Long-term stability and parameterization of the reference frame

Session 3

Agenda:
16h00 – 17h30

- This presentation : X. Collilieux D. Thaller and various contributions
- R. Haas, thermal deformation at Onsala VLBI telescope
- Discussions

Acknowledgments (by alphabetic order):
Z. Altamimi, S. Bachmann, P. Charlot, S. Lambert, D. Lercier, L. Métivier, J. Ray

Part 1

ITRF parametrization

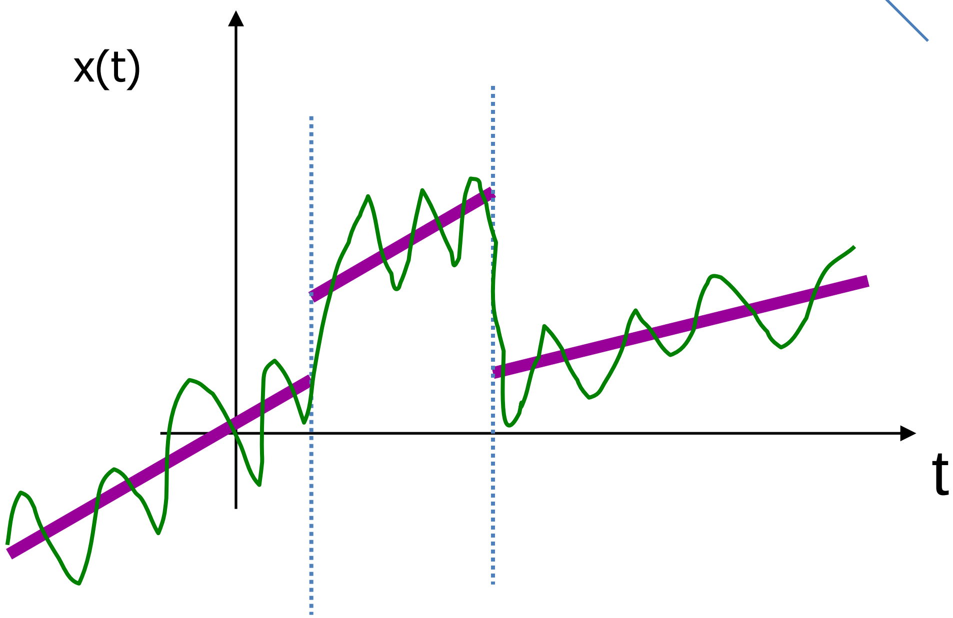
Tectonic motions

ITRF parameterization

Current modeling

$$X^i_{inst}(t) = \boxed{X^i_{ITRF}(t)} + \boxed{\sum_j \Delta X^i_j(t)}$$

(IERS conventions)



Collection of models recommended by the IERS conventions

ITRF parameterization – tectonic motions

Co-seismic deformation

➢ Earthquakes may generate offset in position time series from Mw = 5.0 *(Blewitt et al. 2012)*. 53393 EQs since 1980 according to NEIC USGS database

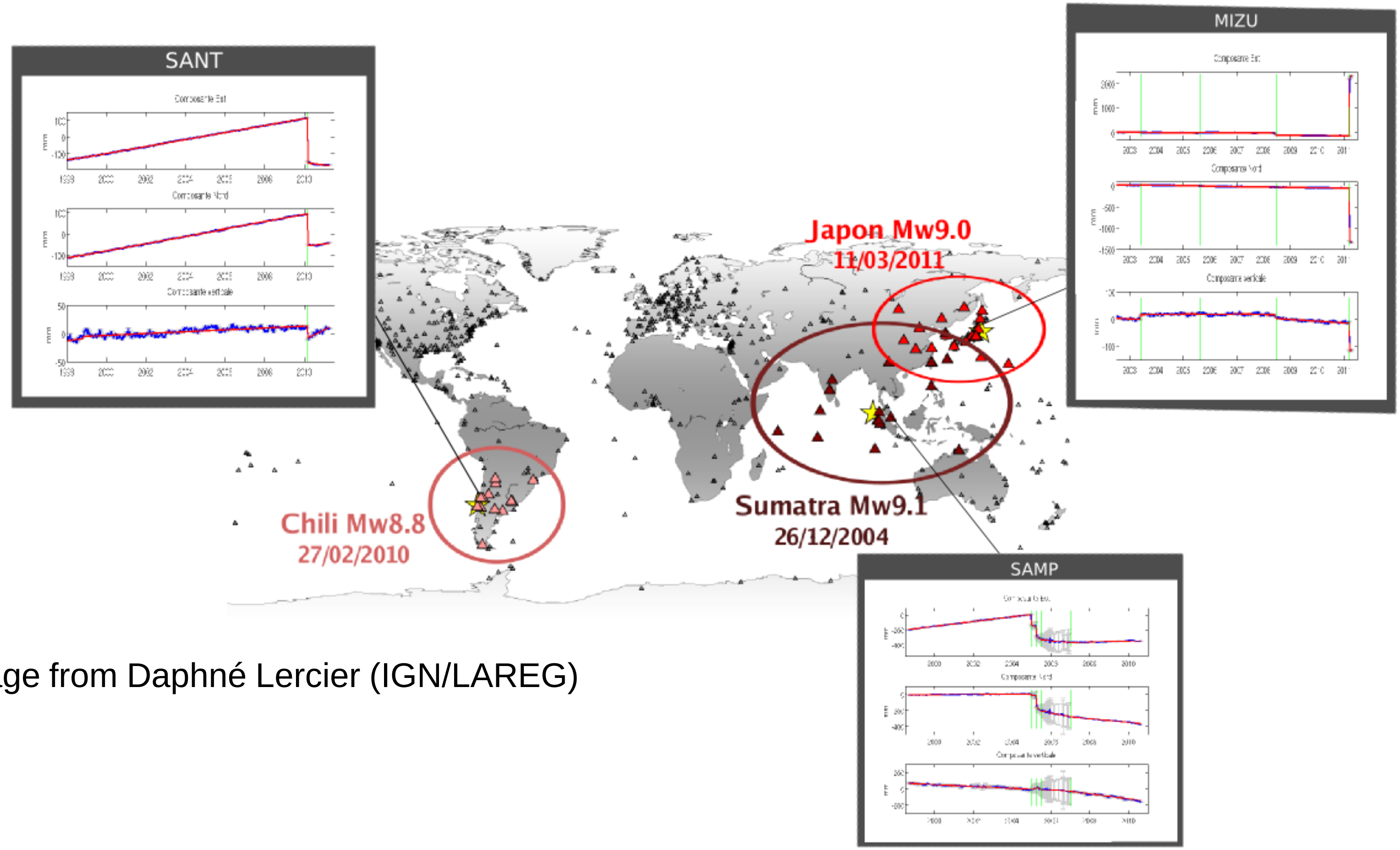


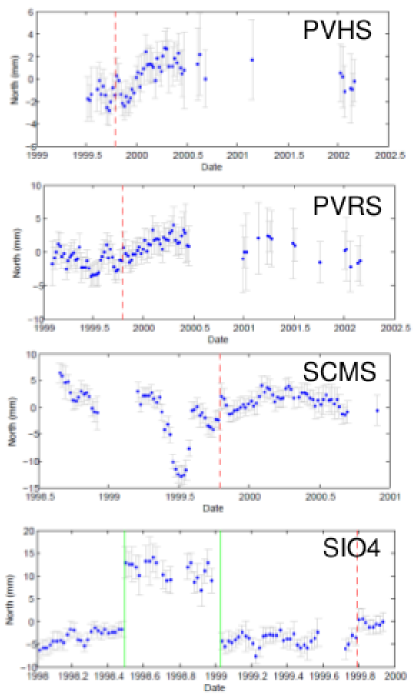
Image from Daphné Lercier (IGN/LAREG)

