**GPS/GLONASS Eclipsing - Fortran subroutine *eclips.f***

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**Introduction.**
In 2008, an eclipsing model (Kouba 2008), based on a simplified approach of Bar-Sever (1996), has been implemented in a FORTRAN subroutine *eclips.f* for the GPS Block IIA and IIR satellites. Namely, the Block IIA and IIR satellite behave the same during the eclipsing noon (when closest to the Sun) making nearly 180 degree "yaw" turns (around the body-z axis, which points to the Earth's center). When the nominal yaw-turn rate exceeds the respective maximum Block IIA and IIR hardware rates of 0.10 - 0.13 and 0.2 deg/sec, the GPS satellites start turning with the maximum hardware rate until the yaw-angle "catches" up with the nominal yaw-rate (see Fig. 1). This may take up to 30 min for the slow Block IIA satellites. However, the shadow crossing behaviors of Block IIR and IIA satellites ares completely different. The newer Block IIR satellites maintain the nominal yaw-orientation during a shadow crossing and only perform a turn, analogous to the above noon-turn maneuver when they cannot keep up with the nominal orientation (see Fig. 1). A Block IIA satellite, upon a shadow entry, starts turning with a maximum hardware rate (Fig. 2). Furthermore, upon the shadow exit, the Block IIA satellites try to recover in a largely unknown manner, this is why the first half an hour after shadow exit, the Block IIA satellite orientation is largely uncertain and the corresponding data should be deleted (Bar-Sever 1996). For more details on the Block IIA/IIR eclipsing, see Kouba (2008).

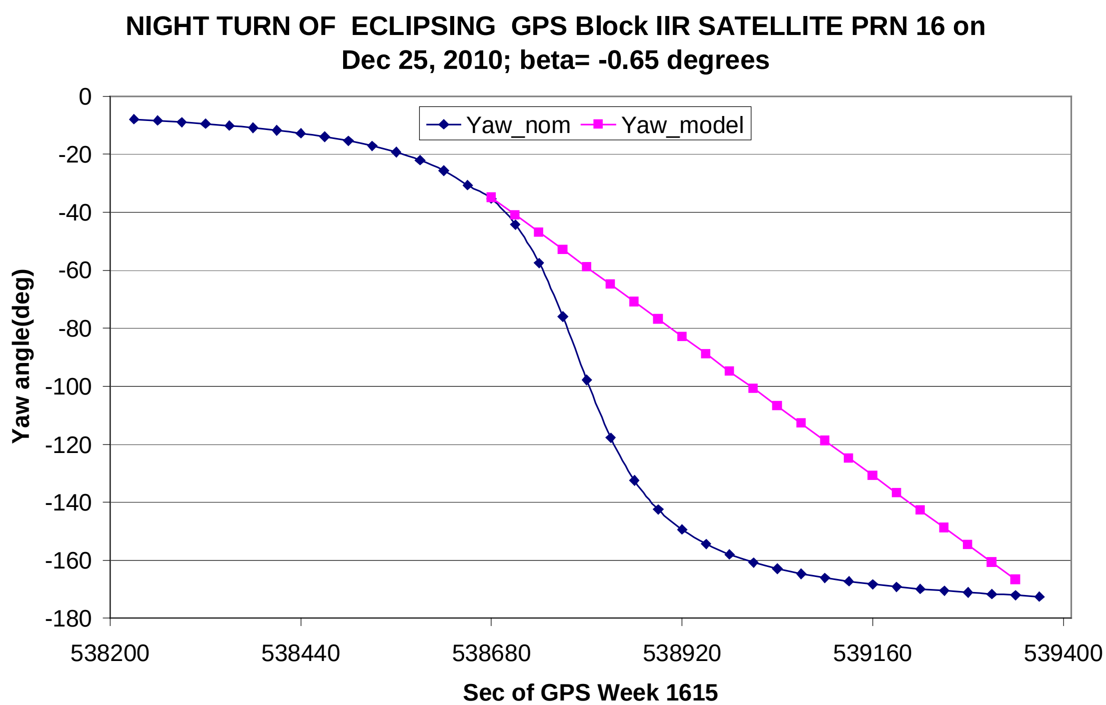


**Figure 1**. Yaw-attitude angles (the angle between the body-x and the velocity direction) during a night-turn maneuver (*Yaw_model*) of the Block IIR GPS PRN 16, on Dec. 25, 2010 (seen at the IGS station *conz*). Also shown are the nominal yaw-attitude angles (*Yaw_nom*). Note that noon-turn maneuvers of all the GPS (Block IIA, IIR (and IIF)) satellites are completely analogous, i.e., the maximum yaw turning starts only after they are unable to keep up with the nominal yaw-orientation.

