Evaluating the pre-flight GPS Block IIR/IIR-M antenna phase pattern measurements

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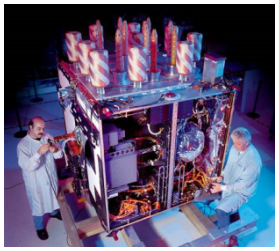
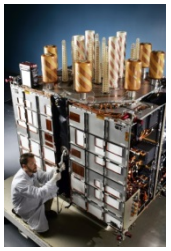
Background

- 12 Block IIR and 8 IIR-M SVs launched between July 1997 and August 2009 to replenish GPS constellation
  - "Backbone" of the current constellation, two-thirds of all active GPS SVs
- Two different antenna panel types in use
  - „Legacy" panel on first 8 IIRs
  - „Modernized" panel on final 4 IIRs and all 8 IIR-Ms
  - Each housing a 12-element L-band helix array





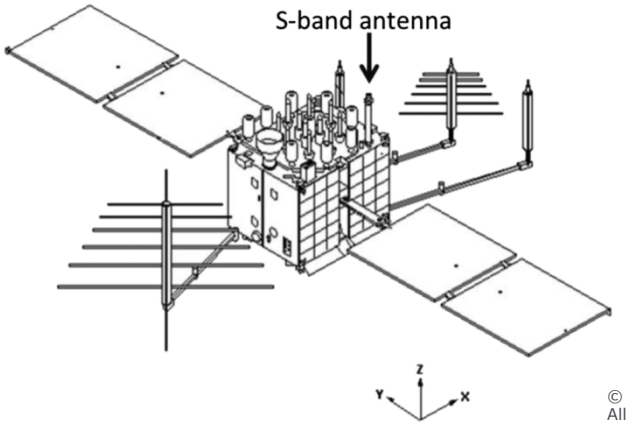
- Manufacturer, Lockheed Martin (LMCO), has measured phase and directivity patterns for each SV antenna on both GPS carrier frequencies L1 and L2 prior to launch
- Data publically released in February 2014 (⇒ www.lookheedmartin.com)

Outline

- Antenna pattern measurement system
- Characterize measured phase patterns
- Comparison to estimated phase patterns (ESOC, IGS)
  - Phase center offsets (PCOs)
  - Phase center variations (PCVs)
- Summary and conclusions

Antenna Pattern Measurement System

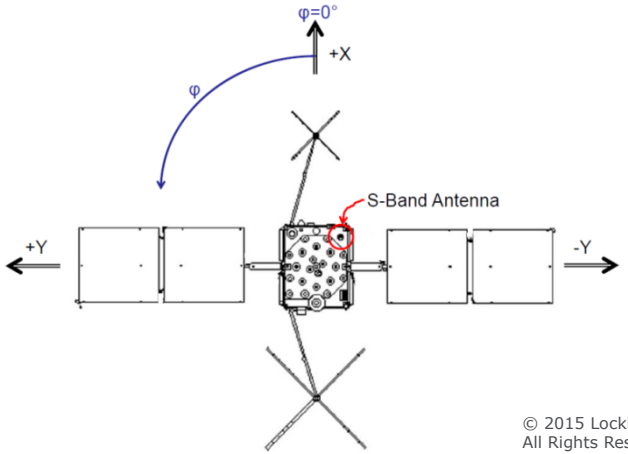
- Body-fixed RF
  - +Z axis along L-band antenna toward Earth (nadir)
  - +Y axis along solar panel axis, S-band antenna in (+X, -Y) corner
  - +X axis completes right-handed set, points *against* Sun (≠ ANTEX RF)

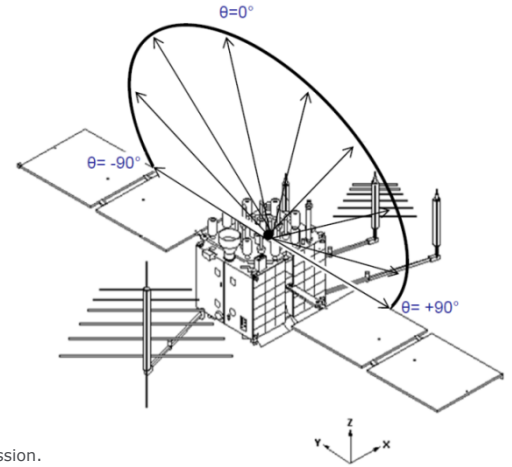


- Measurements taken at intervals of 10° in azimuth from 0° to 360° and 2° in elevation from -90° to +90°

Antenna Pattern Measurement System

- Azimuth φ counted anti-clockwise from +X axis (φ = 0º) toward +Y axis (φ = 90º) when looking along -Z axis toward deep space
- Elevation θ counted from +Y axis (θ = -90º) through nadir (θ = 0º) to –Y axis (θ = -90º)





- Reference wrt center-to-mass given by NGA offsets (W. Marquis, pers. comm.) ⇒ http://earth-info.nga.mil/GandG/sathtml/

Post-processing of Measured Phase Patterns

Convert azimuth/elevation angle pairs (φ, θ) according to ANTEX RF conventions

$$\alpha(\varphi) = 270° - \varphi, \quad \eta(\theta) = |\theta|$$

Build ionosphere-free linear combination (L3)

$$\phi_{L3} = 2.54573 \cdot \phi_{L1} - 1.54573 \cdot \phi_{L2}$$

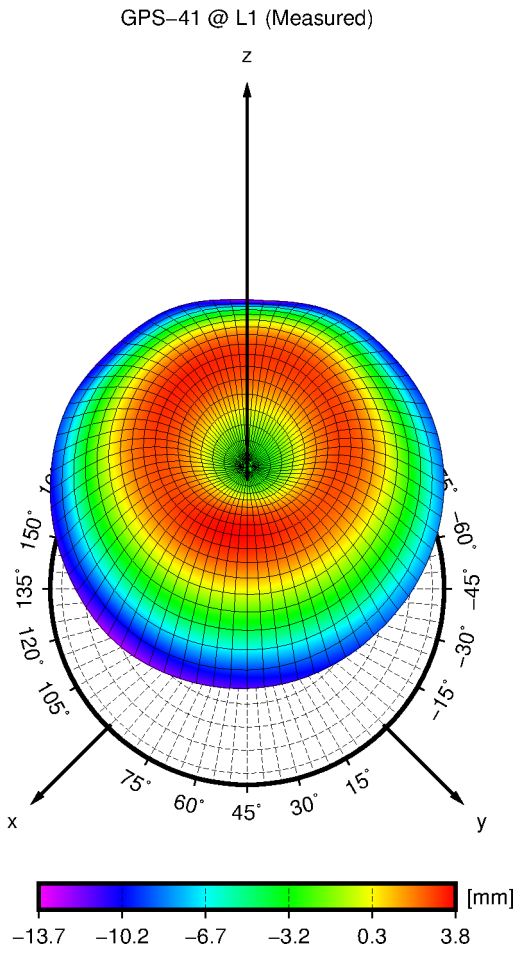
Minimize pattern for $0 \leq \eta \leq 14°$ through least square fit of

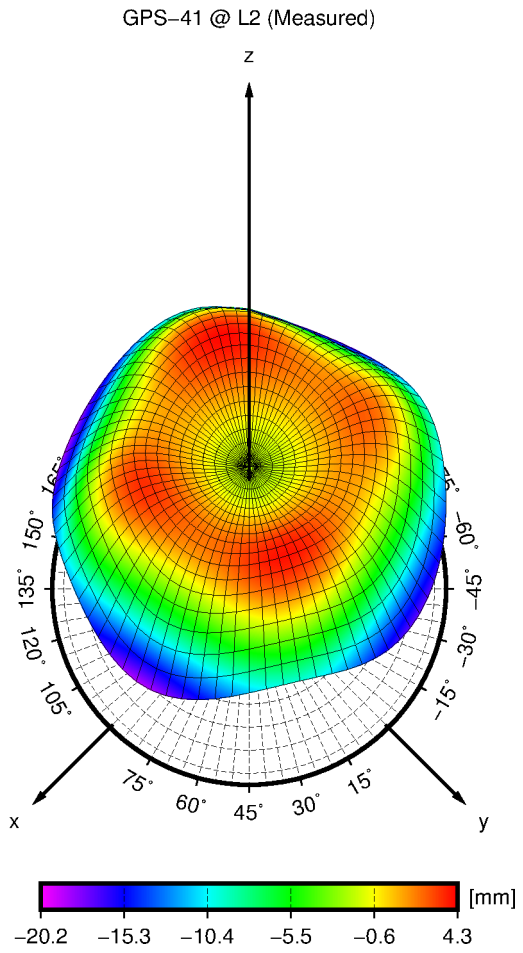
$$\Delta x \cdot \sin(\alpha) \cdot \sin(\eta) + \Delta y \cdot \cos(\alpha) \cdot \sin(\eta) + \Delta z \cdot \cos(\eta) + r$$

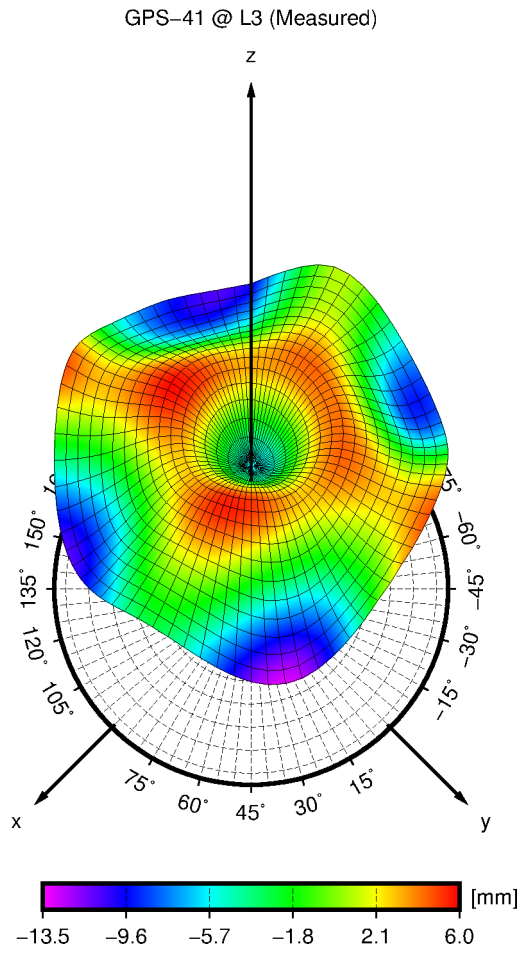
Compute associated phase center offsets wrt center-of-mass

$$x = \Delta x - x_{NGA}, \quad y = \Delta y - y_{NGA}, \quad z = \Delta z + z_{NGA}$$

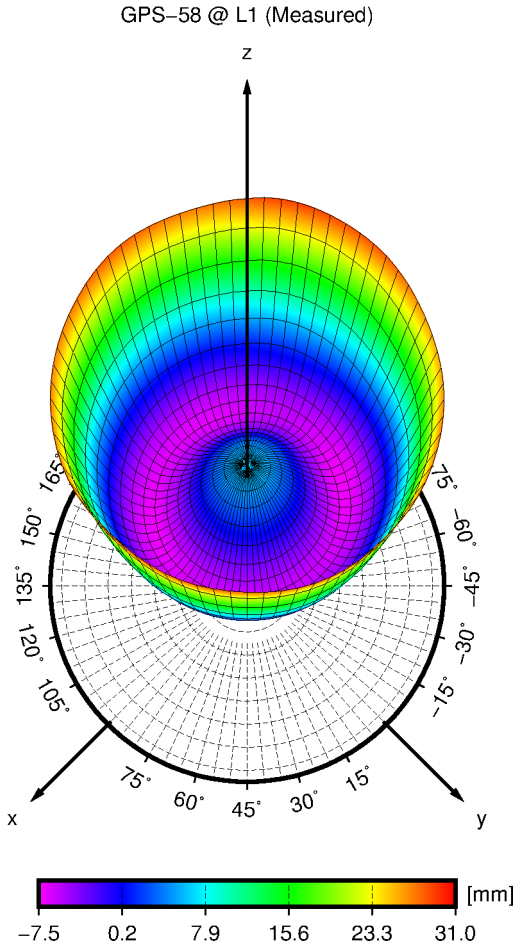
Measured Phase Patterns – Legacy Panel

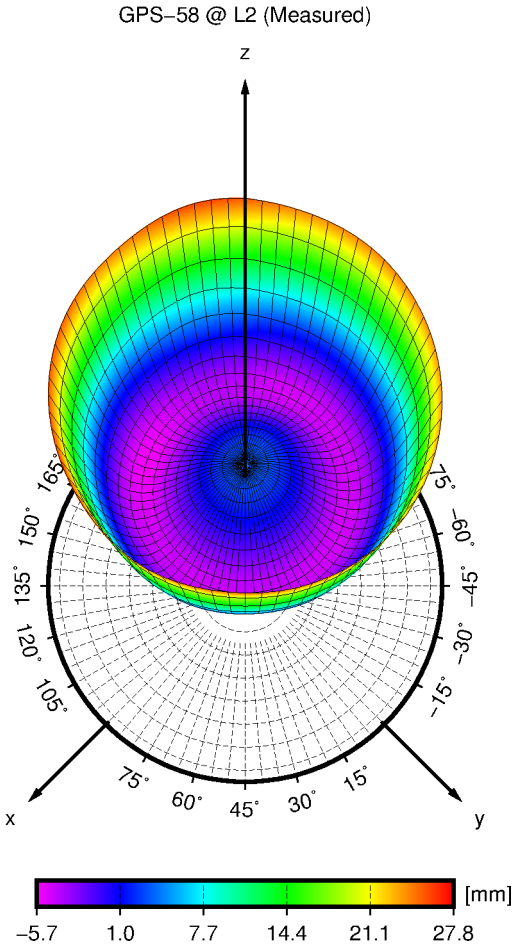


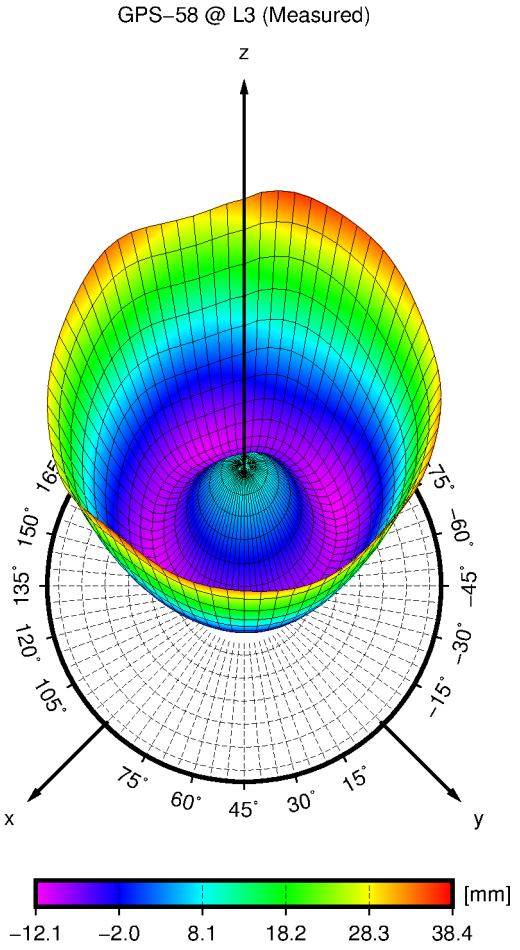




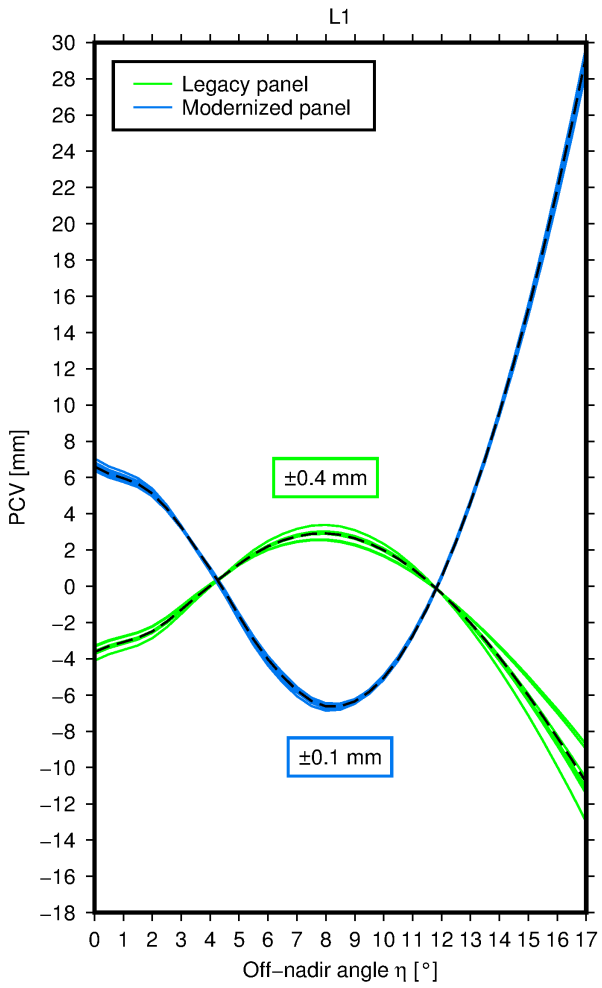
Measured Phase Patterns – Modernized Panel

