# First results from combining the GPS orbits and clocks of the IGS 2nd reprocessing campaign

Jake Griffiths
Naval Research Laboratory

Kevin Choi
National Geodetic Survey

IGS INTERNATIONAL GNSS SERVICE

*Special thanks to Jim Ray (NOAA/NGS, retired)*

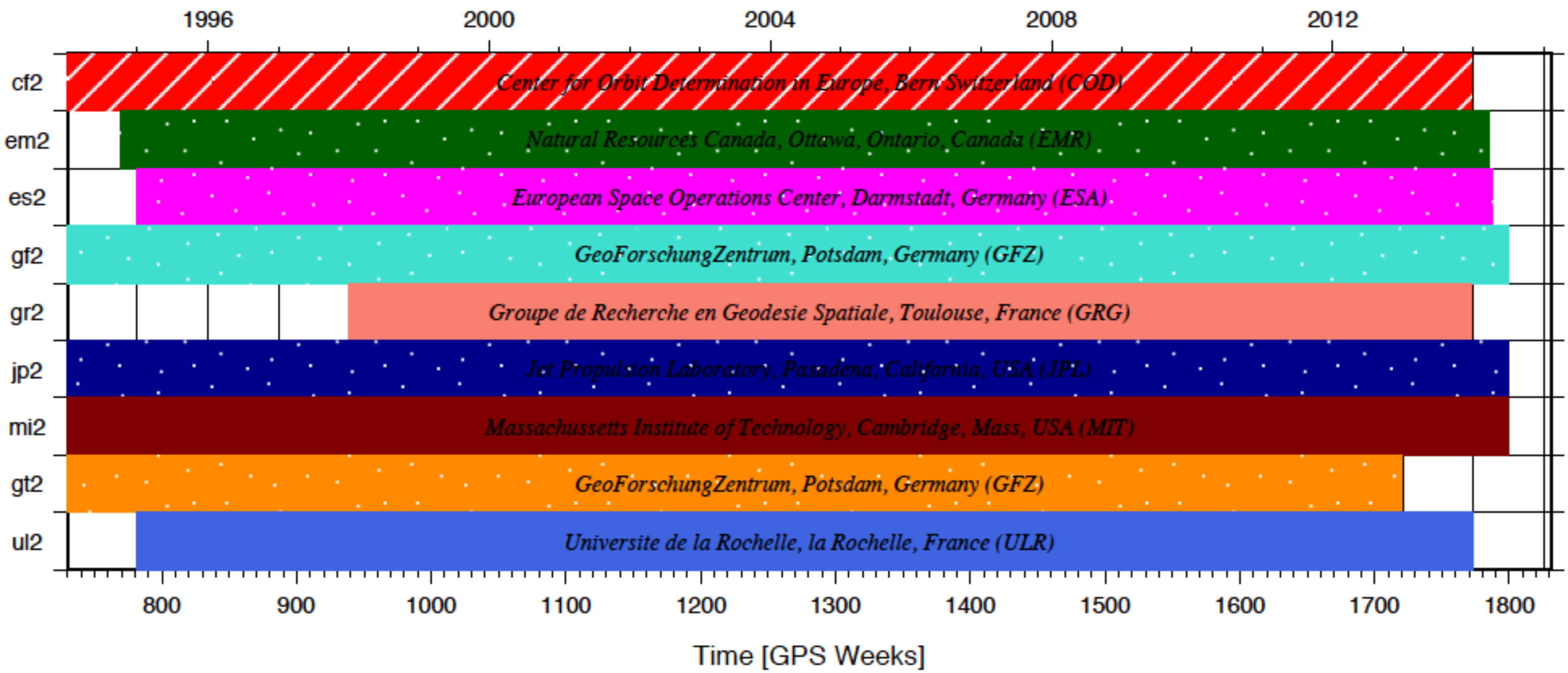
# Why Reprocessing Again?

- The Analysis Centers have completed their 2nd reanalysis of the full history of GPS and GLONASS data collected by the IGS global network from 1994.0 until ~2014.0
- The reprocessing was completed using the latest models and methodologies, which offers the potential for full consistency over time using IGS08/IGb08 as the *a priori* terrestrial reference frame and associated antenna calibrations
- This effort follows the successful 1st full reprocessing by the IGS, which provided the GNSS input for ITRF2008
- Likewise, this 2nd reprocessing has provided the GNSS input for ITRF2014
  - *see next talk by P. Rebischung et al.*
- In addition, the combined products offer the potential to study geodynamics at higher temporal resolution, and possibly with improved accuracy and precision

# Contributed Products

- Eight contributing Analysis Centers (ACs)
  - COD, EMR, ESA, GFZ, GRG, JPL, MIT and ULR
- Daily GPS & GLONASS orbits and GPS satellite clocks
  - 15-minute intervals (SP3c format)
- Daily GPS satellite and tracking station clocks
  - 5-minute intervals (clock RINEX format)
  - no 30-second clocks: insufficient number of acceptable 30s clock ACs
- Daily Earth rotation parameters (ERPs)
  - x & y coordinates of pole
  - rate-of-change of x & y pole coordinates
  - excess length-of-day (LOD)
- Terrestrial coordinate frames with ERPs
  - with full variance-covariance matrix (SINEX format)
  - also includes Z-offset parameters for satellite antennas (with removable constraints to official igs08.atx values)

# Time Spans of AC Contributions




- 7 operational ACs
  - COD, EMR, ESA, GFZ (GF2), GRG, JPL, MIT
- 2 TIGA ACs to densify ground network with stations collocated at tide-gauges
  - GFZ (GT2), ULR

| LEGEND |
|---|
| slash: snx, sp3, erp [brdc clk in sp3] |
| dots: snx, sp3, clk (5m), erp |
| solid: snx, sp3, clk (30s), erp |

# AC Measurement Models

| | CODE (COF) | EMR | ESA | GFZ | GRG | JPL | MIT | ULR |
|---|---|---|---|---|---|---|---|---|
| **Observable Type** | DbDiff (weak redundant) | UnDiff | UnDiff | Undiff | UnDiff | UnDiff | DbDiff (weak redundant) | DbDiff (weak redundant) |
| **Data Rate** | 3 min | 5 min | 5 min +30 sec for clocks | 5 min | 15 min (30s for clocks) | 5 min | 2 min | 2 min |
| **RHC phase rotation corr.** | Yes (Wu et al., 1993) | Yes (Wu et al., 1993) | Yes (Wu et al., 1993) | Yes (Wu et al., 1993) | Yes (Wu et al., 1993) | Yes (Wu et al., 1993) | Yes (Wu et al., 1993) | Yes (Wu et al., 1993) |
| **Elevation Cutoff** | 3 deg | 10 deg | 10 deg | 7 deg | 12 deg | 7 deg | 10 deg | 10 deg |
| **Elevation-dependent Inverse Weights ($sigma^2$ = )** | $1 / \cos^2(z)$ | $1/\sin(e)$ | $1 / \sin^2(e)$ | $1 / 2\sin(e)$ for $e < 30$ deg | none | $1/\sin(e)$ | $a^2 + (b^2 / \sin^2(e))$ a,b from site residuals | $a^2 + (b^2 / \sin^2(e))$ a,b from site residuals |