In May 2010, the first of the new generation GPS satellites Block IIF (PRN25/SVN62) has been added to the GPS constellation of Block IIA and IIR satellites. The new satellite, apart from having a more stable clock, transmitting two more signals C2 (L2C) and L5, also has a different phase center variations (PCV) and behaves quite differently from the Block IIA and IIR satellite during eclipsing (Dilssner 2010). While the Block IIF "noon" turns are the same as for all the GPS satellites, the night turns (shadow crossings) are different for each GPS Block type.

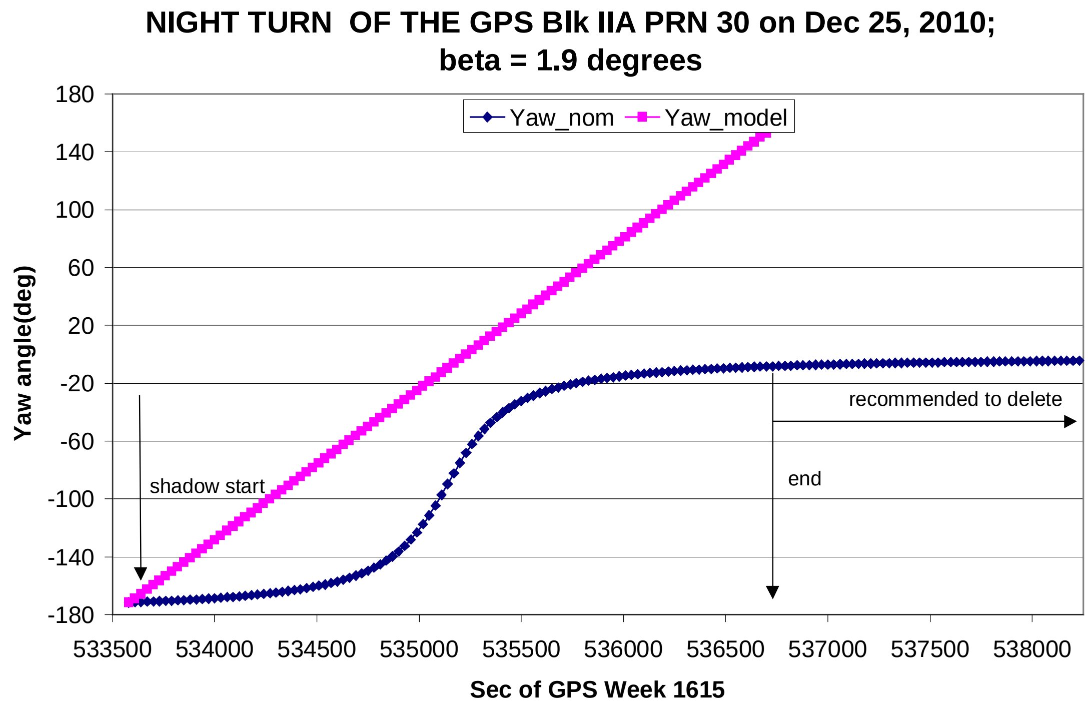


**Figure 2**. A night-turn maneuver (*Yaw_model*) of the Block IIA GPS PRN 30, on Dec. 25, 2010 (seen at the IGS station *conz*). Also shown are the nominal yaw-attitude angles (*Yaw_nom*). Note that after a shadow entry, a Block IIA GPS satellite starts yawing with the maximum yaw-rate. After the shadow exit, the Block IIA GPS satellite yaw-orientation is uncertain for up to 30 minutes, so this data has to be deleted.

The new Block IIF satellite behaves the same as the Block IIR for shallow night eclipsing (the angle $|\beta|$ > 8 degrees (the Sun elevation angle with respect to the orbital plane)). However, when $|\beta| \leq 8$ degrees, after the shadow entry, the Block IIF satellite starts turning in the required direction with a constant rate of 0.06 deg,/sec until the shadow exit, then it tries to recover the nominal orientation. However, for noon turns, the Block IIF satellite uses the maximum hardware yaw rate of 0.11 deg/sec (see Dilssner 2010 for more details). Note that a proper modeling of eclipsing yaw orientations is even more important/crucial for the Block IIF than it is for IIA, due to a large body-x offset of 0.394 m (the Block IIA offset is 0.279 m).