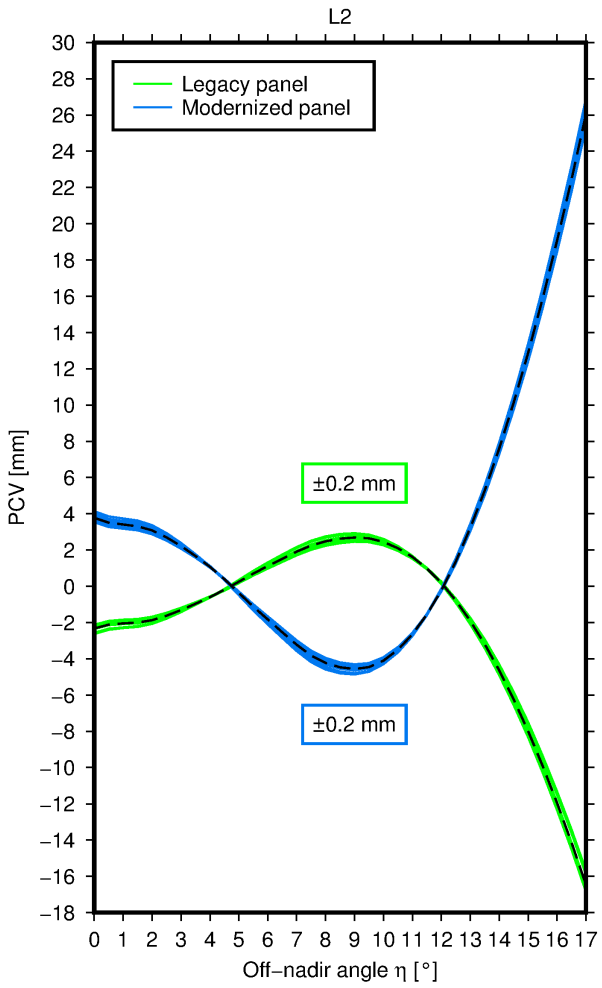


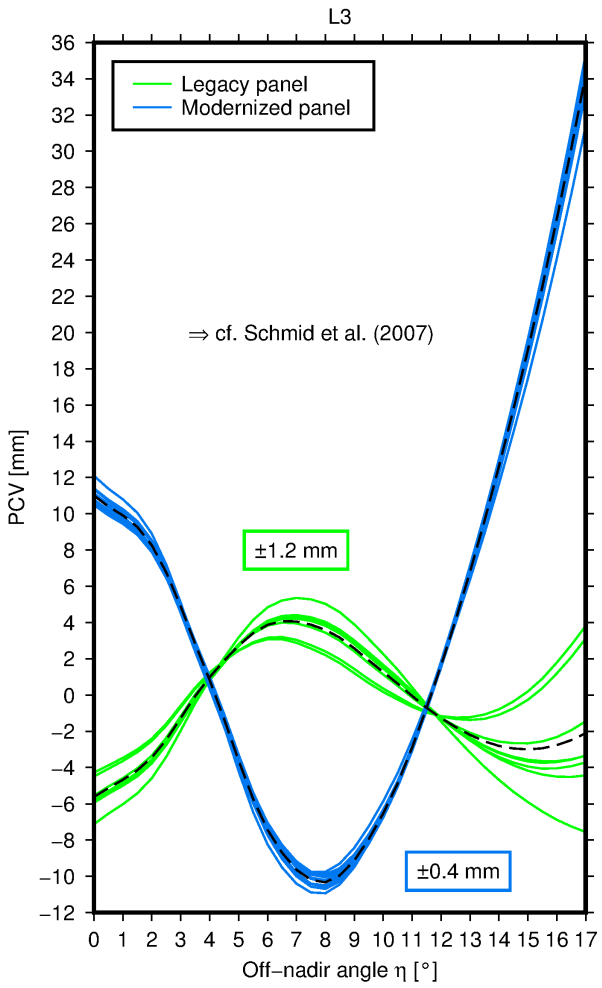




SV-specific vs. Mean Phase Patterns

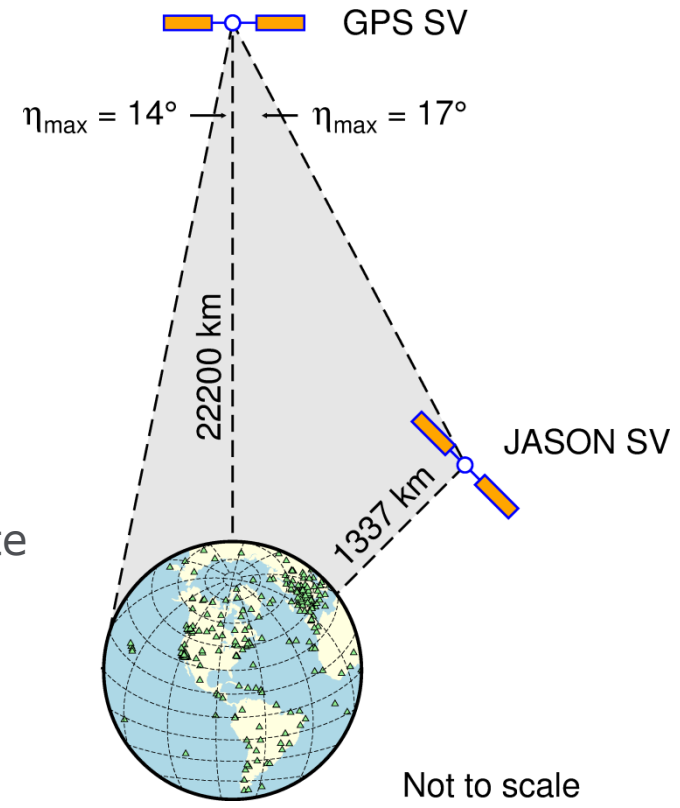




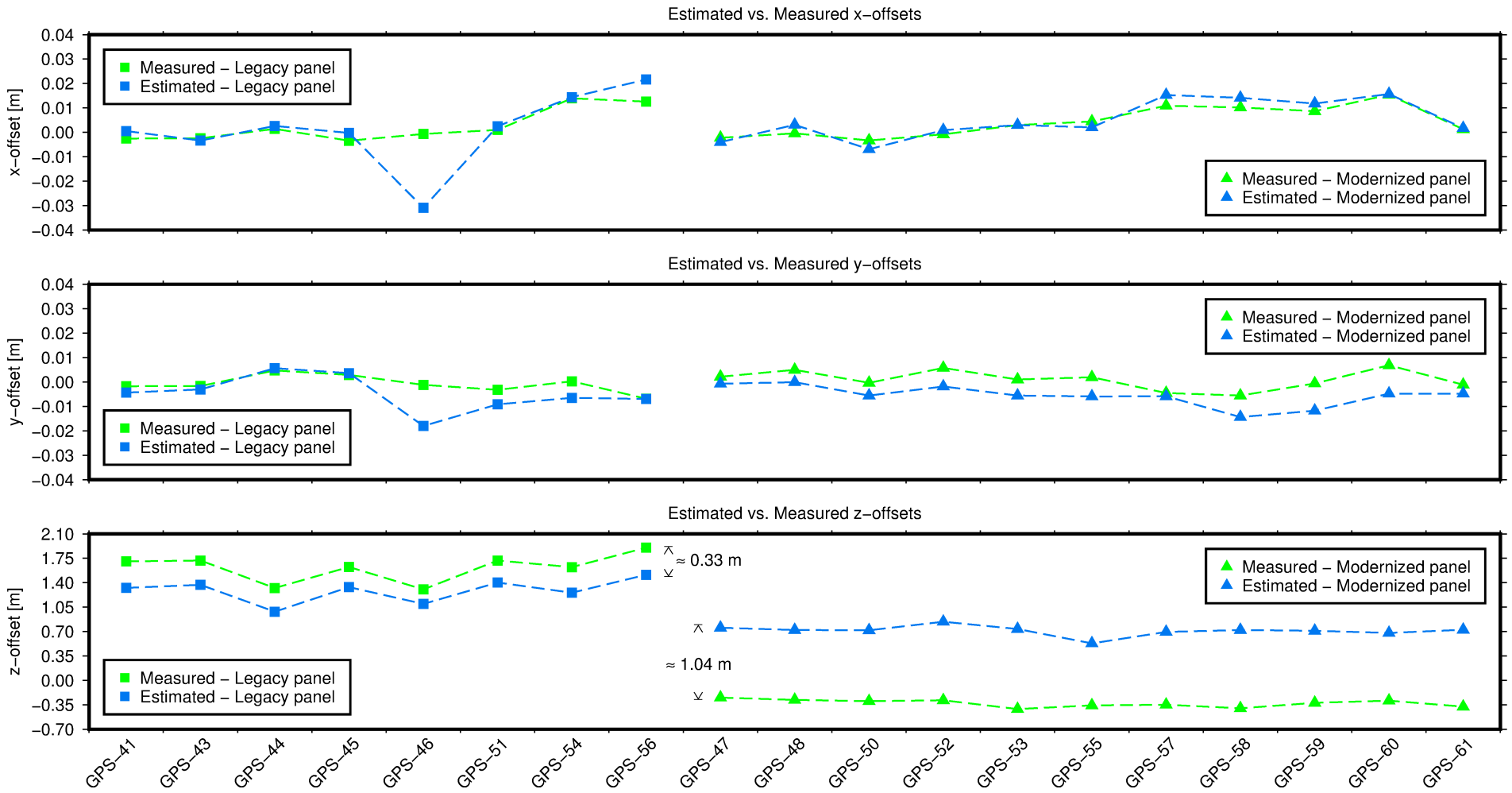


Comparison to estimated phase patterns

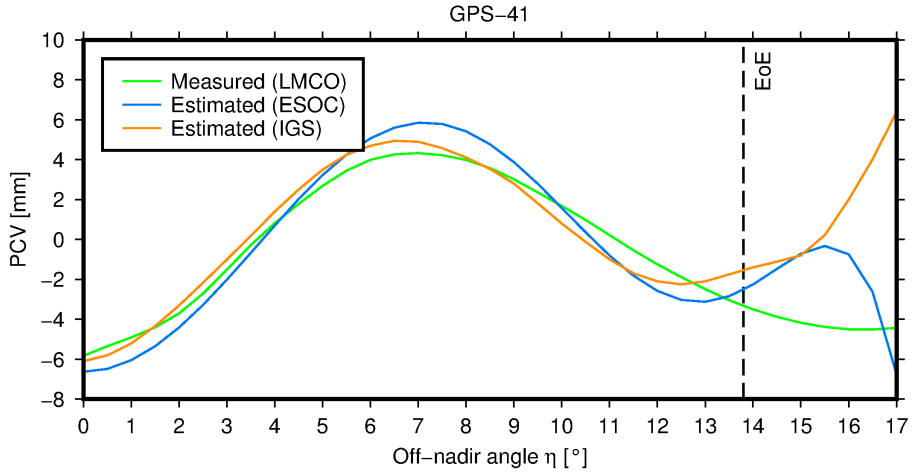
- ESOC's approach for deriving the GPS antenna phase patterns
  - Process ground- and space-based tracking data simultaneously in a single solution
  - Select Jason-1/2 to sample GPS antennas down to 17° off-nadir
  - Use spherical harmonics (8,4) to account for both azimuthal and non-azimuthal variations
  - Estimate parameters for both GPS transmit antennas and Jason receiver antennas
  - Combine daily antenna and station coordinate parameters on NEQ-level

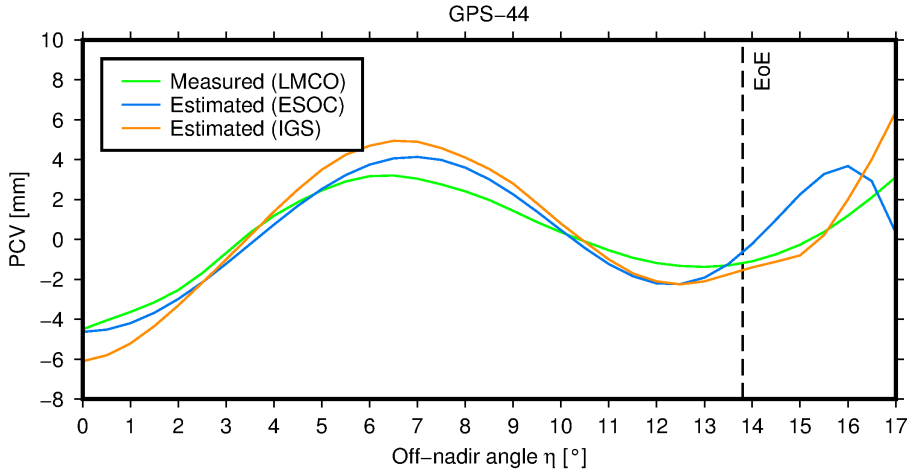


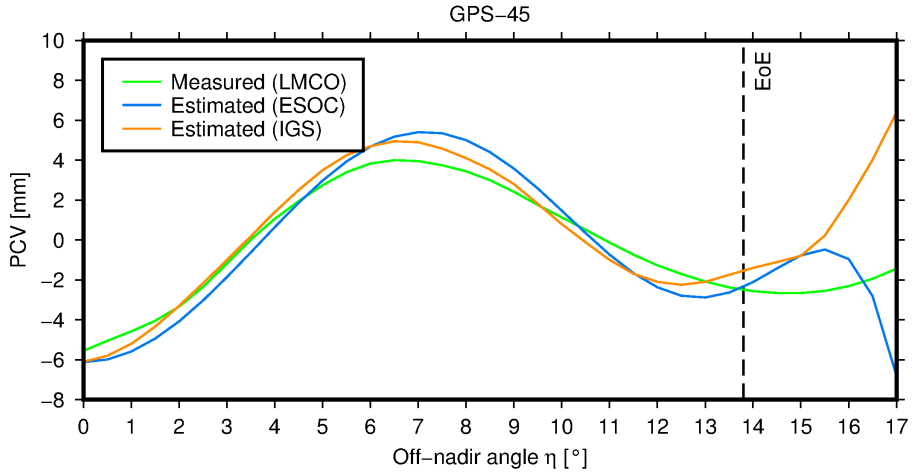
Estimated vs. Measured – Offsets

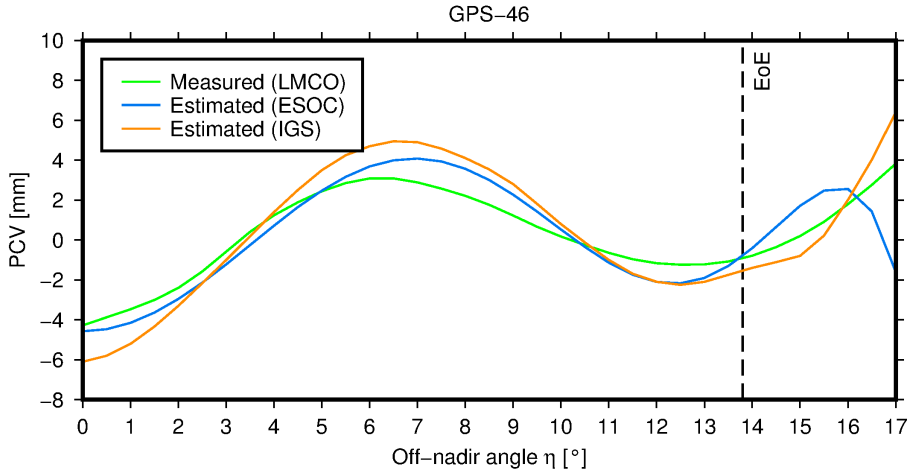


Estimated vs. Measured – Legacy Panel









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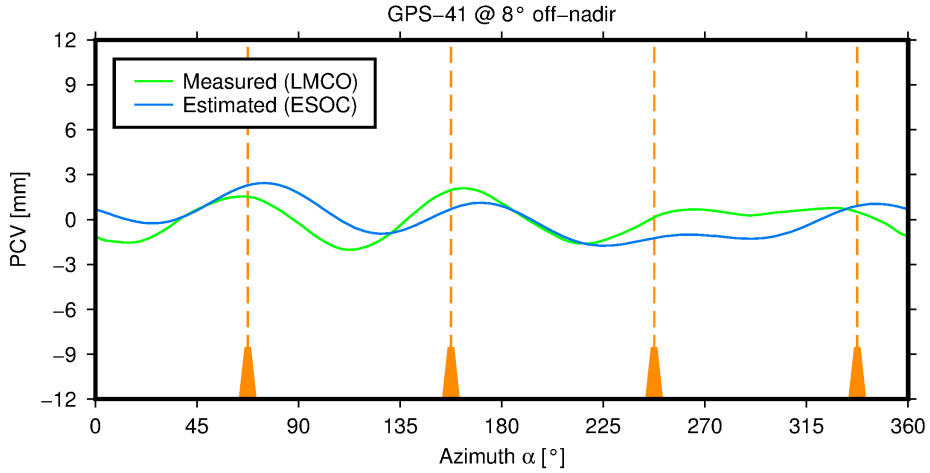

