

Galileo IOV Spacecraft Metadata and Its Impact on Precise Orbit Determination

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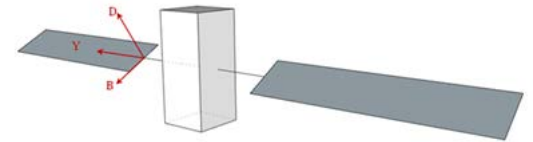
Outline



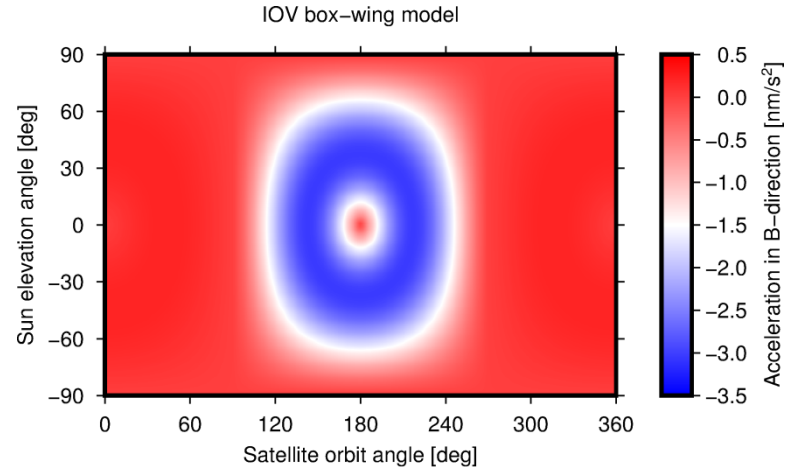
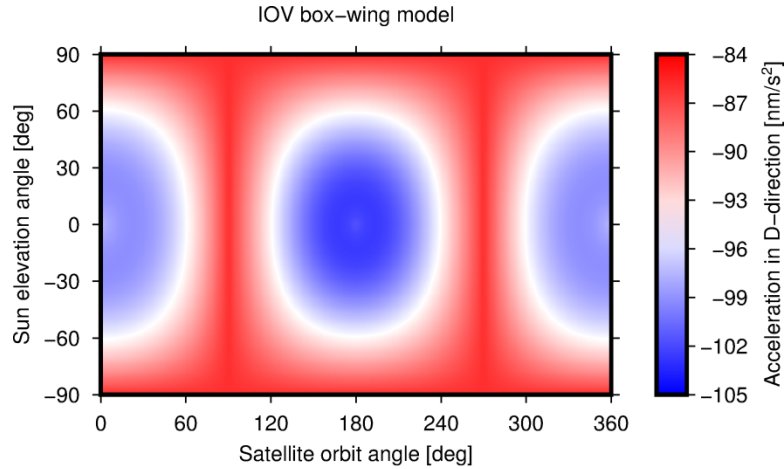
- Introduction
- Effect of IOV spacecraft metadata on Galileo POD
- Antenna phase center parameters
- Yaw steering law
- Summary & Conclusions



- December 2016: GSA disclosed spacecraft metadata for Galileo IOV
 - Publicly available through European GNSS Service Center (GSC) web site (<https://www.gsc-europa.eu/support-to-developers/galileo-iov-satellite-metadata>)
 - Includes phase center parameters for navigation antenna (NAVANT), signal group delays, yaw steering law, as well as surface geometry and material properties suitable for analytical “box-wing” (BW) radiation pressure force modeling
- IOV BW model has been generated for use in NAPEOS, ESOC’s state-of-the-art software package for high-precision orbit determination
 - Represents satellite as simple six-sided “box” with two attached “wings”
 - Allows for a priori computation of SRP and Earth albedo force
 - Accounts for periodically changing orientation of satellite’s elongated cuboid body in Sun-orientated “DYB” frame



Introduction (cont'd)



