The International Terrestrial Reference Frame: current status and future challenges

Zuheir Altamimi, Xavier Collilieux, Laurent Métivier, Paul Rebischung, Daphné Lercier
IGN France
Email: zuheir.altamimi@ign.fr
Outline

• **Introduction:**
  – Brief description of space geodesy techniques
  – ITRF construction

• **ITRF and science applications**
  – Sea Level
  – Glacial Isostatic Adjustment (GIA)
  – Plate Motion

• **Limiting factors and challenges for the future**
  – Network configuration
  – Technique systematic errors
  – Site velocity and tie discrepancies at co-location sites
  – Discontinuities in station position time series
  – Site non-linear motions

• **Conclusion**
The ITRF: Combination of 4 techniques:

- GNSS
- DORIS
- VLBI
- SLR

International Terrestrial Reference System (ITRS)

Origin, Scale, Orientation

International Terrestrial Reference Frame (ITRF)

Earthquake
Very Long Baseline Interferometry

VLBI

Quasar: quasi-stellar radio source

\[ \delta g \equiv \tau(t) = \frac{\vec{B} \cdot \vec{S}}{c} + \Delta \tau(t) \]

Earth surface

Radiotelescope 1

Baseline \( \vec{B} \)

Radiotelescope 2

Geometric Delay \( \delta g \)
**Lunar Satellite**

**Laser Ranging**

**Measuring Time Propagation**

Earth → LLR Telescope → Passive Satellite → LLR SLR → Moon

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Navigation Message sent by each satellite:
- Orbit parameters
- Clock corrections

GNSS Measurements:
- Pseudorange
- Phase
DORIS
Doppler Orbitography and Radiopositioning Integrated by Satellite

- French Technique developed by CNES and IGN
- Uplink System: on-board receiver measures the doppler shift on the signal emitted by the ground beacon
Current networks: stations observed in 2011

- **VLBI/IVS**
- **SLR/ILRS**
- **GPS/IGS**
- **DORIS/IDS**
Co-location Site

Two or more geodetic instruments at the same site. Connected via local survey, example: GGAO

\[ D\mathbf{X}_{(\text{GPS,VLBI})} = X_{\text{VLBI}} - X_{\text{GPS}} \]
Total # of VLBI (48), SLR (32), DORIS (56) sites & their co-locations with GPS/GNSS

Co-located with GPS

<table>
<thead>
<tr>
<th>VLBI</th>
<th>SLR</th>
<th>GPS</th>
<th>DORIS</th>
</tr>
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<tbody>
<tr>
<td>39</td>
<td>27</td>
<td>43</td>
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New generation
What is a Reference Frame?

- Earth fixed/centred RF: allows determination of station location/position as a function of time

- It seems so simple, but … we have to deal with:
  - Relativity theory
  - Forces acting on the satellite
  - The atmosphere
  - Earth rotation
  - Solid Earth and ocean tides
  - Tectonic motion
  - …

- Station positions and velocities are now determined with mm and mm/yr precision
Why is a Reference Frame needed?

- **Precise Orbit Determination for:**
  - GNSS: Global Navigation Satellite Systems
  - Other satellite missions: Altimetry, Oceanography, Gravity

- **Earth Science & Societal Applications**
  - Mean sea level variations
  - Hazard mitigation and tsunami warning
  - Plate motion and crustal deformation
  - Glacial Isostatic Adjustment (GIA)
  - ...

- **Geo-referencing applications:** positioning, navigation, surveying...
Input data: station position time series

GPS

SLR

VLBI

DORIS

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ITRF Construction

Time series stacking

Local ties

Velocity equality

at co-location sites

Combination

ITRF X V, EOPs

Long-term Solutions

DORIS
GPS
SLR
VLBI

DORIS
GPS
SLR
VLBI

X V, EOPs
**ITRF scientific requirements**

- **ITRF stable in the long term**: 0.1 mm/yr

  $\implies$ **Stable**: Linear time evolution (no discontinuities) of its defining parameters:
  