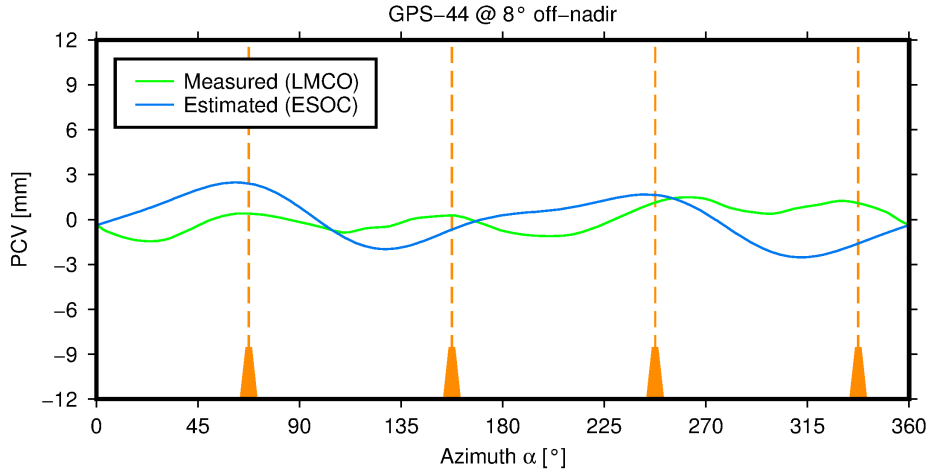

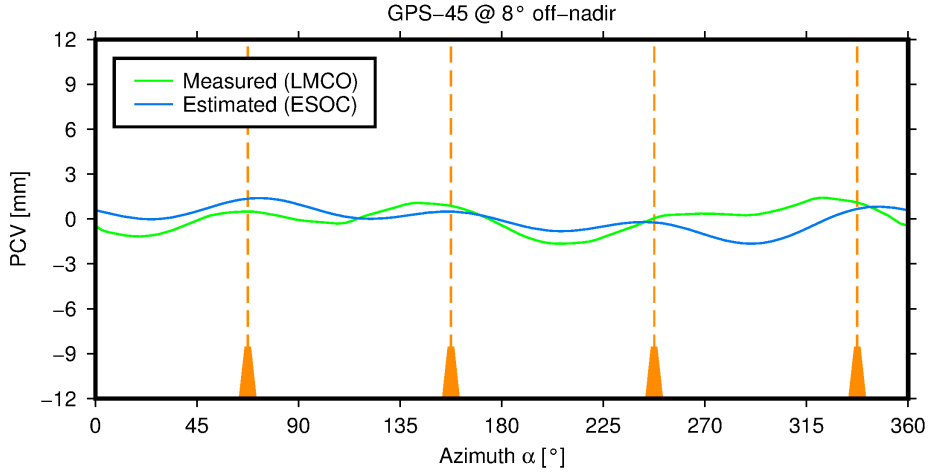

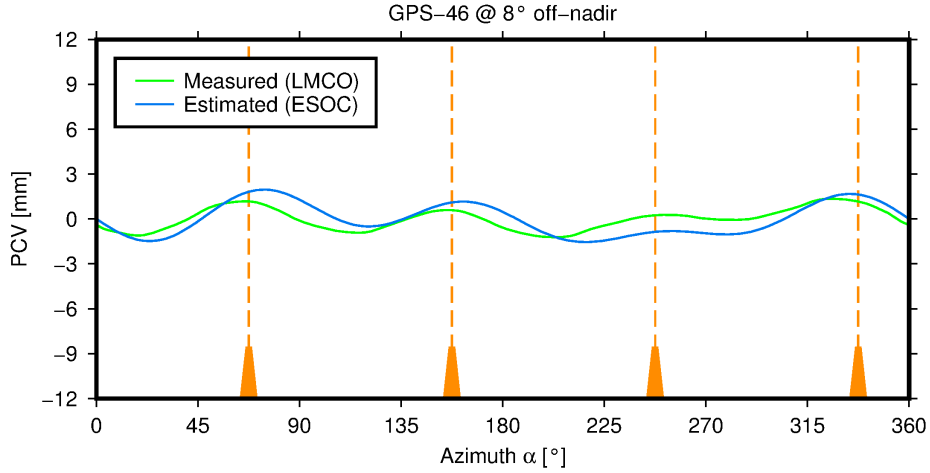

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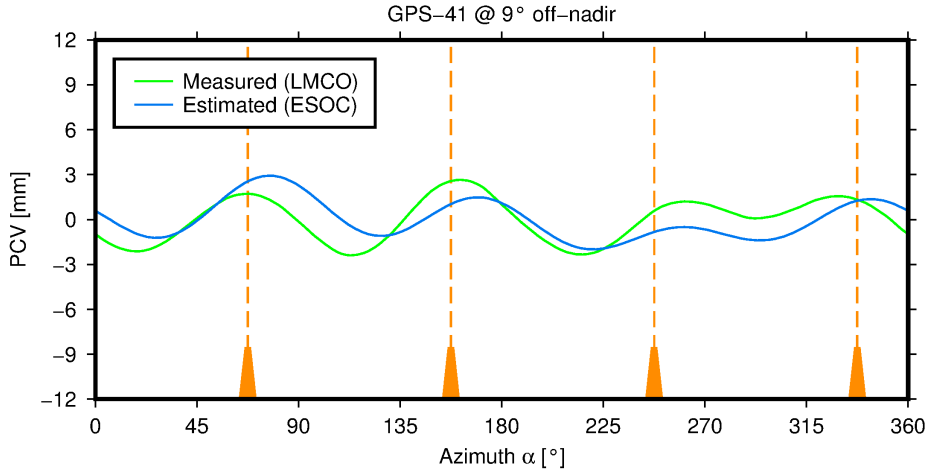

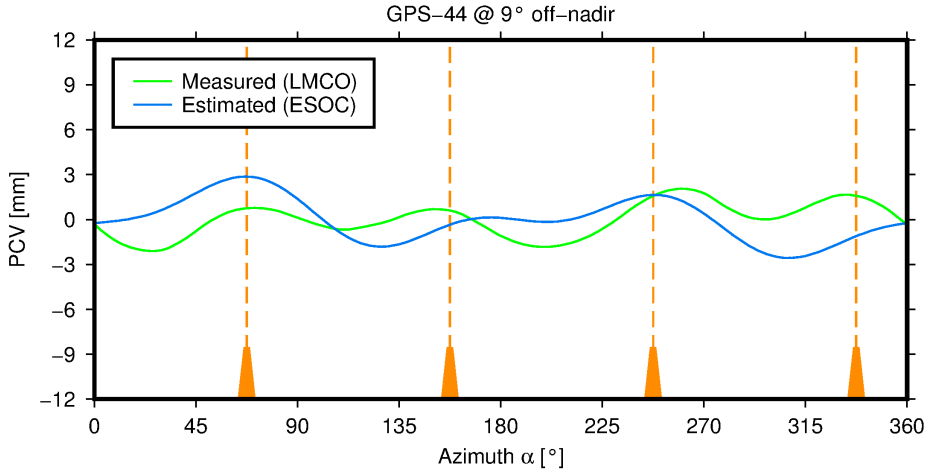

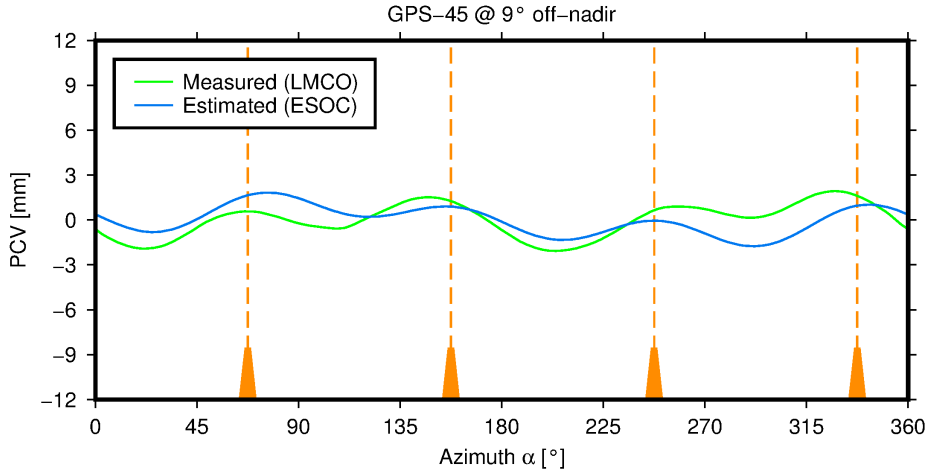

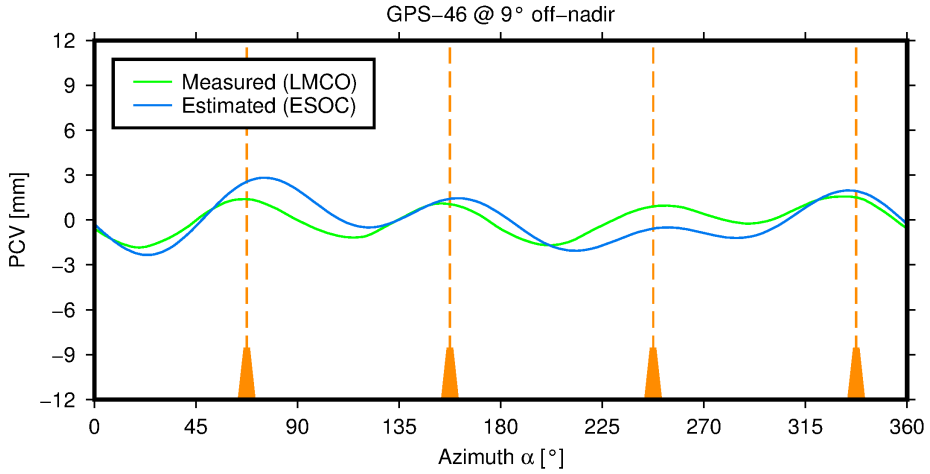

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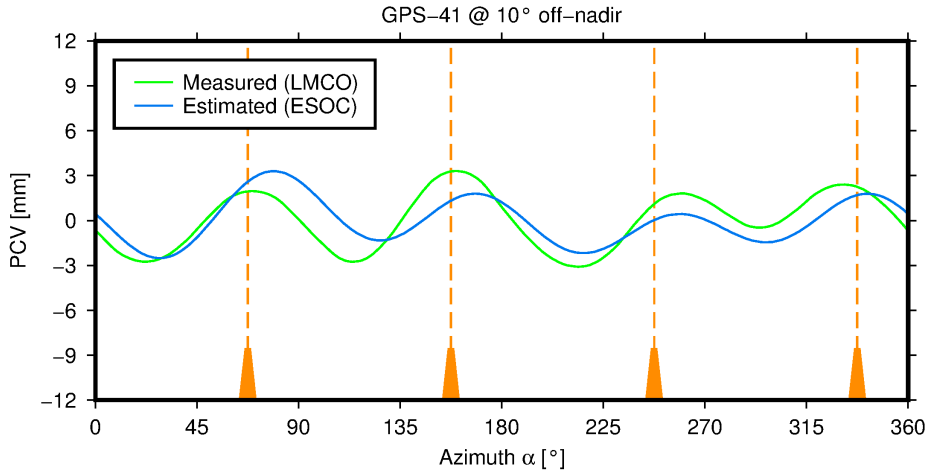

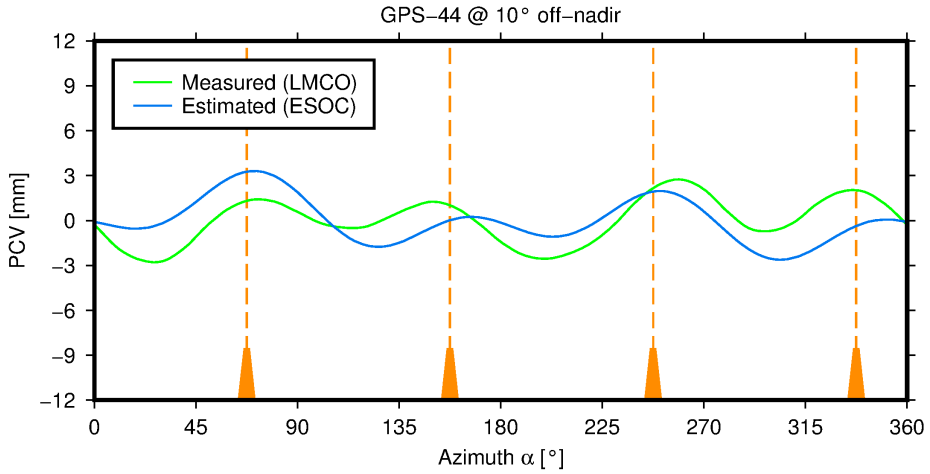

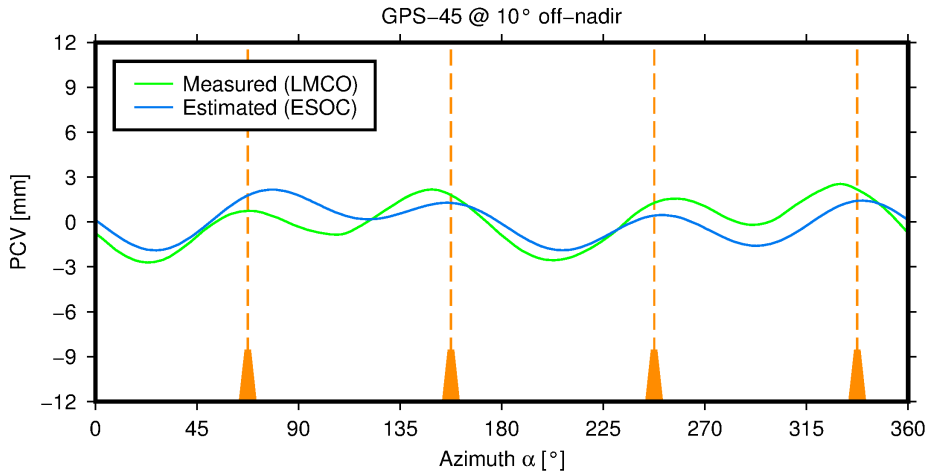

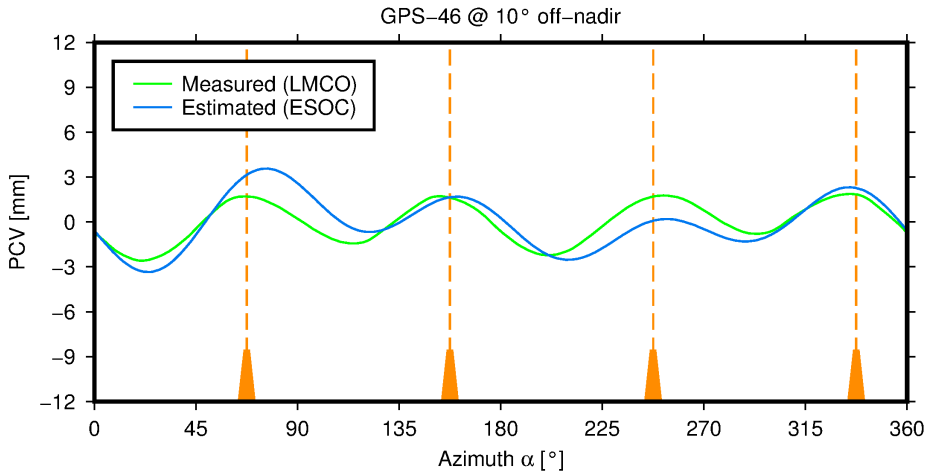

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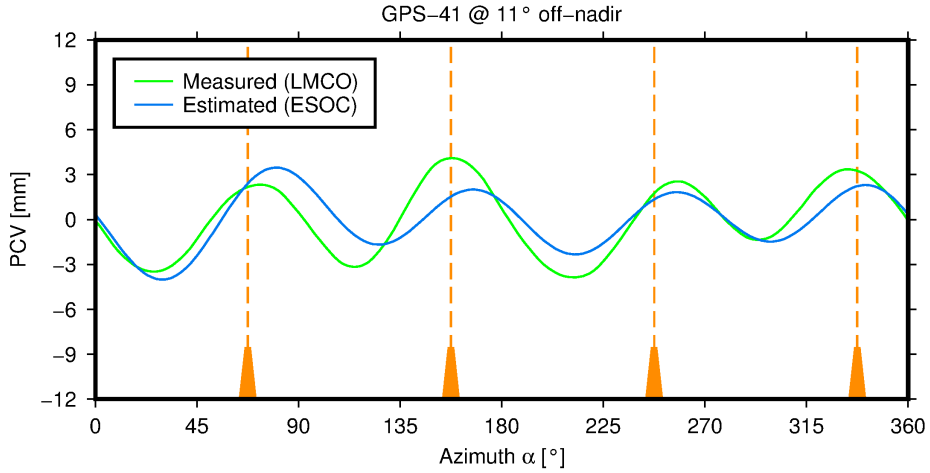