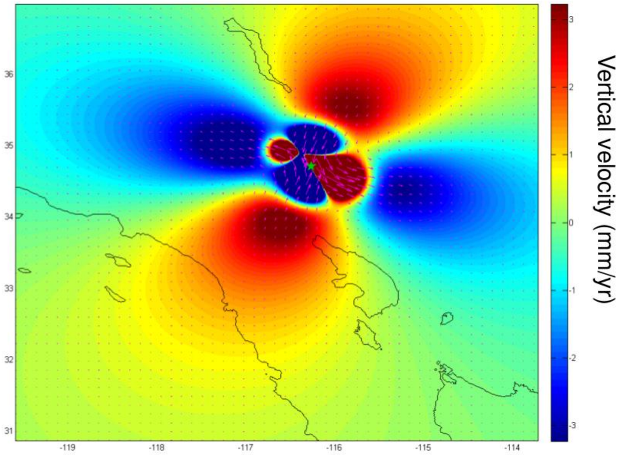
ITRF parameterization – tectonic motions

Co-seismic deformation

• Magnitude of the effect: from sub-millimeters to meters. Difficult to detect when the amplitude is small

Ex:





Métivier et al. (2013)

Fig. 2: Ground displacement induced by Hector Mine (HM) earthquake the October 16th 1999, determined from co-seismic modelling. The green star show the location of source. The colours stand for vertical displacement and pink arrows for horizontal displacements

See also Tregoning et al. (2013)

ITRF parameterization – tectonic motions

Co-seismic deformation

- How to deal with these effects when detected ?
  - ➢ Same discontinuity list for co-located sites (identical epochs!)
  - ➢ 2 solution numbers should be introduced in the SINEX (done by IGS)

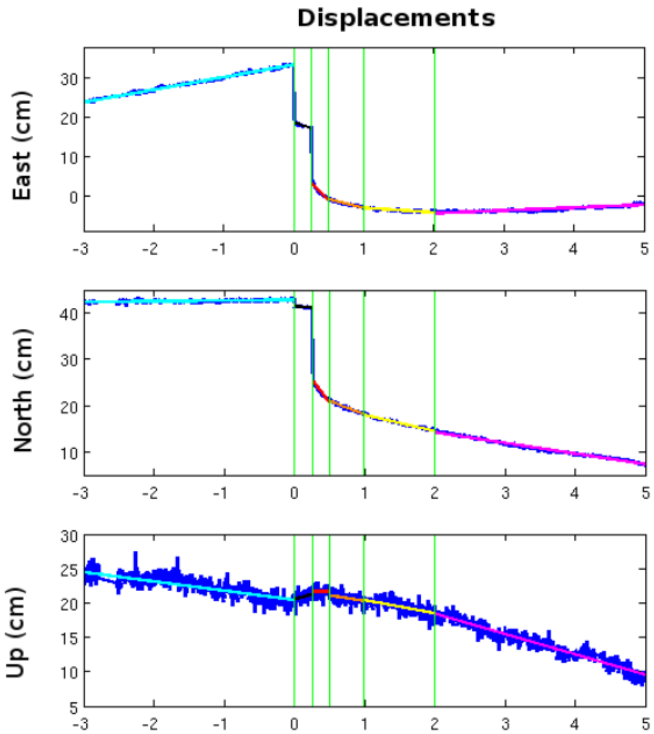
- How to detect co-seismic offsets?
  - ➢ PPP sub-daily solutions
  - ➢ IGS realtime service
  - ➢ Web service to supply co-seismic deformation maps

ITRF parameterization – tectonic motions

Inter and post-seismic deformations

$$X^i_{inst}(t) = X^i_{ITRF}(t) + \sum_j \Delta X^i_j(t)$$ *(IERS conventions)*

Like for any non-linear effect that do not include sub-weekly variations. Should the effect be included in: ITRF coordinates? a recommended geophysical model?



<u>Current handling:</u> in ITRF coordinates

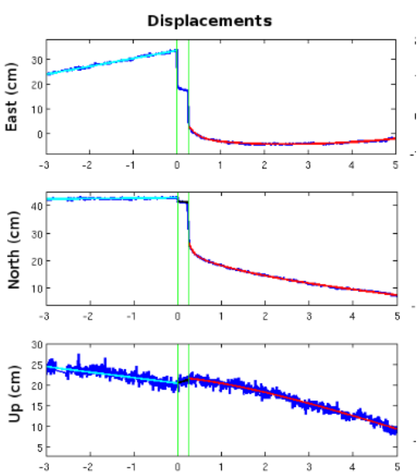
- Consistency between space-geodetic techniques at co-located sites required (identical epochs for the events)
- Continuity of position time series as long as there is no co-seismic (or equivalent) event

ITRF parameterization – tectonic motions

Inter and post-seismic deformations

$$X^{i}_{inst}(t) = X^{i}_{ITRF}(t) + \sum_{j} \Delta X^{i}_{j}(t)$$ *(IERS conventions)*

Like for any non-linear effect that do not include sub-weekly variations. Does the effect be included: in ITRF coordinates? In a recommended geophysical model?



© D. Lercier

Fig. Parametric modeling of the station coordinates

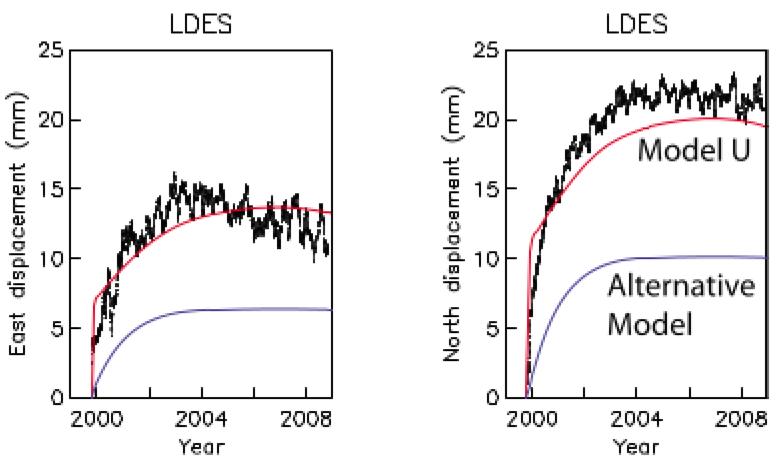


Fig. Observed vs. Modeled displacements as a function of two visco-elastic structures *(Pollitz and Tahtcher, 2010)*

- ➢Description of function in SINEX format?
- ➢The position time series has to be reconstructable!

Part 2

ITRF parametrization

Loading effects

ITRF parameterization – Loading effects

Non-tidal loading effects

Surface fluid mass motions

mass + motion changes →

EOP variations
(polar motion, LOD excitation)

mass (load) changes →

Terrestrial frame effects:

- CM/CF relative origin shifts (“geocenter motion”)
- station displacements (CF)

mass (geopotential) changes →

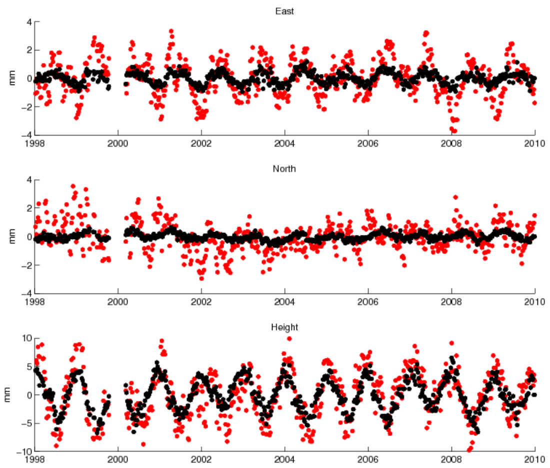
Satellite orbit perturbations

© *J. Ray*

ITRF parameterization – Loading effects

Non-tidal loading effects

• Fluid contributions are usually separated (hydrology, ocean, atmosphere) but exchanges between the « different layers » exist



Collilieux et al. (2011)

