Session 1: Introduction to 3D Reference Frames / Datums

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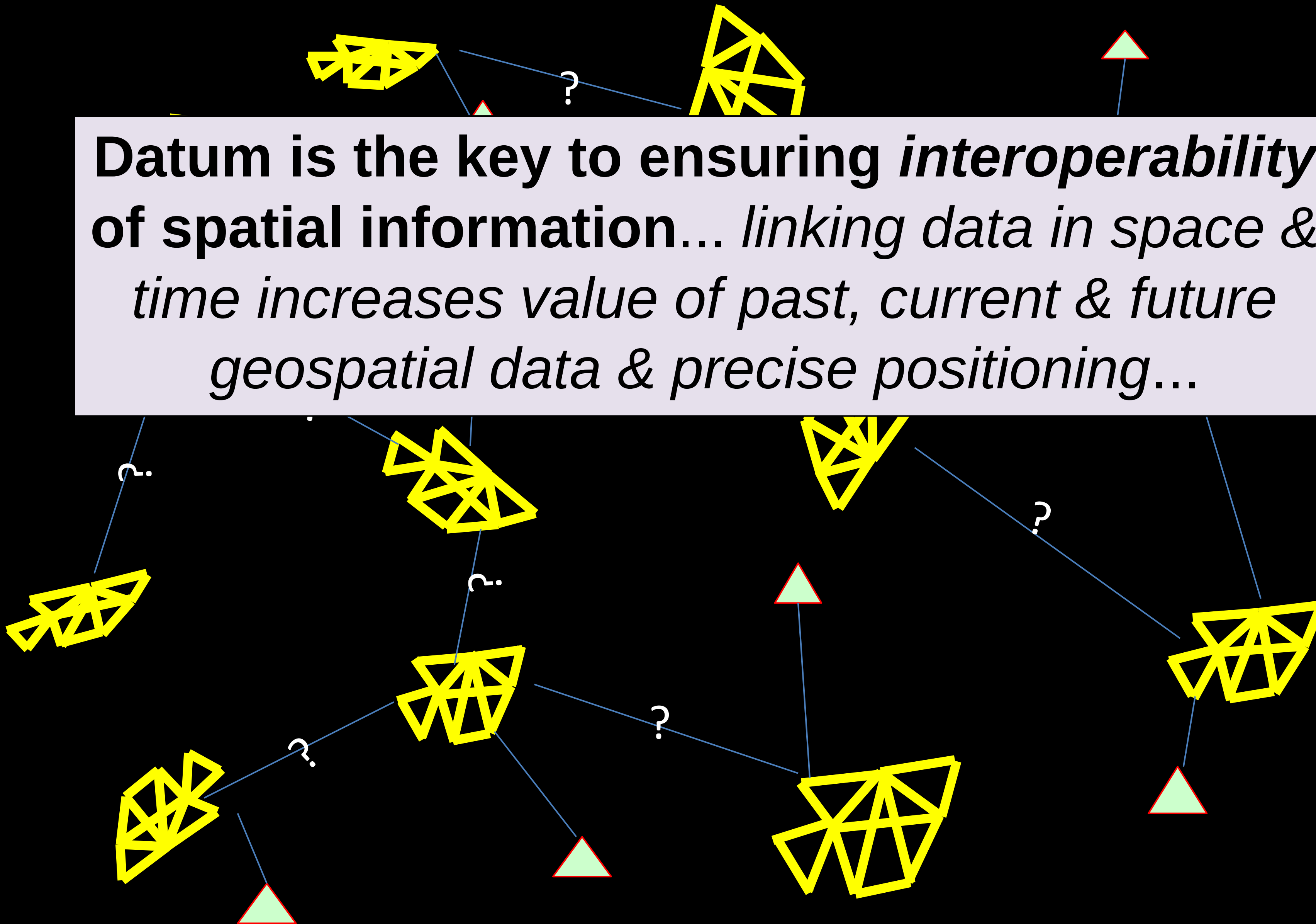
Geodetic framework links networks & points...



Datum is the key to ensuring *interoperability* of spatial information... *linking data in space & time increases value of past, current & future geospatial data & precise positioning*...

“ A middle-aged rocky planet, Earth offers a wondrous combination of interconnected systems. From its molten core below to the ionosphere above, planetary layers interact dynamically, moving constantly, affecting climate and environment, and impacting life of all forms on the planet. Quantifying these changes is essential to understanding the underlying processes well enough to identify their root causes and to anticipate and respond to future changes. **Precise global geodesy is an essential tool to capture these changes.** “ *(my emphasis)*

Committee on the National Requirements for Precision Geodetic Infrastructure; Committee on Seismology and Geodynamics; National Research Council; ISBN 978-0-309-15811-4, 156 pages (2010)

Dual Function of Geodesy...

- Geodesy is the *foundation* for the representation of horizontal & vertical position (& its variation) in global

"System Earth", *and in particular its dynamics (4-D) and geometry/gravity interactions*.

Despite differences in mission requirements of ***Geodetic Science*** *&* ***Geodetic Practice****, the geodetic infrastructure, datums, GNSS technology & methodology can now support* <u>*both*</u> *...*

Space Geodetic Techniques

Global Geodesy

IAG Structure since 2003

International Union of Geodesy and Geophysics (IUGG)

International Association of Geodesy (IAG)

- Council
- Executive Committee
- Bureau
- Office
- COB

Commission 1
Reference Frames

Commission 2
Gravity Field

Commission 3
Earth Rotation & Geodynamics

Commission 4
Positioning & Applications

Inter-Commission Committee on Theory (ICCT)

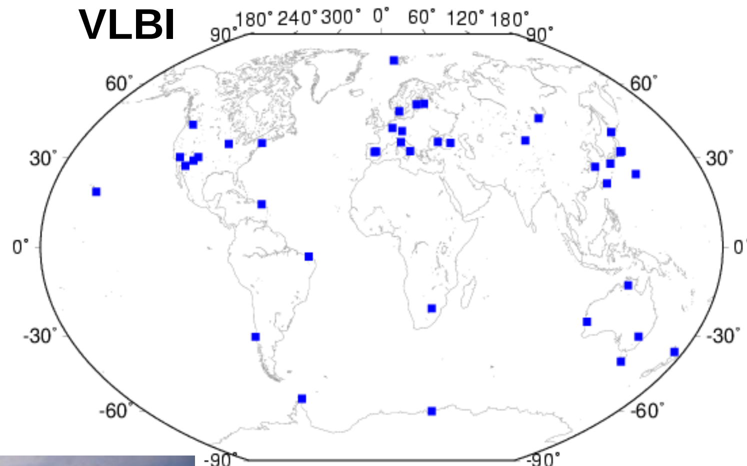
Services: **IERS** **IGS** **IGFS** **BGI** **ICET** **BIPM**

ILRS **IVS** **IDS** **ICGEM** **IGeS** **IDEMS** **PSMSL**

Global Geodetic Observing System (GGOS)

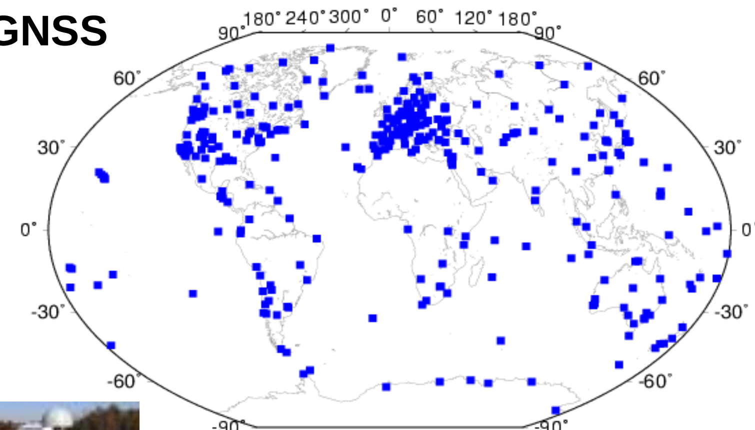
Significant ground-based infrastructure for geometrical services…

VLBI



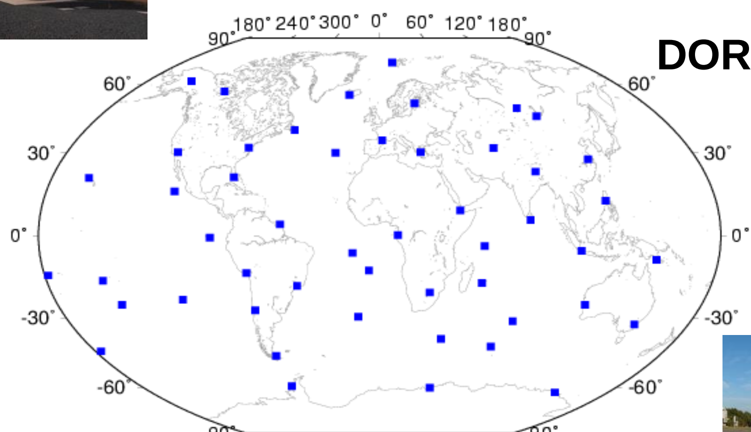
VLBI stations observed in 2011

GNSS



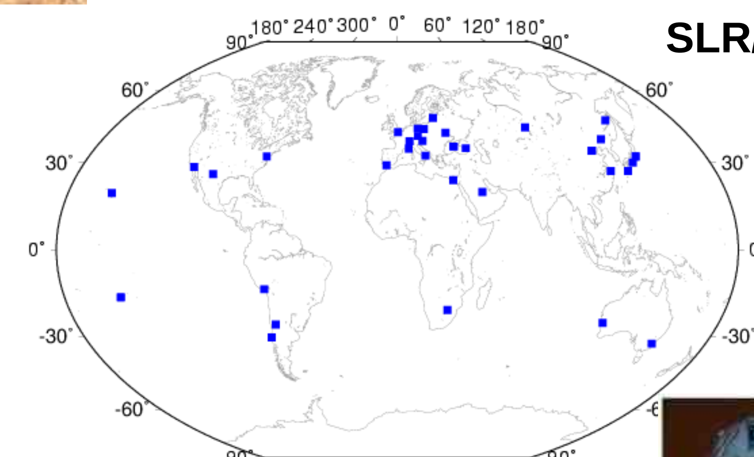
GPS/IGS stations observed in 2011

DORIS



DORIS stations observed in 2011

SLR/LLR



SLR stations observed in 2011

IAG Services

http://www.iag-aig.org

Geometry

IERS: International Earth Rotation and Reference Systems Service

(ILS in 1899, BIH in 1912, IPMS in 1962, IERS in 1987)

IGS: International GNSS Service *(1994)*

IVS: International VLBI Service *(1999)*

ILRS: International Laser Ranging Service *(1998)*

IDS: International DORIS Service *(2003)*

Gravimetry

IGFS: International Gravity Field Service *(2004)*

BGI: Bureau Gravimetrique International *(1951)*

IGeS: International Geoid Service *(1992)*

ICET: International Centre for Earth Tides *(1956)*

ICGEM: International Centre for Global Earth Models *(2003)*

IDEMS: International Digital Elevation Models Service *(1999)*

Ocean

PSMSL: Permanent Service for Mean Sea Level *(1933)*

Std

BIPM: Bureau International des Poids et Mesures *(Time 1875)*

Modern Geodesy's Capabilities

Geodesy **now** defined in terms of the following *capabilities*:

1. Determination of precise global, regional & local 3-D (static or kinematic) *positions on or above the Earth's surface.*
2. Mapping of *land, sea & ice surface geometry*.
3. Determination of the Earth's (time & spatially) *variable gravity field.*
4. Measurement of ***dynamical*** *(4-D) phenomena*:

   - *Solid Earth* *(incl. cryosphere)*: surface deformation, crustal motion, GIA, polar motion, earth rotation, tides, water cycle, mass transport, etc.
   - *Atmosphere*: refractive index, T/P/H profiles, TEC, circulation, etc.
   - *Ocean*: sea level, sea state, circulation, etc.

The Value of Reference Frames to Society (1)

- **Fundamental geoscience**… *solid earth geophysics, atmospheric, cryospheric & oceanographic processes, hydrology*
- **Global Change studies**… *climate change (causes & effects), water cycle & mass transport changes, sea level rise, mesoscale circulation, GIA, polar studies*

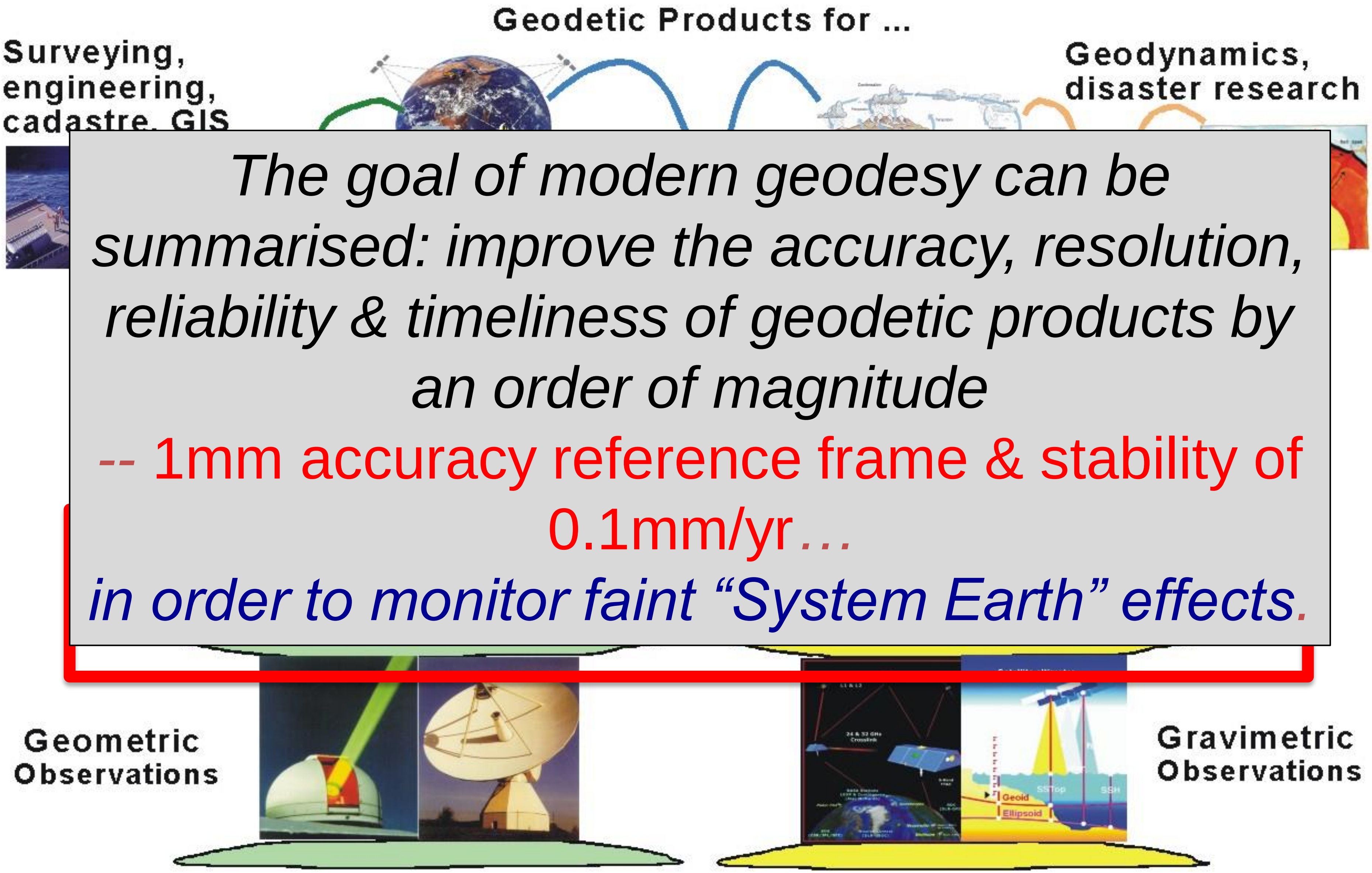
> - Need continuity of ITRF to **very high accuracy**… *to be provided by the full ensemble of **space geodetic techniques***
> - Primary signals are derived from (small) changes or trends in **geodetic parameters**
> - Use GNSS to **connect** to the **ITRF**
> - Extensive use of **IGS products**… *but careful data processing strategies are necessary*

The Value of Reference Frames to Society (2)

- **Geohazard research**… *seismic, volcanic, landslip, storms, sea state, flooding, tsunami, space weather*
- **Geodetic reference frames**… *ITRF, national datums & SDI, gravity, timing*
- **Engineering**… *precise positioning/navigation, atmospheric sounding, geo-referencing platforms, operational geodesy, radar & laser imaging/scanning, engineering geodesy, surveying*

> - ITRF traceability… *"fit for purpose" conditions apply*
> - Long-term **stability** not necessarily important for many applications
> - Use **GNSS** to connect to the national or local datum, and used for densification
> - Extensive use of IGS & national/local **CORS** data… *simplified data processing tools are often adequate*

Monitoring Geometric & Gravimetric Signatures



The goal of modern geodesy can be summarised: improve the accuracy, resolution, reliability & timeliness of geodetic products by an order of magnitude

-- 1mm accuracy reference frame & stability of 0.1mm/yr…

in order to monitor faint "System Earth" effects.

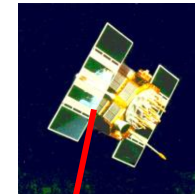
ITRF: Implications for Geodetic Science & Geodetic Practice

- Today's geodetic technologies, infrastructure, services & methodologies are so powerful that **motion** of every point on the Earth's surface is *measurable*
- GNSS *both* **defines** ITRF & allows easy **connection** to ITRF/datum
- Global Change studies demand monitoring of geodetic time-series against the **highest accuracy/stability ITRF**
- Time-varying coordinates are the "signal" for the geosciences, however they are "noise" (or nuisance) for the geospatial community and positioning/navigation users in general
- Datums based on ITRF by defining a Ref Epoch <u>and</u> (traceable) connection provided via (mainly) GNSS CORS or groundmarks
- ***Recognition by UN-GGIM of the importance of the GGRF, geodetic infrastructure & open data policies***

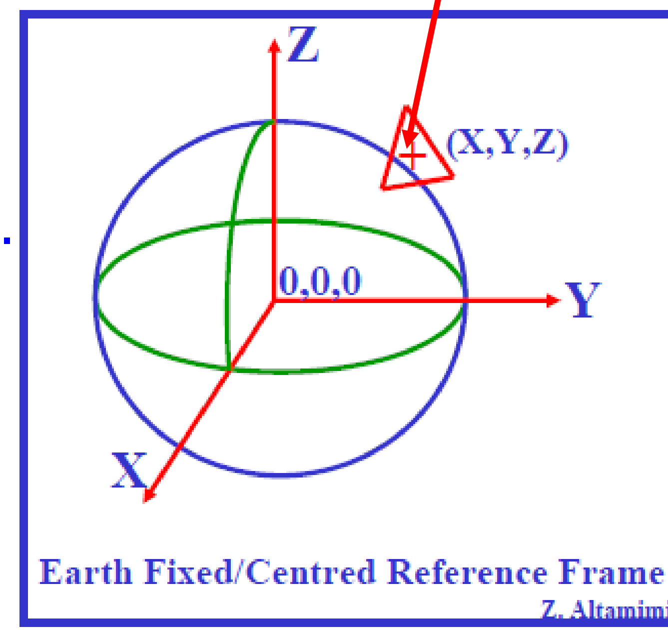
Global Reference Systems & Frames

A Modern GGRF... *such as the ITRF*

- ECEF RF: allows determination of station position wrt stable continuously maintained GGRF
- All geocentric datums directly or indirectly aligned with ITRF, now maintained by the IAG Services
- All points, objects, geodetic control marks, GNSS CORS or geodetic observatories on the surface of the Earth **move** (i.e. 4D coordinates):
  – Crustal motion
  – Local deformation
  – Ground subsidence or uplift
  … etc
- It is now easy to **connect** to the ITRF... *several GNSS techniques give ITRF coordinates directly*
- **It has never been easier to build an ITRF-based national datum**



Origin, Scale & Orientation



http://www.iers.org

http://itrf.ign.fr

GPS/GNSS Global Satellite Datums

- Satellite orbits are naturally related to the *Geocentre*, and computed in a Cartesian system oriented by the Earth's rotational motion... *this is the class of* ***Earth Centred Earth Fixed*** *(ECEF) terrestrial datums...*
- *Datum defined* by the coordinates of CORS:
  - official GPS* ground tracking/monitoring stns ("Control Segment" – CS)
  - other ground network (e.g. IGS CORS)
- *Realised* by the GNSS ephemerides:
  - **broadcast**... (<1m accuracy) computed by the CS
  - **precise**... (few cms accuracy) computed by non-CS (e.g. IGS, or commercial services)
- Accessed by either:
  - **Relative positioning**... connecting to terrestrial points (e.g. CORS)
  - **Point positioning**... PPP *almost* same accuracy as DGNSS

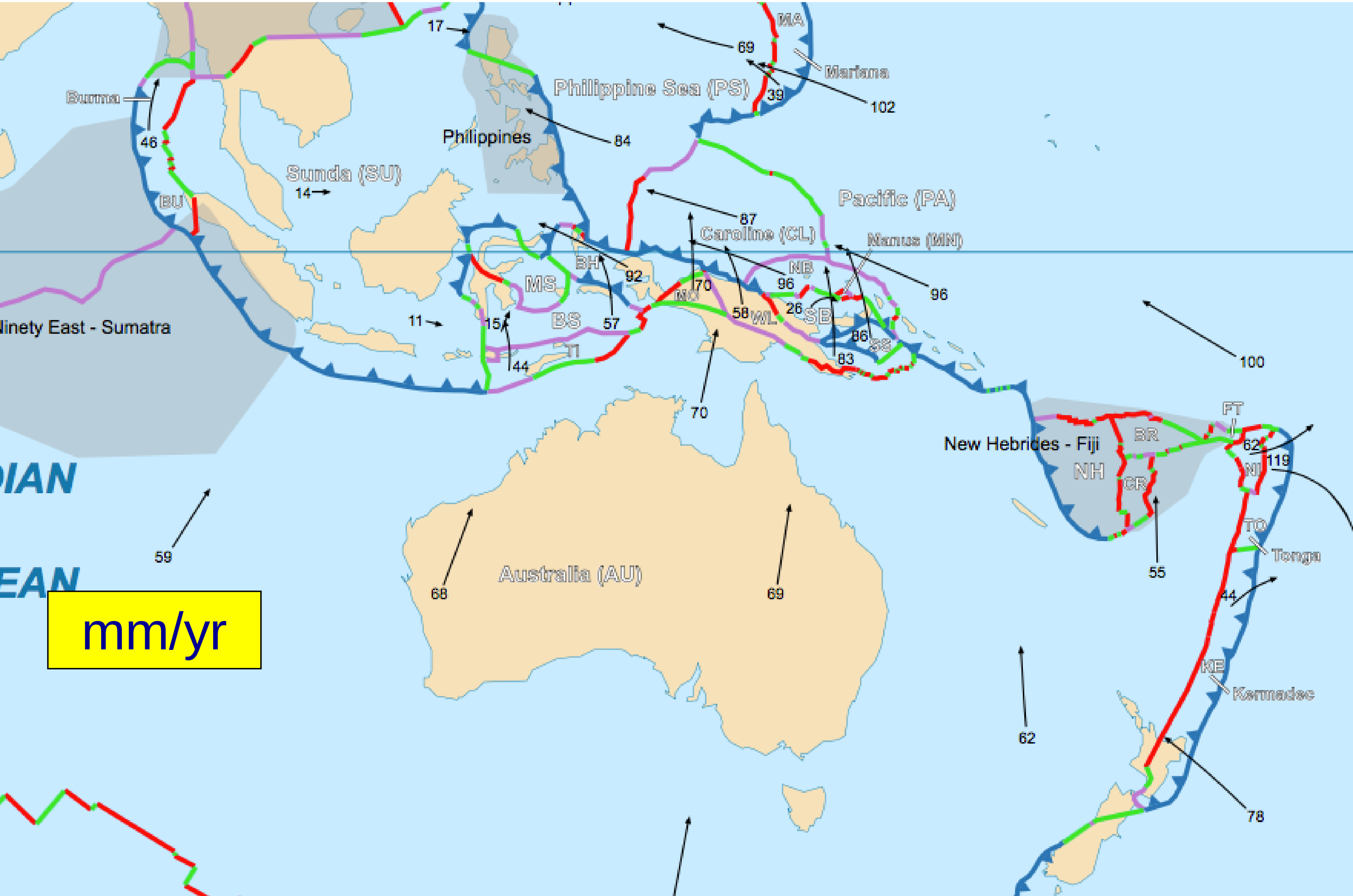
* GLONASS, Galileo, BeiDou have different GNSS datums defined also by their own CS

WGS84, ITRF2014, GDA94

- The official GPS* datum is the ECEF World Geodetic System 1984 (**WGS84**) -- datum for satellite coordinates transmitted in Navigation Message... *GPS SPP results are expressed in WGS84 only at few metre level of accuracy*
- Most accurate & stable ECEF reference system is the **ITRS** -- realised by coordinates in **ITRFyy** frame (e.g. **ITRF2014**) and IGS precise ephemeris, *hence geodetic GNSS is related to ITRFyy, & provides basis of modern geodetic datums, but is not a "plate-fixed" datum*... *also used in PPP techniques*
- Many national datums such as the Geocentric Datum of Australia (**GDA94**) are ECEF-type datums (at an epoch date) determined using GNSS (& other) techniques, hence *all **relative** positioning in Australia using GDA94 geodetic control points result in coordinates in this datum... typically do NOT incorporate station velocities, as such datums are "plate-fixed"*

* GLONASS, Galileo, BeiDou have different GNSS datums defined also by their own CS

Earth-Fixed or Plate-Fixed?



