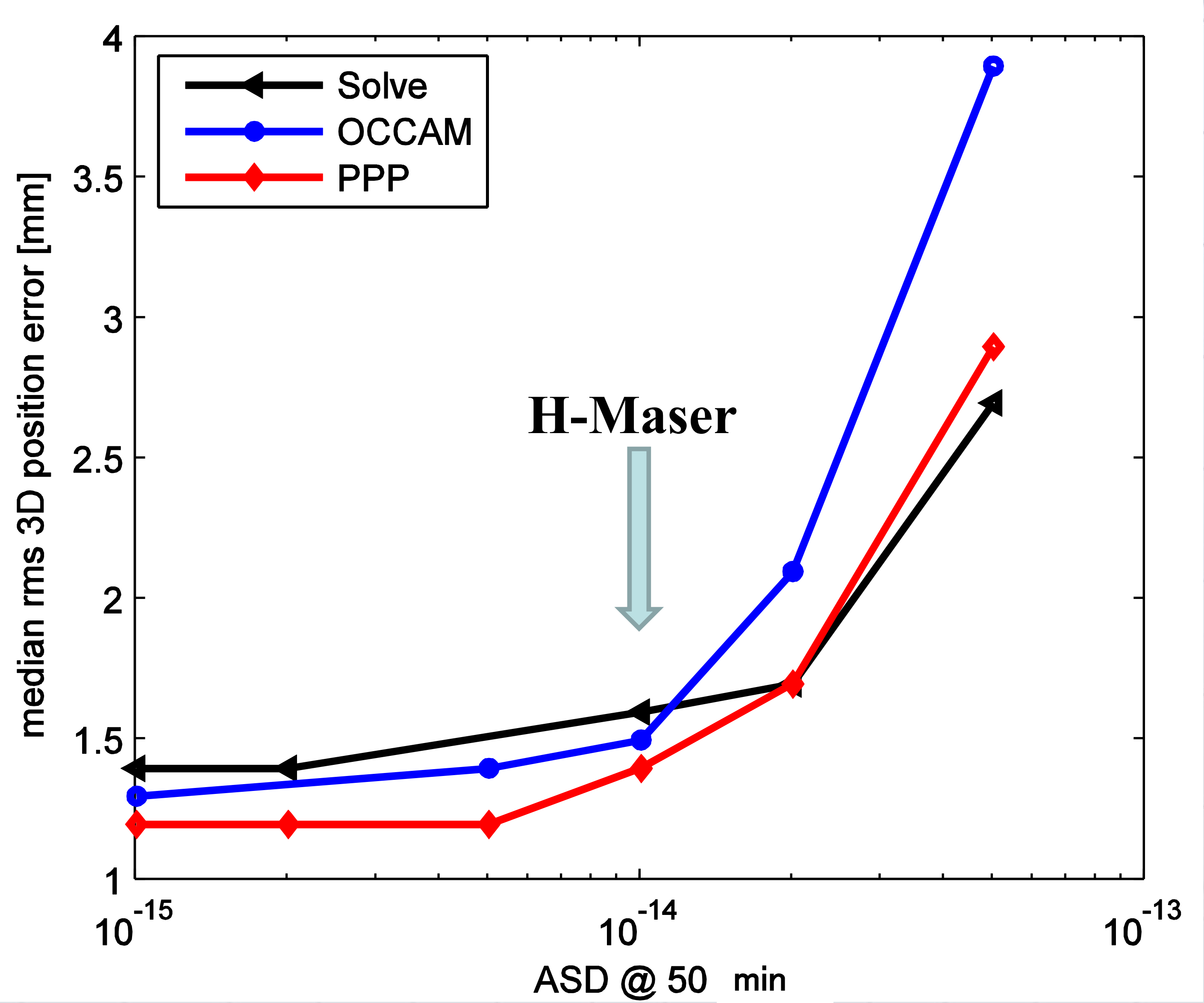
zwd: turbulence model -Vienna

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

wn: 4psec/bsl

Test of different clock performance

→ **More accurate clocks wouldn‘t be worth much**



Conclusions of the simulations

- 1 mm goal is realistic
- Troposphere is the limiting factor
- Turbulence model gives realistic estimates
  - Good agreement with CONT05 analysis
- Slew rate tests show better results for fast antennas
  - Slew speed >6°/sec in azimuth, preferably 12°/sec
- Improvements depend on scheduling
  - Uniform sky coverage
- Accuracy of today‘s h-masers is sufficient (but more precise clocks in connection with precise frequency transfer via fibre glass will offer new perpsectives)

