Dancing in the Dark:
How GNSS Satellites Cross the Earth’s Shadow

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Attitude constraint: Sun-Earth-pointing

\[ \beta = \text{elevation of the Sun with respect to orbital plane}; \quad \mu = \text{geocentric orbital angle between satellite and midnight} \]
Attitude constraint: Sun-Earth-pointing

Satellite angular momentum vector

Earth–Sun vector

90° − β

Noon (μ = 180°)

Satellite (μ)

Midnight (μ = 0°)

Orbit trajectory

Nominal yaw-attitude (Bar-Sever 1996):

\[ \psi = \text{ATAN2}(-\tan \beta, \sin \mu) \]

β = elevation of the Sun with respect to orbital plane; μ = geocentric orbital angle between satellite and midnight
- $\beta$-angle varies while Earth revolves around the Sun
- Eclipse season every six month; four to eight weeks long
- Satellite passes through Earth’s shadow once-per-revolution
- Eclipse lasts up to one hour (GLONASS $\leq 53$ min, GPS $\leq 54$ min)
Earth’s shadow

- Shadow is divided into two cone-shaped regions; umbra and penumbra
- When S/C enters umbra (penumbra), the
  1. solar radiation pressure is zero (umbra) or changing (penumbra)
  2. thermal re-radiation force changes as S/C temperature drops down
  3. ACS solar sensors can no longer control the attitude
SLR residuals for ESA “repro-1” orbits
- High yaw-rates required around noon and midnight for small $\beta$-angles
- Singularity for $\beta = 0^\circ$: nominal yaw-rate at $\mu = \pm 180^\circ$ and $\mu = 0^\circ$ becomes infinite $\Rightarrow$ instantaneous $180^\circ$ yaw-flip required
- Actual yaw-angle temporarily lagging behind nominal one
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Rapid noon and midnight turn maneuvers

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- Actual yaw-angle temporarily lagging behind nominal one
- 3-axis stabilized ACS
- Hardware yaw rates: 0.10 ... 0.13°/s
- Noon-turn manoeuvre for |β| < 3.6 ... 4.9°
- Yaw bias implemented into ACS to make yaw direction predictable during eclipse (prior to 1994, ACS was driven by noise ⇒ erratic yaw motion)
- Navigation antenna array eccentricity: $x_0 = 27.9$ cm; $y_0 = 0.0$ cm
- Offset for LRA on-board SVN 35/36: $x_0 = 86.26$ cm; $y_0 = -52.45$ cm

Degnan and Pavlis 1994
S/C is rotating around its z-axis with maximum rate for up to 90 min
- Yaw reversal may occur, depending upon yaw angle at shadow exit
- Determination of post-shadow manoeuvre is particularly challenging; mis-modeling has negative impact on SRP parameters
- Inconsistencies among IGS ACs due to different yaw-attitude handling
- Three ACs (EMR, GFZ, JPL) solve for yaw-rates and use JPL model; the others stick to nominal attitude model
- EMR, GFZ and JPL reject data from shadow exit until 30 min thereafter
Inconsistencies among IGS ACs due to different yaw-attitude handling

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IGS clock solutions for GPS Block II/IIA

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- EMR, GFZ and JPL reject data from shadow exit until 30 min thereafter
- 3-axis stabilized ACS
- Hardware yaw rate: 0.2°/s
- S/C “knows” when it crosses Earth’s shadow; nominal attitude is maintained
- Noon-/midnight-turn manoeuvres for |β| < 2.4°; duration up to 15 min (Kouba 2009)
- No antenna eccentricity in x and y
- Precise knowledge of yaw-attitude during eclipse season less critical
- Lack of telemetry data
- 30-sec code & phase measurements from global GPS/GLONASS network
- 1\textsuperscript{st} step: IGS-like multi-GNSS analysis
- 2\textsuperscript{nd} step: Estimation of satellite clocks & phase centre positions epoch-by-epoch ("reverse kinematic point positioning")
- Nominal yaw-attitude model employed
- Yaw error reflected in horizontal PCOs

\[ \Delta \psi = \text{ATAN2}(-y_0', -x_0') \]

