# Analysis of high-frequency EOP (HFEOP) models and their impact on GPS data processing

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# Motivation for Analysis

- Model currently recommended by **IERS** for effects of ocean tides on ERP, Ray et al. (1994*, Science*) and Chao et al. (1996, *JGR*), is > 20 years old. Known deficiencies; in particular, **model for libration effects is not used due to inconsistency with tide models** (Desai and Sibois, 2017, *JGR*)

- Modern alternatives demonstrate improvements using decade(s) of space geodetic measurements.

| Tidal Models | | |
|---|---|---|
| IERS Conventions | Based on TPX 0.4 | Current |
| Desai and Sibois | Based on TPX 0.8. | Better on GNSS |
| Madzak et al | Tidal model | Better on VLBI |
| Ray | Based on TPX 0.9 | Newer tide model |
| Lyard | FES2014 | Newer tide model |
| **Empirical Models** | | |
| Gipson | Derived from VLBI data | Fit using VLBI, better on GNSS |
| Artz et al | Derived from VLBI and GNSS | Untested on other techniques |

***reference in this study***

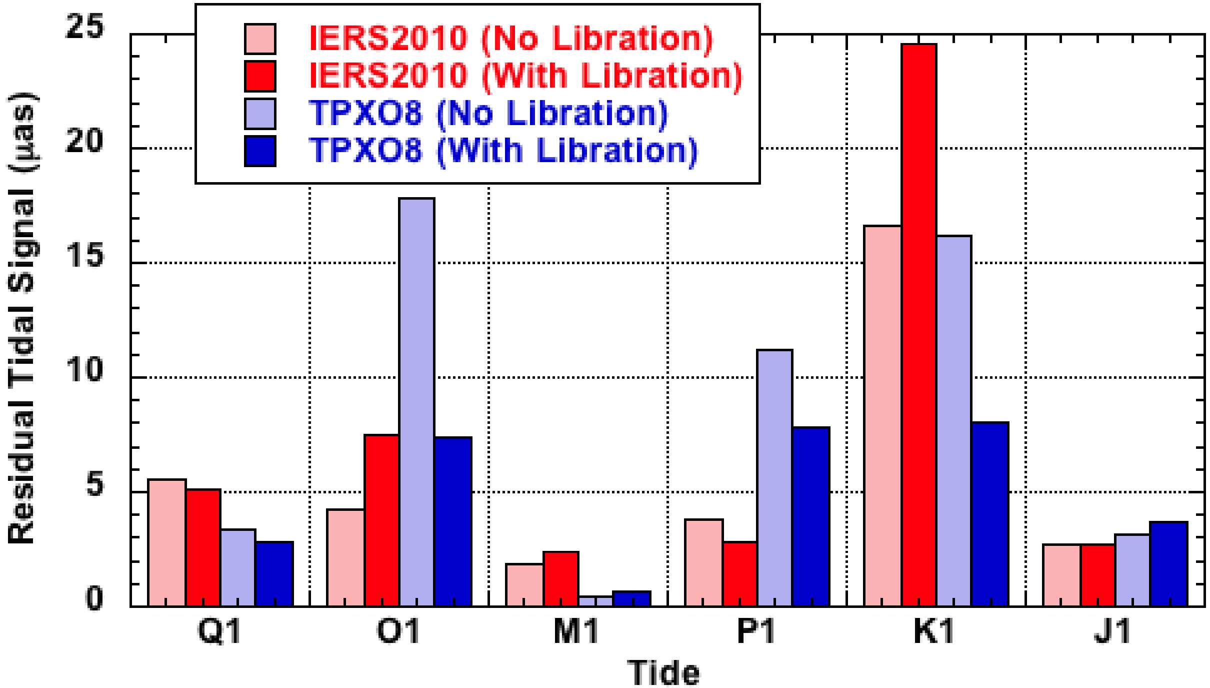
***models tested here***

***associated ERP model derivation/implementation/testing = future work for Sibois/Desai***

***table created by J. Gipson for IERS WG on HF-EOP presentation at AGU 2018***

- Key difference between Gipson and Desai-Sibois models lies in their derivation:
  - Gipson = purely empirical model based solely on VLBI observations
  - ➔ benefits from long record (30 years) of VLBI observations
  - ➔ sensitive to VLBI-specific systematic errors
  - ➔ need for careful bookkeeping of effects modeled independently vs. absorbed in fitting (e.g. atmospheric tides?)
  - Desai-Sibois = geophysical/ocean-based model
  - ➔ not tied to any specific observation technique
  - ➔ benefits from significant evolution of ocean tide models over the past 20 years (e.g. improved hydrodynamics models, longer-duration altimetry data for assimilation)
  - ➔ sensitive to deficiencies in the various geophysical models involved.

# Consistency with libration model




- TPXO8 (Desai-Sibois): libration model reduces residual tidal signals in most cases.
- IERS2010: libration model tends to increase residual tidal signals, especially for largest O1 and K1 components.
- Gipson model used in testing accounts for libration model -> consistency by design

➔ *<u>Better consistency of modern models with conventional libration model.</u>*

# Models tested for ocean tides effects on HF-EOP

- Effects and models of interest in this investigation:
  - diurnal and semi-diurnal variations on ERPs from ocean tides:
    - amplitudes of few hundred µas for polar motion; a few µs for UT1
  - libration effects:
    - prograde diurnal component of polar motion variations; amplitudes of up to 16 µas
    - semidiurnal component of UT1; amplitudes of up to 2 µs

- 3 models discussed in this analysis:
  - model currently recommended by **IERS Conventions 2010** (71 tidal lines)

*Note that when discussing IERS model, only models for ocean tide effects on sub-daily EOP are used;* ***model for libration effects IS NOT USED due to inconsistency with tide models***

  - **Gipson model with libration effects** as modeled by Mathews and Bretagnon (2003, *Astron. Astrophys.*) accounted for (71 tidal lines): https://ivscc.gsfc.nasa.gov/hfeop_wg/models/2017a_astro_lib_xyu.txt
  - **Desai-Sibois model in conjunction with** Mathews and Bretagnon (2003) **model for libration effects** (159 tidal lines)

# Related geophysical/astronomical models used in processing

| | Precession/Nutation | Ocean tides | Libration | Atmospheric tides |
|---|---|---|---|---|
| **IERS (baseline)** | **P03/IAU2000/2006** | **model of reference** | **not used** | **not included not modeled** |
| Gipson | P03/IAU2000/2006 *was nutation adjusted in VLBI processing that led to HFEOP model derivation?* | model under test | implicitly used since included as a priori to model for ocean tides effects | not included/modeled explicitly *either independently modeled when ocean tide model was derived or absorbed into ocean tide model?* |
| Desai-Sibois | P03/IAU2000/2006 | model under test | used | not included not modeled |

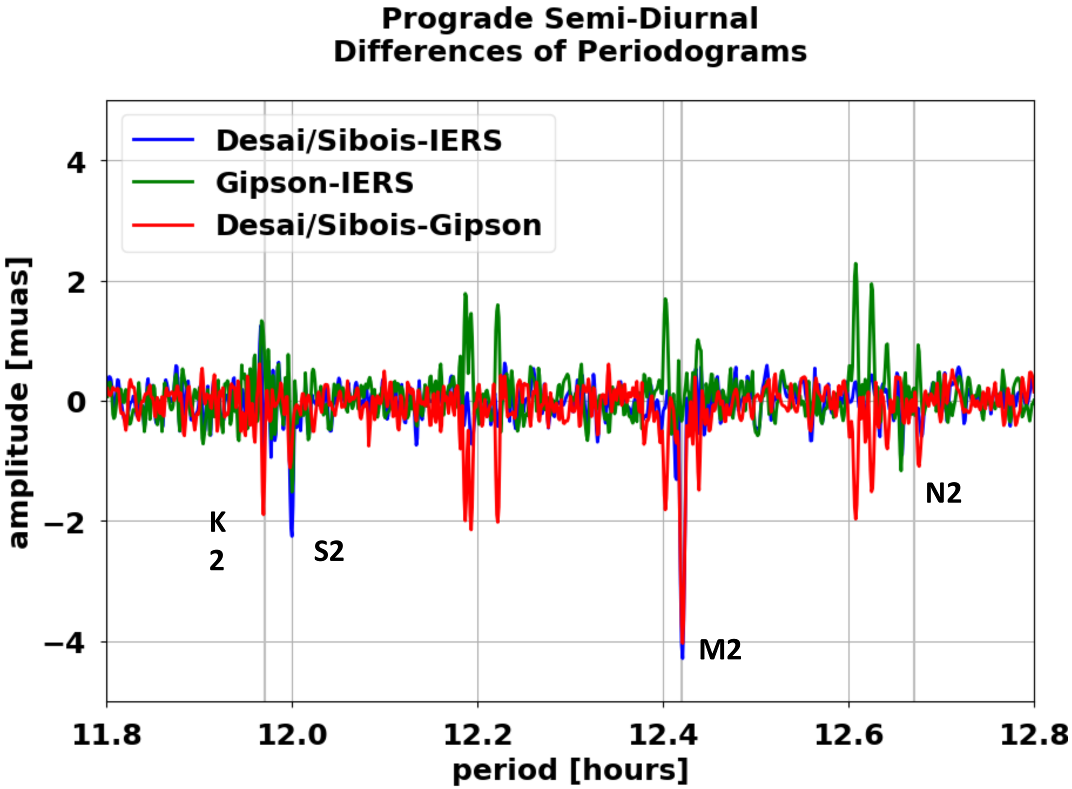
# Analysis of high-frequency polar motion

- 4 years (2010-2013) of GPS only 5-min data reprocessed using JPL's legacy GIPSY-OASIS software package
- Polar motion coordinates estimated every 15 minutes; rates not estimated
- UT1-UTC/LOD not estimated
- 3-day arcs, 25% of 60 stations fixed for each arc
- Central-day estimates used in analysis
- Set up is identical between the 3 solutions analyzed with the exception of the sub-daily ERP model used

In particular:

- Same data/network used by the three solutions
- Same daily nominal EO file used by the three solutions (IERS Bulletin A)
- All cases apply:
  - daily values of ERPs using IERS Bulletin A (to model variations with period > 2 days)
  - Conventional nutation model from Mathews et al. (2002) which includes effects of ocean tides, consistently with conventional ocean tide model.