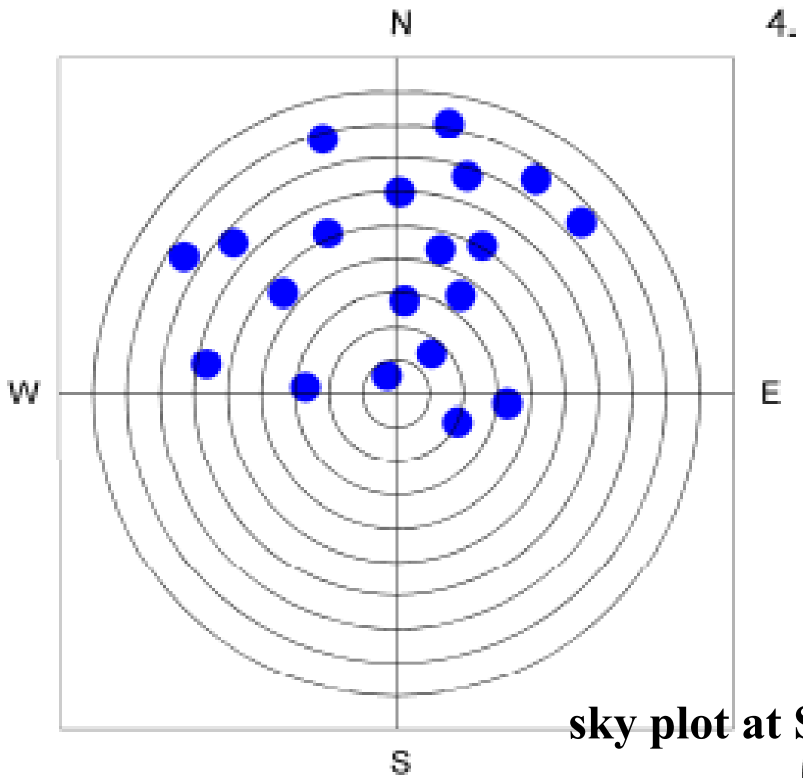
Different VLBI2010 scheduling strategies

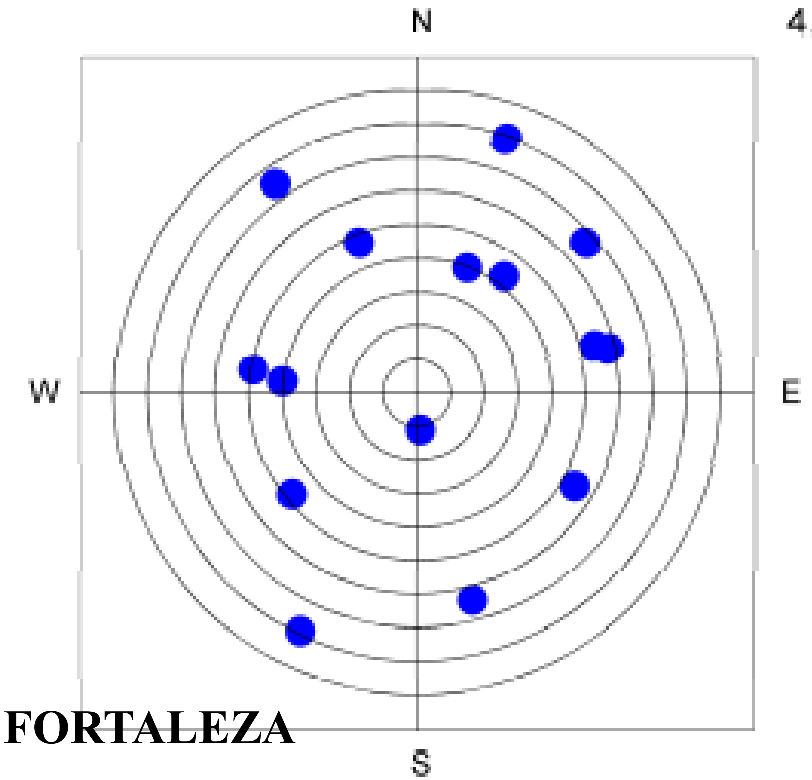
The V2C decided to test different scheduling strategies

