

# **Geodetic Very Long Baseline Interferometry (VLBI) and its future perspectives**

**Berlin, September, 14, 2012**

**Harald Schuh**



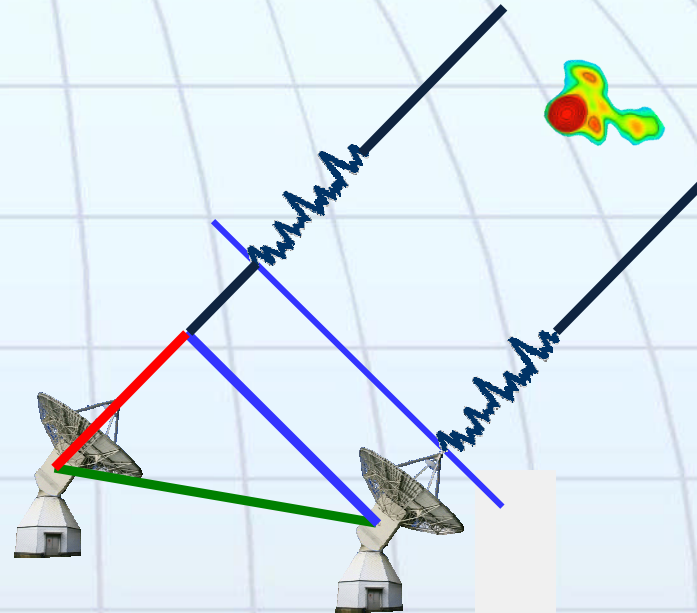
TECHNISCHE  
UNIVERSITÄT  
WIEN

Vienna University of Technology

14.09.2012, Harald Schuh

# The principle of VLBI

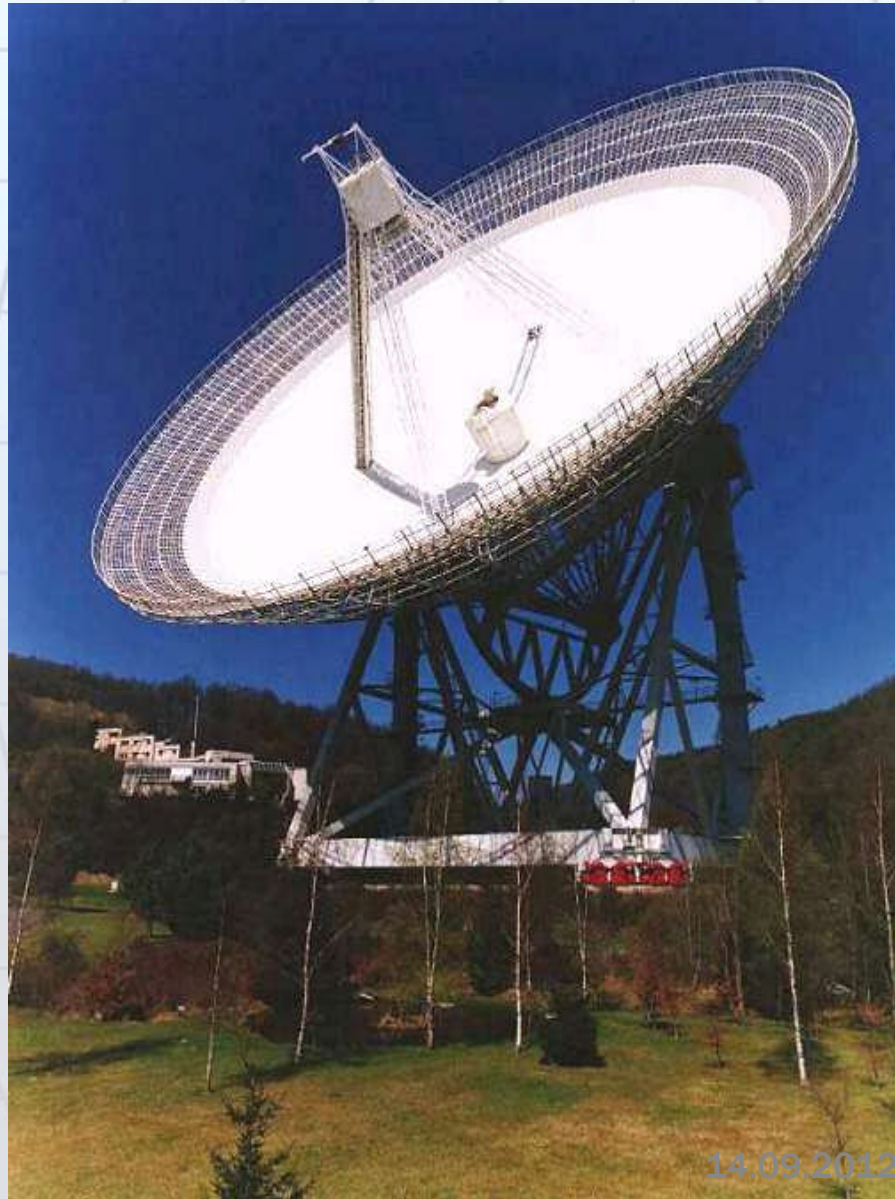
$$\tau = -\frac{1}{c} \mathbf{b}^T \mathbf{W} \mathbf{S} \mathbf{N} \mathbf{P} \mathbf{k}$$



**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)



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## Wettzell (20 m)







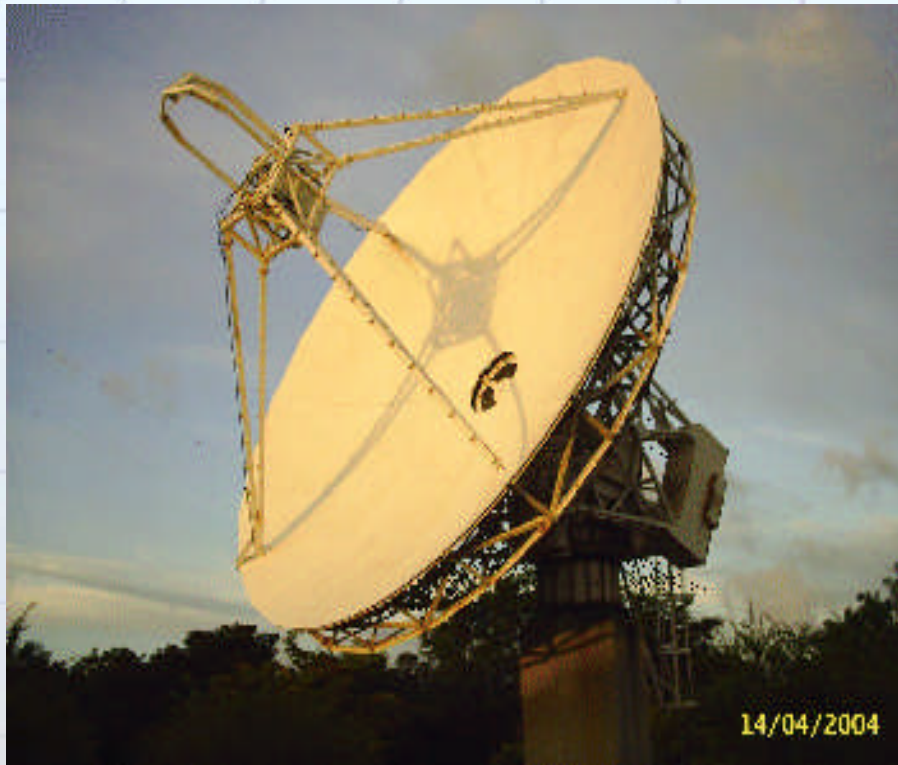
**Ny-Ålesund (20m)**  
**Spitsbergen, Norway**



**O'Higgins (9m)**  
**Antarctica**



# VLBI in South America



**Fortaleza (14.2 m)**  
**(Brazil)**



**TIGO (6m)**  
**(Concepción, Chile)**



**Kashima (34 m)**



**Shanghai (25 m)**



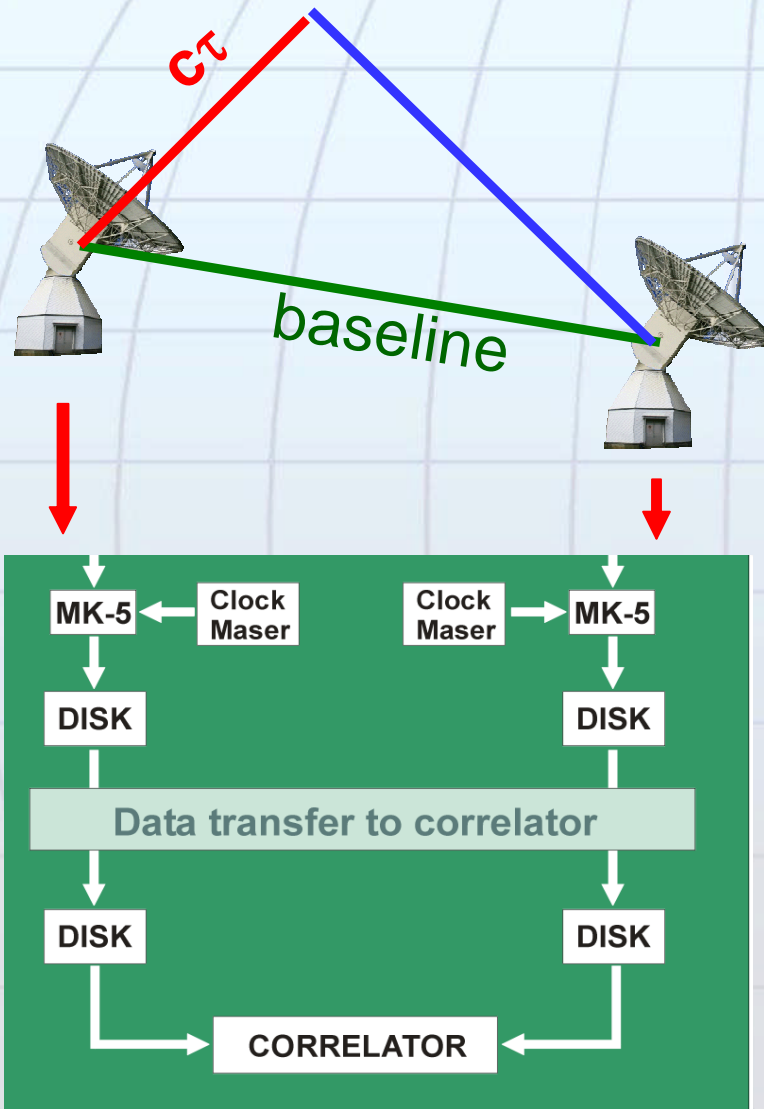
14.09.2012, Harald Schuler 技術』をご見学

# **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 ~  $10^{-15}$  @ 50min)
  - Data recording
    - Harddisk (MK-5)
    - e-transfer
- Correlation
  - $\sigma_t \sim 10$  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 as of June 2012)

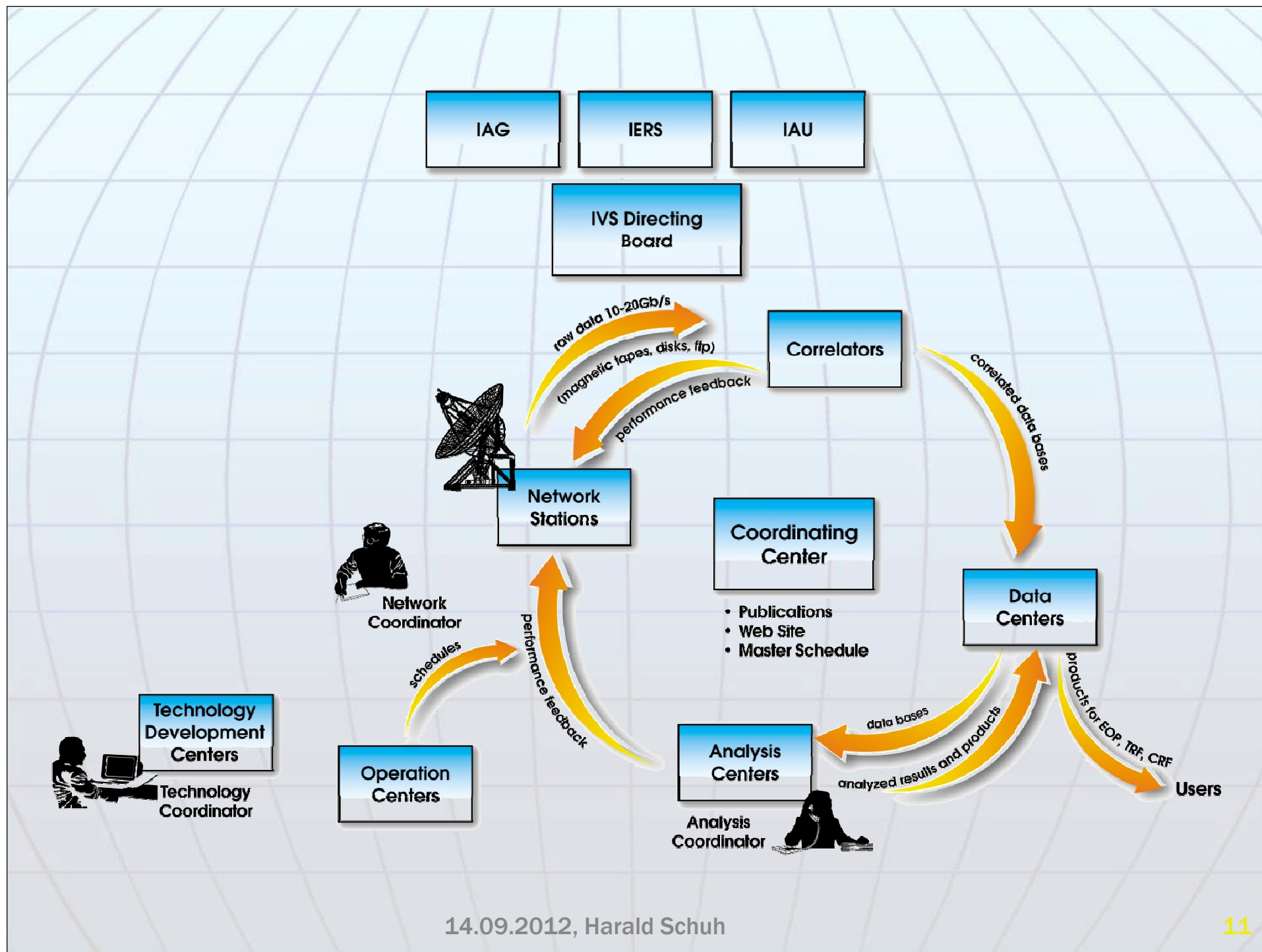
## IVS goals:

- ⚡ 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)

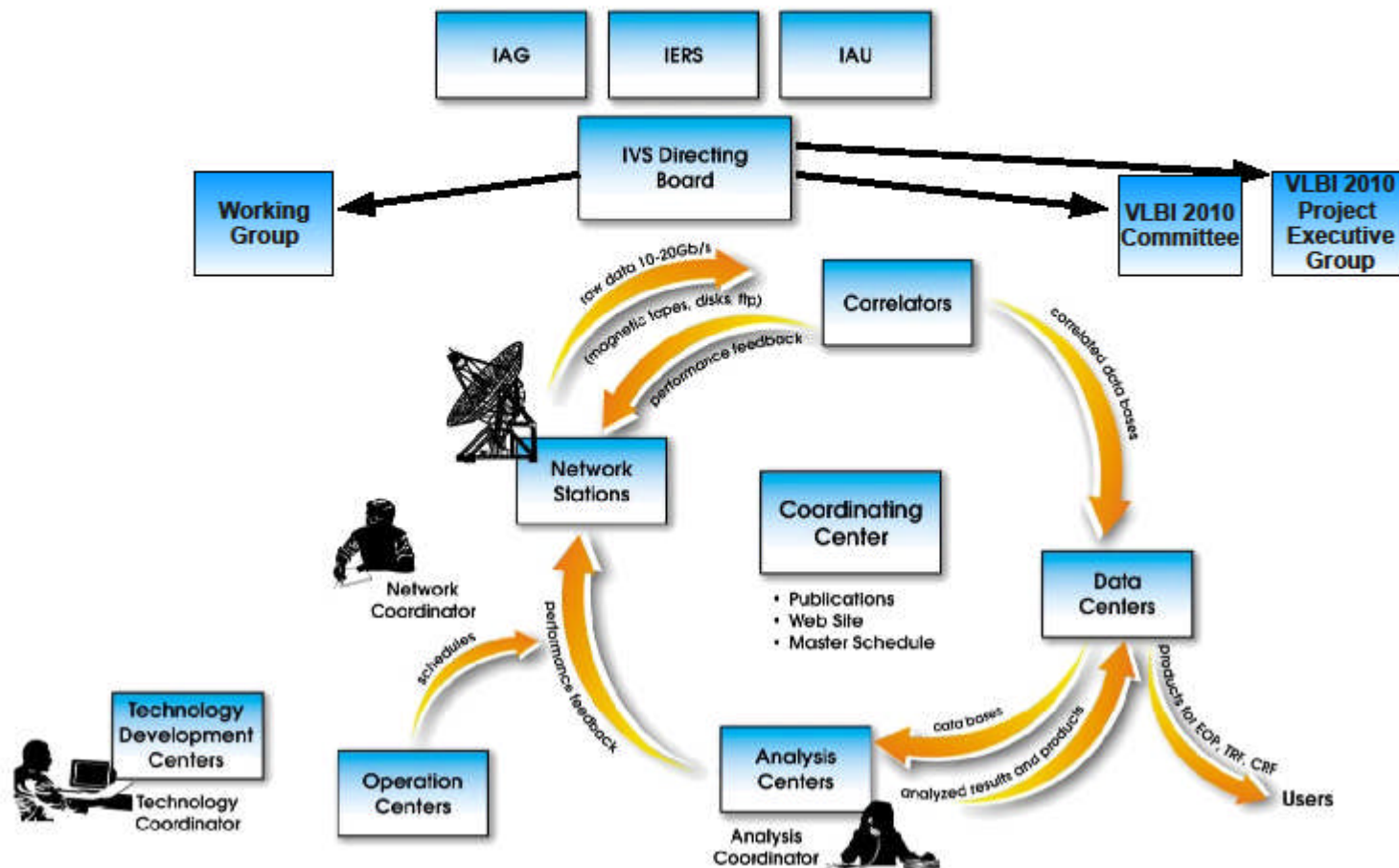
## Main tasks of the IVS are: coordinate VLBI components, guarantee provision of products for CRF, TRF, and EOP

- ⚡ IVS inauguration was on March 1, 1999
- ⚡ IVS 10th Anniversary event on March 25, 2009
- ⚡ 81 Permanent Components supported by >40 institutions in >20 countries
- ⚡ ~270 Associate Members





# IVS Components



# IVS Components (Status June 2012)





# VLBI2010: Origins, Status and Future

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# VLBI product: CRF

## ICRF2

Adopted by IAU (2009)

Resolution B3

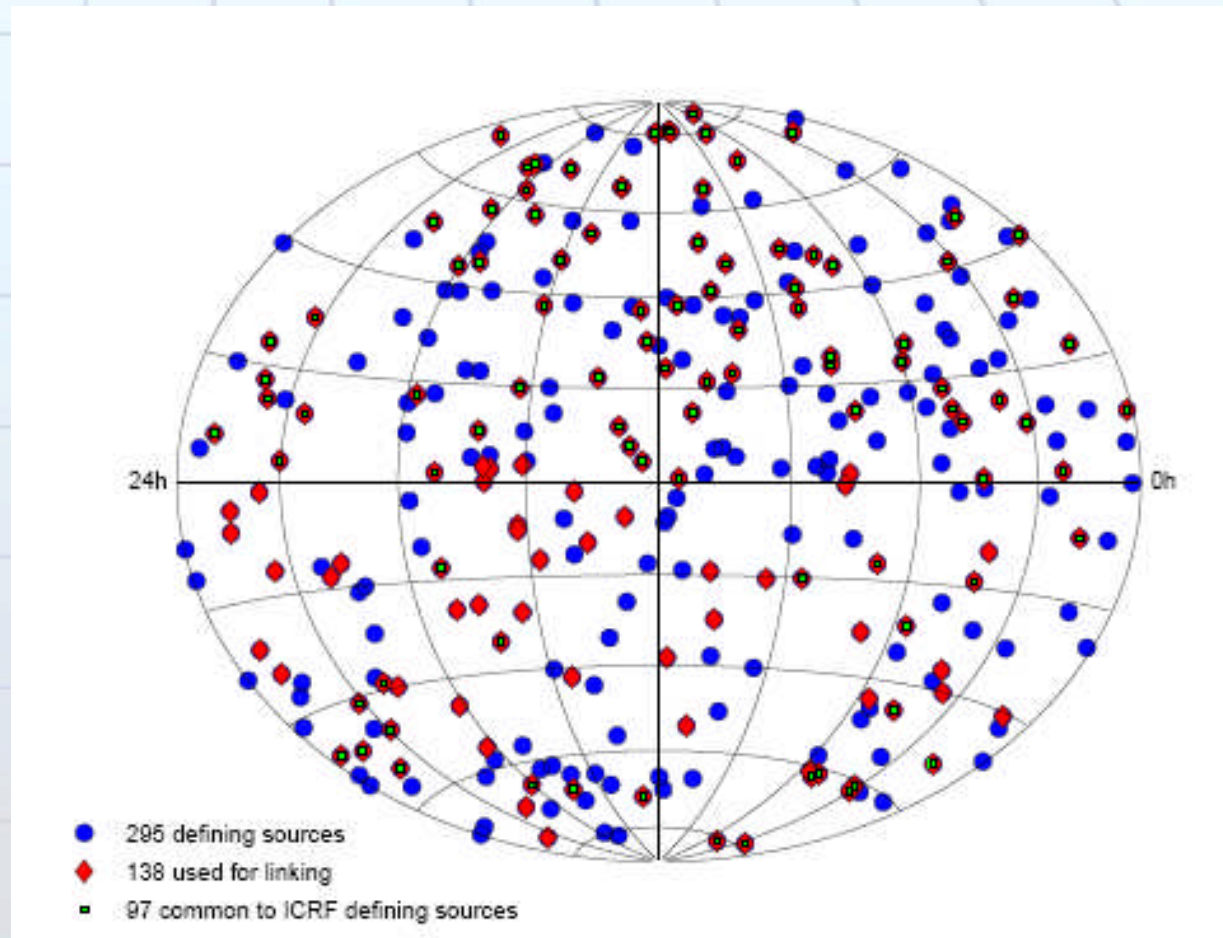
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total: 3414

