The International Terrestrial Reference Frame (ITRF)
ITRF2014 and future plans

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Of the..................
Content

• ITRF general description

• ITRF2014 Input Data, Network

• ITRF2014: Innovations in modelling the nonlinear station motions:
  – Periodic signals: annual, semi-annual
  – Post-Seismic Deformation (PSD)

• ITRF2014 Key performance indicators

• Roadmap for future plan: ITRF2020
How the ITRF is constructed?

• Input:
  – Time series of mean station positions (at weekly or daily sampling) and daily EOPs from the 4 techniques
  – Local ties in co-location sites

• Output:
  – Station positions at a reference epoch and linear velocities
  – Earth Orientation Parameters

Combination model

\[
X_s^i = X_c^i + (t_s^i - t_0) \dot{X}_c^i + T_k + D_k X_c^i + R_k X_c^i + (t_s^i - t_k) \left[ \dot{T}_k + \dot{D}_k X_c^i + \dot{R}_k X_c^i \right]
\]

\[
\dot{X}_s^i = \dot{X}_c^i + \dot{T}_k + \dot{D}_k X_c^i + \dot{R}_k X_c^i
\]

\[
\begin{align*}
x_S^p &= x_C^p + R2_k \\
y_S^p &= y_C^p + R1_k \\
UT_S &= UT_C - \frac{1}{f} R3_k \\
\dot{x}_S^p &= \dot{x}_C^p \\
\dot{y}_S^p &= \dot{y}_C^p \\
LOD_S &= LOD_C
\end{align*}
\]
ITRF Construction

Time series stacking

Local ties

Velocity equality at co-location sites

Combined data sources:
- DORIS
- GPS
- SLR
- VLBI

Long-term Solutions

Step 1

ITRF Specifications:
- Origin: SLR
- Scale: SLR & VLBI
- Orientation: Alignment to previous ITRF

Step 2

ITRF X V, EOPs
### ITRF2014: Input data

<table>
<thead>
<tr>
<th>Service/Technique</th>
<th>Number of Solutions</th>
<th>Time span</th>
<th># of sites</th>
</tr>
</thead>
<tbody>
<tr>
<td>IGS/GNSS/GPS</td>
<td>7714 daily</td>
<td>1994.0 – 2015.1 (21 yrs)</td>
<td>884</td>
</tr>
<tr>
<td>IVS/VLBI</td>
<td>5328 daily</td>
<td>1980.0 – 2015.0 (35 yrs)</td>
<td>124</td>
</tr>
<tr>
<td>ILRS/SLR</td>
<td>244 fortnightly</td>
<td>1980.0 – 1993.0</td>
<td>96</td>
</tr>
<tr>
<td></td>
<td>1147 weekly</td>
<td>1993.0 – 2015.0 (35 yrs)</td>
<td></td>
</tr>
<tr>
<td>IDS/DORIS</td>
<td>1140 weekly</td>
<td>1993.0 – 2015.0 (22 yrs)</td>
<td>71</td>
</tr>
</tbody>
</table>
ITRF2014 Network: VLBI
ITRF2014: GNSS

884 sites
1054 stations
1882 discontinuities

Site #
696
188
ITRF2014: Modelling nonlinear station motions

- Position time series of all stations exhibit periodic signals
- More than 100 sites are subject to Post-Seismic Deformation due to major earthquakes

Precisely modeling the above leads to more robust secular frame and site velocities.
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) and its harmonics
Periodic Signals

Annual & semi-annual terms estimated, using:

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

- $\Delta X_f$: total sum of all frequencies
- $n_f$: number of frequencies
- $\omega_i = \frac{2\pi}{\tau_i}$
- $\tau_i$: period of the $i$th frequency

$\Rightarrow$ 6 parameters per station & per frequency, i.e. $a$ & $b$
along each $X$, $Y$, $Z$ axis.
Periodic Signals

Annual & semi-annual terms estimated, using:

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

$$\Delta X_f$$ total sum of all frequencies

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

$$\tau_i$$ period of the ith frequency

$$\Rightarrow$$ 6 parameters per station & per frequency, i.e. a & b along each X, Y, Z axis.
Estimating seasonal signals
vs
applying non-tidal atmospheric loading (NTAL) model?

Three IGS cumulative solutions:

- **STD**: Periodic signals NOT estimated, NTAL model NOT applied
- **NTAL**: Non-tidal atmospheric loading model applied before stacking
- **F2**: Annual and semi-annual signals estimated

*NTAL model provided by Tonie van Dam*
Station WRMS Diffs (NTAL – F2)

- Positive values mean better performance for seasonal terms estimation
- Negative values mean better performance for NTAL
Impact of estimating seasonal signals on site velocities (STD – F2)

- Negligible impact on horizontal velocities $<< 0.1 \text{ mm/yr}$
- Up to 1 mm/yr change in vertical velocities, for stations with large seasonal signals/number of discontinuities, or/and data gaps in time series
Impact of estimating seasonal signals on Polar Motion

GPS/IGS PM Diff. (Standard - Annual+Semi-Annual signal removed) - uas

XPO

YPO
Post-Seismic Deformations
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

Post-seismic deformation
PSD Correction

Regularized Position (ITRF2014)

$\delta X_{psd}(t)$

Observed Position
How to use ITRF2014 PSD models?

\[
X_{PSD}(t) = X(t_0) + \dot{X}(t - t_0) + \delta X_{PSD}(t)
\]

Regularized Position (ITRF2014)

\[
\delta L(t) = \sum_{i=1}^{n_l} A_i^l \log(1 + \frac{t - t_i^l}{\tau_i^l}) + \sum_{i=1}^{n_e} A_i^e (1 - e^{-\frac{t-t_i^e}{\tau_i^e}})
\]

Local Frame

Tsukuba Trajectory

GNSS

Trajectory: Blue: Raw, Green: Linear, Red: PSD model
Vertical gray lines represent discontinuities

VLBI

Trajectory: Blue: Raw, Green: Linear, Red: PSD model
Vertical gray lines represent discontinuities
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:
DORIS, SLR & VLBI scales wrt ITRF2014

Full time series of scale factors

Scale factors of SLR and VLBI solutions selected to define ITRF2014 scale

SLR to VLBI scale offset: 1.4 ppb = ~8 mm.