- **using the software SKED and all the possibilities built in the software**
- **using a source based approach with specified source switching intervals called: *uniform sky***

using a slightly changed version of SKED

using the uniform sky approach





sky plot at Station FORTALEZA

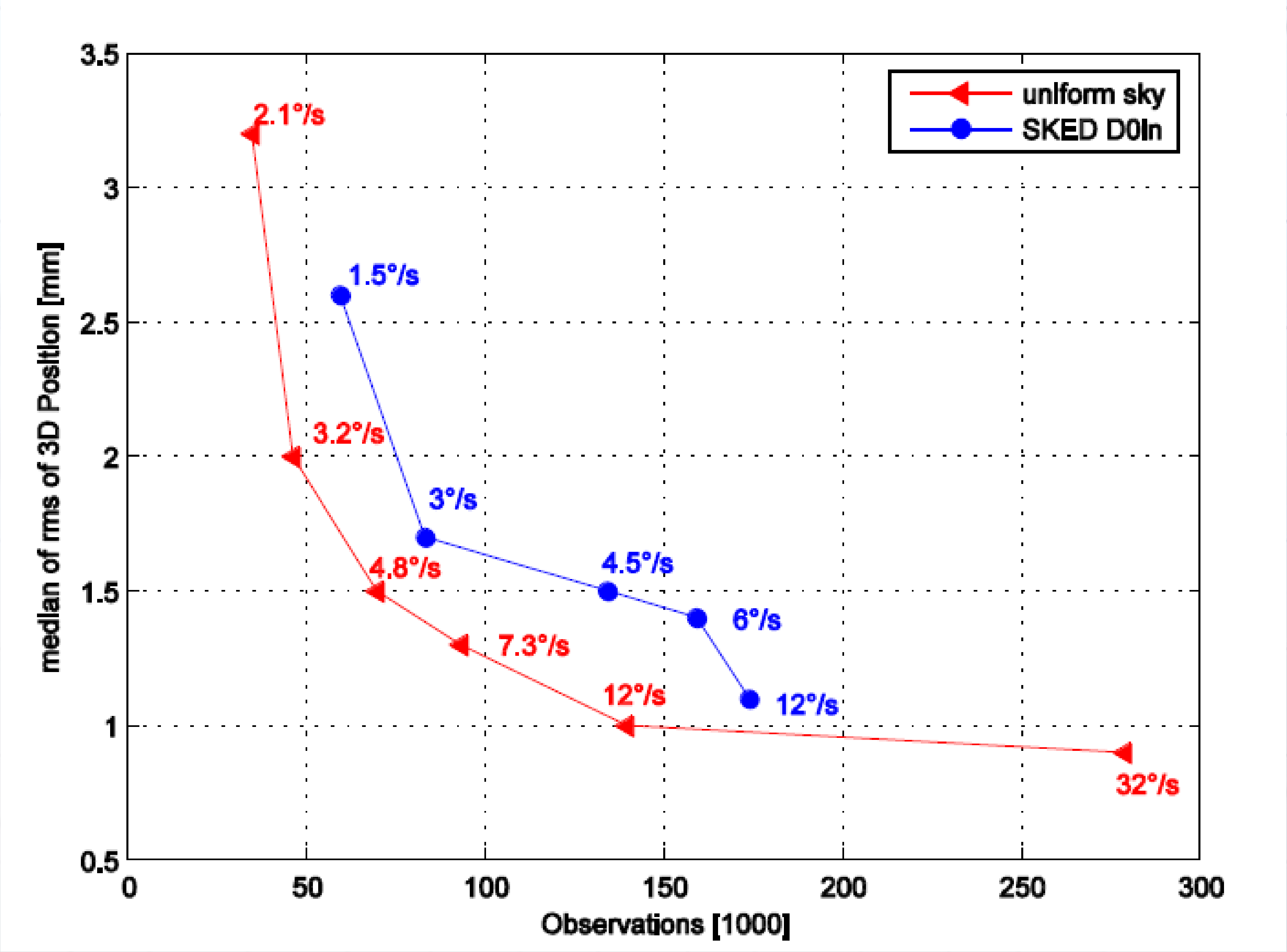
6 min

observations are often clustered

observations are well distributed

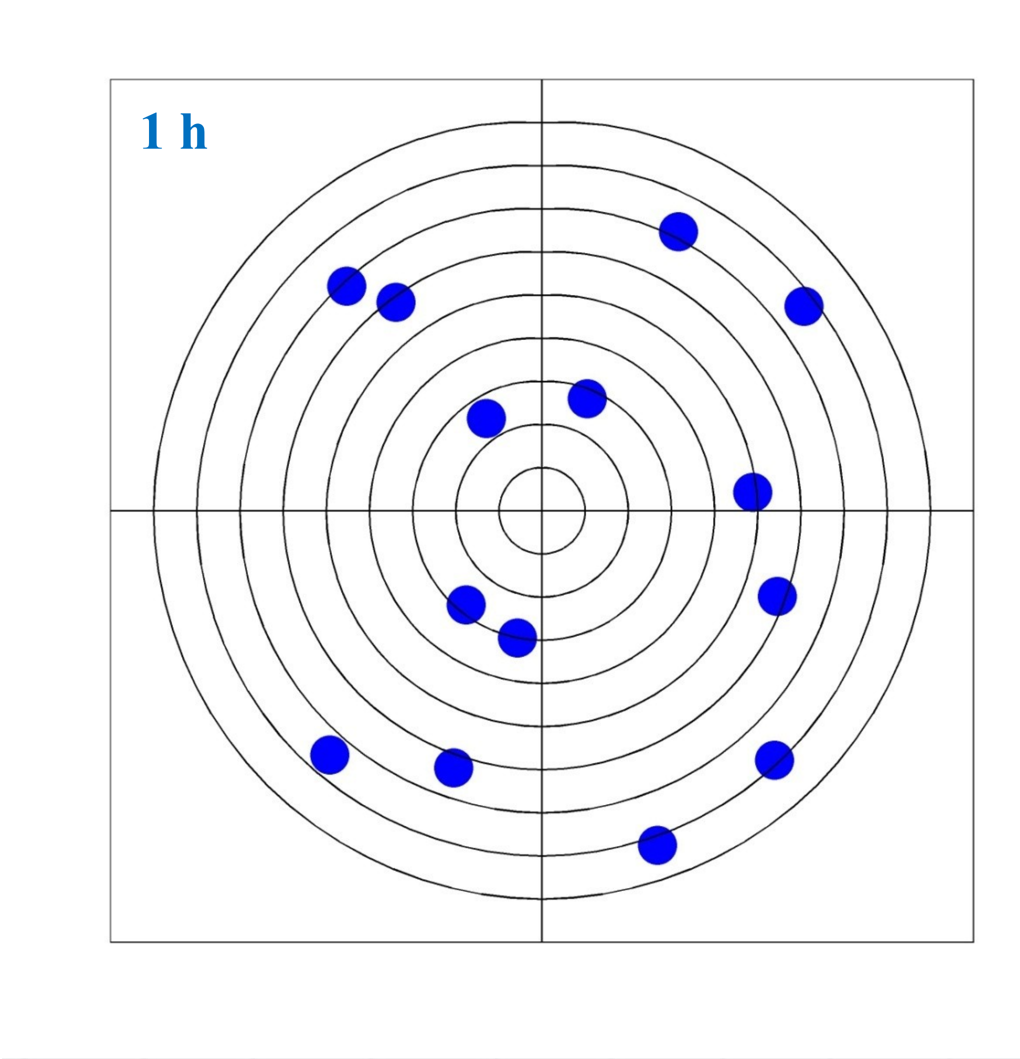
Different VLBI2010 scheduling strategies (2)

rms of 3D station positions

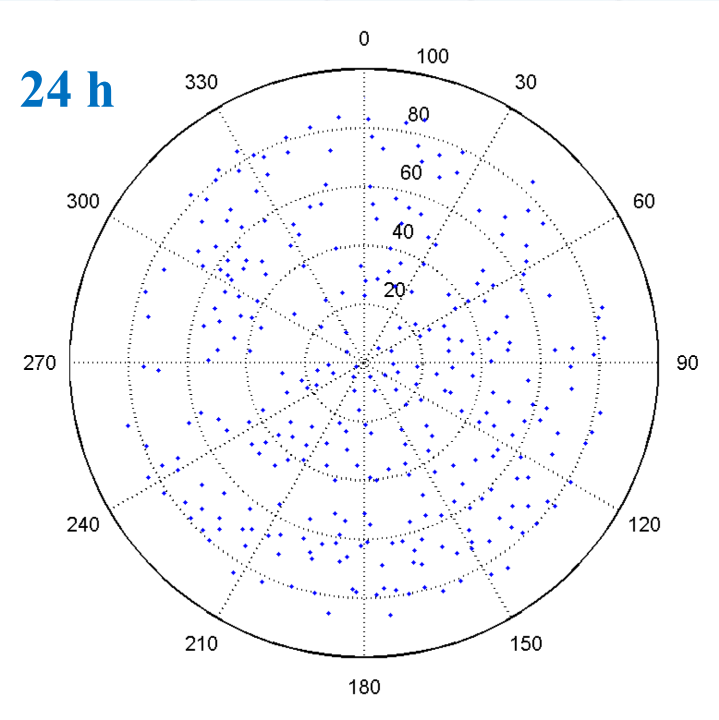


Comparing CONT05 and VLBI2010 schedules (1)