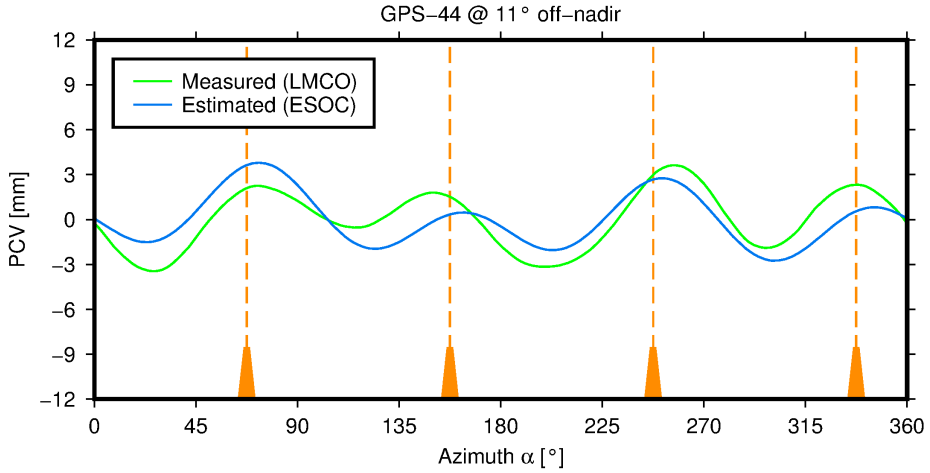

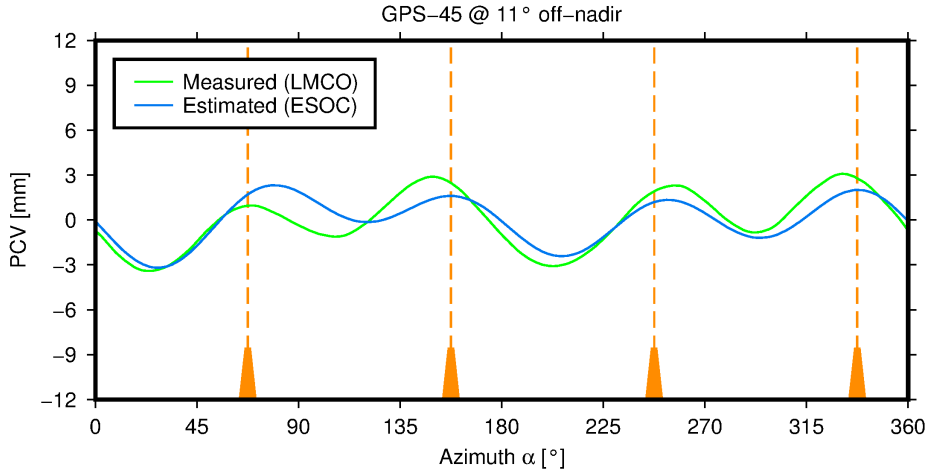

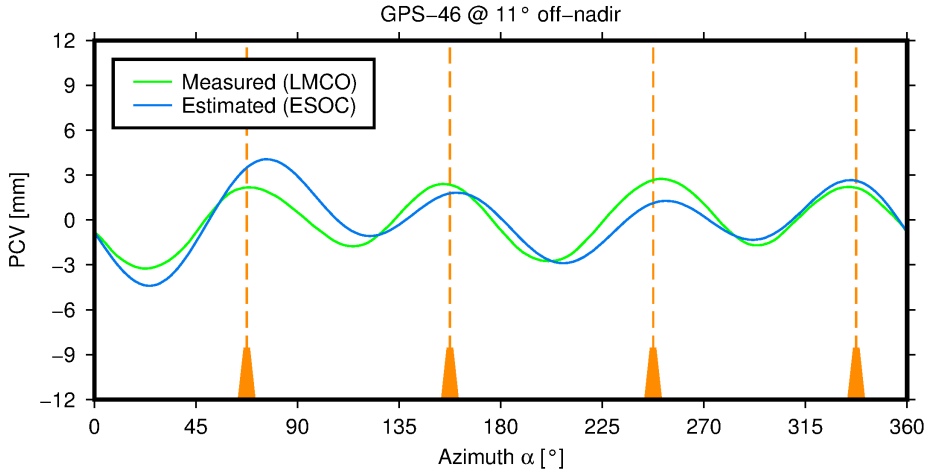

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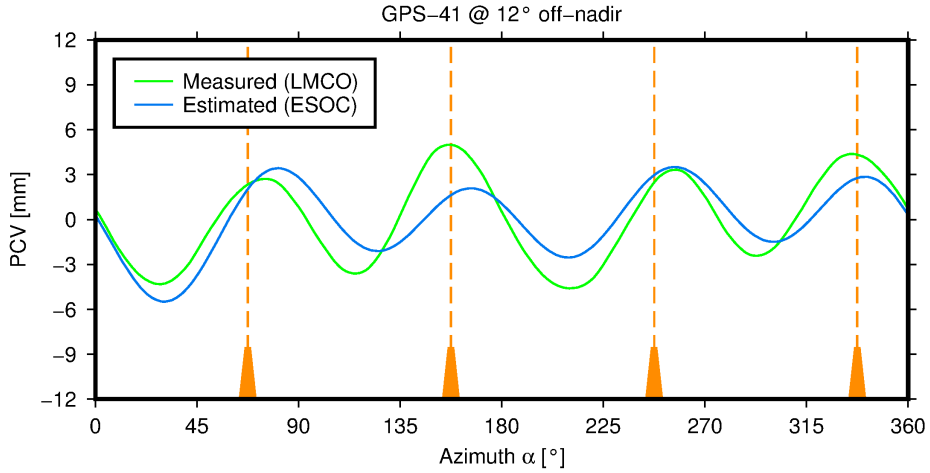

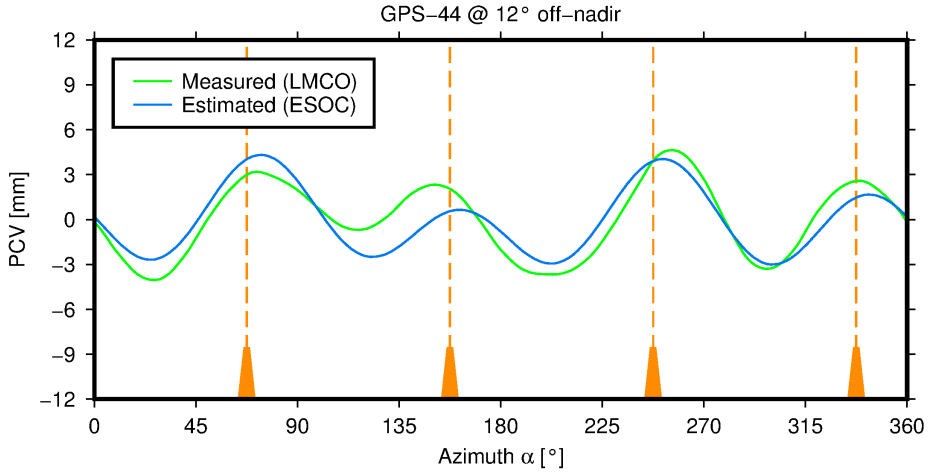

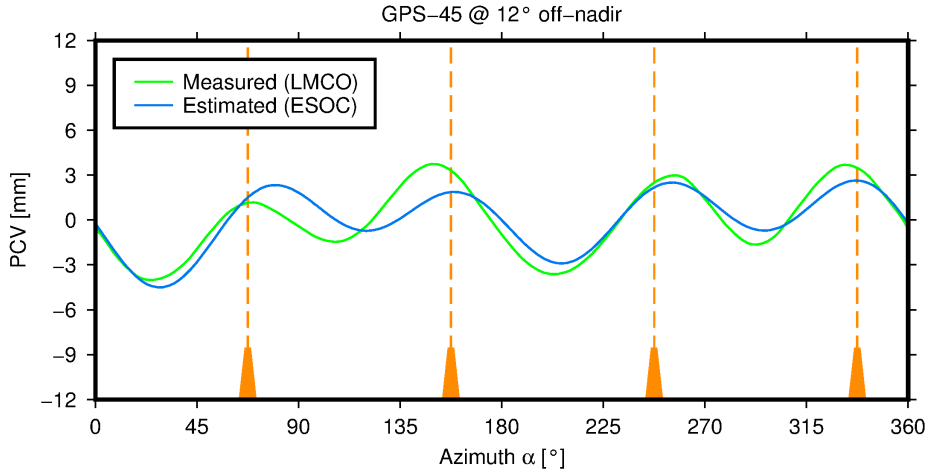

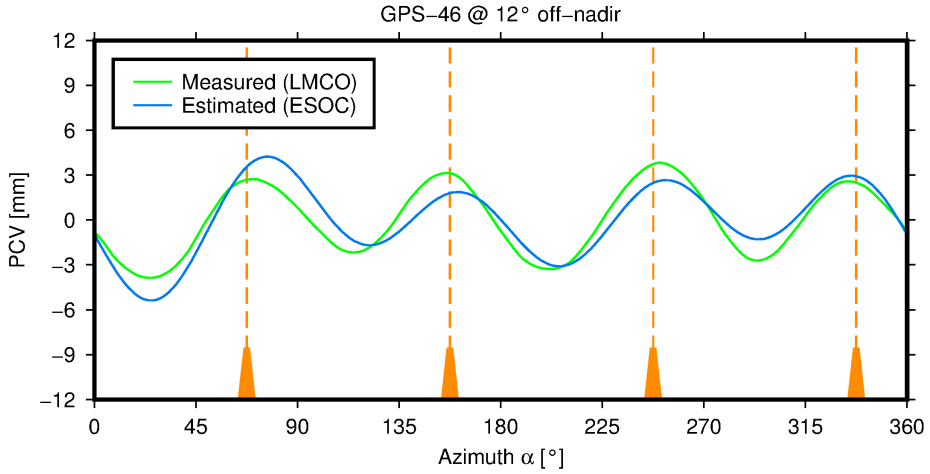

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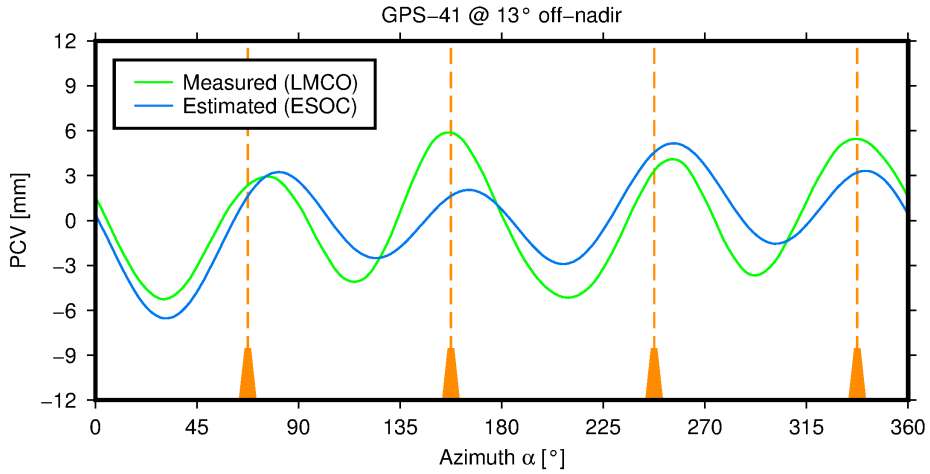

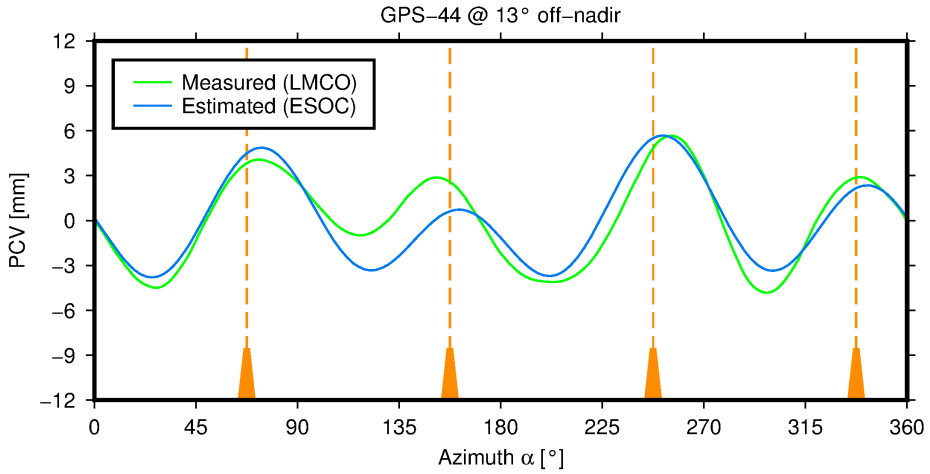

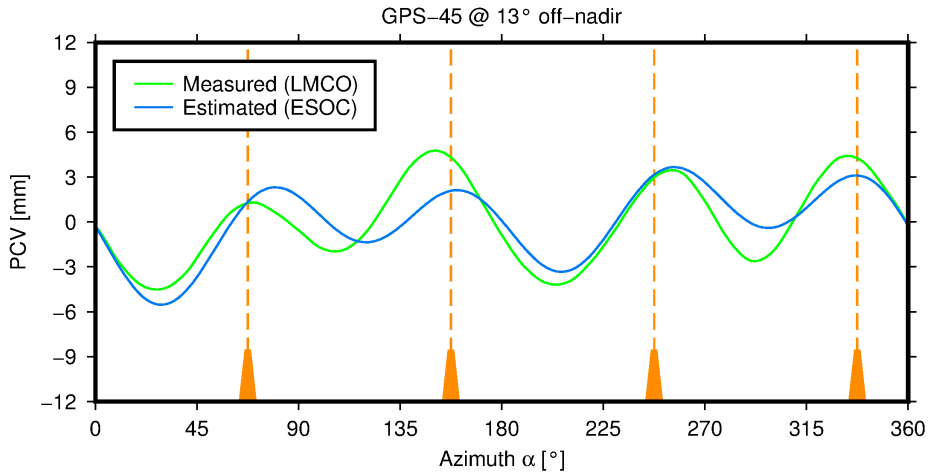

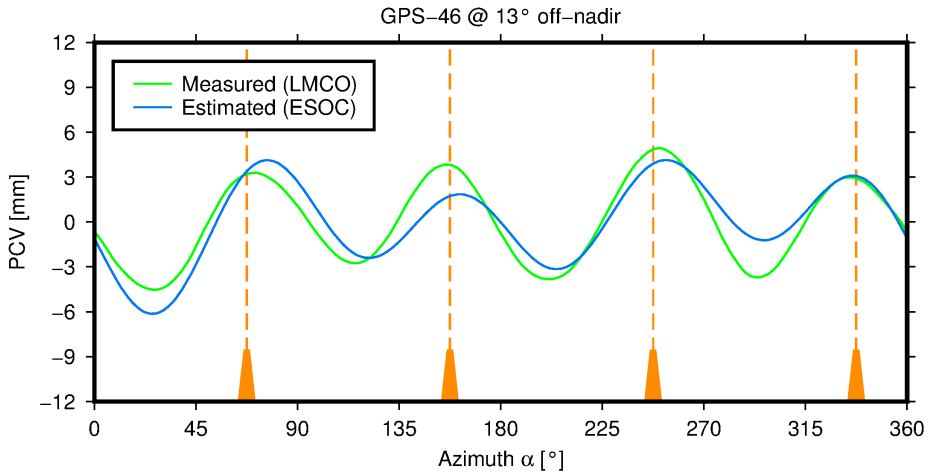

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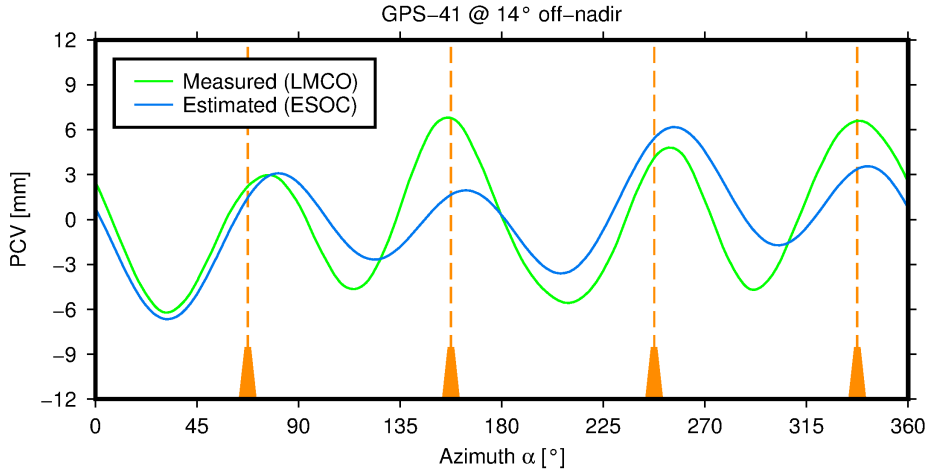