**GPS Block IIF Eclipsing Implementation**

In order to distinguish the new Block IIF satellite, the new block flag of 6 has been introduced for GPS in the *eclips.f* subroutine (the flags are IIA=3. IIR= 4, 5), which overlaps/collides with the GLONASS block flags, which may also start with the Block flag of 6. Consequently, the new version of the *eclips.f* subroutine, is using the satellite PRN numbers (GPS ≤ 32 and GLONASS PRN > 32 (I.e. GLONASS R1=33 etc.)) to uniquely identify GLONASS and/or GPS.

Furthermore, as described above, the Block IIF employs a unique shadow-crossing scheme. Since the Block IIF also has the IIA body coordinate frame (with no Block IIR body-x coordinate axis reversals) and the shadow crossing is similar to the Block IIA one, the Block IIF shadow modeling has been grouped with the Block IIA one. The only difference is that the Block IIF rotates with the constant rate of 0.06 deg,/sec in the direction of the nominal night turning. When $|\beta| < 4$ degrees, this scheme "overshoots" the nominal yaw orientation at the shadow exit, the difference can reach up to 20 degrees for $\beta \simeq 0$ degrees. This is also apparent in shadow yaw angle solutions shown in Fig. 7 of Dilssner (2010). This is why a post shadow recovery maneuver had to be implemented for the Block IIF (Fig. 3) and for completeness, also for the Block IIA (Fig. 4), even though this data interval should not be used, see below). So, both the Block IIF and IIA recoveries share identical source codes in *eclips.f*.

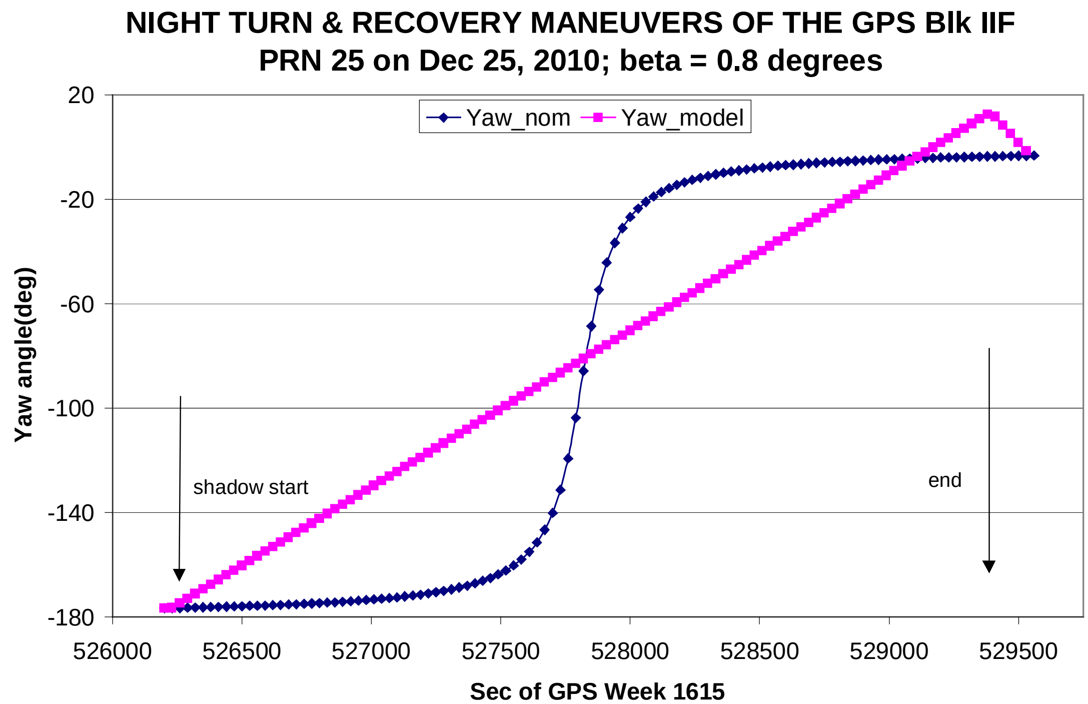


**Figure 3**. The GPS Block IIF night-turn maneuver (seen at the IGS station *wtzr*), implemented according to Dilssner (2010): upon a shadow entry, the satellite starts turning with the 0.06 deg/sec yaw rate until the shadow exit (*Yaw_model*), after that it tries to recover to the nominal yaw orientation (*Yaw-nom*) with the maximum hardware rate of 0.11 deg./sec.