Sky plot over 1 hour at station WETTZELL

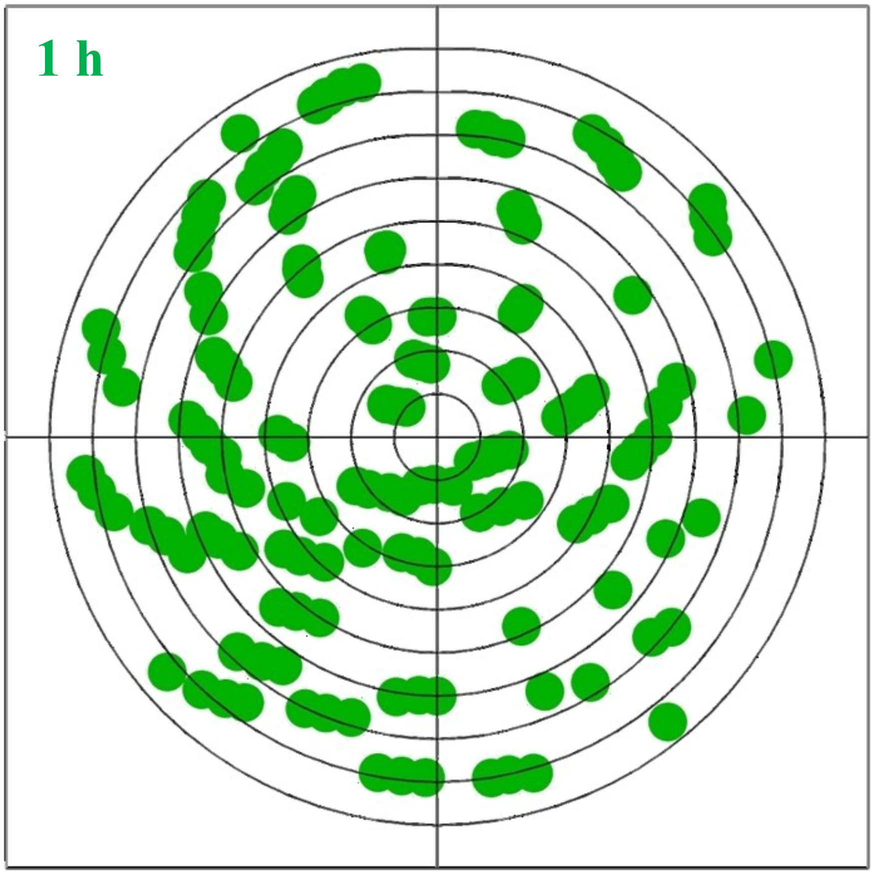


	scan/h
CONT05	14
VLBI2010 SKED	147
VLBI2010 uniform sky	120

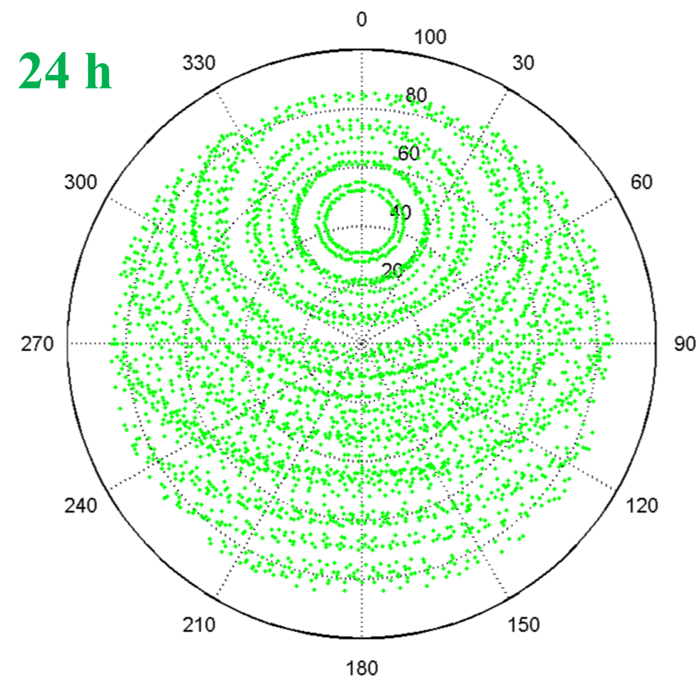


Comparing CONT05 and VLBI2010 schedules (2)

