Estimation of Satellite Antenna Phase Center Corrections for BeiDou

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Abstract

China's BeiDou Navigation Satellite System (BDS) currently has a total of 14 operational satellites in geostationary and non-geostationary orbit, offering positioning and navigation services to users in the Asia-Pacific region. In this work, we present early phase center corrections for the L-Band transmitter antenna arrays aboard the Inclined Geosynchronous (IGEO) and Medium Earth Orbiting (MEO) BeiDou spacecraft. More than one year of BeiDou triple-frequency (B1, B2, B3) measurement data, collected by 39 ground stations of the International GNSS Service's MGEX tracking network, is used to derive the satellites' antenna phase center offsets (PCOs) and variations (PCVs) for the ionosphere-free linear combinations B1-B2 and B1-B3, respectively. Processing is carried out in daily batches using the most recent version of ESOC's multi-GNSS analysis software, the Navigation Package for Earth Observing Satellites (NAPEOS). The parameterization of the PCVs is done in conventional IGS-style, that is, using piece-wise linear functions of the satellite nadir angle with 13 (MEO) and 9 (IGEO), respectively, linear segments. Applying the new PCO/PCV corrections to the BeiDou observables shows improved performance relative to the currently recommended standard offset values (x = 0.6 m, y = 0.0 m, z = 1.1 m). Initial comparisons of overlapping orbit solutions suggest that the orbit accuracy (3D RMS) of the MEO spacecraft is substantially improved by more than a third. The orbital component that benefits most from the advanced phase center modeling is the MEOs along-track component.

Background

It is well known nowadays that any kind of GNSS measurement refers to the electrical phase center of the transmitting antenna, which is neither a physical nor a stable point in space. The variation of the phase center location as a function of the direction of the outgoing signal for a specific frequency is what we call the phase center variation (PCV). The mean phase center is usually defined as the point for which the phase of the signal shows the smallest (in the sense of "least-squares") PCVs. The point of reference for describing the motion of a satellite, however, is the spacecraft center of mass (COM). The difference between the position of the mean phase center and the COM is what we typically call the satellite antenna phase center offset (PCO). The mean phase center and its variations must be precisely known so that we can tie the GNSS measurements consistently to the satellite's COM. Whereas a lot of effort has been put in by the International GNSS Service (IGS) throughout the last decade to create a consistent dataset of PCOs and PCVs ("igs08.atx") for all types of GPS and GLONASS spacecraft antennas, no such parameters have been made available for BeiDou so far. Preliminary offset values (x = 0.6 m, y = 0.0 m, z = 1.1 m) as recommended for use within the Multi-GNSS Experiment (MGEX) project are taken from satellite drawings and therefore can only give a rough estimate of where the "true" phase center is actually located. PCOs from the spacecraft manufacturer (x = 0.634 m, y = -0.003 m, z = 1.075 m) were recently disclosed by Lou et al. (2014) and are expected to be more precise. Experience with the GPS Block II/IIA antenna shows, however, that offsets from pre-launch calibrations are not necessarily compatible with the existing terrestrial reference frame (TRF). To preserve consistency, the IGS pursues the approach of estimating the radial offset components (z-PCOs) of the transmitter antennas and aligning them to the TRF scale.

Processing Strategy

- Combined multi-GNSS processing scheme with 62 GPS-only and 39 GPS/BDS stations to determine BDS transmitter antenna parameters; only Trimble NetR9 RX sites providing B3 (Fig. 1)
- Free estimation of x-PCOs and z-PCOs; mean station height (scale) aligned to IGS08/ITRF2008
- PCV estimation from nadir to 9° and 13°, respectively (Fig. 2)
- Rigorous combination of daily estimates on normal equation level