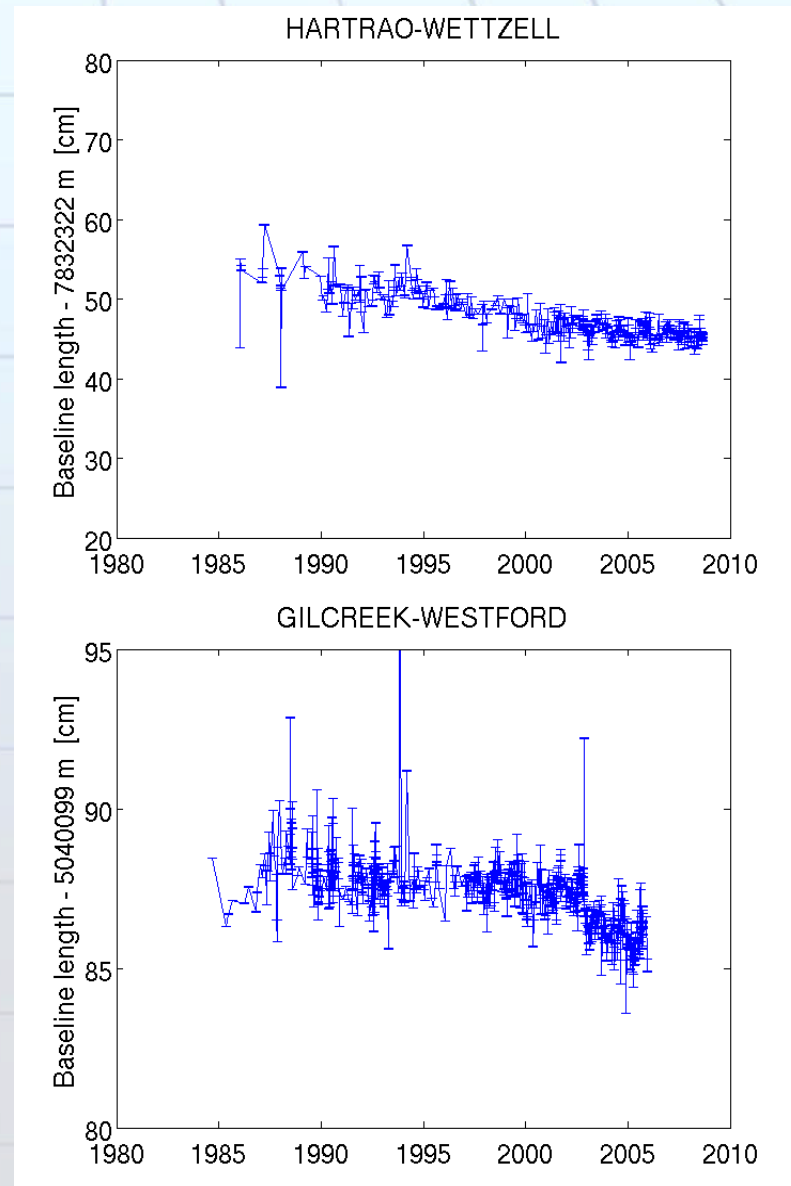
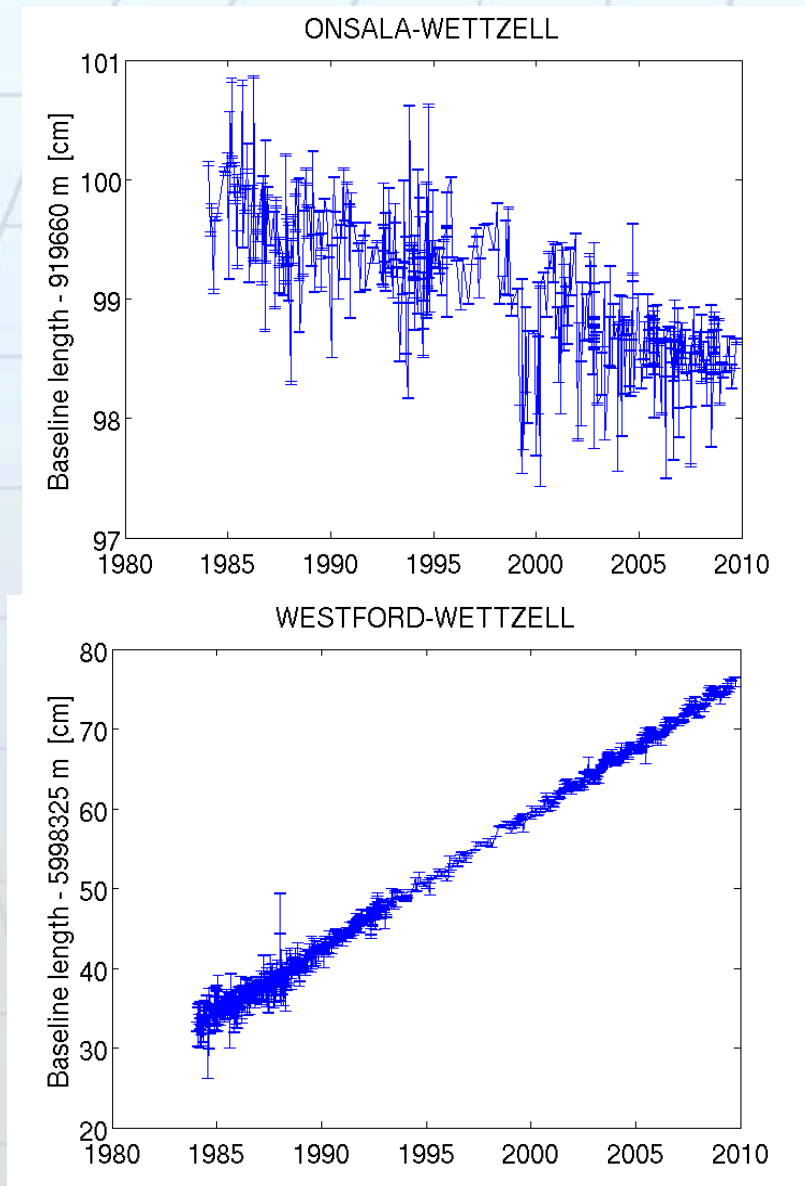
defining: 295

linking: 138

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

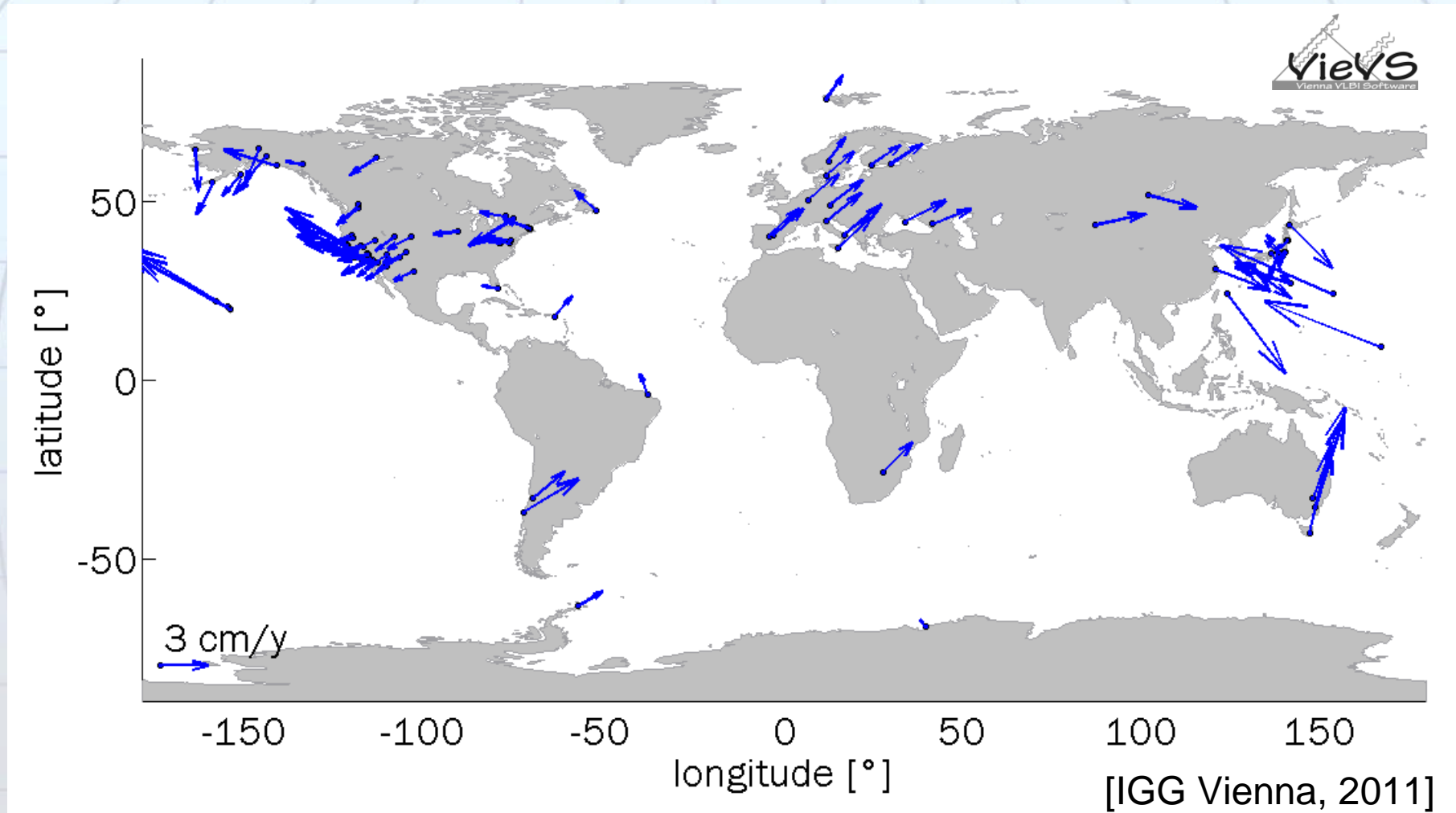


# VLBI product: baseline lengths and the TRF



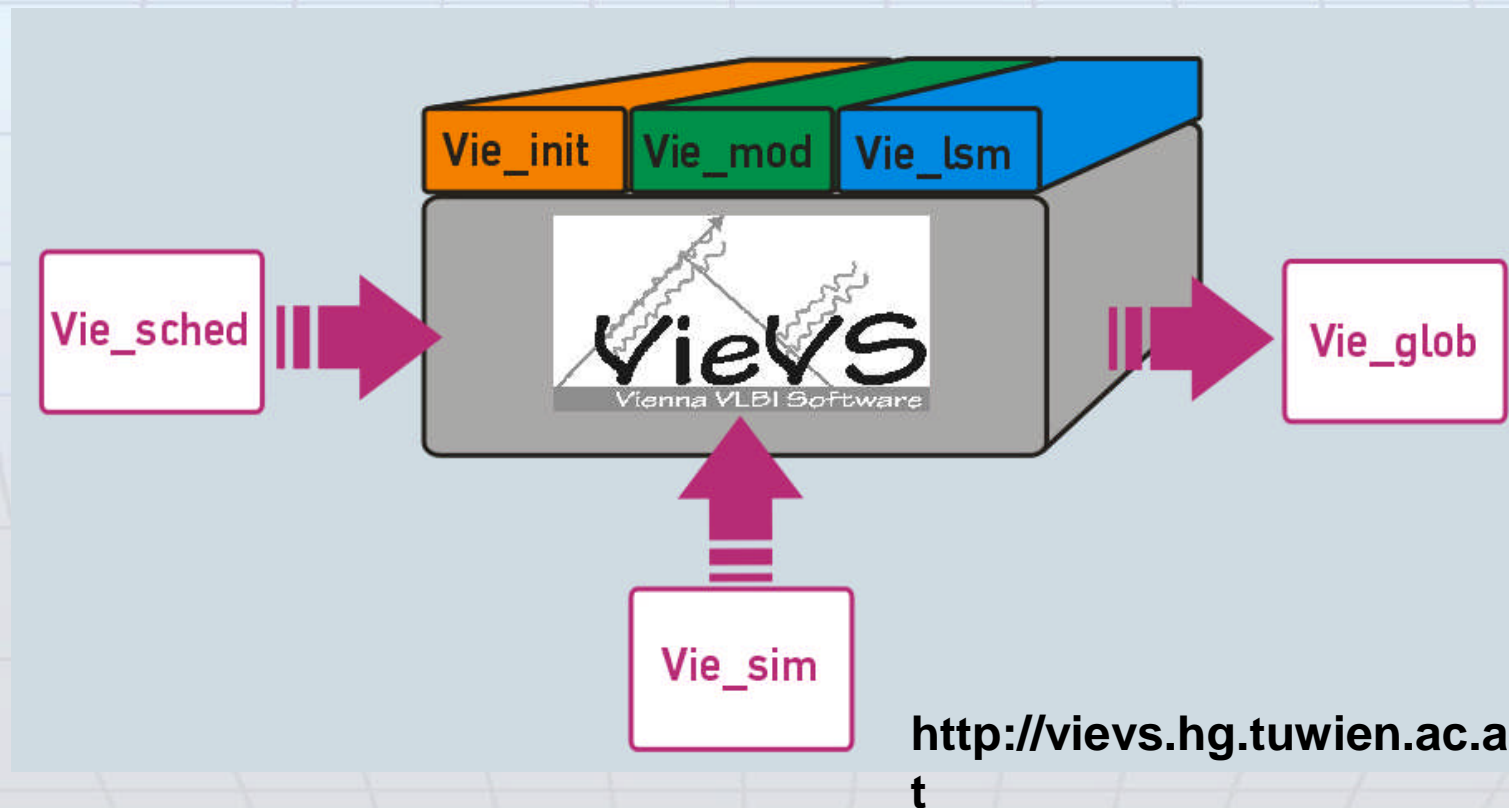


# VLBI product: Station velocities



# Vienna VLBI Software (VieVS)

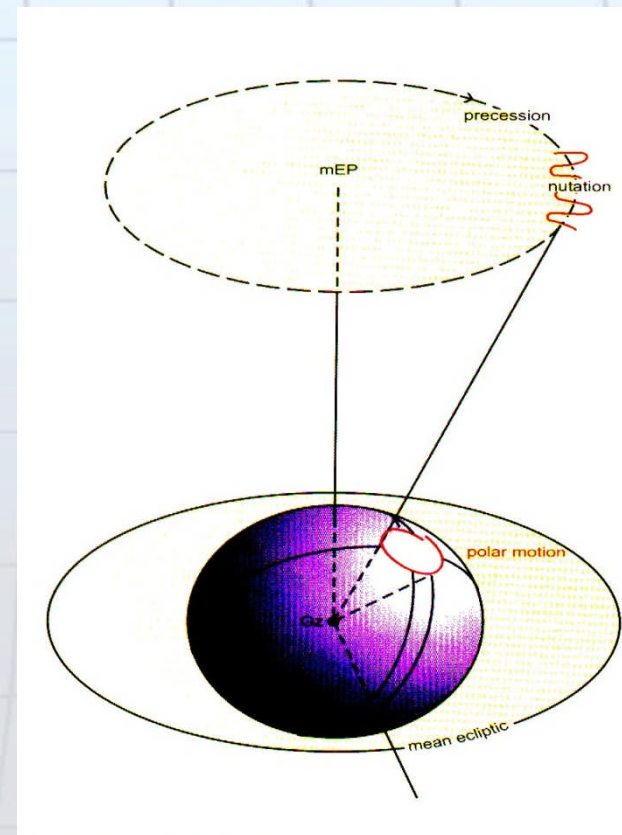
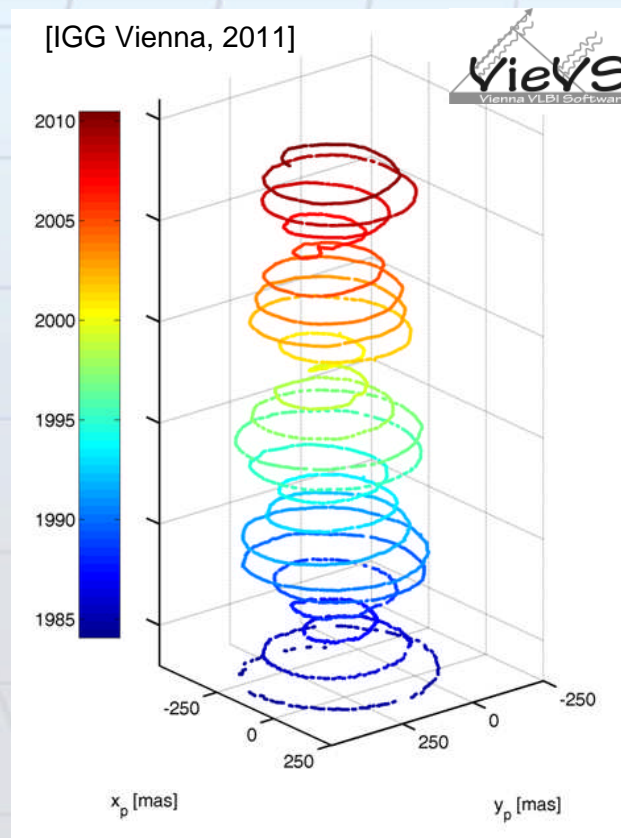
- ⚡ Developed at IGG Vienna since 2008
- ⚡ Written in MATLAB
- ⚡ Easy to use through graphical user interfaces



# VLBI product: Earth Orientation Parameters (EOP)

📡 Earth rotation parameters  $x_{\text{pole}}$ ,  $y_{\text{pole}}$ ,  $d\text{UT1}$