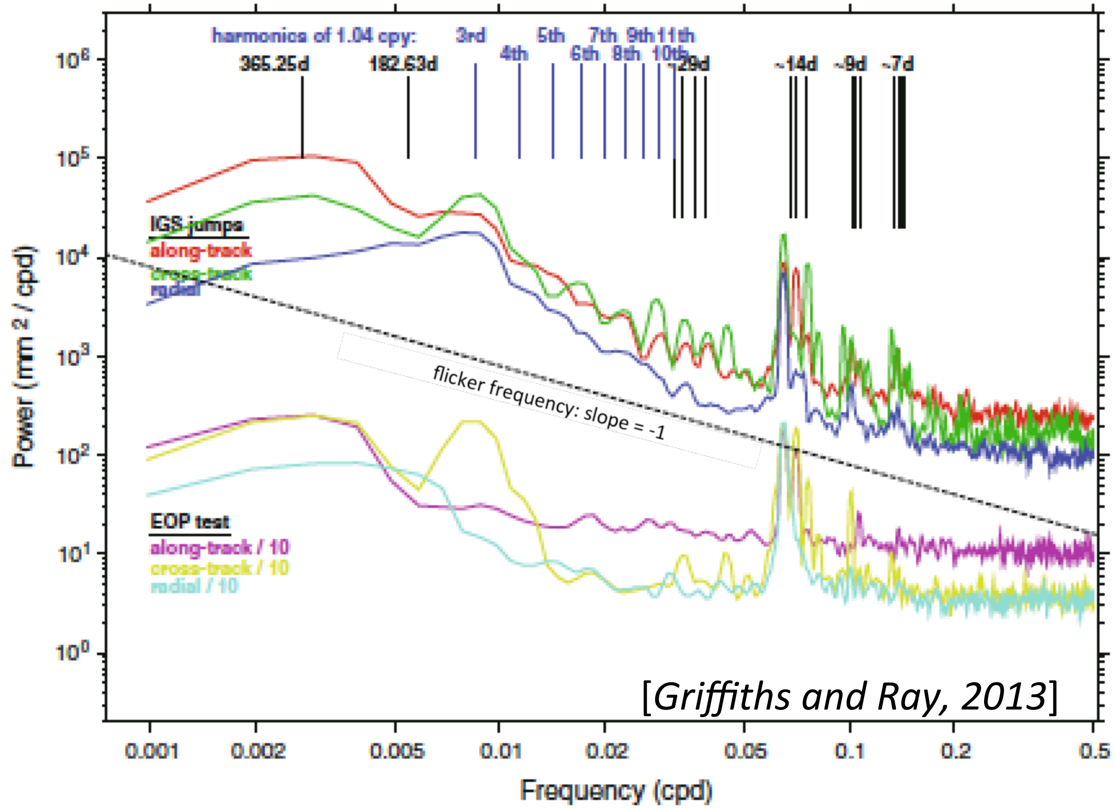
# AC *a priori* Terrestrial Frame

| | CODE (COF) | EMR | ESA | GFZ | GRG | JPL | MIT | ULR |
|---|---|---|---|---|---|---|---|---|
| **Strictly daily integrations for SINEX files/params?** | Yes | Yes | Yes | Yes | Yes | No: 30-hr data spans | Yes | Yes |
| **Use IGS08/IGb08 for frame alignments?** | N/A (NEQ) | Yes: fiducial free; a posteriori rotational alignment to IGb08 using core RF stations | Yes: NNR using RF stations (but submitting free NEQs) | Yes: NNR using core RF stations | Yes: NNR using core RF stations | Yes: Fiducial free; a posteriori rotational alignment to IGb08 using core RF stations | Yes: NNR using core RF stations | Yes: NNR wrt a selection of IGb08 core station coordinates |
| **Use igs08.atx antenna calibrations?** | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| **Adjust SV antenna Z-offsets (with tight but removable constraints)?** | Yes | Yes | Yes | Yes | No | Yes | Yes | Yes |
| **Orbits consistent with AC TRF (origin & orientation)?** | Yes | Yes | Yes but... For orbit/clock consitency both are generated based on NNR+NNT wrt IGb08 using core RF stations The difference between NNR and NNR+NNT orbits is at the sub-mm level | Yes | Yes | Yes | Yes | Yes |
| **What frame origin is used to realize AC CLK?** | IGb08 | IGb08; by applying 3 translations to satellite clocks based on daily alignment | NNR+NNT wrt IGb08 using core RF stations (same as orbits) | IGb08 | NNR+NNT(TZ-only) wrt IGb08 using core RF stations | IGb08 | IGb08 | IGb08 |
| **Do you remove geocenter offsets? If so, is relevant information reported in your SINEX?** | Yes:Yes | No:N/A | No:N/A | Yes:Yes | No:N/A | No:N/A | No:N/A | No:N/A |