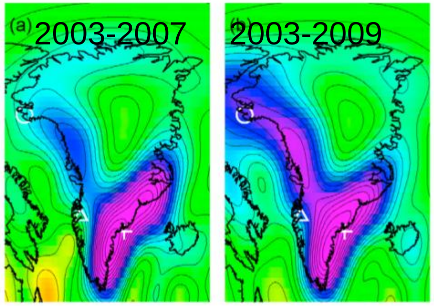
Raw GPS (IGS combined)

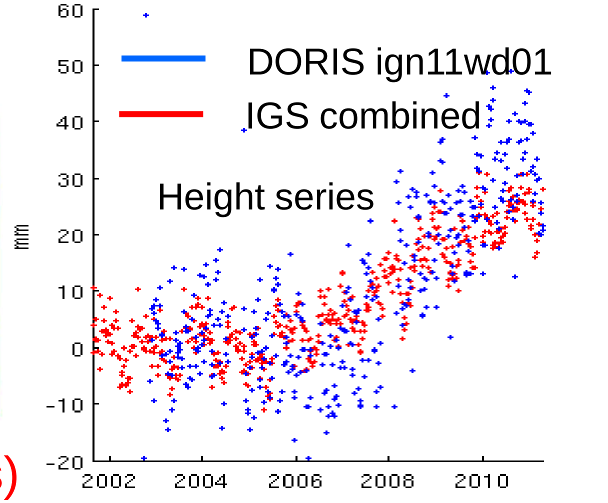
Load model (sum of the three main contributions)

Ex: YAR2 (Australia)

• Sometimes missing contributions in the models (ex: ice).

Khan et al., (2010)





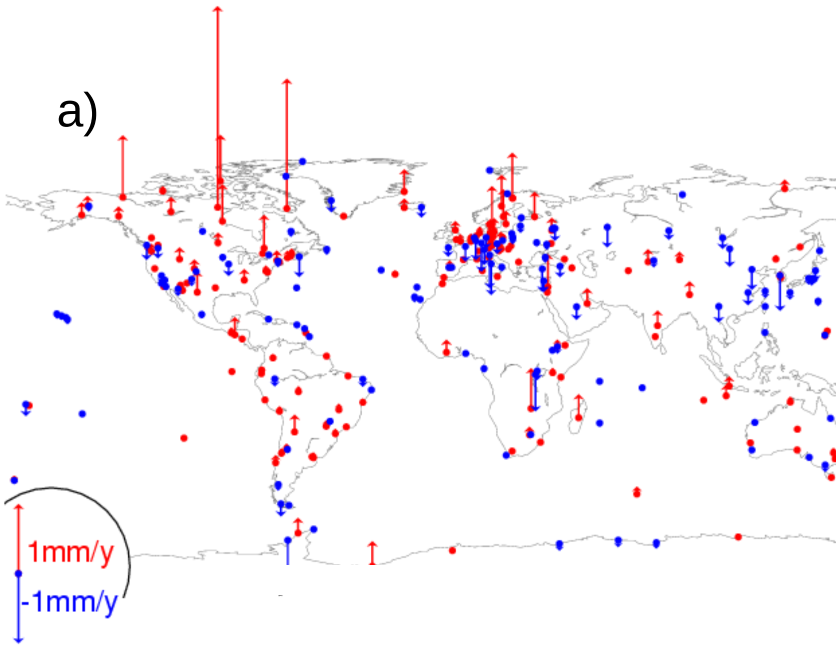
➢ Supply displacement models for ice melting area (poles)

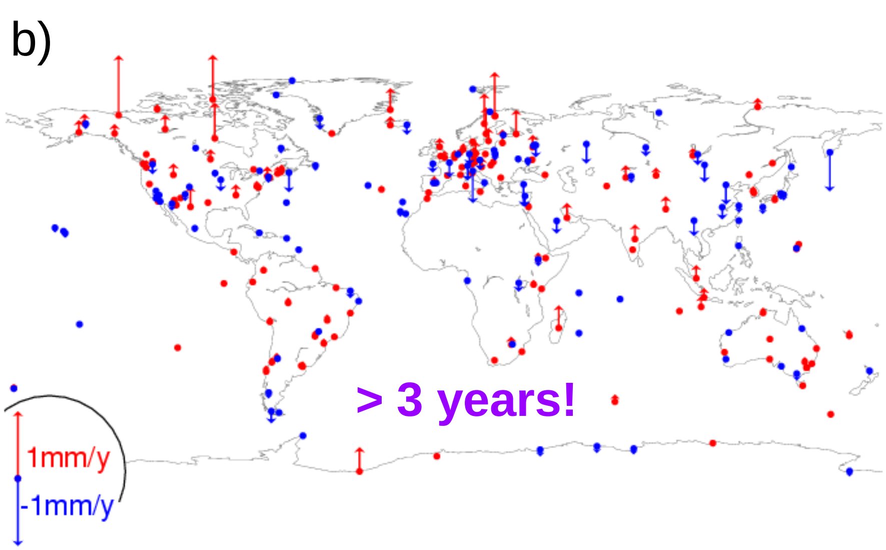
ITRF parameterization – Loading effects

Non-tidal loading effects

- Trends in the models. EX: non-tidal atmospheric loading model (van Dam)

IERS campaign (Collilieux et al., 2013)





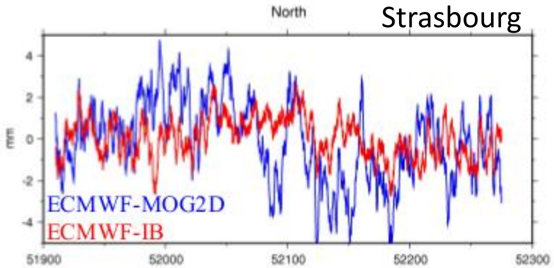
Vertical velocity differences from two multi-technique combinations. With or without NT-ATML applied.
a) all stations b) obs. greater than 3 years

ITRF parameterization – Loading effects

Non-tidal loading effects

- Non-tidal models are **not** IERS Class 1 type (i.e., not essential & required *a priori*)
  - see IERS Conventions (2010) Introduction
  - still considered useful though. Need < 1 mm accurate models

- Many models available (Petrov and Boy, van Dam, Boy, Wijaya et al. (TU-Wien), Eiksson and MacMillan etc…)
  - Differences between models can be significant



(Boy, ETS 2006)

Fig. North displacement series using IB assumption or MOG2D ocean model (CM)

- ➢ Differences and consistency between the models have to be quantified
- ➢ Are combined models useful? (successful for polar motion cf. Chen et al.; 2013)
- ➢Define unified file formats for providing loading corrections (either gridded or station-specific models)

ITRF parameterization – Loading effects

Non-tidal loading effects

- How should the IERS handle those effects?

❖ a priori if the models are accurate enough (in sub-daily/sub-weekly band)
The most accurate approach (solve potential aliasing problems)

SLR: Atmospheric loading induces systematic bias due to “Blue-Sky effect” (*Otsubo et al., 2004; Sosnica et al., 2013*)

Sosnica et al. (2012)

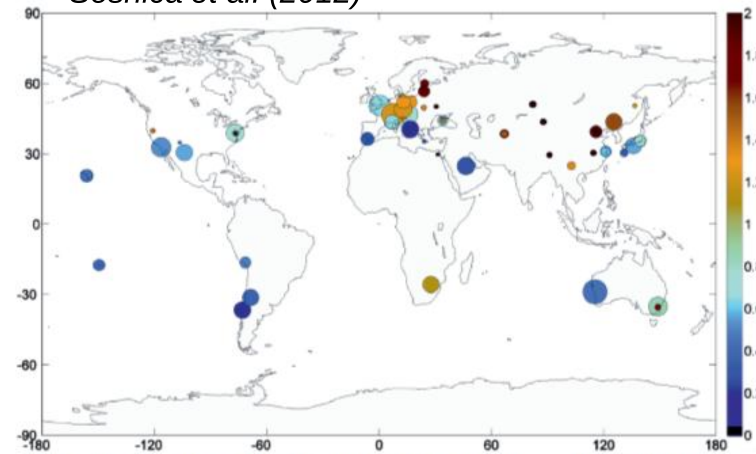


Fig. 4: The Blue-Sky effect on SLR stations as the difference between the mean atmospheric loading correction applied to SLR stations when SLR station observes, and the mean correction to SLR stations for the entire time series. Units: mm

NB: In addition to the expected origin change, slight origin change (sub-millimeter) has been noticed *(Dach et al., 2012; Collilieux et al., 2013)* but no long-term effect

➢ Store mean corrections in the SINEX if any non-recommended model is used (but also with recommended models if any in the future)

➢ Latency of the models for operational use

ITRF parameterization – Loading effects

Non-tidal loading effects

- How should the IERS handle those effects?