# Residual polar motion in semi-diurnal frequency band

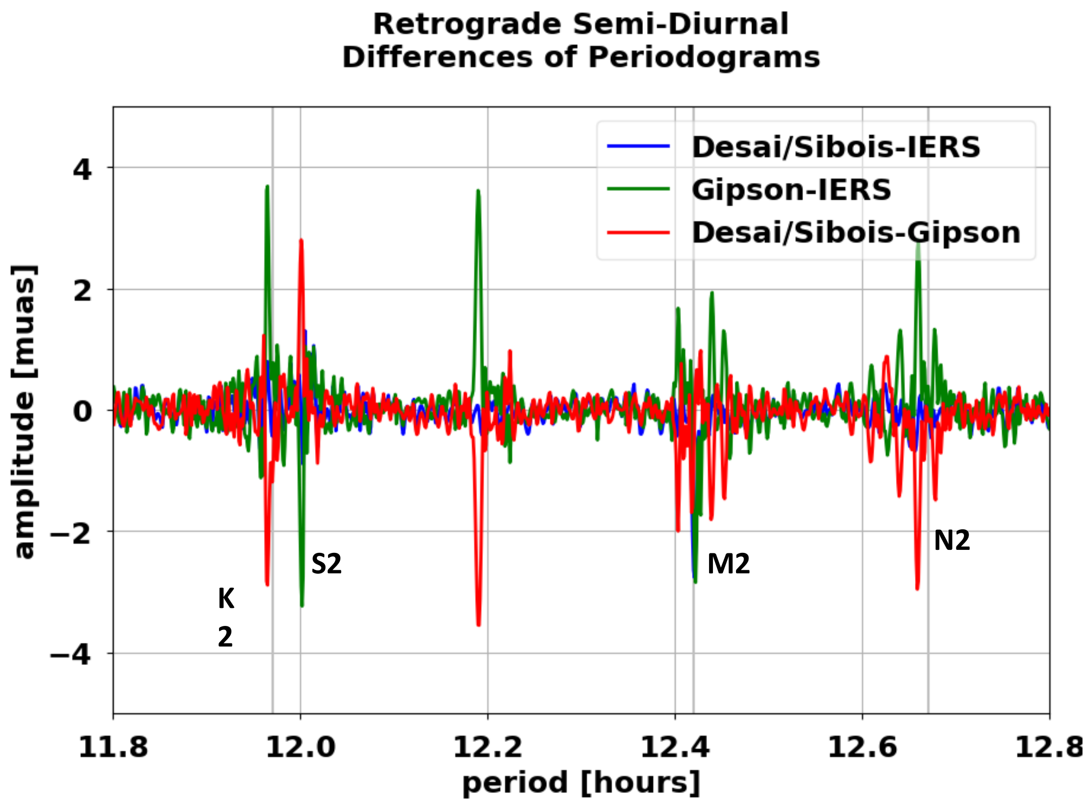



Overall, more residual signal observed for Gipson model; least amount of residual signal noticed for Desai-Sibois model.

| | K2 | S2 | M2 | N2 | RSS |
|---|---|---|---|---|---|
| **IERS** | 1.1 | 3.9 | 5.1 | 1.4 | 6.66 |
| **Gipson** | 2.5 | 2.4 | 4.8 | 1.0 | 6.00 |
| **Desai-Sibois** | 1.8 | 1.7 | 0.8 | 0.7 | 2.69 |

residual amplitudes at major semi-diurnal tides in prograde direction. Units are microarcseconds. Results were obtained through unconstrained least-squares adjustment.

# Residual polar motion in semi-diurnal frequency band

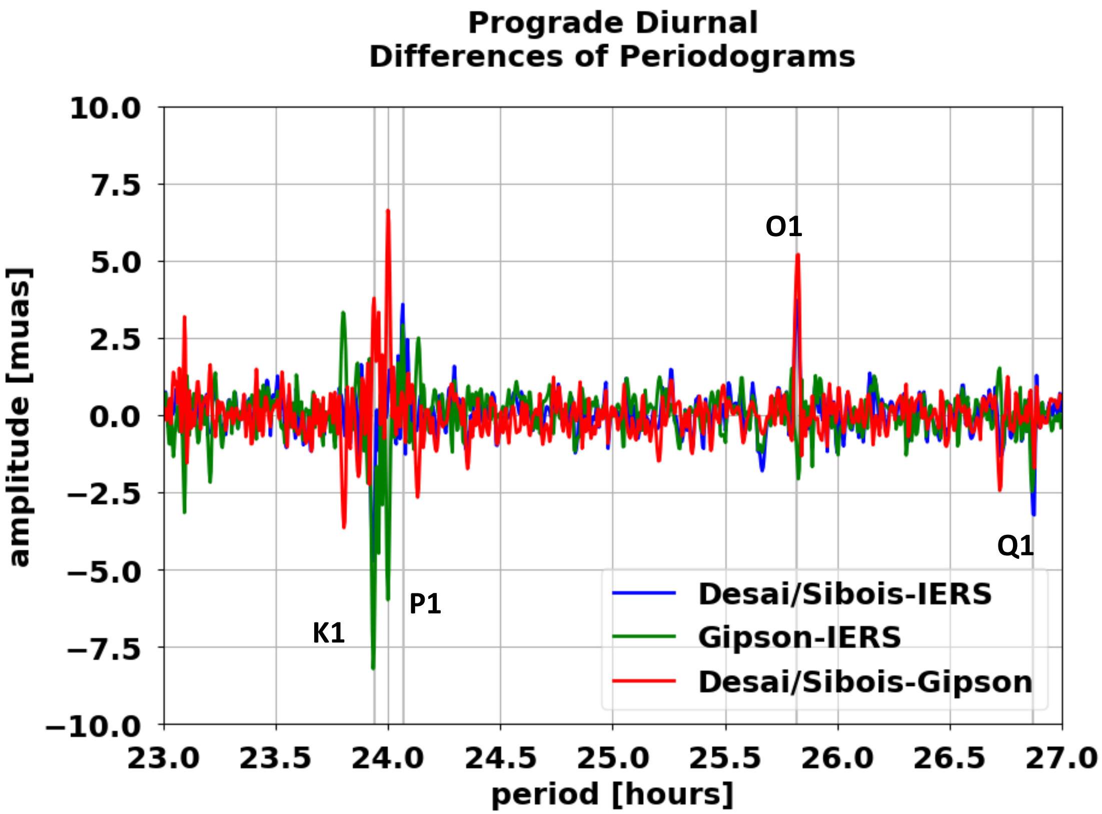



Overall, more residual signal observed for Gipson model; least amount of residual signal noticed for Desai-Sibois model. Notable exception at 12h (S2).

| | K2 | S2 | M2 | N2 | RSS |
|---|---|---|---|---|---|
| **IERS** | 2.7 | 7.6 | 8.0 | 3.5 | 11.89 |
| **Gipson** | 4.3 | 5.5 | 5.7 | 5.8 | 10.72 |
| **Desai-Sibois** | 2.9 | 7.9 | 5.2 | 3.0 | 10.34 |

residual amplitudes at major semi-diurnal tides in retrograde direction. Units are microarcseconds. Results were obtained through unconstrained least-squares adjustment.

# Residual polar motion in diurnal frequency band




Overall, more residual signal observed for Desai-Sibois model; least amount of residual signal noticed with Gipson model.
Peak at S1 (24.0) possibly due to atmospheric tide accounted for in Gipson model?

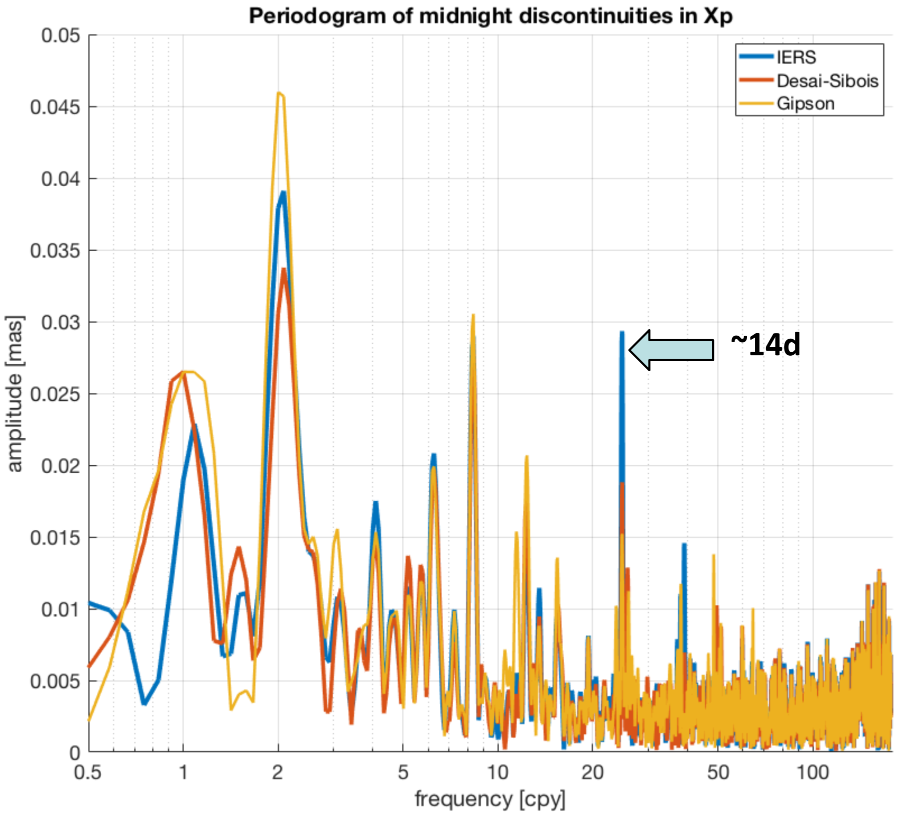
| | K1 | P1 | O1 | Q1 | RSS |
|---|---|---|---|---|---|
| **IERS** | 20.8 | 4.1 | 3.7 | 5.2 | 22.14 |
| **Gipson** | 12.5 | 7.1 | 2.6 | 2.7 | 14.86 |
| **Desai-Sibois** | 16.1 | 7.7 | 7.5 | 2.3 | 19.49 |

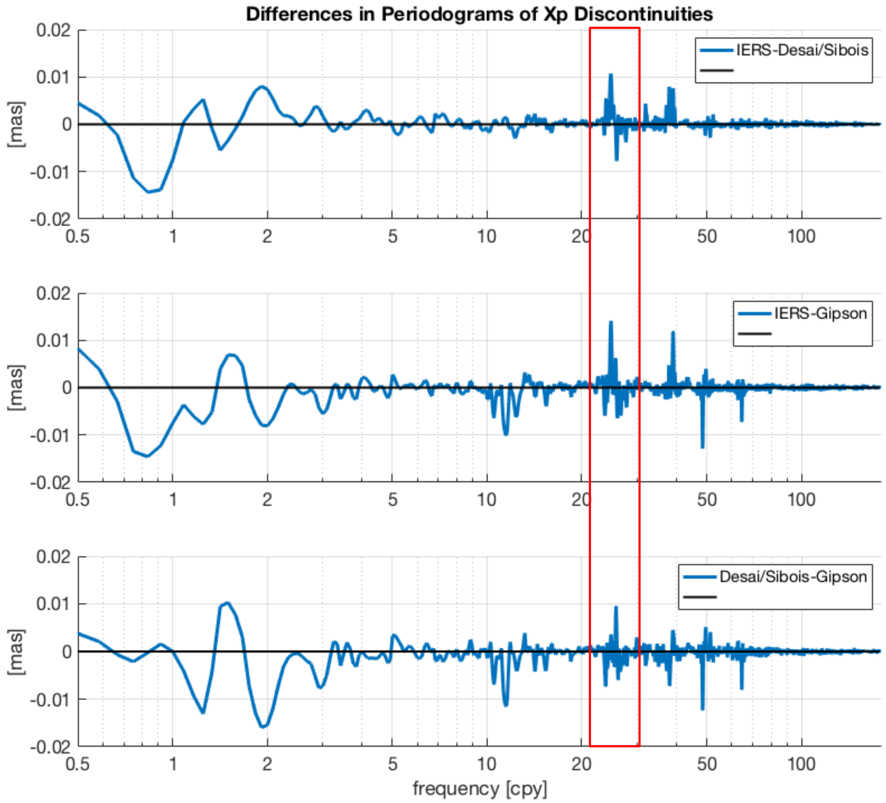
residual amplitudes at major diurnal tides in prograde direction.
Units are microarcseconds. Results were obtained through unconstrained least-squares adjustment.