  - **Origin components**: 0.1 mm/yr
  - **Scale**: 0.01 ppb/yr (0.06 mm/yr)

**Current accuracy $\geq$ 1 mm/yr**
ITRF evolution:
Network, Precision & Accuracy
Network evolution (ITRF88)
Network evolution (ITRF2008)
Precision evolution
ITRF accuracy

Evolution of the spatial consistency of vertical velocities: ITRF2000
ITRF accuracy

Evolution of the spatial consistency of vertical velocities: ITRF2005
ITRF accuracy

Evolution of the spatial consistency of vertical velocities: ITRF2008
ITRF and Science Applications
ITRF and Science Applications

• Sea level variability in space and time
  – An origin Z-drift of 2 mm/yr ==> errors in satellite altimetry data:
    • up to 0.3 mm/yr on global mean sea level
    • up to 1.8 mm/yr on regional sea level at high latitudes
  – A scale drift of 0.1 ppb/yr ==> drift up to 0.6 mm/yr in mean sea level determined by tide gauges records

• Glacial Isostatic Adjustment (GIA)
  – Z- and scale drifts ==> same impact as for sea level

• Plate motion (horizontal velocities)
  – Z-drift ==> change in North velocity
Impact of reference frame on mean sea level


TP & Jason-1: Radial orbit diffs (ITRF2005 minus CSR95/ITRF2000) (over the oceans)

Beckley et al., GRL, 2007
ITRF2005 & Tide Gauges

Woppelmann et al., GRL (2009)
ITRF2008 & Post Glacial Rebound

Métrivier et al., 2012, GRL

Spherical Harmonics of Degree 2 (vertical velocities)

Current Ice Melting?

Anomaly in Rotational feedback

ITRF2008

GIA Models
ITRF and Plate motion
ALL ITRF2008 Site Velocities: time-span > 3 yrs

509 sites
Selected Site Velocities

Plate angular velocity $\omega_p$ is estimated by:

\[ \dot{X}_i = \omega_p \times X_i \]

OR

\[ \dot{X}_i = \omega_p \times X_i + \dot{T} \]

Argus et al. 2010

206 sites
Comparison btw ITRF2008 and NNR-NUVEL-1 and NNR-MORVEL56

Velocity differences after rot. rate transformation

**NNR-NUVEL-1A**
- RMS:
  - East: 2.5 mm/yr
  - North: 2.0 mm/yr
- $R_y = 0.025$ mas/yr

**NNR-MORVEL56**
- RMS:
  - East: 1.7 mm/yr
  - North: 1.7 mm/yr
- $R_x = 0.084$ mas/yr

Green: 1-2 mm/yr
Blue: 2-3 mm/yr
Orange: 3-4 mm/yr
Red: 4-5 mm/yr
Black: > 5 mm/yr
ITRF: what are the challenges & questions?

• Improving co-location sites (the big issue)
  – Network configuration
  – Tie discrepancies
  – Velocity discrepancies

• Mitigating Technique systematic errors?

• Improving the process of detection of discontinuities in the station position time series

• Modeling site non-linear motions
Data used for this presentation & in preparation for ITRF2013

• Space Geodesy:
  **SLR**: ILRS contribution to ITRF2008, extended up to 2013.96 by ILRS operational weekly SNX solutions
  **VLBI**: GSFC 2011b session-wise solutions: 1983-2013.9
  **GNSS**: IGS operational weekly solutions: 1994-2013.9
  **DORIS**: Not used here

• Local ties:
  – ITRF2008 local ties
  – New ties, including, Brewster, GGAO & McDonald, performed by the US National Geodetic Survey (NGS)
Analysis Strategy

• ITRF-type analysis:
  – Time series stacking ==> station Pos&Vel / technique
  ==> Residual time analysis: stability analysis:
discontinuities in positions & changes in velocities
  – Inter-technique combination: Pos&Vel + local ties
  ==> evaluate level technique agreement in velocities and
  with local ties