❖ a posteriori. Avoid adding extra-noise to the solutions.
Amplitude of sub-daily/sub-weekly signals gnerally smaller than longer periods
Best if corrections are added before the frame definition (NEQ level)
Warning: gravitational effect for satellite techniques! Ex: IDS approach (model gravity variations)

➢ More effective if observation epochs are available (especially important for non-continuous observing techniques, necessary for SLR) -> store mean corrections

For NT-ATML, a priori vs. A posteriori approaches are similar at the 0.2 mm WRMS in ITRF for each component for all techniques except for SLR (> 0.5 mm WRMS) (Collilieux et al., 2013)

➢ Should be compared to a priori with loading model including all contributions

ITRF parameterization – Loading effects

Non-tidal loading effects

- Consistency when using models

  ○ Consistency of background models used for generating the loading corrections as well as for the space-geodetic data analysis (e.g., handling of tidal loading part)

  ○ Consistency between ITRF long-term coordinates and loading displacement models. Any trends in the models could be added twice if ITRF computed without loading models

<u>NB:</u> Up to now. No datum change (long-term) ever reported when using loading model

  ○ Warning: possible conflict if a geocenter motion model is recommended by the IERS. Education/documentation necessary

Part 3

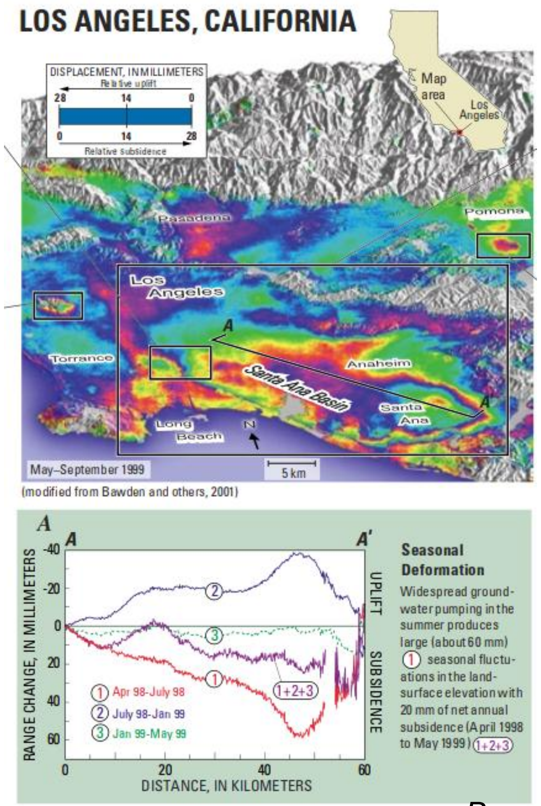
ITRF parameterization

Other effects

ITRF parameterization – Other effects

Anthropogenic effects

- Few examples



Bawden et al. (2001)

Example of INSAR vs. GPS series

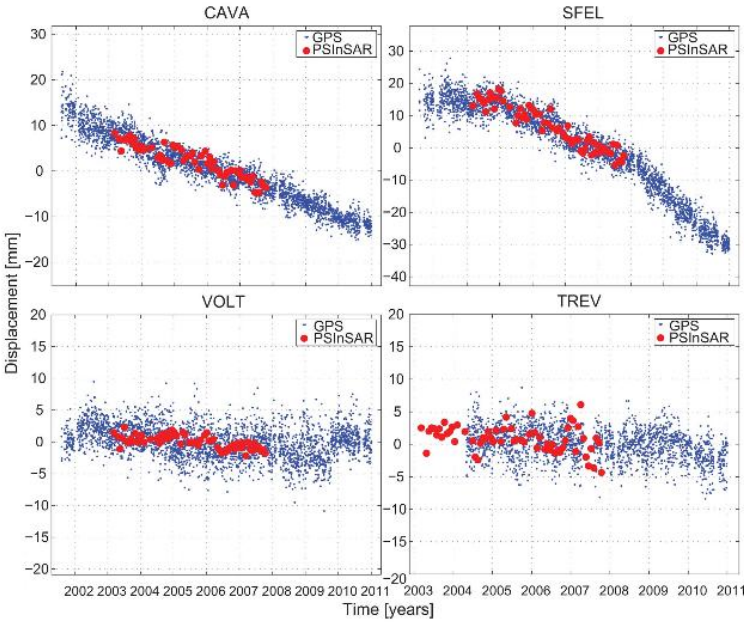


Figure 5. PSInSAR and CGPS time series projected along the satellite line of sight.

Bock et al. (2012) Venice Lagoon

Station managers feedback probably available ?

- ➢ Reject stations with « uncontrolled motion »?
- ➢ except if co-located. Consistency btw co-located instruments to be checked

ITRF parameterization – Other effects

Thermal deformation of the bedrock/monument

- Sub-millimeter effect.

Yan et al. (2009)

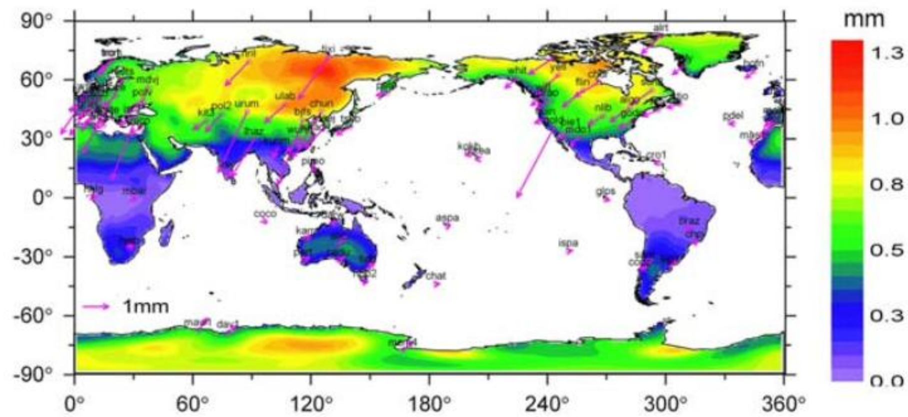


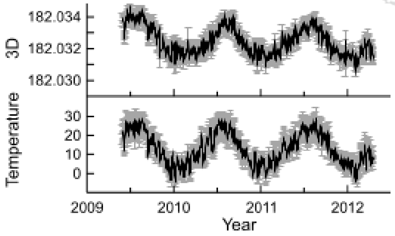
Figure 1. Annual amplitudes of bedrock thermal vertical displacements as determined from the model (contours) and annual thermal vertical displacement vectors for the 86 IGS stations. The vector amplitude A and phase φ are defined as $A\sin(\omega(t - t_0) + \varphi)$. Where t_0 is 1999.0 and ω is the annual circular frequency. The vector lengths represent the amplitudes. The phases are counted counterclockwise from the east.