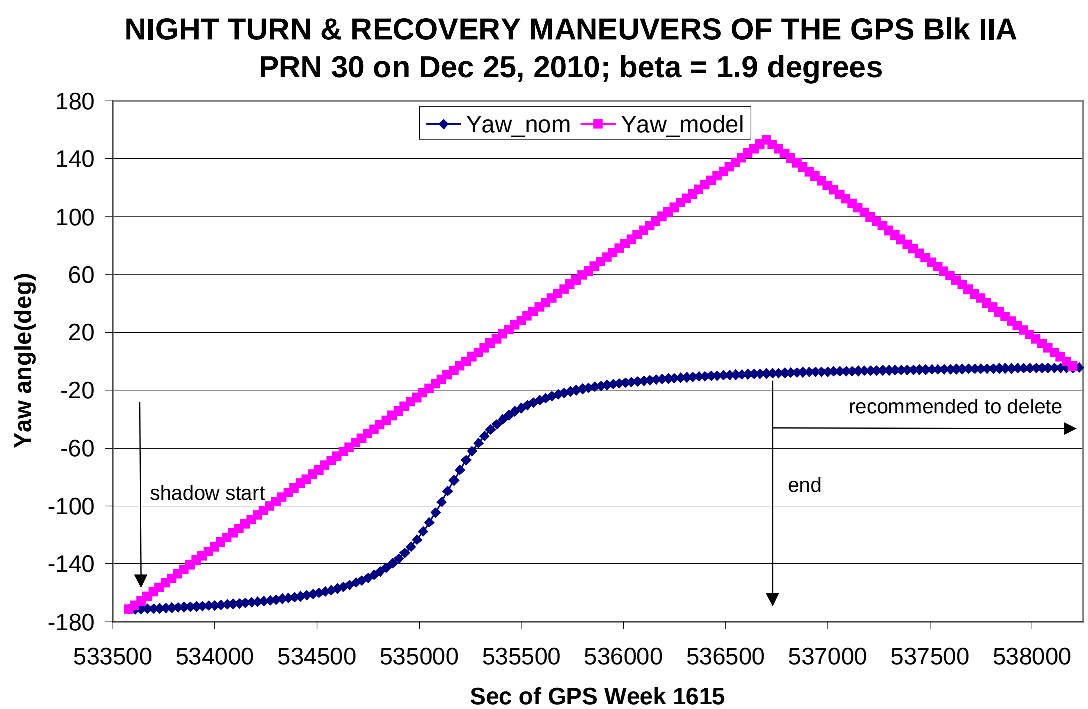


**Figure 4.** The original shadow crossing for Block IIA (Fig. 2), but with the newly implemented shadow exit recovery, (using the same post-shadow recovery logic/source codes as for the Block IIF)

No modifications was necessary for Block IIF noon-turn maneuvers and night turns when $|\beta|> 8$ deg., since they are the same for all the GPS Block types and the Block IIR, respectively. However, when $|\beta| \leq 8$ deg., the Block IIF night-turn maneuver is unique, though similar to the Block IIA one. Namely, instead of turning always in the positive direction with the maximum hardware rate, the Block IIF satellite is turning in the nominal night-turn direction, but with a lower constant rate of 0.06 deg./sec. Both the Block IIF and IIA satellites then try recover using the respective maximum yaw rate after a shadow exit, which may take only a few minutes for the Block IIF satellite (see e.g., Fig. 3) and up to a half an hour for the Block IIA ones (Fig. 4). Unlike for the Block IIF, the Block IIA misorientation after a shadow exit could be large, even close to 180 degrees, then it is not certain which way the satellite will try to recover. For various reasons, Block IIA yaw orientations at shadow exits may be in error up to 10 degrees and more. So, even with the new recovery scheme, still it is not recommended to use the data from the Block IIA post shadow recovery interval (and in particular when the shadow exit misorientation is near 180 degrees). So, it is recommended that only the flagged Block IIA post-shadow recovery interval is excluded (i.e. when the data epoch is greater than the shadow exit time and the variable *IECLIPS=1* is returned). This, in most cases, is much shorter than the constant 30-min recovery period, suggested previously by Bar-Sever (1996) and Kouba (2008). For example, when a Block IIA happens to be close to the nominal orientation at the shadow exit, requiring only a few minutes to reach the nominal orientation. Then only a few minutes of data need to be excluded (i.e. when are flagged with *IECLIPS=1*), rather than 30 min of data excluded before.