• Analysis strategy
  – Weighting local ties: use lower bound sigma and down-
  weight discrepant ties
  – Equating velocities as a function of their agreement
SLR/ILRS intrinsic origin & scale
VLBI/GSFC (2011b) intrinsic scale
GNSS & VLBI vertical velocity discrepancies

Formal error ± 0.3 mm/yr
GNSS & SLR vertical velocity discrepancies

Formal error ± 0.3 mm/yr
VLBI & SLR vertical velocity discrepancies

UP velocity Diffs btw SLR and VLBI

+1 mm/y
-1 mm/y

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GNSS & VLBI horizontal velocity discrepancies

Formal error ± 0.2 mm/yr
GNSS & SLR horizontal velocity discrepancies

Formal error $\pm 0.2$ mm/yr

Horizontal Velocity Discrepancies between GNSS and SLR
VLBI & SLR horizontal velocity discrepancies
Tie Discrepancies

Differences between Terrestrial Tie and Space Geodesy estimates
Possible causes of tie discrepancies:
Local Survey &/or technique systematic errors

Precision of local survey:
probably not better than 3 mm
Current status of co-locations

• Without GPS/IGS, we have:
  – VLBI-SLR : 8 co-locations only (5 current)
  – VLBI/SLR-DORIS : 10 co-locations only

• IGS-GPS IS the link between SLR, VLBI & DORIS

• Is GPS free from site-dependent errors, e.g. uncalibrated radomes?
GNSS & VLBI Tie Discrepancies

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GNSS & SLR Tie Discrepancies

GPS-VLBI Tie Residuals

North

East

Up

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GPS & Tie Discrepancies

GPS and Tie Discrepancies

mm

METS  HERS  WTZR  WTZR  HRAO  STR2  YAR2  YAR2  YARR

mm

METS  HERS  WTZR  WTZR  HRAO  STR2  YAR2  YAR2  YARR

mm

METS  HERS  WTZR  WTZR  HRAO  STR2  YAR2  YAR2  YARR

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Scale Factors of VLBI & SLR wrt ITRF2008

Ten combination tests, varying the lower bound tie sigma

Still preliminary

1 ppb ~6 mm

3 mm as lower bound tie sigma is used in this analysis
Technique systematic errors
Technique Systematic Errors: GNSS

• GNSS do not “see” the true geocenter (PhD work of Paul Rebischung)

• Under-determined TRF scale due to PCVs & PCOs of the ground & satellite antennas;

• Uncalibrated radomes (can be >1 cm errors)

• Local environment, esp near antenna (can be >1 cm)

• 50 % of the IGS sites have discontinuities in the position time series due to equipment changes

==> Serious impact on site velocities
IGS/GNSS data availability for RF sites

Data & Discontinuities -- Primary Core RF

- Discontinuities

Courtesy Jim Ray
Technique Systematic Errors: VLBI

- Sparse sessions, not all designed for the reference frame (see next animation for sessions in 2011)
  - Usually 6-8 stations, twice a week –rarely ~20 stations

- Axis offset errors, (Sarti et al., 2011)

- Elevation-dependent antenna deformations, esp. for large antennas (can be ~1 cm height effect), (Sarti et al., 2009)
In the following slides:
Animation of VLBI site distribution

- **Per session during February 2011:** 14 sessions – duration: 14 seconds

And then:

- **Per month during 2011:** duration: 12 seconds
VLBI session February 01, 2011
VLBI session February 02, 2011
VLBI session February 03, 2011
VLBI session February 07, 2011
VLBI session February 08, 2011
VLBI session February 09, 2011
VLBI session February 10, 2011
VLBI session February 14, 2011
VLBI session February 17, 2011
VLBI session February 21, 2011
VLBI session February 22, 2011
VLBI session February 23, 2011
VLBI session February 24, 2011
VLBI session February 28, 2011
And now VLBI observed sites per month, during 2011
VLBI observed sites January
VLBI observed sites February
VLBI observed sites March
VLBI observed sites April
VLBI observed sites May
VLBI observed sites June
VLBI observed sites July
VLBI observed sites August
VLBI observed sites September
VLBI observed sites October
VLBI observed sites November
VLBI observed sites December
VLBI observation availability