The WGS84 Datum (1)

ECEF Cartesian system defined by a global set of U.S. National Geospatial-Intelligence Agency (NGA) (formerly NIMA, formerly the Defense Mapping Agency) satellite tracking stations

- Maintained by the *assigned* Cartesian coordinates of the tracking stations in the GPS **Control Segment**
- Transferred to the satellite ephemerides during the *orbit determination process* carried out by the **Master Control Station**
- Uploaded to the satellites and broadcast to users in the **Navigation Message**
- Ultimately *realised* anywhere on Earth by the GPS single point positioning (SPP) coordinates, ***but accuracy is only few metres***

http://en.wikipedia.org/wiki/WGS84

The WGS84 Datum (2)

The general user often accepts GPS coordinates "in the WGS84 datum"... not aware of the issues or relationships with other, more precise datums

- In mid-1994 WGS84 was re(de)fined to align it with ITRF91 (at decimetre level) -- *WGS84(G730)*, at the beginning of 1997 WGS84 was again re(de)fined to align it with ITRF94 (sub-decimetre level) – *WGS84(G873)*, at the beginning of 2002 realigned to ITRF2000 (cm level) – *WGS84(G1150)*, in Feb 2012 realigned to ITRF2008 (cm level) – *WGS(G1674),* in Oct 2013 realigned again – *WGS(G1762)*
- WGS84 datum changes station coordinates each year to account for tectonic motion, hence epoch is "yyyy.5", e.g. for 2015 it is "2015.5"
- Nowadays an ITRF coord (easy to determine) can be used as a surrogate for a WGS84 coord (impossible to determine with high accuracy)

http://www.unoosa.org/pdf/icg/2012/template/WGS_84.pdf

http://www.ga.gov.au/earth-monitoring/geodesy/geodetic-datums/other/wgs84.html

The WGS84 Datum (3)

NGA.STND.0036_1.0.0_WGS84 2014-07-08

Table 2.2 WGS 84 (G1762) Cartesian Coordinates* and Velocities for Epoch 2005.0

Station Location	NGA Station Number	X (m)	Y (m)	Z (m)	$\dot{X}$ (m/yr)	$\dot{Y}$ (m/yr)	$\dot{Z}$ (m/yr)
Air Force Stations							
Colorado Springs	85128	-1248599.695	-4819441.002	3976490.117	-0.0146	0.0009	-0.0049
Ascension	85129	6118523.866	-1572350.772	-876463.909	-0.0002	-0.0057	0.0110
Diego Garcia	85130	1916196.855	6029998.797	-801737.183	-0.0448	0.0176	0.0331
Kwajalein	85131	-6160884.028	1339852.169	960843.154	0.0201	0.0663	0.0295
Hawaii	85132	-5511980.264	-2200246.752	2329481.004	-0.0098	0.0628	0.0320
Cape Canaveral	85143	918988.062	-5534552.894	3023721.362	-0.0126	0.0016	0.0011
NGA Stations							
Australia	85402	-3939182.512	3467072.917	-3613217.139	-0.0409	0.0030	0.0485
Argentina	85403	2745499.034	-4483636.563	-3599054.496	0.0045	-0.0079	0.0085
England	85404	4011440.890	-63375.739	4941877.084	-0.0127	0.0168	0.0101
Bahrain	85405	3633910.105	4425277.147	2799862.517	-0.0324	0.0096	0.0270
Ecuador	85406	1272867.304	-6252772.044	-23801.759	0.0067	0.0013	0.0108
US Naval Observatory	85407	1112158.852	-4842855.557	3985497.029	-0.0150	-0.0001	0.0024
Alaska	85410	-2296304.083	-1484805.898	5743078.376	-0.0222	-0.0068	-0.0086
New Zealand	85411	-4749991.001	520984.518	-4210604.147	-0.0219	0.0127	0.0205
South Africa	85412	5066232.068	2719227.028	-2754392.632	-0.0012	0.0197	0.0168
South Korea	85413	-3067863.250	4067640.938	3824295.770	-0.0263	-0.0091	-0.0094
Tahiti	85414	-5246403.943	-3077285.338	-1913839.292	-0.0422	0.0515	0.0327

Notes: * Coordinates are at the Antenna Reference Points.

Reference http://earth-info.nga.mil/GandG/sathtml/ for current values

ITRS & ITRF

ITRS / ITRF

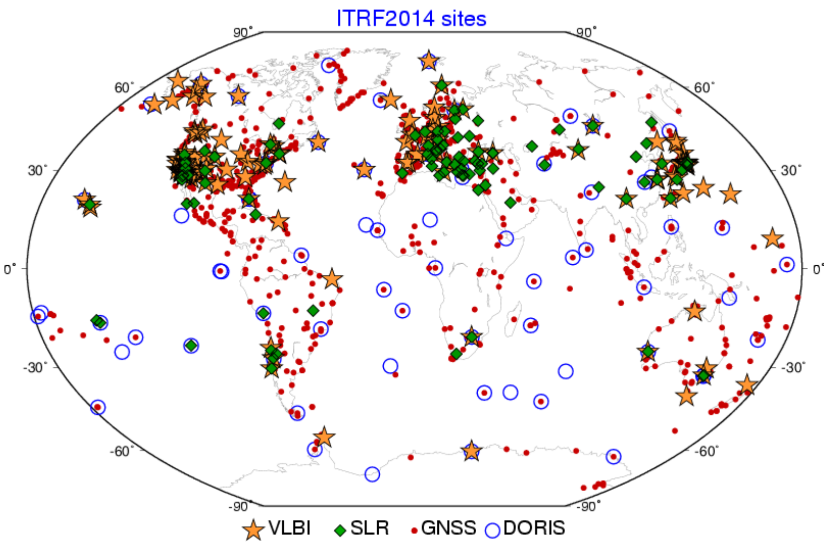
- **International Terrestrial Reference System** (ITRS) & the **International Terrestrial Reference Frame** (ITRF) are maintained by the "International Earth Rotation & Reference System Service" (IERS) (http://www.iers.org)
- Definition of Earth-fixed (i.e. mantle-fixed) ITRS:
  - *Origin* coincides with the Geocentre (Earth centre-of-mass)
  - Orientation of *fundamental plane*:
    Earth's mean equator for the period 1900-1905
  - Direction of *principal direction*:
    intersection of plane through Greenwich and equatorial plane

- In practice realised by observed positions *and* motions (i.e. 4D) of global network of geodetic observatories and permanent GNSS tracking stations
- There are different coordinate & velocity sets representing different realisations of ITRS, e.g. ITRF92, ITRF94, 2000, 2005, 2008, 2014 (http://itrf.ensg.ign.fr/)



International Terrestrial Reference System

- Realised and maintained by IAG & IAU Product Centre of the **International Earth Rotation & Reference Systems Service** (IERS)
- ITRS **realisation** is the "International Terrestrial Reference Frame" (ITRFyy) ("yy" is year of computation, not necessarily coordinate/datum Ref Epoch
- **Individual** TRF solutions ("SINEX" files) from VLBI, SLR, GNSS and DORIS services
- Set of station positions and velocities, estimated by **combination** of VLBI, SLR, GNSS and DORIS TRF solutions
- Need <u>all</u> space geodetic techniques, *and based on co-location sites*, i.e. **cannot use GNSS alone**... GNSS is also for densification of, or connection to, ITRF



Past: **ITRF92,..., 2000, 2005, 2008**

Current: **ITRF2014**

http://www.iers.org

http://itrf.ign.fr

Space Geodetic Techniques for RF

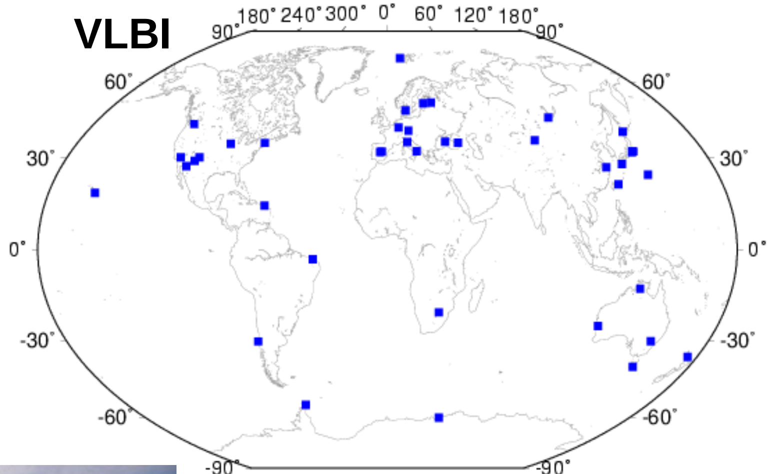
Contribution of Geodetic Techniques to the ITRF

Mix of techniques is fundamental to realise a RF that is stable in origin, scale, & with sufficient coverage...

Technique Signal Source Obs. Type	VLBI Microwave Quasars Time difference	SLR Optical Satellites Two-way absolute range	GNSS Microwave Satellites One-way, range difference	DORIS
Celestial Frame & UT1	Yes	No	No	No
Polar Motion	Yes	Yes	Yes	Yes
Scale	Yes	Yes	No (but maybe in the future!)	Yes
Geocentre ITRF Origin	No	Yes	Future	Future
Geographic Density	No	No	Yes	Yes
Real-time & ITRF access	Yes	Yes	Yes	Yes
Decadal Stability	Yes	Yes	Yes	Yes

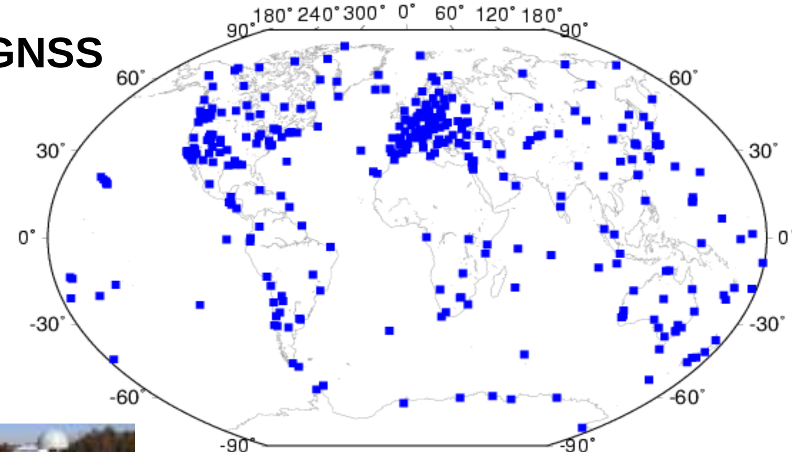
Space Geodesy Networks

VLBI



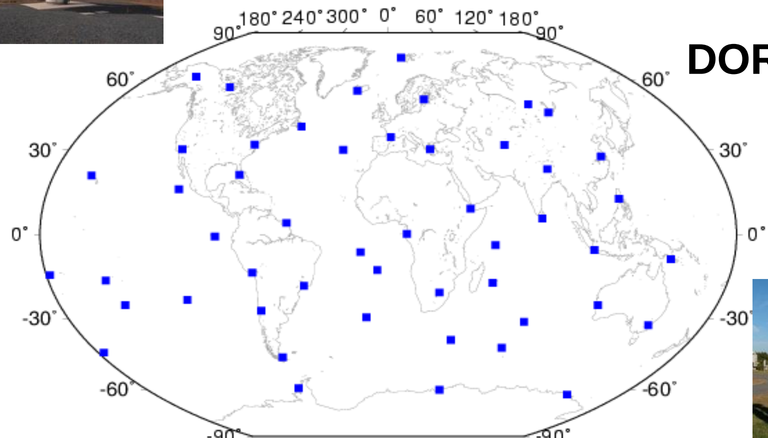
VLBI stations observed in 2011

GNSS



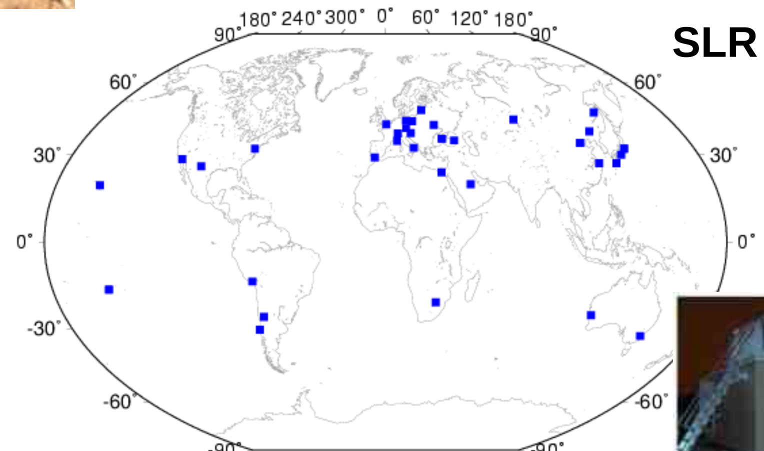
GPS/IGS stations observed in 2011

DORIS



DORIS stations observed in 2011

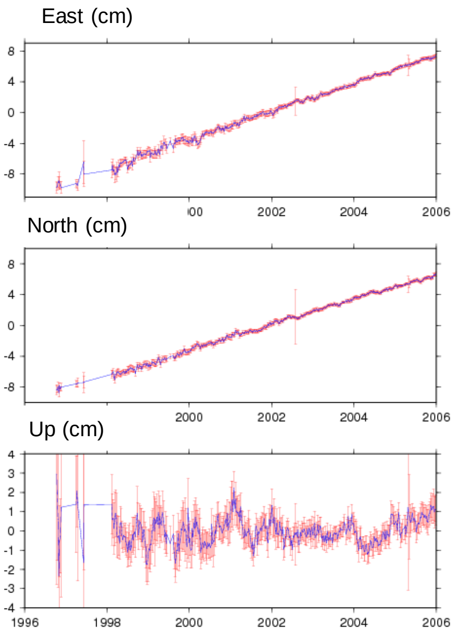
SLR

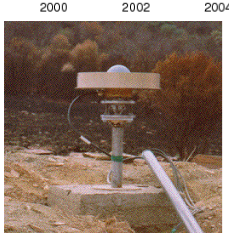


SLR stations observed in 2011

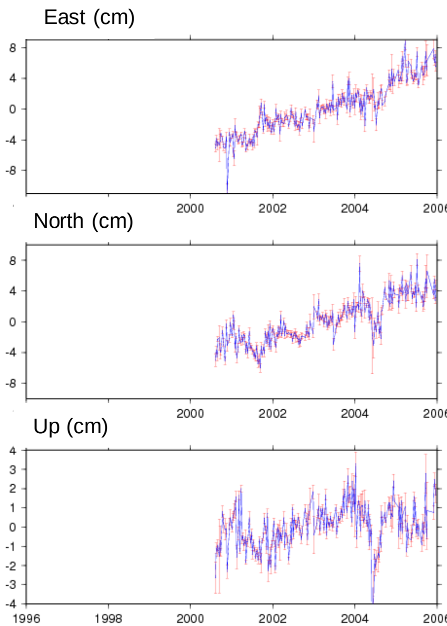
Input Data: Station Position Time Series