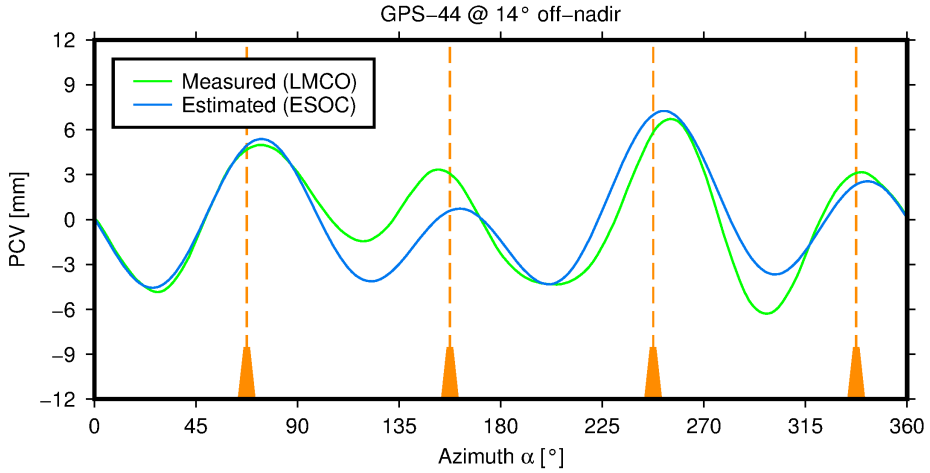

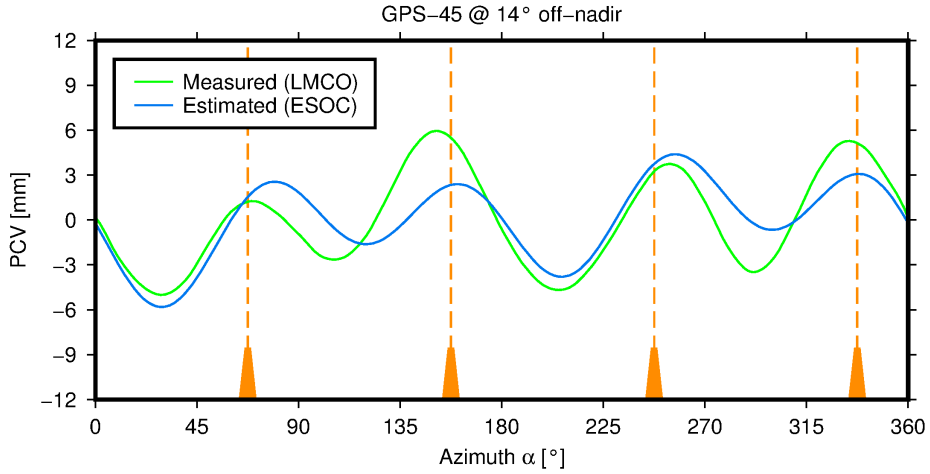

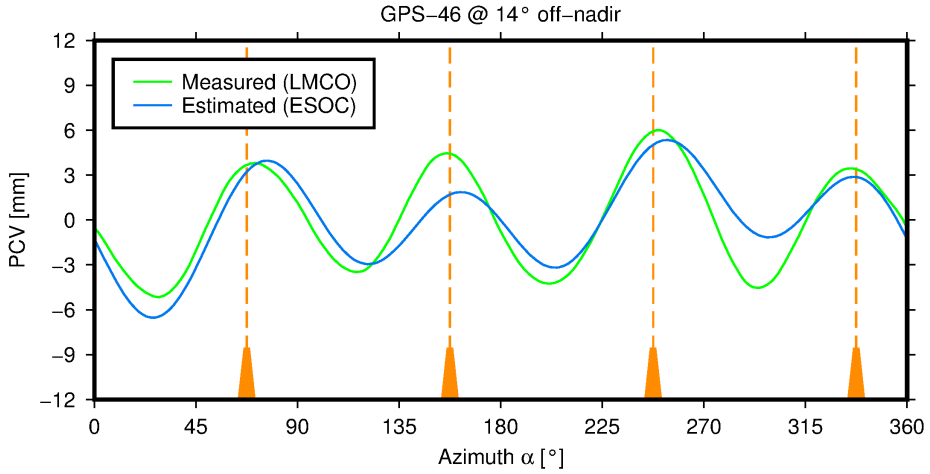

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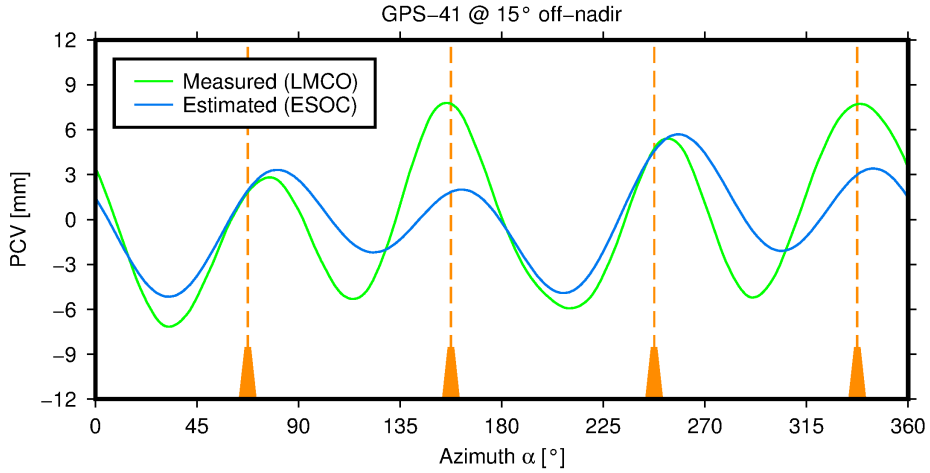

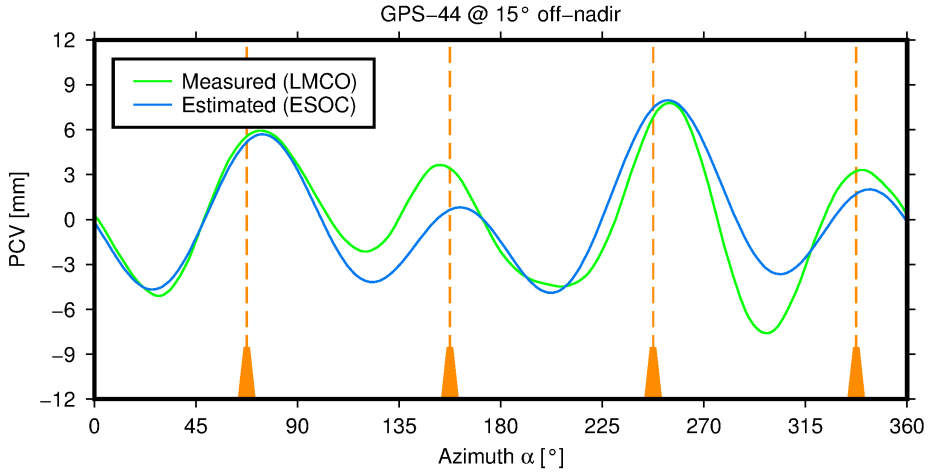

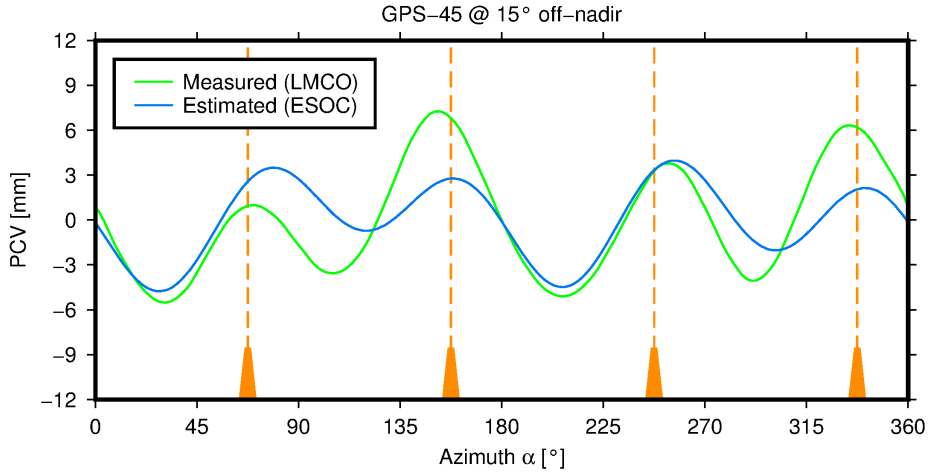

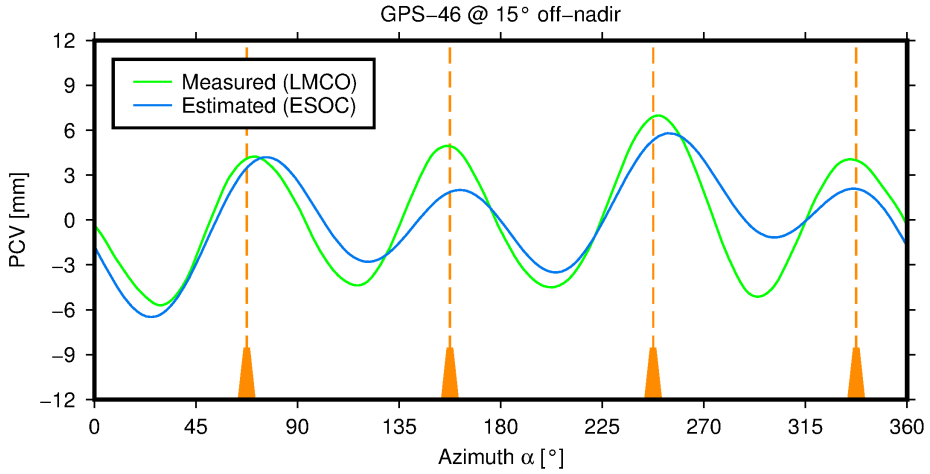

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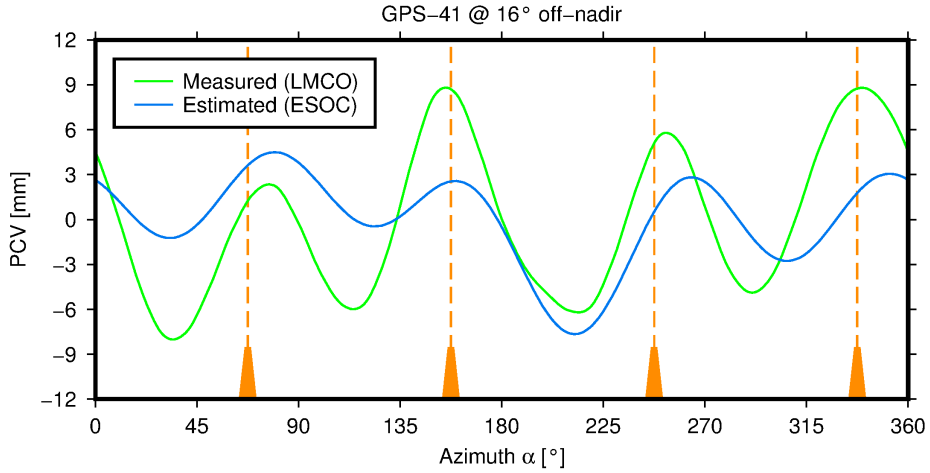
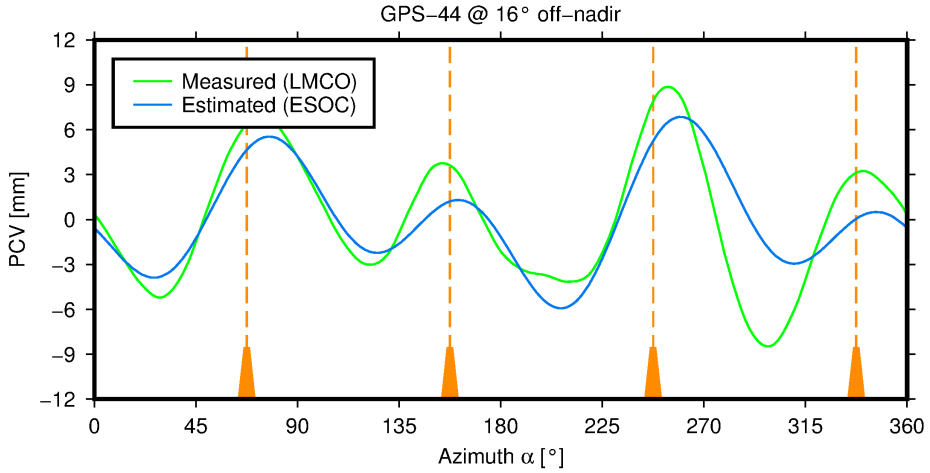
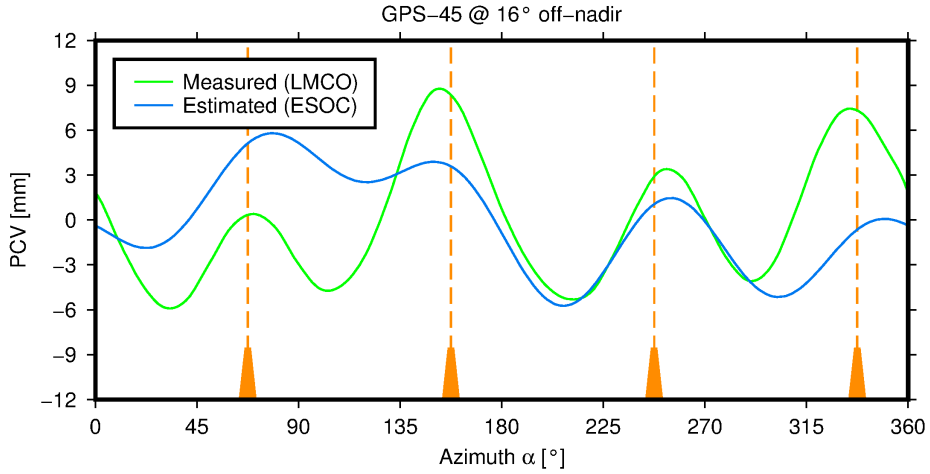
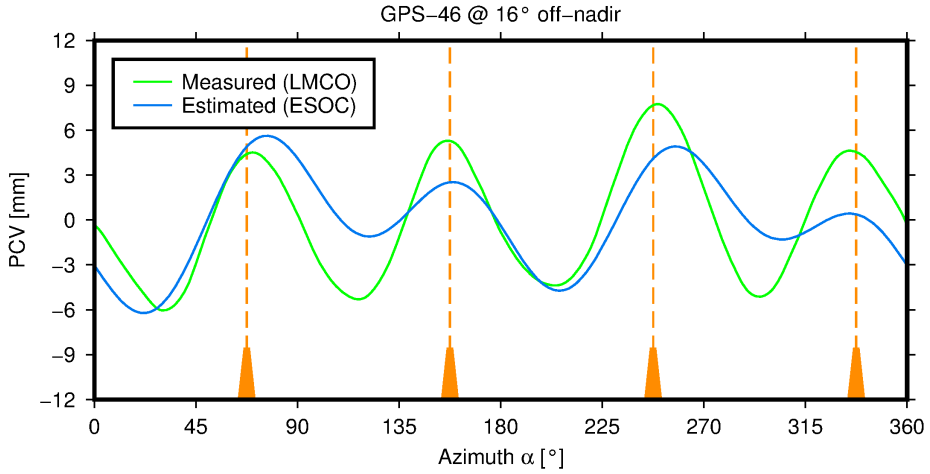
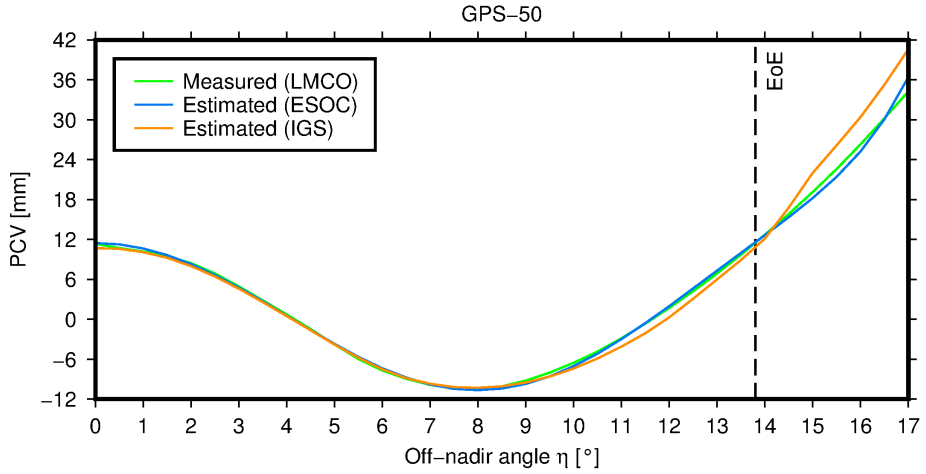