# AC Satellite Dynamics and Inertial Reference Frame

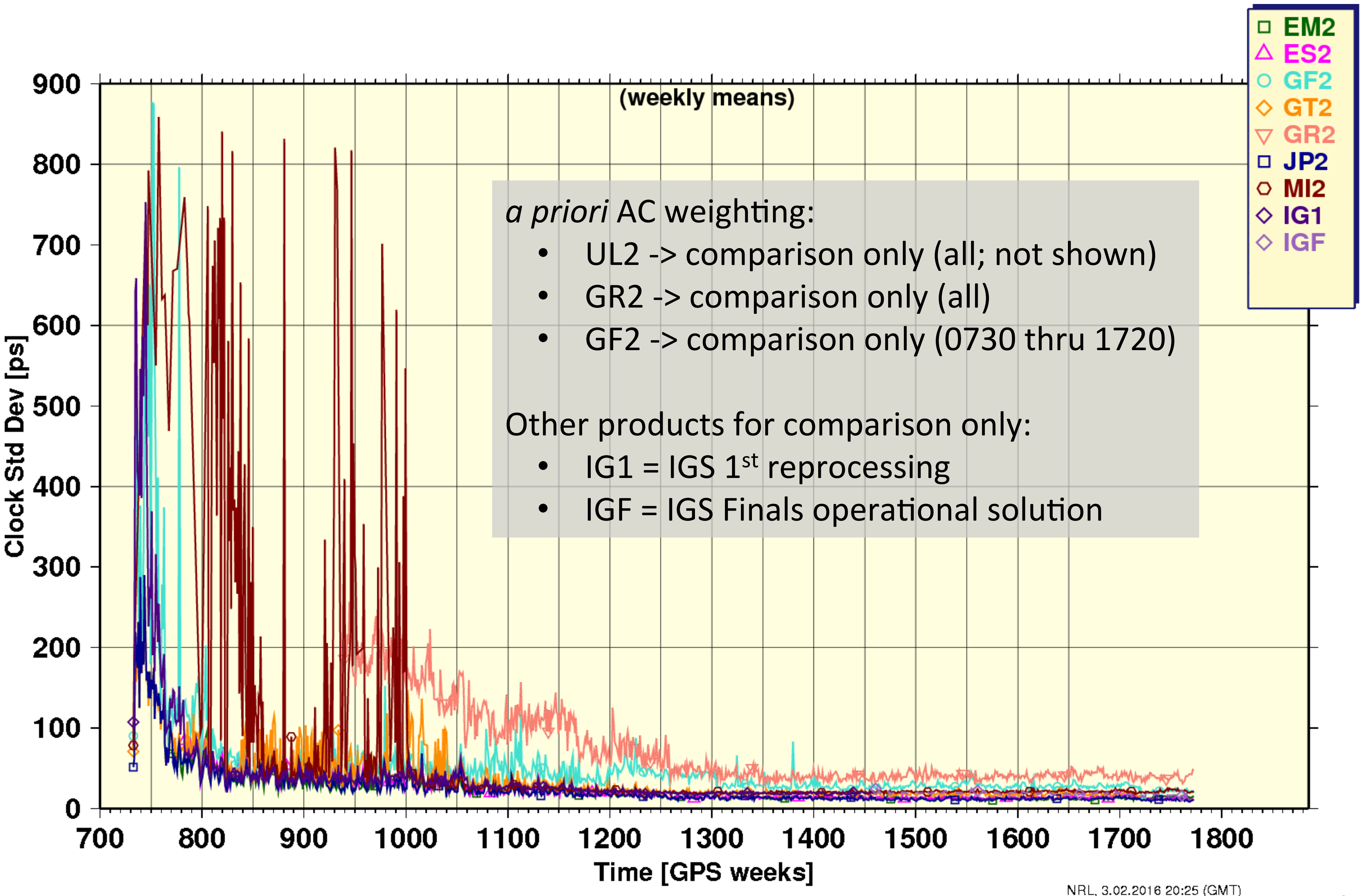
| | CODE (COF) | EMR | ESA | GFZ | GRG | JPL | MIT | ULR |
|---|---|---|---|---|---|---|---|---|
| a priori Nutation & EOPs | IAU 2000AR06; BuA ERPs | IAU 2000AR06 BuA ERPs | IAU 2000AR06 BuA ERPs | IAU 2000; GFZ ERPs | IAU 2000AR06 (NRO); BuA ERPs | IAU 2006A; BuA ERPs | IAU 2000; BuA ERPs | IAU 2000; BuA ERPs |
| Subdaily EOP tide model? | IERS 2010; sub nutation | IERS 2010 | IERS 2010 | IERS 2010 & PMsdnut.for | IERS 2010 | IERS 2010 | IERS 2010 | IERS 2010 |
| PM & UT1 librations included? | applied | ? | PM: IERS PMsdnut.for routine; UT1: IERS UTLIBR.F routine | applied | applied | No | applied | applied |
| SRP Params (& constraints) | D,Y,X scales + X 1/rev; no constraints | X,Y,Z scales stochastic | Box-wing model for apriori modeling of the Solar Radiation Pressure Forces D,Y,B scales + B 1/rev; no constraints | D,Y,X scales + X 1/rev; no constraints | D (to sun) scale , Y-bias+ X & D 1/rev; no constraints | JPL GSPM13 nominal model (Sibois et al, 2014).X,Y,Z scales stochastic | D,Y,B scales + D,Y,B 1/rev; constraints applied between days | D,Y,B scales + D,Y,B 1/rev |
| Velocity Breaks (& constraints) | @ 12:00 + constraints | none | none; along-track plus along-track 1/rev accels | @ 12:00 + constraints | stoch. impulse during ecl. | none | none; 1/rev constraints | none |
| Satellite Attitude in Daylight | GPS: nominal GLO: nominal | GPS: nominal GLO: nominal | GPS: nominal GLO: nominal | GPS: nominal GLO: nominal | GPS: nominal GLO: nominal | GPS: nominal | GPS: nominal | GPS: nominal |
| Blk II & IIA Attitude for Eclipses | nominal | yaw rates applied (Bar-Sever, 1996) | nominal | yaw rates estimated (initials from ??) | yaw rates applied (Kouba, 2009) | nominal yaw rates applied (Bar-Sever, 1996) and yaw rates estimated | yaw rates applied Kouba (2009) | yaw rates applied (Bar-Sever, 1996) |
| Blk IIF Attitude for Eclipses | nominal | nominal | nominal | nominal | yaw rates applied (Dilsner 2010) | model applied, from BOEING | yaw rates appplied (Kouba 2013) | nominal |
| GLO SV Attitude for Eclipses | nominal | N/A | yaw rates applied (Dilsner, 2010) | yaw rates estimated (initials from Dilsner, 2010) | yaw rates applied (Dilsner 2010) | N/A | N/A | N/A |
| Shadow Zones | E+M: umbra & penumbra | E: umbra & penumbra | E+M: umbra & penumbra | E+M: umbra & penumbra | E+M: umbra & penumbra | E+M: umbra & penumbra | E+M: umbra & penumbra | E+M: umbra & penumbra |
| Earth reflected (visible) radiation | applied (wk 1749) | applied | applied | applied (wk 1758) | applied | applied | applied (wk 1746) | applied |
| Earth emitted (infrared) radiation | applied (wk 1749) | applied | applied | applied (wk 1758) | applied | applied | applied (wk 1746) | applied |
| Block-specific satellite thrusting due to signal transmission :.igs.org/orbits/thrust-p | GPS: applied (wk 1749) GLO: applied (wk 1749; all SVs 100W) | GPS: repro2 (wk 1786) GLO: N/A | GPS: none GLO: none | GPS: applied (wk 1758) GLO: applied (wk 1758, 100W) | GPS: applied since week 1718 GLO: none | GPS: applied | GPS: applied (wk 1746) | GPS: applied |
| Relativistic Effects: dynamic corr (Ch. 10, eqn 12) | Schwarzschild: Yes Lense-Thirring: No de Sitter: No | Schwarzschild: Yes Lense-Thirring: Yes de Sitter: No | Schwarzschild: Yes Lense-Thirring: No de Sitter: No | Schwarzschild: Yes Lense-Thirring: Yes de Sitter: No | Schwarzschild: Yes Lense-Thirring: Yes de Sitter: No | Schwarzschild: Yes Lense-Thirring: Yes de Sitter: No | Schwarzschild: Yes (began wk 1785) Lense-Thirring: No de Sitter: No | Schwarzschild: Yes Lense-Thirring: Yes de Sitter: No |
| Relativistic Effects: grav bending applied (Ch. 11, eqn 17) | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |

# Known Improvements, Remaining Errors




- Orbits
  - Sub-daily alias and draconitic orbit errors persist, e.g.
    - IERS Conventions model for diurnal and semi-diurnal EOP variations unchanged
    - Empirical solar radiation pressure models still being used
  - Improved rotational alignment
    - Bug corrected in ACC software for applying TRF rotations to orbits prior to orbit combination http://acc.igs.org/orbits/acc_report_final_rotations.pdf
  - Earth albedo and antenna thrust models implemented
    - combined effect: ~0.75 ppb, or ~2 cm at GPS altitude
- Clocks
  - Inconsistent yaw modeling amongst ACs leads to non-trivial satellite-specific clock biases (up to ~10 ns) during satellite eclipses