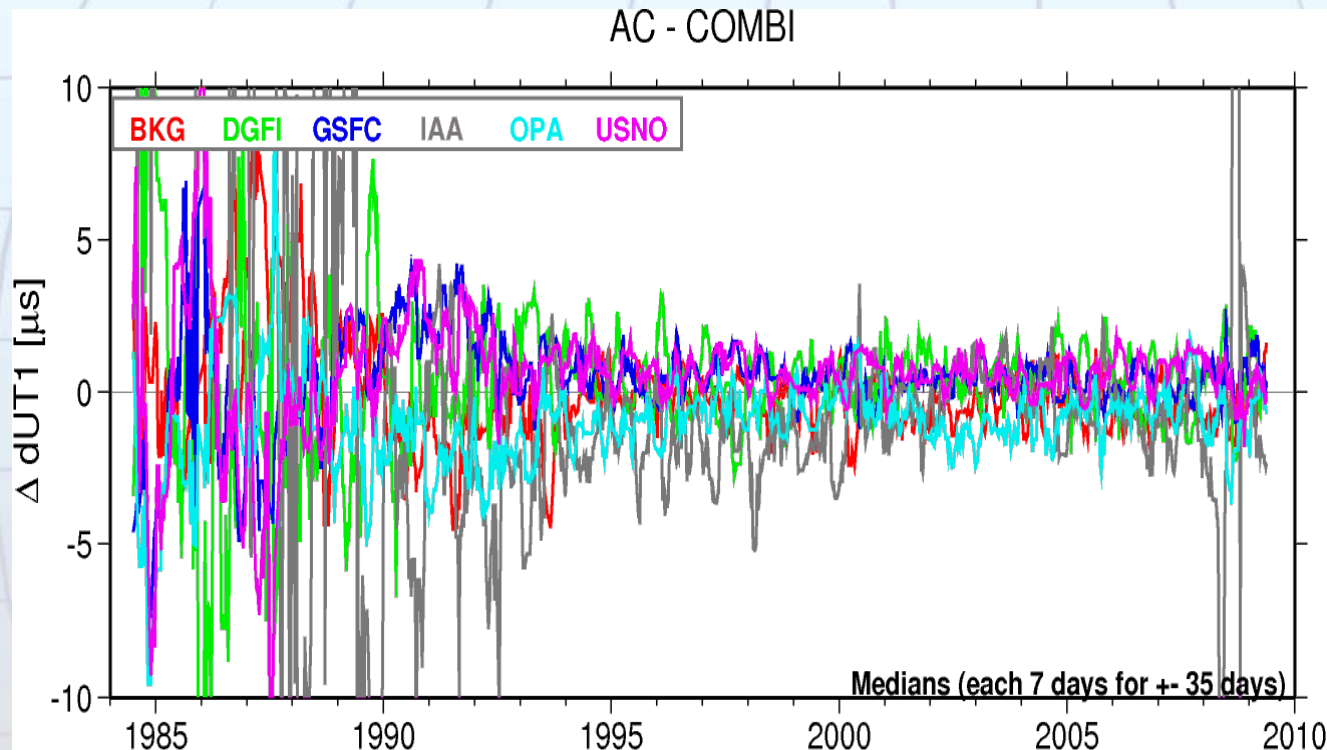
📡 Precession / Nutation parameters





# 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**
  - $d\psi, d\epsilon$
  - $x_p, y_p$
  - UT1-UTC
- **Combined solution from 6 Analysis Centers**
- **20-30% improvement**
  - accuracy
  - robustness
- **R1 & R4 since 2002**

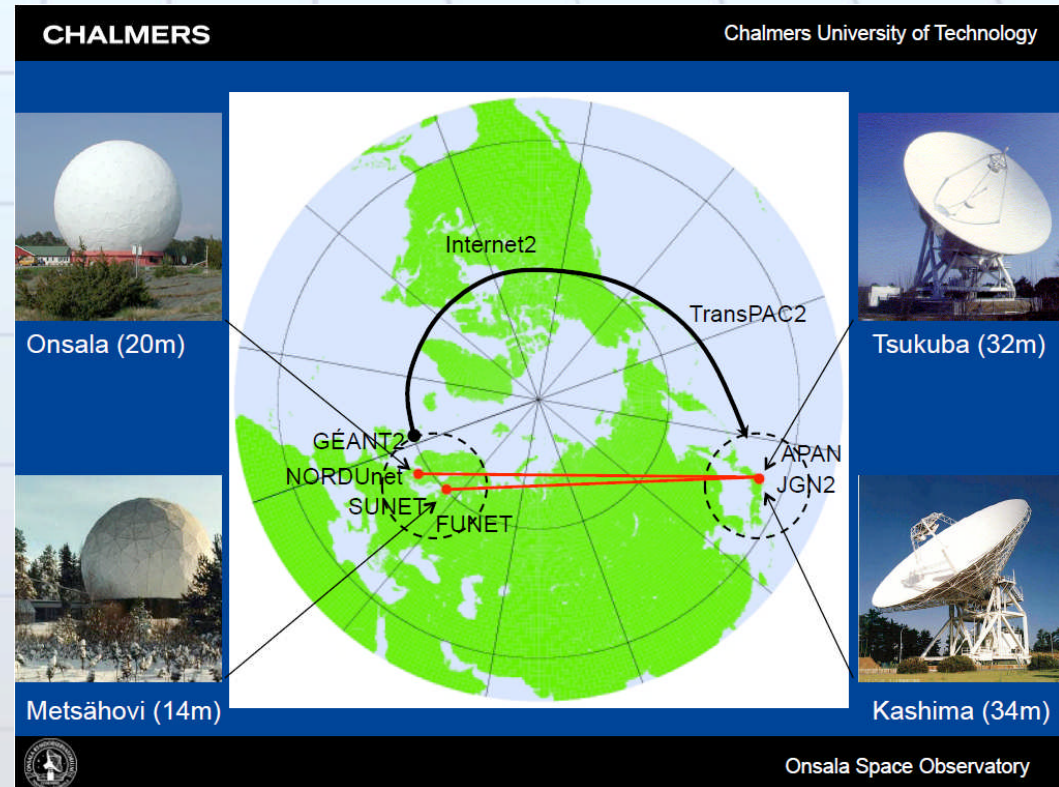
# e-VLBI Intensives (1h)

⚡ 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]

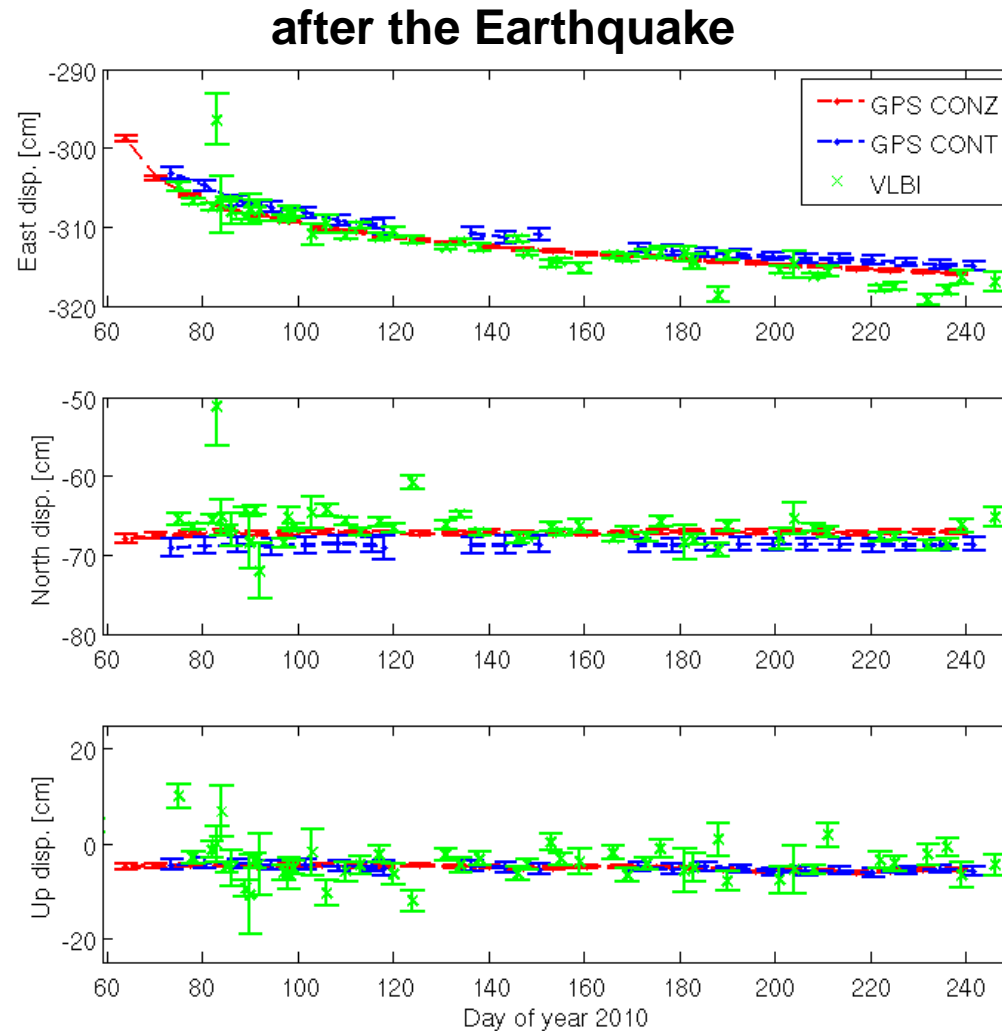


[Haas et al., 2011:  
Ultra-rapid dUT1-observations with e-VLBI]

# Displacement of TIGO Concepción

⚡ The Earthquake moved Concepción by about 3 m to the west

⚡ Similar results are obtained from GPS measurements

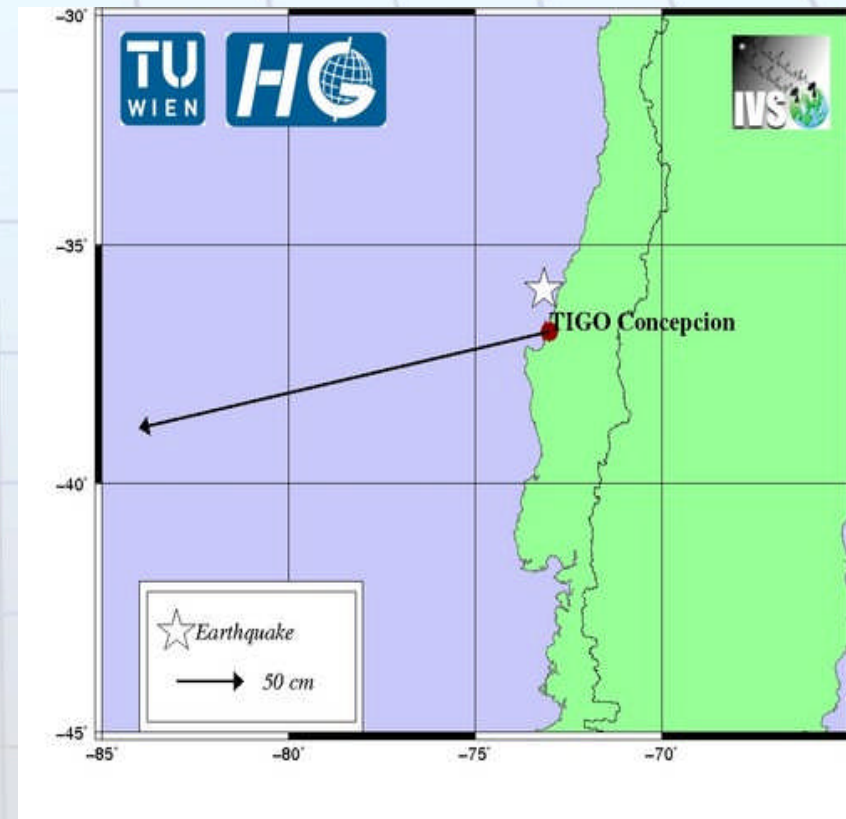


[IGG Vienna, 2010]



# VLBI product: Station motions

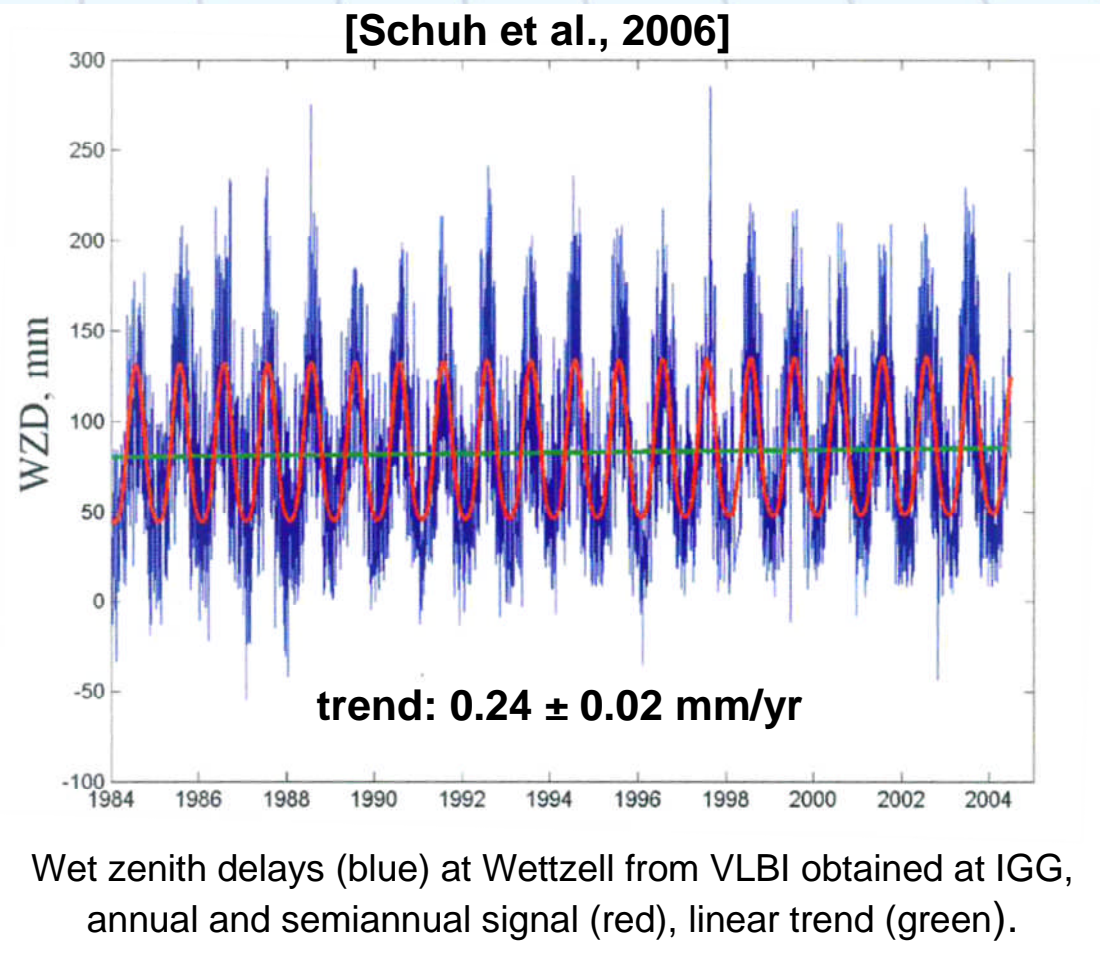
- ✎ Displacement of the TIGO radio telescope in Concepción caused by the magnitude 8.8 Earthquake on Feb 27, 2010.

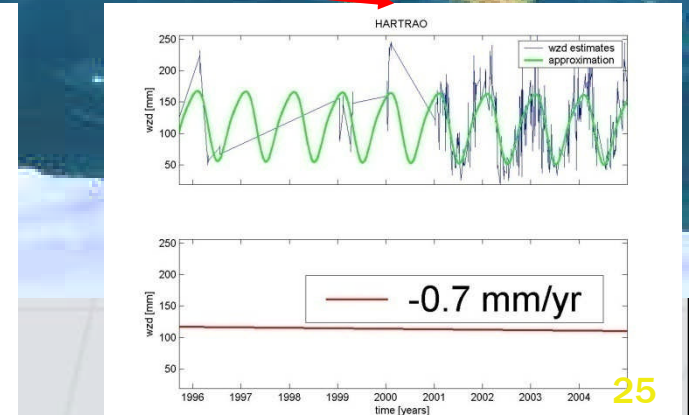
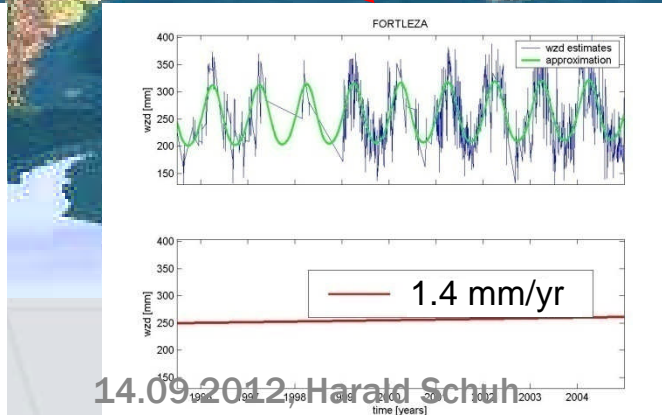
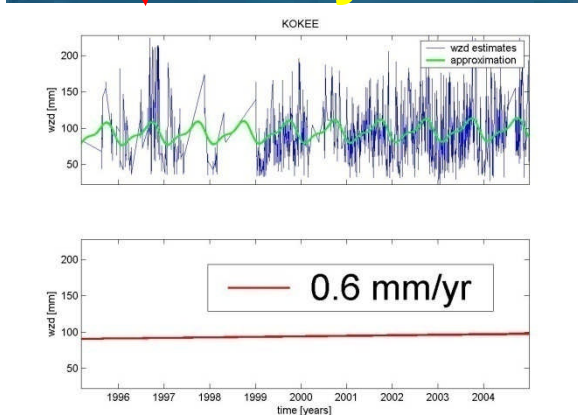
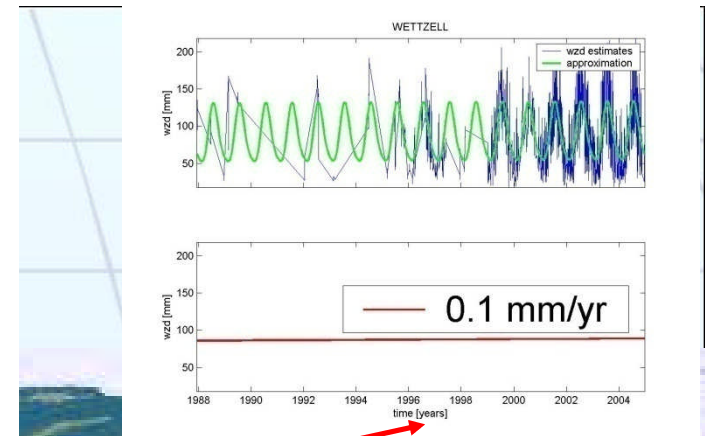
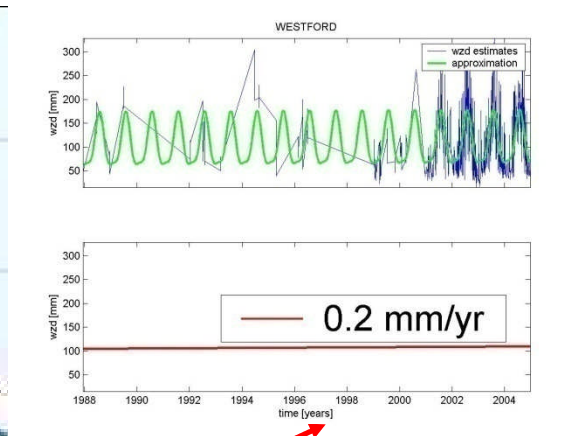
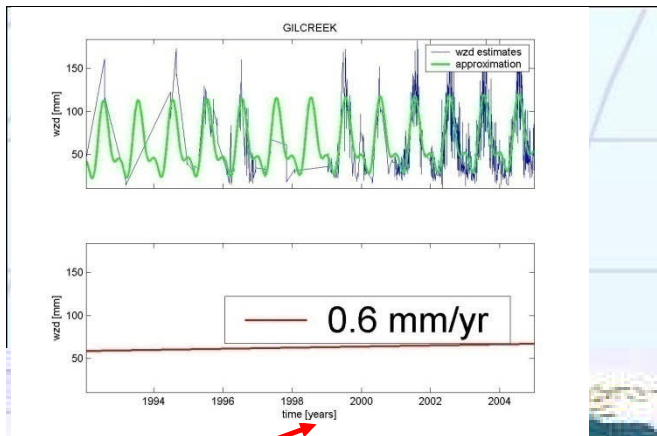