**GLONASS Eclipsing**

In 2008, no GLONASS specific eclipsing model has been implemented in *eclips.f* and none was needed, since at that time all the GLONASS satellites were typically switched off during their eclipsing periods. However, the new GLONASS M-series satellites (currently 24) now have replaced the old satellites. The M-series satellites operate continuously, even during the eclipsing periods. A proper GLONASS eclipsing is even more critical than for the GPS Block IIA/IIF satellites, due to the large GLONASS satellite body-x offset of –545 mm.

There was not any information available about GLONASS eclipsing until recently, when Dilssner et al (2010) has studied the yaw-attitude behavior of GLONASS-M satellites during shadow crossing and eclipsing noon-turns. He has used a “reverse PPP” approach, where the GLONASS antenna offsets and attitudes are determined from fixed orbits and clocks of non-eclipsing satellites, which is analogous to a standard PPP. Based on these analyses, Dilssner et al (2010) has also developed a precise GLONASS eclipsing model.

Unlike GPS satellites, during noon-turns, the GLONASS-M satellites start turning with the maximum yaw-rate of 0.25 deg./sec (the same for all the GLONASS satellites) well before the nominal yaw-rate exceeds the maximum hardware rate. Furthermore, the hardware yaw-rate turning period is symmetric around the eclipsing noon (Fig. 5) and it depends on the $\beta$ angle. The hardware yaw-rate turning period can last up to 12 min. for $\beta = 0$ deg. and it is about 0 min when $|\beta|= 2.03$ deg. For $|\beta|> 2.03$ deg. there is no need for noon-turn maneuvers, as the hardware yaw-rate can keep up with the nominal yaw-rates (see below). This GLONASS noon turning is quite efficient, since in most cases, except for when $\beta \simeq 0$, this noon-turn maneuver approximates well the nominal yaw-orientation, much better than an asymmetric GPS noon-turn maneuver does (compare Fig. 5 and Fig. 1). The GLONASS shadow crossing is also quite different from the GPS one, GLONASS M-series satellites start turning with the maximum (hardware) yaw-rate immediately upon a shadow entry and stop rotating when the shadow exit yaw-orientation is reached, which always happens well before shadow exits. From there on, until reaching the shadow exit, the constant yaw-orientation is maintained (see Fig. 6). Note that a GLONASS satellite is shadow eclipsing when $|\beta|< 14.20$ deg. and also note that Dilssner et al (2010) has chosen the Block IIA GPS body x, y - coordinate axis convention also for the GLONASS eclipsing model (i.e., no Block IIR x-coordinate axis reversal).