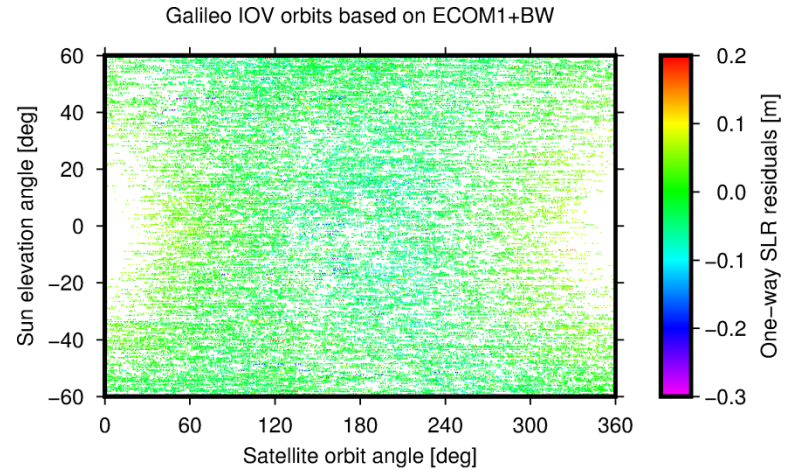
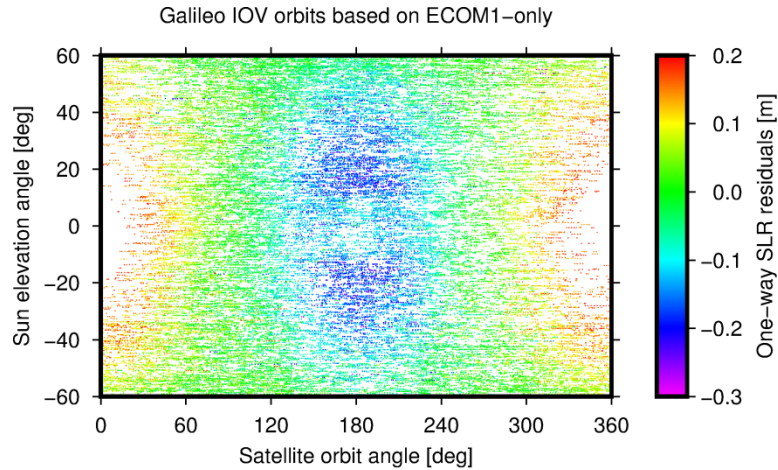
- BW model produces twice-per-rev signal in D with peak-to-peak amplitude up to 20 nm/s² and once-per-rev signal in B with peak-to-peak amplitude up to 4 nm/s², depending on Sun elevation angle

Evaluate effect of IOV metadata on Galileo POD



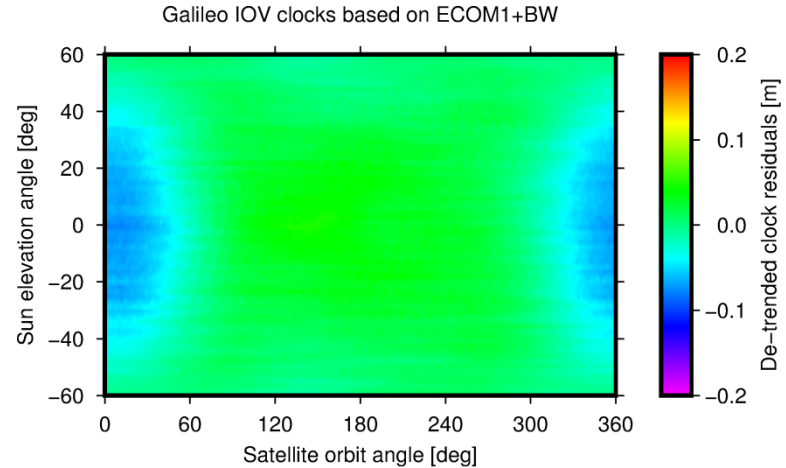
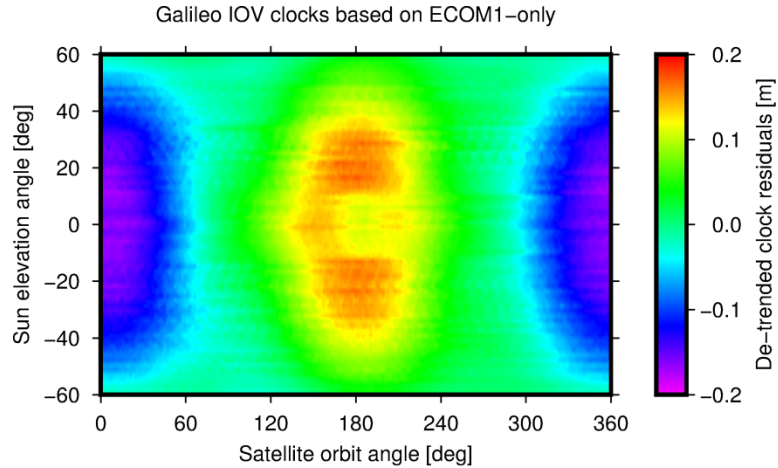
- Reanalyze full history of Galileo tracking data the global International GNSS Service (IGS) network has collected since 2012
- Generate orbit and clock solutions based on widely used Empirical CODE Orbit Model (ECOM) with and without IOV a priori BW model
- Use metadata as well as standard IGS-recommended phase center model ("igs08.atx") for IOV NAVANT
- Analyze impact on following metrics: phase residuals, laser ranging residuals, satellite clock residuals, orbit overlap residuals, narrow-lane ambiguities