# Impact on GPS network solutions

- 3 years (2014-2016) of GPS only, 5-min data processed using GipsyX software
- Solutions use JPL’s strategy for contribution to final IGS products
- 30-hour arcs, 80 stations, no-net-rotation constraint applied
- Setup is strictly identical among the 3 types of solutions with the exception of the sub-daily ERP model.
- Same data/network used by the three solutions
- Same daily nominal EO file used by the three solutions (IERS Bulletin A)
- Reference frame is IGS14
- All cases apply:
  - daily values of ERPs using IERS Bulletin A (to model variations with period > 2 days)
  - Conventional nutation model from Mathews et al. (2002) which includes effects of ocean tides, consistently with conventional ocean tide model.
- Statistical and spectral analyses of:
  - Polar motion and right ascension of the ascending node (RAAN) discontinuities at midnight for each arc
  - ERP estimates
    - Xp, Yp, Xp rate, Yp rate, UT1-UTC, UT1-UTC rate estimated daily
  - orbit and clock overlaps (internal consistency of solutions)
  - orbit and clock differences (direct inter-solution comparison)
  - ambiguity resolution performance
  - PPP

# Polar motion discontinuities (Xp)



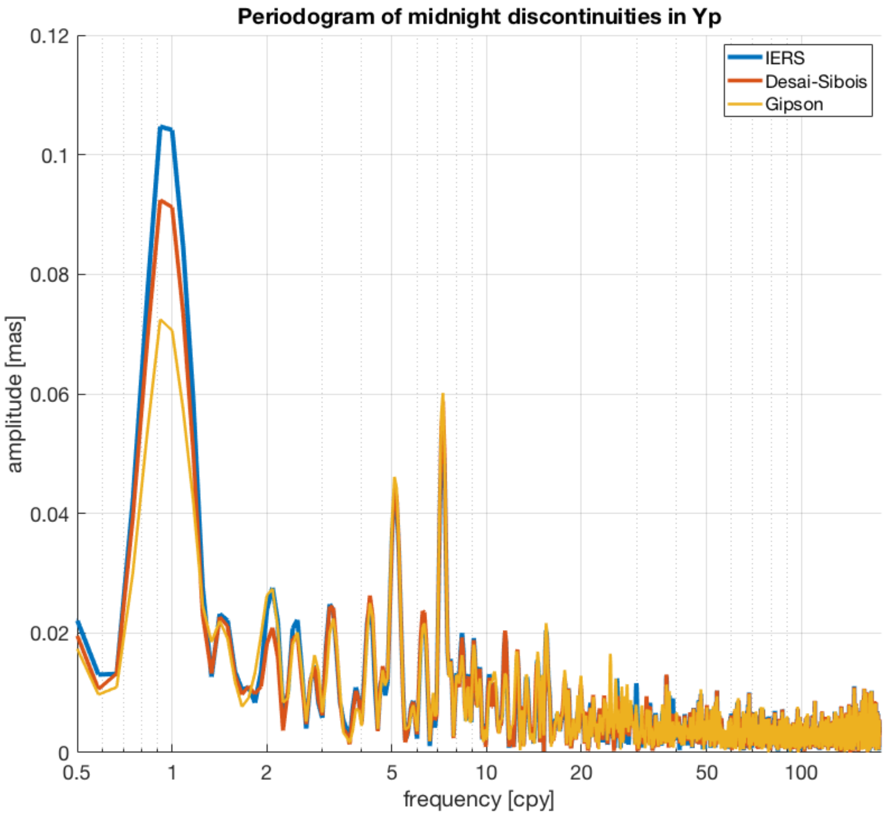

PM discontinuities are computed at midnight:

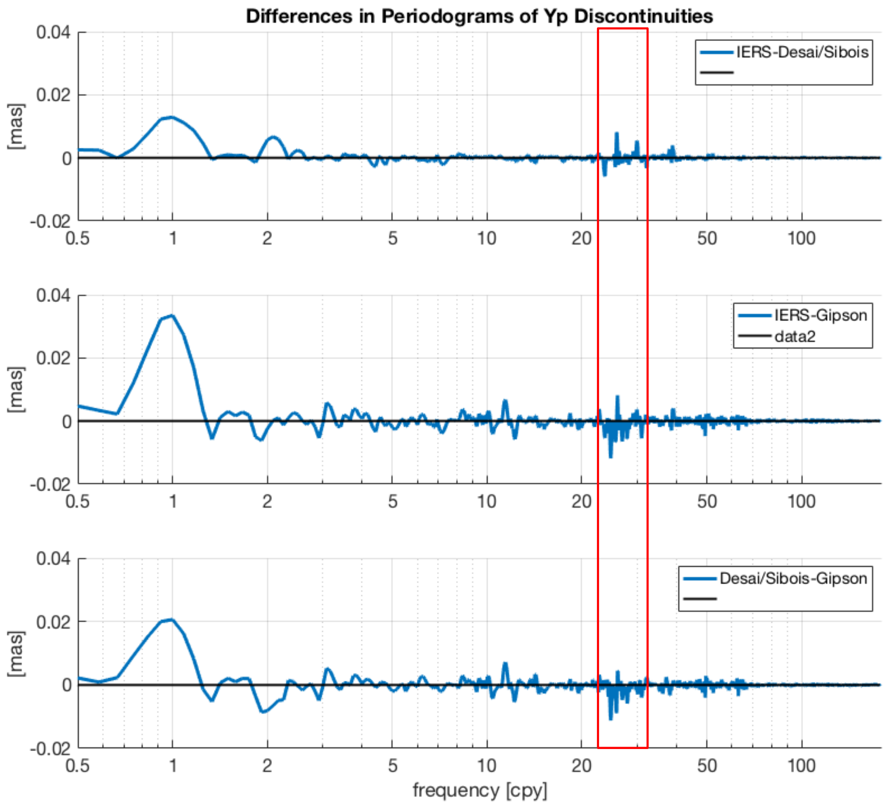
- all ERP bias and rate solutions are referred to 12h on central day of the arc
- use estimated biases and rates to propagate the solution for day d forward to 24h and backward to 0h for the solution corresponding to day d+1

Periodograms show reduction of the 14-day signal when modern models are used.

**Reduction is largest for Gipson model.**

# Polar motion discontinuities (Yp)

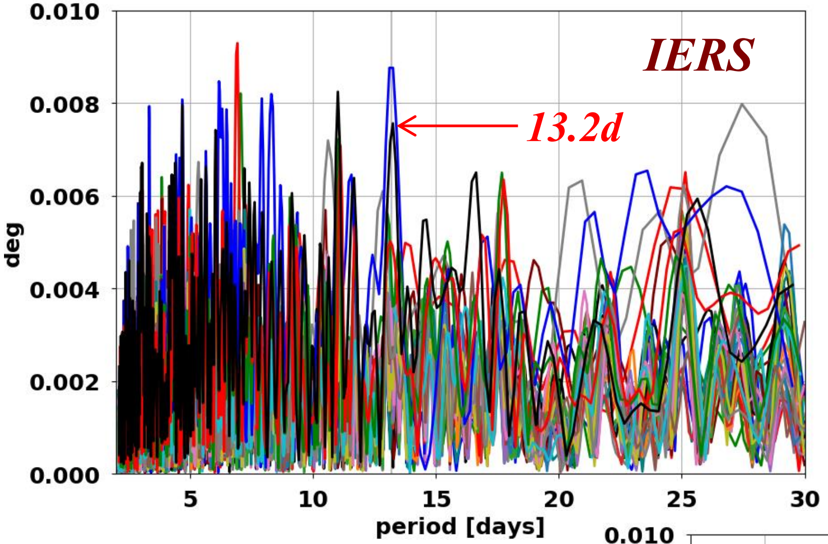


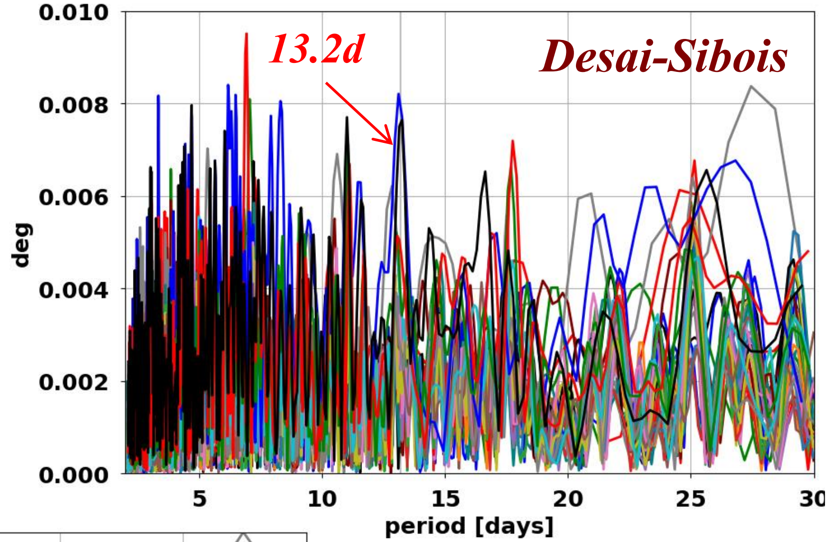



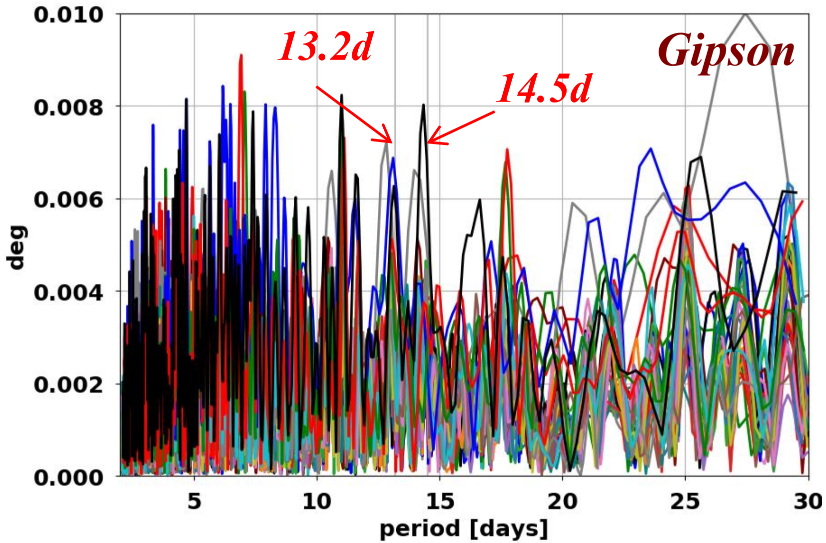

Periodograms show reduction of the 14-day signal when using modern models.
**Reduction is largest for Desai-Sibois model.**

# Right Ascension of Ascending Node (RAAN) discontinuities (midnight overlaps)

- RAAN discontinuities typically associated with deficiencies in sub-daily UT1 models
  - T. Springer showed full mitigation of 14d-period-signal when switching from IERS model to Gipson model and reduction of the signal when switching from IERS model to Desai-Sibois model. Here signal is seen at 13.2d; significantly reduced using Gipson but 14.5d signal appears?