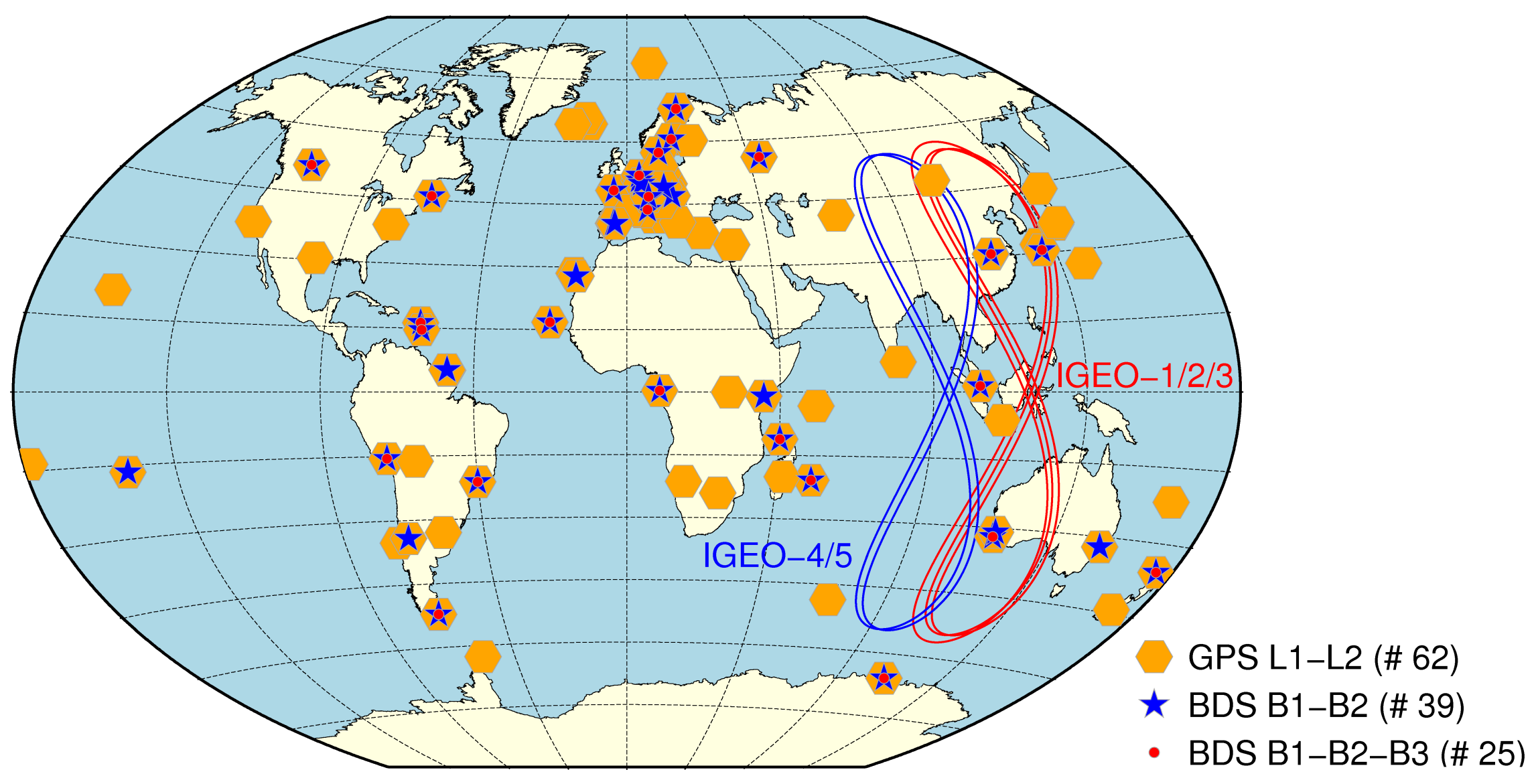

Fig. 1: Geographical distribution of tracking sites along with IGEO ground tracks.