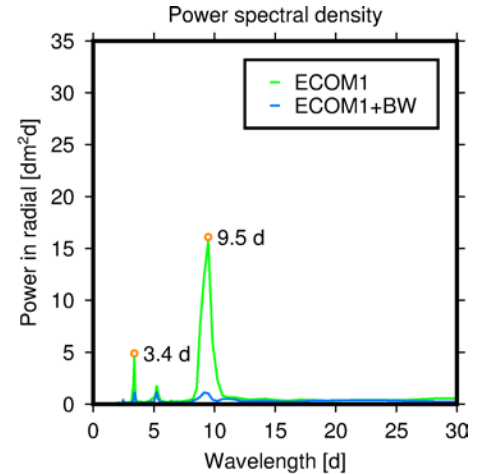
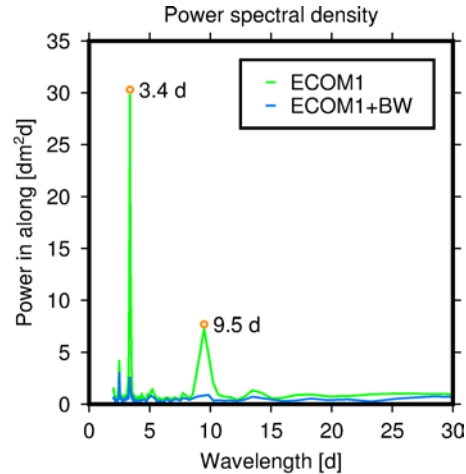
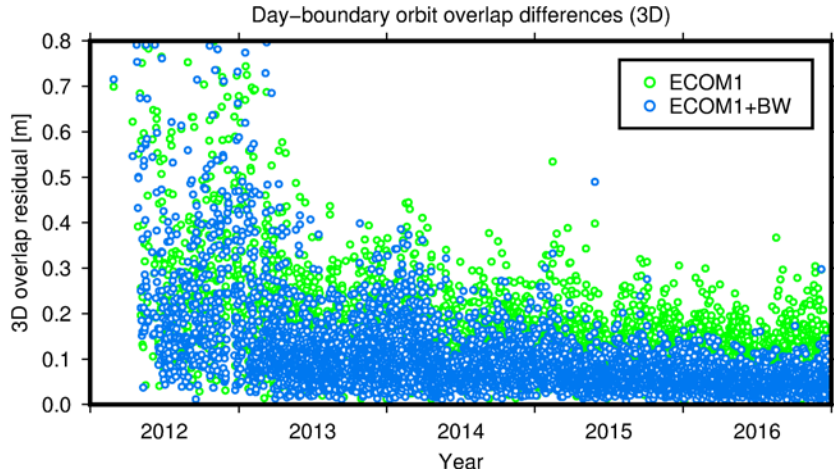
- Reveal radial decimeter-level errors in ECOM1-only orbits
- Factor two improvement; BW model reduces RMS from 0.084 to 0.037 m
- Mean bias of -0.010 ± 0.082 m without and -0.017 ± 0.034 m with BW model; anticipated to be zero when taking Earth IR + antenna thrust into account