# Clock Combination



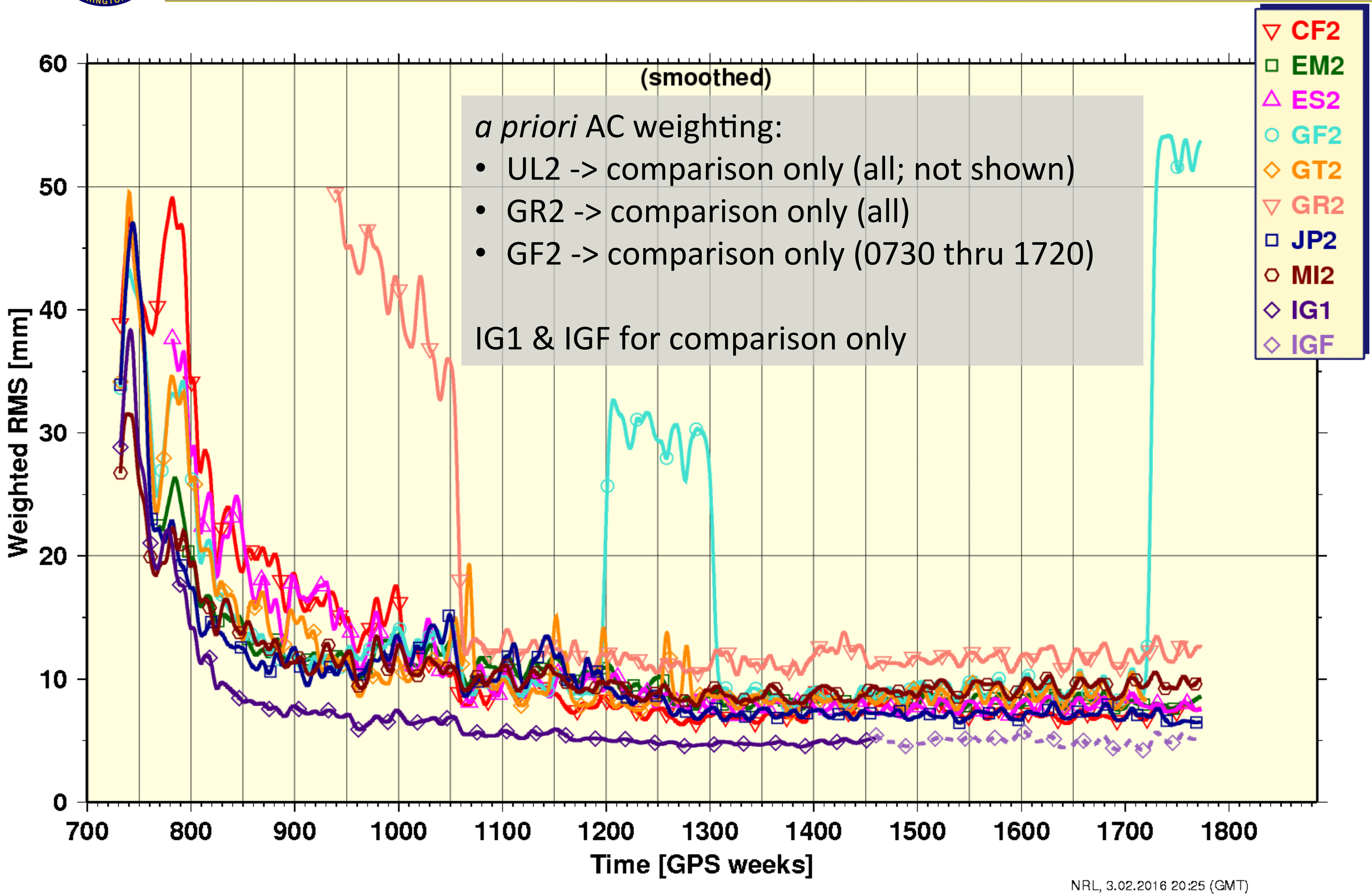

*a priori* AC weighting:

- UL2 -> comparison only (all; not shown)
- GR2 -> comparison only (all)
- GF2 -> comparison only (0730 thru 1720)

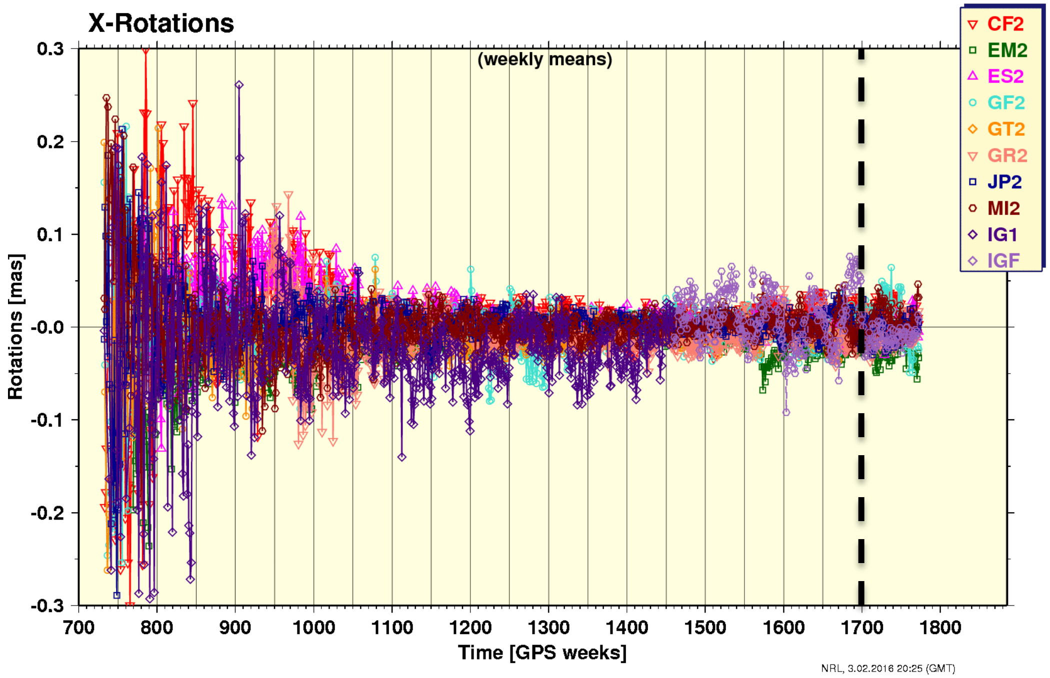
Other products for comparison only:

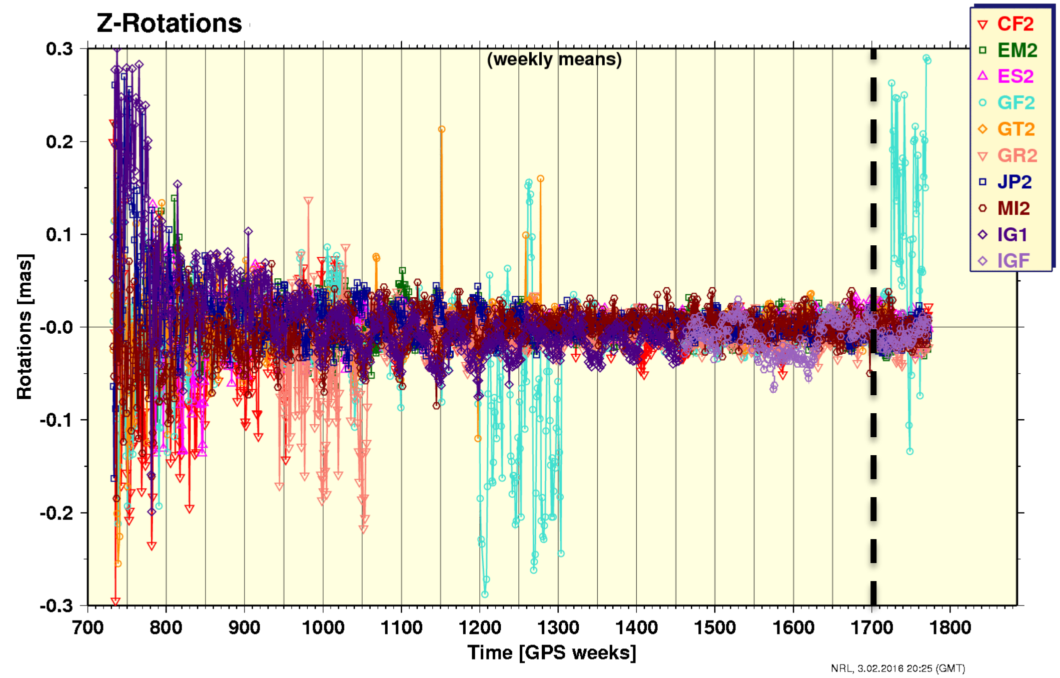
- IG1 = IGS 1st reprocessing
- IGF = IGS Finals operational solution