# Climate studies using VLBI

- ⚡ 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**





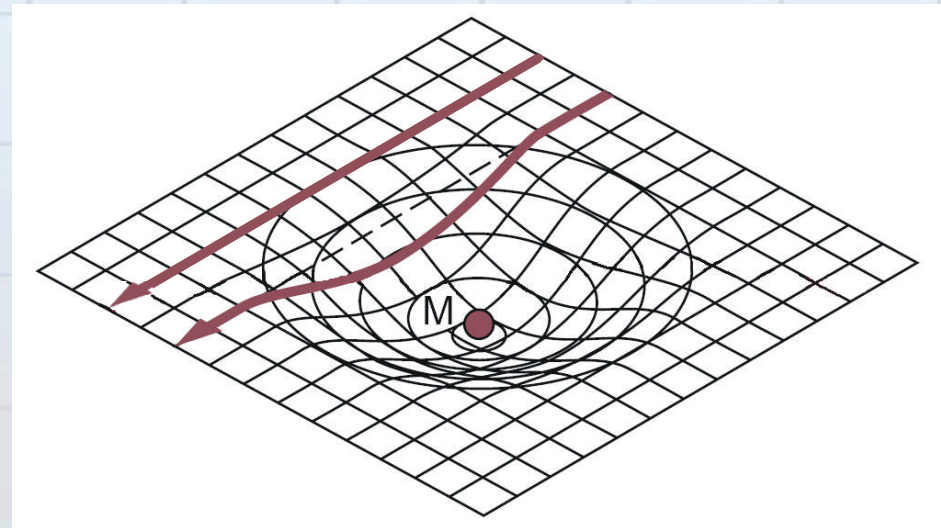


# Gravitational time delay

## Gravitational delay of n-th solar system

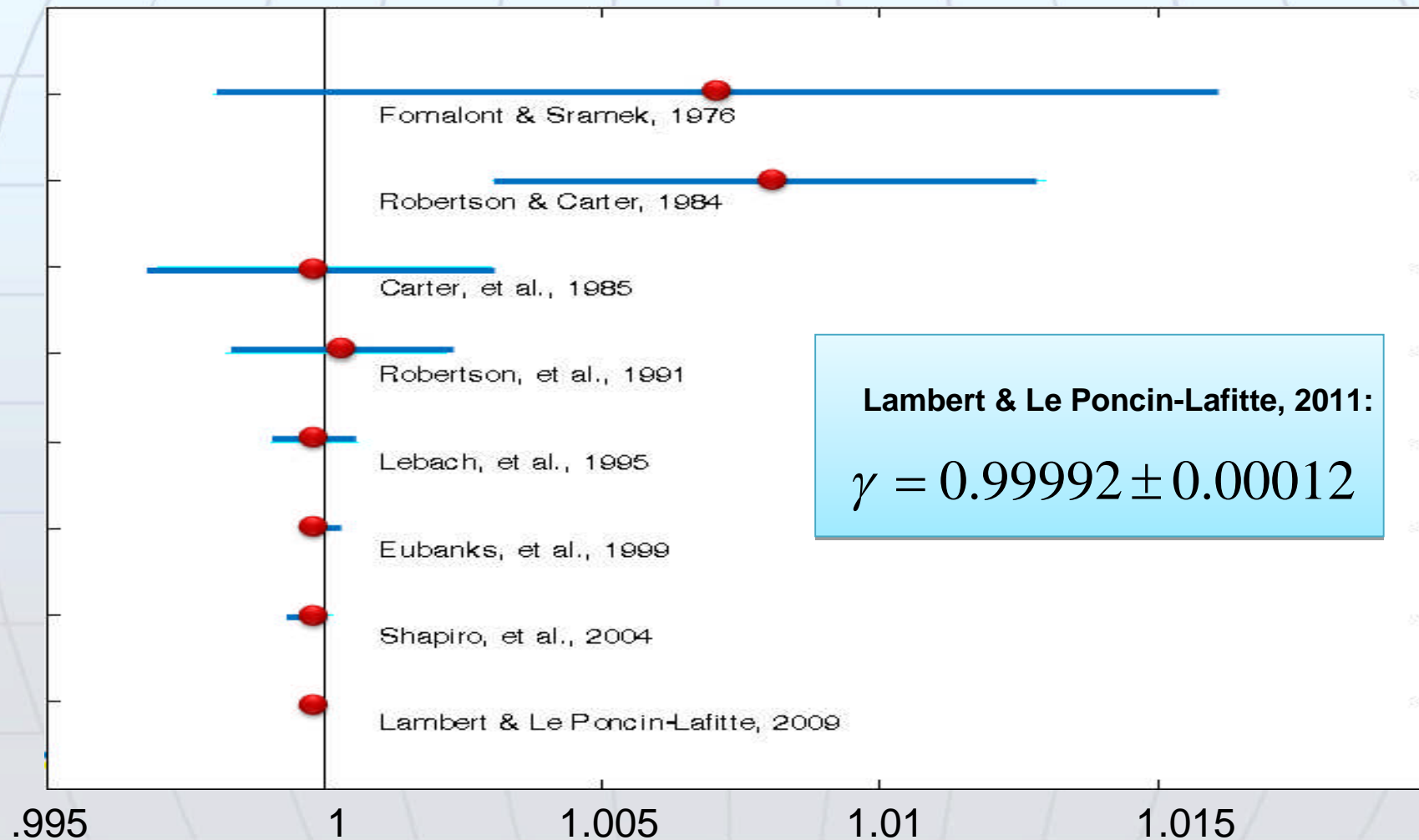
$$\tau_{g,n} = (1 + \gamma) \cdot \frac{GM_n}{c^3} \cdot \ln \left( \frac{\left| \overset{\rho}{\mathbf{x}}_{1,n} \right| + \overset{\rho}{\mathbf{x}}_{1,n} \cdot \overset{\rho}{\mathbf{k}}}{\left| \overset{\rho}{\mathbf{x}}_{2,n} \right| + \overset{\rho}{\mathbf{x}}_{2,n} \cdot \overset{\rho}{\mathbf{k}}}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

$\overset{\rho}{\mathbf{x}}_{i,n}$  ... position vector of station i  
w.r.t. center of mass of n-th  
body  
 $\overset{\rho}{\mathbf{k}}$  ... unit vector towards source



# VLBI product: relativistic parameters

$\gamma$	„Mass-induced spatial curvature“	$\equiv 1$ (GR)
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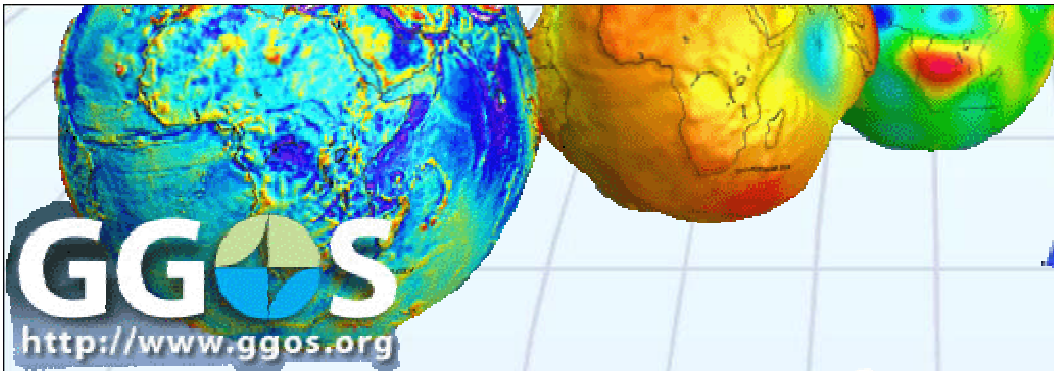


# VLBI and GGOS

- ⚡ 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)







# Global Geodetic Observation System (GGOS)

JASON

GNSS

GRACE

CHAMP

VLBI

SLR

tsunami detection<sup>29</sup>

14.09.2012, Harald Schuh



# 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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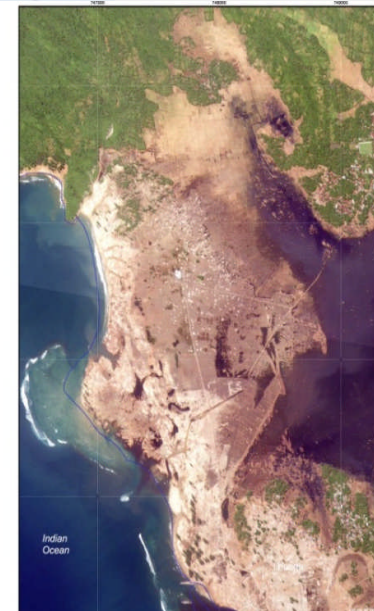
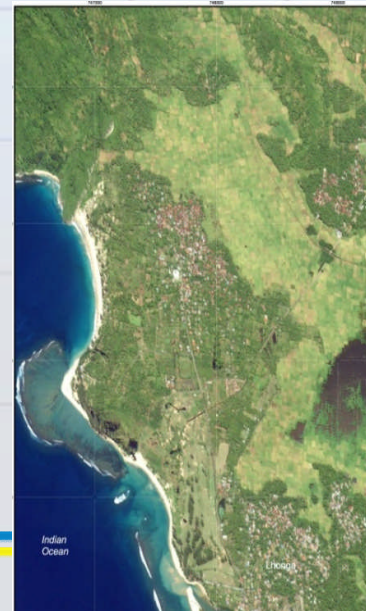
IV. VLBI2010

V. NEW PERSPECTIVES





# 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

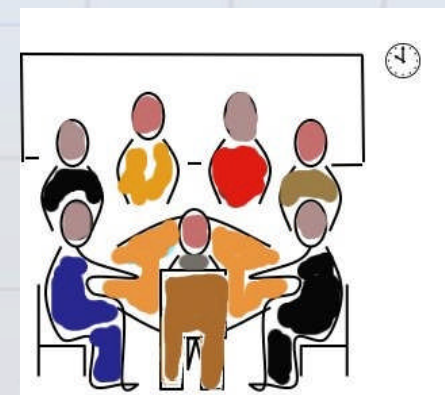


**Continuous monitoring is absolutely crucial**

14.09.2002, Harald Schaub

# 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

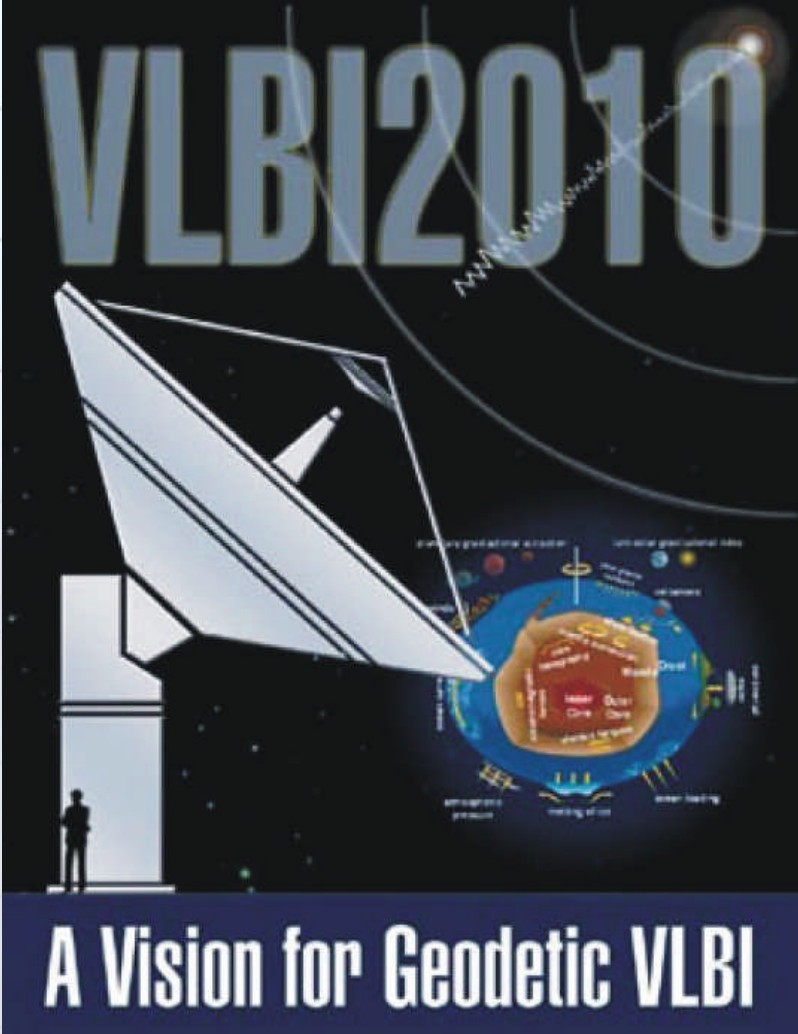


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# WG 3 report



[http://ivsc.gsfc.nasa.gov/about/wg/wg3/IVS\\_WG3\\_report\\_050916.pdf](http://ivsc.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

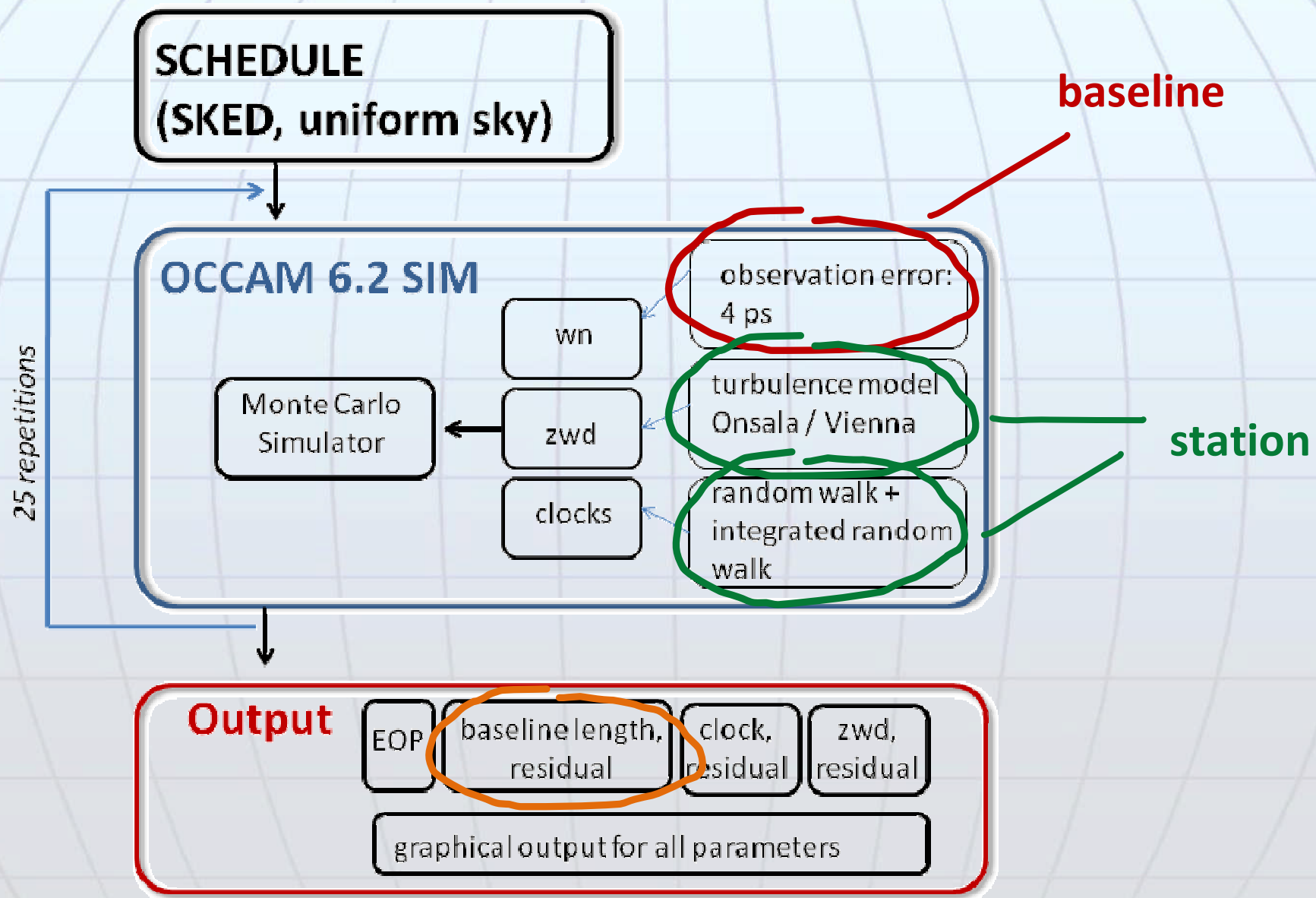
- ✎ the **VLBI2010 Committee (V2C)** was established in September 2005
- ✎ to encourage the implementation of the recommendations of WG3

# VLBI2010 – V2C activities

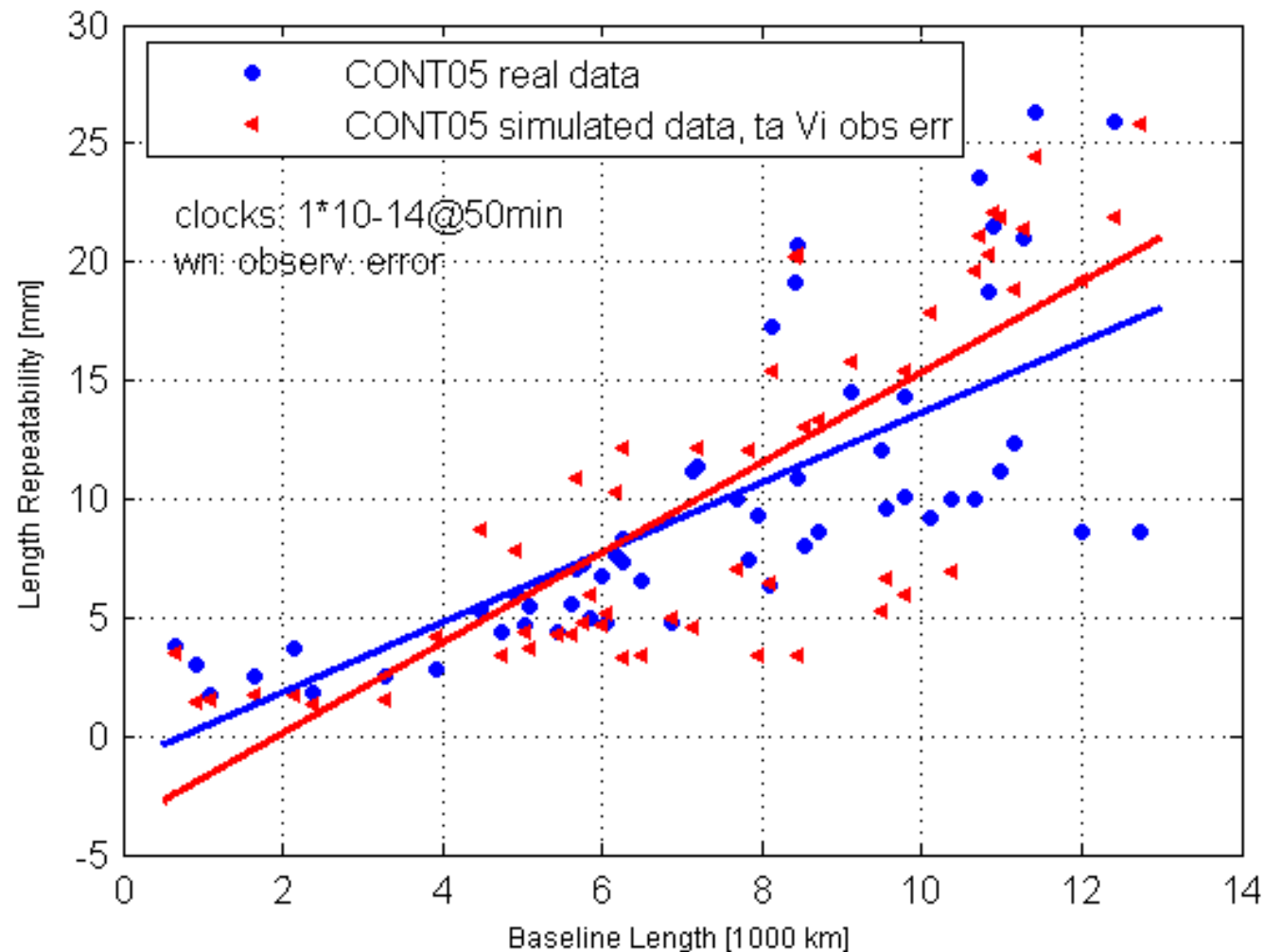
-  system studies
-  Monte Carlo simulations
-  development projects
-  prototyping