Satellite clock residuals



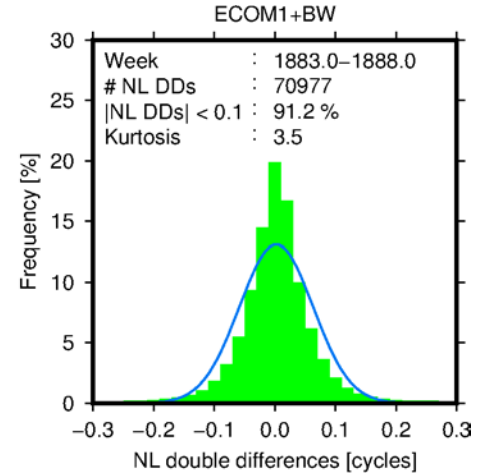
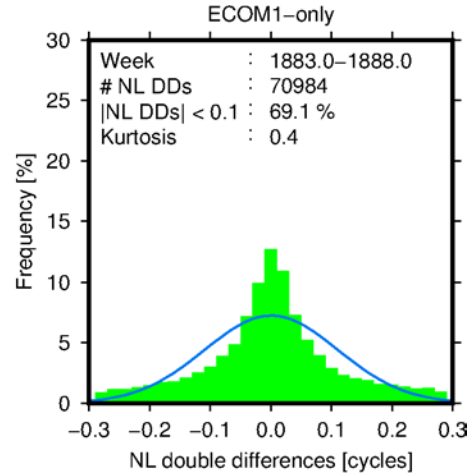
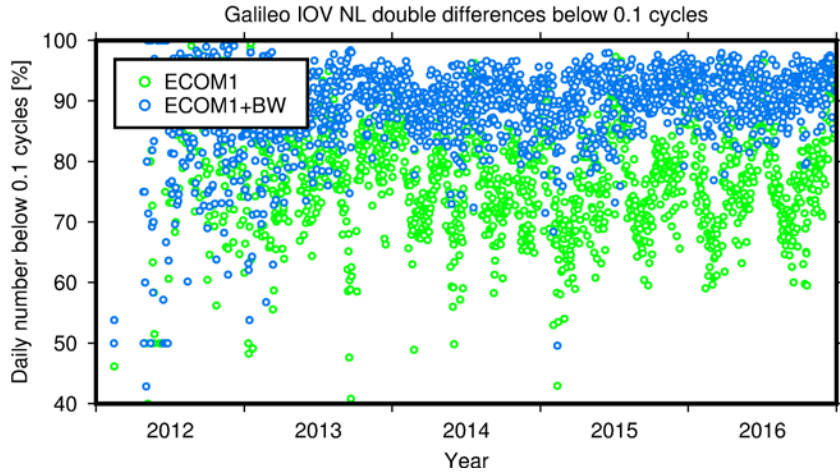
- Capitalize on satellites' ultra-stable passive hydrogen masers (PHMs) and use clock estimates after first-order fit as measure for orbit modeling accuracy
- Similar once-per-rev signature as seen before in SLR residuals
- Factor two improvement in RMS, from 0.089 m w/o to 0.038 m w/ BW model