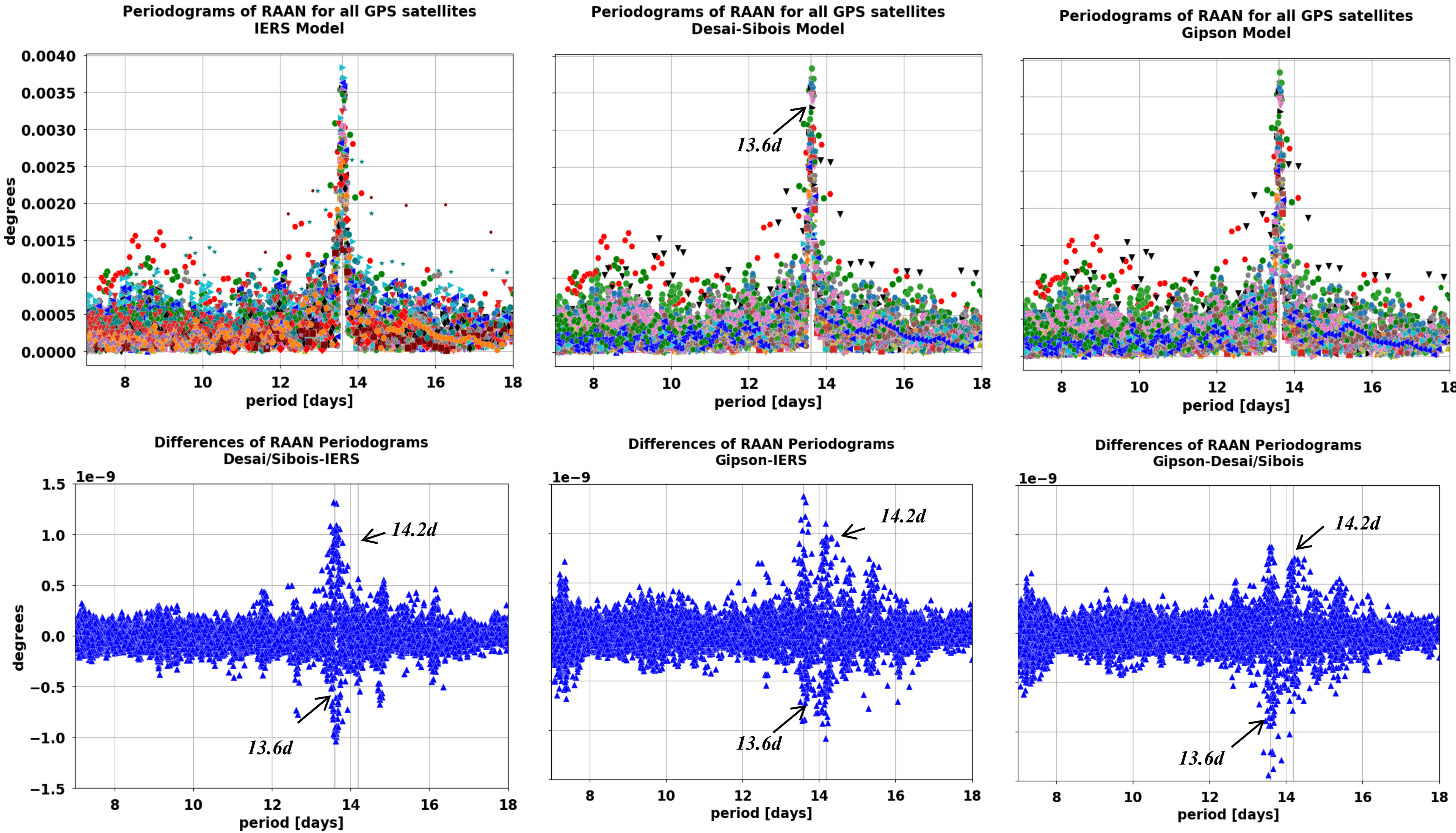


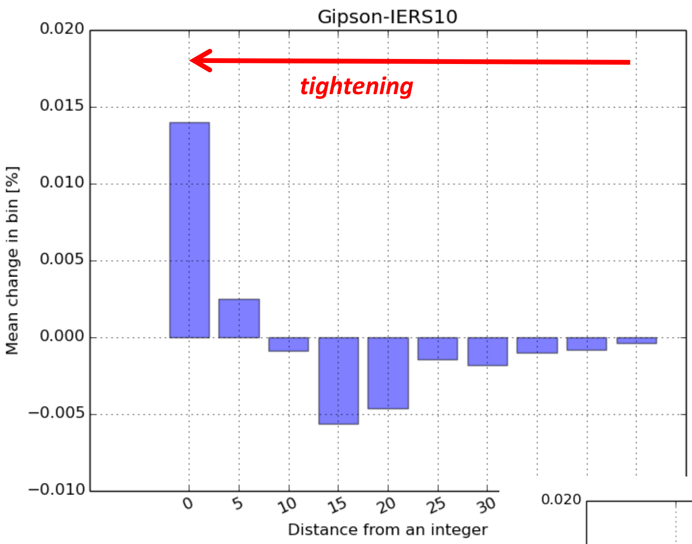
# Right Ascension of Ascending Node (RAAN) discontinuities

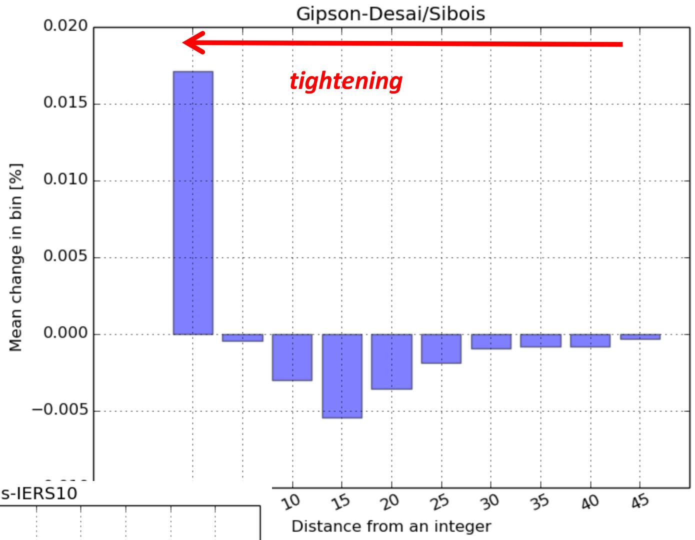
- Periodograms of daily non-overlapping time series of RAAN and inter-model differences of those periodograms

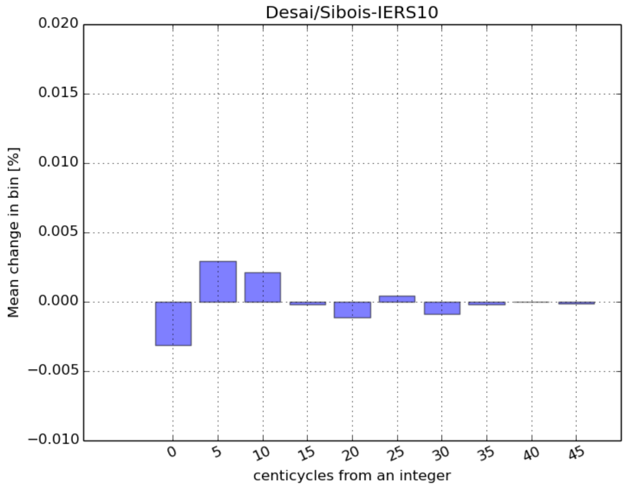


# Performance of ambiguity resolution

- Ambiguity resolution analysis
  - improvement in bias fixing means better measurement modeling
  - overall tightening of the histogram closer to integer for solutions corresponding to the modern models → negligible improvement for Desai-Sibois model but **relatively significant improvement for Gipson model.**



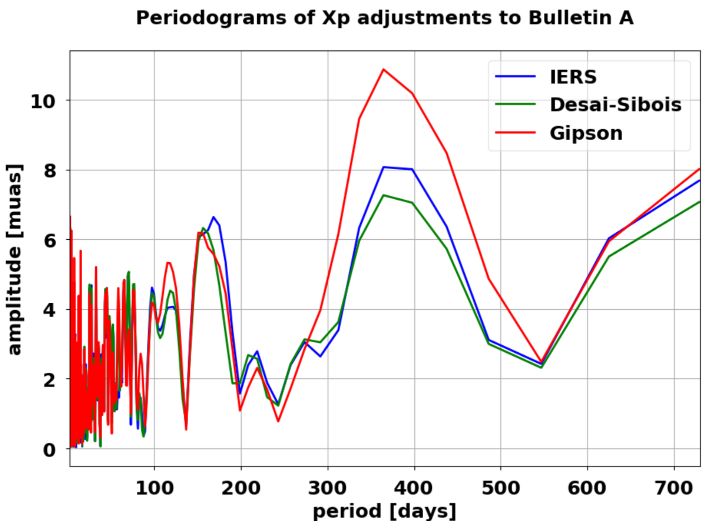



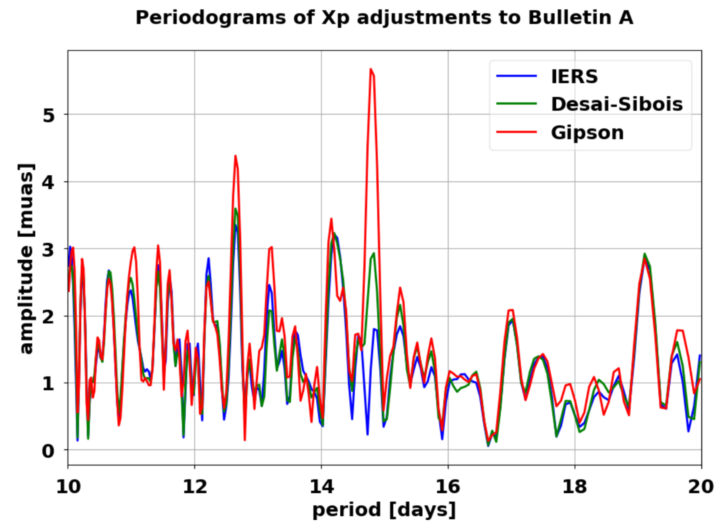



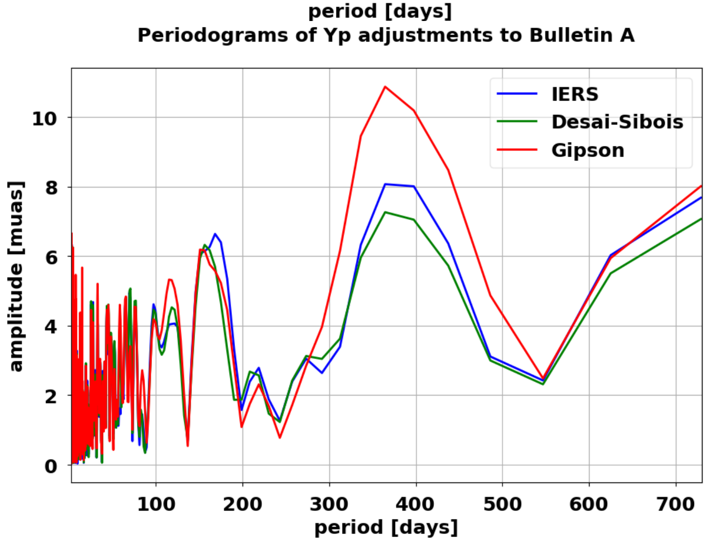
# Analysis of daily ERP estimates

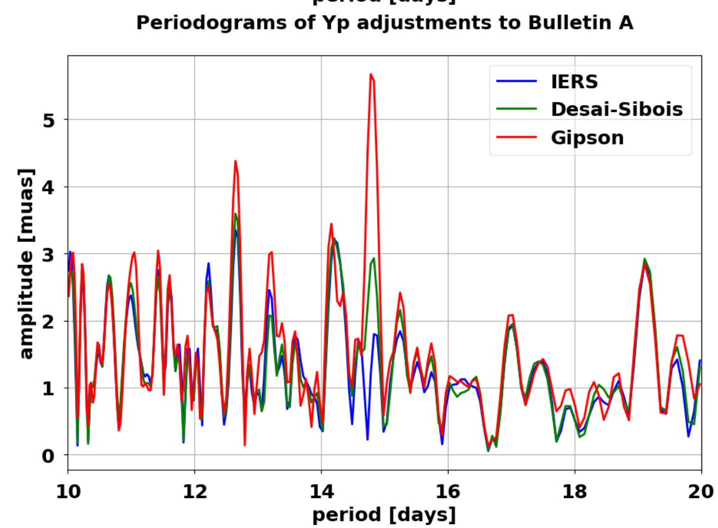
ERP adjustments to Bulletin A = adjustments to daily estimates using IERS-recommended model ➔ baseline “IERS” solution intrinsically more internally consistent.