# VLBI 2010 Monte Carlo simulations



# CONT05: real data versus Monte Carlo simulator



zenith wet delay (zwd)

turb. model Vienna

clocks

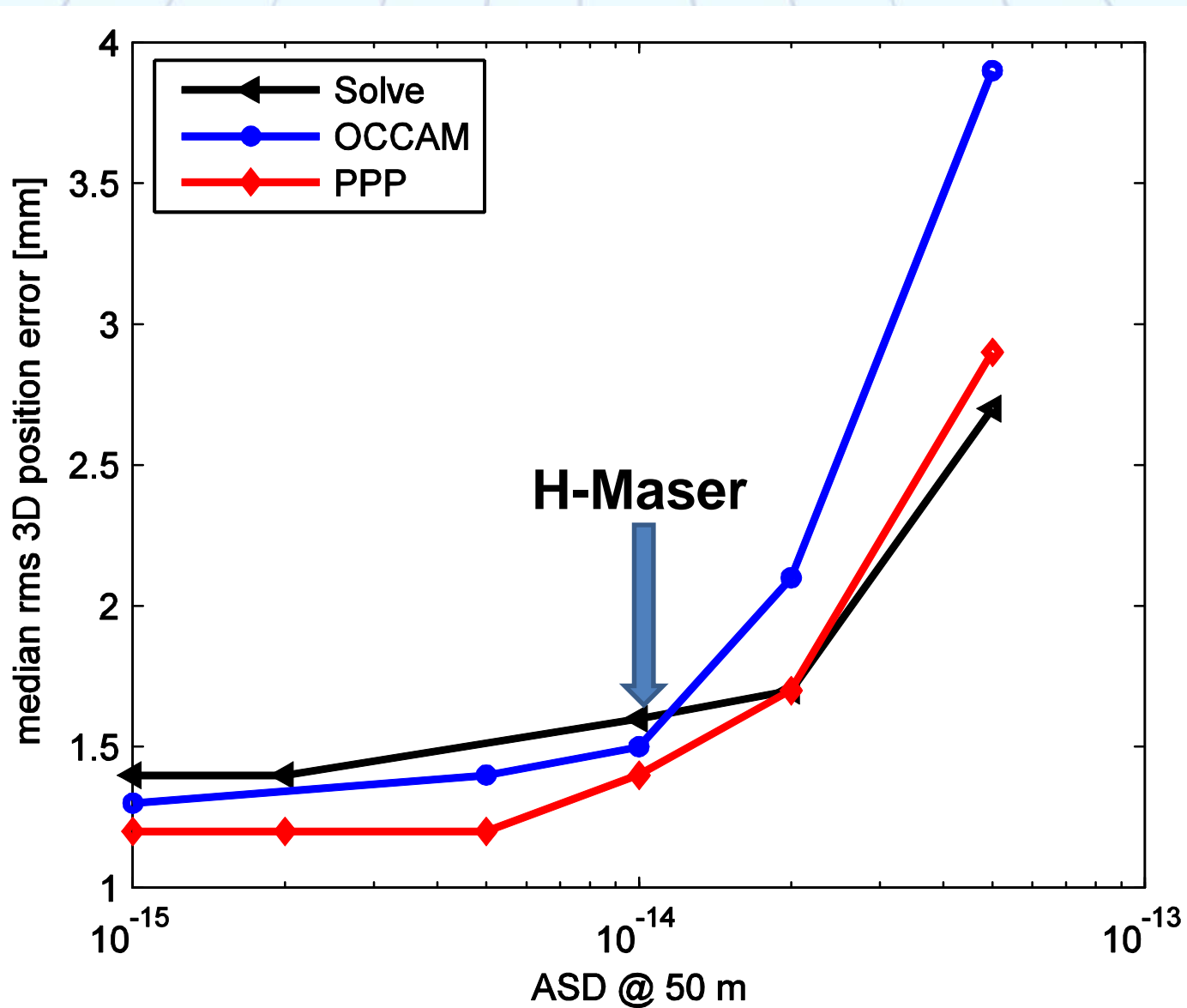
$1 \cdot 10^{-14} @ 50 \text{min}$  (ASD)

white noise

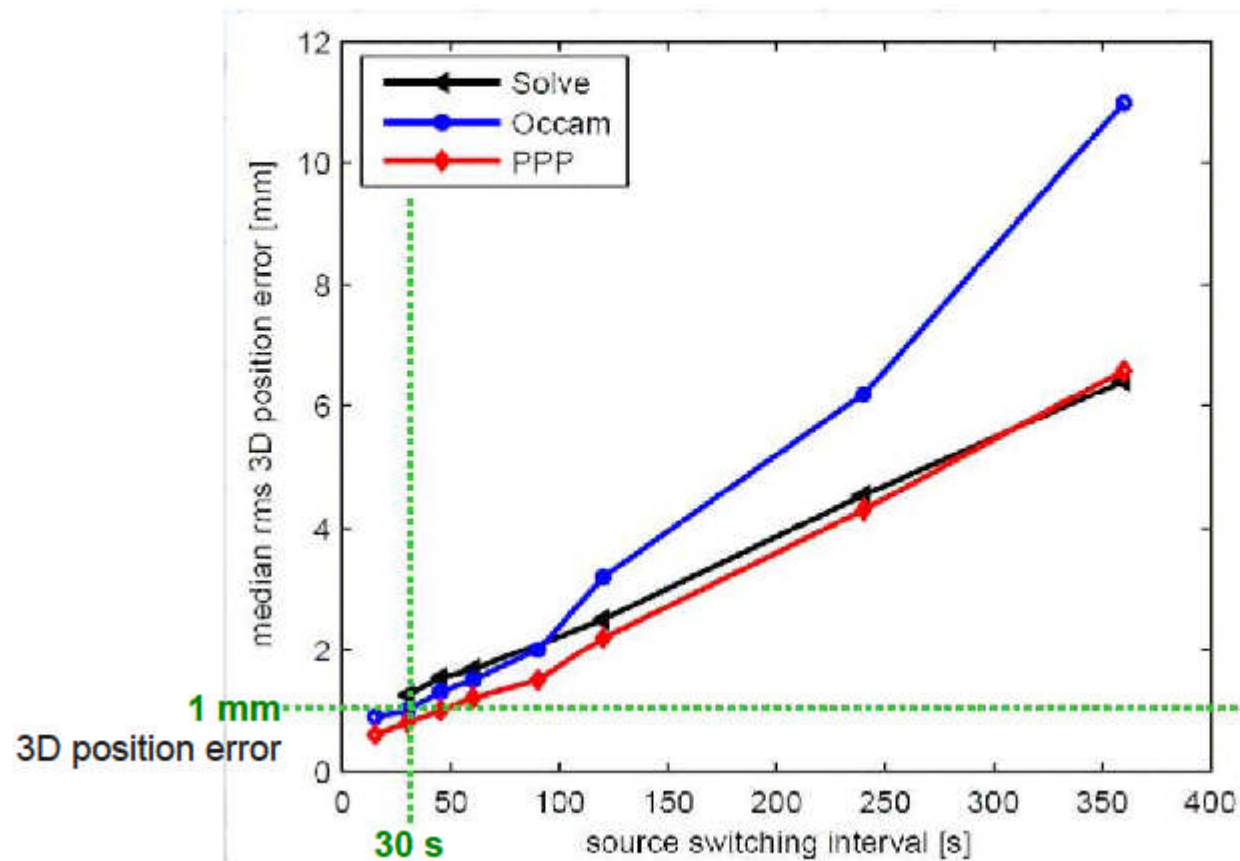
obs. error

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

# Test of different clock performance



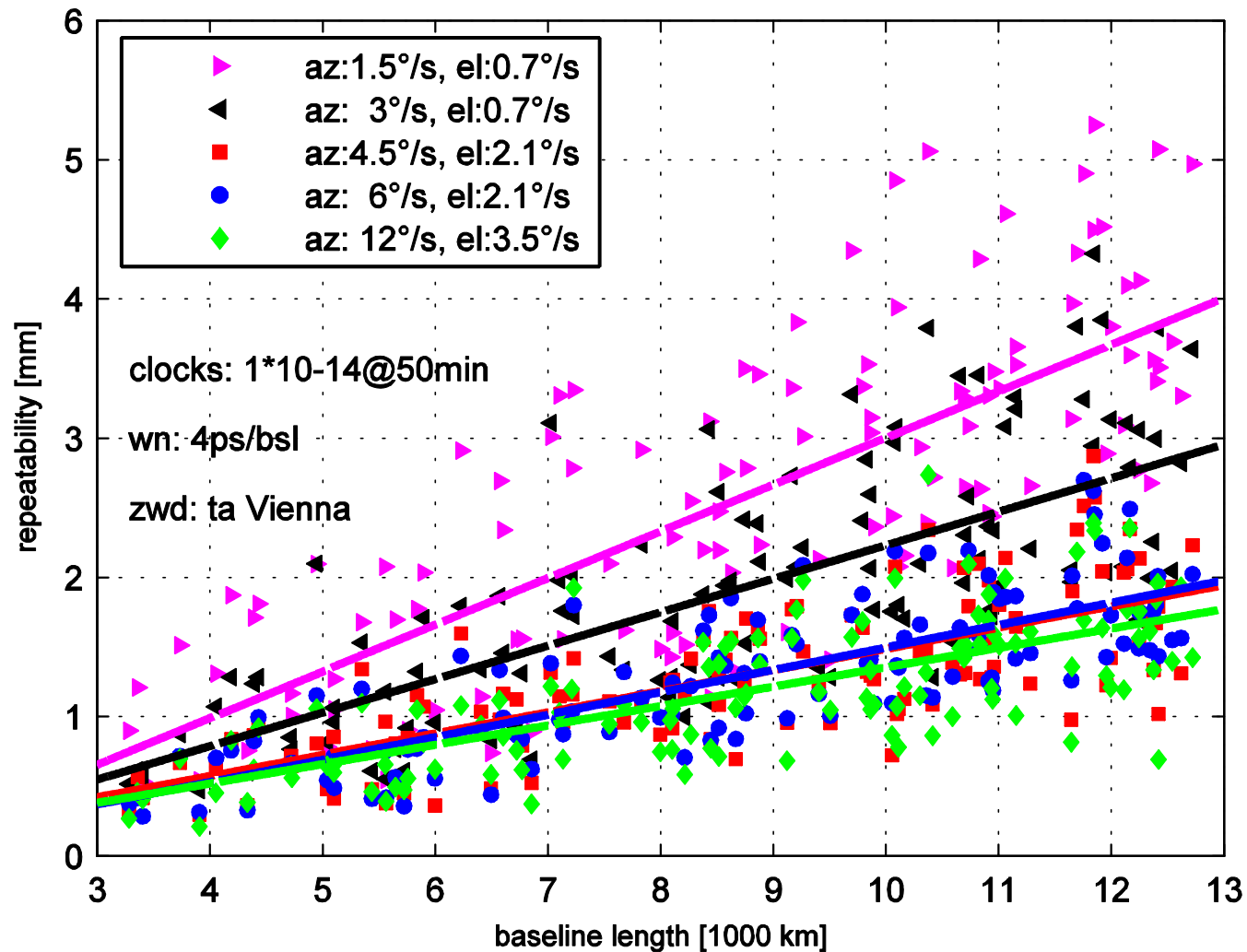
## Ex.: Source switching intervals





# Slew speed tests using SKED

## Baseline length repeatability



zwd:  
turbulence  
model -  
Vienna  
clocks:  
1·10<sup>-14</sup>@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, 256 Mbps	8–16 Gbps
data transfer	usually ship disks, some e-transfer	e-transfer, e-VLBI, ship disks when required



<ftp://ivscg.gsfc.nasa.gov/pub/misc/V2C/TM-2009-214180.pdf>

# **VLBI2010 – a completely new generation of VLBI hardware and software**

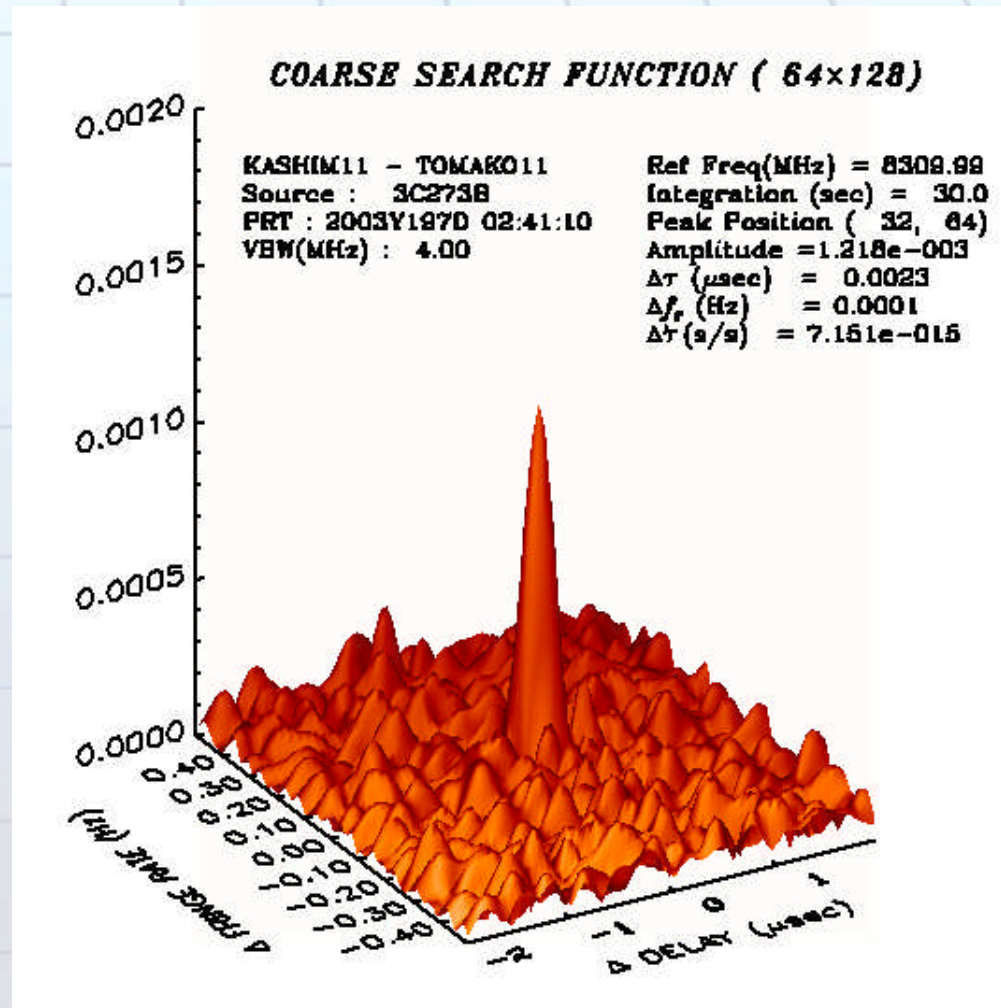
VLBI2010 also includes

⚡ 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**

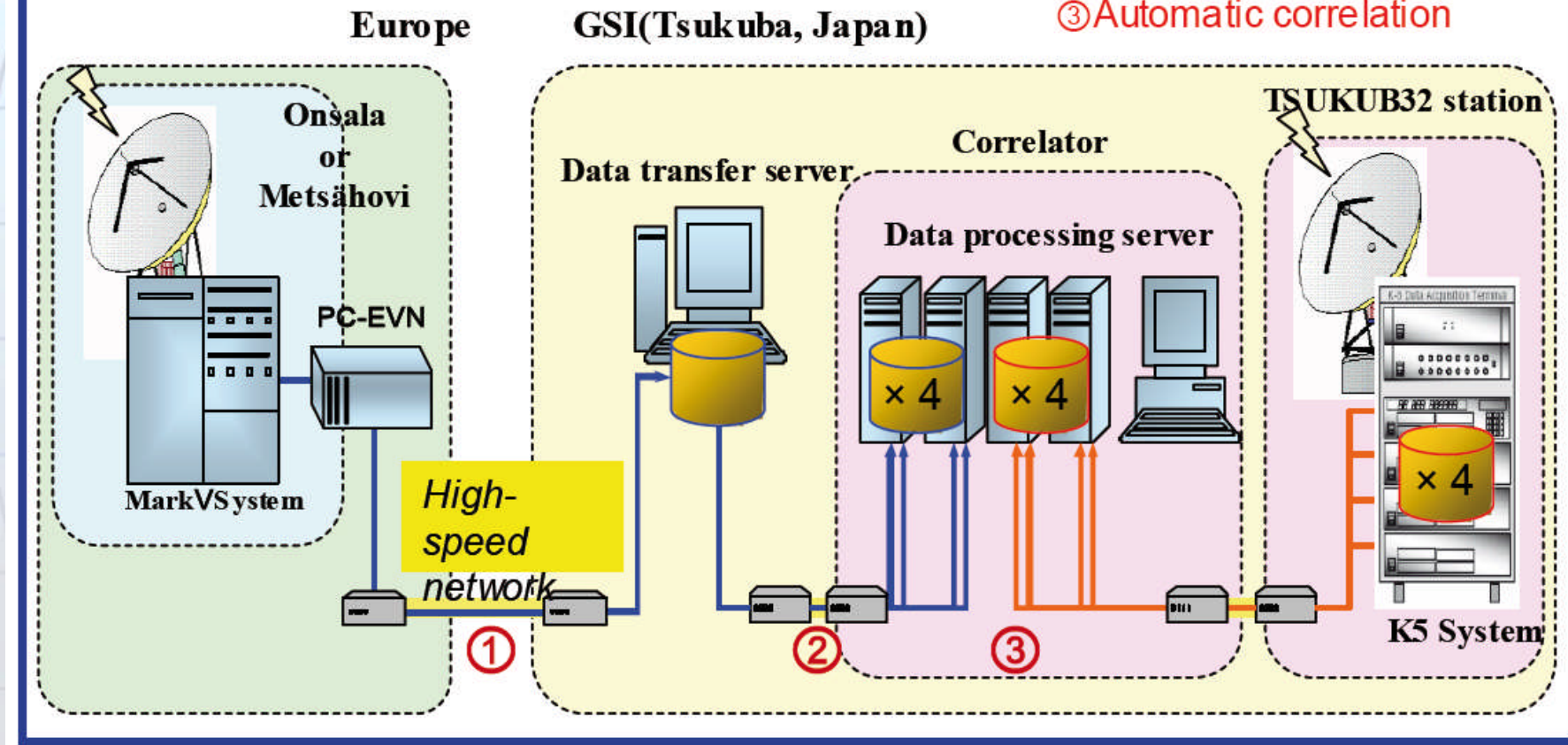
VLBI2010 also includes

- ✎ software correlation
- ✎ automation of data analysis

# VLBI analysis automation

[Sekido et al., 2008]

- ① Real time data transfer
- ② Automatic data conversion
- ③ Automatic correlation



# 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)

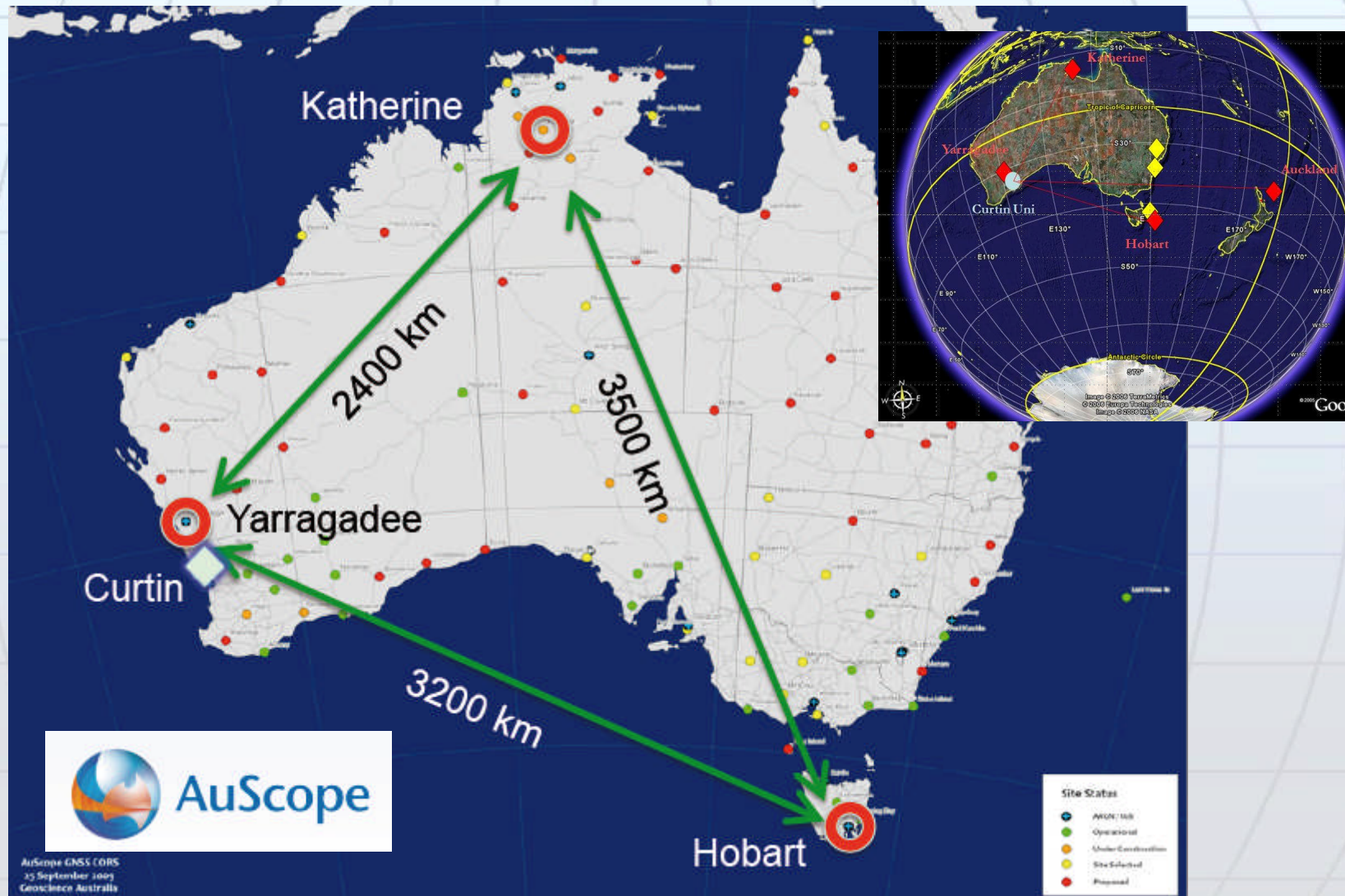


Dedication of the 1st VLBI2010 antenna by the Governor of Tasmania; Feb-09-2010; Mt. Pleasant Observatory, TAS, AUS