Day-boundary orbit overlap residuals



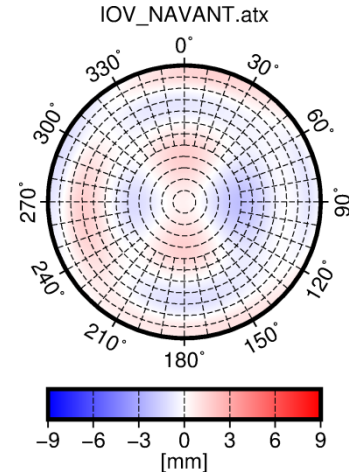
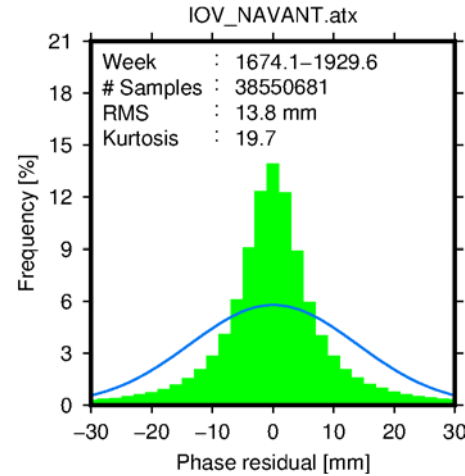
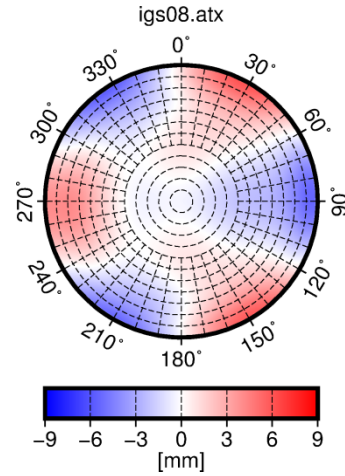
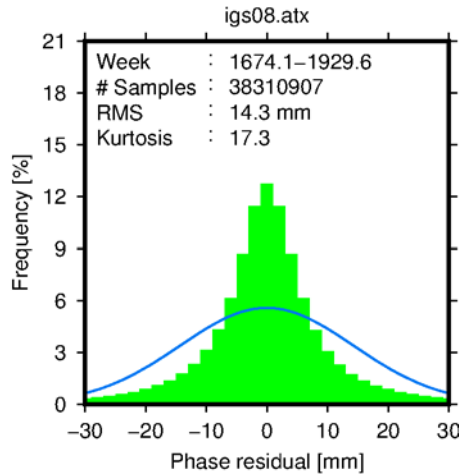
- Factor two improvement in all three directions, radial, along, and cross
 - Peaks near 1st and 3rd harmonic of 10-day ground track repeat cycle greatly reduced
 - 0.118 m without and 0.062 m with BW model (3D-RMS)
- Improvement from “free” to “fixed” is 23% without and 43% with BW model
 - ⇒ [BW model facilitates Galileo integer ambiguity resolution](#)

Ambiguity resolution performance



- Five-to-ten-times-tighter distribution of NL fractionals when using BW model
- Number of NL double differences closer than 0.1 cycles from nearest integer constantly around 90% now

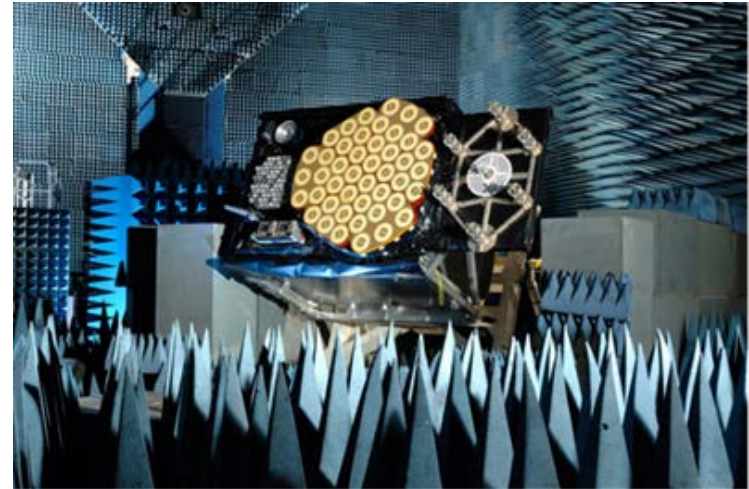
Carrier phase residuals



- 4% lower phase residual RMS and 0.6% increase in number of measurement points after replacing “igs08.atx” with “IOV_NAVANT.atx”
- Three-fold antenna pattern emerges after least-squares spherical harmonic fit to igs08.atx residuals