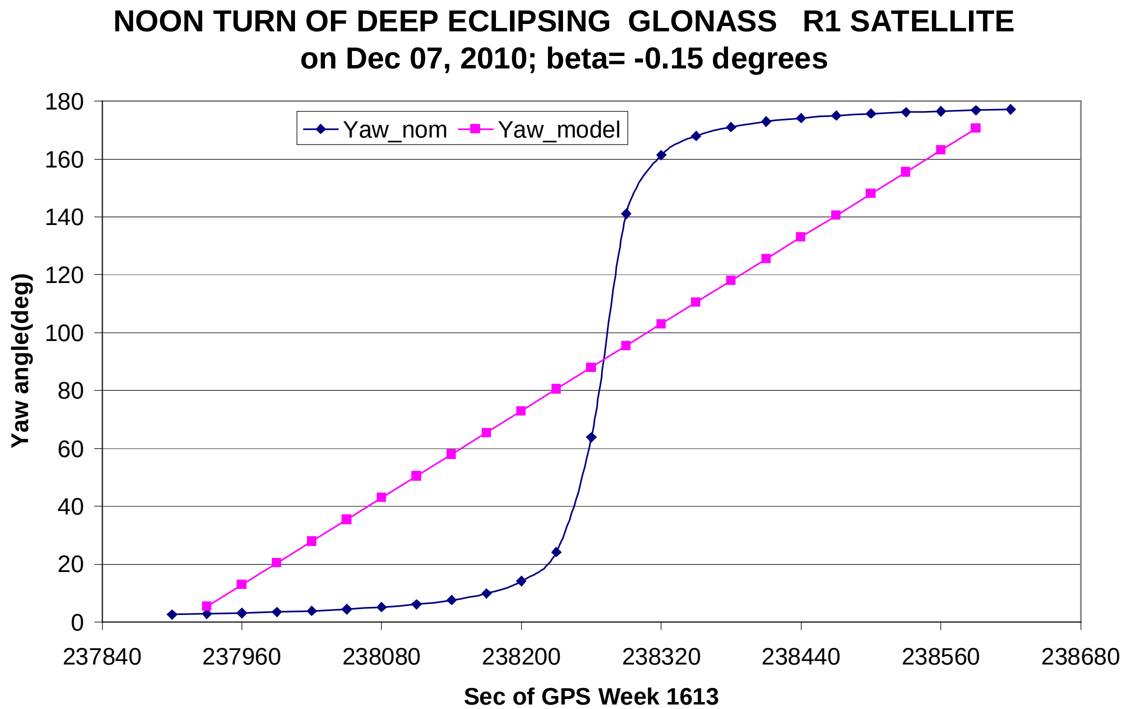


**Figure 5**. A noon-turn maneuver (*Yaw_model*) of the GLONASS-M R1 satellite, on Dec. 07, 2010 (seen at the IGS station *conz*). Also shown are the nominal yaw-attitude angles (*Yaw_nom*). The maximum yaw-turning period is symmetric and depends on the $\beta$ angle.

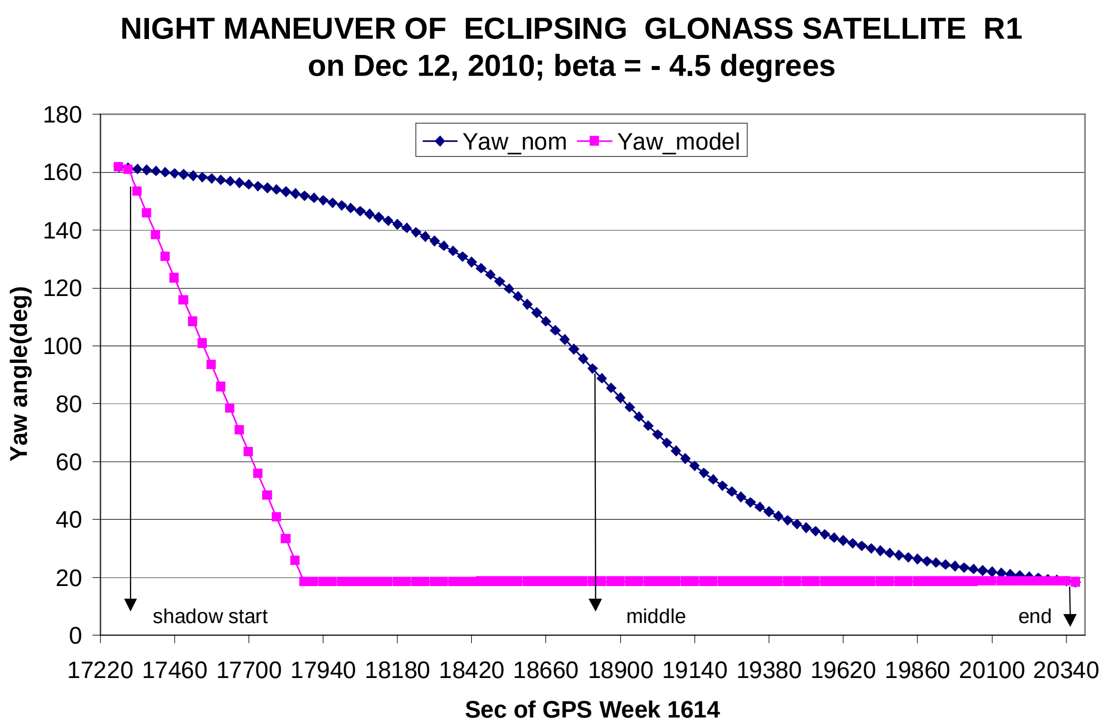


**Figure 6**. A night-turn maneuver (*Yaw_model*) of the GLONASS-M R1, on Dec. 12, 2010 (seen at the IGS station *conz*). Also shown are the nominal yaw-attitude angles (*Yaw_nom*). Note that after a shadow entry, all GLONASS-M satellites start yawing with the maximum (hardware) yaw-rate, until the shadow exit yaw orientation is reached, after that the shadow exit yaw-orientation is maintain until the shadow exit when the nominal yaw-orientation is then resumed.