- No clear correlation between GPS/Grace residuals and temperature *(Tesmer et al., 2011)*

ITRF parameterization – Other effects

Thermal deformation of the bedrock/monument

• Thermal expansion of building and monument. Example of YEBE-YEB1 baseline *(Santamaria-Gomez et al., 2012)*.
In this case, likely to be related to YEB1 building



➢ Any need to revisit guidelines for station manager to avoid/minimize deformations of the antenna mounting?
➢ Monitor short baselines at co-location sites (multiple GNSS sites, tie vectors (Haas et al., 2013))

• The IVS routinely applies thermal deformation corrections (Nothnagel, 2009). Also applied in tie surveys (Kallio, 2013)

➢ Easy access to continuous temperature series at VLBI sites and others

• What about thermal deformation for other technique instruments ?

ITRF parameterization – Other effects

Residual signals?

•Are they real motions? Technique specific?

<u>Ex:</u>
• DORIS and VLBI antenna tilts (either modeled or data rejected) for known effects
• GNSS equipment changes and unexplained offsets

➢ Check consistency at co-location sites.

• In some cases, they can be parameterized with simple functions. Ex: seasonal

➢ if estimated, should these residual signals be provided to the users?

ITRF parameterization – Other effects

Epoch frames?

• Epoch frames fit Earth's deformation but also residual technique specific errors. Coordinate variation should be the same for all techniques at the same site

• Best approach to tie technique specific frames (local ties, space ties) at weekly/monthly basis still under research

➢Could series of multi-technique combination help solving discrepancies at co-location sites?

➢How to use the epoch-specific frames in the analysis? parameterized motion of the stations, format definitions, software implementations, guidelines, etc. needed

Part 4

ICRF parameterization

ICRF parameterization

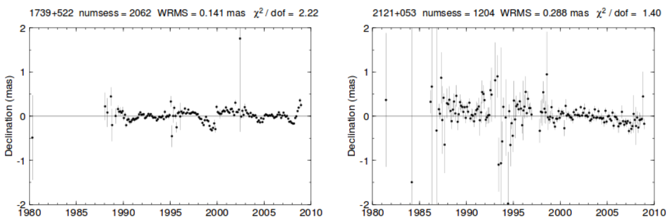


Fig. source coordinate series *(Fey et al., 2009)*

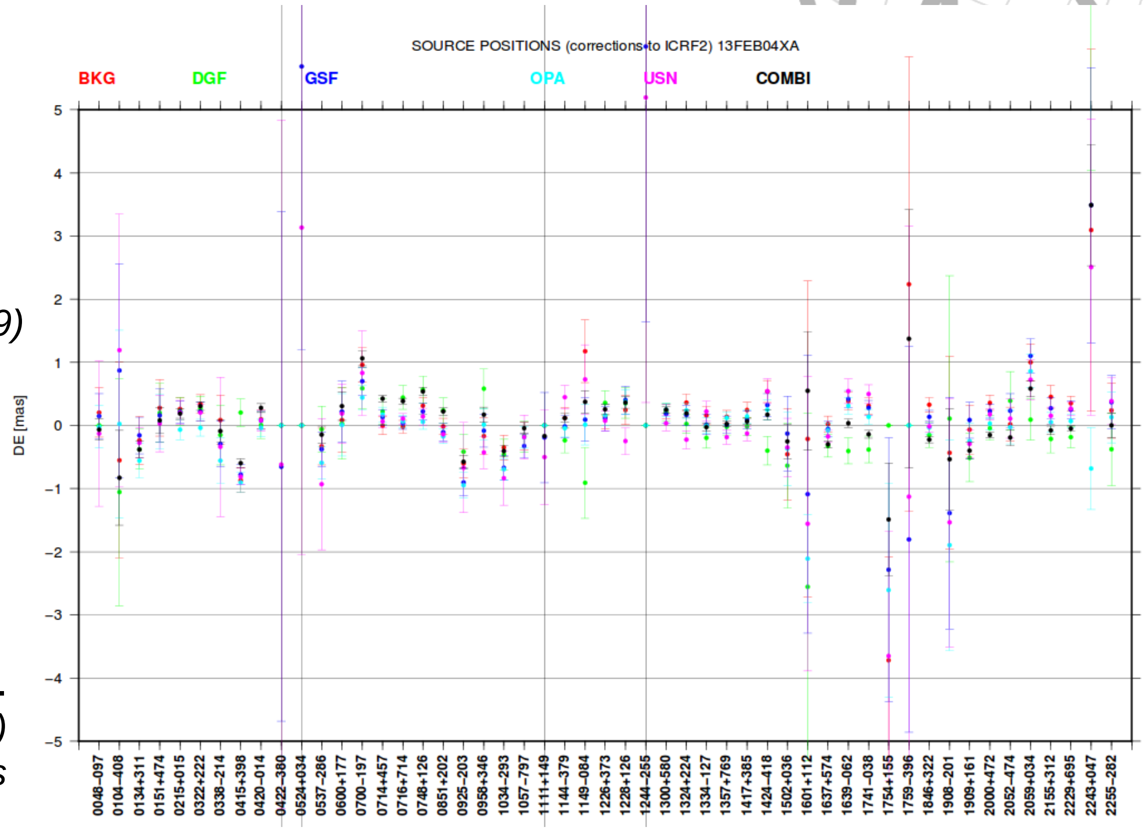
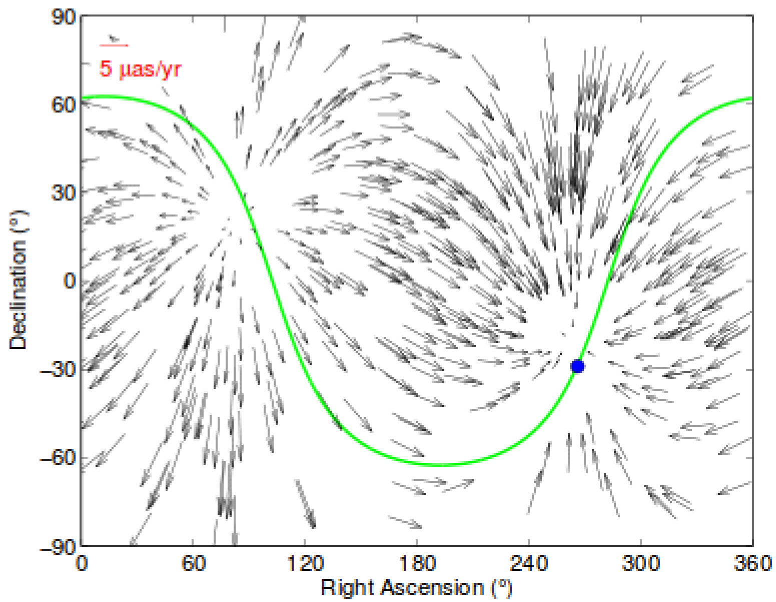


Fig. source declination differences w.r.t. ICRF2 session 13FEB04XA*(S. Bachmann)*
Similar figure for right ascensions

- No proper motion for radiosources expected but
  - Secular aberration
  - Source structure

ICRF parameterization

Secular aberration drift

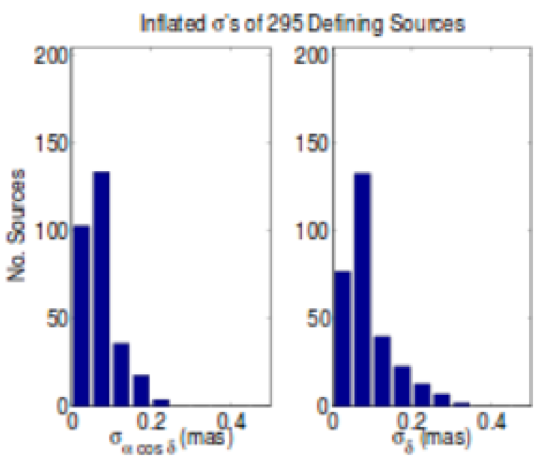


Titov et al. (2011)

- proper motion related to solar system movement w.r.t. galactic center: ~ 5 µas/yr Recently estimated by VLBI with comparable magnitude to the expectation

- up to 0.15 mas after 30 years compared to the formal errors of the sources coordinates:

(Fey et al., 2009)

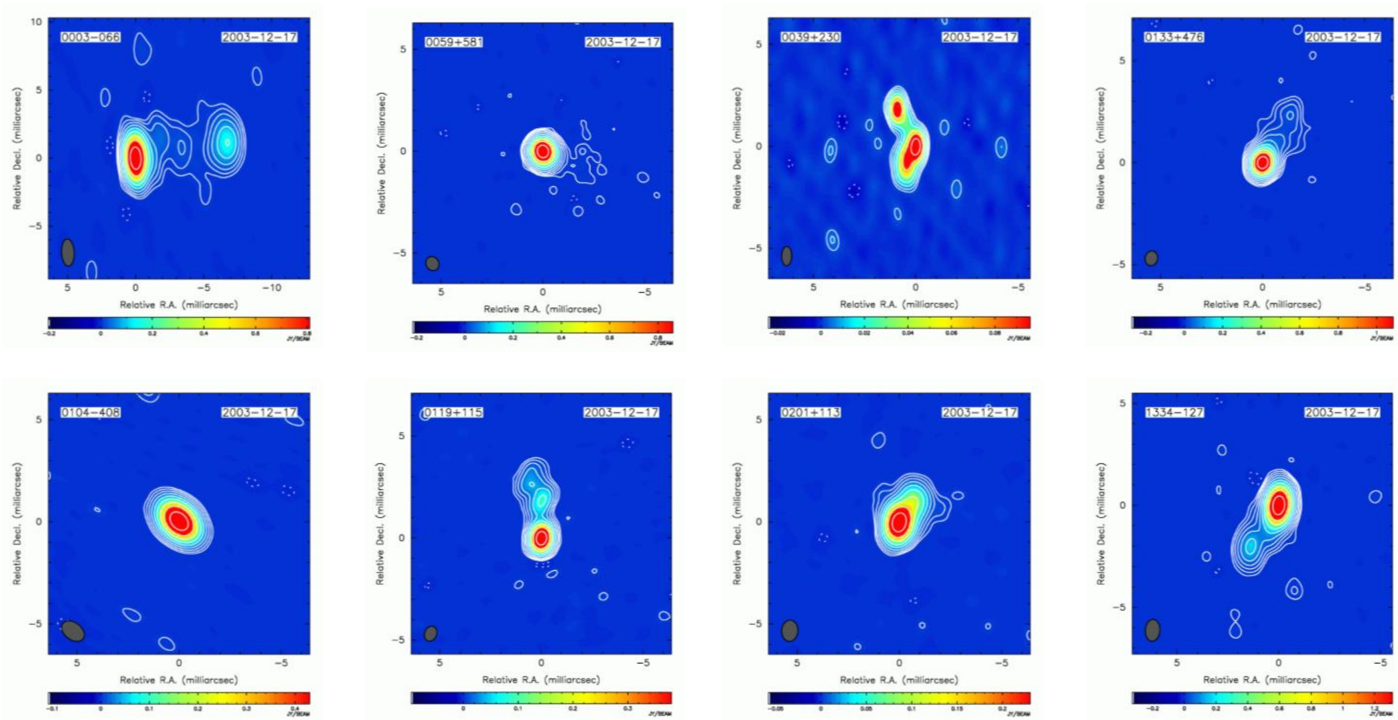


➢ supply source coordinate at a given epoch with corrective formula ?

ICRF parameterization

Source structure

- Not all radiosources are point-like
- Their structure generally varies with time

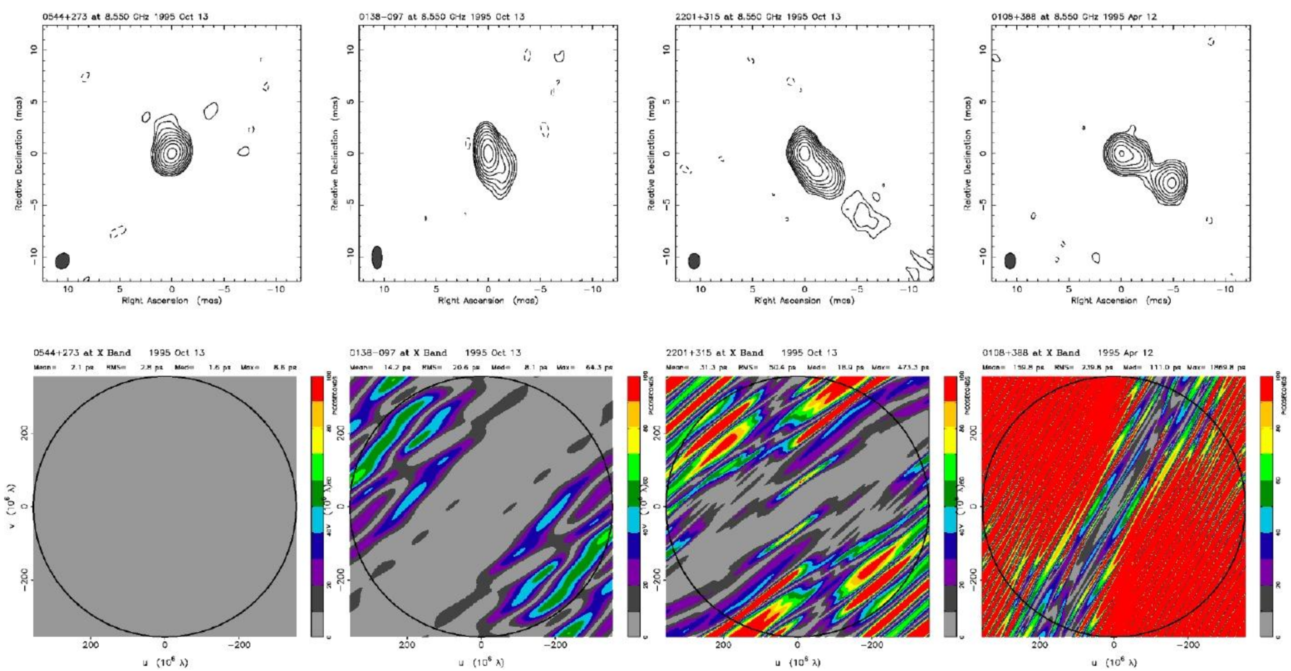


Two databases: Radio Reference Frame Image Database (RRFID) - USNO
Bordeaux VLBI Image Database (BVID)

ICRF parameterization

Source structure

The effect on the delay observable due to the source structure depends on the length and orientation of the VLBI baseline relative to the structure



Impact of the structure on the delay

http://www.obs.u-bordeaux1.fr/BVID

ICRF parameterization

Source structure

Requirements to model source structure

- High dynamic range VLBI maps at the proper epochs
  →Monitoring on short time scales

- Identification and accurate location of a compact feature (source core) that is stable over time
  →Misalignment directly translates into source position errors from epoch to epoch…
  →A few tens of μas accuracy desirable

- Proper registration of the S band and X band maps at the sub-mas level
  →Not so easy because of difference in resolution and opacity problems

- All data for a given source must be corrected (one cannot mix corrected and uncorrected data as otherwise it would look as different sources)

If these conditions are not met, it is best not to correct for source structure as otherwise it may make things worse than if not correcting…

ICRF parameterization

Source structure

<ins>The solution(s)…</ins>

- Use only the most compact sources
  → structure index < 3
  (IERS Technical Note 35)