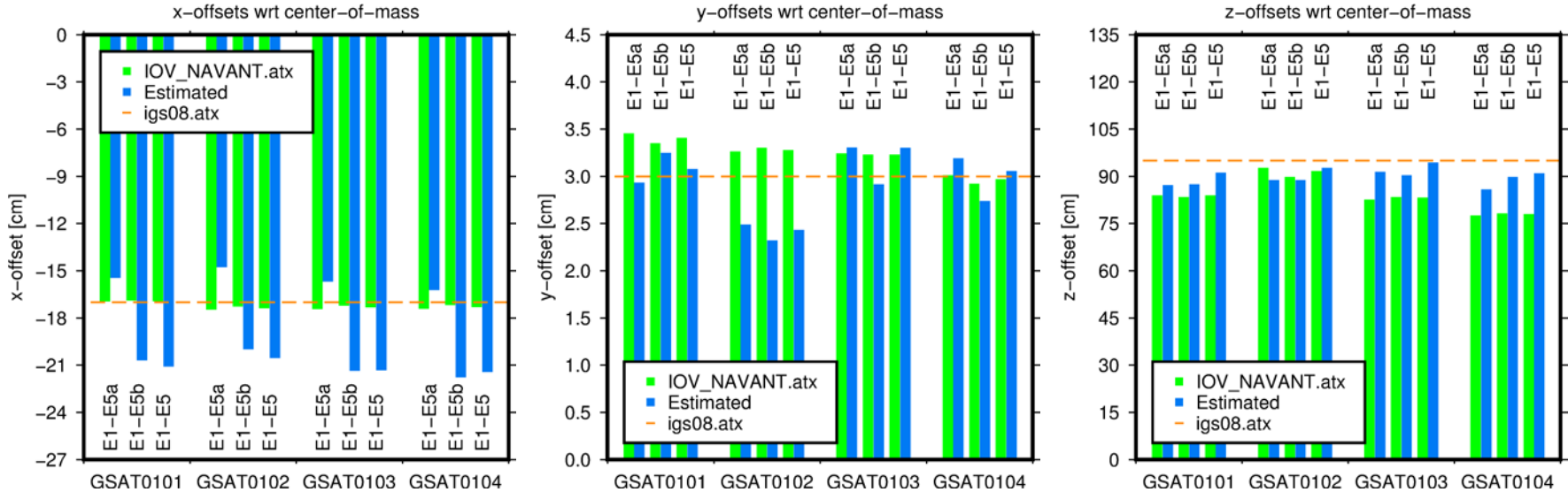
Antenna phase center parameters

- Phase center offset (PCO) and variation (PCV) parameter for each signal and spacecraft antenna inferred from pre-launch anechoic chamber measurements (https://www.gsc-europa.eu/sites/default/files/sites/all/files/IOV_NAVANT.atx)
- Evaluate phase center parameters using Galileo live signals
 - Exploit full history of IGS tracking data (2012-2016) to estimate PCOs and PCVs