GNSS

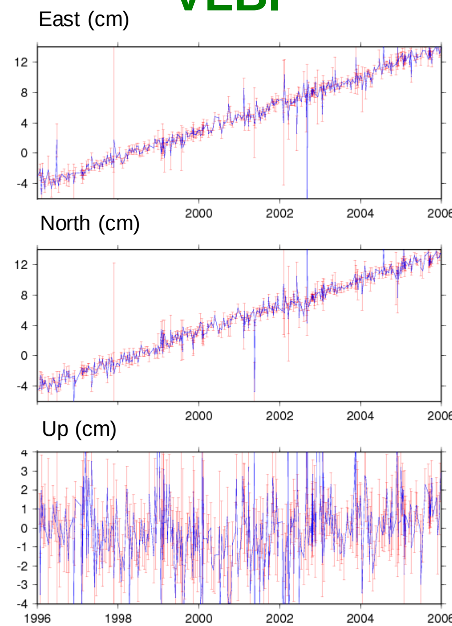




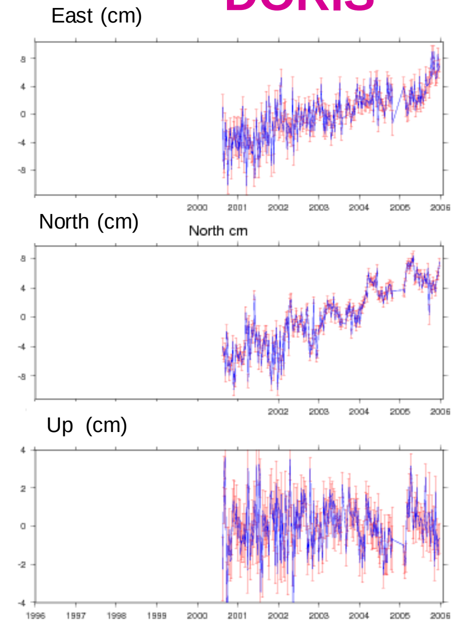
SLR



VLBI



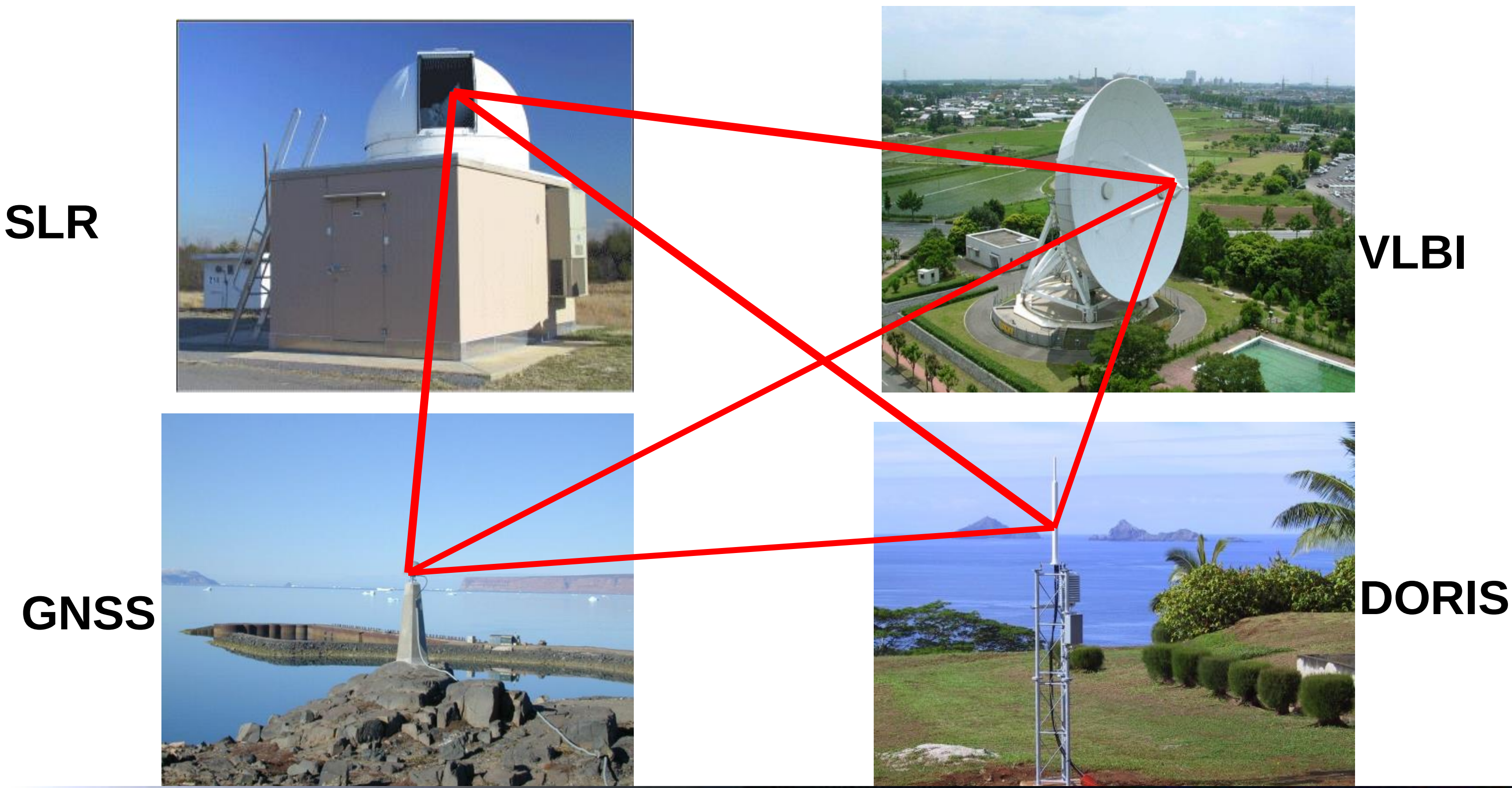
DORIS



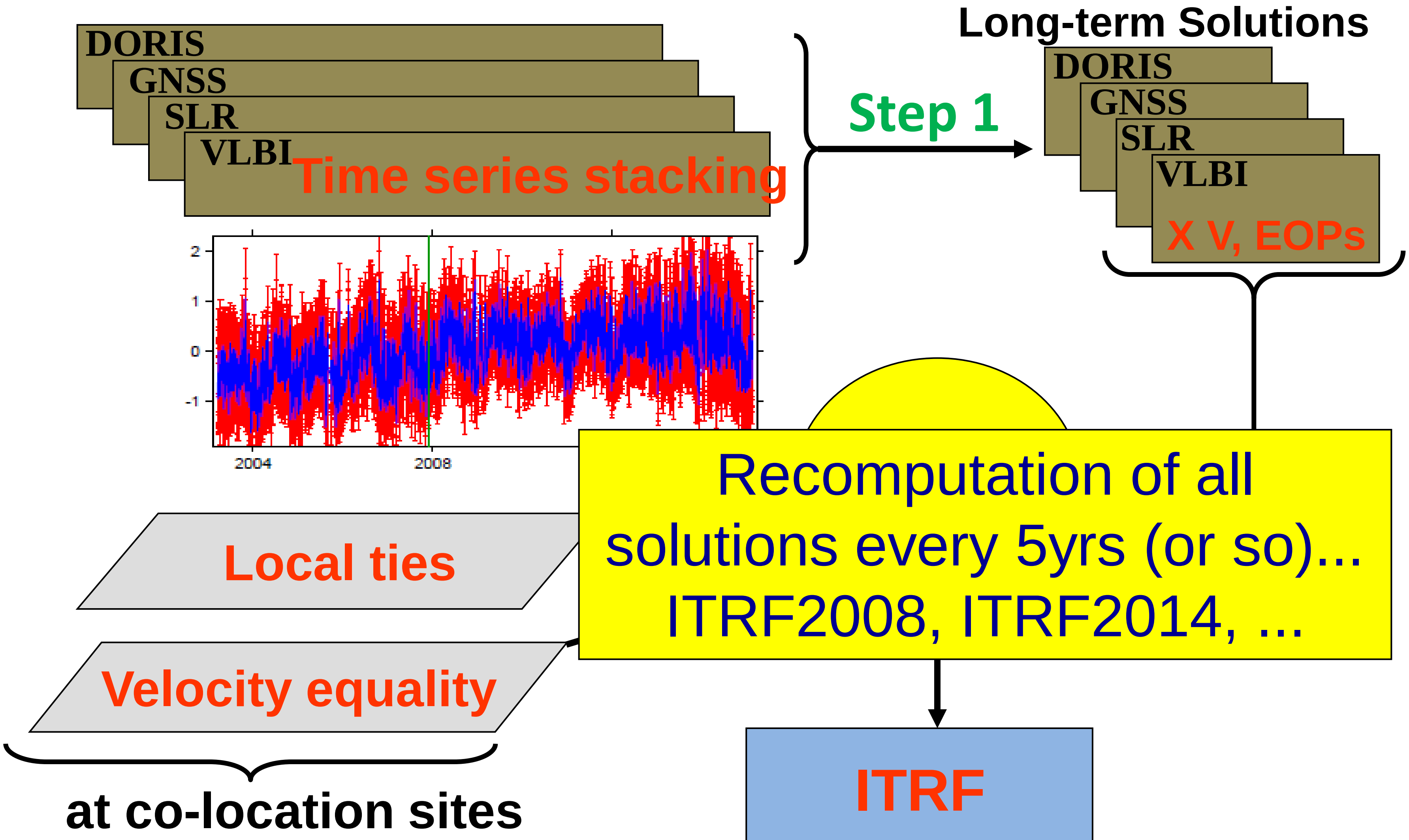
Co-location Sites for ITRF

- Site where two or more space geodetic instruments are operating
- Surveyed in 3D, using terrestrial tie observations or relative GNSS
- DX, DY, DZ (connection baselines) are computed

$$DX_{(GPS,VLBI)} = X_{VLBI} - X_{GPS}$$



ITRF Construction



ITRF2014 material: Zuheir Altamimi, Paul Rebischung, Laurent Métivier, Xavier Collilieux

$$X_{t1} = X_{t0} + (t_1 - t_0)_{yrs}.V_x$$

$$Y_{t1} = Y_{t0} + (t_1 - t_0)_{yrs}.V_y$$

$$Z_{t1} = Z_{t0} + (t_1 - t_0)_{yrs}.V_z$$

ITRF2008 STATION POSITIONS AT EPOCH 2005.0 AND VELOCITIES
IGS STATIONS

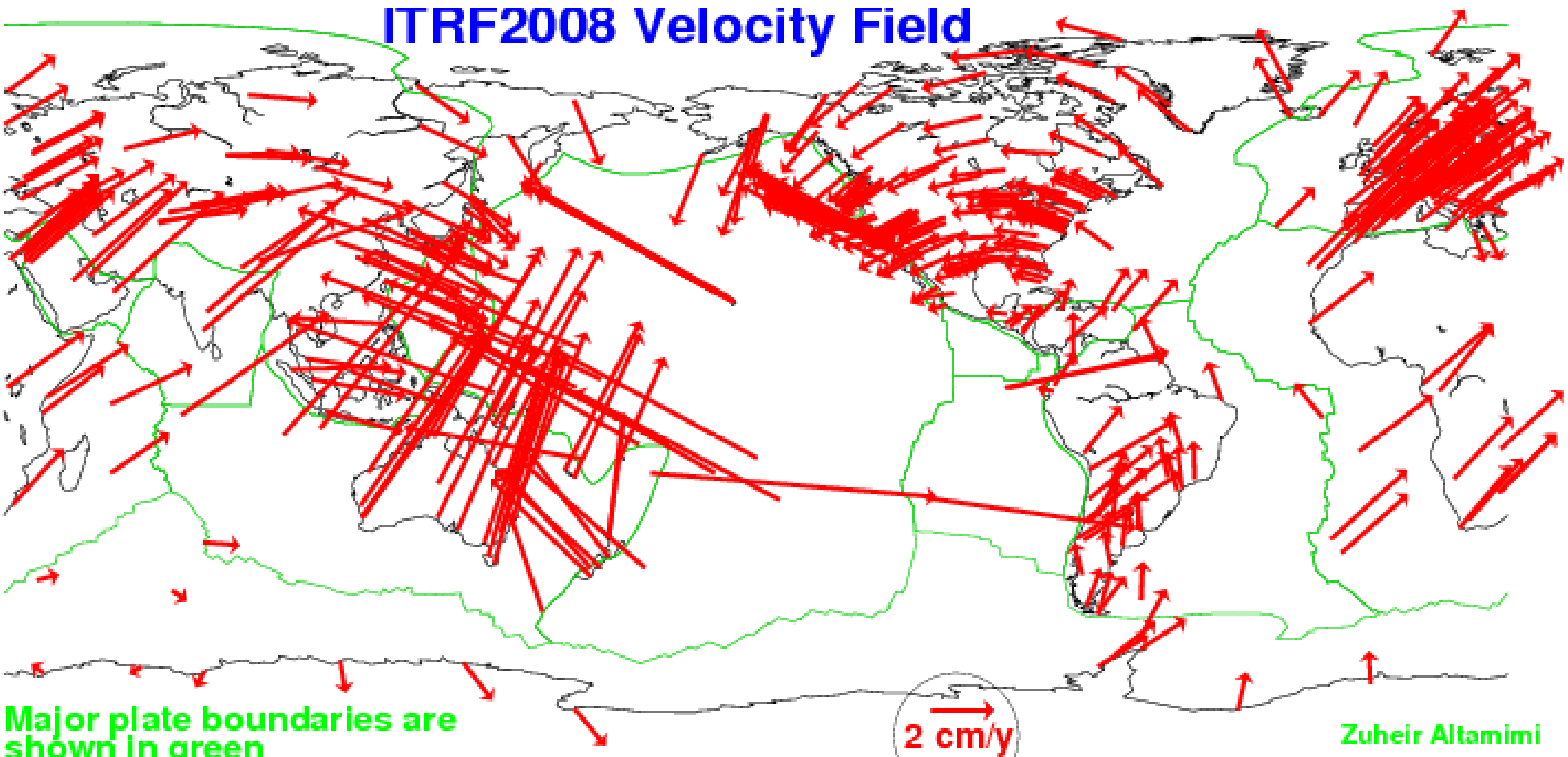
DOMES NB.	SITE NAME	TECH.	ID.	X/Vx	Y/Vy	Z/Vz	Si					
				-----------------------m/m/y	-----------							
50209M001	Auckland	GNSS	AUCK	-5105681.181	461564.035	-3782181.485	0.001					
50209M001				-.0235	-.0024	0.0325	.0001	.0000	.0001			
50209M001	Auckland	GNSS	AUCK	-5105681.175	461564.031	-3782181.482	0.001	0.001	0.001	2	05:307:14940	00:000:00000
50209M001				-.0235	-.0024	0.0325	.0001	.0000	.0001			
50212S001	Dunedin	GNSS	DUNT	-4393728.889	725060.333	-4550896.392	0.001	0.001	0.001	1	00:000:00000	04:358:53943
50212S001				-.0160	0.0352	0.0224	.0001	.0000	.0001			
50212M001	Dunedin	GNSS	OUSD	-4387888.657	733421.168	-4555178.372	0.001	0.001	0.001	1	00:000:00000	04:358:53943
50212M001				-.0160	0.0352	0.0224	.0001	.0000	.0001			
50212S001	Dunedin	GNSS	DUNT	-4393728.892	725060.332	-4550896.390	0.001	0.001	0.001	2	04:358:53943	00:000:00000
50212S001				-.0160	0.0352	0.0224	.0001	.0000	.0001			
50212M001	Dunedin	GNSS	OUSD	-4387888.659	733421.167	-4555178.370	0.001	0.001	0.001	2	04:358:53943	06:170:25200
50212M001				-.0160	0.0352	0.0224	.0001	.0000	.0001			
50212M001	Dunedin	GNSS	OUSD	-4387888.678	733421.163	-4555178.390	0.001	0.001	0.001	3	06:170:25200	07:364:00000
50212M001				-.0160	0.0352	0.0224	.0001	.0000	.0001			
50212M001	Dunedin	GNSS	OUSD	-4387888.697	733421.166	-4555178.408	0.001	0.001	0.001	4	07:364:00000	00:000:00000
50212M001				-.0160	0.0352	0.0224	.0001	.0000	.0001			
50212M002	Dunedin	GNSS	OUS2	-4387890.825	733420.410	-4555176.345	0.001	0.001	0.001	1	00:000:00000	01:286:00000
50212M002				-.0160	0.0352	0.0224	.0001	.0000	.0001			
50212M002	Dunedin	GNSS	OUS2	-4387890.826	733420.412	-4555176.343	0.001	0.001	0.001	2	01:286:00000	04:358:53943
50212M002				-.0160	0.0352	0.0224	.0001	.0000	.0001			
50212M002	Dunedin	GNSS	OUS2	-4387890.828	733420.410	-4555176.340	0.001	0.001	0.001	3	04:358:53943	06:239:79200
50212M002				-.0160	0.0352	0.0224	.0001	.0000	.0001			
50212M002	Dunedin	GNSS	OUS2	-4387890.829	733420.405	-4555176.342	0.001	0.001	0.001	4	06:239:79200	00:000:00000
50212M002				-.0160	0.0352	0.0224	.0001	.0000	.0001			
50213M003	RAROTONGA	GNSS	CKIS	-5583182.157	-2054143.546	-2292166.707	0.001	0.001	0.001			
50213M003				-.0340	0.0538	0.0326	.0001	.0001	.0001			
50214S001	CHRISTCHURCH	GNSS	LYTT	-4588536.011	585996.282	-4376497.022	0.001	0.001	0.001			
50214S001				-.0165	0.0361	0.0228	.0001	.0000	.0001			
50214M001	CHRISTCHURCH	GNSS	MQZG	-4580569.617	590465.621	-4384380.006	0.001	0.001	0.001	1	00:000:00000	01:246:00000
50214M001				-.0165	0.0361	0.0228	.0001	.0000	.0001			
50											46:00000	00:000:00000

Note multiple coordinates for some sites, representing "breaks" in time series possibly due to earthquake jolts

http://itrf.ign.fr/ITRF_solutions/2008/doc/ITRF2008_GNSS.SSC.txt

t_0 = 2005.0 for ITRF2008

Global Geodetic Reference Frame ITRF2008



VLBI	SLR	GNSS	DORIS	Vector Tie
				

Updated by ITRF2014

http://itrf.ensg.ign.fr

ITRFyy... 2000, 2005, 2008, 2014

- Each successive realisation of the ITRS is an *improvement* in accuracy (of positions & motions), *but ITRS axes DO NOT move wrt deep mantle (they are “earth-fixed”), but DO move wrt surface tectonic plates*
- Stn coordinate can be transformed into other ITRFyy realisations using a 7-parameter *similarity transformation* model at the *same epoch in time*, e.g. ITRF92 to ITRF97, ITRF2005 to ITRF2008... *otherwise difference in epoch must also be taken into account*
- Crustal motion is accounted for through stn velocities, *and may reach over 10cm/yr*
- Earthquake jolts lead to new station coords & velocities
- Station coords in an ITRFyy system are propagated forward (or backward) in time using the station velocities, e.g. 1994 to 2014, taking care if there were station coord “jumps” due to earthquakes
- ITRFyy is determined by the IERS using mainly observations from the IGS’s GNSS network (**http://www.igs.org**), plus SLR, VLBI & DORIS results from the other IAG services
- Epoch of definition of station coords for ITRF2014 is 2010.0

Further Remarks re ITRFyy, WGS84...

- ECEF datums are products of the Space Age
- ITRS is the ECEF datum with the highest accuracy... *ITRF2008 is the current reference frame (coord epoch 2005.0)*
- ITRF2014 was released 21 January 2016
- ITRFyy realisations consist of coordinates *and* velocities of globally distributed fundamental geodetic stations... *most of which are GNSS CORS operated by the IGS*
- WGS84 is the datum for GPS... *now <u>equivalent</u> to ITRFyy*
- Transformation models between ITRFyy, WGS84 and many national datums are available
- ITRF2008 & WGS84 model tectonic motion by *linear* velocities... *but not ITRF2014*
- ITRFyy coords are obtained for the *current* date (e.g. using epoch coords + velocity propagation)
- National datums do not accommodate time-varying coords... *they are typically "plate-fixed" frames & not ITRF-equivalent*

ITRFyy... *some more comments*

- ITRF is getting *more accurate* due to addition of more data since last update, better models & processing software, <u>and</u> archive of past data
- ITRF *degrades with time* since date of computation because assumption of **linear** (for pre-ITRF2014) or **non-linear modelled** (ITRF2014) station velocities may not be correct, <u>and</u> earthquakes cause "jumps" in station coords
- *Similar comments re national datums, irrespective of whether datum is "dynamic" or "static"*

Relationship with other reference systems:

WGS 84 (G1674) is aligned to ITRF2008 with the same epoch of 2005.0. The purpose of this alignment is to ensure scientific integrity and follow best practices. The ITRF incorporates multiple methods to realize the reference system such as satellite laser ranging and very-long-baseline interferometry that NGA does not include. Adjusting WGS 84 to ITRF allows the reference frame to take advantage of those methods without directly incorporating them into the coordinate determination software.

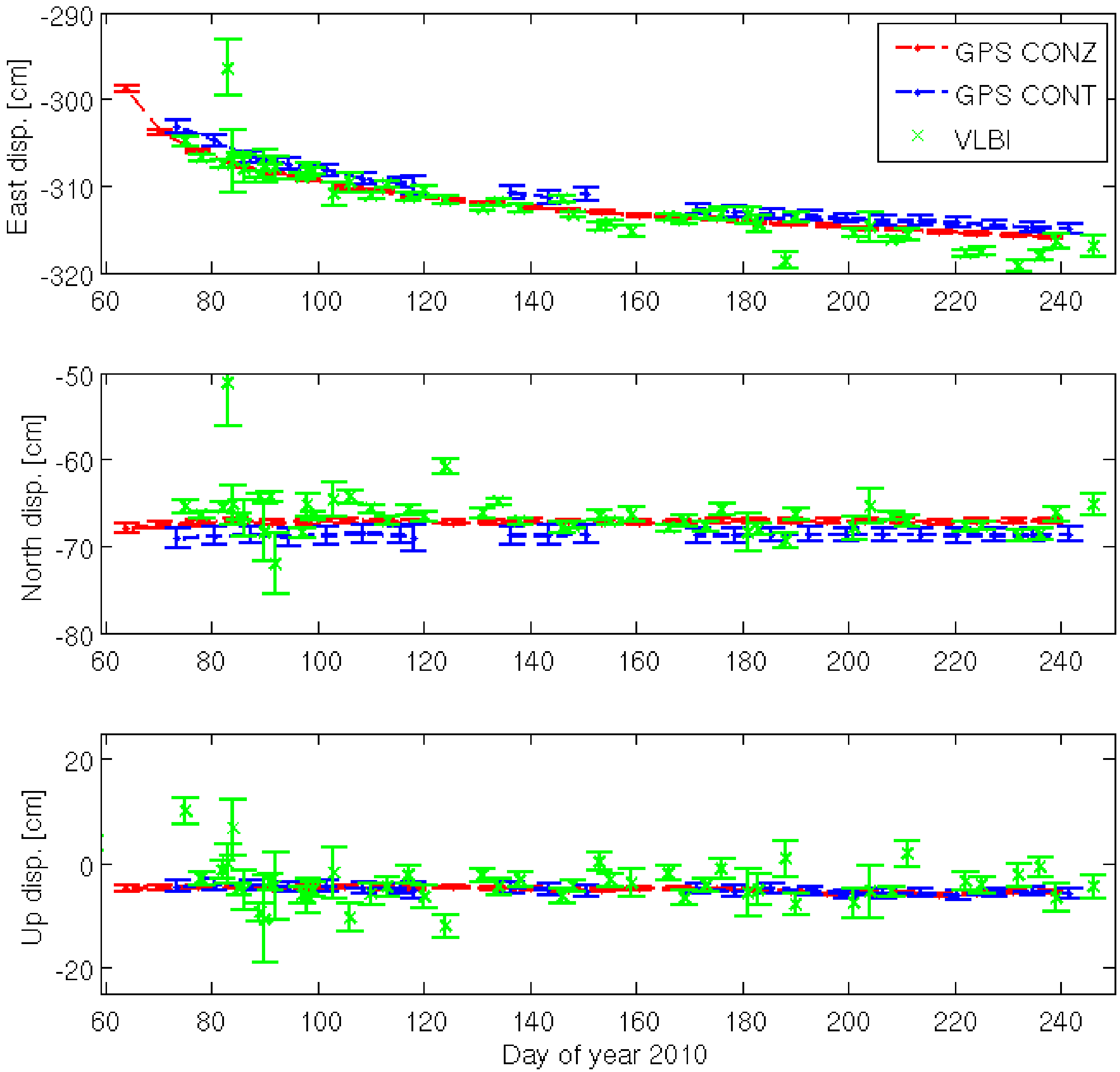
Transformation Parameters

The parameters are defined from the listed reference frame to WGS 84 (G1674) at epoch 2005.0.

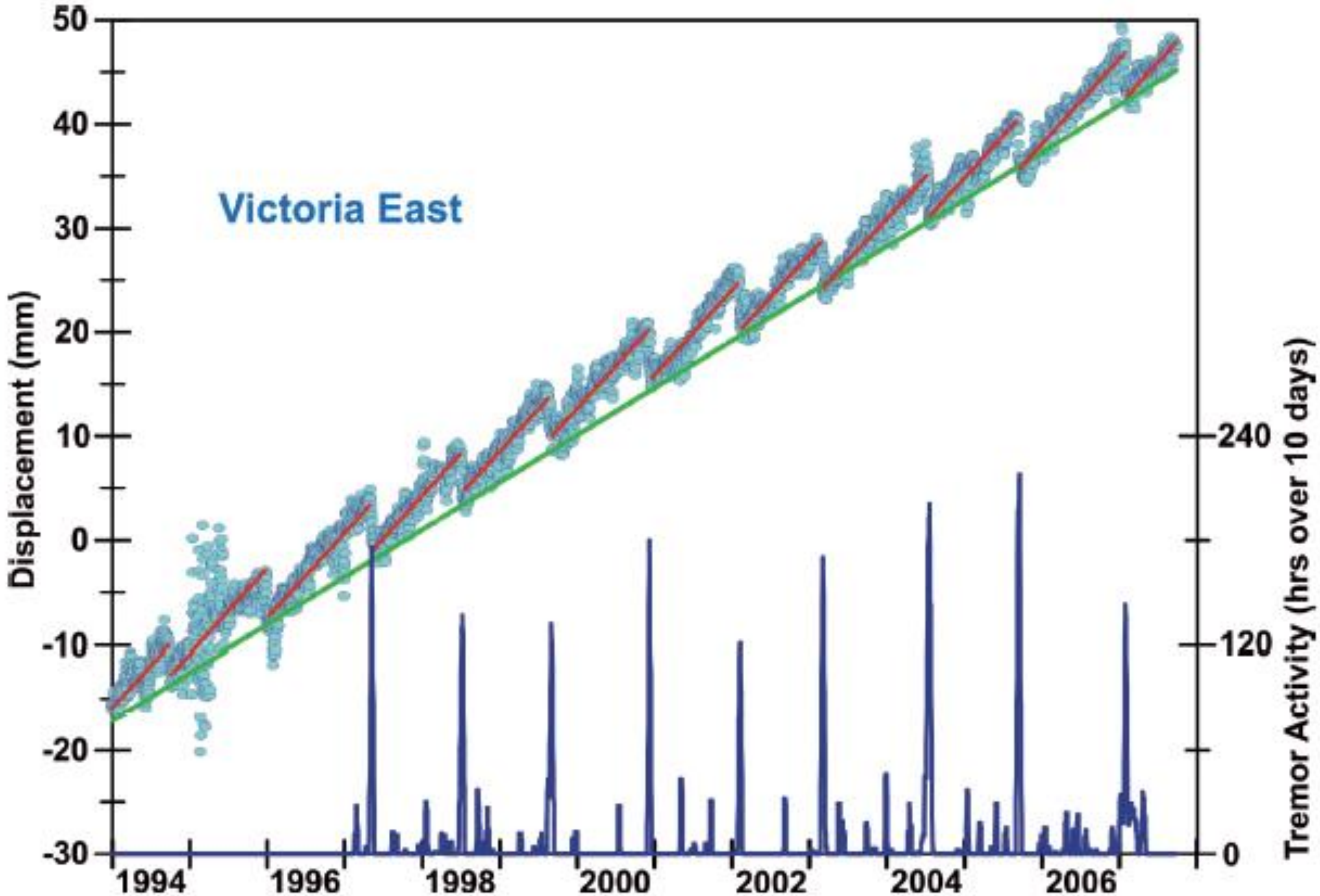
Reference Frame (reference frame epoch)	Tx (mm) (sigma)	Ty (mm) (sigma)	Tz (mm) (sigma)	D (ppb) (sigma)	Rx (mas) (sigma)	Ry (mas) (sigma)	Rz (mas) (sigma)
WGS 84 (G1150)# (2001.0)	-4.7 5.9	11.9 5.9	15.6 5.9	4.72 0.92	-0.52 0.24	-0.01 0.24	-0.19 0.22
ITRF2008* (2005.0)	0	0	0	0	0	0	0

The sign convention for the rotations Rx, Ry, and Rz is what NGA uses in its orbit comparison programs and is opposite to that of IERS Technical Note No. 36, Equation 4.3 and following.
*Zero by construction.