Sky plot over 1 hour at station WETTZELL



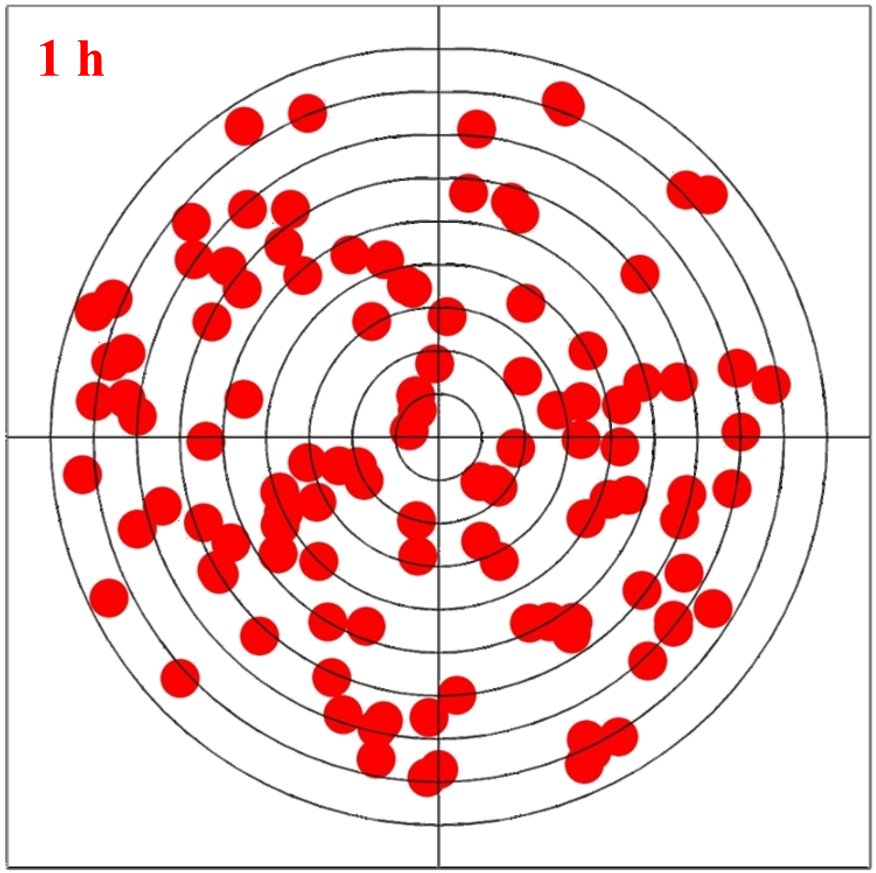
	scan/h
CONT05	14
VLBI2010 SKED	147
VLBI2010 uniform sky	120

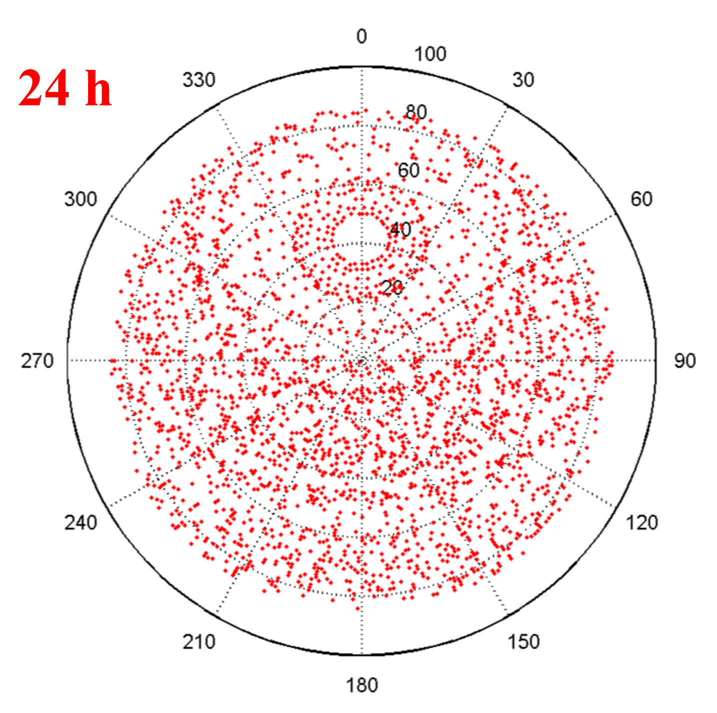


Comparing CONT05 and VLBI2010 schedules (3)