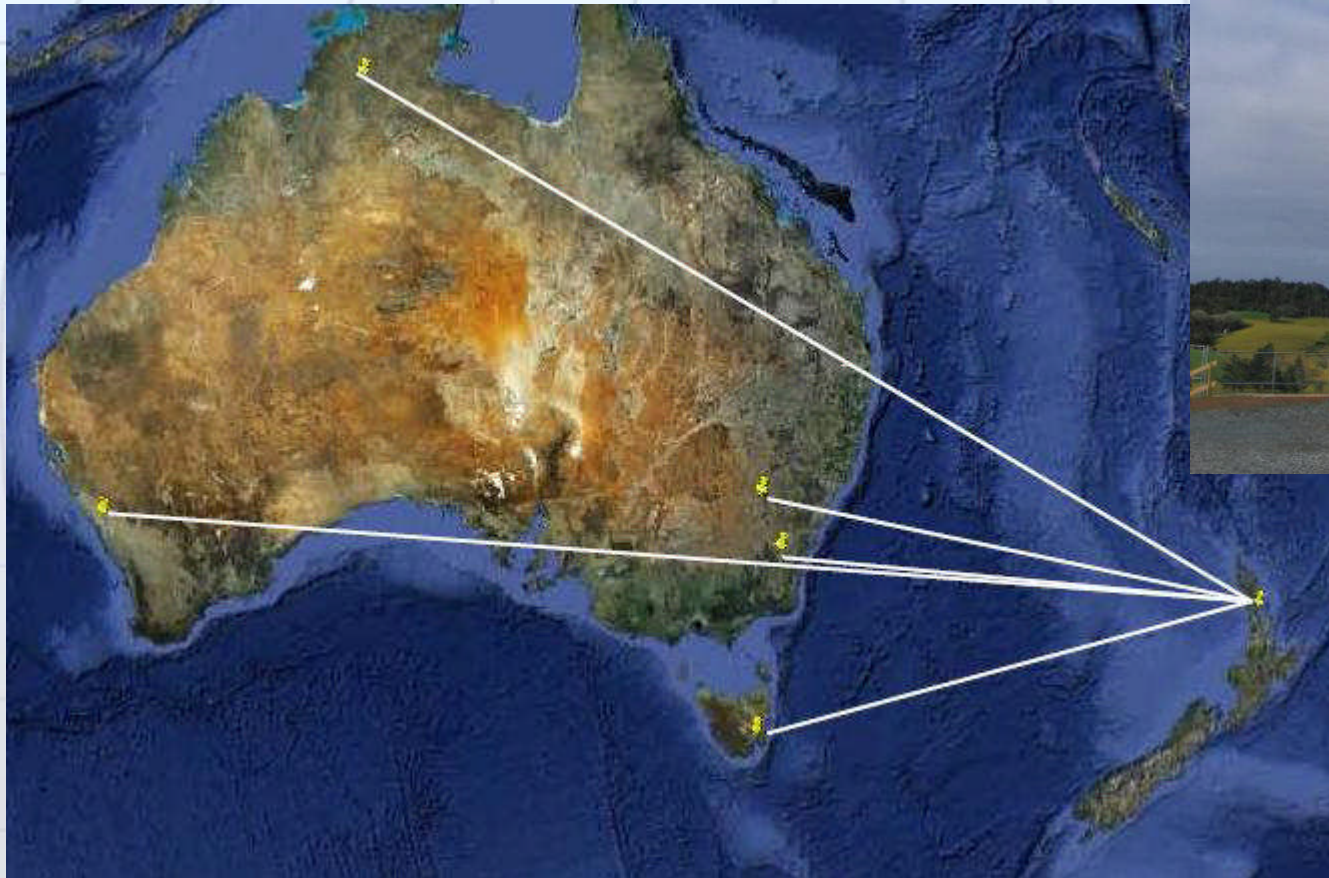


# New VLBI2010 antennas: AuScope (AUS)



# New VLBI2010 antenna: AUT (NZL)

 Auckland





- Spatial Data Infrastructure



Model of the Australian Spatial Data Infrastructure

14.09.2012, Harald Schuh

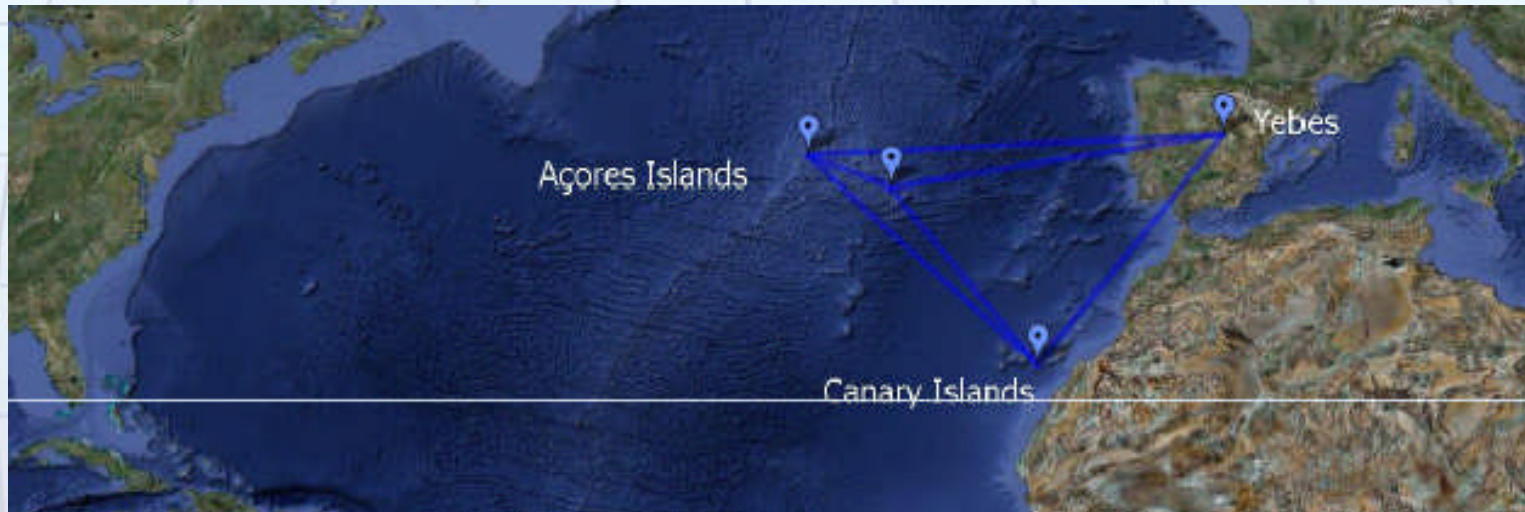
# New VLBI2010 antennas: China





# New VLBI2010 antennas: RAEGE

## RED ATLÁNTICA DE ESTACIONES GEODINÁMICAS Y ESPACIALES (RAEGE)



### 4 new VLBI 2010 antennas (of TTW type)

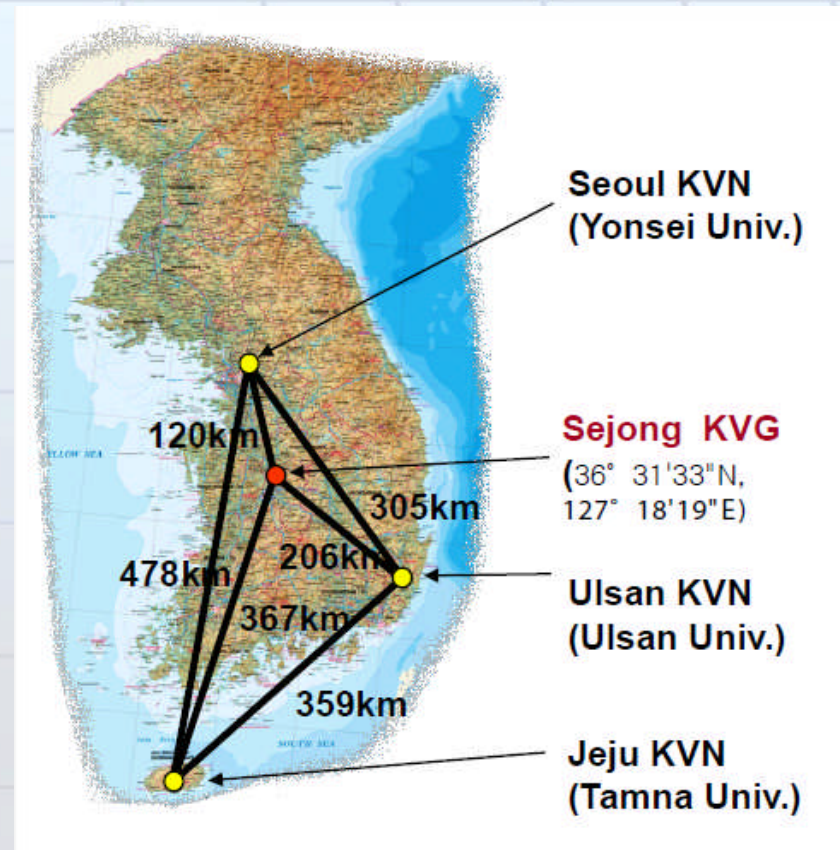
#### Baselines:

- 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.
- Final prototypes are in development.



# VLBI2010 – Current Status (June 2012)

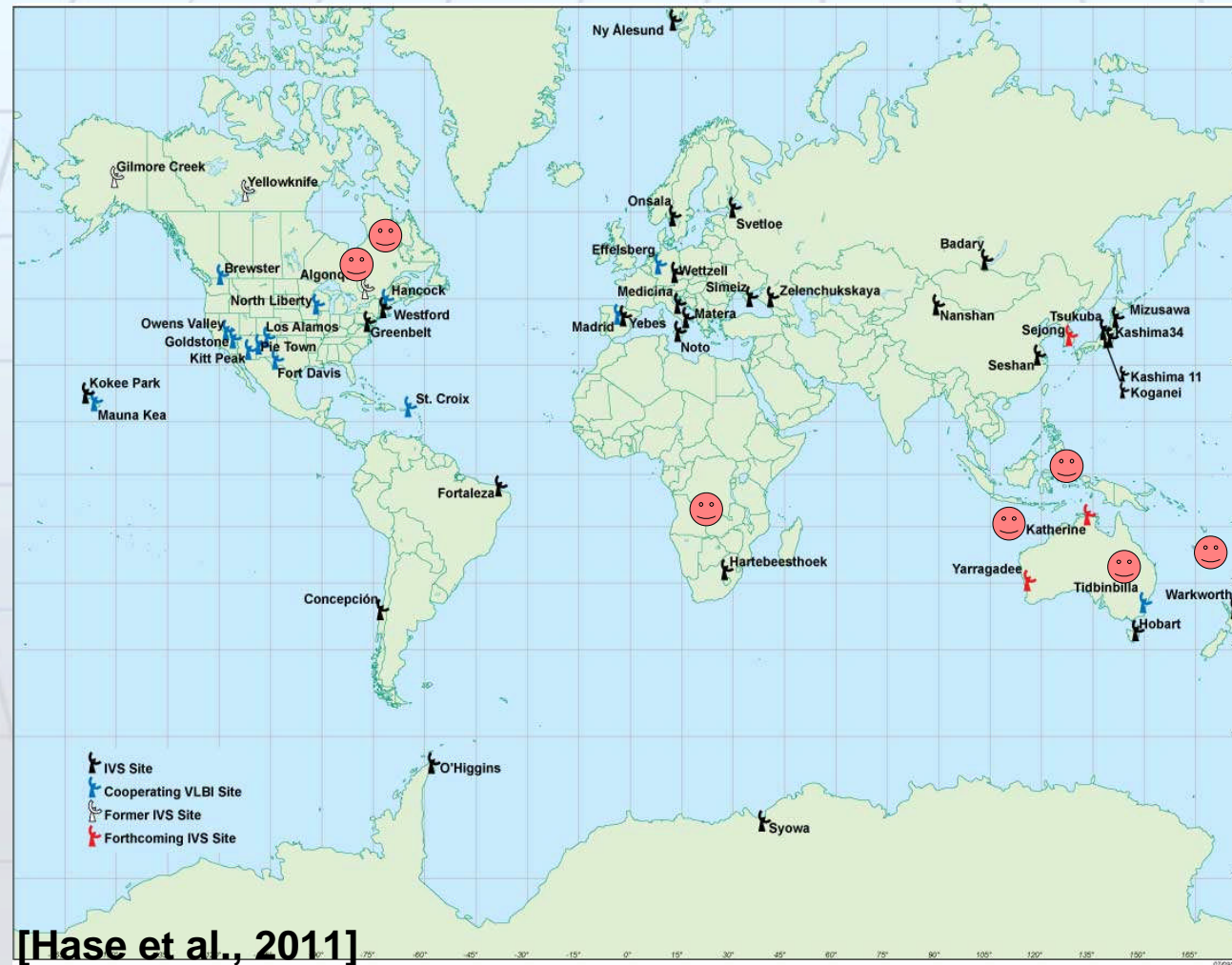
- ✎ **V2PEG (VLBI2010 Project Executive Group)** is in charge of providing strategic leadership to VLBI2010, realization of the concept, contacts on political level, letters of support, visits, consulting etc.
- ✎ **Station Survey (questionnaire)** sent to IVS observing stations asking about their future plans
- ✎ **VGOS (VLBI2010 Global Observing System)** was launched at the IVS General Assembly in Madrid (March 2012)

# Status of VLBI2010 in 2012





# VLBI2010 Network in 2011



**VLBI2010 very fast**

😊 radio telescope

😊😊 twin radio telescope

**VLBI2010 fast**

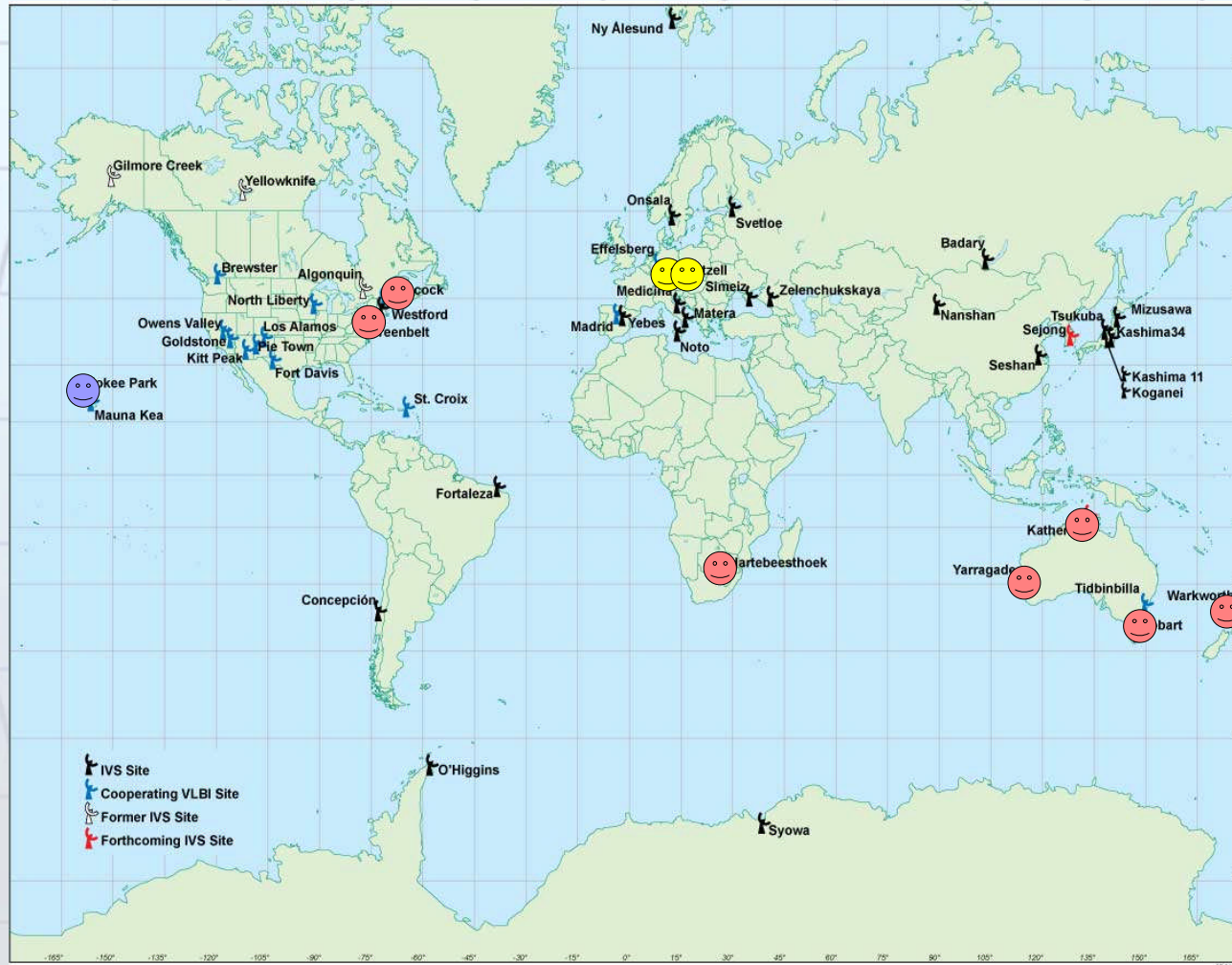
😊 radio telescope

**upgrade legacy**

😊 radio telescope



# VLBI2010 Network in 2012



**VLBI2010 very fast**

😊 radio telescope

😊😊 twin radio telescope

**VLBI2010 fast**

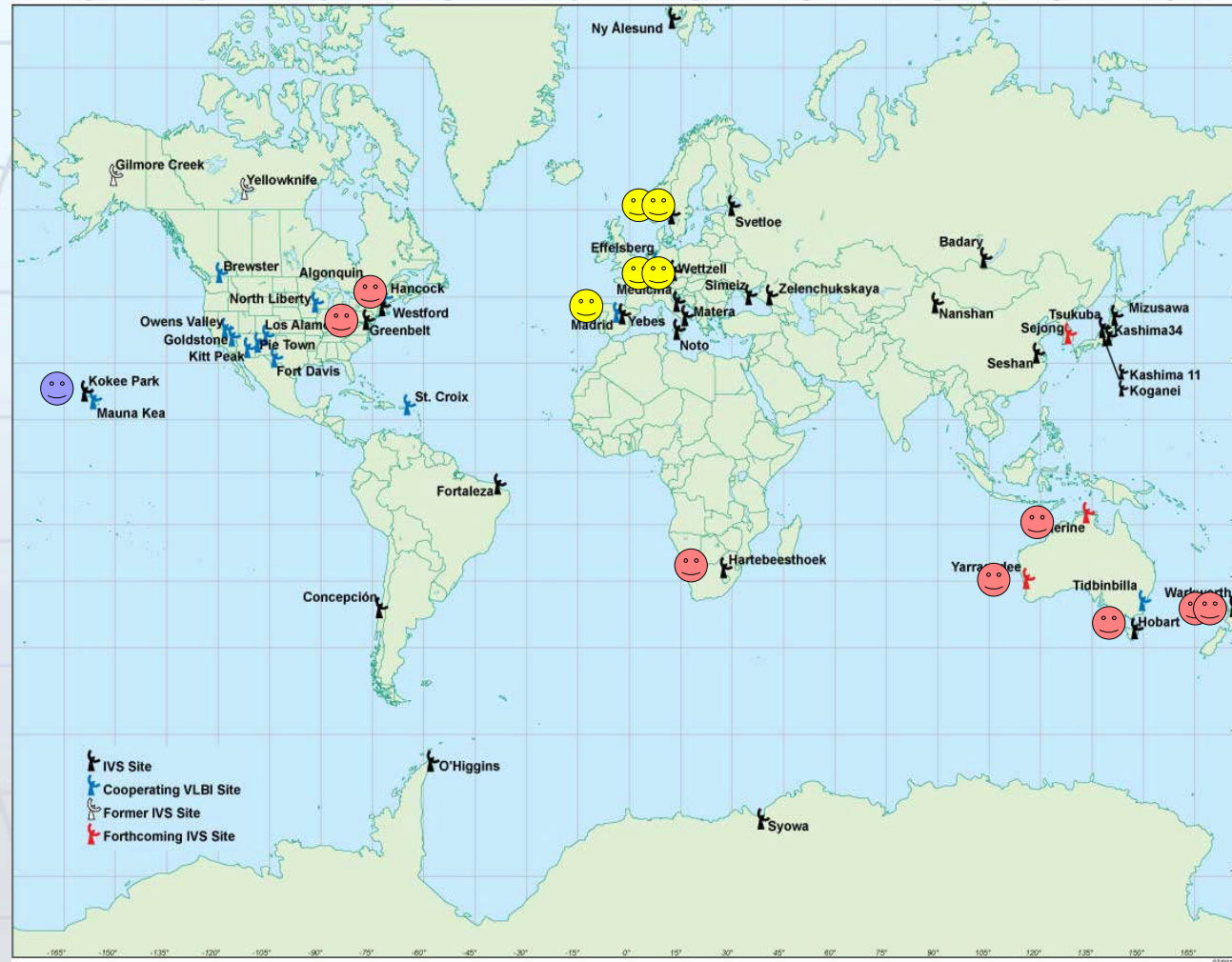
😊 radio telescope

**upgrade legacy**

😊 radio telescope

[Hase et al., 2011]

