The International Terrestrial Reference Frame: Current status and future development

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Outline

- Reference Frame representations for a deformable Earth:
  - Quasi-instantaneous RF
  - Long-term (Secular) RF - main focus here -
- ITRF and site non-linear motions:
  - Periodic signals
  - Co- & Post-Seismic deformation
- Impact of station non-linear motions on the ITRF ?
- Any impact on ITRF defining parameters ?
- Conclusion
Defining a Reference System & Frame:

Three main conceptual levels:

- **Ideal Terrestrial Reference System (TRS):**
  Theoretical definition (Origin, Scale & Orientation)

- **Terrestrial Reference Frame (TRF):**
  Numerical realization of the TRS to which users have access

- **Coordinate System:** Cartesian (X,Y,Z), geographic (λ, φ, h), ...

  - As the TRS, the TRF has an origin, scale & orientation
  - TRF is constructed using space geodesy observations, hence with uncertainties
"Motions" at the surface of the deformable Earth

• Nearly linear motion:
  – Tectonic motion: horizontal
  – Post-Glacial Rebound: Vertical & Horizontal

• Non-Linear motion:
  – Periodic: Annual, Semi & Inter-Annual (caused by loading effects), draconitic
  – Rupture: Co-seismic, Volcano Eruptions, etc.
  – Transient or post-seismic deformation
Reference Frame Representations

• "Quasi-Instantaneous" Frame: mean station positions at "short" interval: few hours, one day, one week
  
  ==> Non-linear motion embedded in time series of quasi-instantaneous frames

• Long-Term Secular Frame: mean station positions at a reference epoch \((t_0)\) and station velocities:

\[
X(t_c) = X(t_0) + \dot{X}(t_c - t_0)
\]

  e.g.:
  - ITRF
  - Cumulative GNSS solution expressed in the ITRF

To define a TRF, 14 parameters need to be specified: Origin (6 components), scale (2), orientation (6)
ITRF Construction

Time series stacking

Local ties

Velocity equality at co-location sites

Long-term Solutions

Step 1

DORIS
GPS
SLR
VLBI
X V, EOPs

Combination

Step 2

DORIS
GPS
SLR
VLBI
X V, EOPs

ITRF Specifications:
- Origin: SLR
- Scale: SLR & VLBI
- Orientation: Alignment to previous ITRF
ITRF Combination: Step 1 (1/2)

• Stacking/accumulating individual time series where the long-term
  – origin of SLR and DORIS
  and
  – scale of VLBI, SLR and DORIS

are defined via internal/intrinsic constraints:

\[
\begin{align*}
\sum_{k \in K} P_k &= 0 \\
\sum_{k \in K} (t_k - t_0) P_k &= 0
\end{align*}
\]

(Altamimi et al., 2007)
DORIS – IDS V4 Intrinsic Origin & Scale

DORIS IDS V4 intrinsic origin and scale

TX (mm)

TZ (mm)

TY (mm)

Scale (mm)
ITRF Combination: Step 1 (2/2)

- Handling of non-linear station motions:
  - Periodic signals: using sinusoidal functions:
    \[ \sum a \cos \omega t + b \sin \omega t \]
  - Post-seismic deformation:
    - Piece-Wise Linear (PWL) function
    - Parametric models (logarithmic or and/exponential)
SLR Intrinsic Origin & Scale
PWL model for (Arequipapa & Concepcion) EQ sites
SLR Intrinsic Origin & Scale
Parametric model applied for Arequipa and Concepcion
SLR Intrinsic Origin & Scale
Parametric model applied for Arequipa and Concepcion
Annual and semi-annual signals removed
VLBI/GSFC2011b Intrinsic Scale

Red: No post-seismic deformation model
Blue: Post-seismic deformation modelled for Tsukuba, Fairbanks and Concepcion

VLBI GSFC Intrinsic Scale (mm) ATML corrected

NKG General Assembly, Göteborg, 1-4 September, 2014
SLR WRMS
PWL model for (Arequipa & Concepcion) EQ sites

SLR ILRS Weekly WRMS (mm)
SLR WRMS
Parametric model applied for Arequipa and Concepcion

SLR ILRS Weekly WRMS (mm)

North   East   Up
SLR WRMS

Parametric model applied for Arequipa and Concepcion

Annual and semi-annual signals removed
Preparation for ITRF2013

- **What’s new?**
  - Reprocessed solutions from the 4 techniques
  - Improving the process of detection of discontinuities in the time series
  - Applying NT-ATML (+) corrections to ITRF2013 input data
  - Periodic signals (at least annual & semi-annual):
    - Co- & Post-seismic deformation (parametric models will be applied)
IGS station position Up residuals: stacked periodogram