**Largest adjustments in polar motion biases observed when switching to Gipson model.**

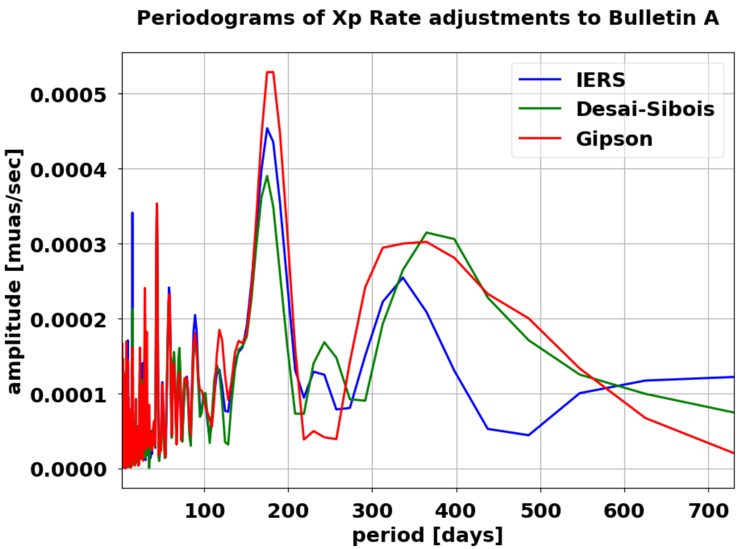


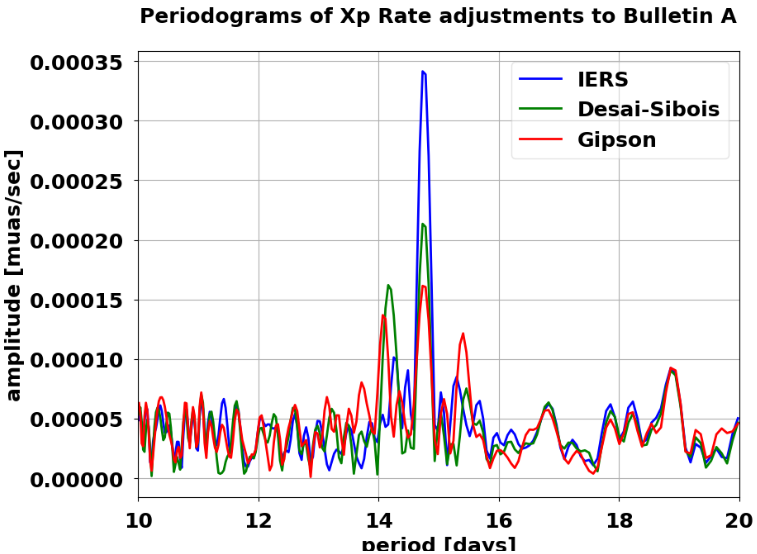



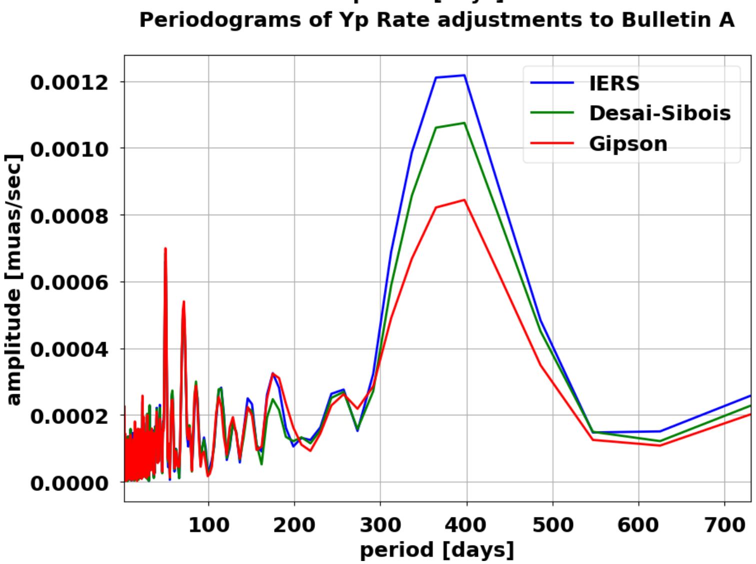



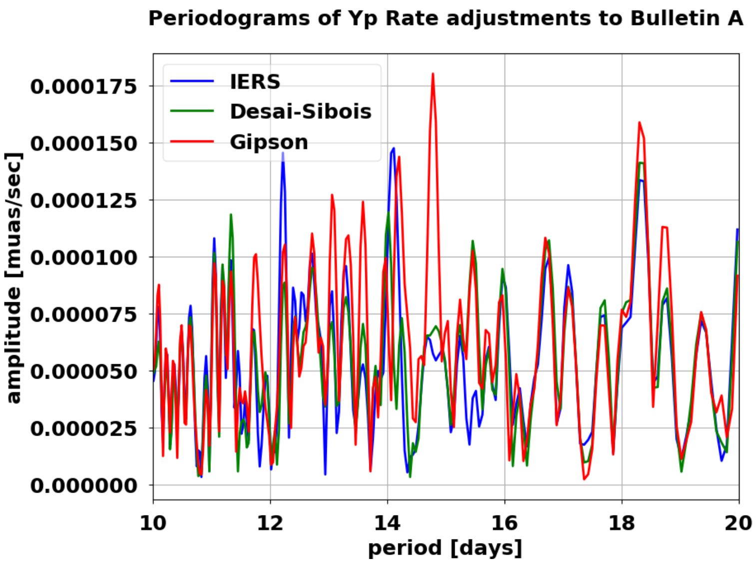



# Analysis of daily ERP estimates



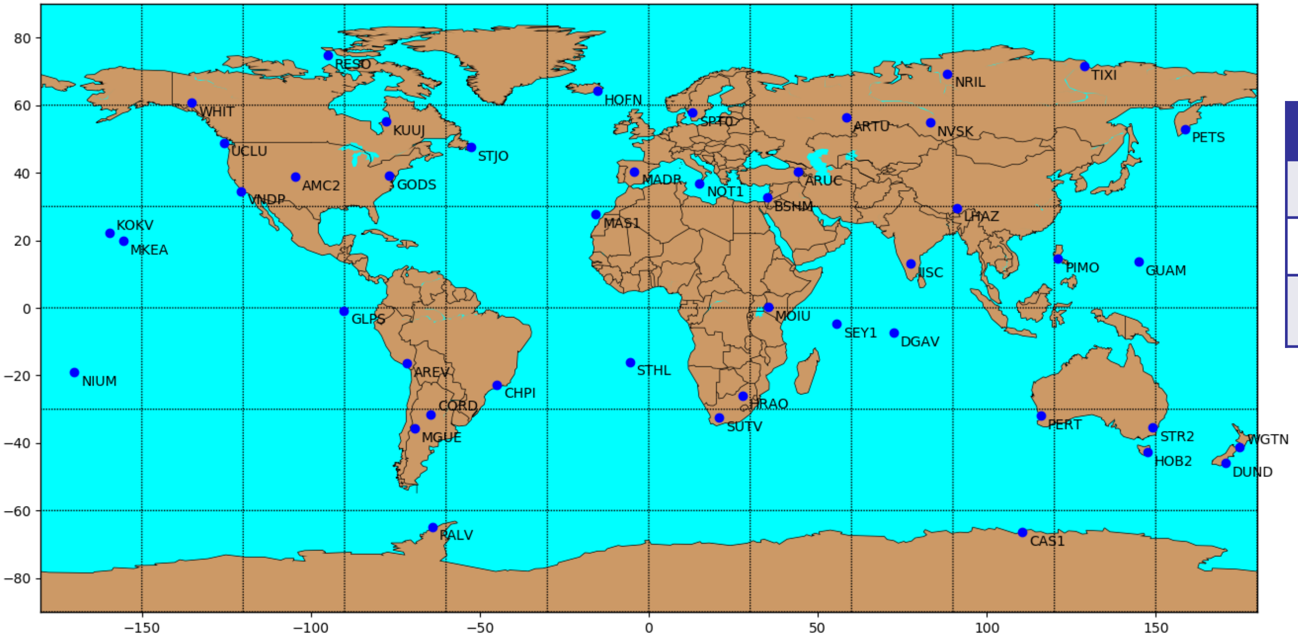



# Precise Point Positioning

- 45 stations PPP-ed over the 3 years processed
- network selected based on best Earth coverage for stations with maximum number of daily solutions over the 3 years analyzed.
- analysis of ENU position deviations: models yield **statistically identical results**. **Spectral analysis does not reveal any performance difference between models**.
- analysis of terrestrial reference frame parameters (translations, rotations, scale) available in backup




| | East | North | Up |
|---|---|---|---|
| IERS | 3.70 | 2.67 | 7.48 |
| Gipson | 3.70 | 2.67 | 7.48 |
| Desai-Sibois | 3.69 | 2.67 | 7.48 |

**repeatability of station position deviation**

# Conclusion and References

- Modern models are available for impact of ocean tides and tidal deformation on Earth Rotation Parameters. Only two alternatives to models currently recommended by the IERS were tested but more are available.
- Two categories of models: **tidal models vs. empirical models** (tied to observation technique(s))
  - fundamental difference in modeling approach with implications in interpretation of signal observed in final products
- Better consistency of modern ocean tide model tested with the conventional libration model; either by design (Gipson model) or from improved consistency in the underlying geophysical models
- From HF polar motion analysis: better performance of Desai-Sibois model in semi-diurnal band but better performance of Gipson model in prograde diurnal band (retrograde diurnal polar motion is nutation by convention, so forced to 0 when models are created)
- From daily EOP estimation analysis: conclusions difficult to draw but overall better performance from Gipson model (per RAAN discontinuities and ambiguity resolution metrics, though difference is not tremendous)
- Any plan for update to the nutation model (Mathews, Herring and Buffet, 2002) to maintain consistency? Would it be needed?
- Future work:
  - investigate further 15-minute estimate time series and discrepancies between daily polar motion discontinuities and polar motion residuals in the diurnal frequency band.
  - include a model for atmospheric tides (e.g. Schindelegger, 2014, 2016)
  - derive/implement/test HF-EOP models based on TPXO9 and/or FES2014