 - Process E1-E5a, E1-E5b, and E1-E5 data
 - Use spherical harmonics (8,3) to capture three-fold antenna pattern
 - Combine all daily antenna and station coordinate parameters on NEO-level
 - Compare final PCO and PCV estimates against pre-launch values



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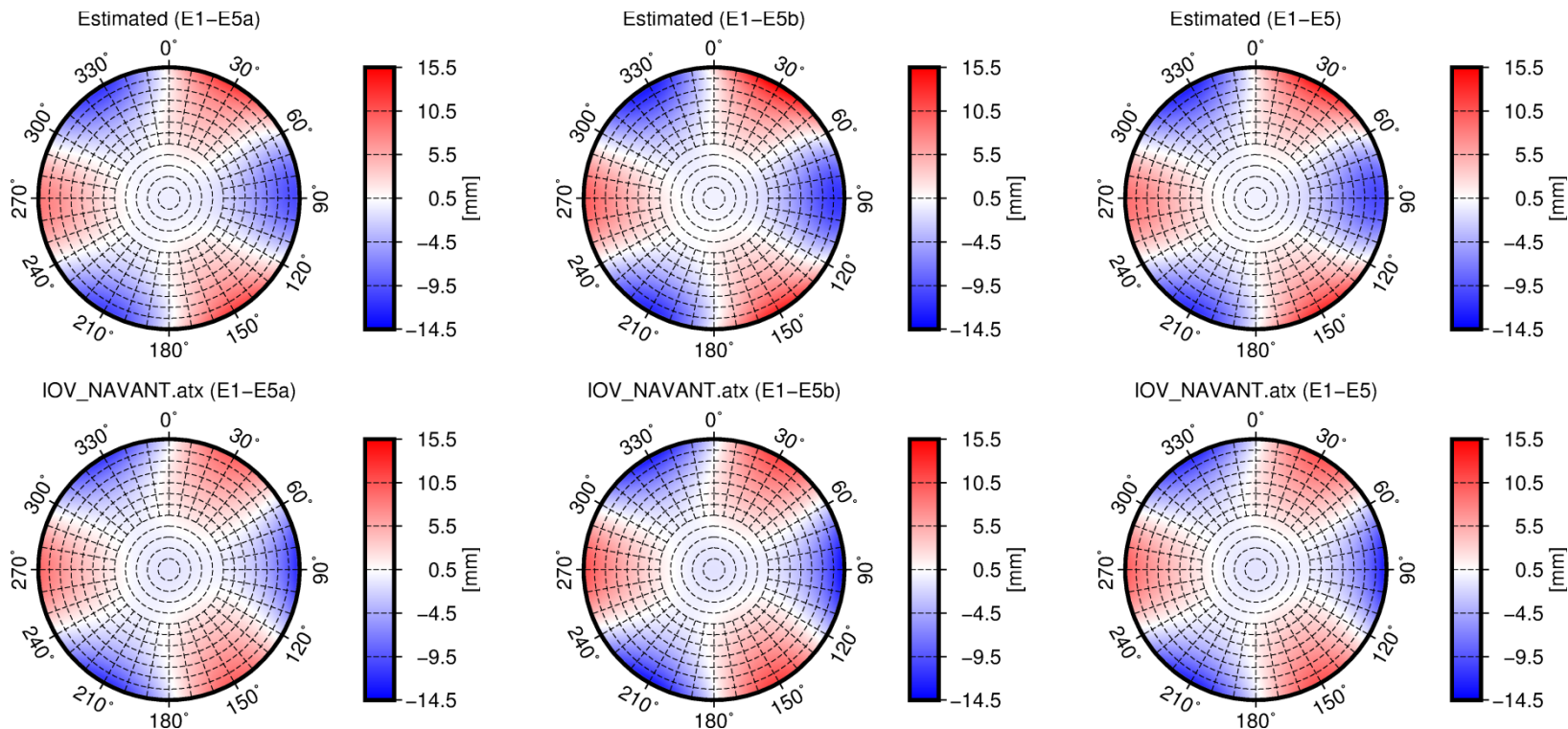
Antenna phase center offsets