**GLONASS Eclipsing Implementation**

The implementation of the GLONASS *shadow crossing model* (Dilssner et al (2010), see also Fig. 6) in *eclips.f* is fairly straightforward, since the times $t_s$ and $t_e$ of a shadow entry and exit are readily available and computed here for all the shadow crossing satellites (see Kouba 2008 for more details). For GLONASS satellites it is based on the Earth's umbra of 14.20 deg., rather than 13.25 deg. used for the GPS satellites. The orbit angles $\mu$ (the geocentric orbit angle between the satellite and the orbit midnight, the most distant point from the Sun, growing counterclockwise in the direction of the satellite motion) of shadow entry and exit can be easily evaluated for all GLONASS satellites as

$$\mu_s = -\dot{\mu}(t_e - t_s)/2 \tag{1}$$

and

$$\mu_e = \dot{\mu}(t_e - t_s)/2\,, \tag{2}$$

where $\dot{\mu} \simeq 0.00888$ deg./sec is the average GLONASS orbital angular velocity (changing slightly from satellite to satellite). Then the yaw-angles ($\psi_s$, $\psi_e$) at the shadow start and exit can be obtained (recall that we are using the Block IIA GPS body coordinate frame convention):

$$\psi_s = ATAN2(-\tan\beta, \sin\mu_s)\,, \tag{3}$$

$$\psi_e = ATAN2(-\tan\beta, \sin\mu_e)\,, \tag{4}$$

where ATAN2 is the usual FORTRAN function of $\tan^{-1}$, giving signed angles between ($-\pi$, $\pi$).

The yaw angles $\psi(t)$ after the shadow start (i.e., for $t > t_s$) is evaluated using $\psi_s$ ($\beta$, $\mu_s$) of Eq. (3):

$$\psi(t) = \psi_s + SIGN[R, \dot{\psi}_s(t_s)]\cdot(t - t_s)\,, \tag{5}$$

where SIGN is the Fortran sign function, $R$ is the GLONASS hardware rate of 0.25 deg./sec and the nominal yaw-rate at the shadow entry is

$$\dot{\psi}_s = \dot{\mu}\tan\beta\cos\mu_s /(\sin^2\mu_s + \tan^2\beta)\,. \tag{6}$$

The yaw-turning of Eq. (5) continues until the exit yaw-angle is reached ($\psi(t) = \psi_e$), which occurs well before $t_e$, after that, $\psi(t)$ is fixed at the $\psi_e$ value until the exit time $t_e$. After the shadow exit ($t > t_e$) the nominal yaw-orientation

$$\psi_n(t) = ATAN2(-\tan\beta, \sin\mu(t))\,; \qquad t > t_e \tag{7}$$

resumes (see Fig. 6, which was generated after an implementation of the above shadow crossing maneuver in the *eclips.f* subroutine).

The GLONASS *noon-turn* maneuver (Dilssner et al (2010); Fig. 5) looks simple and efficient, however an implementation is far from simple or easy. In fact for most eclipsing, except for the deep ones with $\beta \simeq 0$, the GLONASS noon-turns approximate well the nominal yaw-orientation (turns) of Eq. (7). All the GLONASS satellites with $|\beta| < \beta_0$, where

$$\beta_0 = \tan^{-1}(\dot{\mu}/R)\,, \tag{8}$$

will not be able to keep up with the nominal noon-turn and have to undergo a GLONASS noon-turn maneuver which, after the substitution of the GLONASS constant hardware rate of 0.25 degree and $\dot{\mu} \simeq 0.00888$ deg./sec gives $\beta_0 \simeq$ 2.03 degrees. This is significantly smaller than the GPS noon-turn limits of 2.4 – 4.9 degrees.

