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A new yaw attitude algorithm for BDS MEO and IGSOs

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Introduction

In the present, the GNSS body-fixed reference frame definition is followed according to the International GNSS Service (IGS) conventions [3] which are based on the spacecraft body frame of the GPS Block II/IIA satellites. This definition is also compatible with the GPS Block IIF satellites while in the case of the GPS Block IIR the spacecraft frame is designed with a reverse direction (away from the sun) in the X axis of the body-fixed frame.

The situation is similar to the GPS IIA/IIF for the BDS satellites where +X axis points towards the Sun, +Z axis points to the SV's radius vector towards the Earth's centre in the antenna boresight direction, and the +Y axis completes the right handed system while it coincides with the rotation axis of the solar panels.

The yaw angle is the critical parameter which defines the GNSS attitude. Contrary to GPS and GLONASS, BeiDou Inclined Geosynchronous Orbit (IGSO) and Mean Earth Orbit (MEO) satellites do not experience noon-turn and midnight-turn manoeuvres [6], with the exception of the newly launched IGSO6 or C13, formerly C15 (F. Dilssner and P. Steigenberger personal communication).

The yaw regimes of the BDS MEO and IGSOs

Concerning the yaw motion, the BDS satellites are subject to two distinct attitude regimes which depend from the β beta-prime angle (angle between the earth-sun direction and the orbit plane): the yaw-fixed or **orbit normal** (**ON**) mode and the **yaw-steering** (**YS**) or nominal mode.

The nominal yaw angle will be computed by the following equation [7] :

$$\psi = ATAN2(-\tan\beta, \sin\mu) \qquad (1)$$

where, β is the angle between the Sun position vector and the satellite orbital plane and μ is the satellites angle on the orbit plane (ie. orbital angle).

The solar panels are generally oriented as well as possible perpendicular to the sun-direction when the switch from YS regime to ON and vice versa takes place. As a general rule the switch takes place when the β beta-prime angle is closest to 4 degrees and when the satellite's orbital angle μ is closest to 90 degrees [2]. For the BDS GEO satellite, the ON mode is continuously maintained and the yaw angle is zero [5]. As such, in the following, we attempt to build up a new epoch-wise method which detects the attitude modes currently operated and applies the necessary switch that is going to take place : YS to ON or ON to YS.

The new algorithm

So far in the existing literature, there have been two basic assumptions on the MEO/IGSO satellites attitude switch points :

1. The BDS attitude switch YS to ON or ON to YS is taking place at β = 4°
2. As soon as the satellite switches from YS on ON mode, the yaw angle becomes zero [3].

However, there are two important issues with those assumptions :

1. The value of β at the switch point may vary due to some errors in estimating β, e.g., orbit errors from the on-board attitude determination and control system (ADCS).
2. The yaw angle at the switch points is mainly equal to β, since the orbit angle μ will be equal or very close to 90 degrees. Therefore, the sudden change from yaw = β to yaw = 0 would translate to a sudden ***rump-up*** *or* ***rump-down jump*** from the on-board controller.

In our algorithm we introduce two basic principles in order to tackle the above issues :

1. The value of the β threshold for the yaw model to switch will *depend on the broadcasted ephemeris error*.
2. When there is a switch from YS to ON and ON to YS, the yaw angle *does not become zero*, but instead, is equal to β at the point of switch, and all along the ON to YS transitions. Therefore the yaw is following a *β°-fixed law* instead of the *0°-fixed law*.

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Results

For our analyses and computations of the beta and yaw angles we used 3 years (2014-2016) of sp3 BDS orbits, as well as, the DE430 planetary ephemeris.

Tables 1 & 2 below show information of *β, μ* and *ψ* at the switch points for both the IGSO and MEO satellites over 2014-2016. The values in blue are the verified ones from reverse kinematic precise point positioning (PPP) solutions from [2] and [4].