Sky plot over 1 hour at station WETTZELL

	scan/h
CONT05	14
VLBI2010 SKED	147
VLBI2010 uniform sky	120





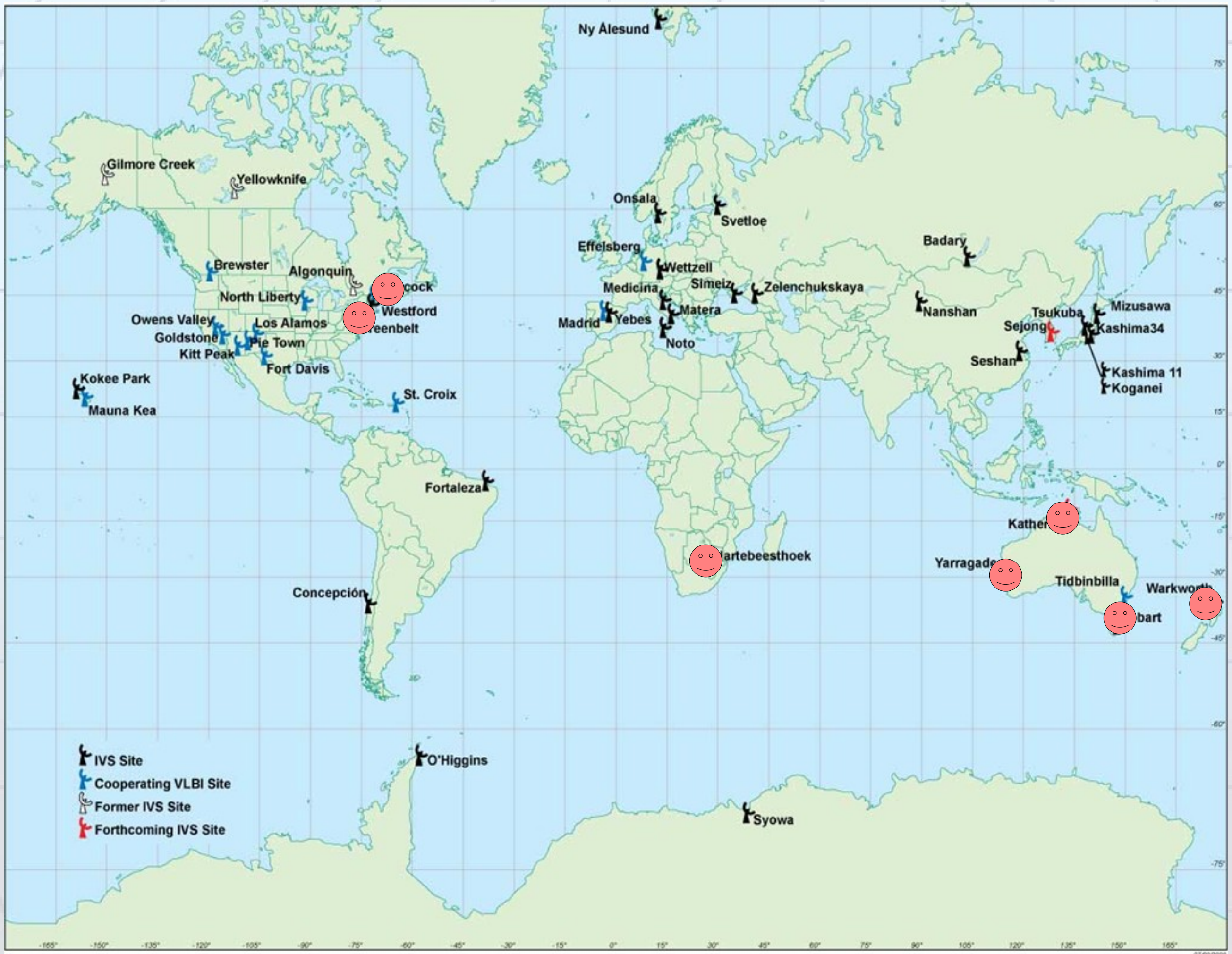
NASA Broadband Delay Proof-of-concept Development Project

- **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
  - First successful test between GSFC and Westford antennas

VLBI2010 – Present Status

- Various hardware and software developments w.r.t. VLBI2010 (e.g. unified data format, IVS WG4)
- IVS was approached from agencies of various countries (Russia, China, Finland, Saudi Arabia, Spain,…) concerning VLBI2010
- Many new aspects and proposals related to VLBI2010 (e.g. involvement in future radio science missions)
- VLBI2010 Project Executive Group (VLBI2010 PEG) since 03/2009 for developing deployment schedules, contacting governmental organizations etc.