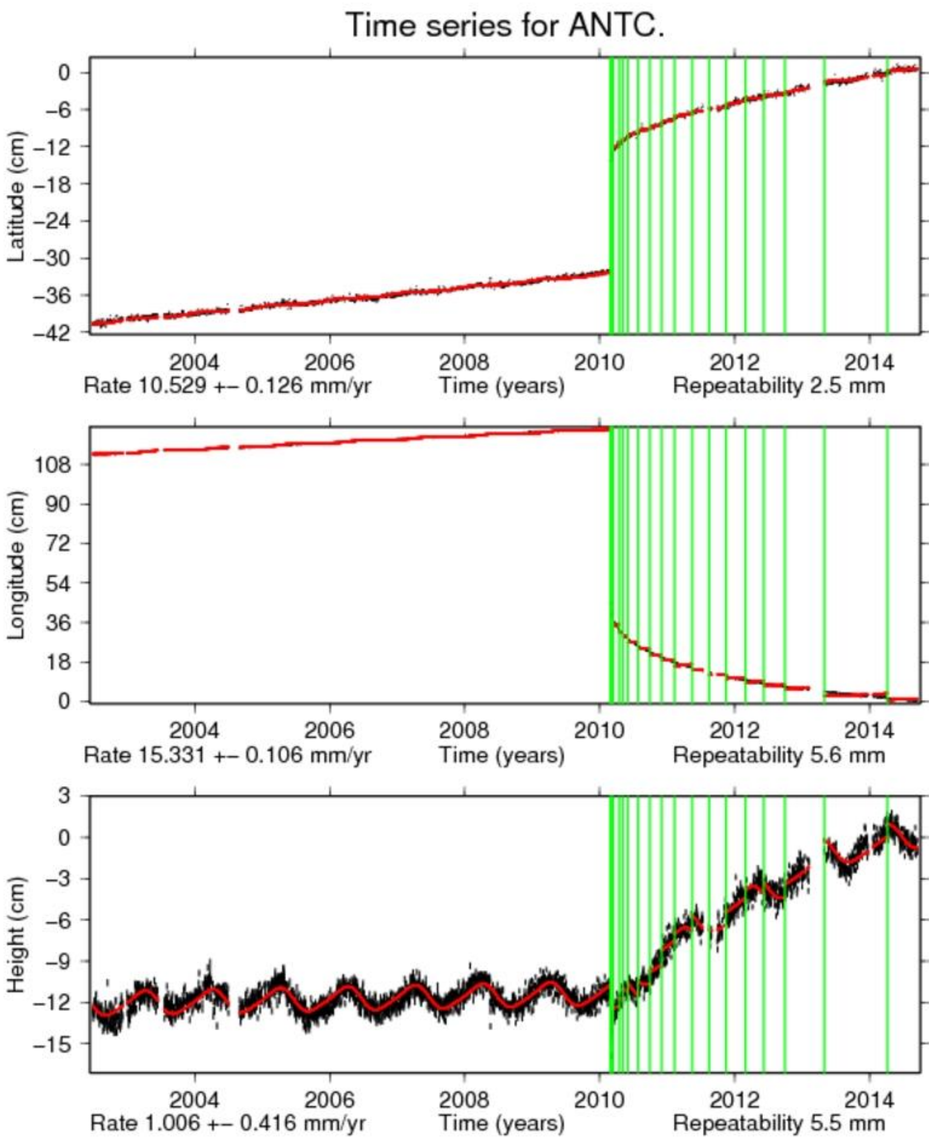
Everything is moving... *e.g. after an earthquake*

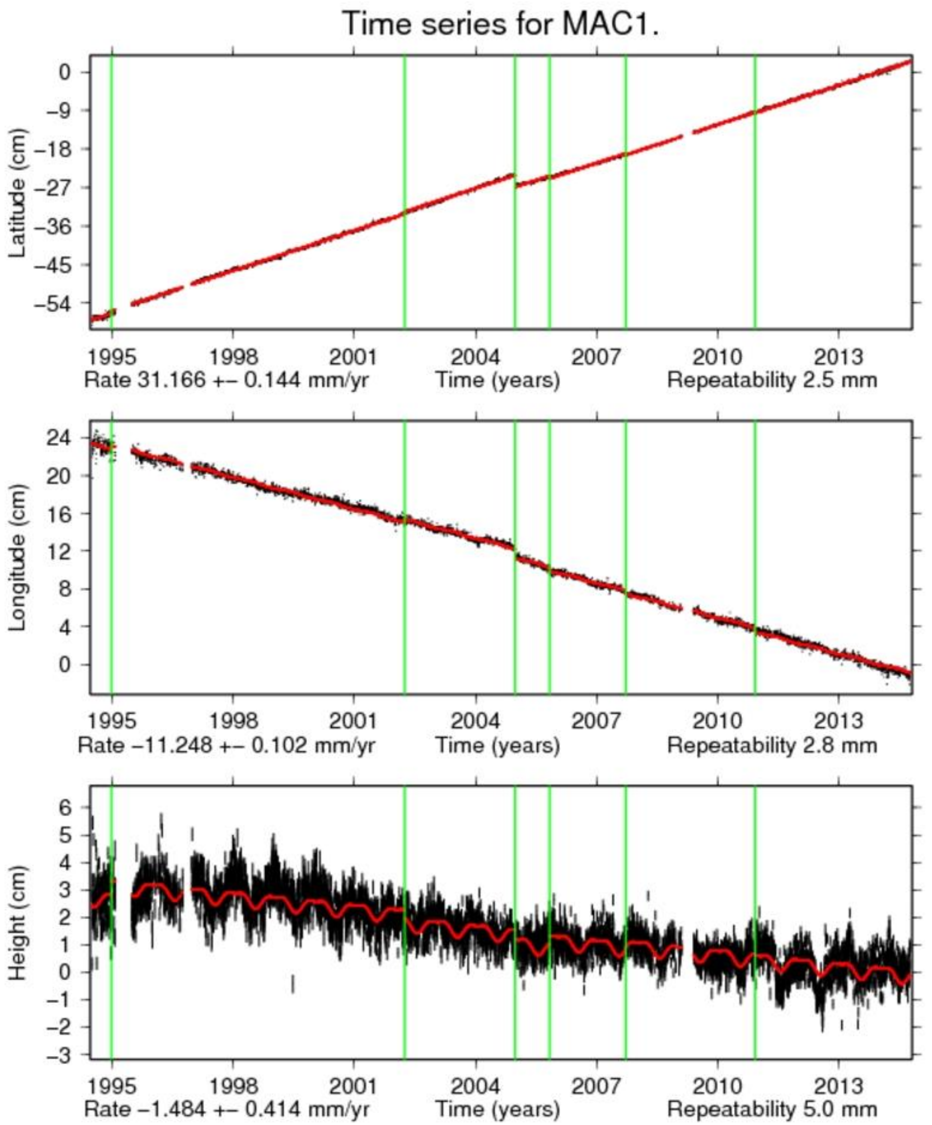


But the station velocity may be uncertain...



Could be lots of “breaks” in coords & vels...

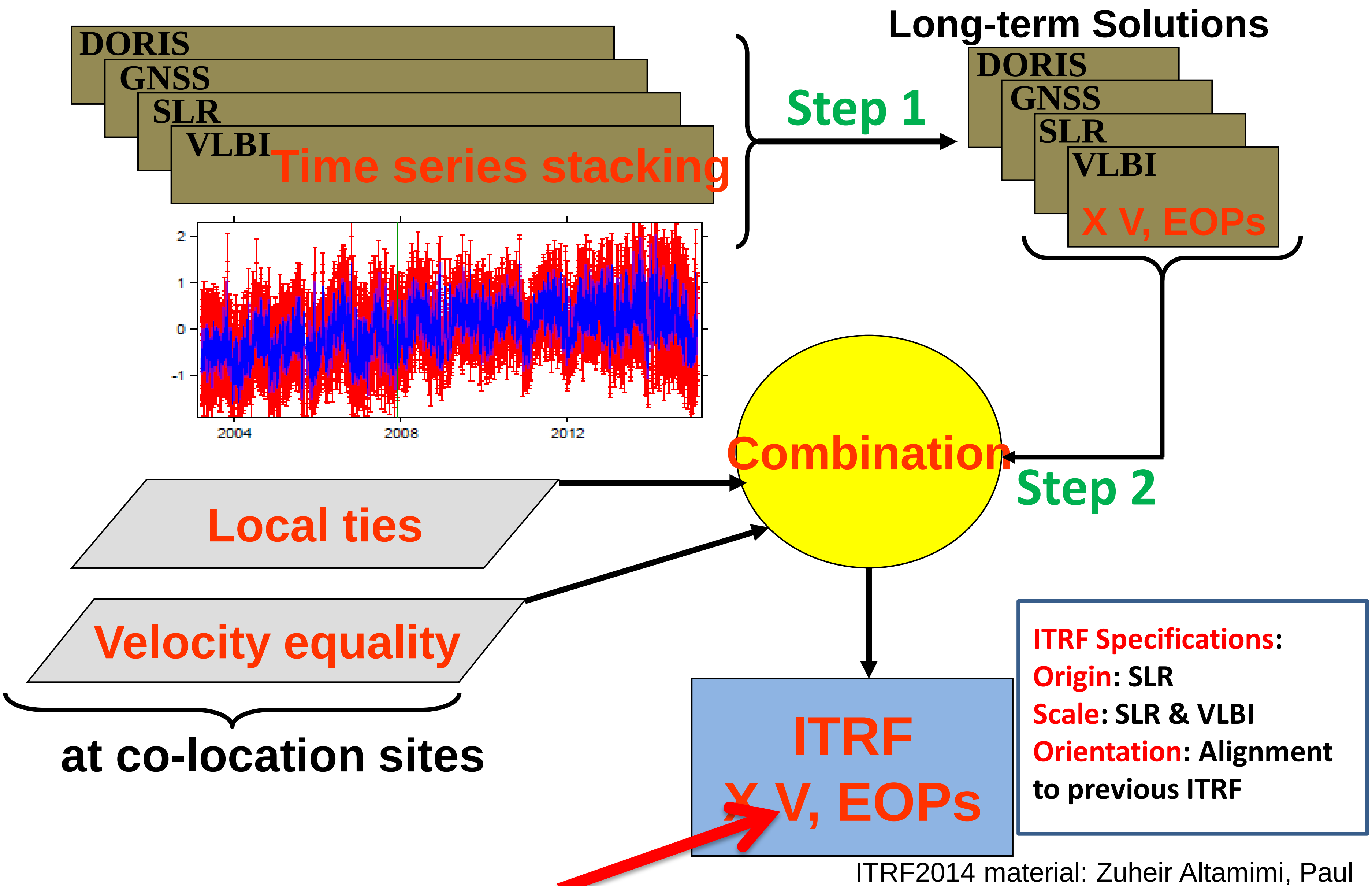




ITRF2014

- ITRF2014 Network
- Modelling of non-linear station motions
  - Periodic signals: annual, semi-annual
  - Post-Seismic Deformation (PSD)
  - Using ITRF2014 PSD models
- ITRF2014 horizontal & vertical velocity fields
- ITRF2014 to ITRF2008 transformation

ITRF2014 Construction



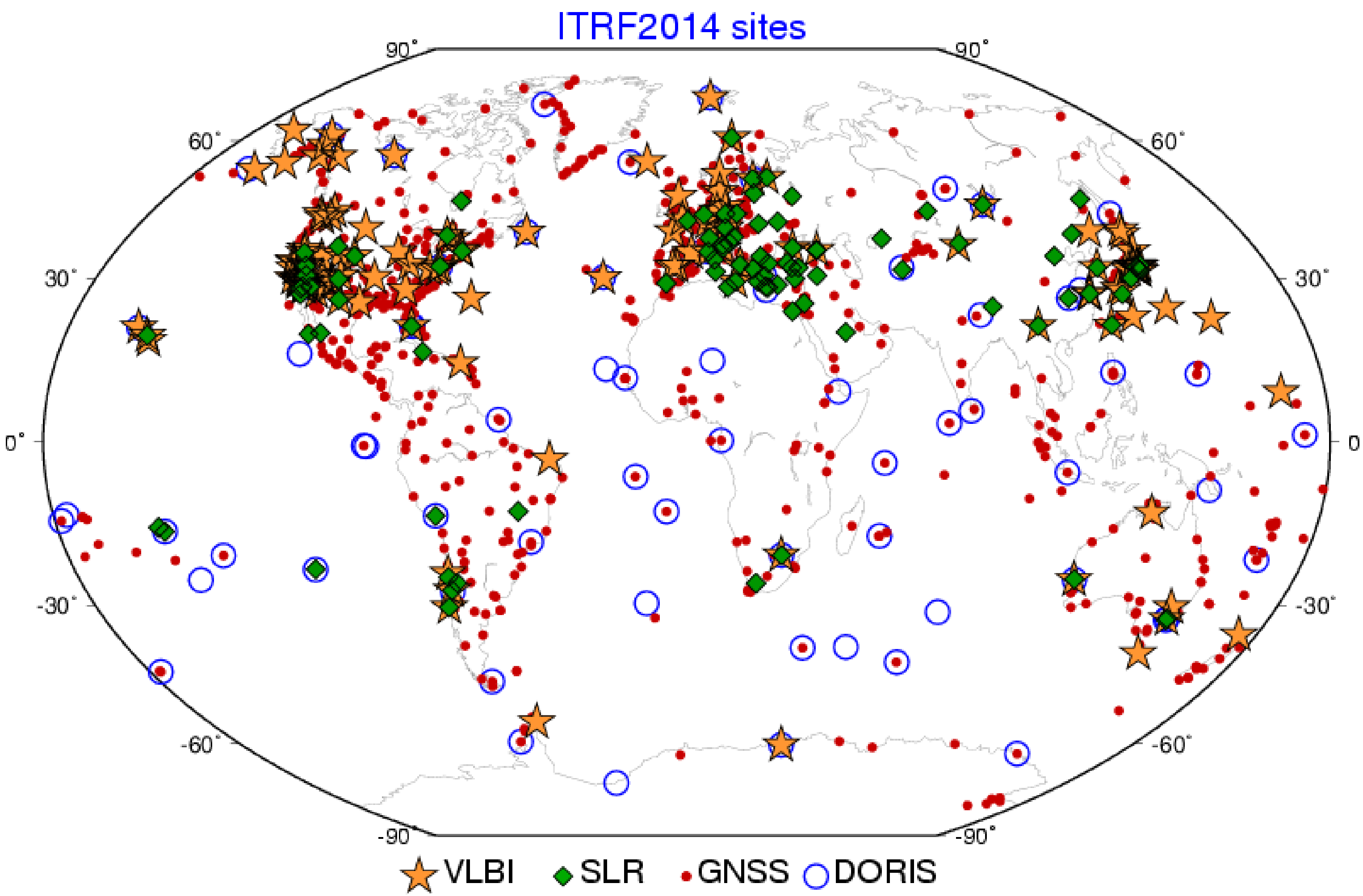
ITRF2014 material: Zuheir Altamimi, Paul Rebischung, Laurent Métivier, Xavier Collilieux

ITRF2014: Input data

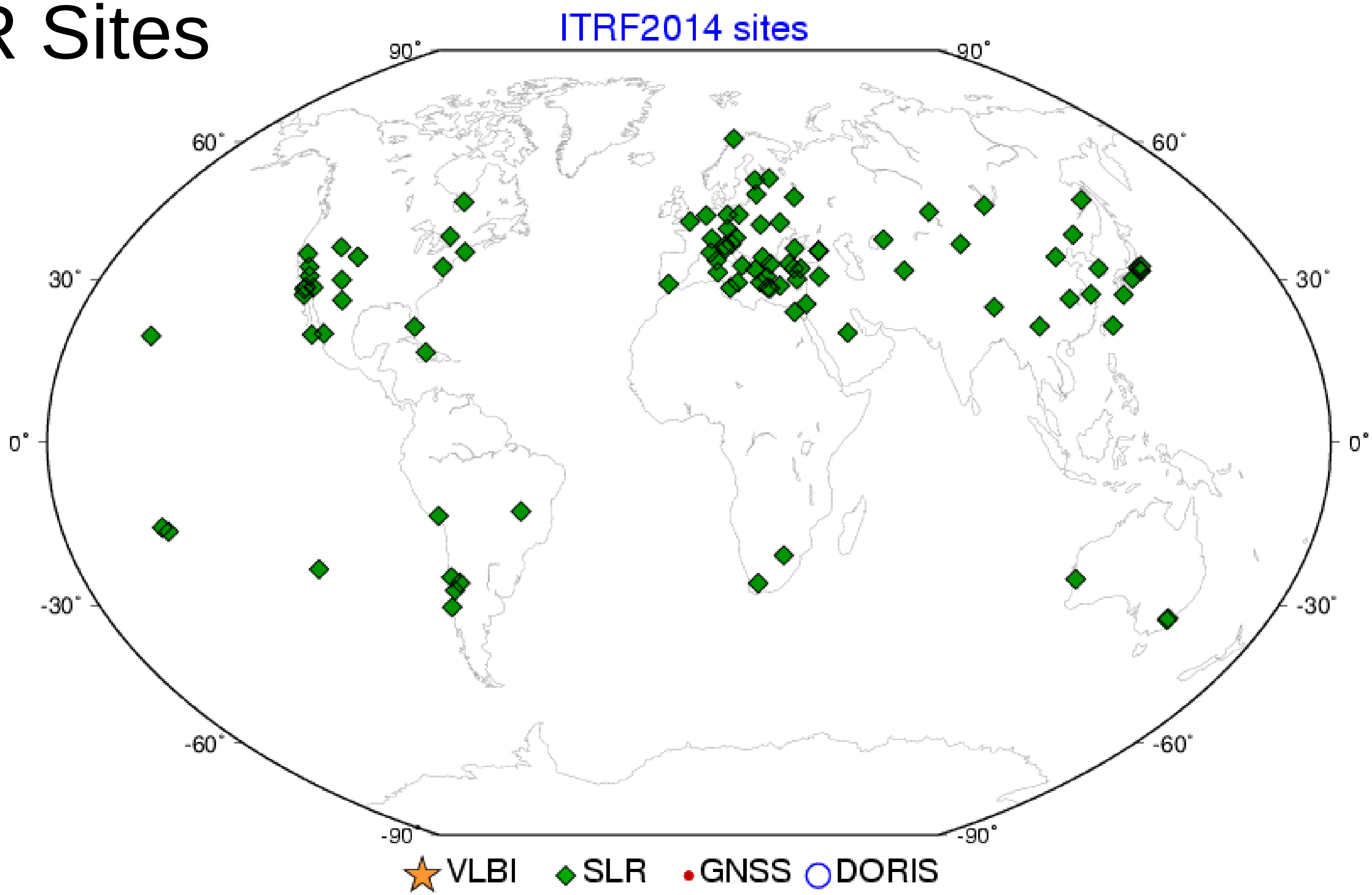
Service/Technique	Number of Solutions	Time span
IGS/GNSS	7714 daily	1994.0 – 2015.1
IVS/VLBI	5328 daily	1980.0 – 2015.0
ILRS/SLR	244 fortnightly 1147 weekly	1980.0 – 1993.0 1993.0 – 2015.0
IDS/DORIS	1140 weekly	1993.0 – 2015.0

ITRF2014: Some statistics

- 1499 stations located in 975 sites
- 91 co-location sites with 2 or more instruments which were or are currently operating
- The IGS network is playing a major role connecting the 3 other techniques:
  - 33 SLR
  - 40 VLBI
  - 46 DORIS