Standard solution
Annual + SemiA
(+1\text{st} +2\text{nd} dracs)
(+1\text{st} +2\text{nd} +4\text{th} dracs)
(+3\text{rd}+6\text{th} dracs)
Annual + SemiA + 7 dracs
ESA Repro2 daily WRMS
(Ann+semi-Ann signals removed)
ESA Repro2 daily WRMS
(Ann+semi-Ann + 7 dracs removed)
ESA GNSS Repro 2  Vertical velocity differences
(Standard – Annual+Semi-Annual)
ESA GNSS Repro 2  Vertical velocity differences
(Standard – Annual+Semi-Annual + 7 dracs)
Position Residuals of Porto Velho, Brazil

Standard Solution

Horizontal:
- Velocity change: 0.2 mm/yr

Vertical:
- Velocity change: 1.7 (±0.15) mm/yr

Ann+semi-ann removed

Horizontal:
- Velocity change: 0.2 mm/yr

Vertical:
- Velocity change: 1.7 (±0.15) mm/yr
Modeling post-seismic deformations

- **Up to ITRF2008:**
  - Piece-wise linear (PWL) function

- **For ITRF2013, parametric models:**
  - Logarithmic
  - Exponential
  - Logarithmic + Exponential
  - Two Exponential functions
Parametric post seismic models

Parametric models for postseismic displacements:

\[ X_i(t) = \begin{cases} X_1(t_0) + V_1 \times (t - t_0), & t < t_{eq} \\ X_2(t_{eq}) + V_2 \times (t - t_{eq}) + D(t - t_{eq}), & t > t_{eq} \end{cases} \]

Parametric postseismic models use logarithmic or exponential functions:

\[ D(t - t_{eqk}) \text{ with} \]

\[ D(t - t_{eqk}) = A \log\left(1 + \frac{t - t_{eqk}}{\tau}\right) \tag{1} \]

or

\[ D(t - t_{eqk}) = A \left(1 - e^{-\frac{t-t_{eqk}}{\tau}}\right) \tag{2} \]

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

or

\[ D(t - t_{eqk}) = A_1 \log\left(1 + \frac{t - t_{eqk}}{\tau_1}\right) + A_2 \left(1 - e^{-\frac{t-t_{eqk}}{\tau_2}}\right) \tag{3} \]

or

\[ D(t - t_{eqk}) = A_1 \left(1 - e^{-\frac{t-t_{eqk}}{\tau_1}}\right) + A_2 \left(1 - e^{-\frac{t-t_{eqk}}{\tau_2}}\right) \tag{4} \]
Sites affected by EQ discontinuities

(Métivier et al., 2014 under review)
Linear Function  Arequipa  Parametric Model

Multiple velocities estimated

One velocity estimated

Lercier et al., 2014, submitted
Linear Function Tsukuba VLBI Parametric Model

Lercier et al., 2014, submitted
Example of GNSS cumulative solution

- **Data:** IGS station position time series (1994-2013)
- **Two cumulative solutions where EQ sites are modelled using:**
  - PWL model
  - Parametric (Log or/and Exp) models for 11 EQ sites
  - Both cumulative solutions are expressed in ITRF2008 using minimum constraints over 80 reference sites

\[
(A^T A)^{-1} A^T (X_R - X_c) = 0
\]

**ITRF**

**Cumulative Solution**

\[\Rightarrow\] Same origin, scale & orientation for both cumulative solutions
Horizontal Velocity changes

After post-seismic models for (shown in green):

AREQ
TSKB
STK2
CHAN
FAIR
CONZ
SANT
ANKR
TUBI
RYEZ
MAC1
Vertical Velocity changes

After post-seismic models for (shown in green):
AREQ
TSKB
STK2
CHAN
FAIR
CONZ
SANT
ANKR
TUBI
RYEZ
MAC1
Conclusion

• Impact of station non-linear motions on the ITRF or a cumulative solution expressed in the ITRF:
  – No impact on the RF defining parameters (origin, scale & orientation)
  – Pos&Vel changes for EQ sites after the events
  – Velocity changes (up to 1 mm/yr) for some sites when removing periodic signals
  – We should be able to precisely define the frame in such a way that Earthquakes & periodic signals have little to no impact on its defining parameters

• ITRF2013: Estimation of
  – Periodic signals ==> more precise velocities
  – Post-seismic deformation using parametric models for major EQ sites.