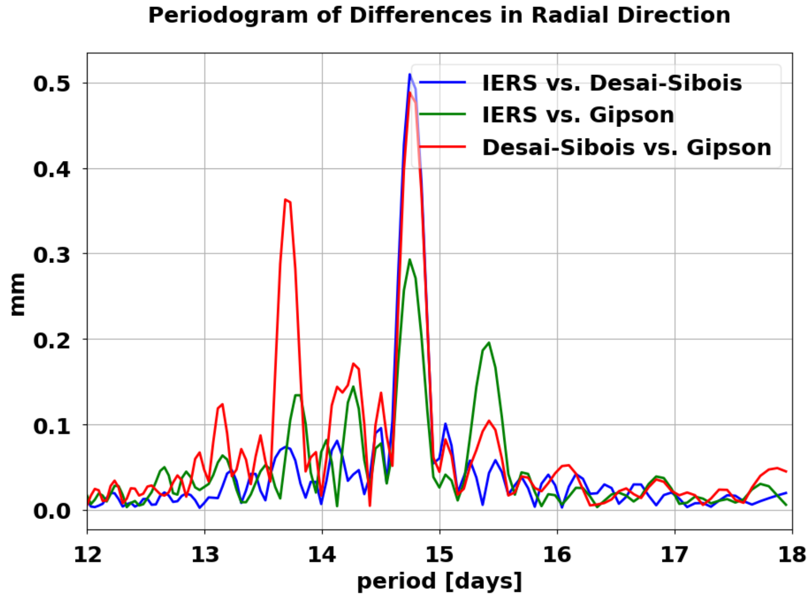
# Conclusion and References

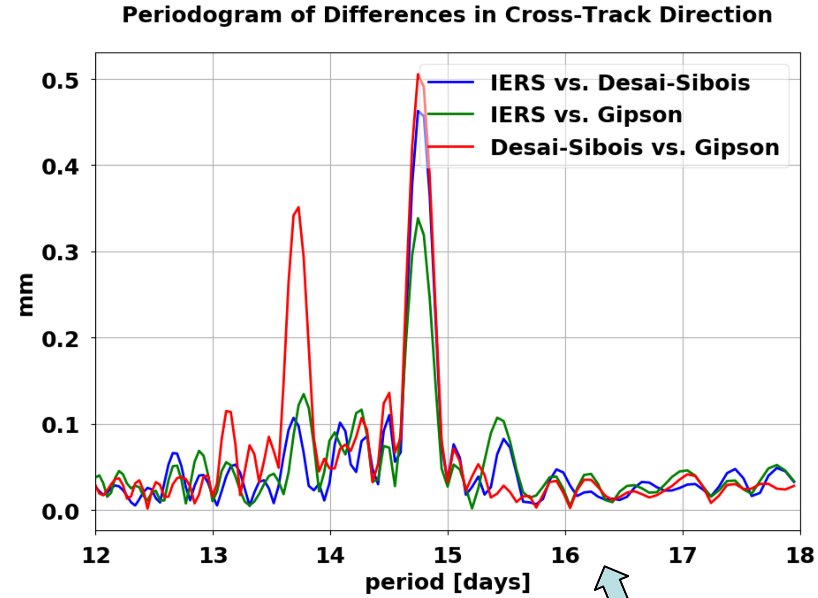
References:

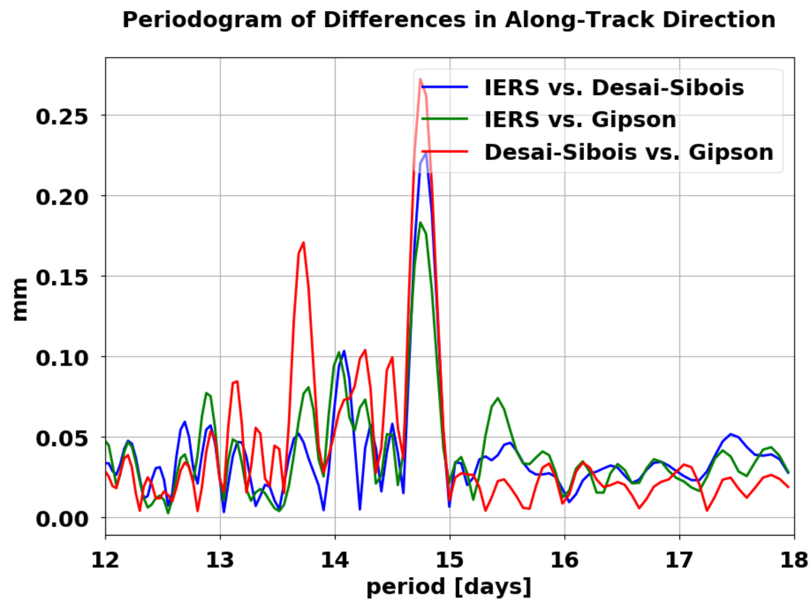

- Petit, G. and Luzum, B. (2010). "*IERS conventions (2010)*" IERS-TN-36
- Gipson, J. and Ray, R. (2009). "A new model of tidal EOP variations from VLBI data spanning 30 years", EGU 2009
- Gipson, J. https://ivscc.gsfc.nasa.gov/hfeop_wg/ and report on Working Group at AGU 2018
- Desai, S.D. and Sibois, A.E. (2016). "*Evaluating predicted diurnal and semidiurnal tidal variations in polar motion with GPS-based observations*". Journal of Geophysical Research: Solid Earth, 121(7):5237-5256
- Sibois, A.E. et al. (2017). "*Analysis of decade-long time series of GPS-based polar motion estimates at 15-min temporal resolution*". Journal of Geodesy
- Mathews, P. M. and Bretagnon, P. (2003). "*Polar motions equivalent to high frequency nutations for a non-rigid Earth with anelastic mantle*". Astronomy & Astrophysics, 400(3):1113-1128

# Backup Slides

# Orbit Differences




should be consistent with periodograms of RAAN discontinuities

# Actual impact on GPS network solutions

**Orbit and clock solutions** generated using different HFEOP models are **statistically of equivalent quality**.

- Post-fit Residuals

| | IERS | Gipson | Desai-Sibois |
|---|---|---|---|
| PC [cm] | rms = 82.3 | rms = 82.3 | rms = 82.3 |
| LC [mm] | rms = 9.8 | rms = 9.8 | rms = 9.8 |

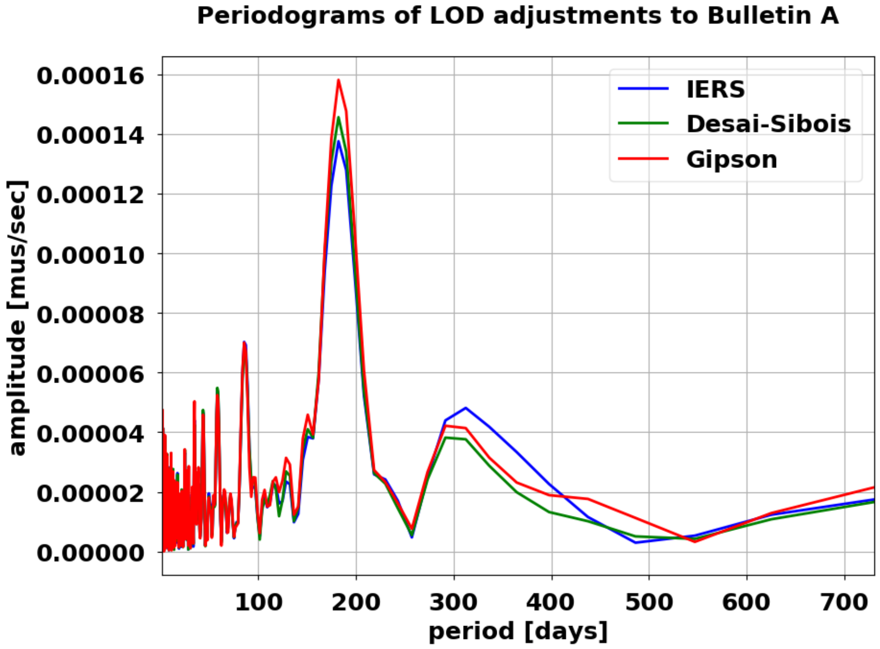
- Orbit/Clock Precision (internal overlaps)

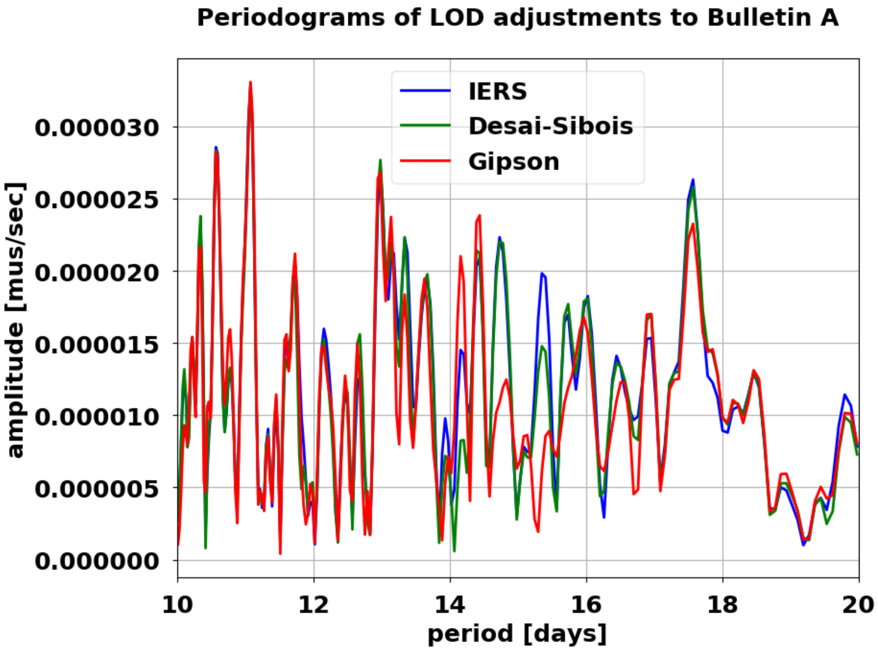
| | IERS | Gipson | Desai-Sibois |
|---|---|---|---|
| 1D-RMS Orbits [cm] | rms = 1.44<br>median = 1.39 | rms = 1.44<br>median = 1.39 | rms = 1.44<br>median = 1.39 |
| RMS clocks [cm] | rms = 2.41<br>median = 2.26 | rms = 2.41<br>median = 2.25 | rms = 2.40<br>median = 2.26 |