VLBI2010 Network in 2011



[Hase et al., 2011]

VLBI2010 very fast

- radio telescope
- twin radio telescope

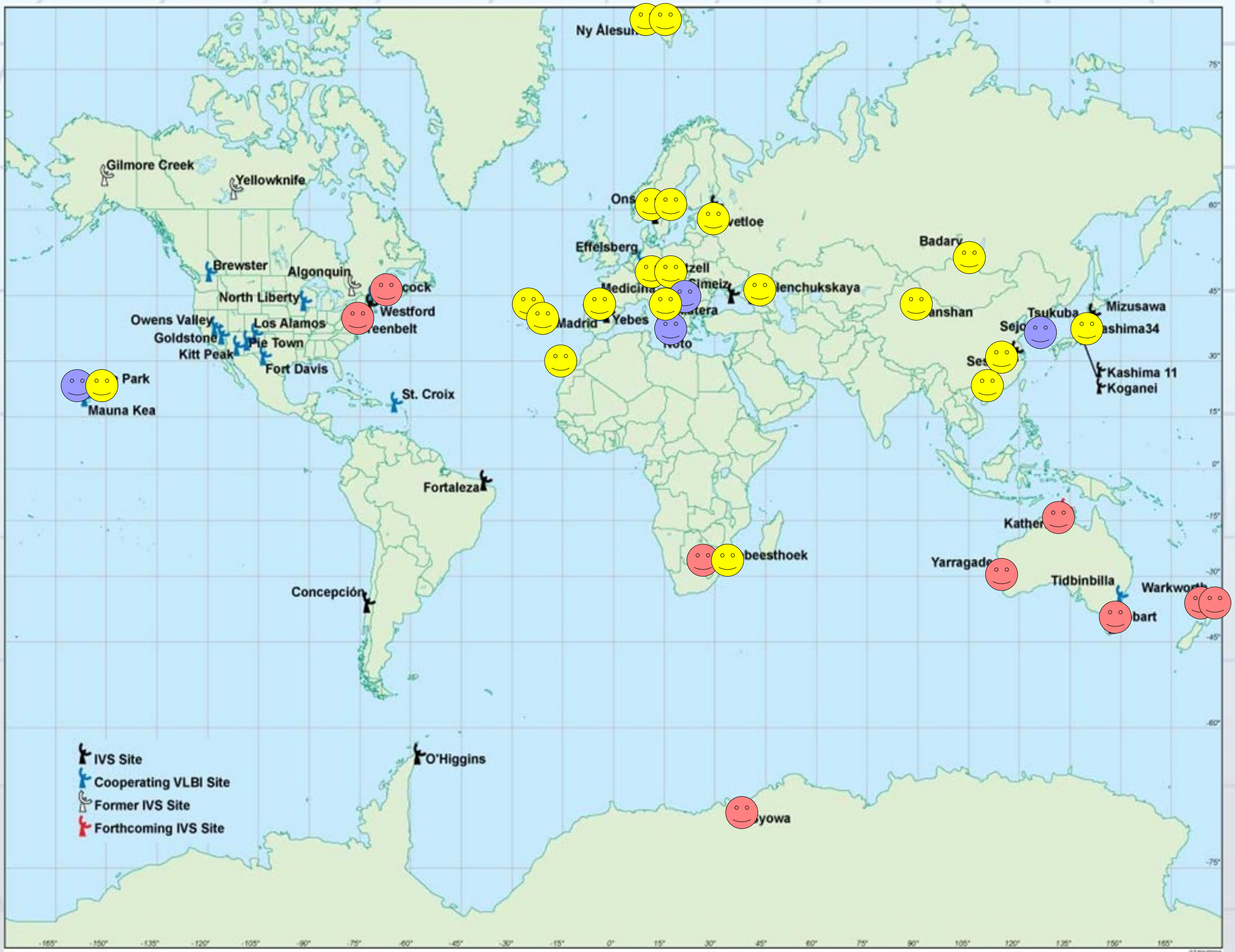
VLBI2010 fast

- radio telescope

upgrade legacy

- radio telescope

VLBI2010 Network in 2017



VLBI2010 very fast

radio telescope

twin radio telescope

VLBI2010 fast

radio telescope

upgrade legacy

radio telescope

[Hase et al., 2011]

VLBI2010 – Challenges

- Establish fibre optic cable links between all antennas and the correlator
  - huge amount of data
  - time factor!
- Handling of disturbing radio interferences (mobile phone, WLAN, …)
- Investigating source structure
- Improve network geometry
- Rigorous combination with other geodetic techniques (co-locations!)

VLBI2010 – upcoming

- VLBI2010 is going to **improve** the results of geodetic VBLI **significantly**.
- VLBI2010 will play a **key role in** the IAG's **GGOS** *(Global Geodetic Observing System)*.