satellite	DOY	β_t°	μ_t°	ψ_t°
C06 from [2] Fig.2a	**096, 2014**	**-3.70**	**89.91**	**3.70**
	093, 2015	-3.89	90.15	3.89
	090, 2016	-4.09	90.11	4.09
C07	023, 2014	3.67	89.86	-3.67
	018, 2015	3.77	89.83	-3.77
	013, 2016	3.96	90.18	-3.96
C08	355, 2015	-3.86	90.14	3.85
	352, 2016	-3.49	89.92	3.49
C09	283, 2014	3.48	89.88	-3.48
	280, 2015	3.72	89.91	-3.72
	277, 2016	3.97	90.09	-3.97
C10	203, 2014	-4.00	89.80	4.00
	198, 2015	-3.97	90.09	3.97
	193, 2016	-4.02	89.90	4.02
C11 from [4] Fig.8c1	**361, 2014**	**-4.05**	**90.17**	**4.05**
	350, 2015	-4.01	89.85	4.01
	339, 2016	-3.81	89.85	3.81
C12 from [4] Fig.8d1	**361, 2014**	**-3.75**	**90.15**	**3.75**
	350, 2015	-4.01	89.85	4.01
	339, 2016	-3.81	89.85	3.81
C14 from [2] Fig.2c	**103, 2014**	**-3.58**	**90.15**	**3.58**
	093, 2015	-3.79	90.18	3.79
	083, 2016	-4.01	89.90	4.01

Table 1 : YS to ON transitions for IGSO (C06-C10) and MEO (C11-C14)

satellite	DOY	β_t°	μ_t°	ψ_t°
C06 from [2] Fig.2b	**104, 2014**	**3.96**	**89.90**	**-3.96**
	101, 2015	4.76	90.11	-4.76
	099, 2016	4.60	90.12	-4.6
C07	036, 2014	-4.35	89.86	4.35
	031, 2015	-4.45	89.80	4.45
	026, 2016	-4.45	89.85	4.45
C08	006, 2014	4.27	89.82	-4.27
	003, 2015	4.42	90.13	-4.42
	365, 2015	4.62	89.84	-4.62
C09	291, 2014	-4.26	90.11	4.26
	288, 2015	-4.02	90.17	4.02
	286, 2016	-4.74	89.83	4.74
C10	217, 2014	4.23	89.86	-4.23
	212, 2015	4.48	89.83	-4.48
	206, 2016	4.00	90.15	-4.00
C11	015, 2014	4.27	90.23	-4.27
from [4] Fig.8c2	**005, 2015**	**3.95**	**89.83**	**-3.95**
	360, 2015	4.00	90.21	-4.00
C12	015, 2014	4.05	90.19	-4.05
from [4] Fig.8d2	**005, 2015**	**4.22**	**89.81**	**-4.22**
	360, 2015	4.28	90.14	-4.28
C14 from [2] Fig.2d	**111, 2014**	**4.25**	**89.88**	**-4.25**
	101, 2015	4.15	90.10	-4.15
	091, 2016	4.01	90.11	-4.01

Table 2 : ON to YS transitions for IGSO (C06-C10) and MEO (C11-C14)

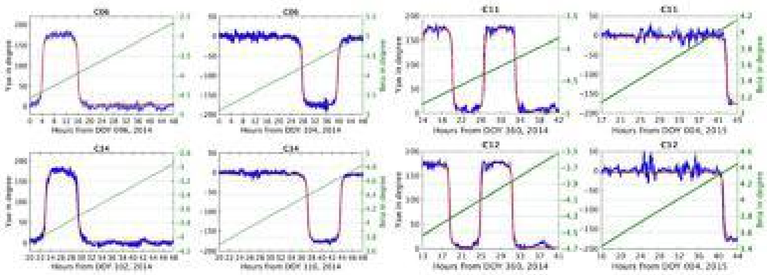

Figure 1 : (Left) C06 and C14 estimated (blue) from Guo et al. (2016) versus our model's (red) yaw angles (ψ –angle), (Right) C11 and C12 estimated (blue) from Dai et al. (2015) versus our model's (red) yaw angle (ψ –angle).

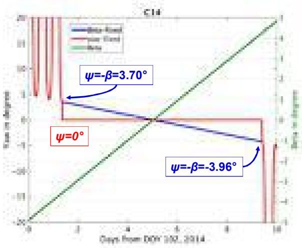

Figure 2 : β°-fixed law instead of the 0°-fixed law in ON mode

Conclusions

- We have developed a model that handles efficiently the transition phases and automatically detects the switch points from YS to ON and ON to YS.
- When in ON mode, it makes more sense for the ADCS system to follow a β°-fixed law for its yaw angle than a 0°-fixed law. If a 0°-fixed law is used in reality, then the ADCS should preform sudden rump-up and rump-down "jumps" to 0° yaw angle.

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