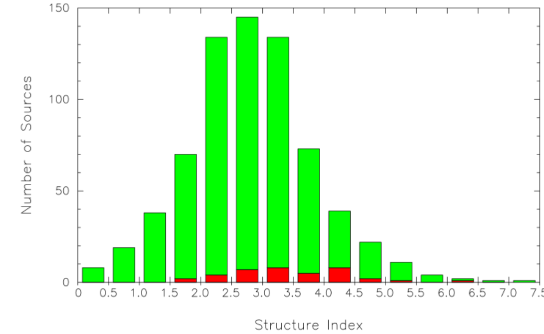
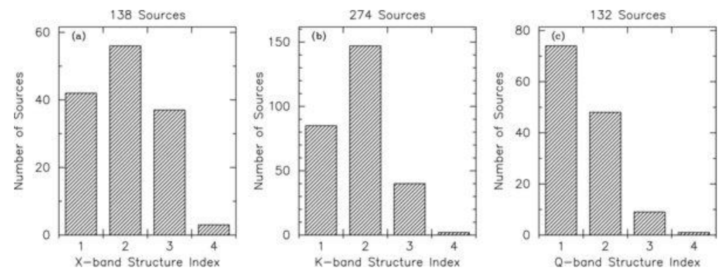
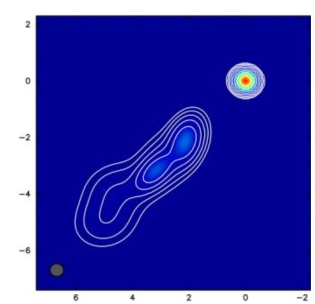


Figure 12: Distribution of the mean structure index for 701 sources with VLBI images available from the USNO Radio Reference Frame Image Database or the Bordeaux VLBI Image Database. The special handling sources discussed in §4 are color-coded in red.

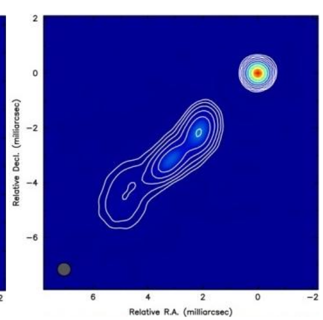
- Go to high frequency (sources more compact)
  → K band (22 GHz), Q band (43 GHz),…
  (Charlot et al. 2010)



- Wait for the next generation IVS network (VLBI2010)
  →Simulations show capability of producing high dynamic range images
  (Collioud & Charlot 2010)



Theoretical model



VLBI2010 simulated image

Thank you

Discussion

Part 1 : tectonic motions

- Same discontinuity list for co-located sites (identical epochs!), consistent post-seismic model (continuous functions) available to users
- 2 solution numbers should be introduced in the SINEX by ACs (done by IGS)
- PPP sub-daily solutions, IGS realtime service and/or Web service to supply co-seismic deformation maps

Part 2 : Loading

- Supply displacement models for ice melting area (poles)
- Differences between the models have to be quantified. combined models?
- Define unified file formats for providing loading corrections
- Store mean load corrections in the SINEX
- Latency of the models for operational use
- A posteriori should be compared to a priori with loading model including all effects

Discussion

Part 3 : Other motions

- Reject stations with « uncontrolled motion »? Check consistency at co-locations
- Any need to revisit guidelines to avoid/minimize deformations of monuments?
- Monitor short baselines at co-location sites (multiple GNSS sites, tie vectors…)
- if estimated, should any residual signals (technique error) be provided to the user?
- Supply information (quality code?) about station quality to the ITRF users
- Is multi-technique frame series the solution? How to use the epoch-specific frames in the analysis?

Additional comments

- Need updated and common metadata block in the SINEX (machine readable)
- If other than offset+drift parameterizations are adopted: the time series of station positions must be reconstructable
- New parameters needed in SINEX? New definitions needed for the parameters?

Part 4 : ICRF

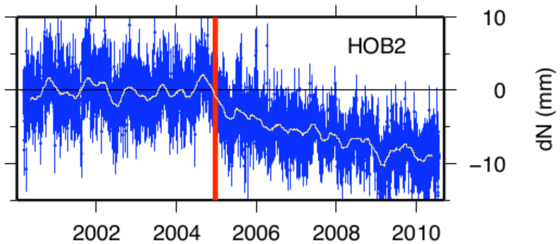
- supply source coordinate at a given epoch with corrective formula ?
- Need VLBI2010 capabilities (larger network, better geometry) for generating updated sequences of images?
- Research needed to assess the reliability of source structure corrections

Backup

ITRF parameterization – tectonic motions

Co-seismic deformation

- 3 cases:
  - only co-seismic offset (no velocity change)
  - offset + velocity change (at sub-decadal time scale)
  - offset + non-linear post-seismic



Tregoning et al. (2013)

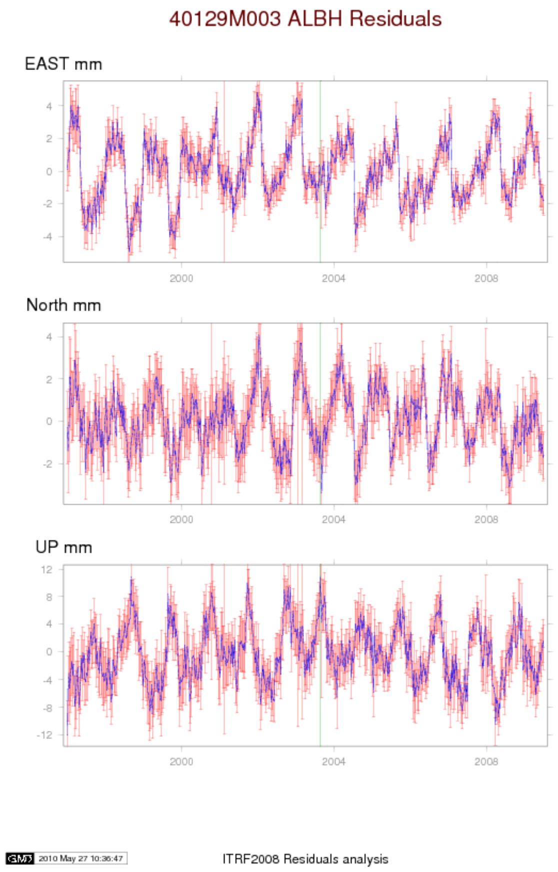
ITRF parameterization – tectonic motions

Co-seismic deformation

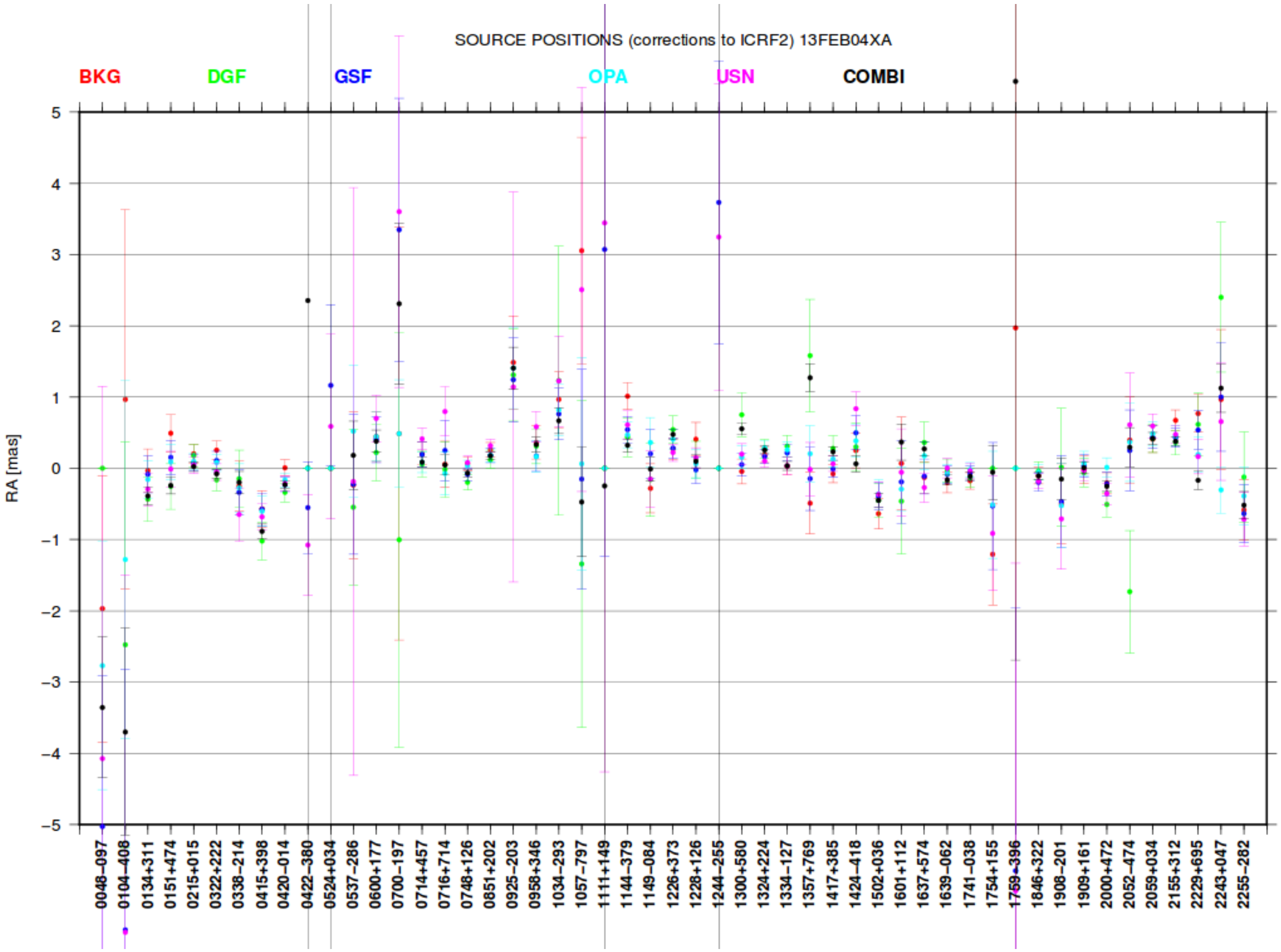
How to deal with quasi-periodic co-seismic? *(Schwartz et al., 2007)*