# VLBI2010 Network in 2013



**VLBI2010 very fast**

😊 radio telescope

😊😊 twin radio telescope

**VLBI2010 fast**

😊 radio telescope

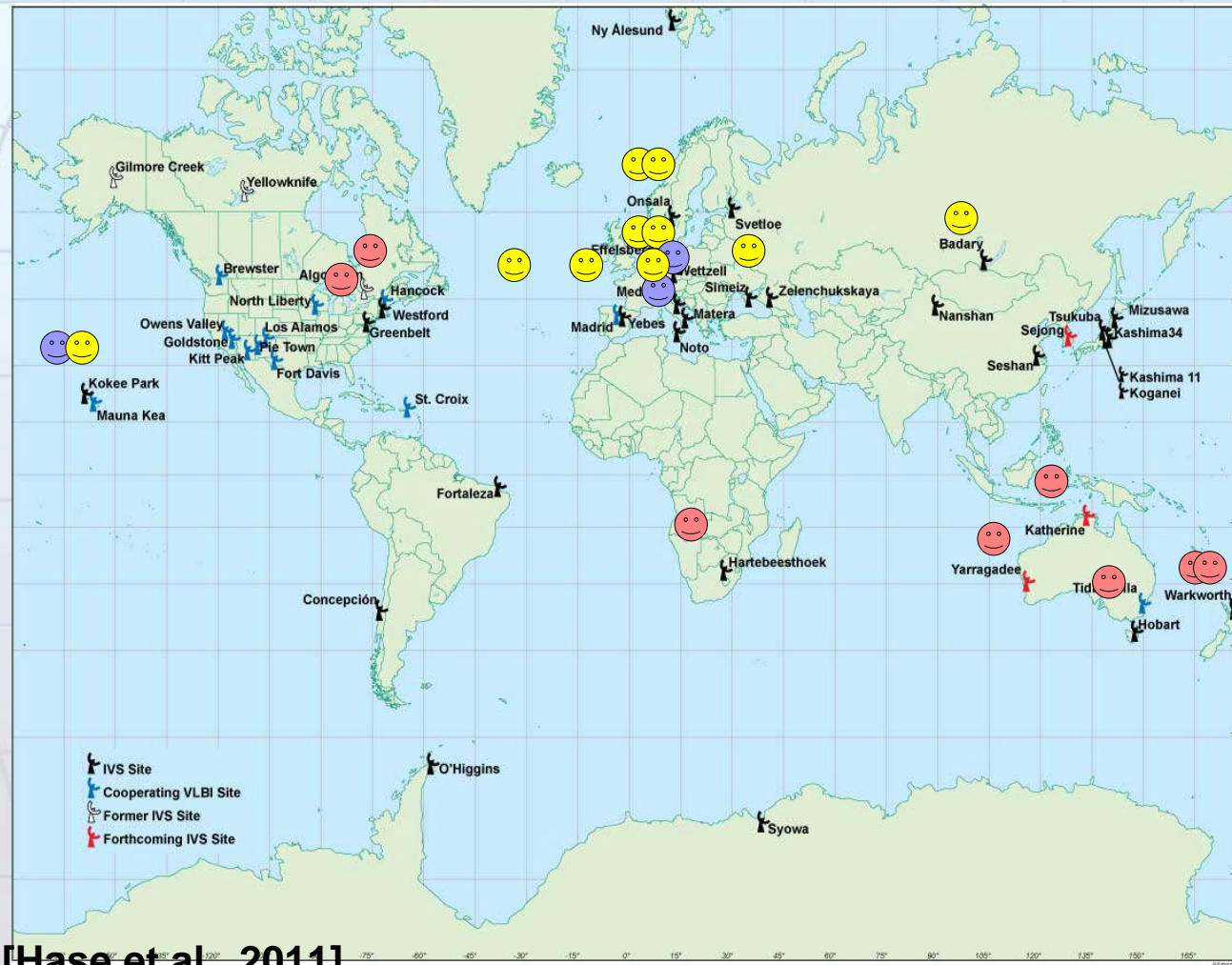
**upgrade legacy**

😊 radio telescope

[Hase et al., 2011]



# VLBI2010 Network in 2014



**VLBI2010 very fast**

☺ radio telescope

☺☺ twin radio telescope

**VLBI2010 fast**

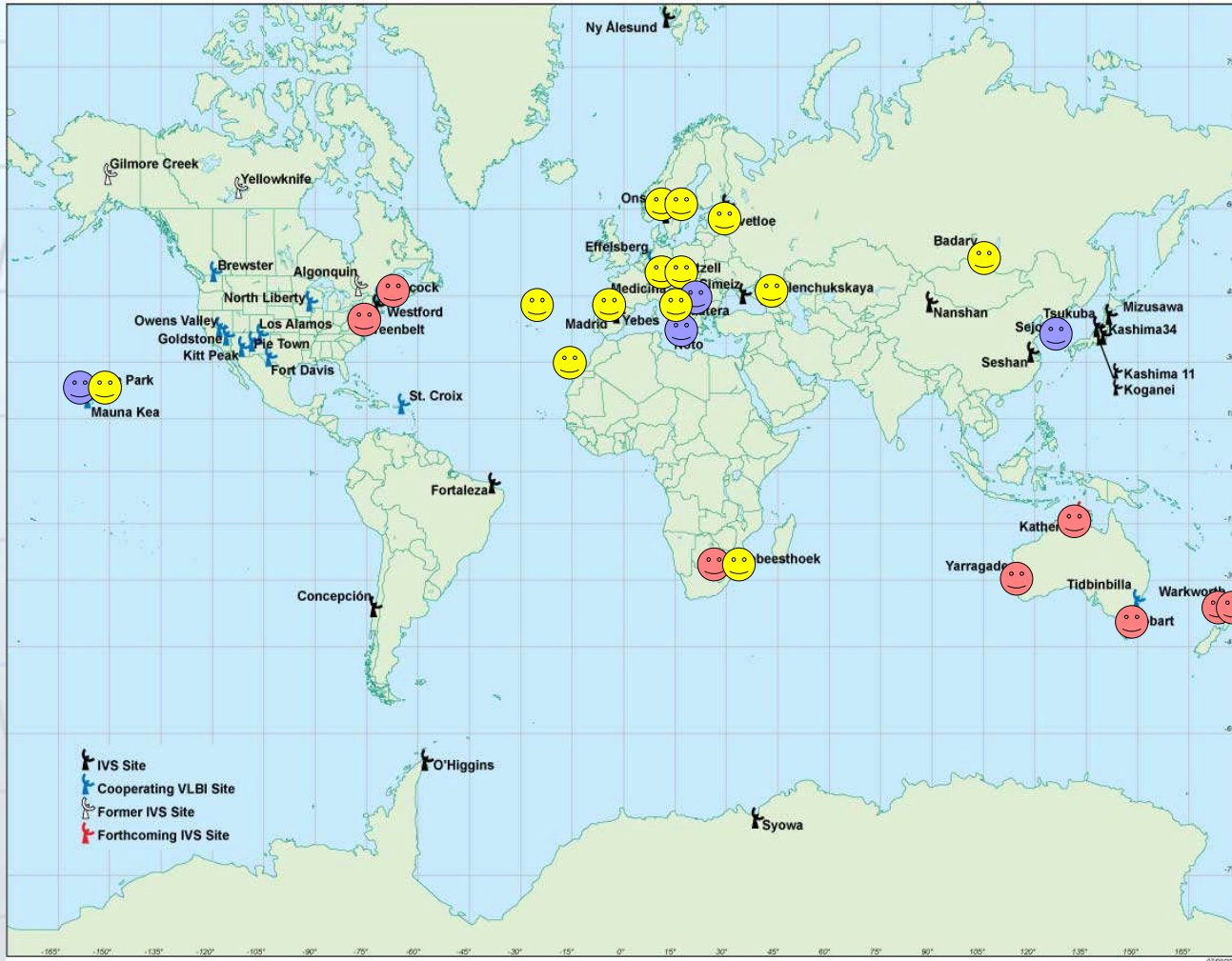
☺ radio telescope

**upgrade legacy**

☺ radio telescope

[Hase et al., 2011]

# VLBI2010 Network in 2015



## VLBI2010 very fast

☺ radio telescope

😊😊 twin radio telescope

## VLBI2010 fast

radio telescope

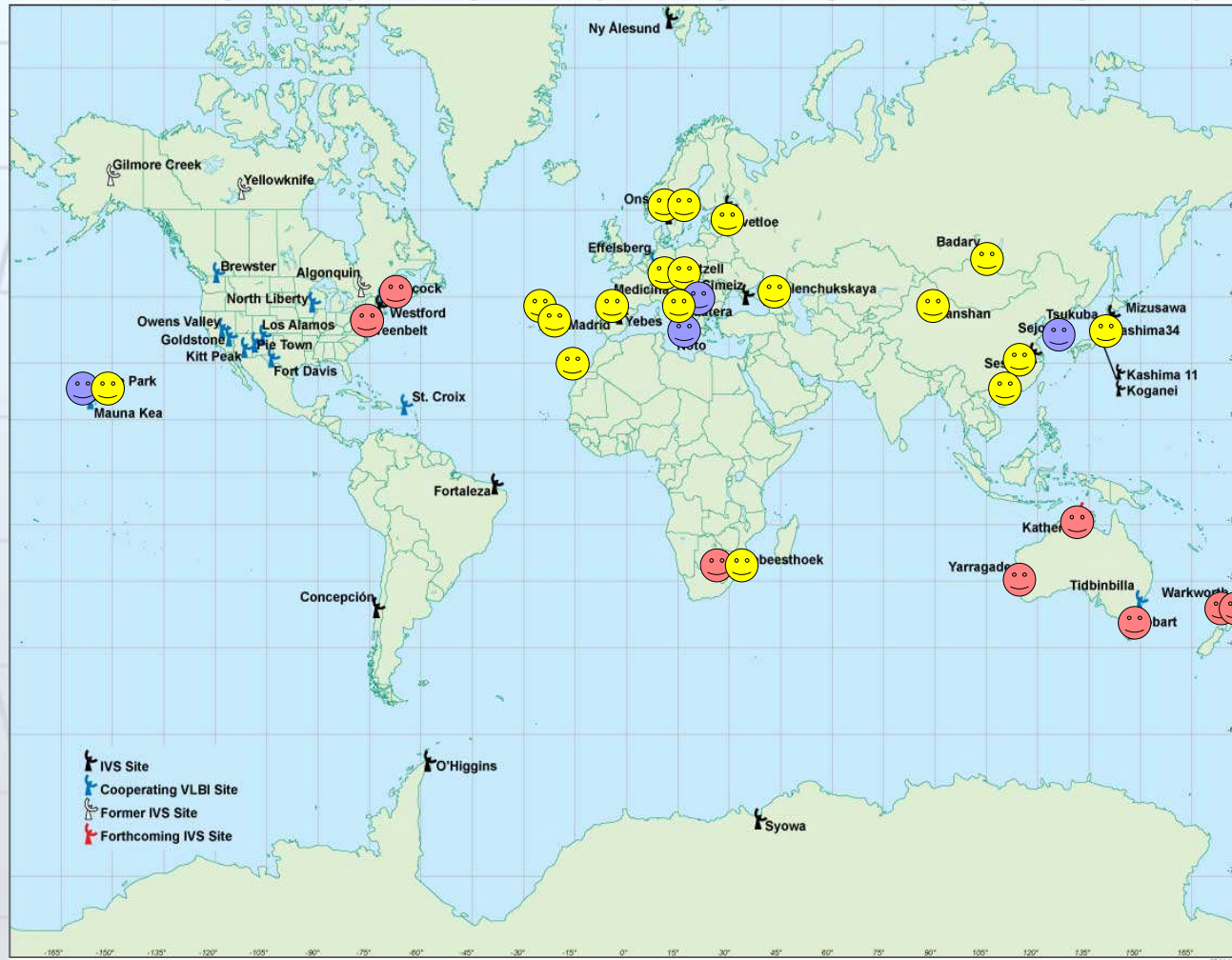
## upgrade legacy

☺ radio telescope

[Hase et al., 2011]



# VLBI2010 Network in 2016



**VLBI2010 very fast**

😊 radio telescope

😊😊 twin radio telescope

**VLBI2010 fast**

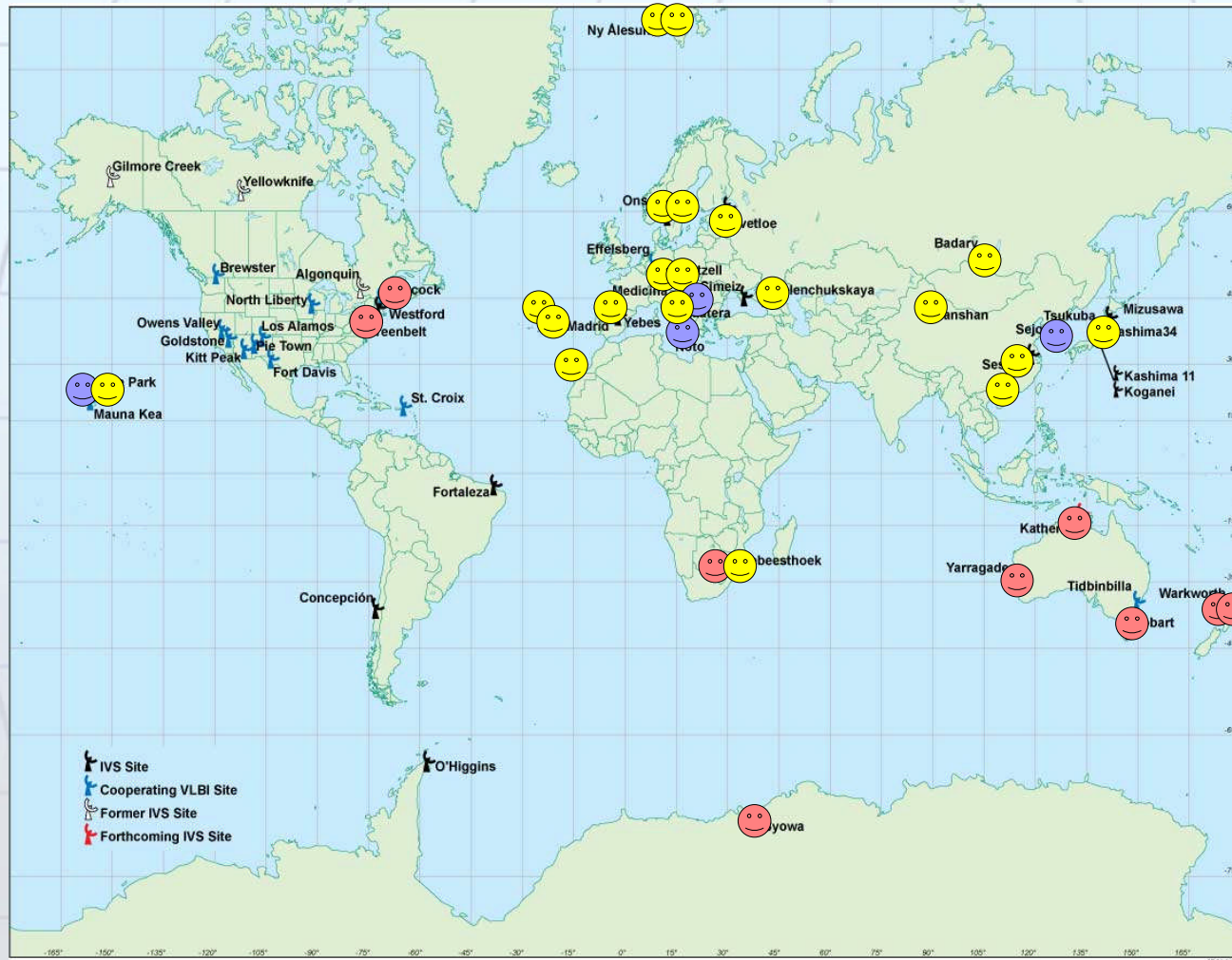
😊 radio telescope

**upgrade legacy**

😊 radio telescope

[Hase et al., 2011]

# VLBI2010 Network in 2017



**VLBI2010 very fast**

😊 radio telescope

😊😊 twin radio telescope

**VLBI2010 fast**

😊 radio telescope

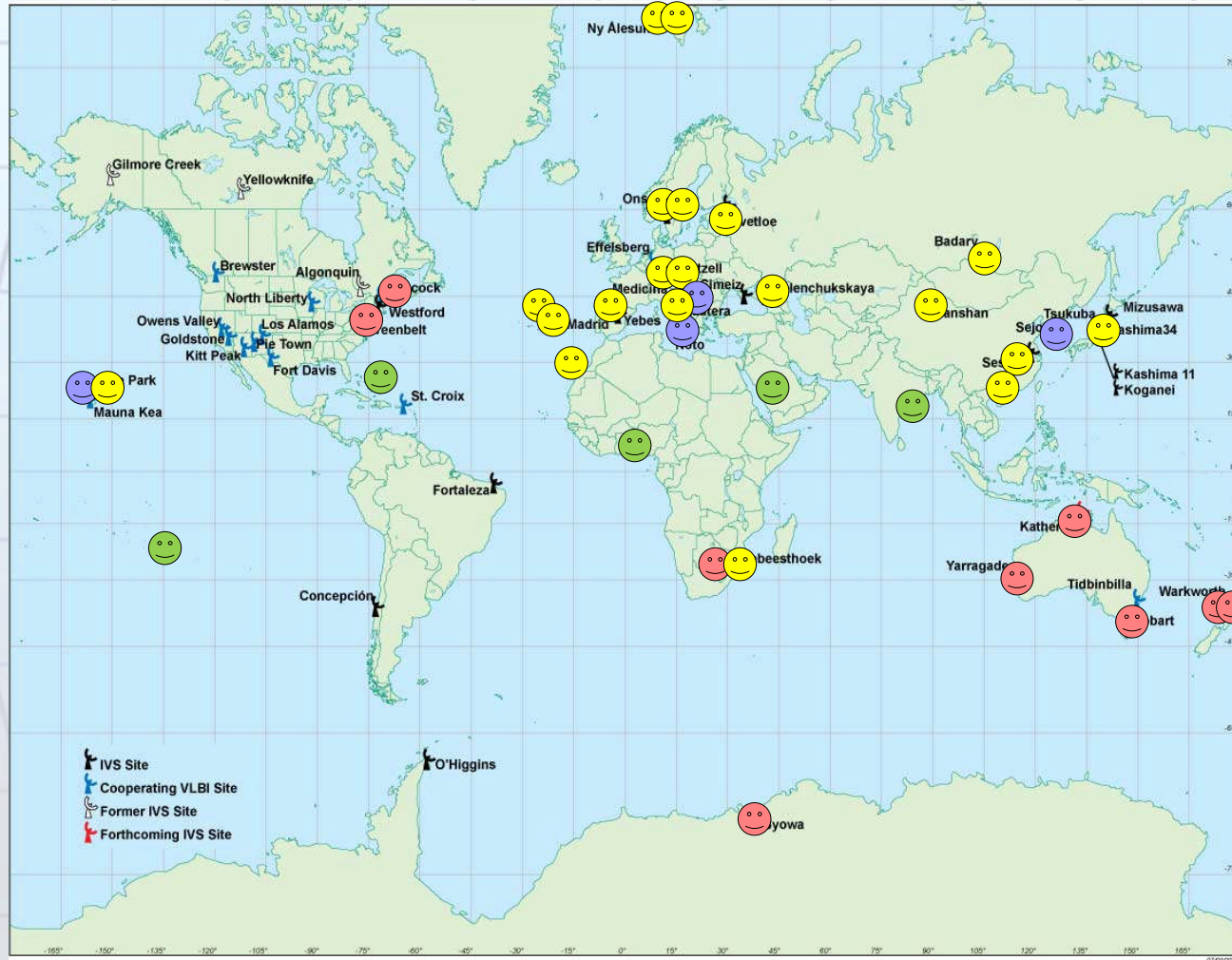
**upgrade legacy**

😊 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. **NEW PERSPECTIVES, e.g. VLBI for Space  
Applications**