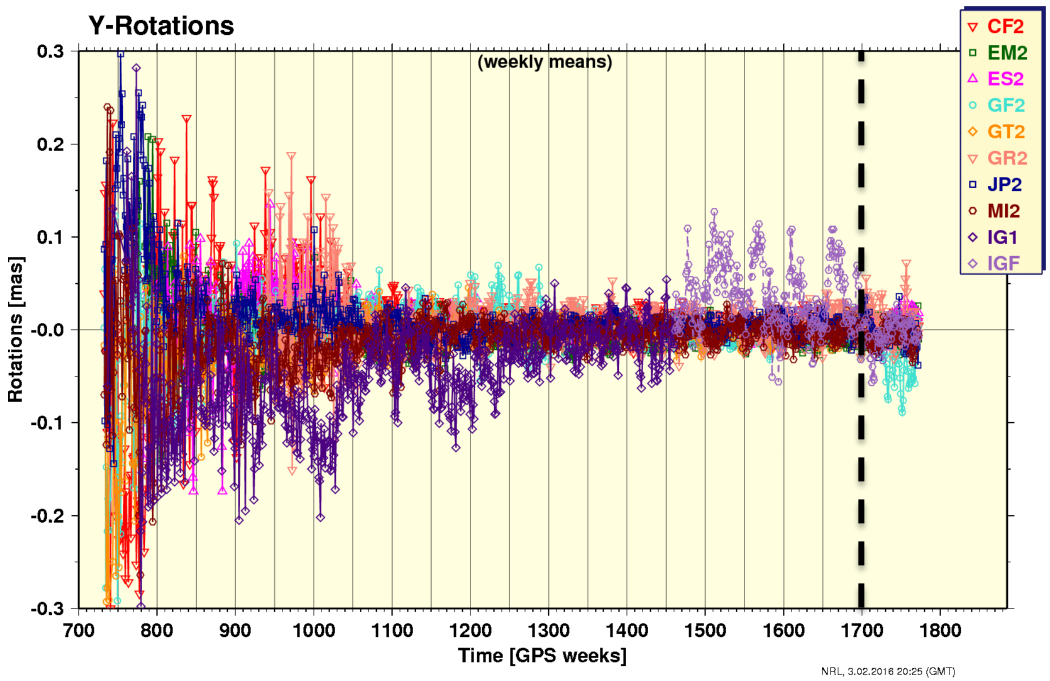
# Orbit Combination: Inter-AC Agreement



# AC Orbital Frame: Rotational Alignment

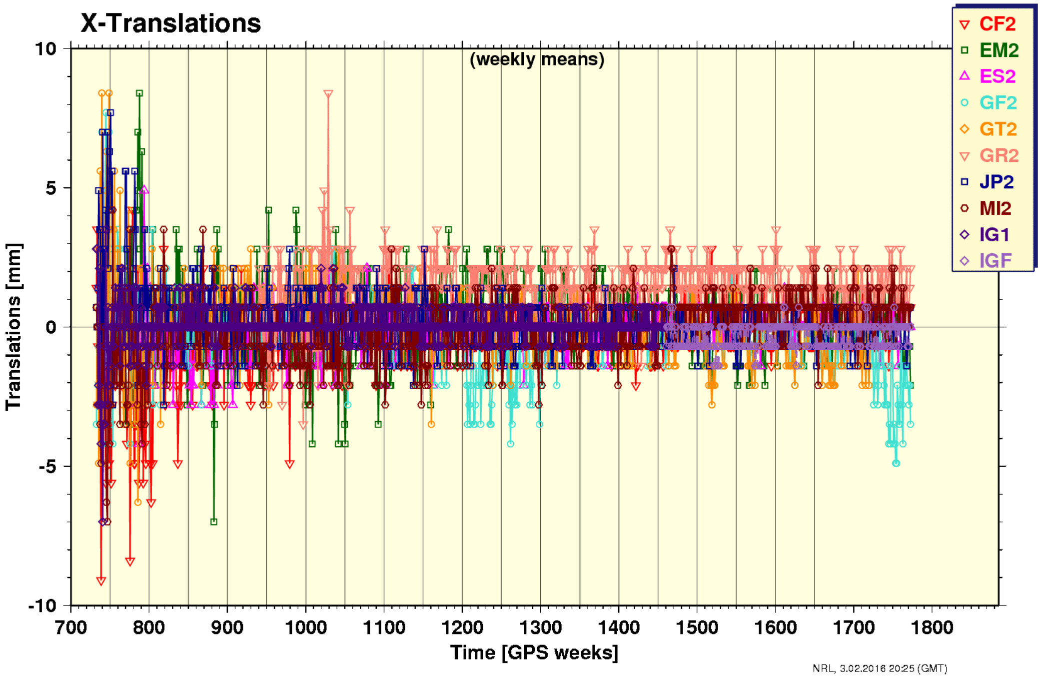


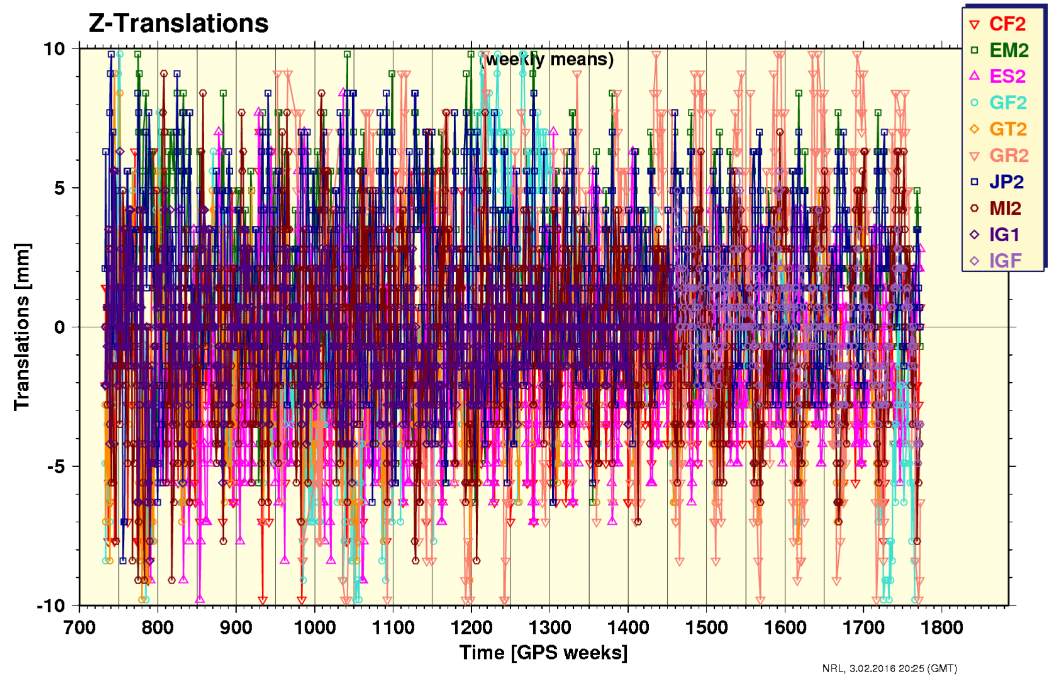



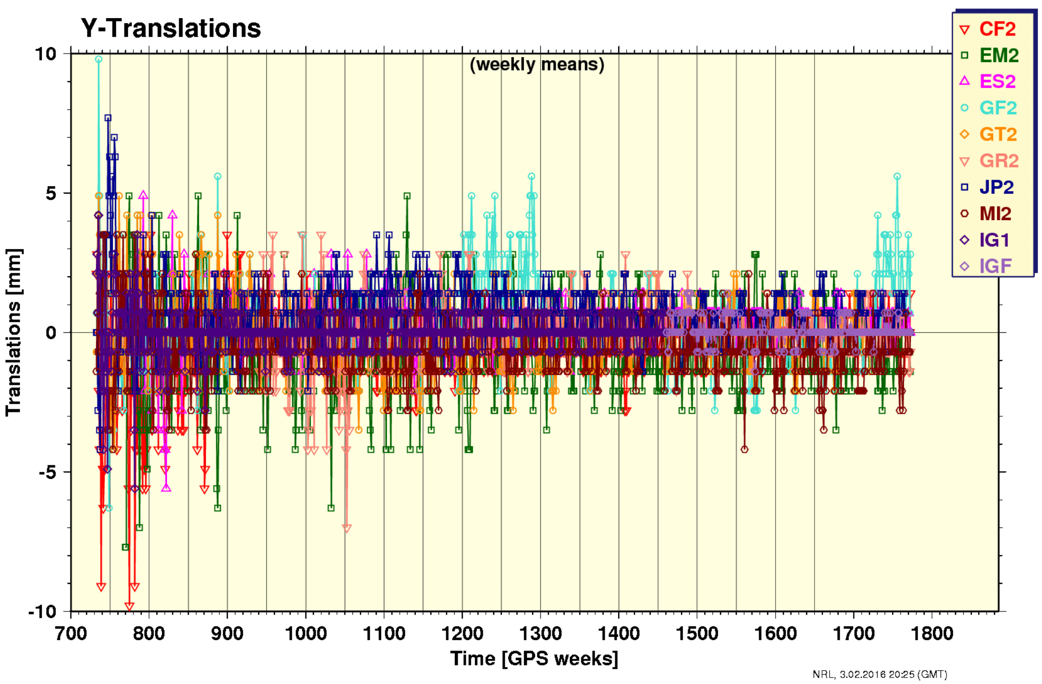




- UL2 very large scatter (not shown)
- Large rotational offsets in early years for CF2, ES2, GT2
- Periods of spurious rotations for GF2
- Large rotations in IG1 and IGF until Wk 1702 (switch to daily products & bug fix in ACC software)
- Repro2 improved rotational stability compared to IG1/IGF?