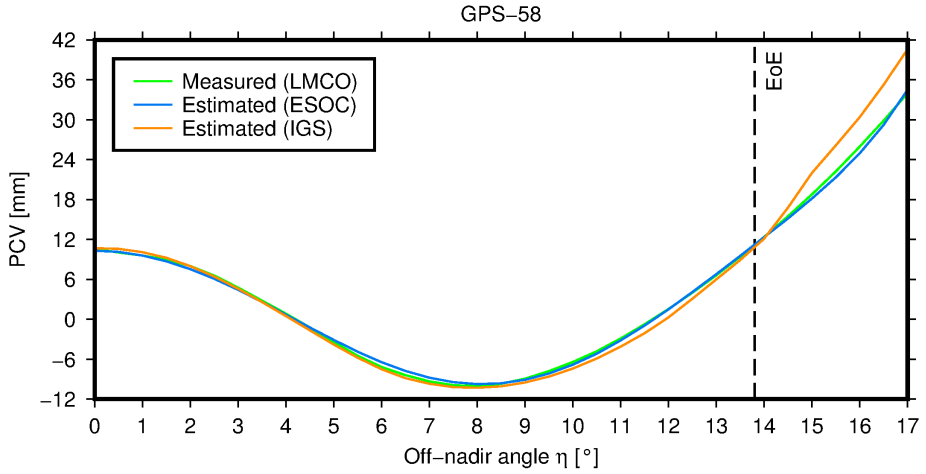


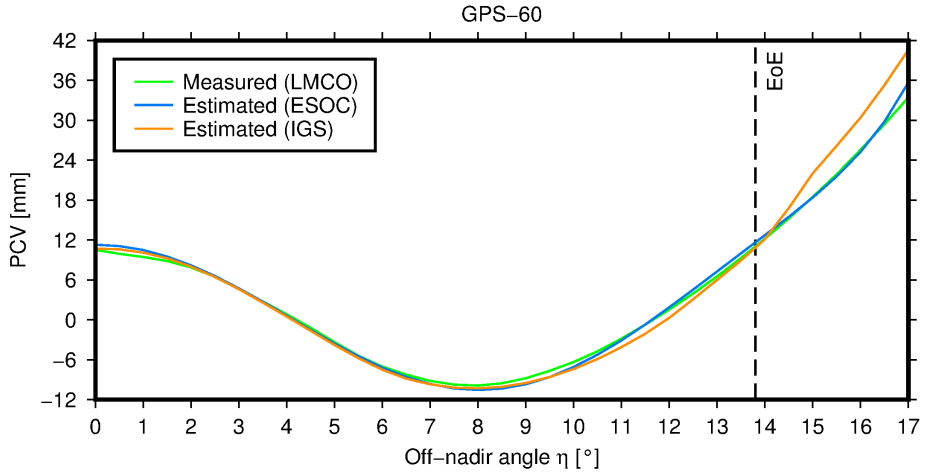


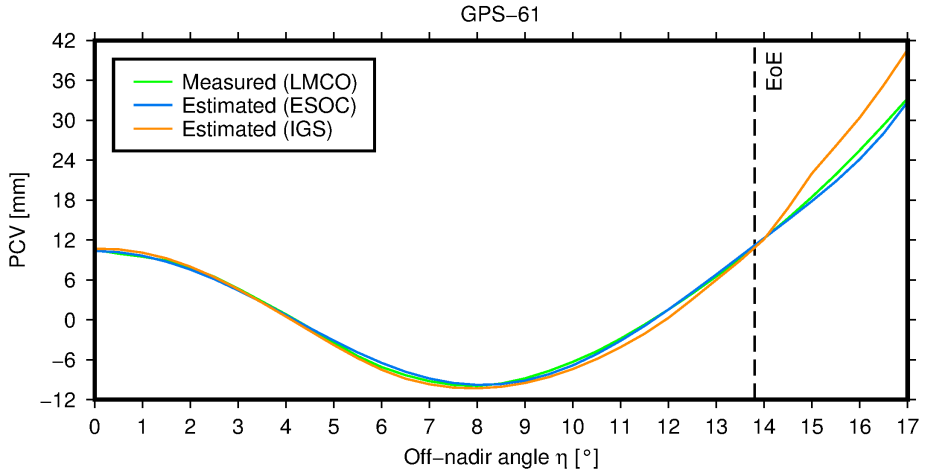


Estimated vs. Measured – Modernized Panel

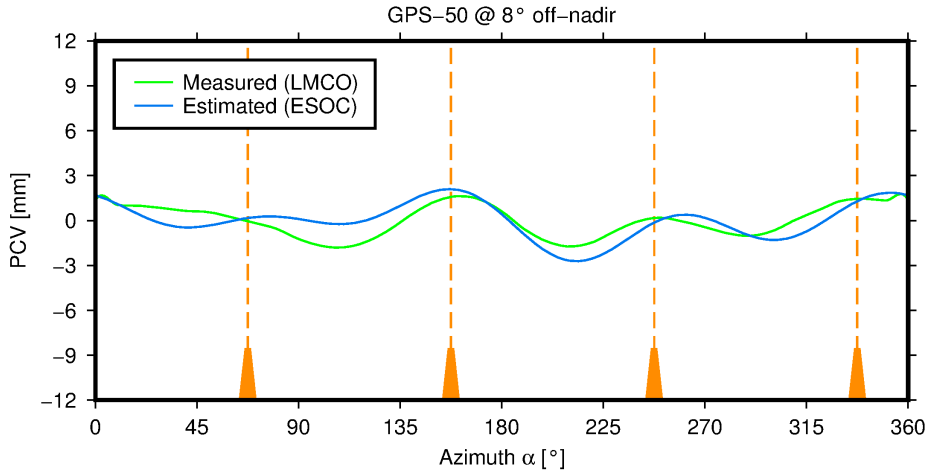


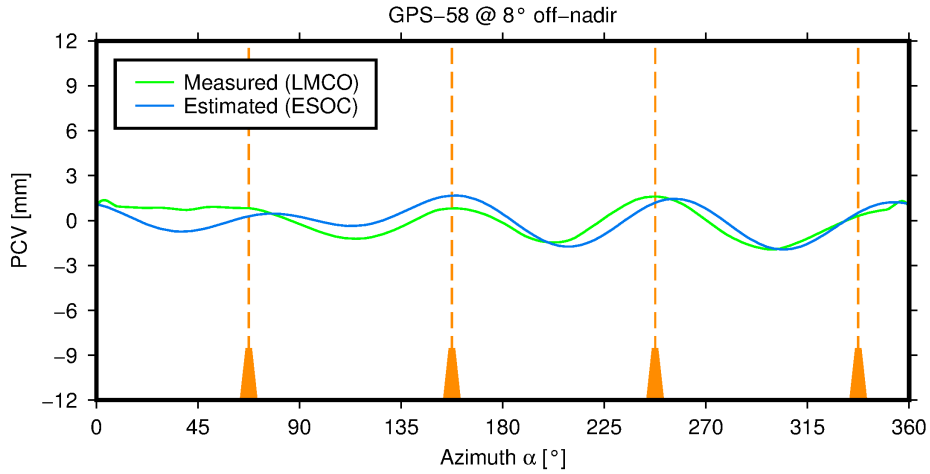


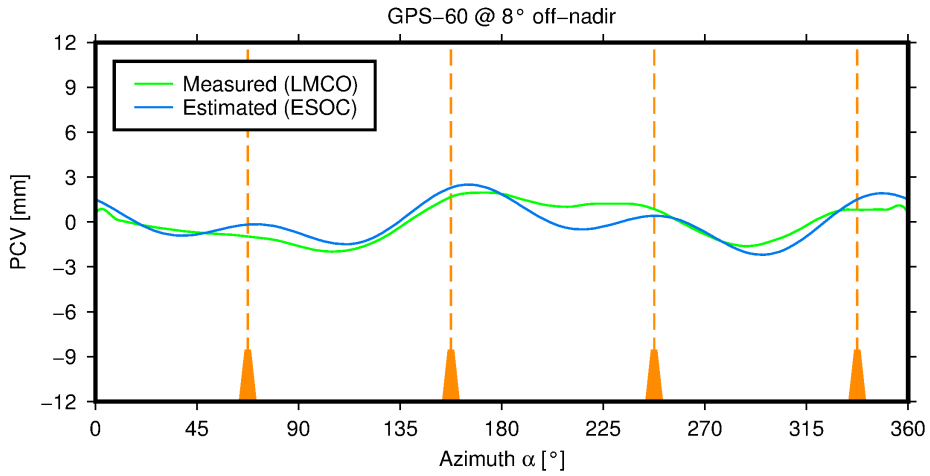


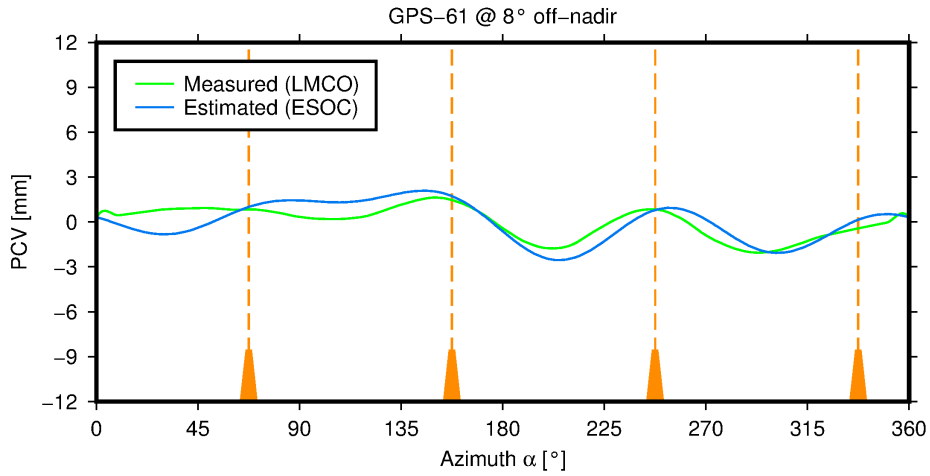


Estimated vs. Measured – Modernized Panel

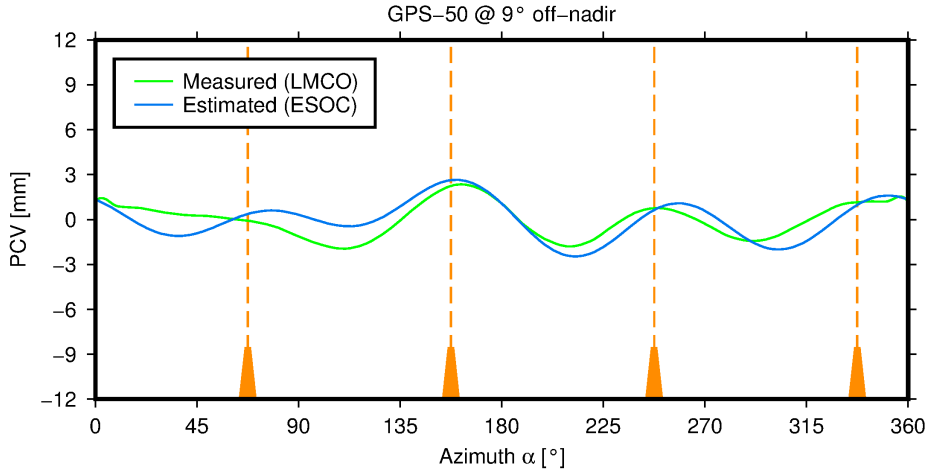


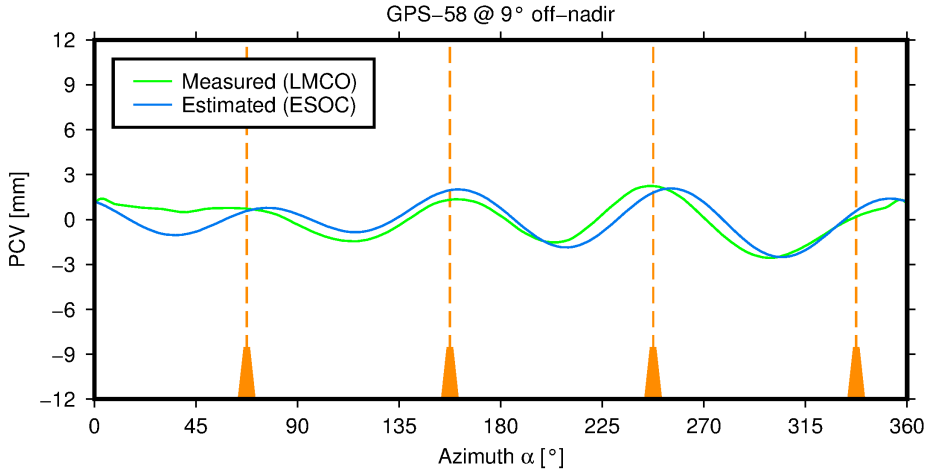


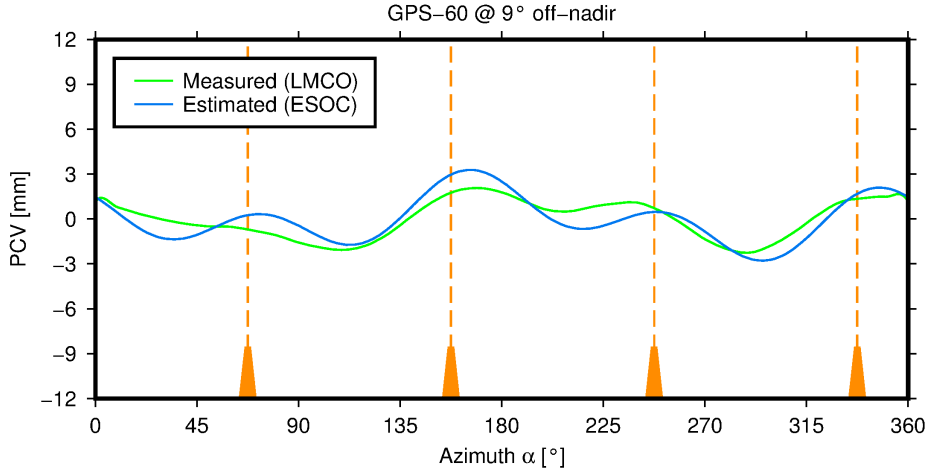


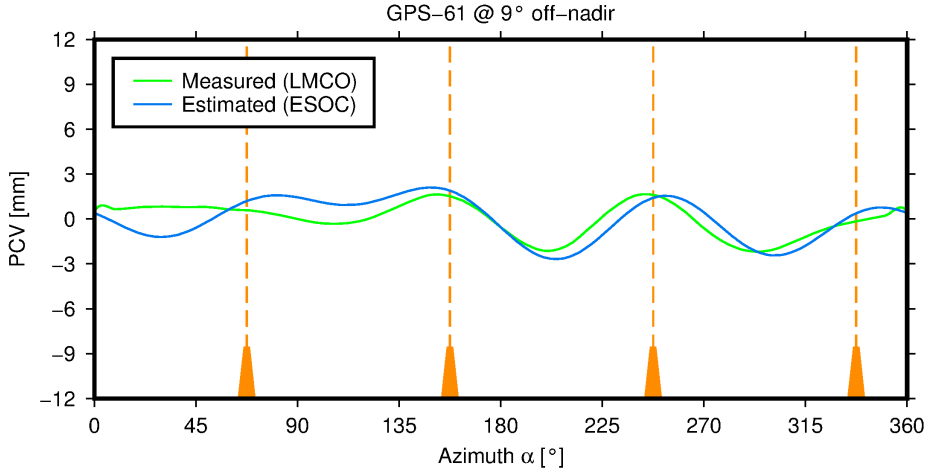


Estimated vs. Measured – Modernized Panel

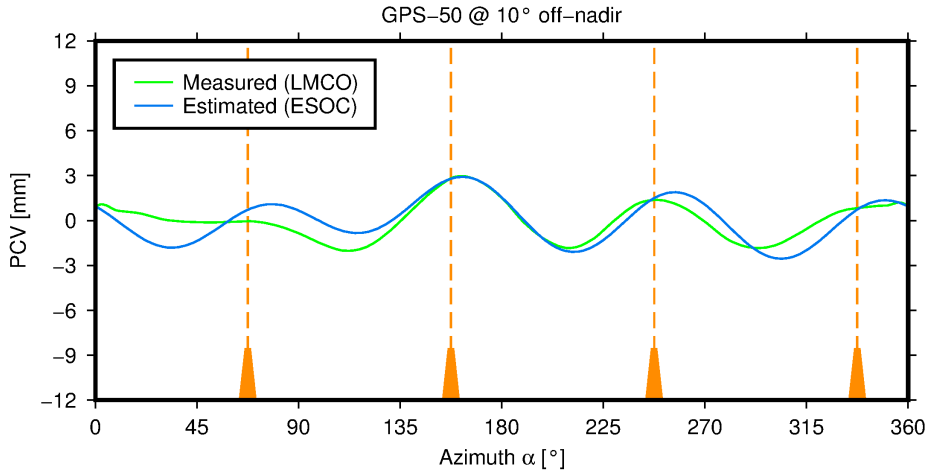


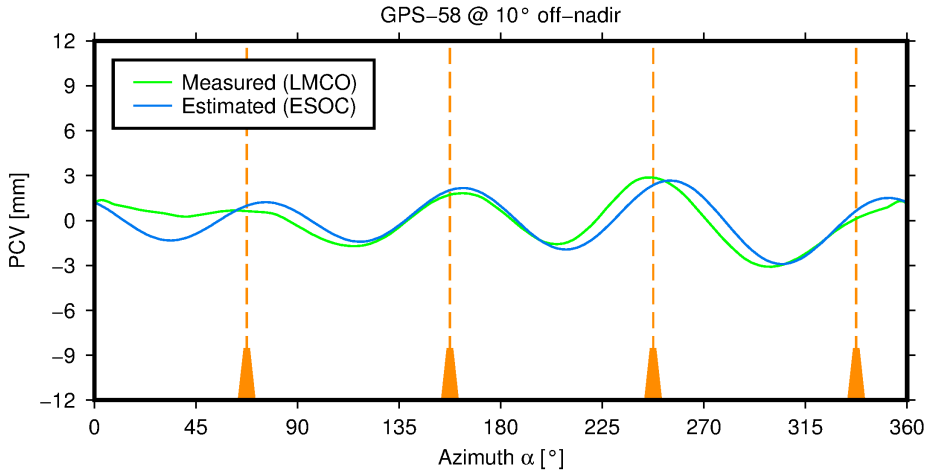


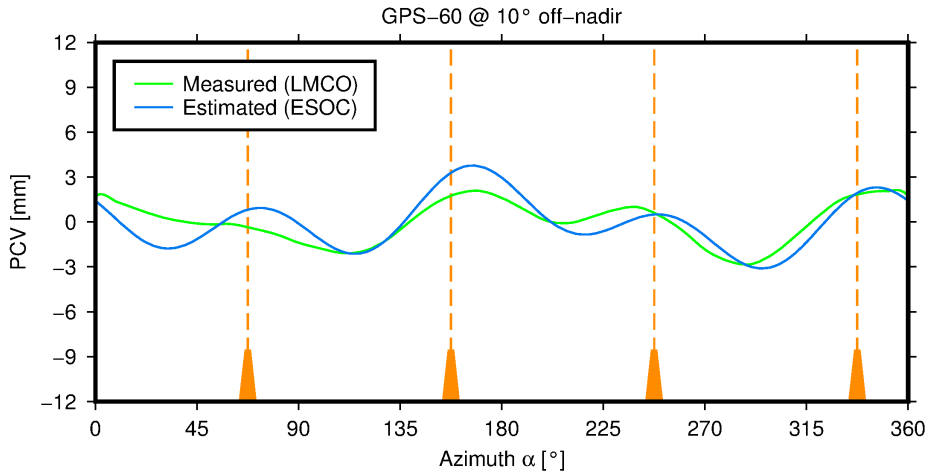


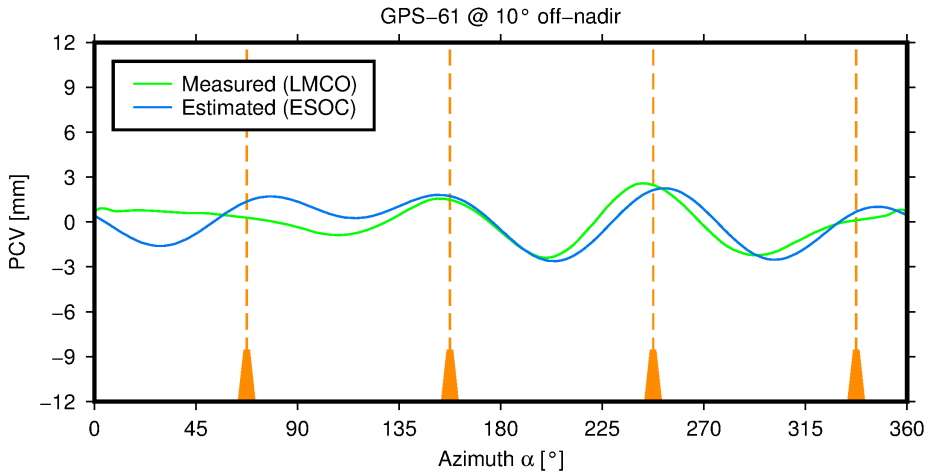


Estimated vs. Measured – Modernized Panel

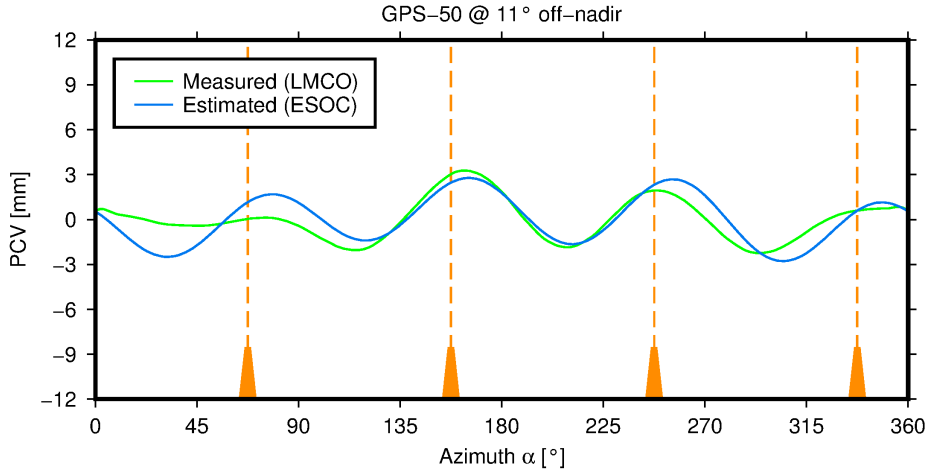


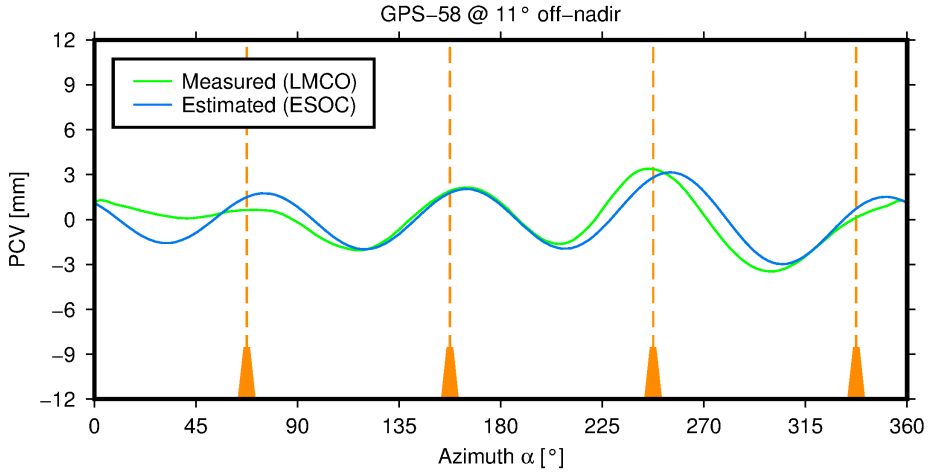


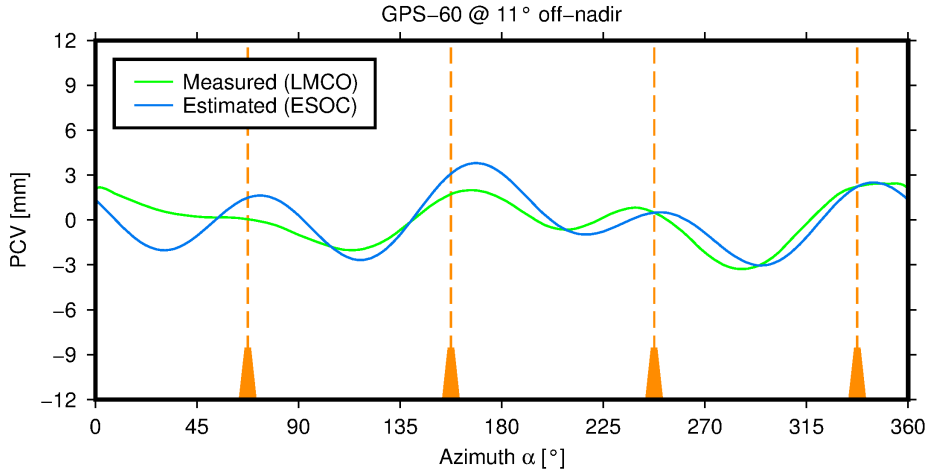


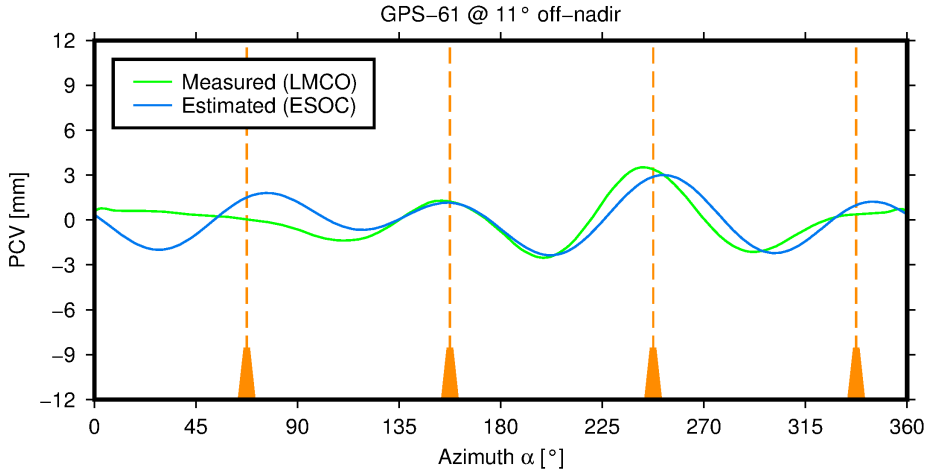


Estimated vs. Measured – Modernized Panel

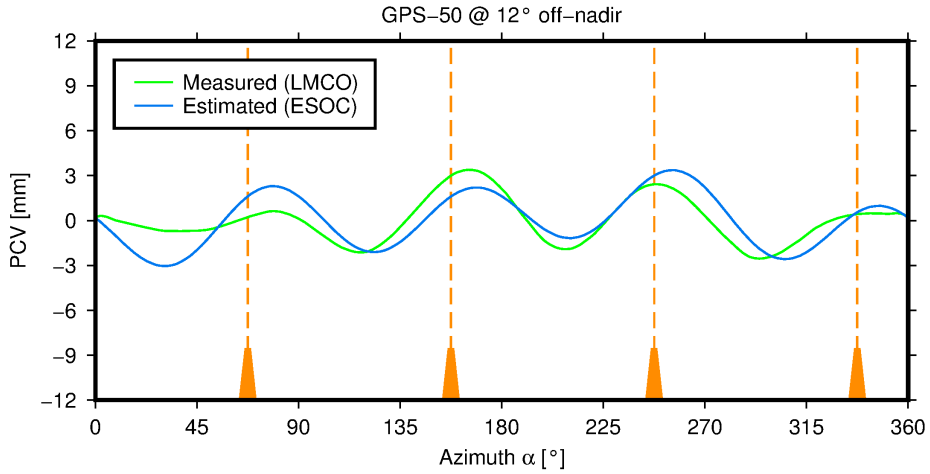


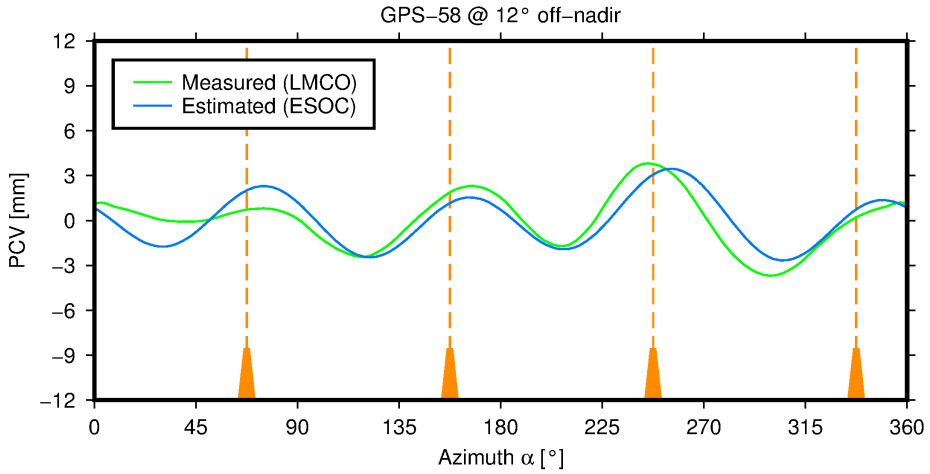