- Ft Davis VLBA < 10 sessions/yr
- Algonquin/Canada & Fairbanks/Alaska Stopped in 2006
- Wettzell
- Westford
- Onsala
Technique Systematic Errors: SLR

- Relatively poor network geometry
- Station-satellite range biases
- Station timing/counter biases

Herstmonceux event timer example: 12 mm bias (Appleby, 2009)
SLR observation availability

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Technique Systematic Errors: DORIS

- Z-geocenter is poorly determined, due mainly to Solar Radiation Pressure (Gobinddass et al., 2009)

- Uncalibrated beacon phase center pattern (Tourain et al., 2012)
  - Calibration tests/evaluation in progress by CNES and IDS...
DORIS observation availability
Site non-linear motion

- Discontinuities in station position time series
- Seasonal signals
  - Loading effects
  - Errors at draconitic sub-periods for GPS
  - Other systematic biases (?)
- Co- & Post-Seismic deformation
Impact of discontinuities on site velocities
Yarragadee GPS up component

Up velocity = -0.18 ± 0.07 mm/yr (with 2 discontinuities)
= -0.29 ± 0.05 mm/yr (with 2 disc. + ann & semi-ann)

If we consider a 3rd discontinuity:
Up velocity = 0.73 ± 0.12 mm/yr (with 3 discontinuities)
= 0.33 ± 0.12 mm/yr (with 3 disc. + ann & semi-ann)
IGS station position Up residuals: stacked periodogram

Up velocity changes
Modeling post-seismic deformations
Current modelling of post seismic deformations in ITRF

It is based on a piecewise linear model for the time evolution of station coordinates.

\[ x_{ITRF}^{I}(t) = x_{ITRF}^{I}(t_0) + \dot{x}_{ITRF}^{I}(t - t_0) + \sum_{k} d_k^{I} H(t - t_k) + \sum_{l} v_l^{I}(t - t_l) H(t - t_l) \]
Parametric post seismic models

Parametric models for postseismic displacements:
\[ \forall i \in \{E, N, U\}, X_i(t) = \]
\[
\begin{cases} 
X_1(t_0) + V_1 \times (t - t_0), & t < t_{eq} \\
X_2(t_{eq}) + V_2 \times (t - t_{eq}) + D(t - t_{eq}), & t > t_{eq} 
\end{cases}
\]

Parametric postseismic models use logarithmic or exponential functions:

\[ D(t - t_{eq}) \text{ with} \]
\[ D(t - t_{eq}) = A \log(1 + \frac{t - t_{eq}}{\tau}) \]  \hspace{1cm} (1)

or
\[ D(t - t_{eq}) = A (1 - e^{-\frac{t - t_{eq}}{\tau}}) \]  \hspace{1cm} (2)

[e.g.: Kreemer et al., 2006]

or
\[ D(t - t_{eq}) = A_1 \log(1 + \frac{t - t_{eq}}{\tau_1}) + A_2 (1 - e^{-\frac{t - t_{eq}}{\tau_2}}) \]  \hspace{1cm} (3)

or
\[ D(t - t_{eq}) = A_1 (1 - e^{-\frac{t - t_{eq}}{\tau_1}}) + A_2 (1 - e^{-\frac{t - t_{eq}}{\tau_2}}) \]  \hspace{1cm} (4)
Agreement between data and models
Conclusion

• The ITRF has improved in precision & accuracy over time
• The most precise/accurate reference frame available today
• Largely disseminated by the four techniques
• Became critical with the increase of GPS/GNSS networks and their science applications
• Accessible everywhere continuously thanks to IGS products
• Most of current VLBI and SLR systems are old generation
• 50% of IGS sites have discontinuities
• Tie discrepancies > 5 mm for a number of co-location sites
• Need to mitigate technique systematic errors
• The ITRF is still not at the level of science requirement
• Needs to be improved by a factor of 10.
Coming this year
ITRF2013

Thank you