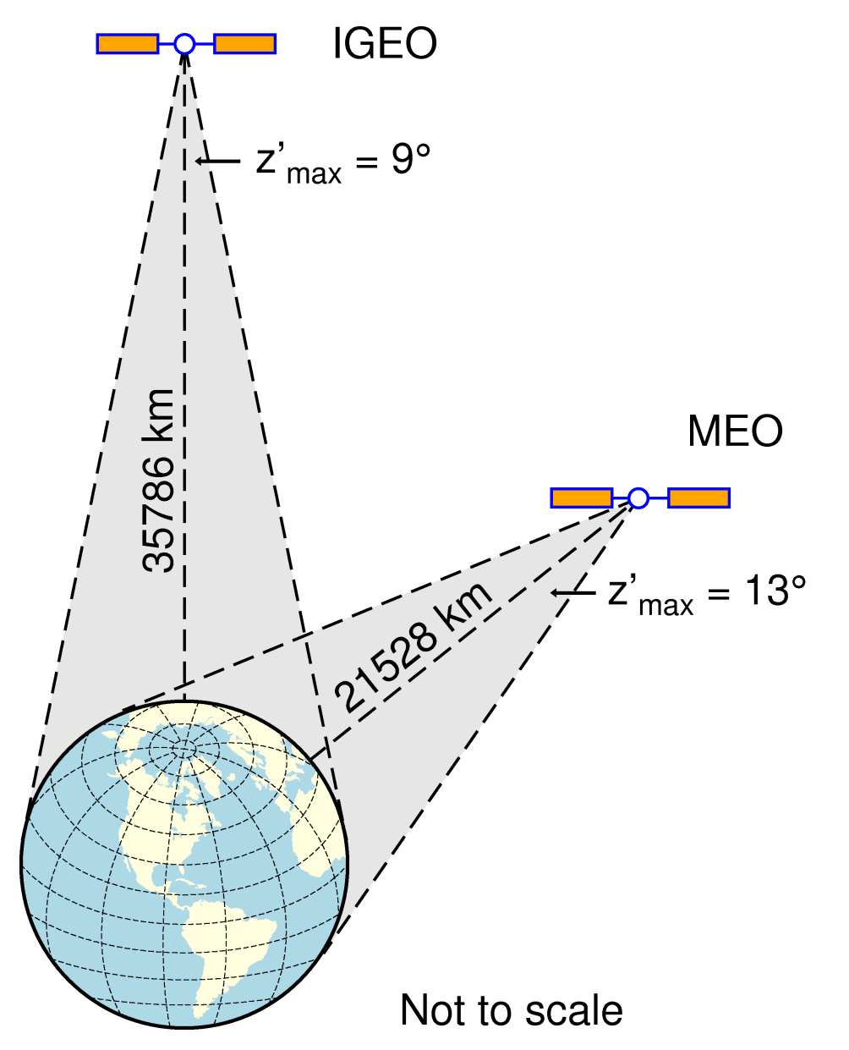

Fig. 2: Maximum nadir angle z'_{max}.

Number of stations	GPS-only: 62, GPS/BDS: 39
Number of satellites	GPS: 31, BDS: 9 (5 IGEOs, 4 MEOs)
Time interval	February 15, 2013 - May 31, 2014
Software	NAPEOS Version 3.8 (modified)
Data	Zero-difference GPS/BDS code and carrier phase observations
Sampling rate	5 minutes
Elevation cut-off	10º
Weighting	Elevation-dependent (weight $w = \cos^2 z$ with zenith angle z)
Ambiguity fixing	Only GPS (82 - 100% per day)
Inter-system biases	Estimated daily for each GPS/BDS receiver
Station coordinates	Weekly solution with no-net-rotation and not-net-scale condition
Orbits	24-hour orbital arcs; initial orbit positions and velocities, 3 constant plus 2 once-per-revolution radiation pressure parameters and 3 tightly constrained along-track parameters for each satellite estimated; Earth albedo and infrared radiation force model
Earth rotation	Estimation of daily pole coordinates and drifts, UT1 and LOD
Ionospheric refraction	First-order effect eliminated by forming ionosphere-free linear combination; higher-order effects not corrected
Tropospheric refraction	A priori ZPDs computed with formula of Saastamoinen using GPT model; ZPDs mapped into slant delays using hydrostatic GMF; ZPDs at 2-hour intervals estimated as continuous piece-wise linear functions using wet GMF; horizontal gradients estimated with 24-hour resolution
TX antenna PCO	GPS: Fixed to igs08_1788.atx values, BDS: Constellation-specific x-offsets and satellite-specific z-offsets estimated, y-offsets fixed to zero
TX antenna PCV	GPS: Fixed to igs08_1788.atx values, BDS: Satellite-specific, nadir-dependent estimation; z'_{max} = 13º for MEOs, z'_{max} = 9º for IGEOs; piece-wise linear modeling with 1º-resolution; PCV(z' = 0º) not set up to prevent NEQ system from becoming singular; fixed to block-specific PCVs (= mean of B1-B2 and B1-B3 PCVs), when estimating PCOs
RX antenna PCO/PCV	Fixed to igs08_1788.atx values

Tab. 1: Summary of processing strategy.