# VLBI for space applications



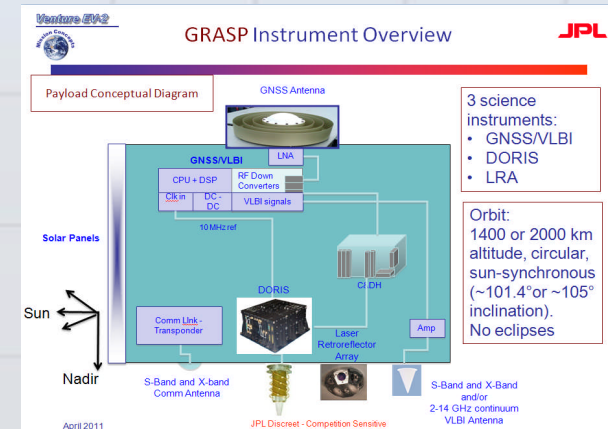
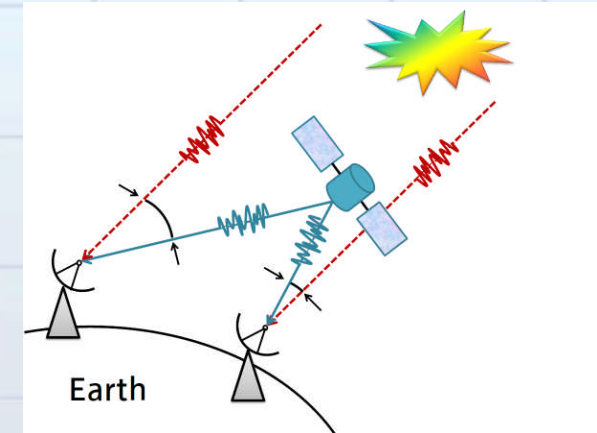
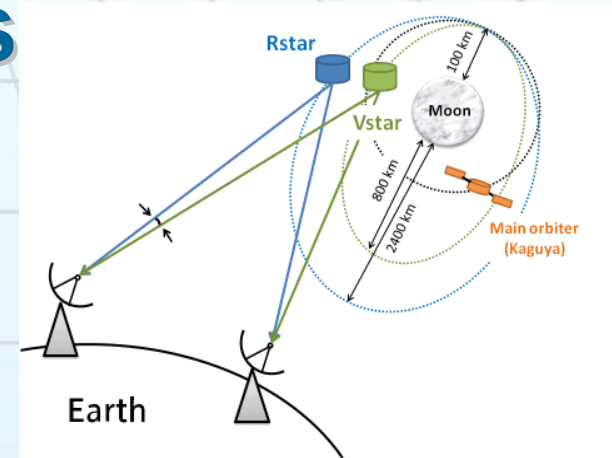
## Satellite VLBI

- Tracking of GNSS satellites (e.g. Tornatore et al., 2010)
- e.g. Geodetic Reference Antenna in Space (GRASP) (Y. Bar-Sever)
- e.g. SC – SC
  - multi-frequency method
  - same beam method
  - e.g. SELENE/Kaguya  
Chang'e lunar missions

Microsatellites for GNSS Earth Monitoring  
(MicroGEM)

## Differential VLBI (D-VLBI)

Quasar – space craft (SC)  
Deep space navigation  
DSN,  $\Delta$ DOR  
NASA, ESA



# Conclusions VLBI2010 and VGOS

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

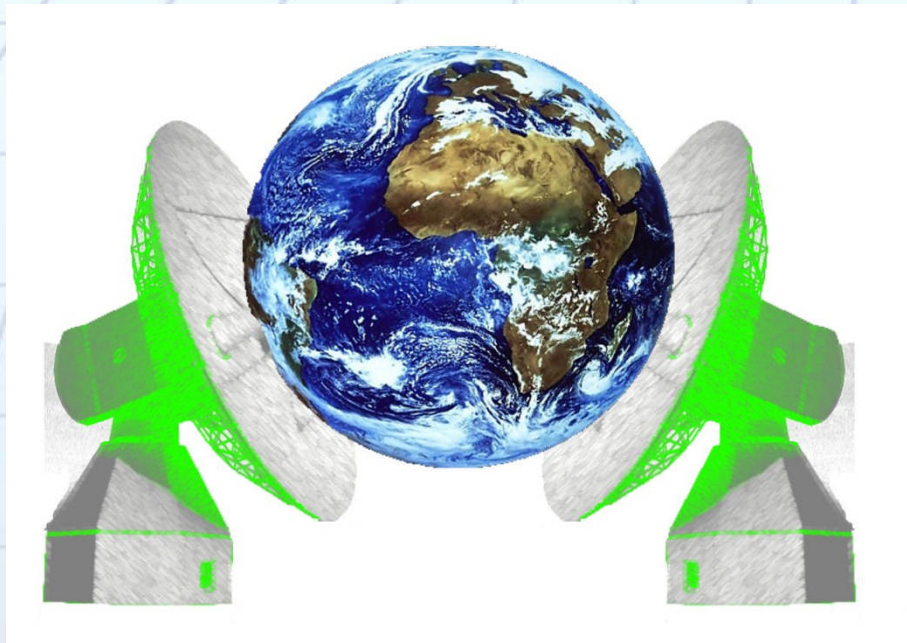


# Concluding remarks

- ⚡ 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]***



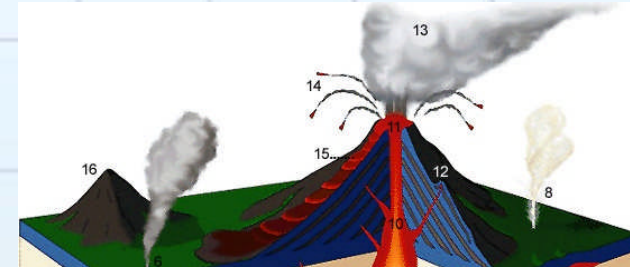
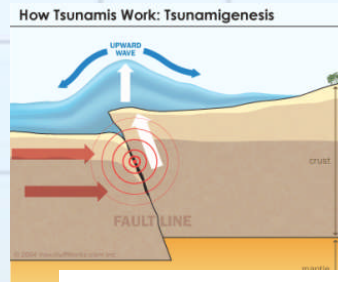


Thank you for  
your attention!

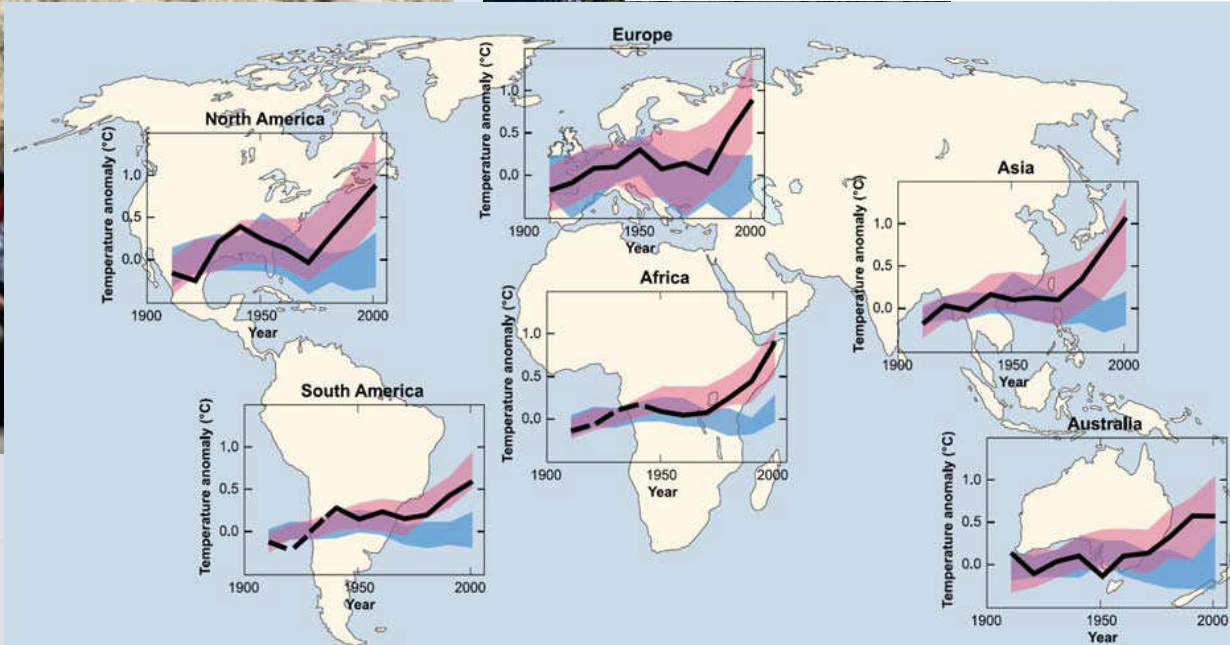
[harald.schuh@tuwien.ac.at](mailto:harald.schuh@tuwien.ac.at)

# New challenges in geoscience

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



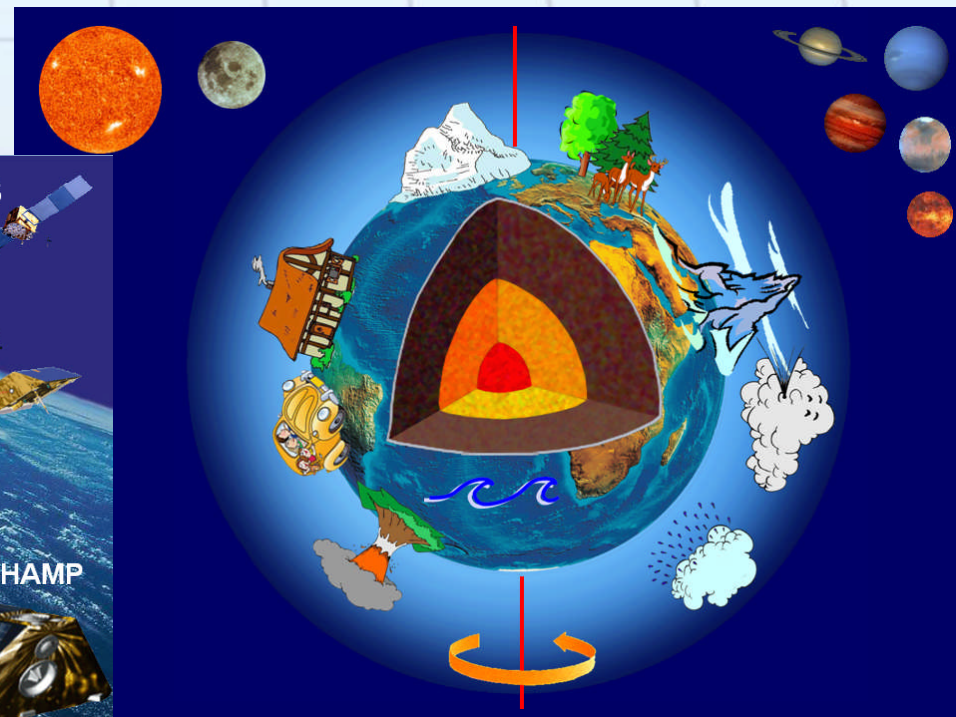
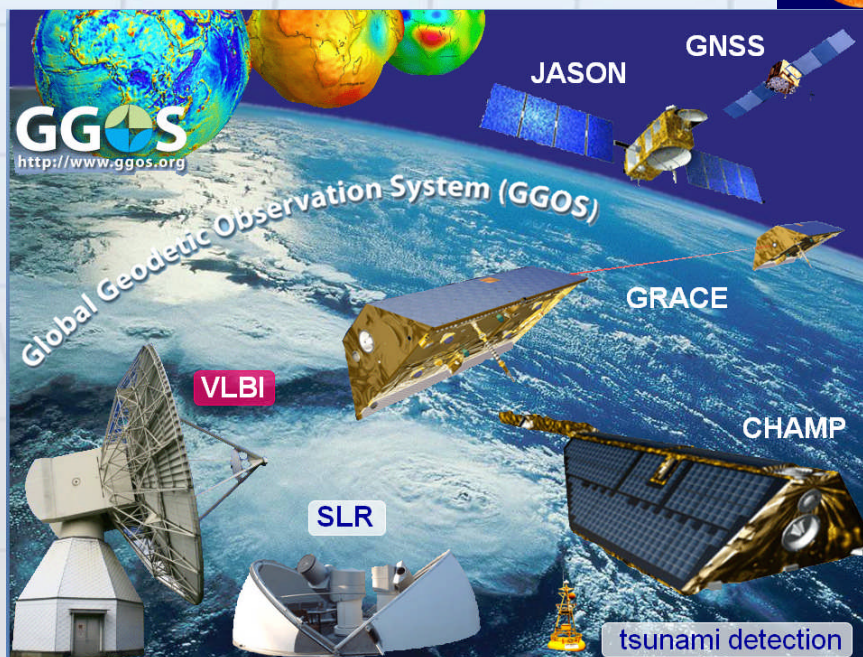
**ipcc**  
INTERGOVERNMENTAL PANEL ON climate change



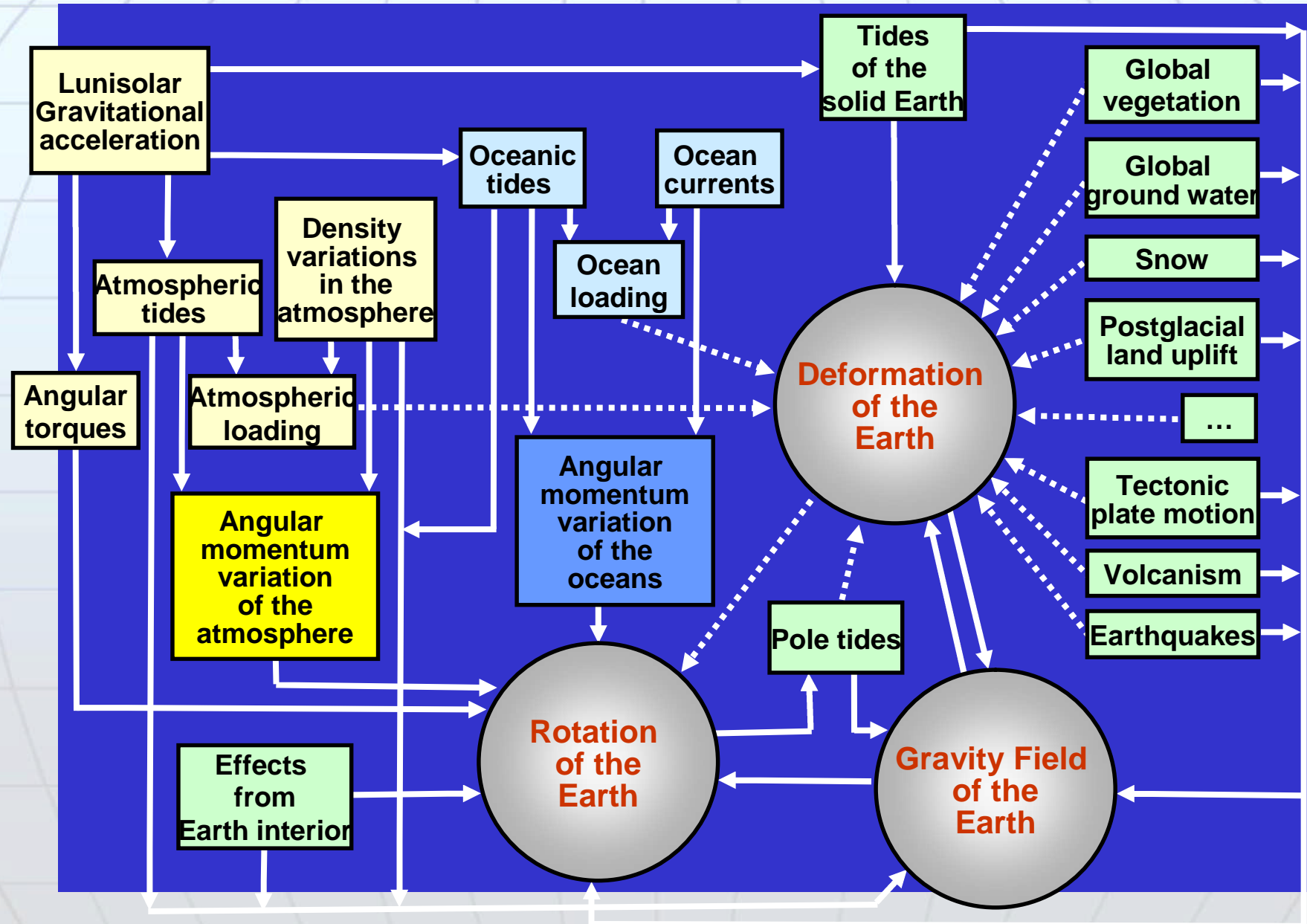


# Approaches

- ⚡ Combination of all available observations in the sense of GGOS
- ⚡ Improve our understanding of the "System Earth"

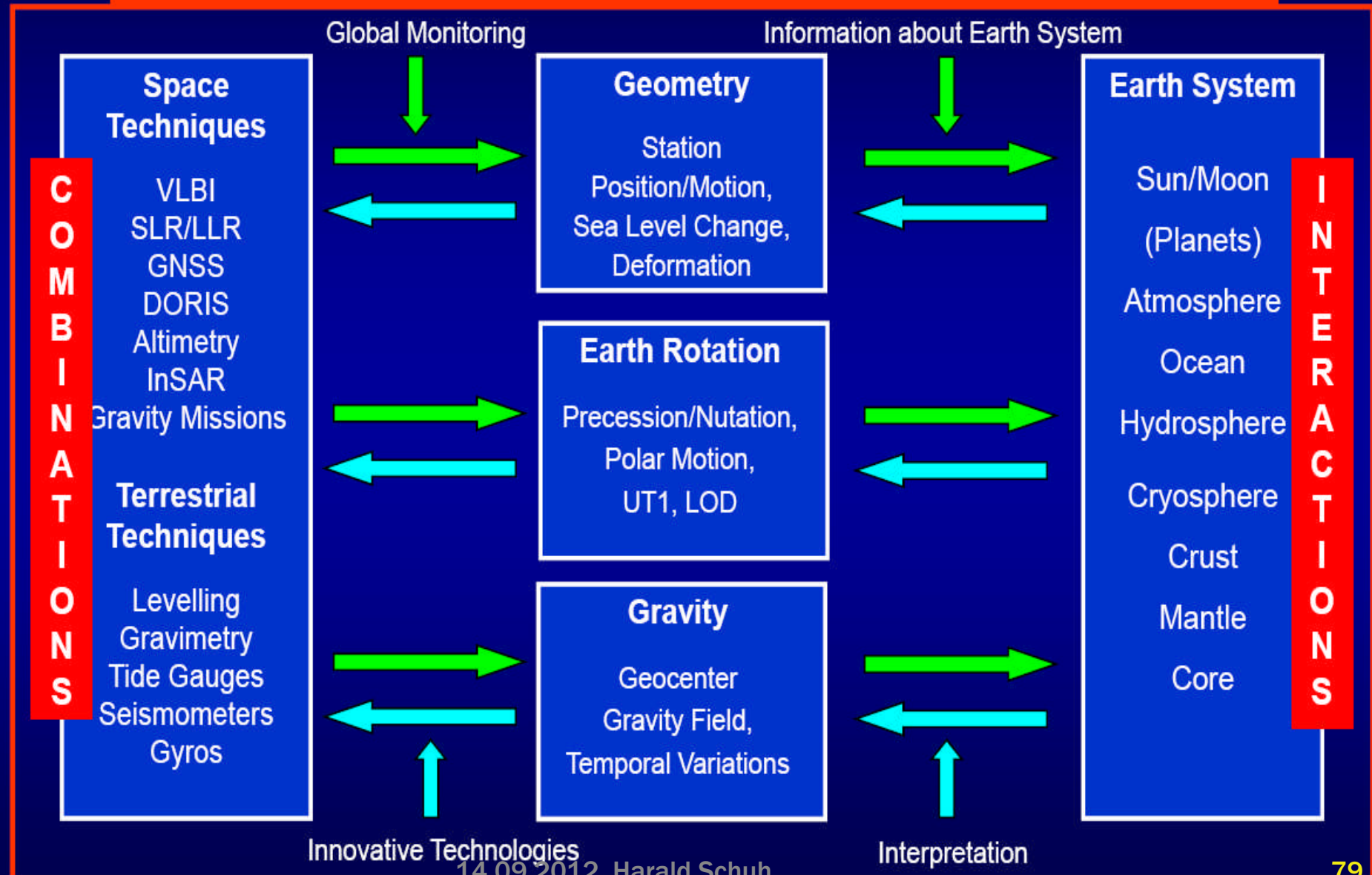


# Model of the Interactions in the Earth System (Schuh, 1995)



# GGOS: Monitoring and Modelling the Earth's System

Reference frames: highest accuracy and long-term stability





# Global 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.