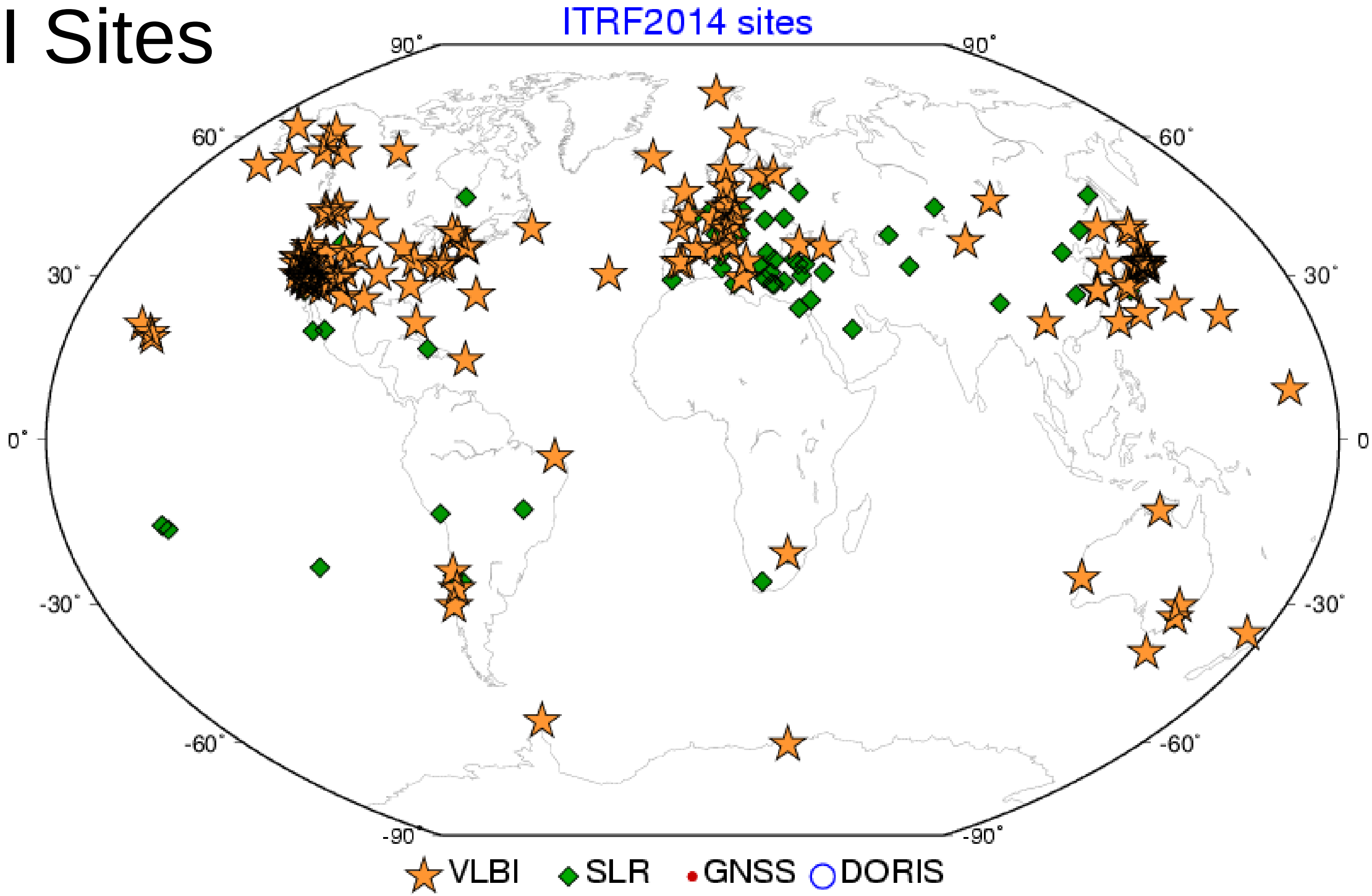

ITRF2014 sites
90°
60°
30°
0°
-30°
-60°
-90
VLBI
SLR
GNSS
DORIS

SLR Sites



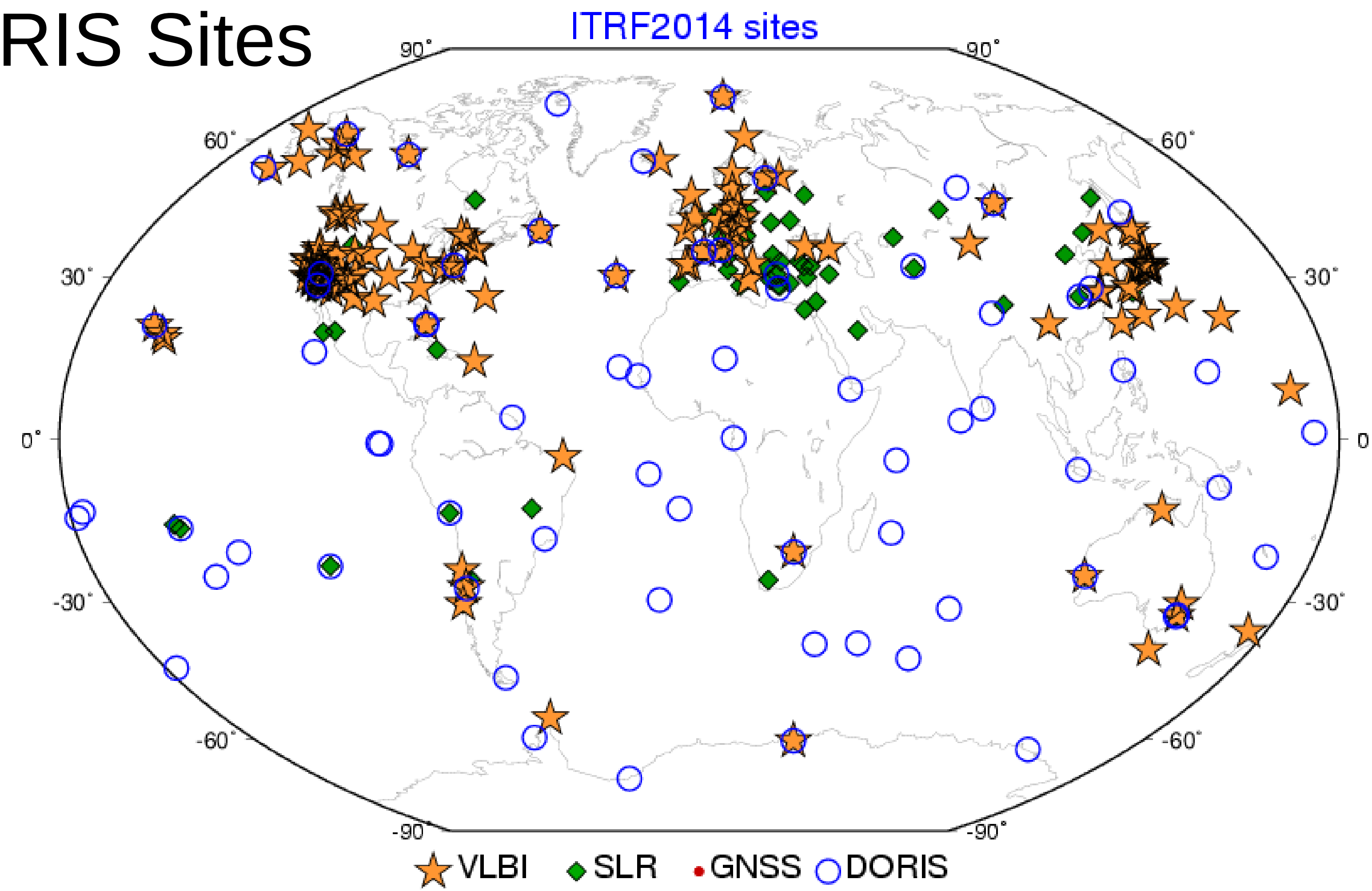
ITRF2014 material: Zuheir Altamimi, Paul Rebischung, Laurent Métivier, Xavier Collilieux

VLBI Sites



ITRF2014 material: Zuheir Altamimi, Paul Rebischung, Laurent Métivier, Xavier Collilieux

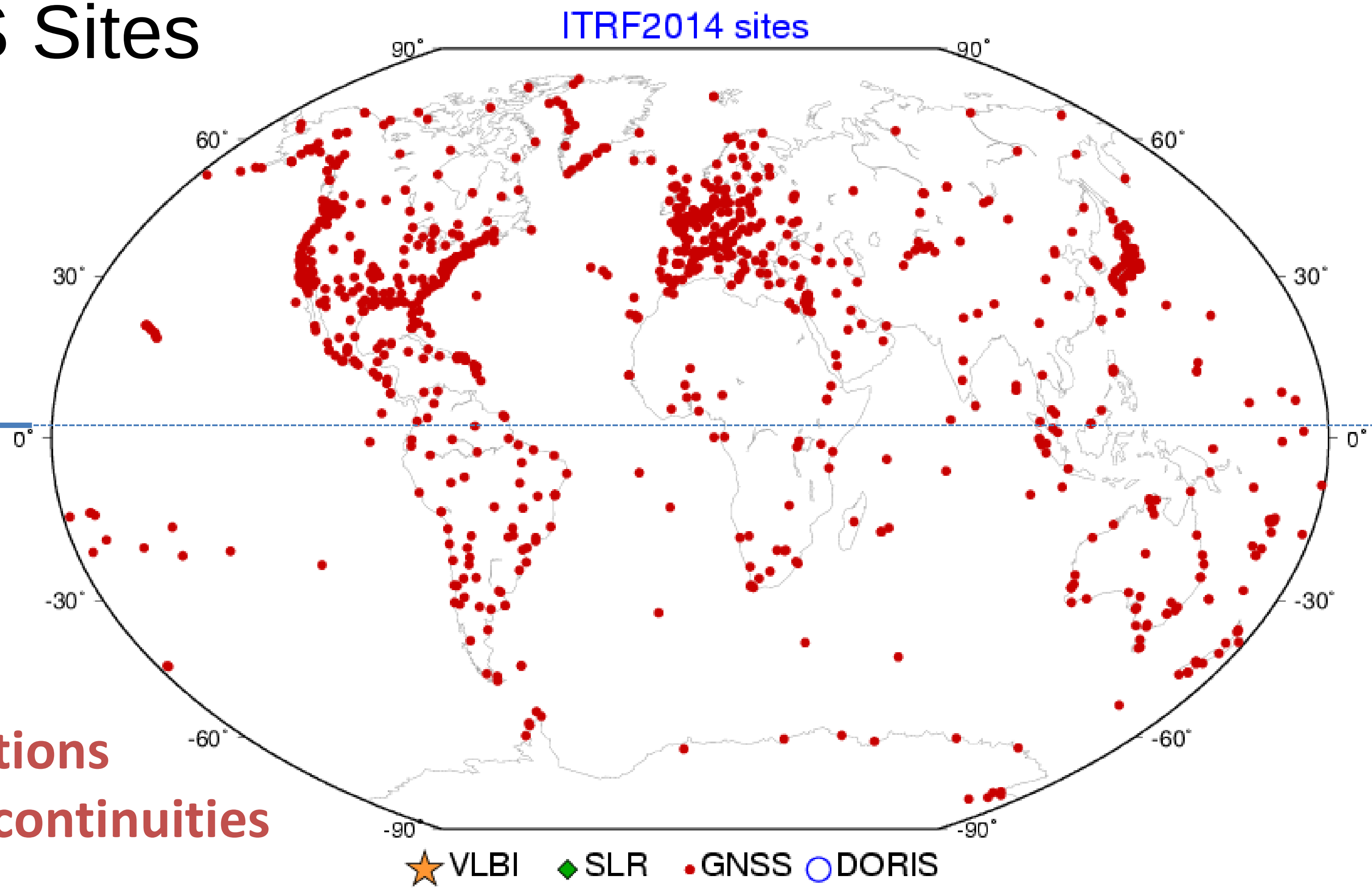
DORIS Sites



ITRF2014 material: Zuheir Altamimi, Paul Rebischung, Laurent Métivier, Xavier Collilieux

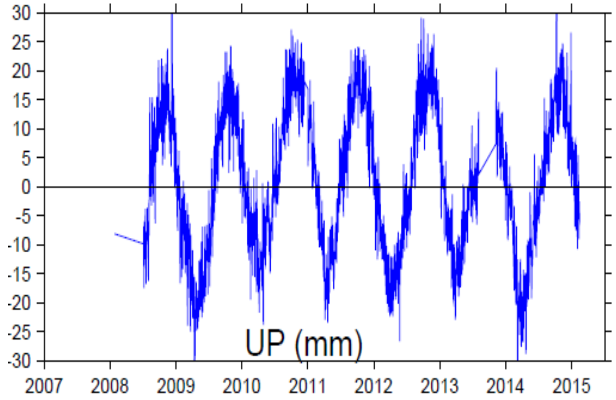
GNSS Sites

Site #
696
188



884 sites
1054 stations
1882 discontinuities

Periodic Signals



- Loading effects:
  - Atmosphere
  - Terrestrial water (Hydrology)
  - Ocean circulation

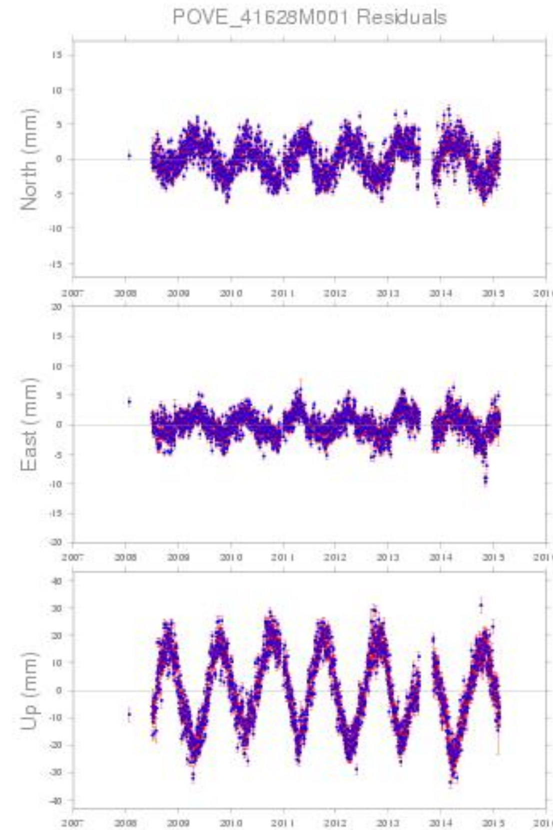
  ==> Annual, semi-annual, inter-annual, but also short periods (e.g. daily) variations

- Technique systematic errors, e.g. GPS draconitic year (351.4 days – period for repeat of GPS/Sun orientation, due to 14.1°/yr satellite RA drift) and its harmonics

Periodic Signals

Annual & semi-annual terms estimated, using:

$$\Delta X_f = \sum_{i=1}^{n_f} a^i \cos(\omega_i t) + b^i \sin(\omega_i t)$$



ΔX_f total sum of all frequencies

n_f number of frequencies

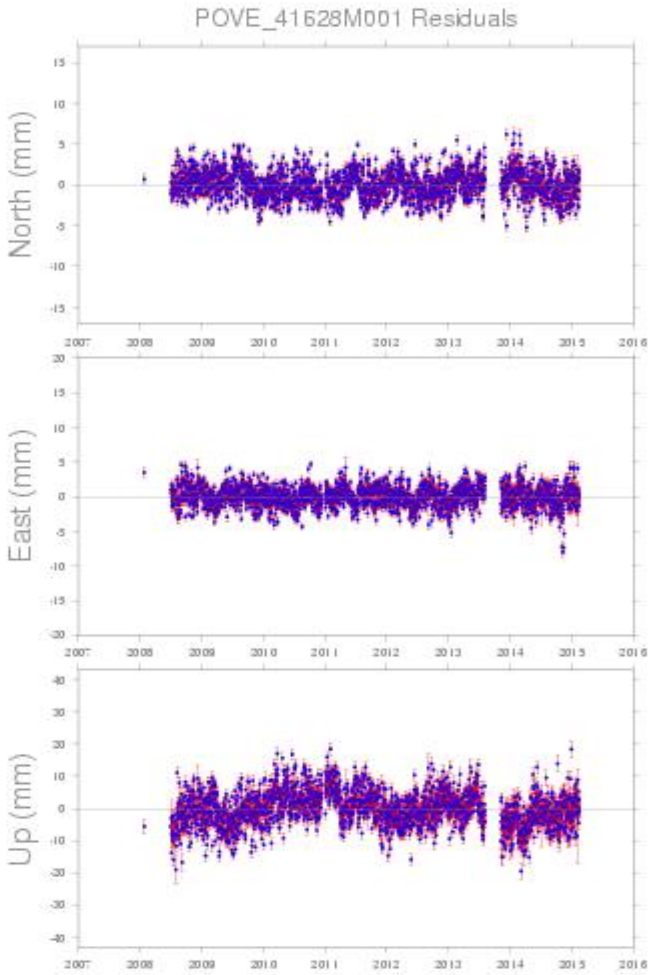
$$\omega_i = \frac{2\pi}{\tau_i}$$

τ_i i^{th} period of frequency i

==> 6 components per station & per frequency, i.e. a & b following the three axis X, Y, Z

Periodic Signals

After application of annual & semi-annual estimated model parameters

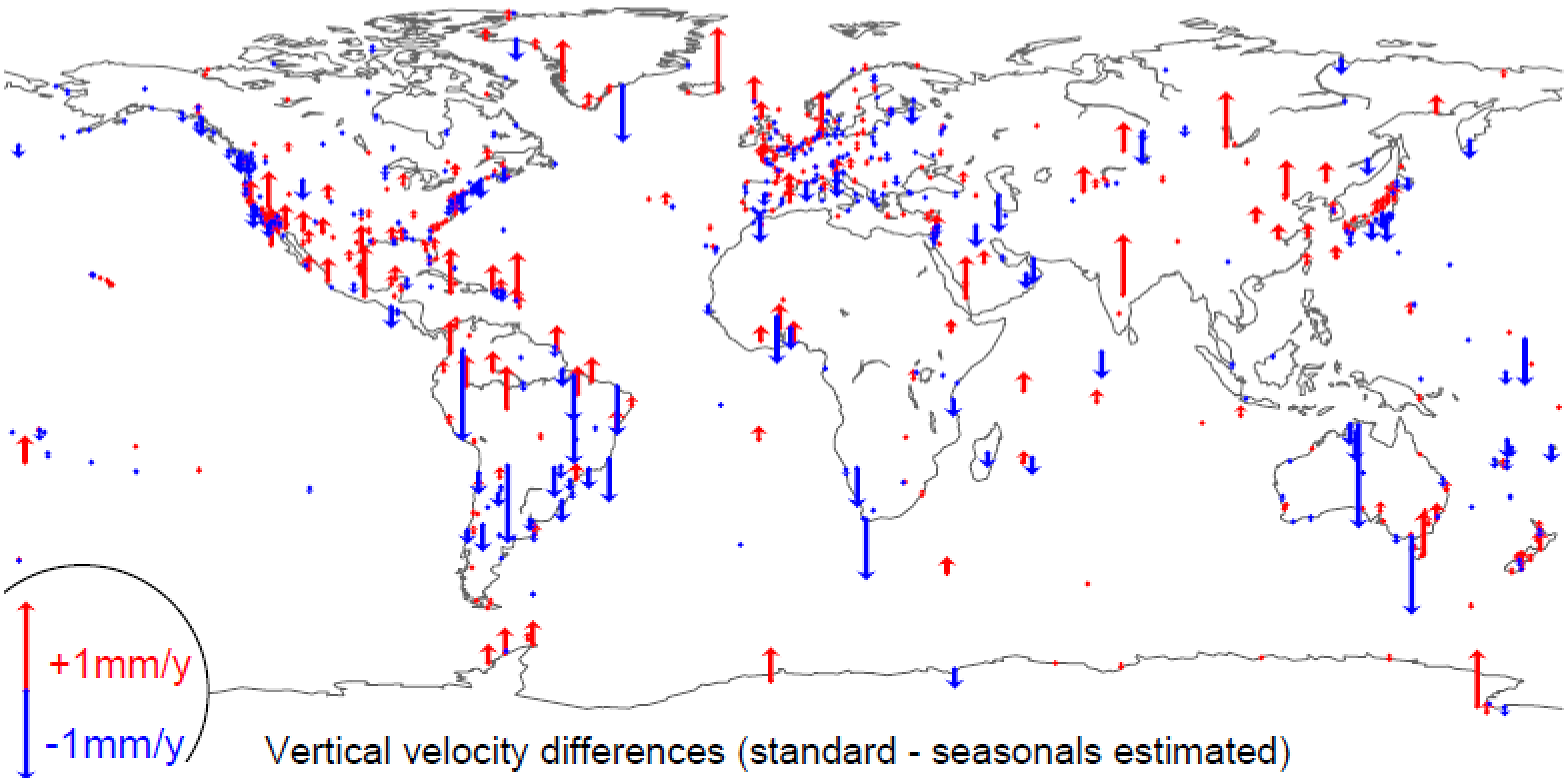


Removing draconitics in addition to annual and semi-annual periods has no impact on site velocities

ITRF2014 material: Zuheir Altamimi, Paul Rebischung, Laurent Métivier, Xavier Collilieux

Impact of Estimating Seasonal Signals

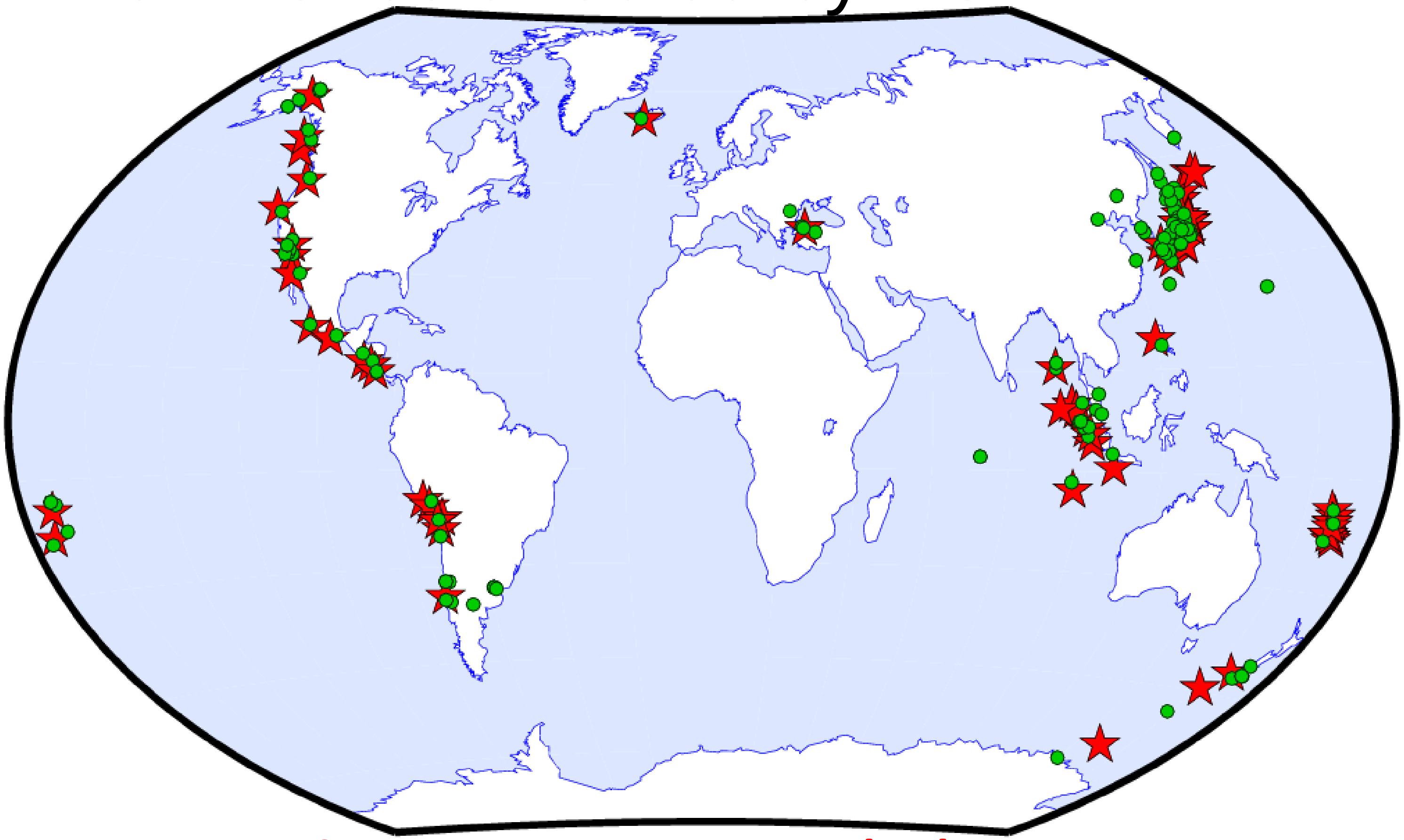
- Negligible impact on horizontal velocities
- Up to 1mm/yr change in vertical velocities, for stations with large seasonal signals, large number of discontinuities, or/and data gaps in time series