Estimated x-PCOs and z-PCOs

- Estimated x-PCOs almost 0.1 m below manufacturer value; z-PCOs clearly exceed manufacturer value of 1.075 m (Tab. 2)
- Observation geometry of IGEO z-PCOs much worse compared to MEOs (see Fig. 2); manifests itself in five times larger "formal" errors ($\sigma_{z\text{-PCO, MEO}} \approx \pm 1$ cm, $\sigma_{z\text{-PCO, IGEO}} \approx \pm 5$ cm)

	x-PCO	z-PCO								
		IGEO-1	IGEO-2	IGEO-3	IGEO-4	IGEO-5	MEO-3	MEO-4	MEO-5	MEO-6
B1-B2	549.0	3049.0	3236.7	3842.6	3973.6	3882.1	2069.5	2313.5	2201.8	2311.7
B1-B3	545.0	3509.5	4121.2	4710.2	5029.8	4935.1	2214.2	2401.9	2336.4	2450.2

Tab. 2: Estimated constellation-specific x-PCOs and satellite-specific z-PCOs for B1-B2 and B1-B3 in mm.

Estimated PCVs

- Satellite-specific PCVs range from -6 to +3 mm (IGEOs) and from -5 to +4 mm (MEOs) (Fig. 3)
- Differences of 1-3 mm among the block are reasonable given that formal errors are on same level
- Differences between block-specific PCVs for B1-B2 and B1-B3 below 1 mm; values can be averaged without significant loss of accuracy (Tab. 3)
- Estimates for IGEO-4/5 less accurate due to lack of data coverage; formal errors three times larger than for other IGEOs ($\sigma_{\text{PCV, IGEO-1/2/3}} \approx \pm 1$ mm, $\sigma_{\text{PCV, IGEO-4/5}} \approx \pm 3$ mm)