# AC Orbital Frame: Origin

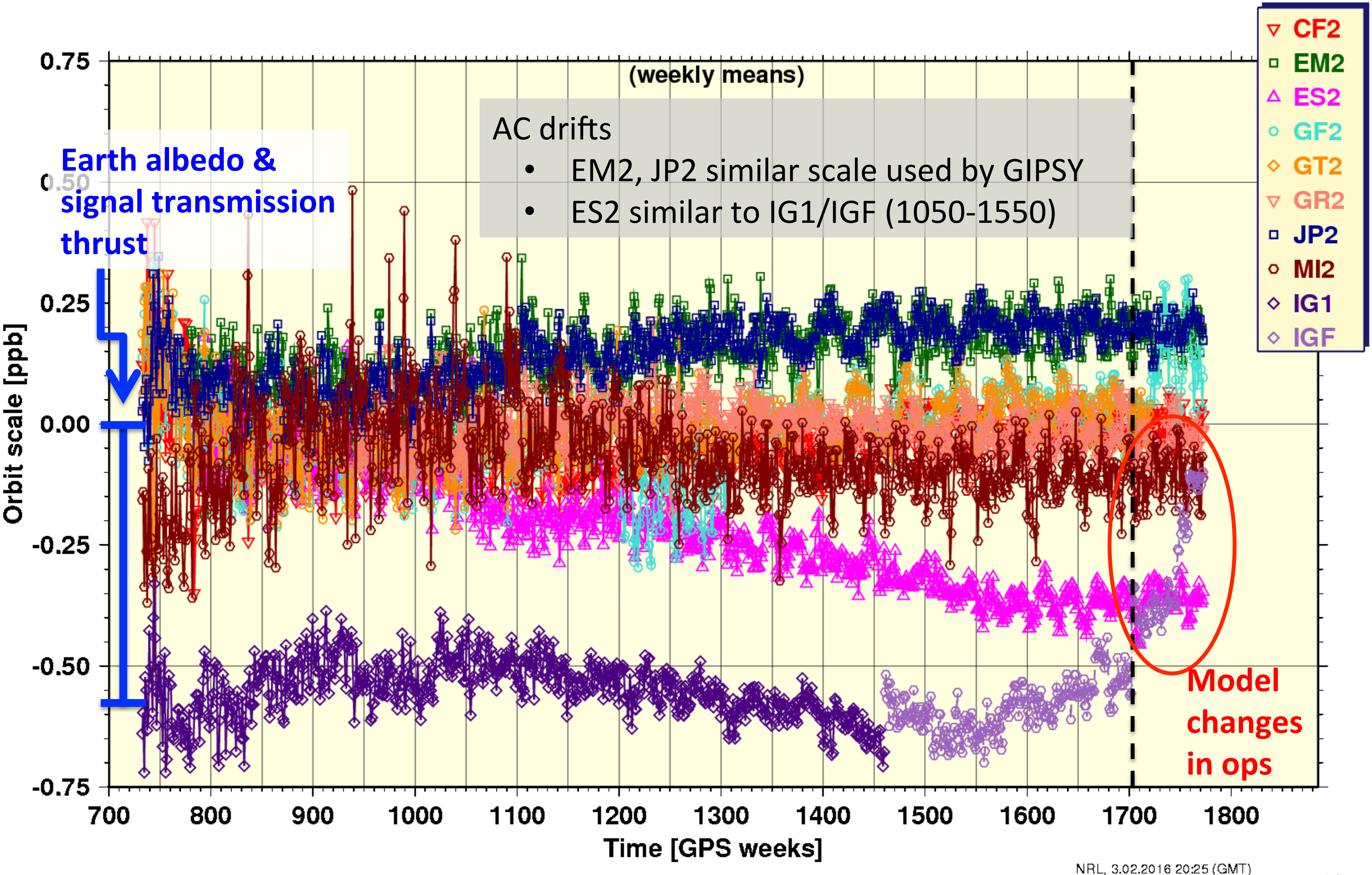


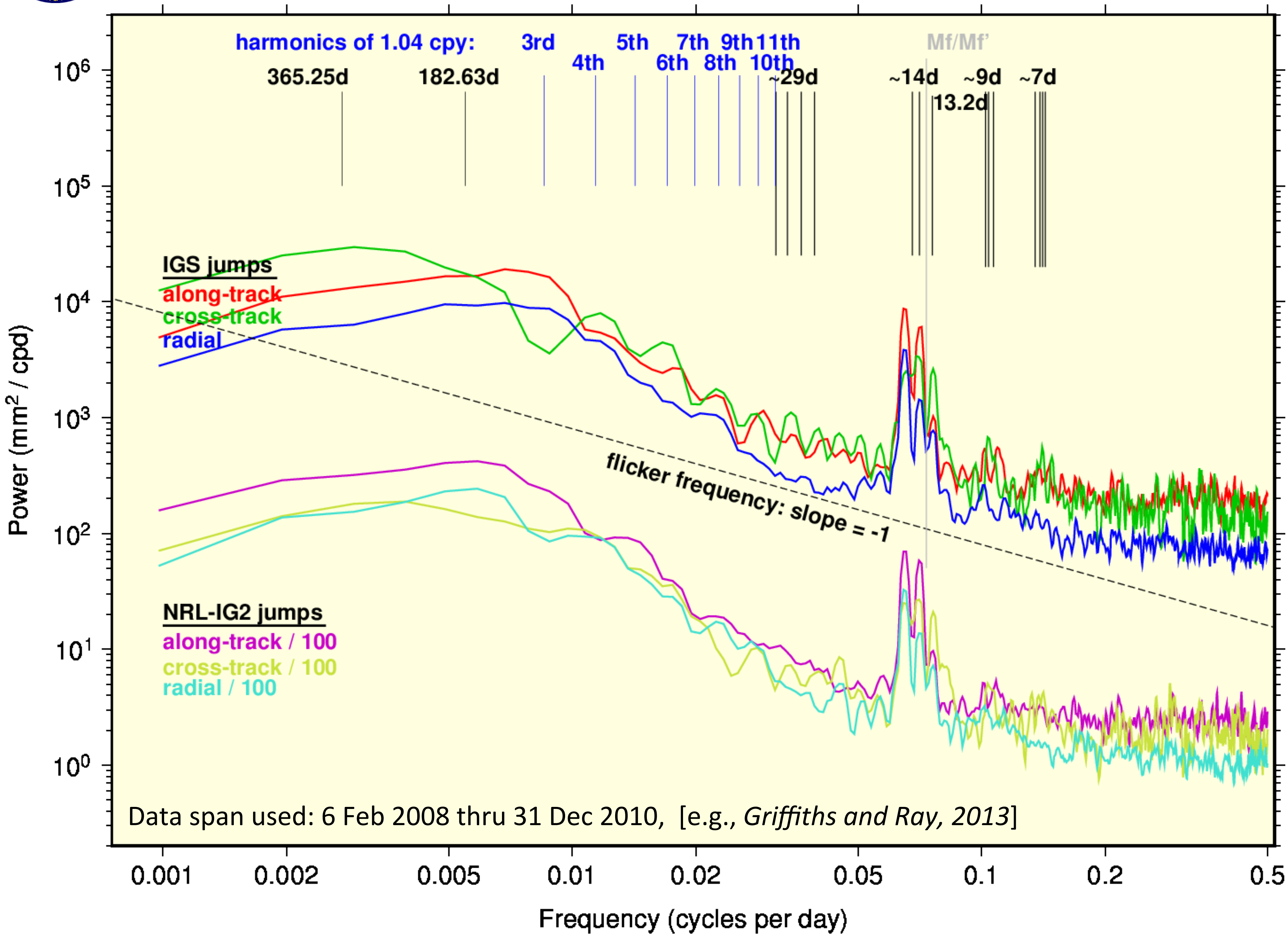




- UL2 very large scatter (not shown)
- GR2, MI2 large scatter in Tx,Ty
- GF2 periods of large offsets
- Strong ~annual Tz motions
- Up to +9/-5 mm Tz motion compared to IG1/IGF
- Slight IG1 Tx,Ty drift