- Mean difference (RMS) of 3 cm for x-PCOs, 1 cm for y-PCOs, 8 cm for z-PCOs
- Values match fairly well with rounded igs08.atx mean (Steigenberger 2016)



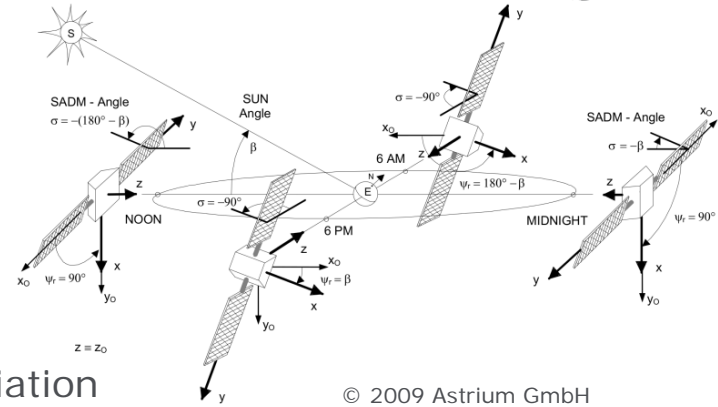
Antenna phase center variations



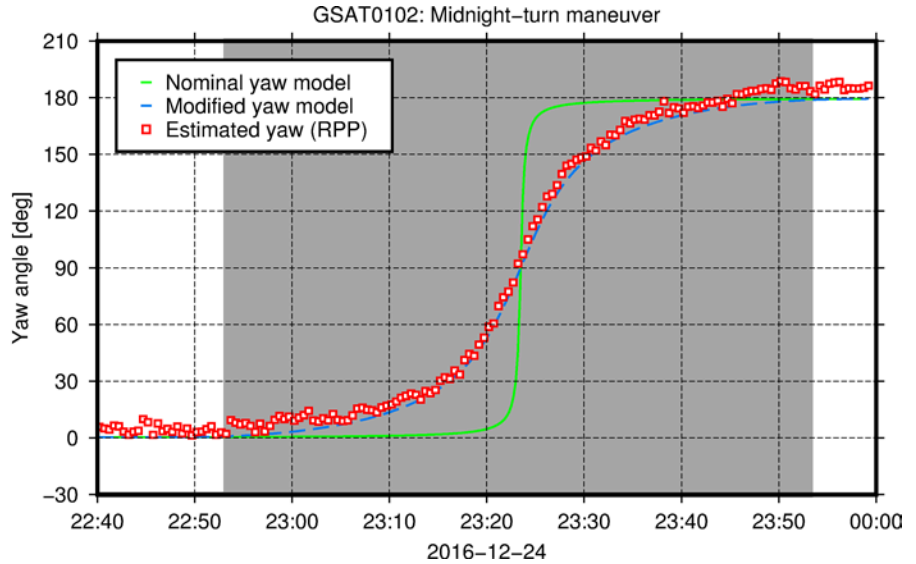
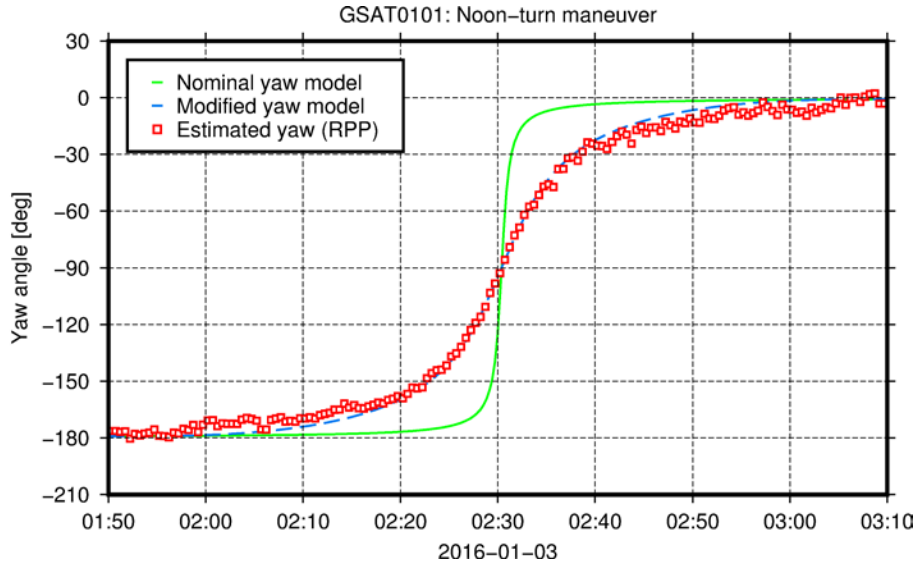
- Estimated PCVs agree with IOV_NAVANT.atx values at the 1-mm level (RMS)

Yaw steering law

- Yaw steering angle ψ_r is rotation angle around Earth-pointing spacecraft Z axis
- Requirements on nominal yaw steering:
 - +Y axis perpendicular to Sun direction
 - +X axis against Sun to prevent heat-critical clock payload from being exposed to solar radiation
- Modified yaw steering when satellite and Sun vector are close to collinearity
 - Pseudo Sun vector which keeps minimum angular distance to spacecraft Z axis
 - Produces milder profile with yaw rate < 0.2 deg/s and acceleration < 0.46 mdeg/s²
- Yaw angle can be evaluated by way of reverse point positioning (RPP)
 - Technique takes advantage of 17 cm horizontal offset of IOV NAVANT from spacecraft's yaw axis to estimate yaw angle



Yaw steering law (cont'd)



- Yaw angle estimates show agreement with modified steering law within 5° RMS
- Scatter attributable to uncertainties in RPP, does not reflect real yaw attitude
- Yaw angle constructed from telemetry closely follows modified steering law too

Summary & Conclusions



- Using IOV metadata in current POD approach substantially improves the orbit
 - Overlap residuals indicate orbit precision of 6 cm (3D-RMS)
 - One-way SLR residuals indicate radial orbit accuracy of better than 4 cm (RMS)
- Improvements are largely due to BW model
 - Factor two improvement in SLR, clock and orbit overlap residuals
 - NL fractionals cluster more tightly around zero, facilitates integer ambiguity resolution
- Antenna phase center model:
 - Small reduction in phase residual RMS over previously available model ("igs08.atx")
 - Good agreement with phase center estimates: 1-8 cm in PCOs, 1 mm in PCVs (RMS)
 - Especially relevant for GNSS-based realization of TRF scale, independent of SLR/VLBI
- Yaw attitude model:
 - RPP estimates confirm close agreement with theoretical law and spacecraft TM