Altamimi et al., IAU 2018, Vienna, August 27, 2018
ILRS/SLR origin components wrt ITRF2014

ILRS/SLR Origin components wrt ITRF2014 (full raw time series)

TX mm

TY mm

TZ mm
ILRS/SLR origin components wrt ITRF2014

ILRS/SLR Origin components wrt ITRF2014 (full raw time series)

Selected weeks defining ITRF2014 long-term origin (seasonals removed)
Preparation for ITRF2020 (1/2)

• Why ITRF2020? After consultation, the majority favors ITRF2020 for different reasons

• ITRF2020 ==> Toward improving the ITRF

• At the techniques level: a number of effects and model updates to be considered, e.g.:
  – SLR range biases
  – VLBI antenna deformation
  – DORIS SRP modelling
  – A number of model updates for GNSS
  – All techniques: Improve data processing to reduce the noise level (see illustration next)
Periodic signals, Discontinuities and Noise level

GPS

VLBI

SLR

DORIS

Hartebeesthoek: at an important co-location site
Preparation for ITRF2020 (2/2)

• ITRF2020 ==> Toward improving the ITRF

• **At the combination level:**
  – Track down the VLBI & SLR scale discrepancy
  – Provide annual & semi annual signals for all techniques in the CM frame
  – Isolate/understand technique discrepancies in seasonal signals at co-location sites
  – Provide accurate annual and semi-annual geocenter motion models for specific applications, e.g. POD
Impact of SLR Range Bias on the Scale

The impact on the scale motivated the ASC to move from the Pilot Project to an operational phase adopting this approach.

Courtesy Erricos Pavlis

Altamimi et al., IAU 2018, Vienna, August 27, 2018
“Instantaneous” position: linear & nonlinear parts

\[ X(t) = X(t_0) + \dot{X}.(t - t_0) + \delta X(t)_{PSD} + \delta X(t)_S + \delta X(t)_G \]

- Regularized position
- \( \sum \) Post-Seismic Deformations
- \( \sum \) Seasonal Signals of all frequencies

Caution: significant discrepancies between techniques
Or a Loading model with ALL contributions (ATM, …)

If seasonal signals are in CF, add Geocenter Motion
Caution: different models exist, with significant differences

All the \( \delta X \) corrections could be part of future ITRF products
Up annual signals: VLBI (CN frame)

\[ Dh = A \cos(2\pi f(t - t_0) + \phi) \]
Up annual signals: VLBI + GNSS (CN Frame)
### Annual Geocenter motion: different estimates

<table>
<thead>
<tr>
<th>Method</th>
<th>Amp X (mm)</th>
<th>Phase X (deg)</th>
<th>Amp Y (mm)</th>
<th>Phase Y (deg)</th>
<th>Amp Z (mm)</th>
<th>Phase Z (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLR CN: Uneven Network</td>
<td>2.1</td>
<td>63.7</td>
<td>3.1</td>
<td>329.1</td>
<td>3.1</td>
<td>22.7</td>
</tr>
<tr>
<td>SLR CN: 8 stations</td>
<td>1.7</td>
<td>60.7</td>
<td>3.6</td>
<td>325.0</td>
<td>2.2</td>
<td>28.7</td>
</tr>
<tr>
<td>SLR Via Multi-technique</td>
<td>1.1</td>
<td>55.7</td>
<td>3.7</td>
<td>356.8</td>
<td>2.3</td>
<td>51.1</td>
</tr>
<tr>
<td>Via GPS Net</td>
<td>1.5</td>
<td>48.0</td>
<td>3.3</td>
<td>335.1</td>
<td>2.0</td>
<td>47.7</td>
</tr>
<tr>
<td>Via VLBI Net</td>
<td>1.7</td>
<td>53.7</td>
<td>3.1</td>
<td>327.1</td>
<td>2.9</td>
<td>55.8</td>
</tr>
</tbody>
</table>
ITRF2014: Horizontal velocity field
ITRF2014: Vertical velocity field

ITRF2014 vertical velocities
ITRF Accuracy/precision
Evolution of the spatial consistency of vertical velocities: ITRF2014
ITRF Accuracy/precision

Vertical velocity differences between ITRF2014 and ICE-6G/GIA model
Summary & Conclusion

• More than 3 decades of R&D to improve the ITRF
• The most precise/accurate reference frame available today
• Accessible everywhere & anywhere thanks to IGS products

• ITRF2014 published in 2016, and in JGR Open Access article
• ITRF2014 innovation: modelling of non-linear station motions
• Estimating seasonal signals
  – A more robust frame and site velocities
  – Performs better than applying a pressure loading model
  – No significant impact on horizontal velocities
• Precise modeling of post-seismic deformations

• Persistent scale offset between VLBI & SLR
• Need to mitigate technique systematic errors in preparation for ITRF2020