The time $t_m$ of a noon-turn middle is already available in the *eclips.f* subroutine (see Kouba 2008 for more details), so that one only needs to find out the yaw-angle of the start $\psi_s$ and at the end $\psi_e$ of the GLONASS noon- turn maneuver. Once we know $\psi_s$ and $\psi_e$, we can compute the start and end times ($t_s$, $t_e$) and the corresponding orbit angles ($\mu_s$, $\mu_e$)

$$t_s = t_m - \frac{1}{2}\left|\psi_e - \psi_s\right| / R \ , \tag{9}$$

$$t_e = t_m + \frac{1}{2}\left|\psi_e - \psi_s\right| / R ; \tag{10}$$

$$\mu_s = 180 - \dot{\mu}(t_e - t_s) / 2 \, , \tag{11}$$

$$\mu_e = 180 + \dot{\mu}(t_e - t_s) / 2 \, . \tag{12}$$

Unfortunately, there is no close formula for $\psi_s$ and $\psi_e$, which depend on the $\beta$ angle. Namely, for $\beta \simeq 0$, the difference $\left|\psi_e - \psi_s\right| / 2$ will be about 90 degrees and for $|\beta| \simeq$ 2.03 degrees it will be nearly zero. The Table 1 demonstrates the complicated dependence of $(\psi_e - \psi_s)$, ($\mu_e$, $\mu_s$) and ($t_e$ , $t_s$) on the Sun angle $\beta$. Dilssner et al (2010) has used 4 iterations of a fairly complex, linear approximation formula. Here, up to 3 iterations of Eqs (9) - (12), together with Eqs (3) and (4) are used instead, starting the iteration with $\left|\psi_e - \psi_s\right| / 2 =$ 75 degrees. Only one iteration is needed when $|\beta|$ is near zero and for $|\beta|$=2.0 deg. 3 iterations are required to keep the errors of $\left|\psi_e - \psi_s\right| / 2$ below 1.7 degrees.

**Table 1**. Dependence of $(\psi_e - \psi_s)$, ($\mu_e$ - $\mu_s$) and ($t_e$ - $t_s$) on the Sun angle $\beta$, computed by the iteration of Eqs (9)-(12), together with Eqs (3) and (4).

| $\lvert\beta\rvert$ | $\lvert\psi_e - \psi_s\rvert$ | ($\mu_e$ - $\mu_s$) | $(t_e - t_s)$ |
|---|---|---|---|
| *deg* | *deg* | *deg* | *sec* |
| 0.0 | 180 | 6.4 | 720 |
| 0.2 | 173 | 6.1 | 690 |
| 0.4 | 164 | 5.8 | 658 |
| 0.6 | 155 | 5.5 | 622 |
| 0.8 | 146 | 5.2 | 582 |
| 1.0 | 135 | 4.8 | 538 |
| 1.2 | 122 | 4.3 | 489 |
| 1.4 | 108 | 3.8 | 433 |
| 1.6 | 92 | 3.3 | 369 |
| 1.8 | 74 | 2.6 | 296 |
| 2.0 | 33 | 1.2 | 132 |

Once $\psi_s$ , $\mu_s$ and ($t_s$ , $t_e$) are known, the GLONASS turn is performed according to Eq. (5) for $t \geq t_s$ and $t \leq t_e$ , otherwise, the nominal yaw angle $\psi_n(t)$ of (Eq. 7) is used.

The subroutine *eclips.f* expects the input body x-coordinate unit vector (in ITRF) and it returns the properly yaw-oriented unit x-vector (with the sign reversal for the Block IIR only) for all the GPS and GLONASS satellites, together with the flag *IECLIPS=1* and *2*, for the night and noon eclipsing maneuvers, respectively. Otherwise, *IECLIPS= 0* and the nominal yaw orientation of the unit x-vectors are returned. For more implementation and usage details, please see the comments in the *eclips.f* source-code.

**References**


Bar-Sever YE (1996) A new model for GPS yaw-attitude, *JoG* 70: 714-723

Dilssner F (2010), GPS IIF-1 Antenna Phase Center and Attitude Modelling, Inside GNSS, September, 59-64

Dilssner F, T Springer, G Gienger and J Dow (2010) The GLONASS-M satellite yaw-attitude model, Advances in Space Research (COSPAR) doi:10.1016/j.asr.2010.09.007

Kouba, J (2008) A simplified yaw-attitude model for eclipsing GPS satellites GPS Solutions 2008: DOI: 10.1007/s10291-008-0092-1 The original publication is available at www.springerlink.com.