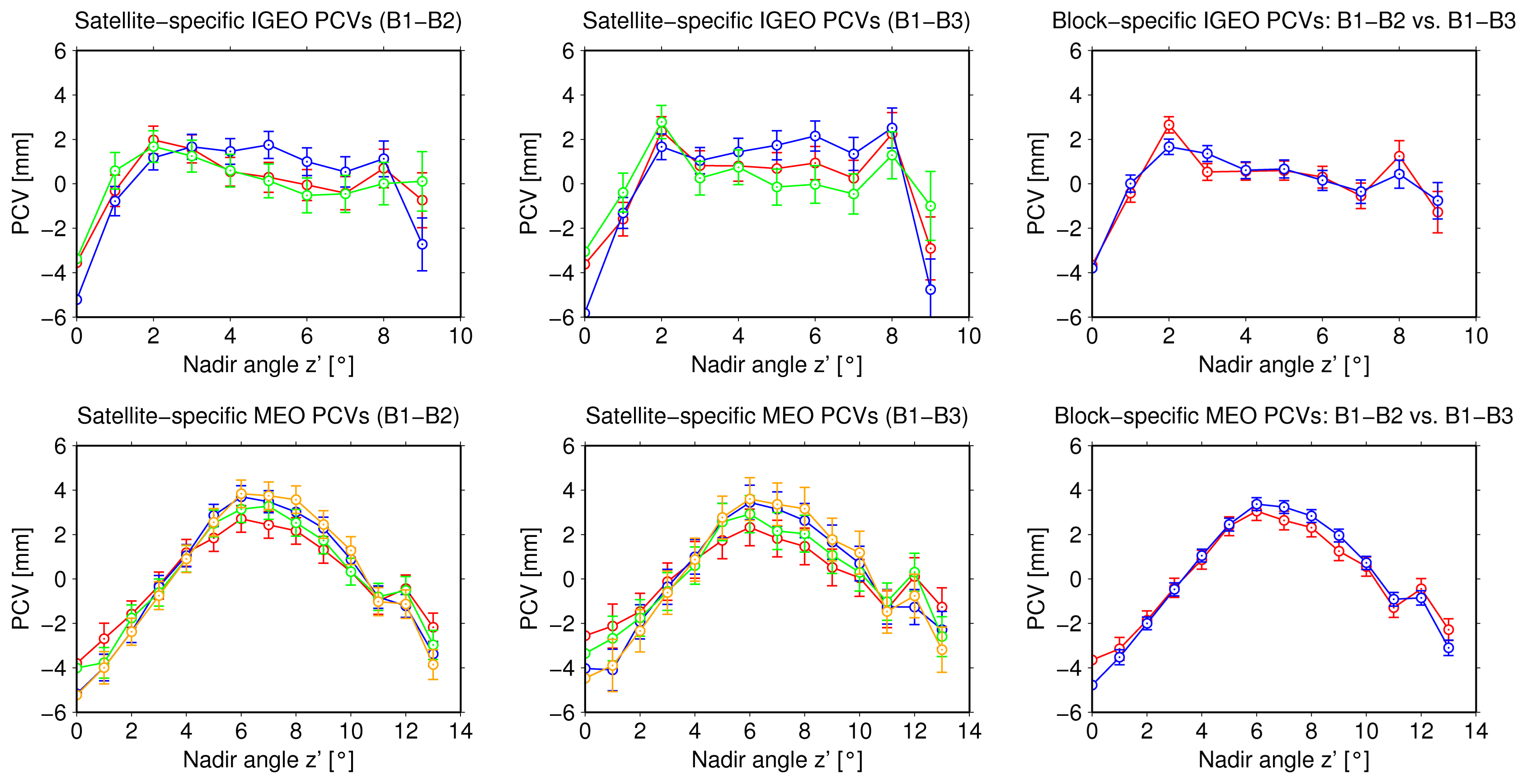

Fig. 3: Satellite- and block-specific IGEO (top) and MEO (bottom) PCV estimates together with error bars representing the formal errors from the variance-covariance matrix. Results for IGEO-4/5 are not shown for reasons of clarity.

	0°	1°	2°	3°	4°	5°	6°	7°	8°	9°	10°	11°	12°	13°
IGEO	-3.73	-0.21	2.16	0.95	0.59	0.63	0.23	-0.45	0.84	-1.02	-	-	-	-
MEO	-4.21	-3.33	-1.93	-0.43	0.96	2.41	3.21	2.94	2.57	1.60	0.64	-1.10	-0.64	-2.69

Tab. 3: Un-weighted mean values of block-specific B1-B2 and B1-B3 PCVs for IGEO and MEO in mm.

Impact on BeiDou POD performance

- Reprocessing of 2014 data using the following transmitter antenna parameters for BeiDou:
  a) Standard PCOs from MGEX and no PCVs
  b) x- and z-PCOs from Tab. 2, y-PCOs set to zero and PCVs from Tab. 3
- Evaluation on the basis of day-to-day orbit overlaps and post-fit carrier phase residuals
- 3D overlap RMS for MEOs goes down by 39%; greatest improvement in along-track (Fig. 4-5)
- Residual RMS reduces from 10.30 to 10.14 mm (B1-B2) and from 10.52 to 10.35 mm (B1-B3)
- Non-significant improvement in IGEO overlaps and residuals