ITRF2014 material: Zuheir Altamimi, Paul Rebischung, Laurent Métivier, Xavier Collilieux

Post-Seismic Deformations & ITRF2014

ITRF2014 Sites affected by PSD



Red Stars: EQ Epicentres (58)

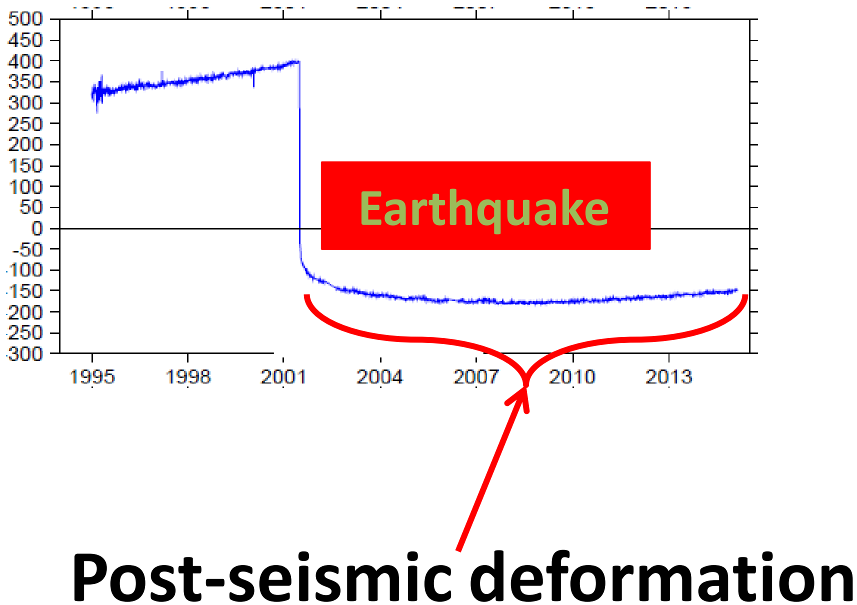
Green circles: ITRF2014 sites (117)

ITRF2014 material: Zuheir Altamimi, Paul Rebischung, Laurent Métivier, Xavier Collilieux

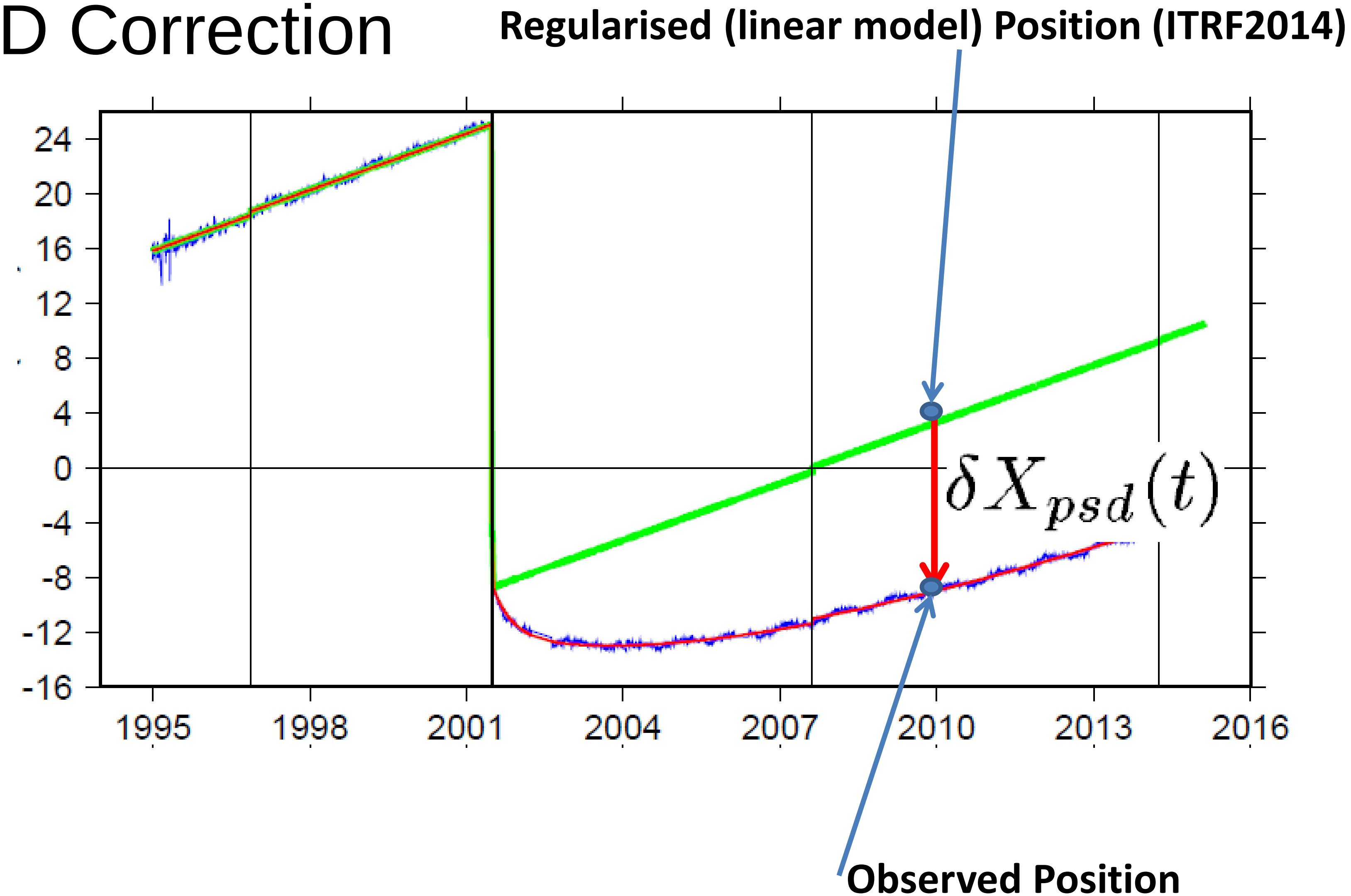
Post-Seismic Deformations

- Fitting parametric models using GNSS/GPS data
  – at major GNSS/GPS Earthquake sites
  – apply these models to the 3 other techniques at co-location EQ sites

- Parametric models:
  – Logarithmic
  – Exponential
  – Log + Exp
  – Two Exp



PSD Correction



ITRF2014 material: Zuheir Altamimi, Paul Rebischung, Laurent Métivier, Xavier Collilieux

Using ITRF2014 PSD Models?

Regularised (linear model) Position (ITRF2014)

$$X_{PSD}(t) = \boxed{X(t_0) + \dot{X}(t - t_0)} + \delta X_{PSD}(t)$$

$$\delta L(t) = \sum_{i=1}^{n^l} A_i^l \log(1 + \frac{t - t_i^l}{\tau_i^l}) + \sum_{i=1}^{n^e} A_i^e (1 - e^{-\frac{t - t_i^e}{\tau_i^e}})$$

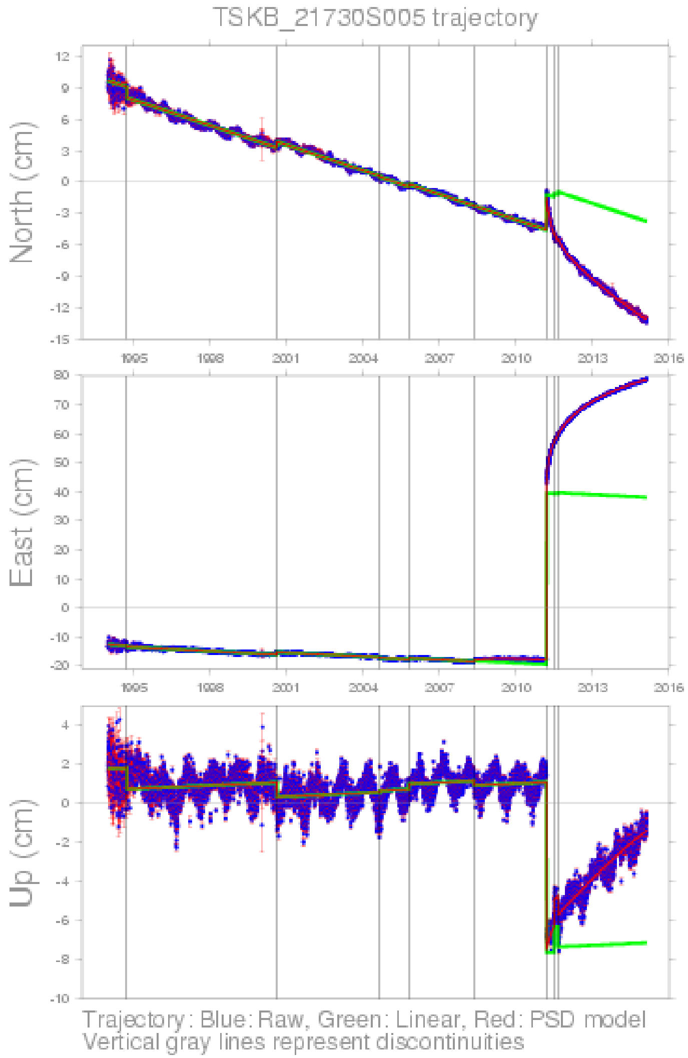
Local Frame

PSD Subroutines available at ITRF2014 Web site:
http://itrf.ign.fr/ITRF_solutions/2014/

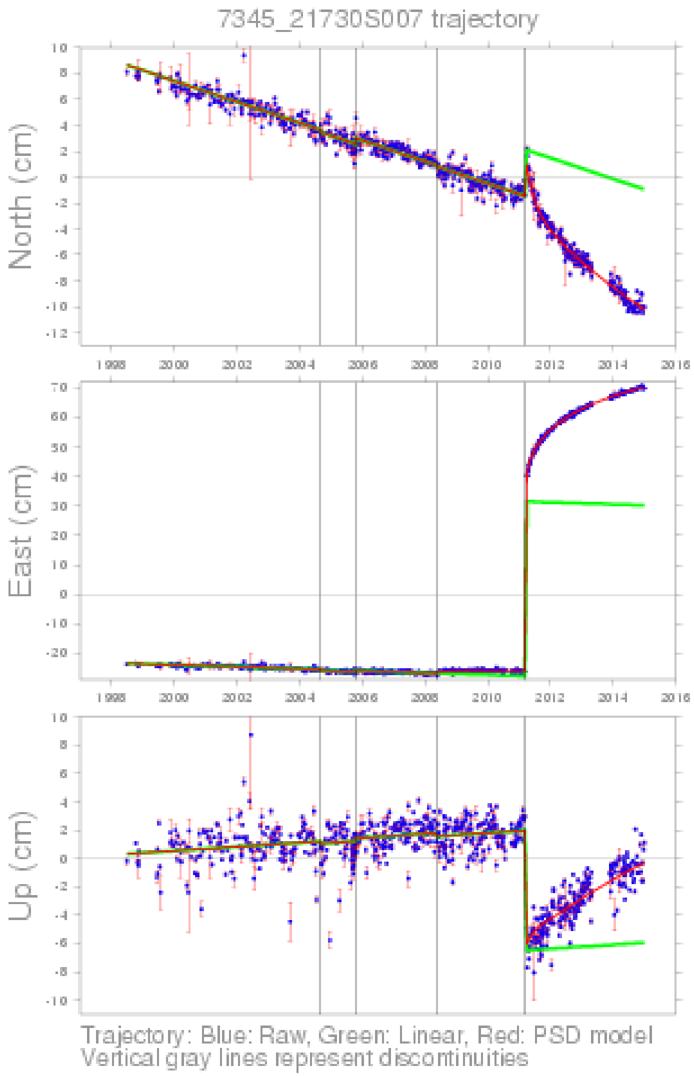
```
      subroutine parametric (modn,dtq,a1,t1,a2,t2,d)
C
C Author: Zuheir Altamimi (zuheir.altamimi@ign.fr), IGN France
C
C Last updated: August 17, 2015
C
C Compute the post-seismic deformation/correction "d
C #     Model
C 0     PWL (Piece-Wise Linear Function)
C 1     Logarithmic Function
C 2     Exponential Function
C 3     Logarithmic + Exponential
C 4     Two Exponential Functions
C
C IN:
C modn: model #
C dtq : time difference (t - t_Earthquake) in decima
C a1: amplitude 1 of the parametric model, if modn =
C a2: amplitude 2 of the parametric model, if modn =
C t1: relaxation time 1, if modn = 1 or 2 (or 3 or 4
C t2: relaxtaion time 2, if modn = 3 or 4
C
C OUT:
C d: post-seismic correction
C
C Units: - mm for a1, a2, d
C        - year for t1, t2
C
C Note: Time unit is decimal year. It is advised to
C (MJD - MJD_Earthquake)/365.25 where MJD is the mod
C
      implicit none

      doubleprecision dtq,a1,t1,a2,t2,te1,te2,d
      integer modn

      d = 0.d0

      if (modn.eq.0) return

      if (modn.eq.1) then
       d = a1*dlog( 1+ dtq/t1)
       return
      end if

      if (modn.eq.2) then
       te1 = dtq/t1
       d =  a1*(1-dexp(-te1))
       return
      end if

      if (modn.eq.3) then
       te2 = dtq/t2
       d = a1*dlog( 1+ dtq/t1) + a2*(1-dexp(-te2))
       return
      end if

      if (modn.eq.4) then
       te1 = dtq/t1
       te2 = dtq/t2
       d = a1*(1-dexp(-te1)) + a2*(1-dexp(-te2))
       return
      end if

      end
```

Tsukuba Trajectory

GPS/GNSS

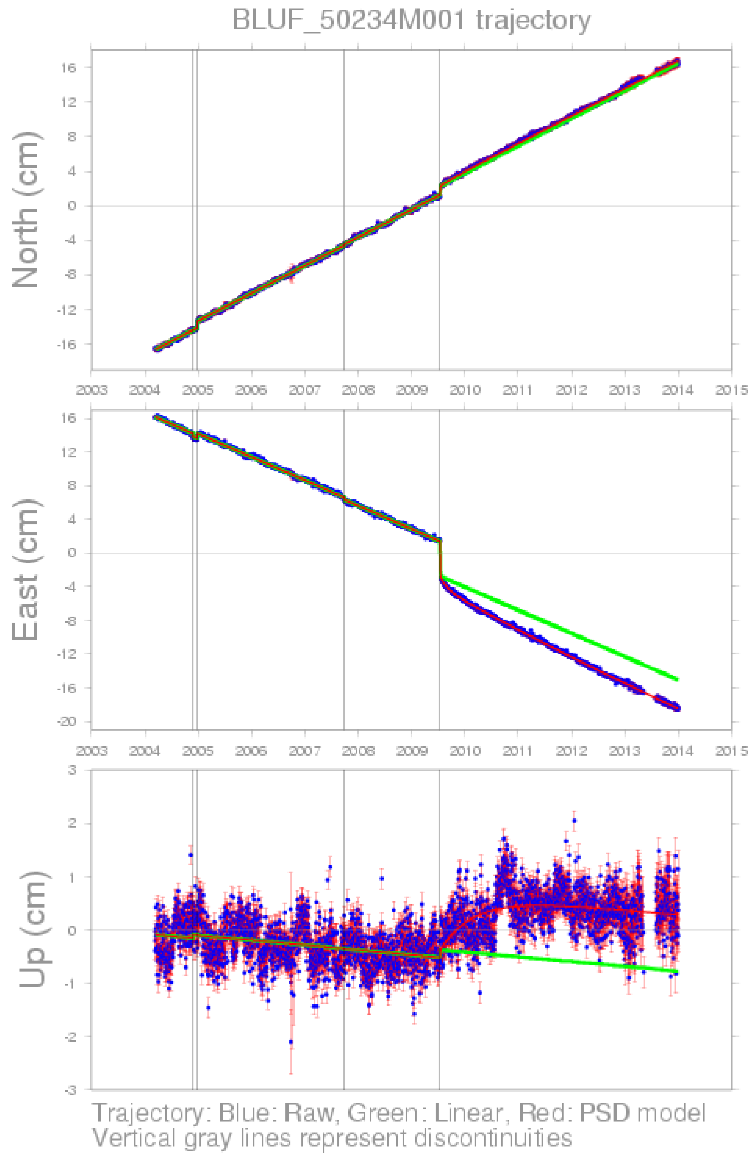


VLBI



ITRF2014 material: Zuheir Altamimi, Paul Rebischung, Laurent Métivier, Xavier Collilieux

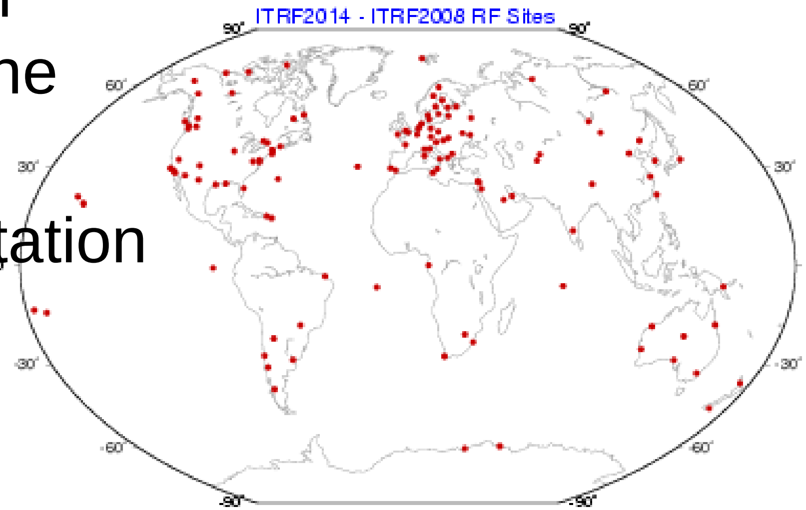
Bluff (New Zealand) Trajectory



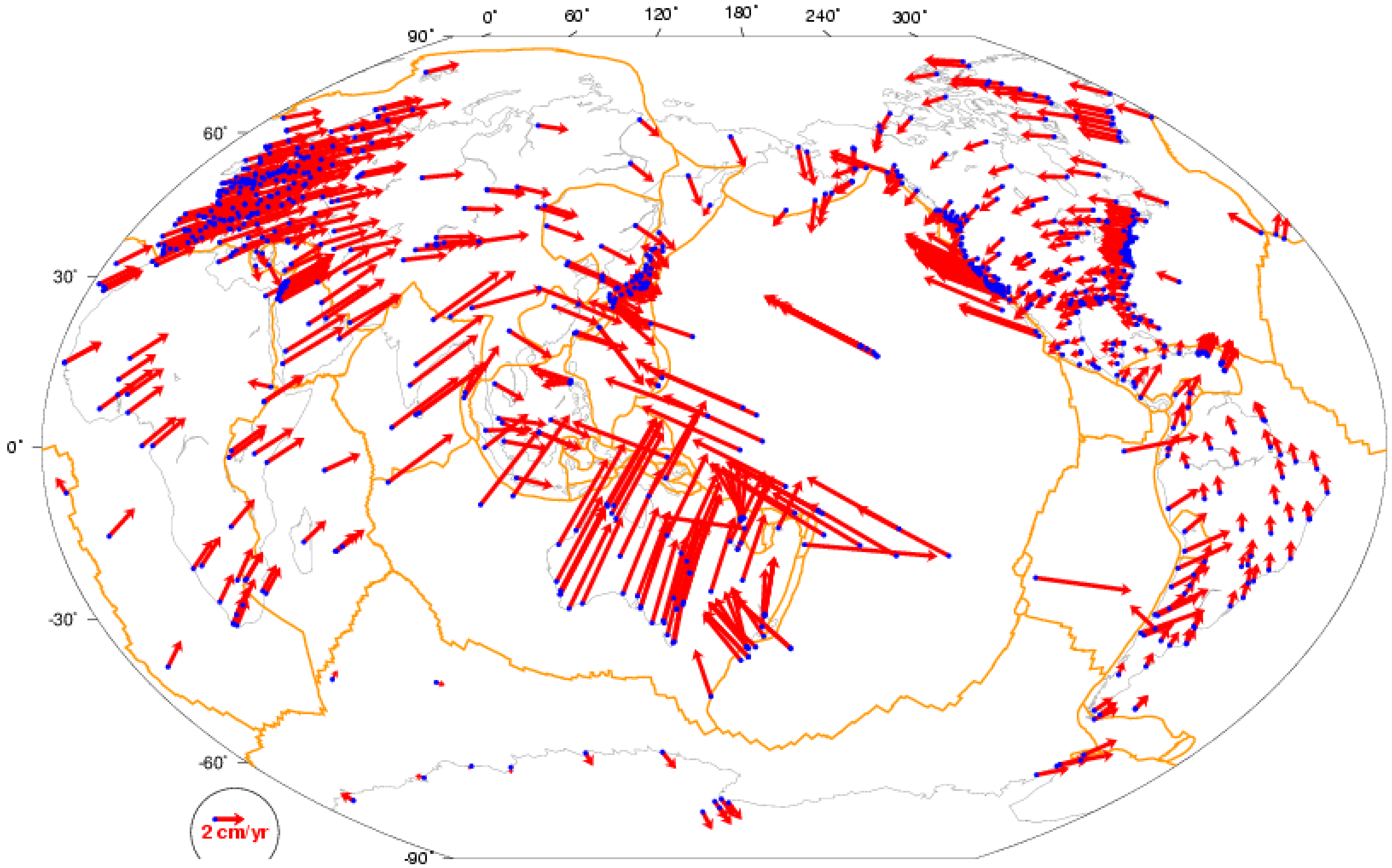
ITRF2014 material: Zuheir Altamimi, Paul Rebischung, Laurent Métivier, Xavier Collilieux

ITRF2014 Frame Specification

- **Origin**: SLR: Zero translation or translation rate between ITRF2014 and SLR frame
- **Scale**: Arithmetic average of VLBI & SLR intrinsic scales: Zero scale or scale rate between ITRF2014 & the VLBI & SLR average
- **Orientation**: Zero rotation and rotation rate wrt ITRF2008, using 127 RF stations:

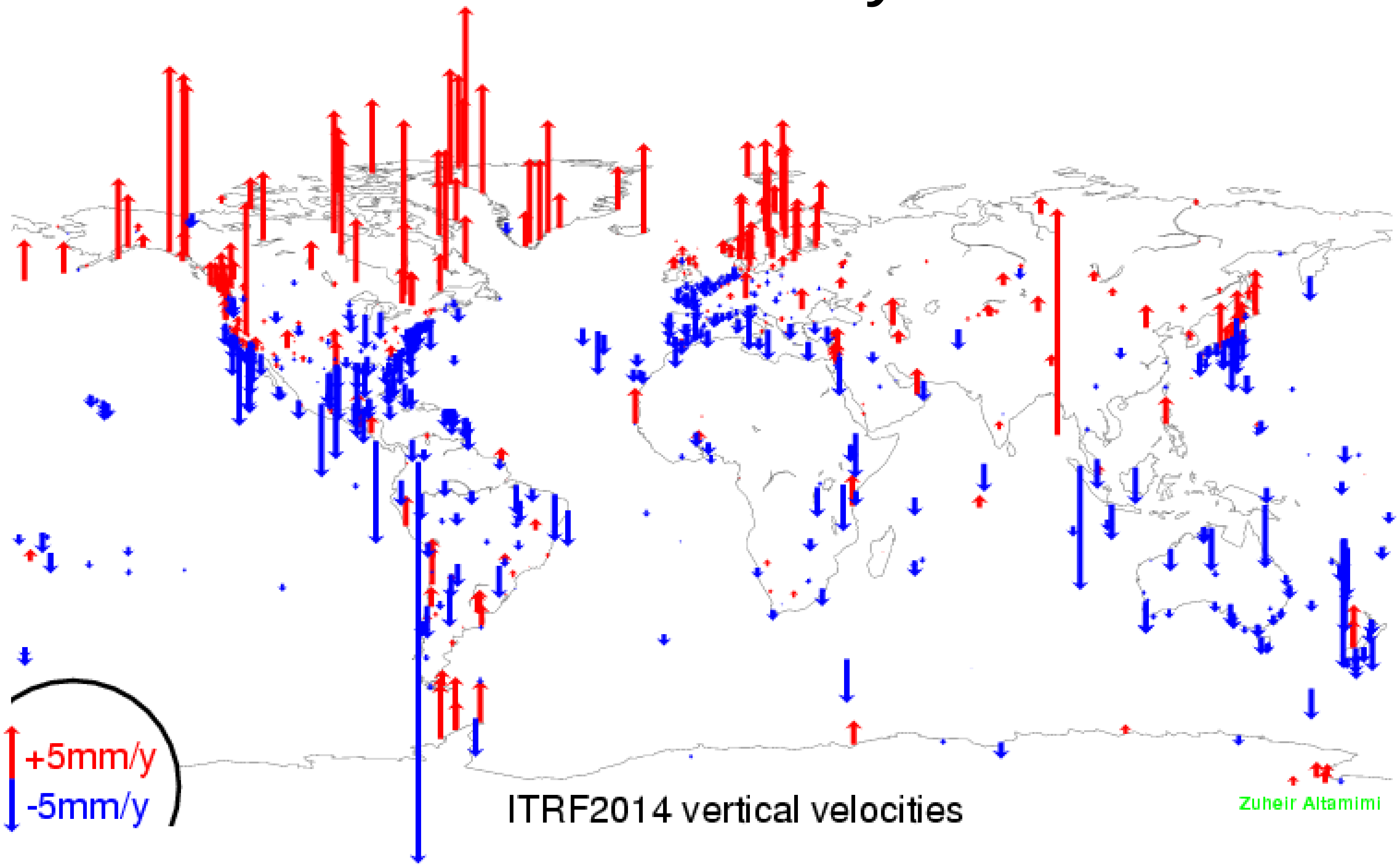


ITRF2014: Horizontal Velocity Field



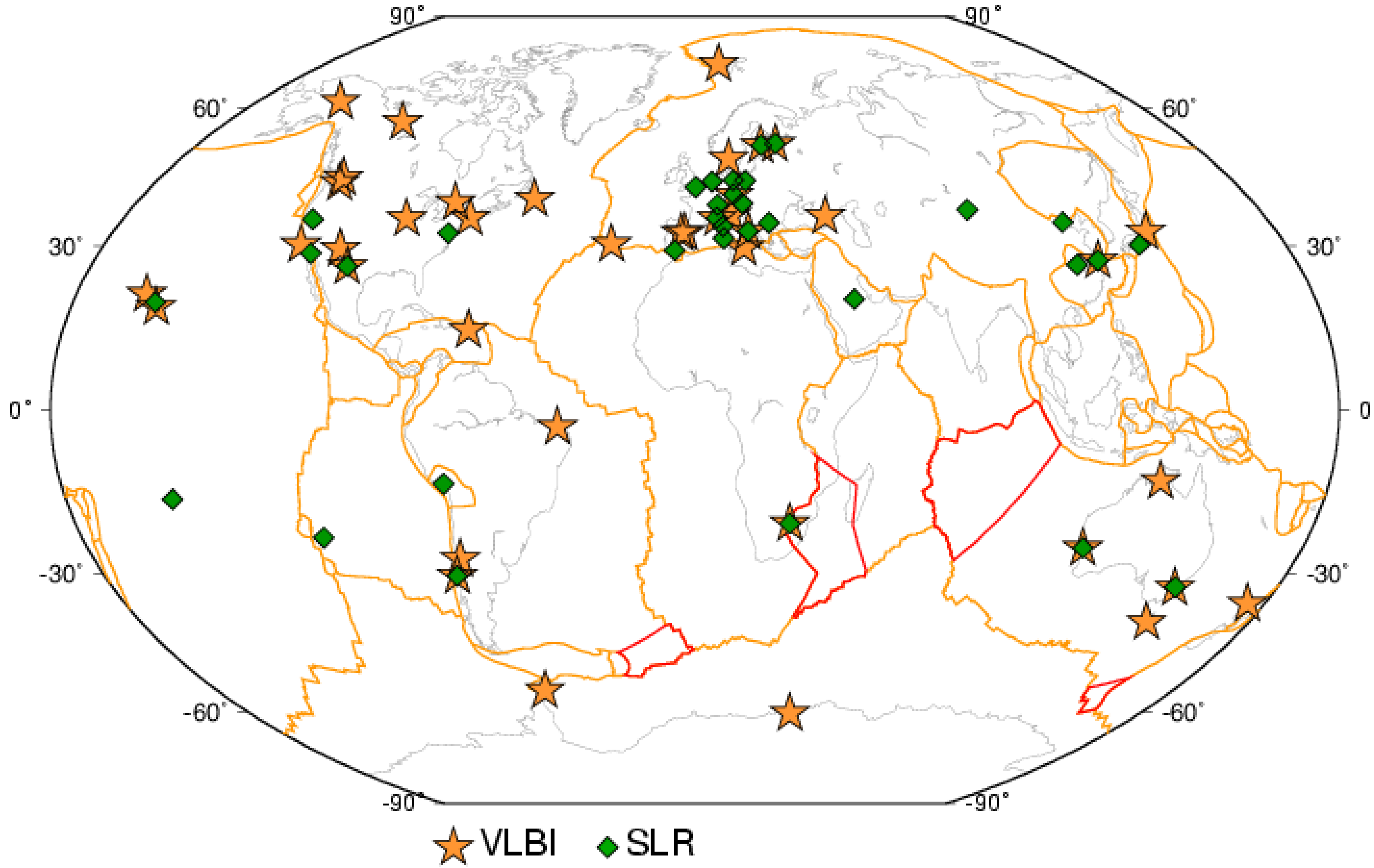
ITRF2014 material: Zuheir Altamimi, Paul Rebischung, Laurent Métivier, Xavier Collilieux

ITRF2014: Vertical Velocity Field



ITRF2014 material: Zuheir Altamimi, Paul Rebischung, Laurent Métivier, Xavier Collilieux

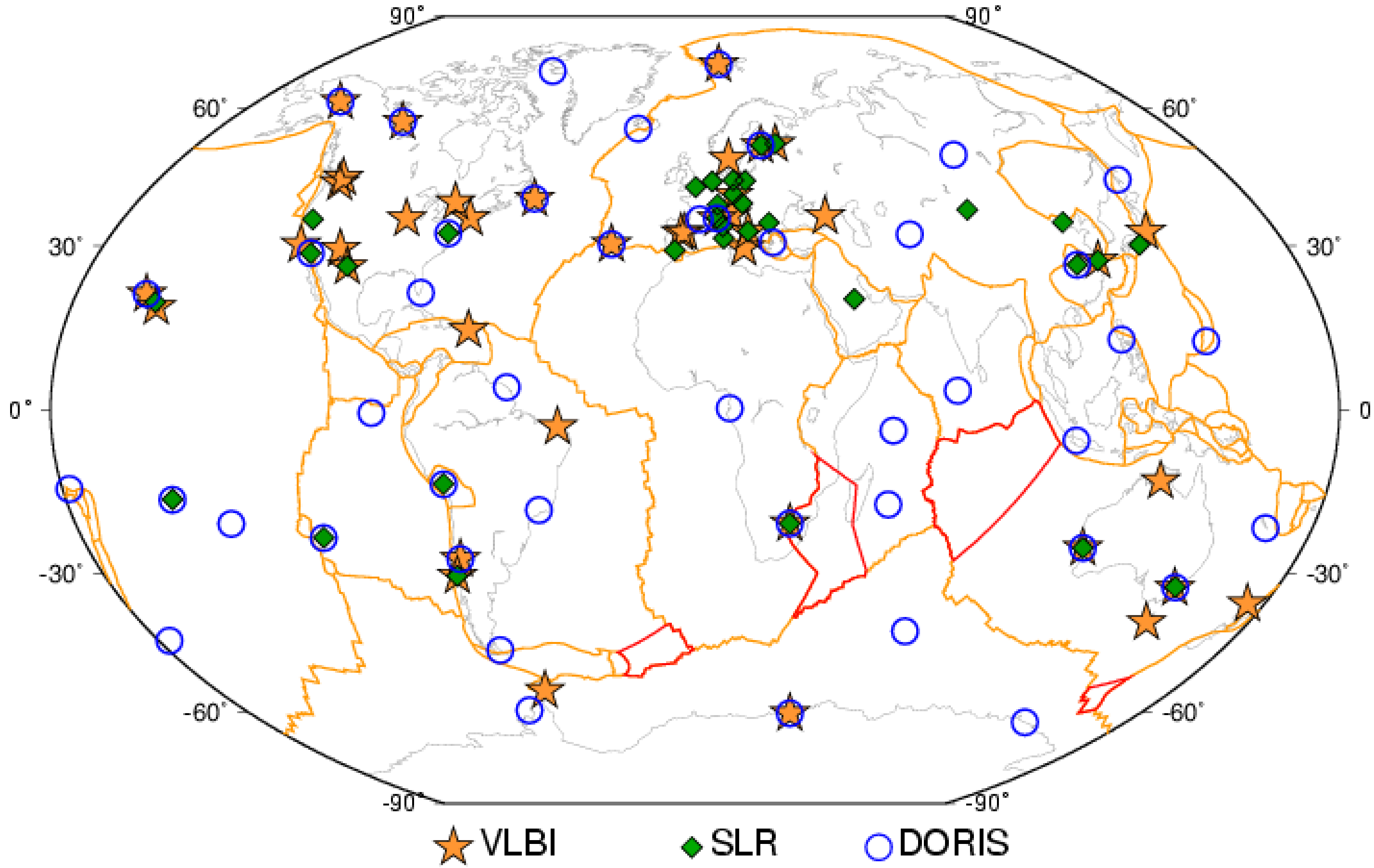
ITRF2014 Co-locations
(VLBI & SLR, co-located with GNSS)



ITRF2014 material: Zuheir Altamimi, Paul Rebischung, Laurent Métivier, Xavier Collilieux

ITRF2014 Co-locations

(VLBI, SLR & DORIS, co-located with GNSS)

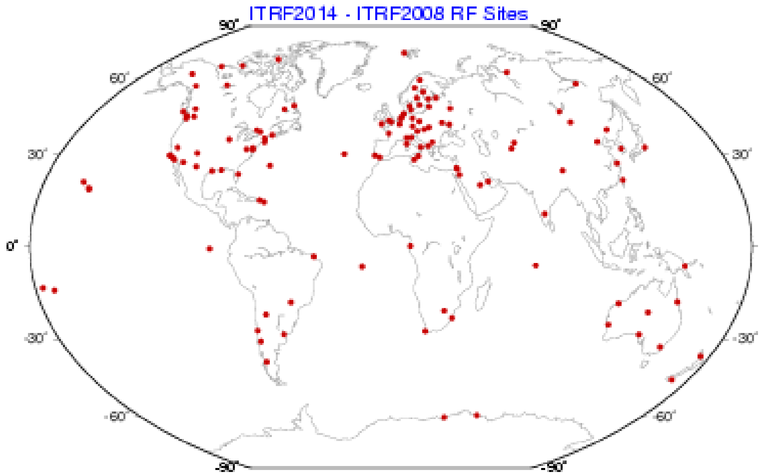


ITRF2014 material: Zuheir Altamimi, Paul Rebischung, Laurent Métivier, Xavier Collilieux

From ITRF2014 to ITRF2008

Using 127 stations

	TX(mm)	TY(mm)	TZ(mm)	Scale (ppb)	Epoch
Offset ±	**1.6 ±0.2**	**1.9 ±0.1**	**2.4 ±0.1**	**-0.01 ±0.02**	**2010.0**
Rate ±	**0.1 ±0.2**	**0.0 ±0.1**	**-0.1 ±0.1**	**0.03 ±0.02**	**-**



ITRF2014 material: Zuheir Altamimi, Paul Rebischung, Laurent Métivier, Xavier Collilieux

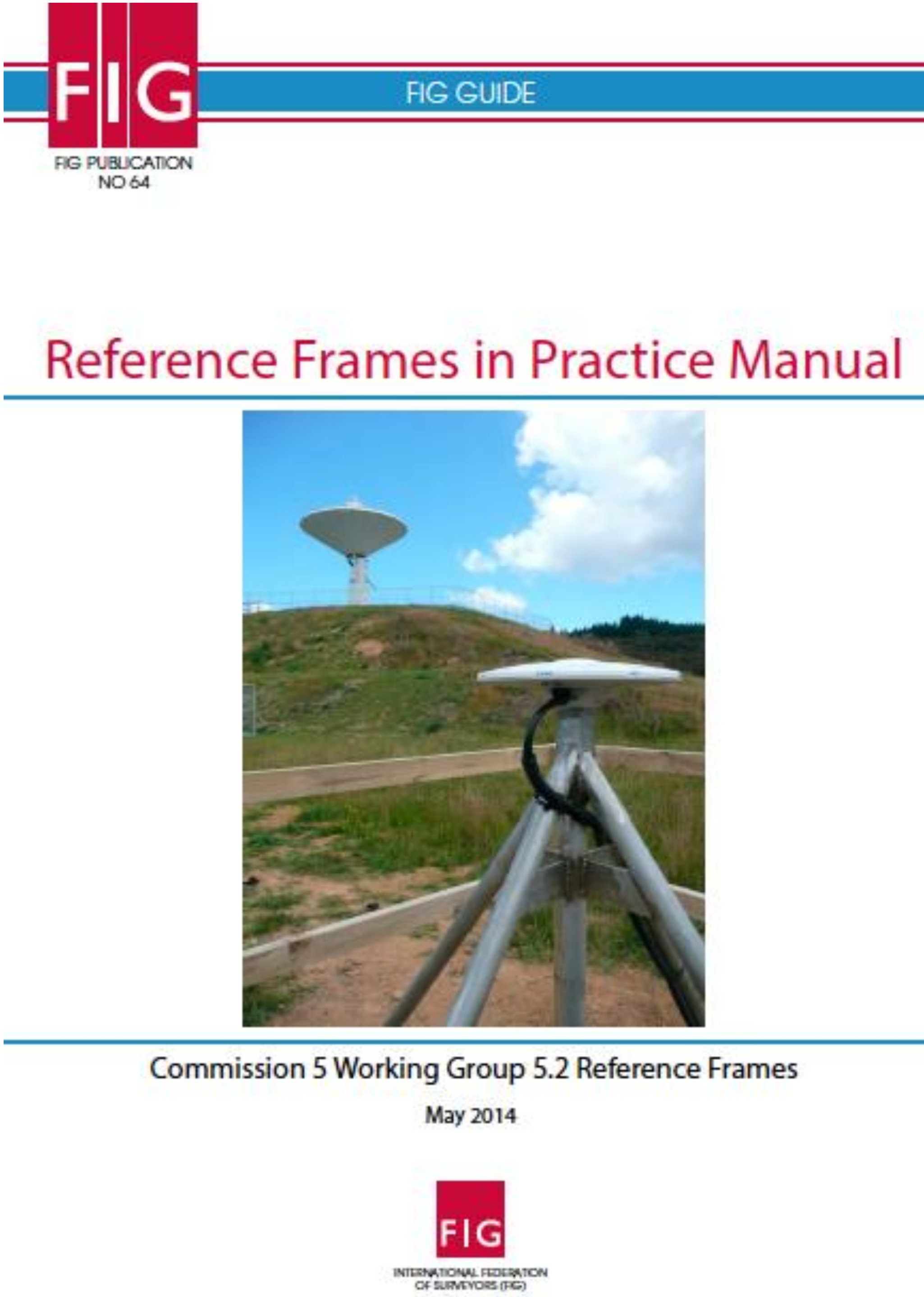
Concluding Remarks

- ITRF2014 innovations:
- Estimating seasonal signals (improves ITRF combination)
  - No significant impact on horizontal velocities
  - Up to 1mm/yr impact on vertical velocities for some stations
  - ***Not part** of ITRF2014 product, just used for internal processing*
- Precise modelling of Post-Seismic Deformations
  - ***Part of** the ITRF2014 product, and used to compute site ITRF2014 coordinate at different epochs*

- Transformation parameters between ITRF2014 & ITRF2008 are small

ITRF2014 material: Zuheir Altamimi, Paul Rebischung, Laurent Métivier, Xavier Collilieux

- Joint production of the IAG & FIG
- Based on experience of several RFIP workshops
- Released at FIG Congress, KL, Malaysia, 16-21 June 2014
- Available from *http://www.fig.net/pub/figpub/pub64/Figpub64.pdf*



GNSS, Modern Geodesy & Reference Frames

Access & Alignment to the ITRF

- Direct use of ITRF coordinat
- Use IGS Product y
  at curr

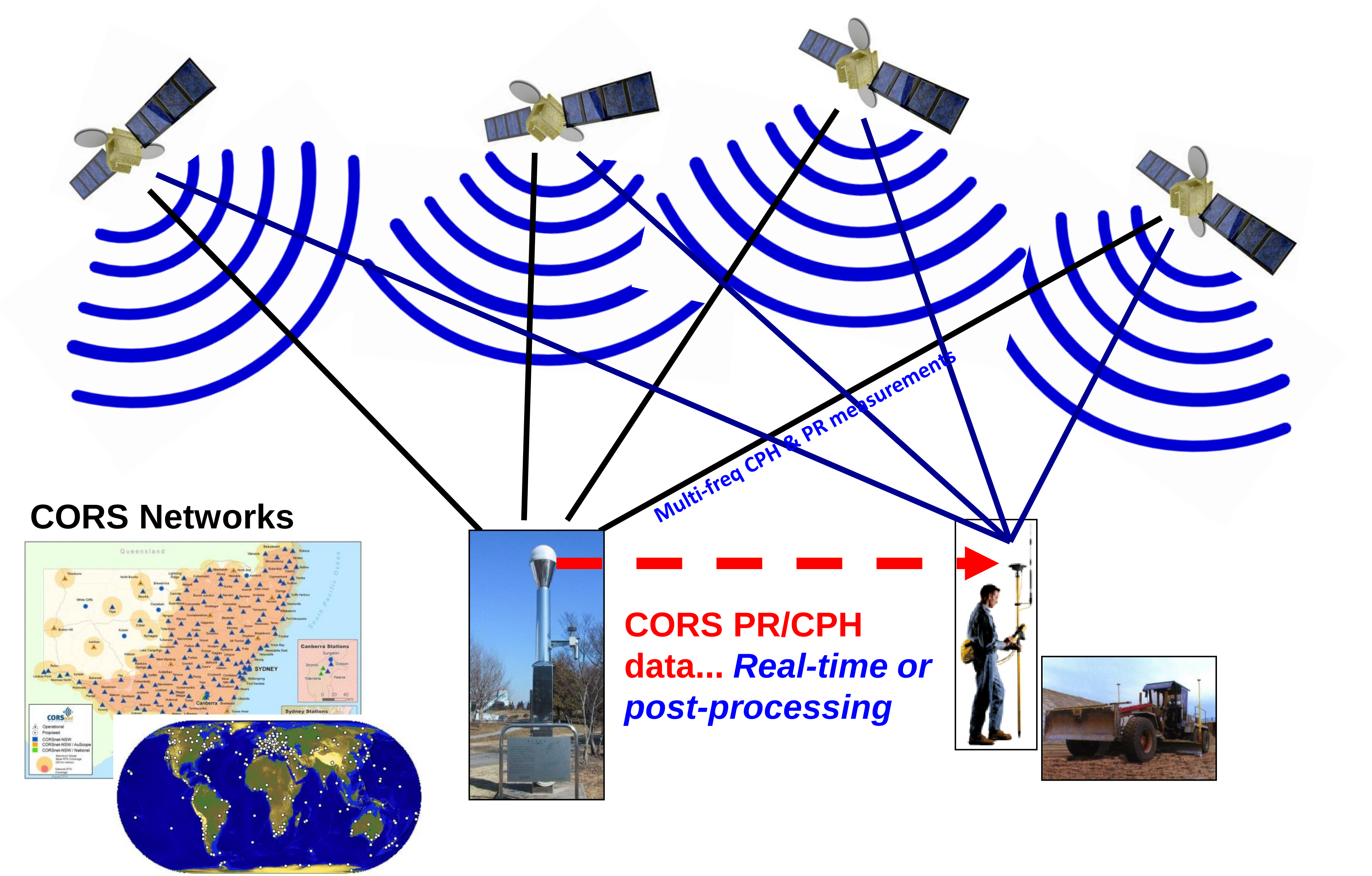
Can use web-based RINEX processing to obtain coords in ITRF2008/IGb08 (soon ITRF2014/IGS14)

bal stations in free

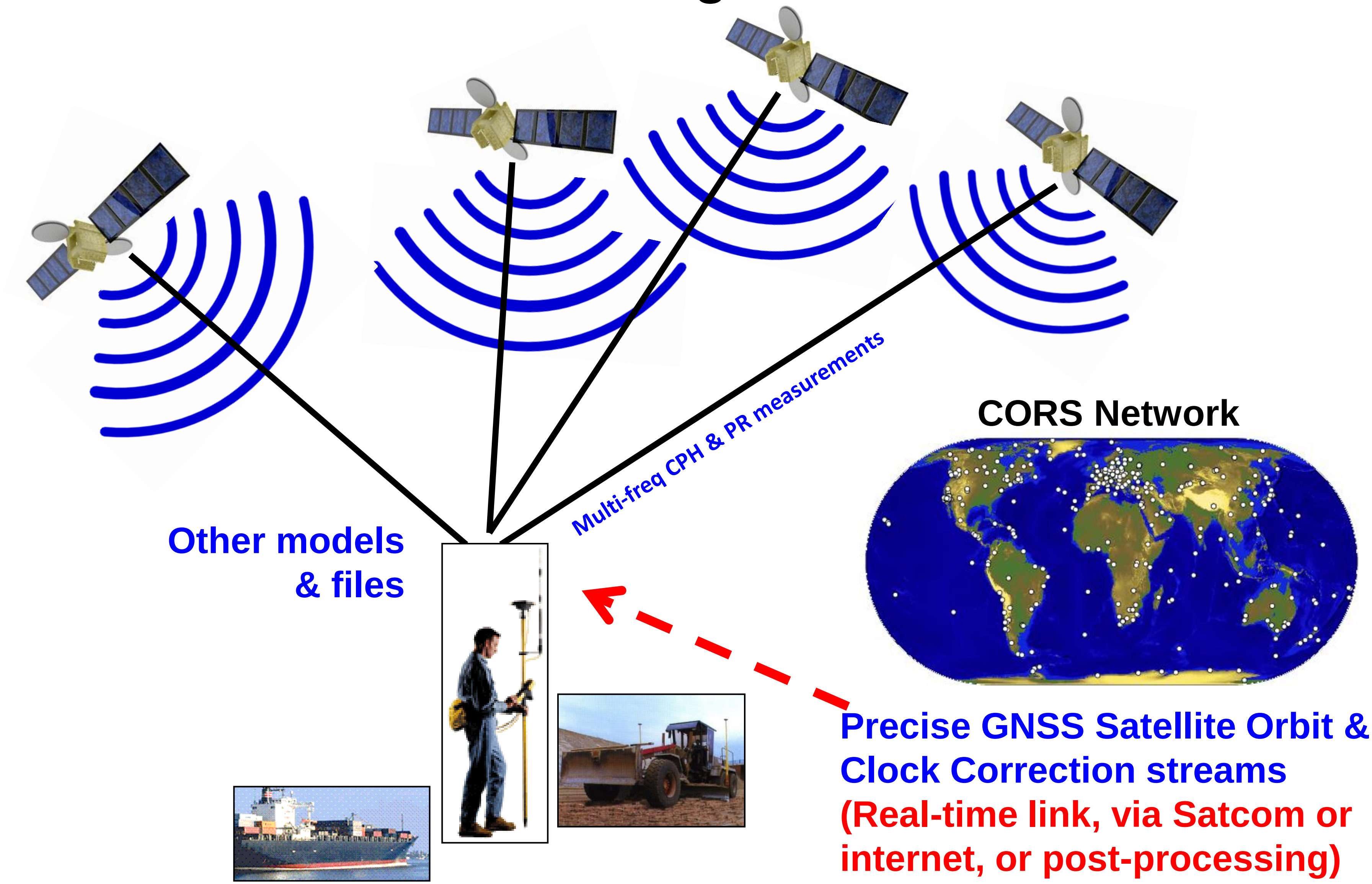
g station coordinates to ITRF values at the central
poch of the observations