- Orbit/Clock Differences

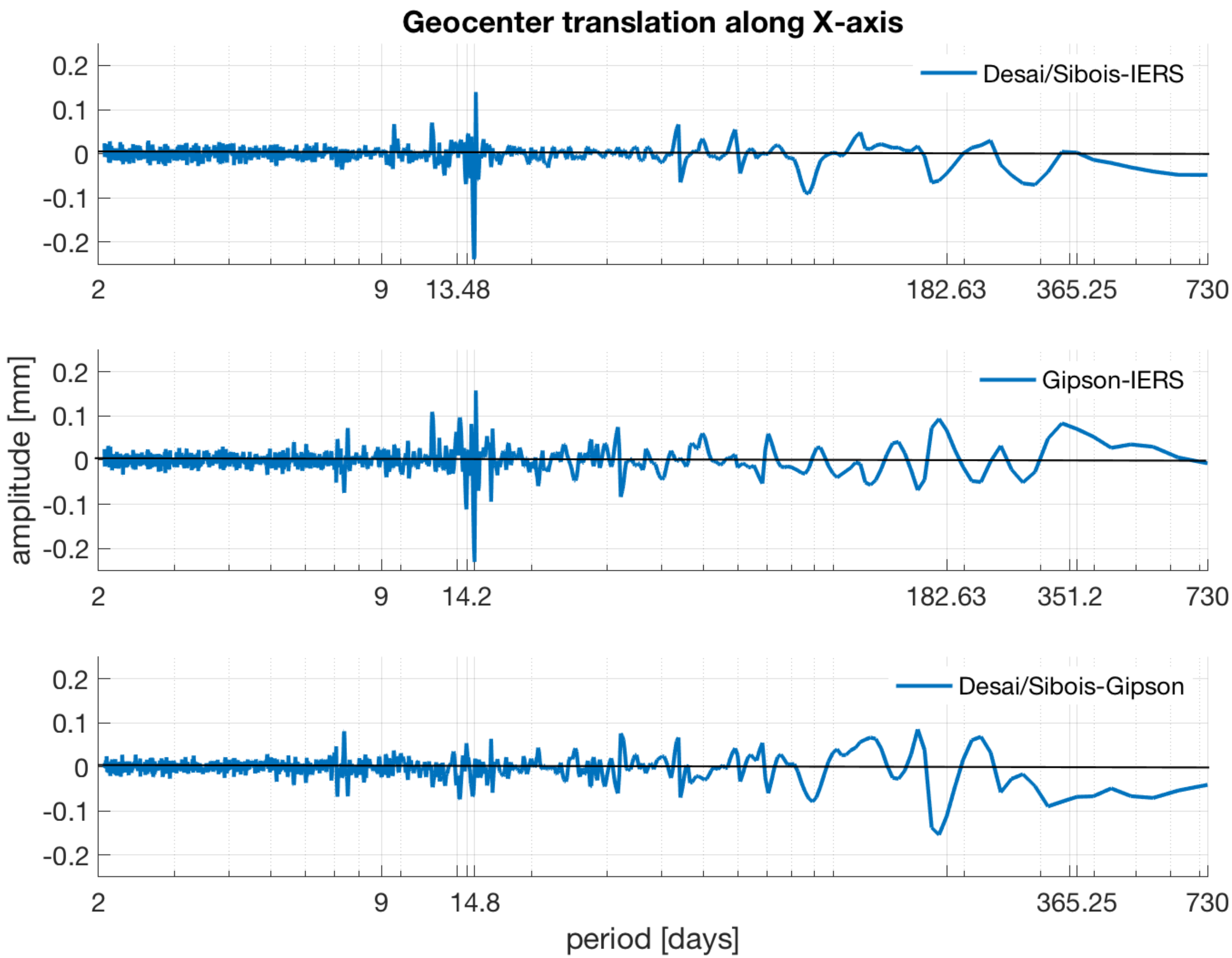
| | IERS vs. Gipson | IERS vs. Desai-Sibois | Gipson vs. Desai-Sibois |
|---|---|---|---|
| 1D-RMS Orbits [cm] | rms = 0.21<br>median = 0.20 | rms = 0.17<br>median = 0.17 | rms = 0.21<br>median = 0.20 |
| RMS clocks [cm] | rms = 0.22<br>median = 0.22 | rms = 0.19<br>median = 0.19 | rms = 0.23<br>median = 0.22 |

# Analysis of daily ERP estimates



# Analysis of Frame Parameters



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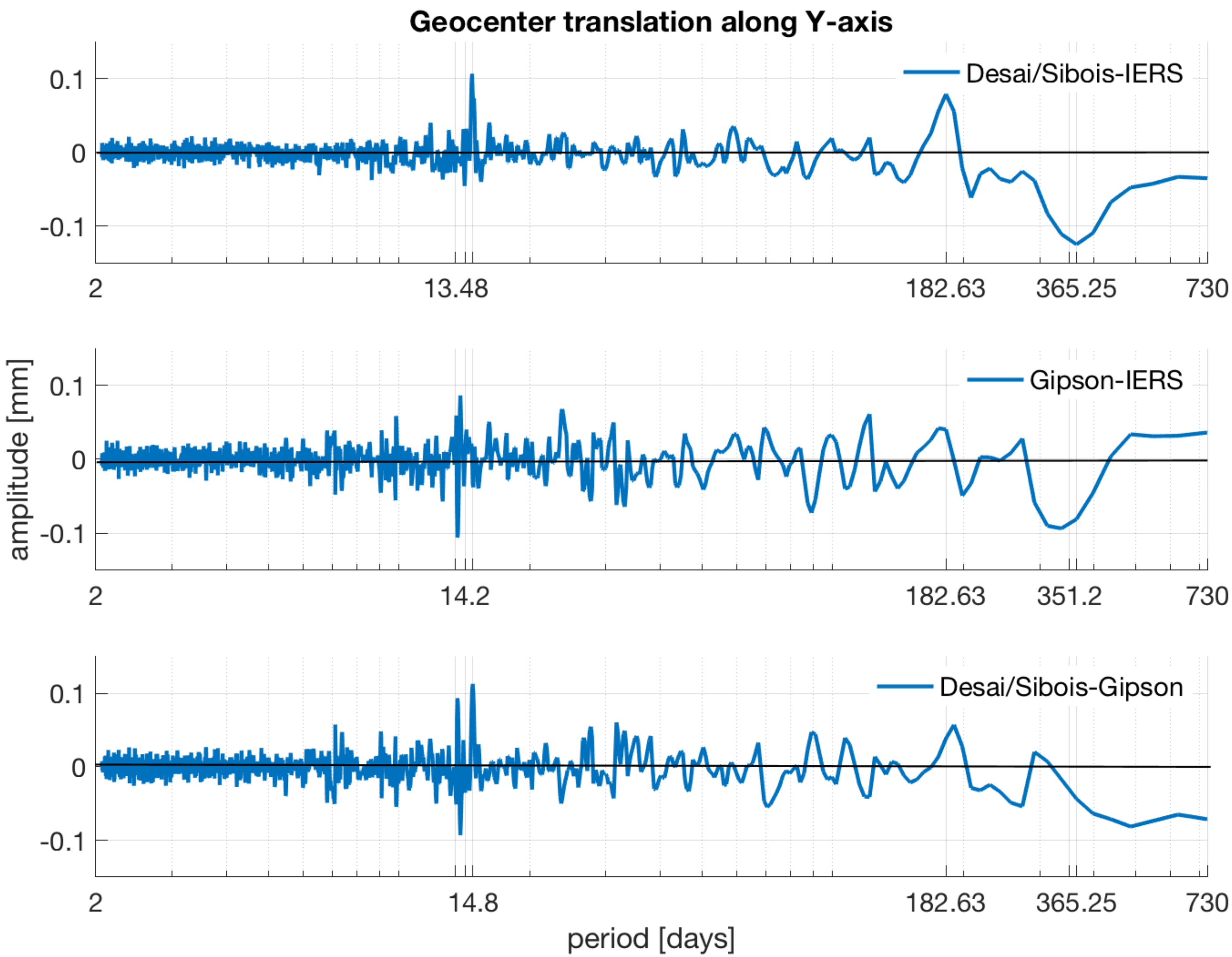

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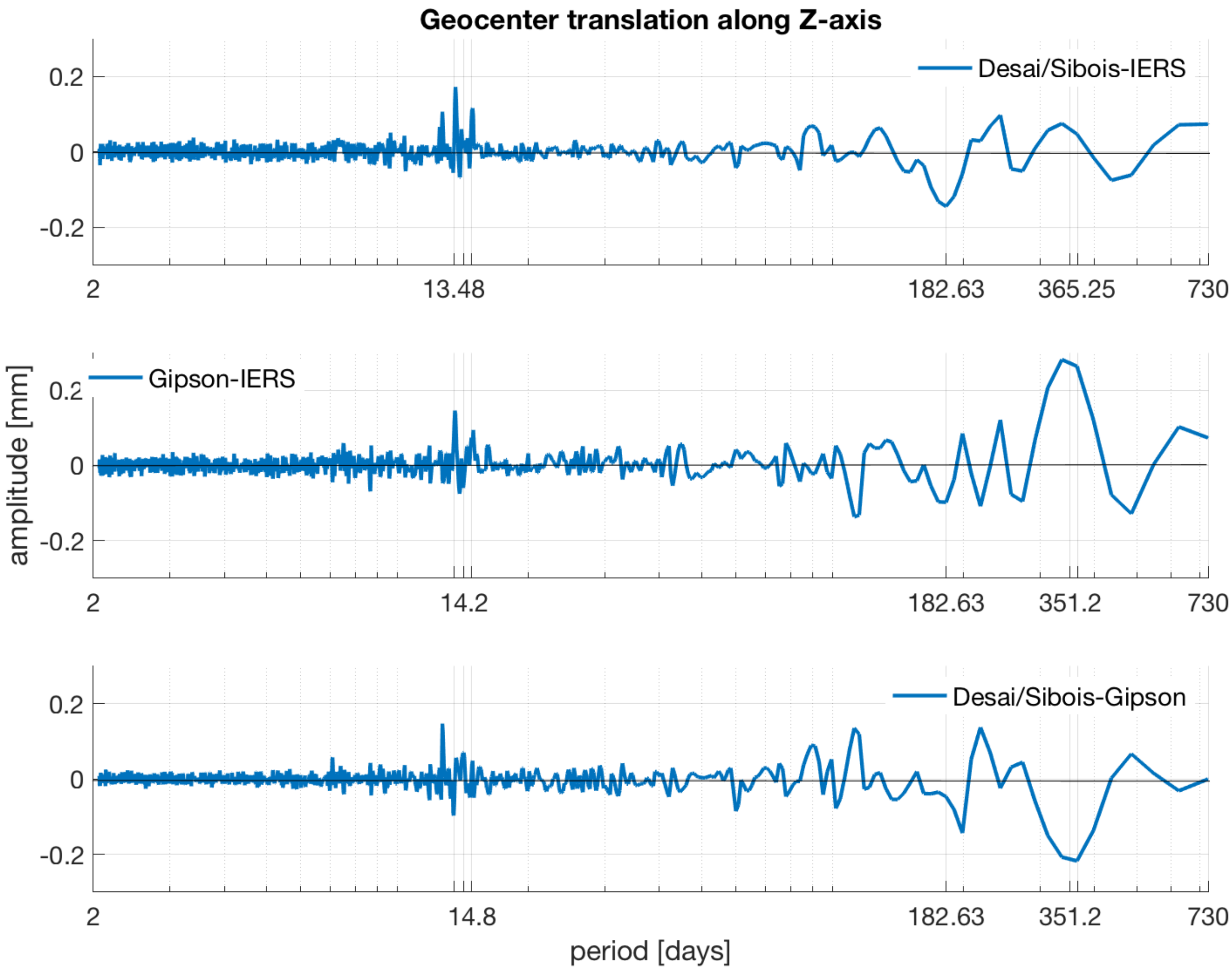