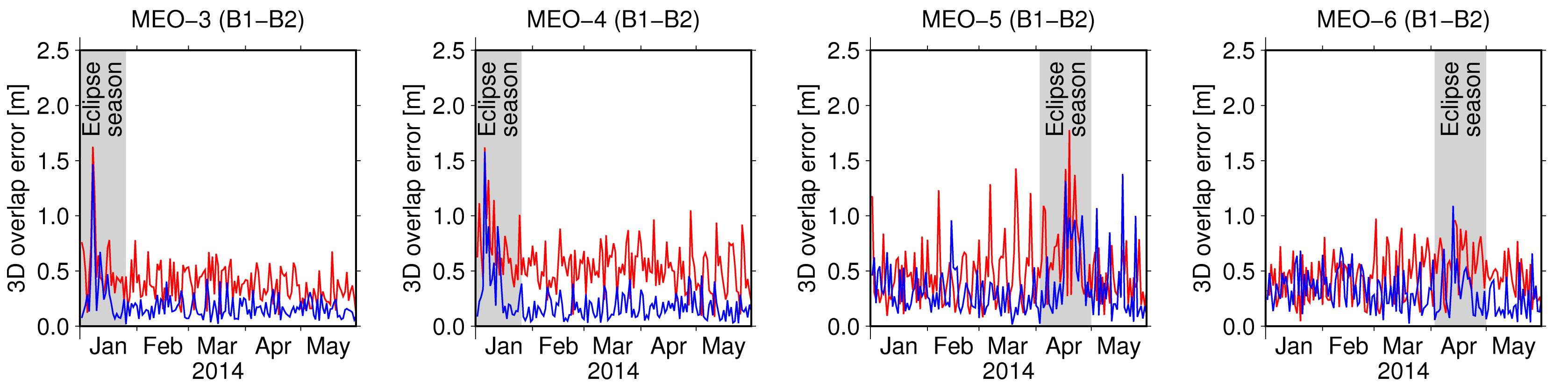

Fig. 4: Day-to-day orbit overlap differences (3D) computed for each MEO spacecraft. The standard PCO-only solution (a) is shown in *red*, the advanced PCV-based solution (b) in *blue*.

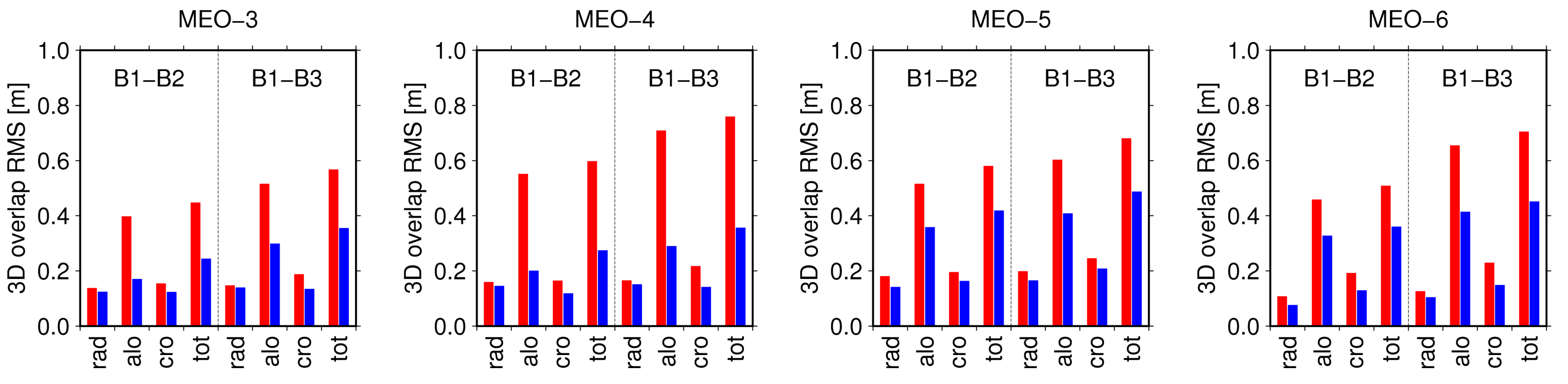

Fig. 5: RMS of orbit overlap differences (3D) computed for each MEO spacecraft and linear combination. The standard PCO-only solution (a) is shown in *red*, the advanced PCV-based solution (b) in *blue*.

References

Lou Y, Liu Y, Shi C, Yao X, Zheng F (2014): Precise orbit determination of BeiDou constellation based on BETS and MGEX network. Sci Rep 4:4692, DOI:10.1038/srep04692.

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