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The BeiDou Attitude Model for Continuous Yawing MEO and IGSO Spacecraft

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China's second-generation BeiDou medium Earth orbit (MEO) and inclined geosynchronous orbit (IGSO) satellites are known to switch from sinusoidal yaw steering (YS) to yaw-fixed orbit normal mode as soon as the acute angle between the solar vector and the orbit plane (beta prime) becomes smaller than approximately 4 degrees. Using reverse point positioning (RPP), we demonstrate in this presentation that three BeiDou-2 spacecraft, one MEO and two IGSOs, do not or no longer obey this rule. The names of the vehicles stepping out of line are BeiDou M6 (C015), IGSO1 (C005), and IGSO6 (C017). Rather than holding their yaw attitude fixed when the Sun is close to the orbital plane, these satellites keep on rotating or yawing about their Earth-pointing z-axes, similar to a Galileo spacecraft. Before the nominal theoretical yaw rate is about to exceed the physical yaw rate limits in the vicinity of orbit noon and midnight, the satellites transition from standard YS to smoothed YS mode. During smoothed YS, the yaw motion is constrained by a maximum yaw rate of 0.16 and 0.09 degree/sec for MEOs and IGSOs, respectively. Basing on these observations, we describe the development and evaluation of an attitude model for the group of continuous yawing BeiDou satellites. The model was developed by empirically fitting a special inverse tangent function to a series of RPP yaw angle estimates, and then built into NAPEOS, the European Space Operation Centre's (ESOC's) state-of-the-art software package for high-precision orbit determination. The model is straightforward to implement and guarantees seamless transition from one attitude regime to the other, that is, from standard YS to smoothed YS and vice versa. We demonstrate that using the new model in our current BeiDou precise orbit determination approach proves to be significantly more accurate than the standard attitude model for BeiDou MEO/IGSO satellites. Our figures of merits are satellite laser ranging residuals, satellite clock residuals, day-to-day orbit overlap differences, and yaw angle estimates. The model removes the dependence of these metrics on the beta prime angle and fits the RPP estimates with approximately 3 degrees of accuracy (1-sigma). The improvements seen can be attributed to a more accurate modeling of the solar radiation pressure forces acting on the spacecraft, the antenna phase center eccentricity, the laser retro-reflector eccentricity, and the antenna phase wind-up correction. The new BeiDou attitude model is among a class of high-fidelity spacecraft models that ESOC is using operationally to provide science-grade orbit and clock solutions for all five GNSS satellite constellations (http://navigation-office.esa.int/products/gnss-products). First RPP results for the five so-called BeiDou-3e experimental satellites launched in 2015 and 2016 suggest that it could also be adopted as the standard yaw model for the third generation of BeiDou MEO and IGSO spacecraft.