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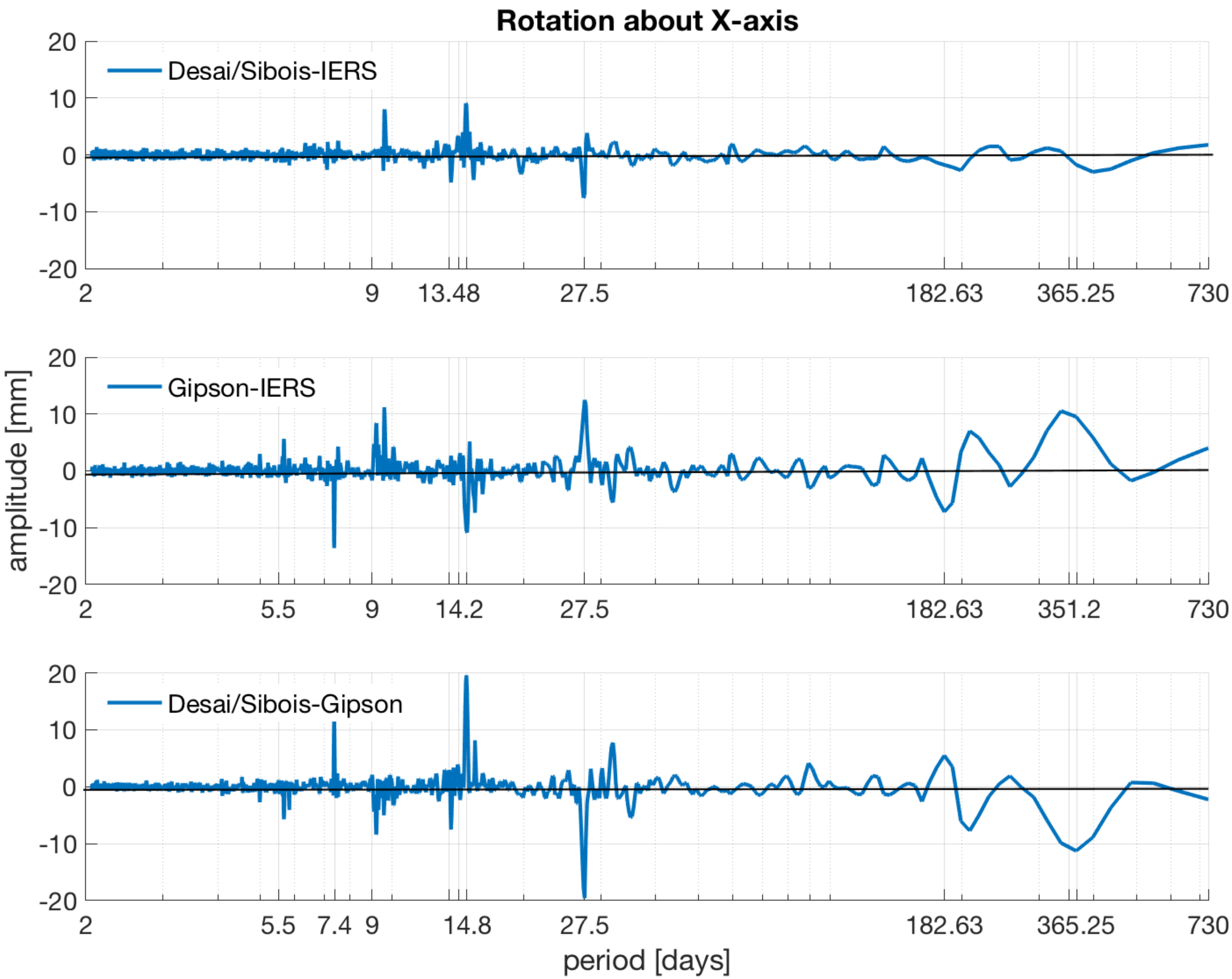

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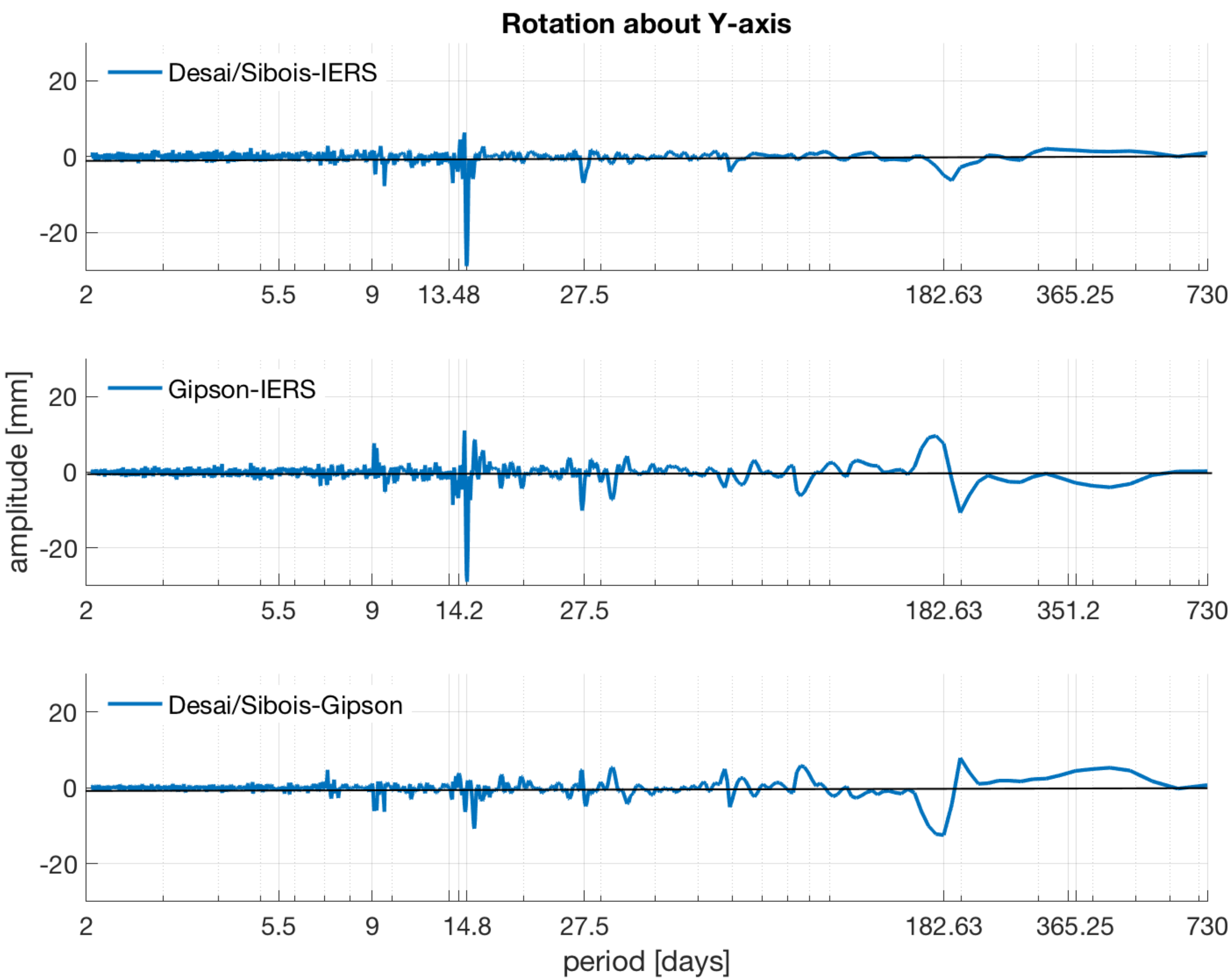

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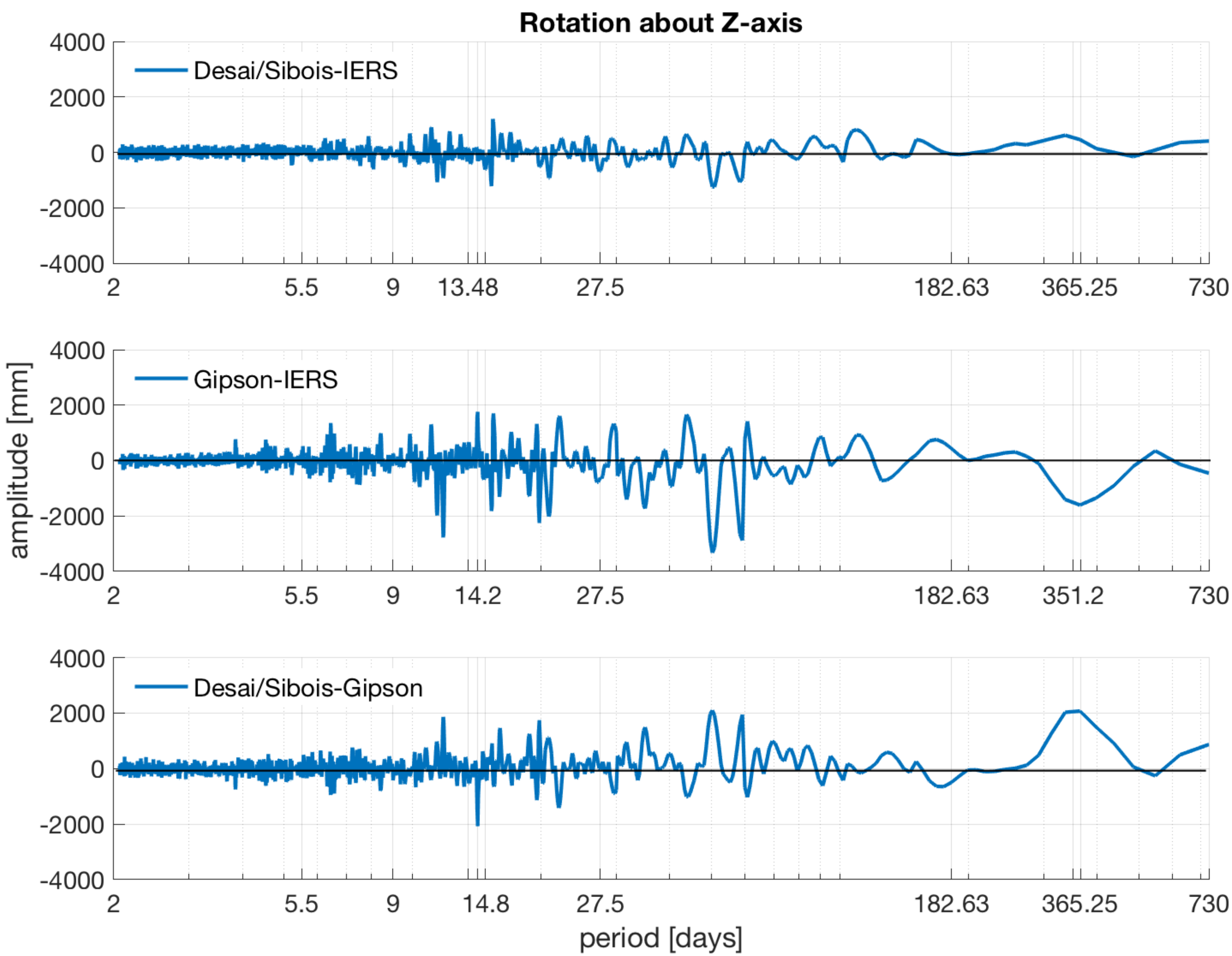

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