- No co-seismic offsets introduced in ITRF up to now

Differences by centimeters but the mean position looks to represent well the averaged motion



ICRF parameterization



ITRF parameterization – Other effects

Thermal deformation of the bedrock/monument

Table 16.1 Summary of short-baseline results

Baseline	Length Distance	Period (years)	Amplitude (mm) North	East	Up	Length
HERS-HERT (L1)	136.5 m	0.993	0.49	1.05	0.42	1.08
HER-HERT (L2)	136.5 m	0.992	0.50	1.09	0.42	1.11
HERS-SOLA	47.6 m	0.972	0.62	0.63	1.23	0.76
HERT-SOLA	89.9 m	1.643	0.54	1.33	1.16	1.32
HURN-POOL	5.3 km	0.947	0.78	0.52	0.49	0.49
HARB-HRAO	2.1 km	1.004	0.37	0.45	6.91	0.86
MAT1-MATE	10.7	1.001	0.60	0.46	0.19	0.77
WTZR-WTZZ	1.6	0.999	0.21	0.08	0.11	0.22
PIN1-PIN2	50.4	0.99	0.09	0.09	0.08	0.09

The quoted period refers to that of the signal in the values o

(Wilkinson et al., 2013)

ITRF parameterization – Network size

Network size

• The number of GNSS stations installed in the world rises exponentially

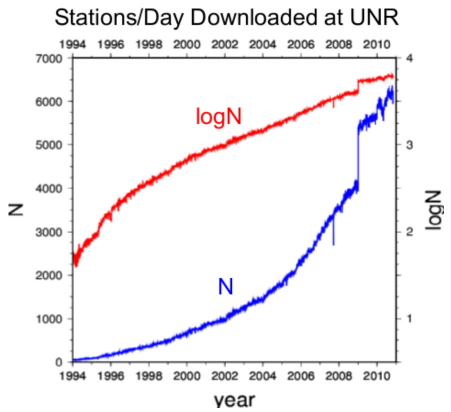


Fig. number of GPS donwloaded RINEW files at the University of Nevada (*Blewitt et al., 2010)*

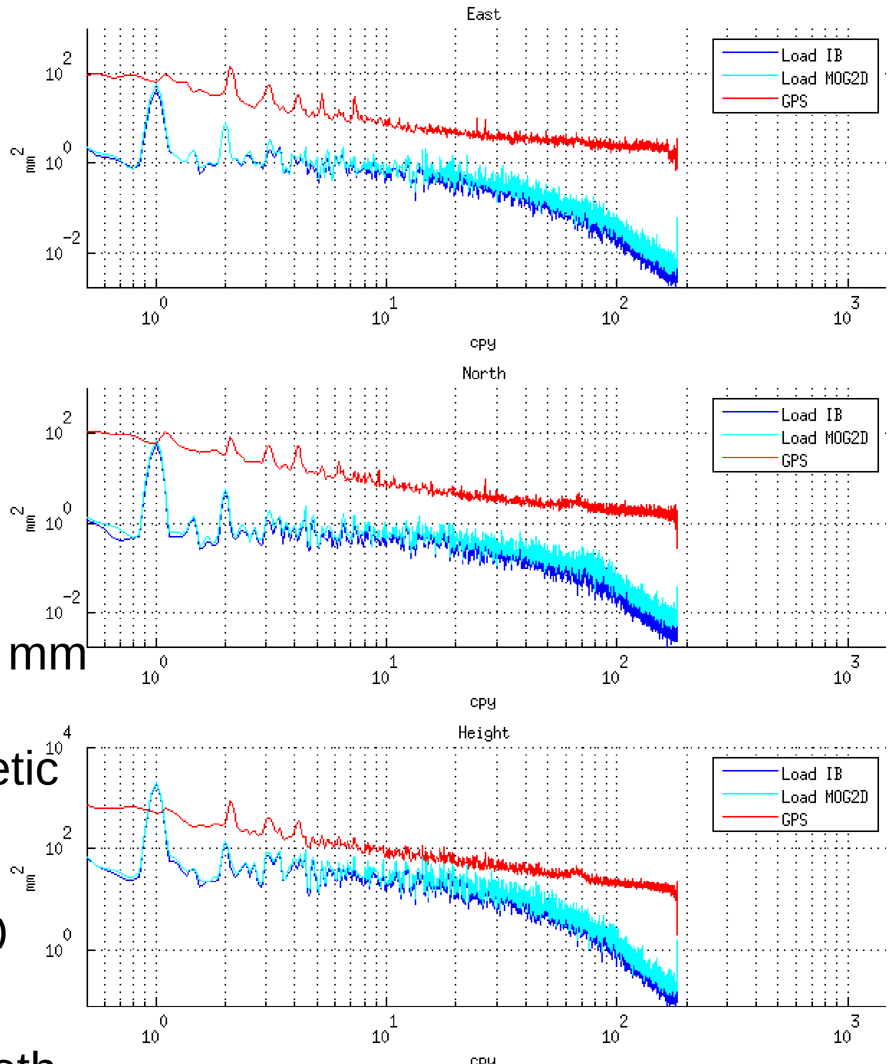
• GNSS: double-difference processing needs more stations than zero-difference processing
• Currently, IGS processes 1260 stations including stations on glaciers, volcanoes etc… Such stations are not submitted to ITRF (561 in ITRF2008).
• Keeping a minimal number of stations insures a better understanding of the variations in the series.

➢ Supply information (quality code?) about station quality to the ITRF users (based on segmentation, post-seismic etc…) ?

ATML vs GPS noise floor

• Average power spectrum for ATML shown (averaged daily)
• Average power spectrum for GPS shown (note: filtered for seasonal / JPL)

• Therefore model load effects are negligible in current 1-d time series, but not for weekly



• Model deformations are **not accurate** to < 1 mm

• corrections should never degrade geodetic accuracies. We should have:

➔ **SNR(load) > 1** & **Signal(load) > Noise(geodesy)**

• note that SNR(load) & SNR(geodesy) both vary with frequency