- Using minimum constraints approach

Differential positioning (CPH)



Precise Point Positioning (PPP)



GNSS Web Processing…

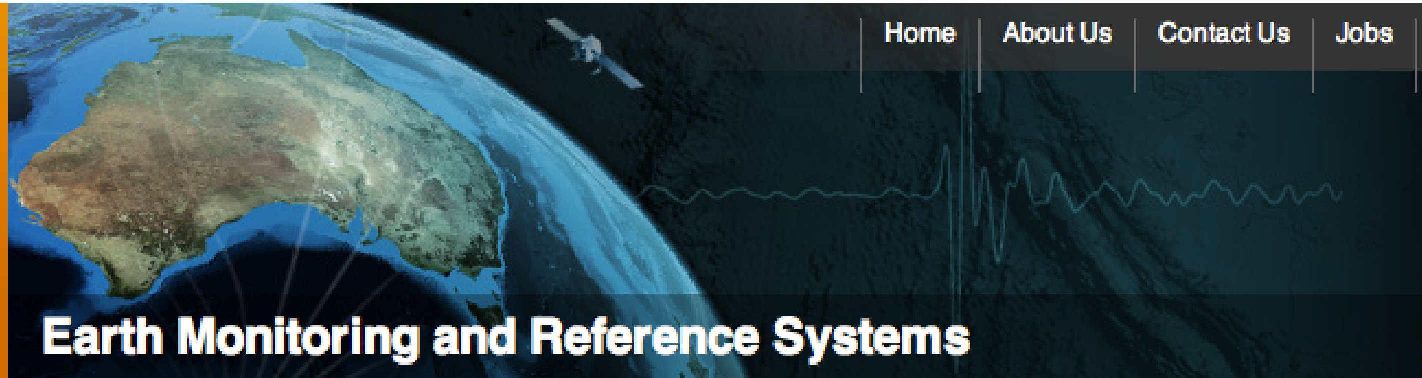
- LINZ *http://www.linz.govt.nz/positionzpp*
- NGS *http://www.ngs.noaa.gov/OPUS/*
- Geoscience Australia *http://www.ga.gov.au/scientific-topics/positioning-navigation/geodesy/auspos/*
- Trimble *http://www.trimblertx.com/*
- UNB *http://gaps.gge.unb.ca/*
- JPL *http://apps.gdgps.net/apps_file_upload.php*
- NRCAN *http://www.nrcan.gc.ca/earth-sciences/geomatics/geodetic-reference-systems/tools-applications/10925#ppp*
- GM
- SO

PositioNZ - Post Processing Service

The LINZ PositioNZ Post Processing Service (PositioNZ-PP) is a free automated service that processes GNSS data to obtain NZGD2000 coordinates.

It creates time savings for surveyors by providing highly accurate positioning information based on LINZ's national network of continuously operating reference Global Navigational Satellite Systems (GNSS) stations. It means users do not need their own specialised GNSS processin

ITRF coords based on IGS frame (IGb08) @ observation epoch... Also national datum NZGD2000 (@ 2000.0 nominal epoch)



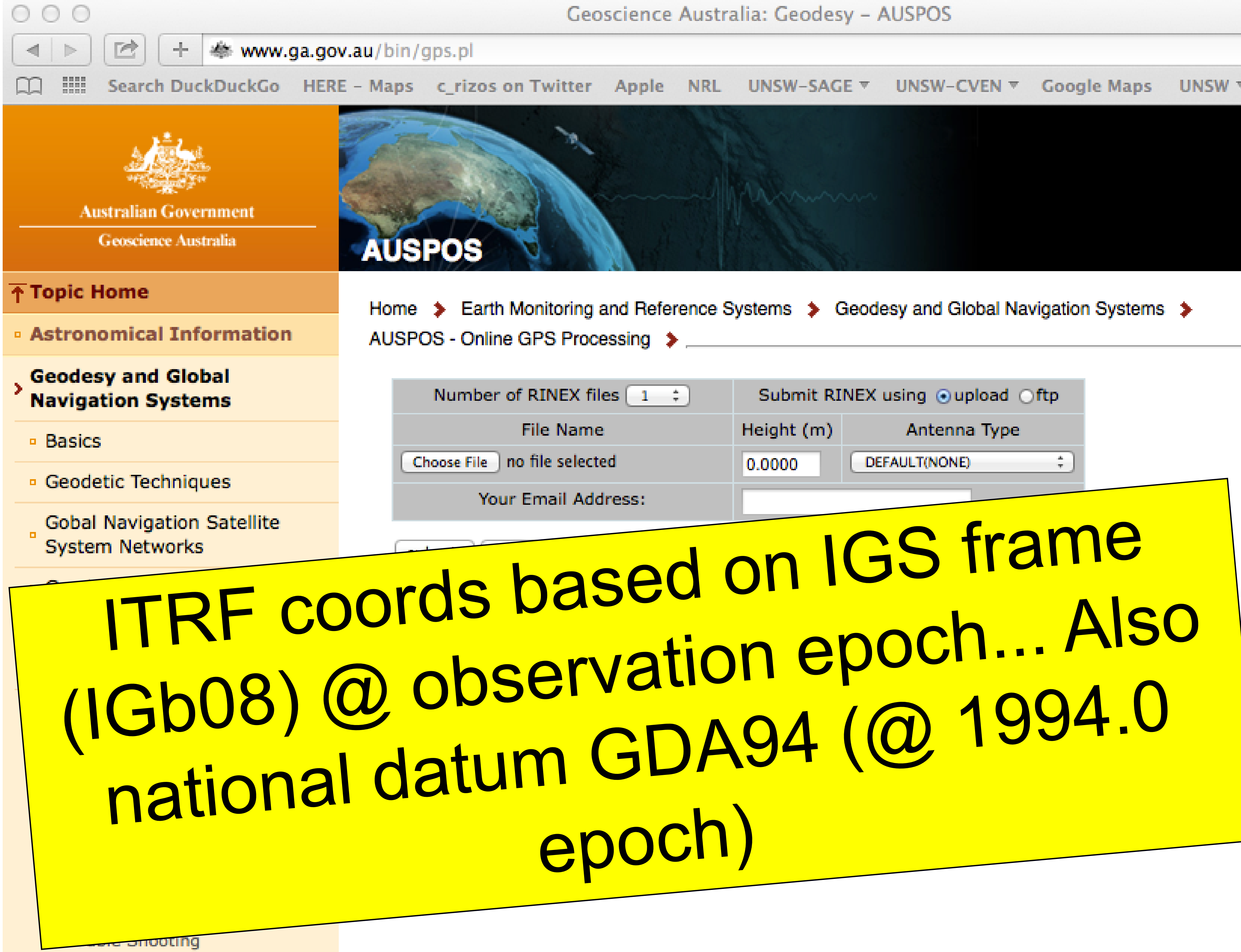
AUSPOS - Online GPS Processing Service

- AUSPOS is a free online GPS data processing facility provided by Geoscience Australia
- AUSPOS takes advantage of both The IGS Stations Network and the IGS product range
- AUSPOS works with data collected anywhere on Earth
- Users submit their dual frequency geodetic quality GPS RINEX data observed in a 'static' mode to the GPS data processing system
- An AUSPOS report will be emailed to you (often in less than 5 mins) containing Geocentric Datum of Australia 1994 (GDA94) and International Terrestrial Reference Frame (ITRF) coordinates

AUSPOS Submission Checklist

Before submitting your GPS RINEX file/s, please ensure:

1. The GPS RINEX file/s contains more than one hour (preferably two) of GPS data
2. The GPS RINEX file/s do not contain any data from the current UT day
3. The GPS RINEX file/s do not contain more than seven days of data
4. The GPS RINEX file/s names do not contain spaces
5. When submitting multiple files, ensure the first four characters / numbers of the file names are not the same
6. You have used the IGS naming convention for the antenna type (refer the National Geodetic Survey (NGS) for more information)
7. The antenna height provided is the vertical distance from the ground mark to the Antenna Reference Point (ARP)



ITRF coords based on IGS frame (IGb08) @ observation epoch… Also national datum GDA94 (@ 1994.0 epoch)

OPUS: the Online Positioning User Service, process your GNSS data in the National Spatial Reference System

www.ngs.noaa.gov/OPUS/about.jsp

OPUS: Online Positioning User Service

National Geodetic Survey

OPUS Menu

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website upgrade expected late Wednesday 19 June

Improved page layout & link to prior frame on published solutions. Enjoy, and **please report any issues**.

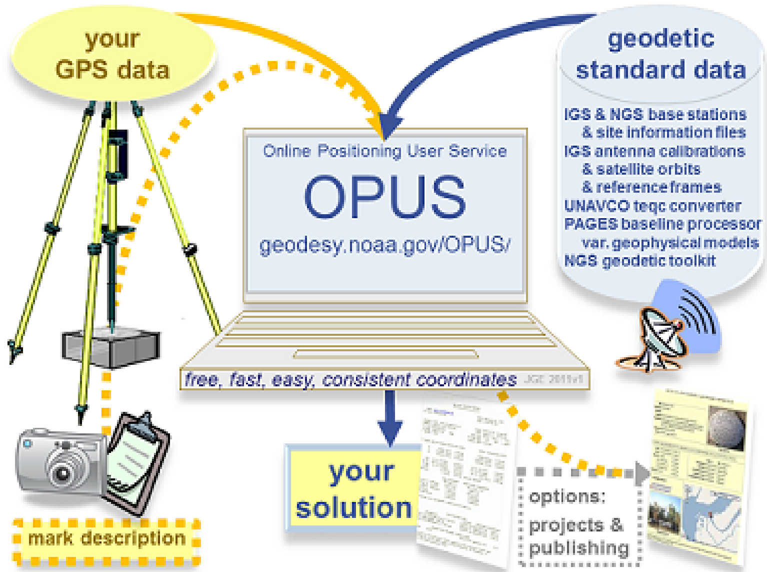
What is OPUS?

This Online Positioning User Service provides simple access to high-accuracy National Spatial Reference System (NSRS) coordinates. Upload a data file collected with a survey-grade GPS receiver and obtain an NSRS position via email.

OPUS requires minimal user input and uses software which computes coordinates for NGS' Continuously Operating Reference Station (CORS) network. The resulting positions are accurate and consistent with other NSRS users.

Your solution is sent privately via email, and, if you choose, can also be shared publicly via the NGS website. To use properly, please familiarize yourself with the information below.

See also **OPUS one-pager** and **observer field log**.



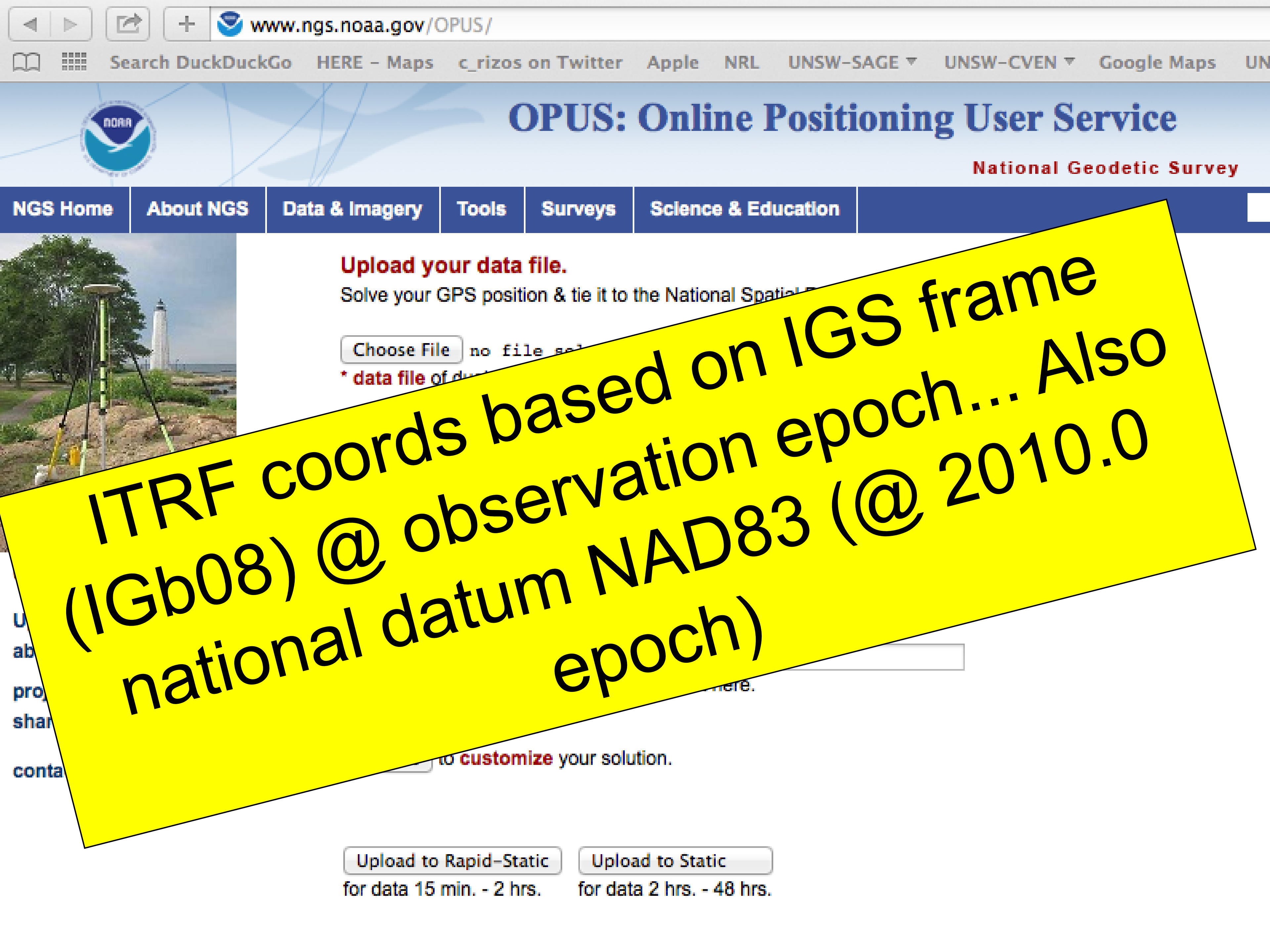
Upload

top ↑

Using OPUS requires just five simple steps:

Data File of dual-frequency GPS (L1/L2) full-wavelength carrier observables:

- Static data only; the antenna must remain unmoved throughout the observing session.
- 15-minutes of data or more, up to 48-hours, but not crossing UTC midnight more than once.
- Files under 2 hours, processed as rapid-static, must include the P2 and either P1 or C1 observables.
- GLONASS or Galileo observables may be included; though only the GPS are used.



www.ngs.noaa.gov/OPUS/
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Apple
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UNSW-SAGE
UNSW-CVEN
Google Maps
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Science & Education
Upload your data file.
Choose File
to customize your solution.
Upload to Rapid-Static
for data 15 min. - 2 hrs.
Upload to Static
for data 2 hrs. - 48 hrs.
ITRF coords based on IGS frame (IGb08) @ observation epoch… Also national datum NAD83 (@ 2010.0 epoch)

Tools and Applications

Natural Resources Canada's Canadian Geodetic Survey (CGS) provides several geodetic tools and their corresponding desktop applications, enabling accurate positioning, heights and coordinates transformations.

The Canadian Spatial Reference System (CSRS) Precise Point Positioning (PPP) tool allows the computation of higher accuracy positions of raw Global Navigation Satellite System (GNSS) data, the GPS·H tool performs the conversion of ellipsoidal heights to orthometric heights, the TRX tool performs transformation of coordinates, INDIR does geodetic Direct (computes the geographic coordinates of the end point) or Inverse (computes distance and azimuth between two points) computations and finally, the NTv2 tool allows for the transformation of coordinates between the North American Datums (NAD) of 1927 and 1983 reference systems. Note that the GSRUG and TRNOBS applications have been discontinued and replaced by TRX.

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Desktop Applications
Satellite Imagery and Air Photos
Canada's Spatial Data Infrastructure
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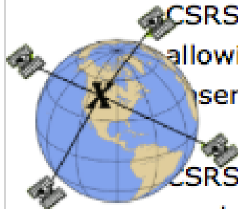
CSRS-PPP



CSRS-PPP is an online application for GNSS data post-processing allowing users to compute higher accuracy positions from their raw observation data.

CSRS-PPP uses the precise GNSS satelli... produce corrected coordin... matter where ... ha...

ITRF coords based on IGS08 frame (IGb08) @ observation epoch... Also national datum NAD83(CSRS) (@ 1997.0, 2002.0, 2010.0 epochs)

Go to CSRS-PPP online tool

...nning the tool

1. Enter email address to which the processing results will be sent
2. Select the processing mode: static or kinematic
3. Select the reference frame of the output coordinates: NAD83 or ITRF

- If NAD83 is the selected reference frame, choose an epoch (see Epochs)

Assuming you have created a valid RINEX observation file from your raw GNSS observation data:

GPS/GNSS Global Satellite D...

Relative positioning uses datum defined by coordinates of CORS station(s)... *no matter what ephemeris is used*

Ideal for propagating national datums that are "static" (i.e. plate-fixed)...

Can then transform to any other national or international datum and epoch...

- R... GNSS ephemerides:
  – **broadcast**... (<1m accu...

Absolute (single-point) positioning datum defined by coordinates of GNSS ephemerides used

These are typically ITRF-based, at observation epoch...

Can then transform to any other national or international datum and epoch...

* GLON... different GNSS datums defined also by their own CS

GNSS Web Processing... *Datums*

Services	Datum
OPUS	• Geodetic, GRS80 Ellipsoid, Cartesian, UTM, **ITRF2008** • **NAD_83(2011)(@2010.0000)**
AUSPOS	• Geodetic, GRS80 Ellipsoid, MGA Grid, Cartesian, **GDA94** • Geodetic, GRS80 Ellipsoid, Cartesian, **ITRF2008**
TrimbleRTX	• **ITRF1988, 1989, 1990, 1991, 1992, 1993, 1994, 1996, 1997, 2000, 2005, 2008** • **NAD83, NAD83-CSRS, NAD83-CORS96, NAD83-2011, NAD83-MA11, NAD83-PA11** • **ETRS89,ETRF2000-R05** • **GDA94** • **SIRGAS2000, SIRGAS95, SIRGAS-CON**
UNB	• Geodetic, GRS80 Ellipsoid, **ITRF2008**
JPL	• Geodetic, GRS80 Ellipsoid, **ITRF2008**
NRCAN	• Geodetic, GRS80 Ellipsoid, UTM coordinates, **ITRF2008** • **NAD83(CSRS)(@1997.0)(@2002.0)(2010.0)**
GMV	• Geodetic, GRS80 Ellipsoid, **ITRF2008** • **ETRS89**
SOPAC	• Geodetic, GRS80 Ellipsoid, **ITRF2008**
PositioNZ-PP	• Geodetic, GRS80 Ellipsoid, Cartesian, **ITRF96, ITRF2008** • Geodetic, GRS80 Ellipsoid, NZTM, Meridional Circuit, **NZGD2000**

GNSS Web Processing... *Data processing*

	Remark	Input Data	Method
OPUS	• GPS	Static (2-48hr), rapid-static (15min-2hr), dual-freq RINEX v2 files	Baseline
AUSPOS	• GPS	Static (min 1hr), dual-freq RINEX v2 files (>2hr recommended)	Baseline
TrimbleRTX	• GPS • GLONASS • QZSS • BeiDou	Static, dual-freq RINEX v2 & v3 files, BeiDou only PRN greater than or equal to 6 (not including GEO satellites)	PPP
UNB	• GPS	Static or kinematic, dual-freq RINEX v2 files, Some control over processing options	PPP
JPL	• GPS	Static or kinematic, single- or dual-freq RINEX v2 files	PPP
NRCAN	• GPS	Static or kinematic, single- or dual-freq RINEX v2 files (2-24hr static recommended)	PPP
GMV	• GPS • GLONASS	Static or kinematic, dual-freq RINEX v2 files	PPP
SOPAC	• GPS	Static (min 1hr), dual-freq RINEX v2 files (>3hr recommended)	Baseline
PositioNZ-PP	• GPS	Static (min 1 hr, recommended 4 hr), dual freq RINEX v2 files	Baseline