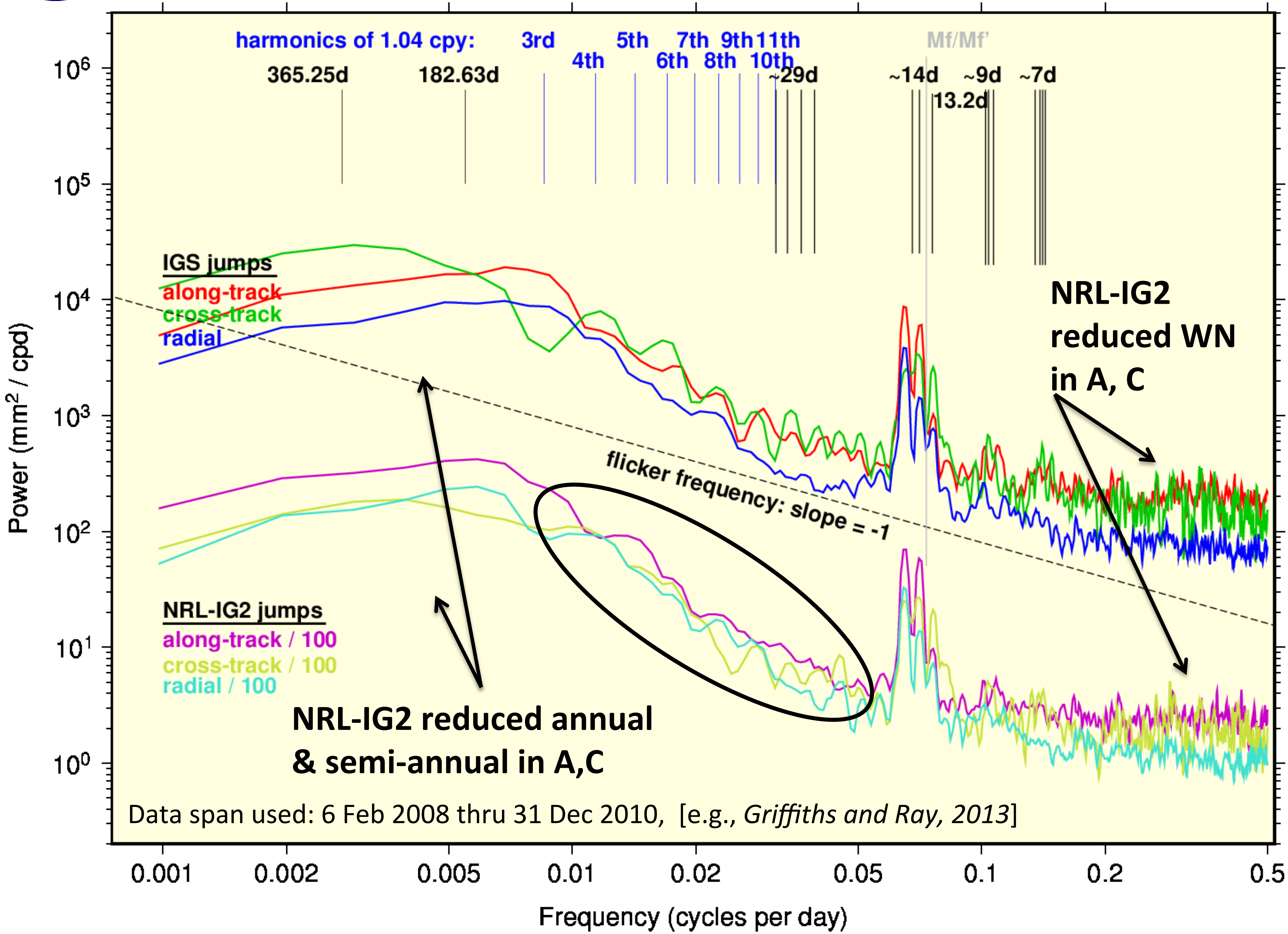
# AC Orbital Frame: Scale



# Preview of Orbit Jump Analysis



# Preview of Orbit Jump Analysis

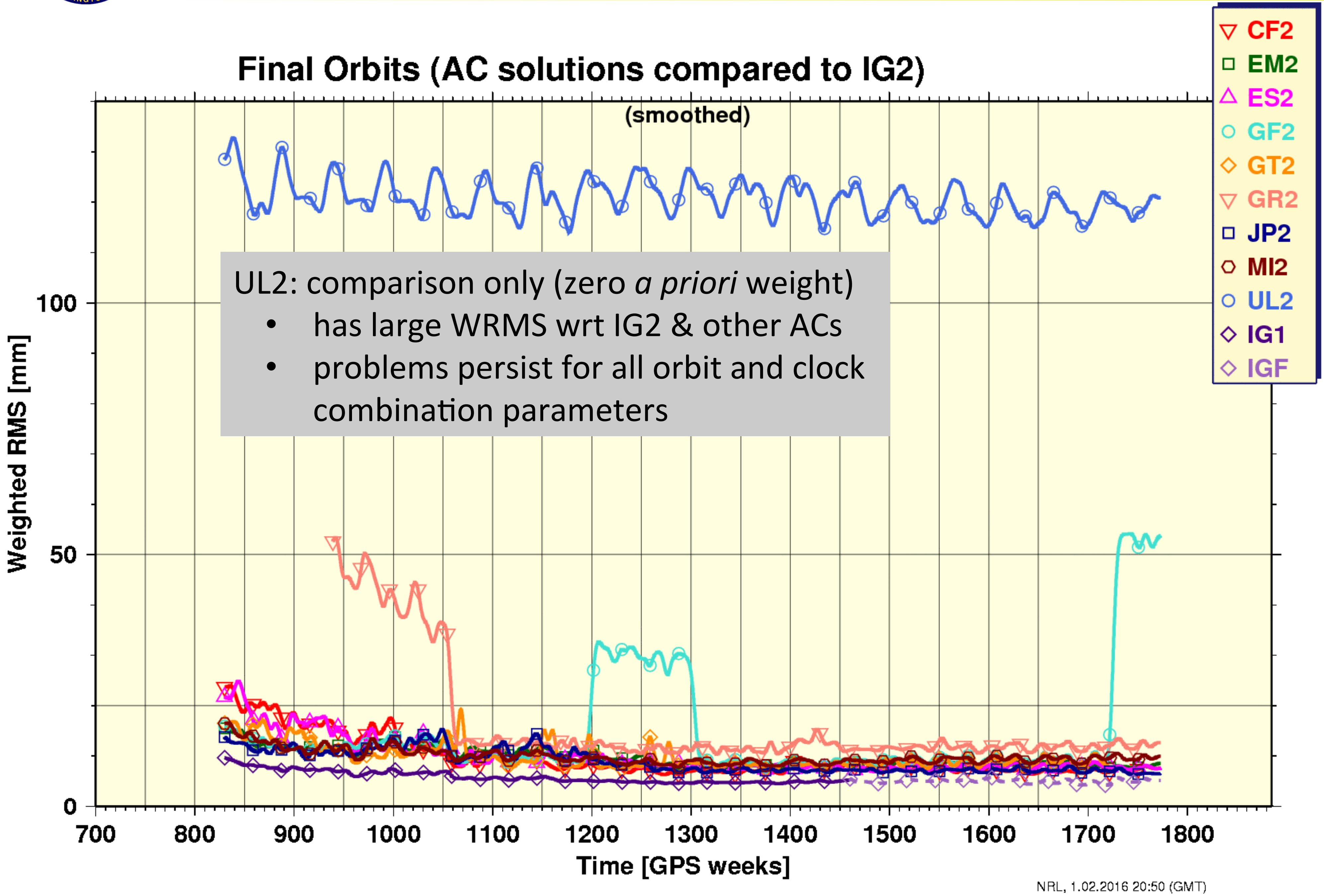


# Conclusions

- Eight ACs contributed terrestrial reference frame, Earth orientation, GNSS orbit, and clock products using IGb08 and igs08.atx
- Initial combinations performed for GPS Wks 730 thru 1772, and initial set of *a priori* weights seems to have mitigated impacts from spurious AC issues
  - AC inputs with spurious departures do not appear to bias combination compared to IG1/IGF
- Main features of NRL-IG2 products compared to IG1+IGF, so far:
  - daily solutions for full time span
  - possibly a reduction in orbit frame rotations over full history; to be verified w/ PPP
  - consistent modeling over full time span (effects of Earth albedo & antenna thrust)
- Remaining combination issues include:
  - apply ocean pole tide rotations to non-conforming ACs (small effect)
  - study possible orbit scale drift (e.g., EMR, JPL, ESA)
  - complete combinations through Wk 1831, mainly to ensure consistency with TRF
  - continue quality assessments to assure highest final quality, mainly
    - extended analysis of orbit jumps
    - PPP solutions using NRL-IG2 orbits & clocks
  - re-combine as needed to address issues found in QA

# Backup Slides

# Orbit Combination: Inter-AC Agreement




UL2: comparison only (zero *a priori* weight)

- has large WRMS wrt IG2 & other ACs
- problems persist for all orbit and clock combination parameters