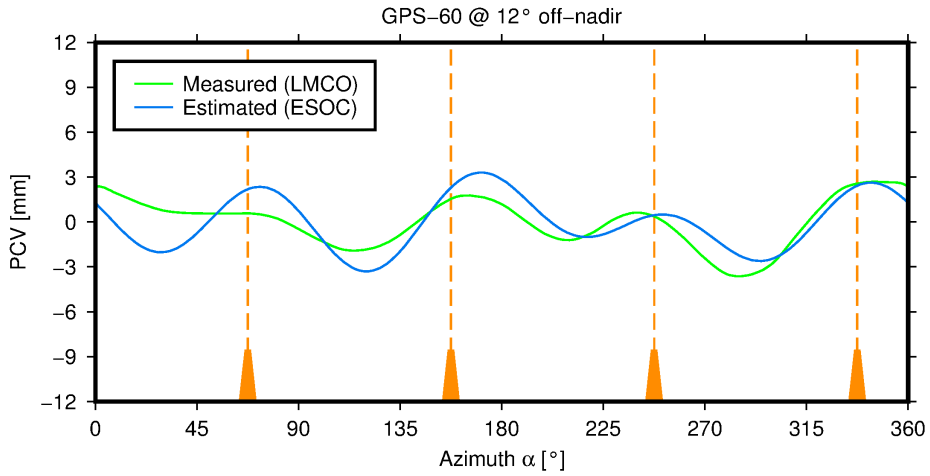


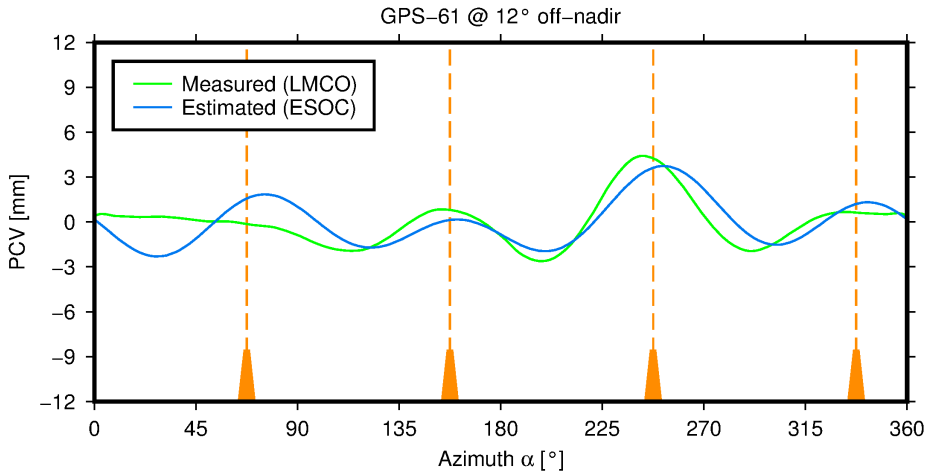


Estimated vs. Measured – Modernized Panel

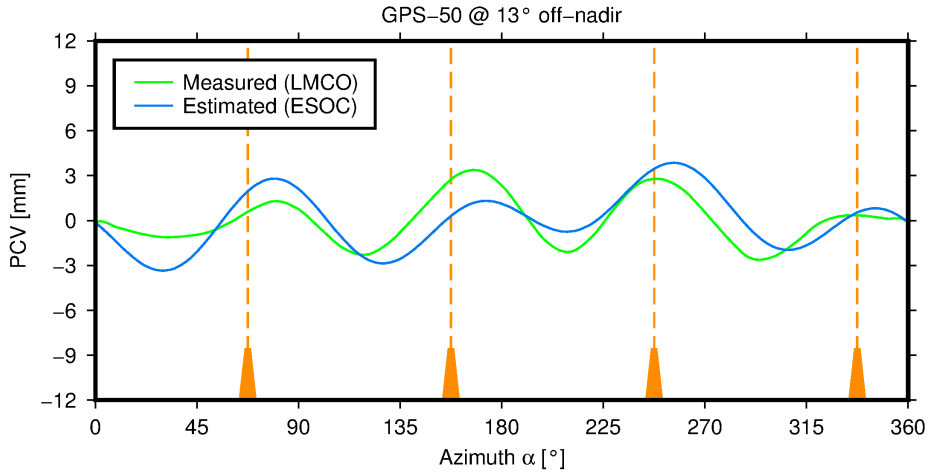


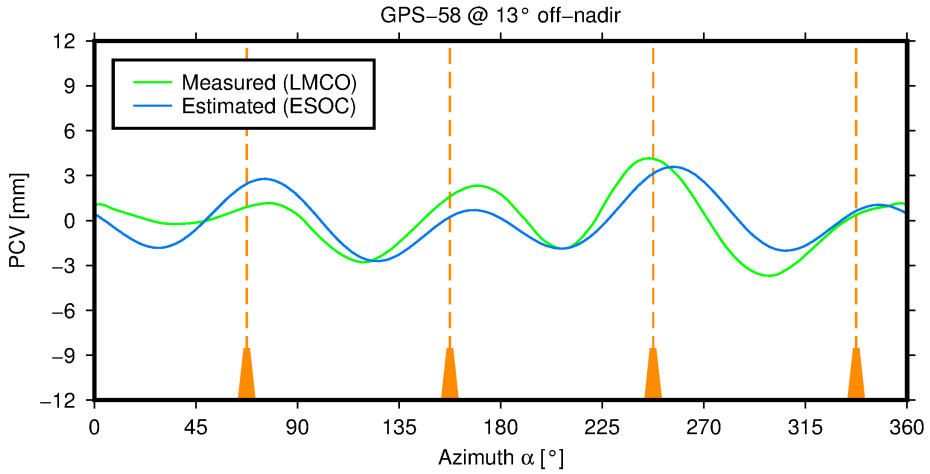


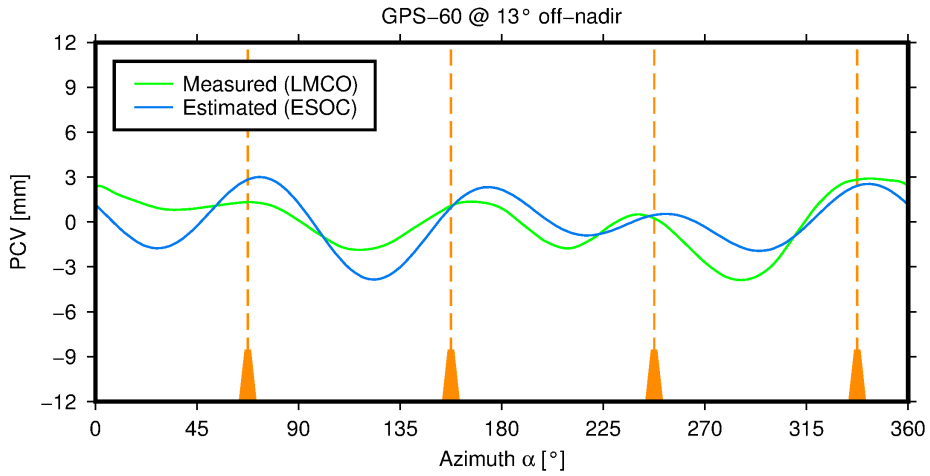


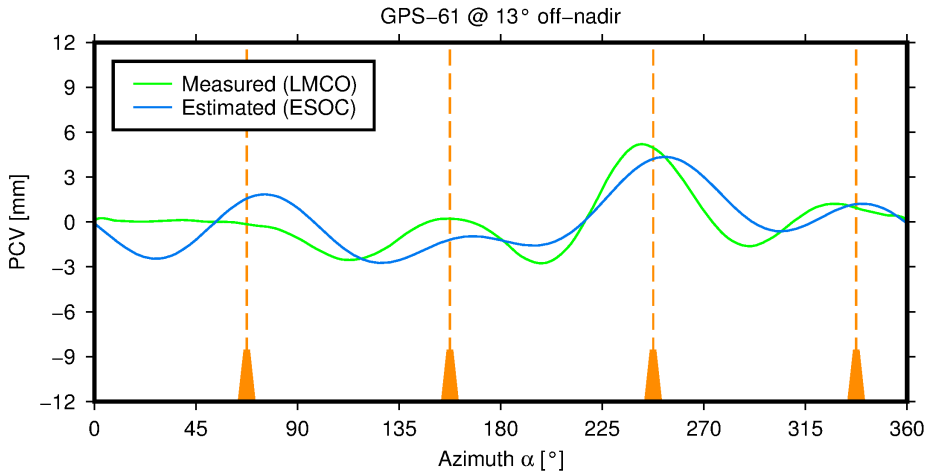


Estimated vs. Measured – Modernized Panel

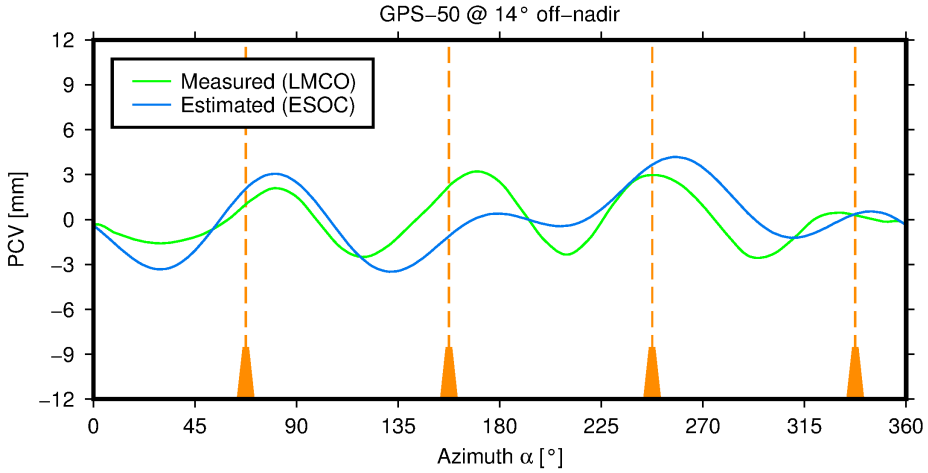


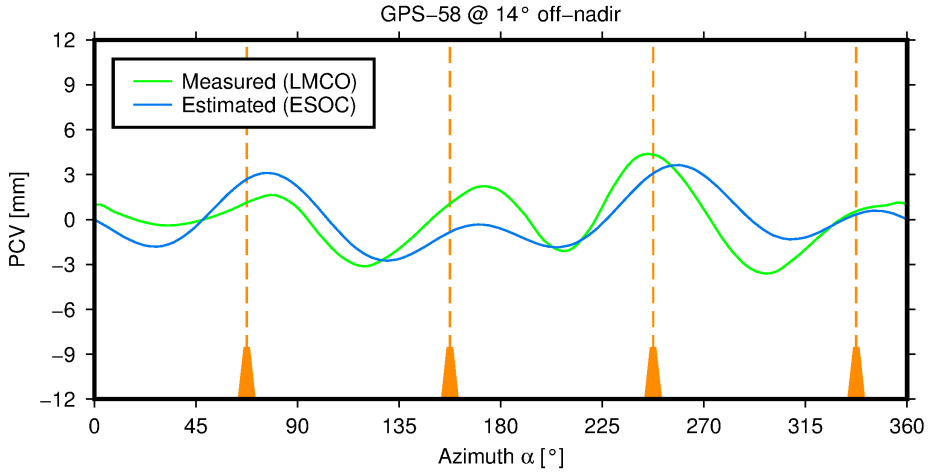


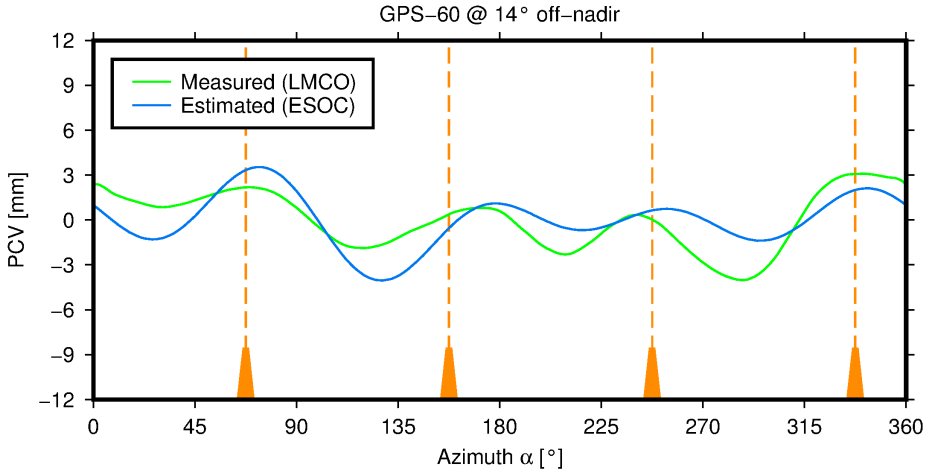


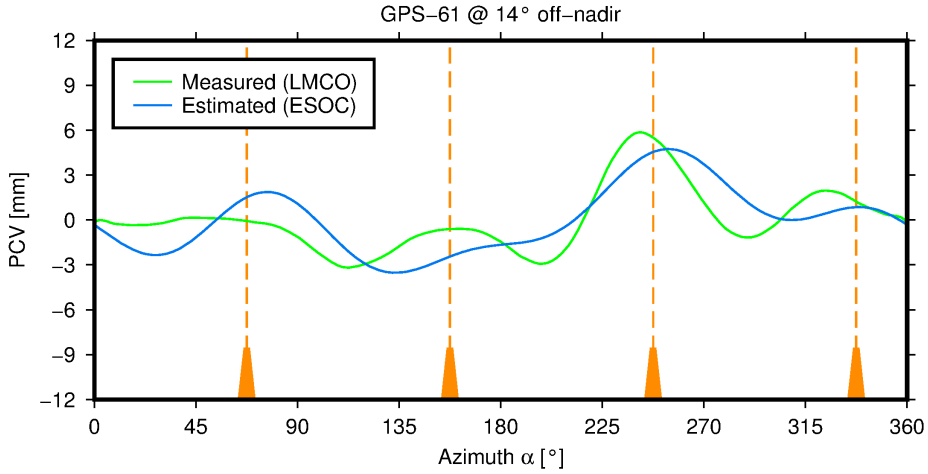


Estimated vs. Measured – Modernized Panel

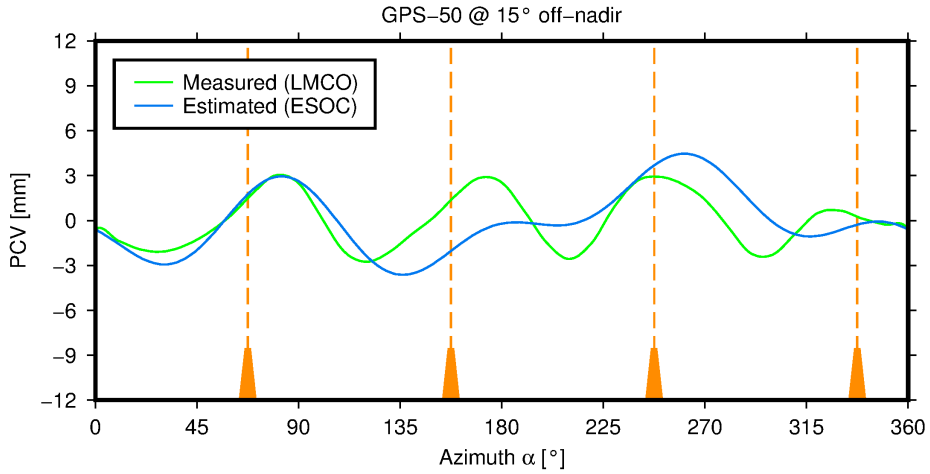


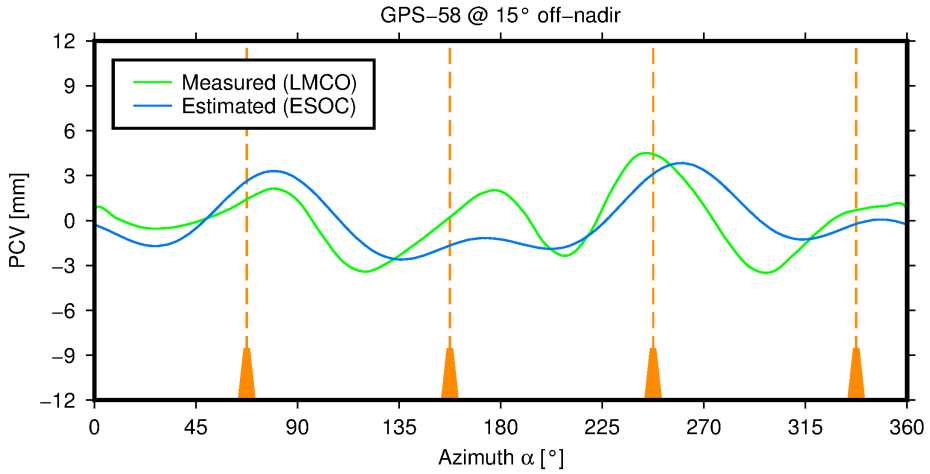


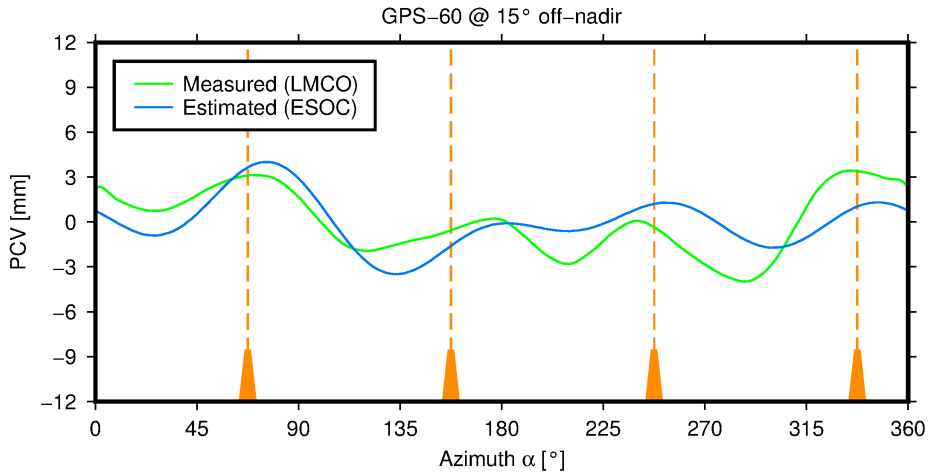


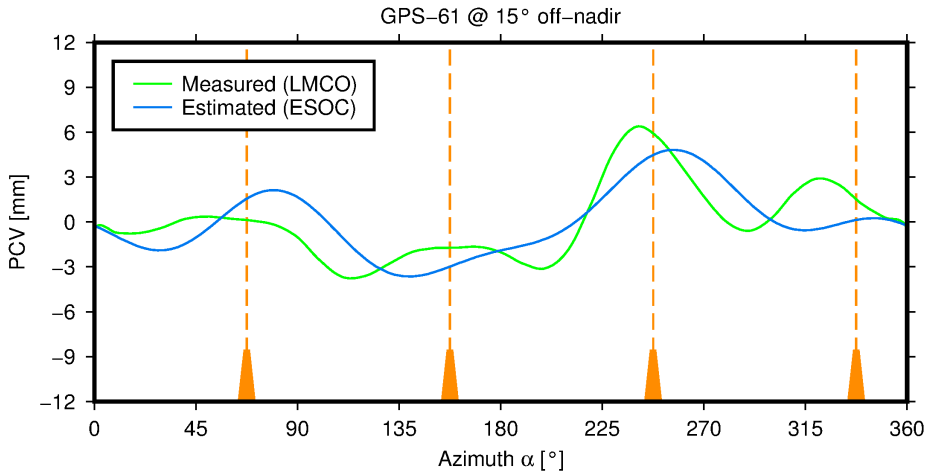


Estimated vs. Measured – Modernized Panel

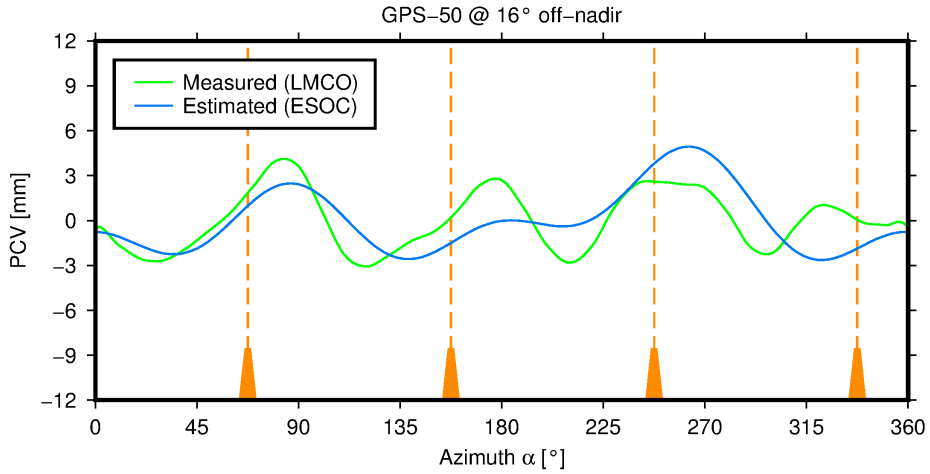


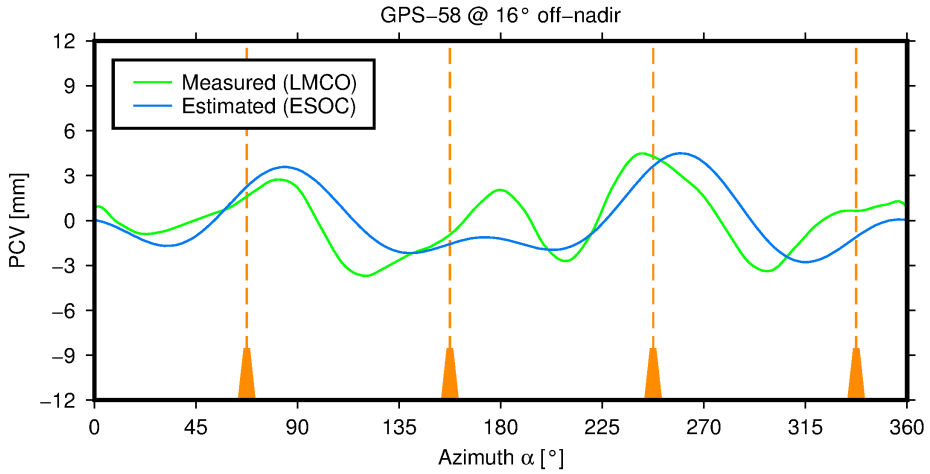


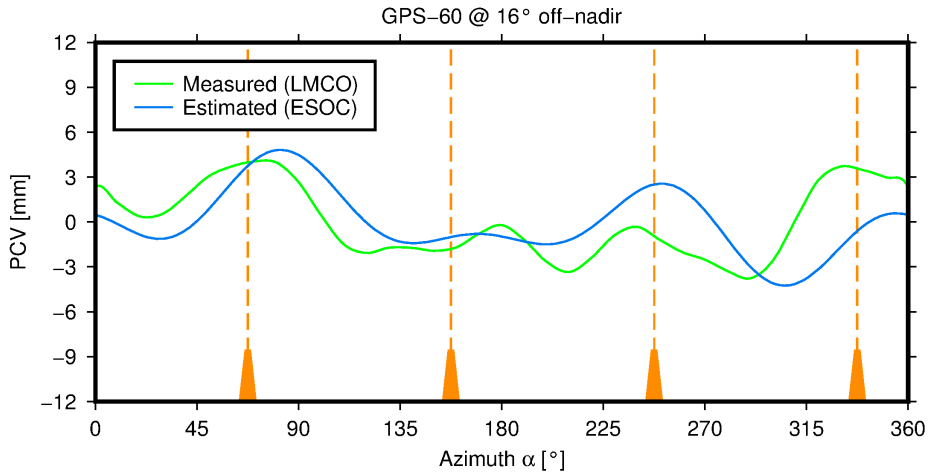


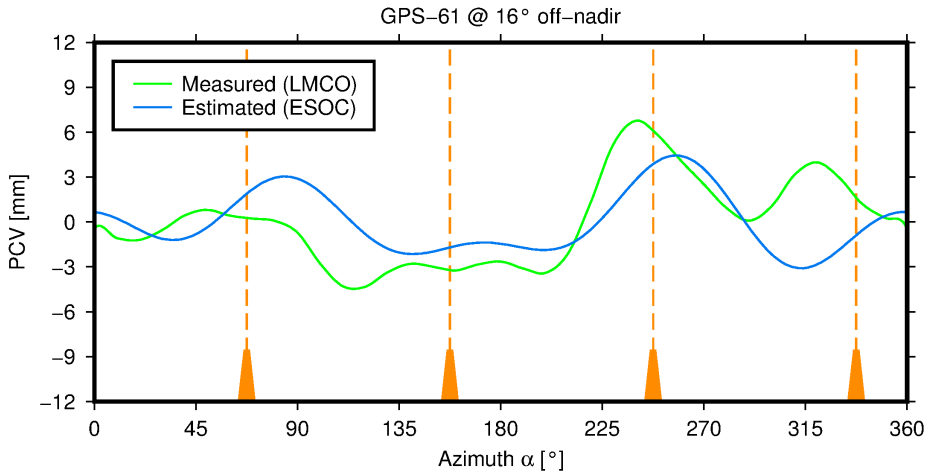


Estimated vs. Measured – Modernized Panel









Summary

Legacy Panel Measurements	Modernized Panel Measurements
• No azimuthal variations in L1; four-fold pattern in iono-free LC originates from L2 • Poor consistency; several mm differences among individual SVs • Good agreement with estimated PCVs except for η > 14°; non-azimuth-dependent parts match to within 1-2 mm • Similarity wrt estimated offsets; measured z-PCOs 0.3 m larger	• Good consistency; sub-mm differences among individual SVs for both L1 and L2 • Excellent agreement with ESOC PCVs, even beyond EoE; non-azimuth-dependent parts agree on sub-mm level • Similarity wrt estimated offsets; measured z-PCOs 1.0 m smaller

Conclusions

- Current approach of the IGS to calibrate GNSS satellite antennas in space yields accurate results
- Differences between estimated and measured PCVs beyond 14° boresight angle likely related to correlations between GPS and LEO antenna parameters
- Consider adopting the measured PCVs for next major update of the IGS phase center model ("igs14.atx")
- Clarification needed regarding use of NGA antenna z-offsets
  - Would pave way for GPS-based realization of the TRF scale
  - Use z-offset estimates otherwise

Backup

Estimated (ESOC) vs. Measured (LMCO)