\[ x_0 = -54.5 \text{ cm} \]
- 3-axis stabilized ACS
- Dynamic model improvements
- Accuracy in roll-pitch-yaw: 0.5°
- Accuracy of solar panel orientation: 2.0°
- “Eclipse passing algorithm” (Revnivykh 2006)
- Navigation antenna array eccentricity:
  \[ x_0 = -54.5 \text{ cm}; \ y_0 = 0.0 \text{ cm} \]
- LRA offset: \[ x_0 = 13.7 \text{ cm}; \ y_0 = 0.3 \text{ cm} \]
- Linear drift in estimated yaw-angle as soon as S/C enters umbra
- S/C is rotating around its z-axis with maximum rate ($R \approx 0.25^\circ/s$)
- Sense of rotation is equivalent to nominal rotation direction
- S/C switches into fixed-yaw mode at the end of required midnight-turn
- S/C is spinning around its z-axis with maximum rate ($R \approx 0.25^\circ/s$)
- Maximum duration 12 min; maximum yaw error $\pm 90^\circ$
- Required yaw rate around noon exceeds hardware rate $R$, if $|\beta| < 2.0^\circ$
- Manoeuvre already starts before required yaw rate exceeds $R$ ($\neq$ GPS)
GLONASS-M yaw-attitude model

- Shadow-crossing regime:

\[
\psi(\mu) = \begin{cases} 
\text{ATAN2}(-\tan \beta, \sin \mu_s) + \frac{\text{SIGN}[R, \dot{\psi}(\mu_s)] \cdot (\mu - \mu_s)}{\dot{\mu}} & \text{if } \mu_s < \mu < \mu_f \\
\text{ATAN2}(-\tan \beta, \sin \mu_e) & \text{if } \mu_f < \mu < \mu_e
\end{cases}
\]

\[
\mu_f = \frac{\dot{\mu} \cdot [\text{ATAN2}(-\tan \beta, \sin \mu_e) - \text{ATAN2}(-\tan \beta, \sin \mu_s)]}{\text{SIGN}[R, \dot{\psi}(\mu_s)]} + \mu_s, \quad \mu_e = -\mu_s = \arccos(\cos \beta_0/\cos \beta)
\]

- Noon-turn regime:

\[
\psi(\mu) = \text{ATAN2}(-\tan \beta, \sin \mu_a) + \frac{\text{SIGN}[R, \dot{\psi}(\mu_s)] \cdot (\mu - \mu_a)}{\dot{\mu}} \quad \text{if } \mu_s < \mu < \mu_e
\]

\[
\mu_a = \frac{\arctan(|\beta|/\sin \mu_0) + |\beta|\mu_0 \cos \mu_0/(\beta^2 + \sin^2 \mu_0) + \pi R/\dot{\mu} - \pi/2}{R/\dot{\mu} + |\beta| \cos \mu_0/(\beta^2 + \sin^2 \mu_0)}, \quad \mu_e = 2\pi - \mu_a
\]

(Dilssner et al. 2010, ASR)
- Second-oldest GLONASS-M spacecraft (launched in Dec 2003)
- No tracking data available from IGS network during shadow crossing
- GNSS signal apparently turned off/on by system operators when satellite enters/leaves the Earth’s penumbra
Satellite keeps nominal yaw-attitude in the shadow (cf. GPS Block IIR)
- Noon- and midnight-turn problem due to limited yaw rate persists
- ACS solar sensors are malfunctioning
- Orbit quality significantly worse compared to other GLONASS-M S/C
- Reprocessing of 30-sec satellite clock solutions w/o solving for PCOs
- Nominal attitude model (red) vs. new attitude model (blue)
- Range error due to mis-modelling of satellite APC correction during noon and midnight may amount to $\pm 19$ cm and $\pm 27$ cm, respectively
- Nominal attitude model (red) vs. new attitude model (blue)
- RMS values during eclipse seasons ~10% higher (red)
- Reduction to “normal” level when employing new attitude model
- Improvement goes along with increased number of observations (~2.5%)
Observability of satellite clocks

- Nominal attitude model (red) vs. new attitude model (blue)
- Number of non-rejected ground stations per satellite and epoch
- Drastic decrease in number of stations satisfying outlier test criteria (red)
- Significant loss of precision; clock solution even failed in some cases
- Nominal attitude model (*red*) vs. new attitude model (*blue*)
- Degradation of the positioning accuracy of up to a few decimetres (*red*)
- Number of satellites may drop below required minimum $\Rightarrow$ solution fails
- Problems do not arise when attitude is properly modelled (*blue*)
- Nominal attitude model (*red*) vs. new attitude model (*blue*)
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- 3-axis stabilized ACS
- GPS IIF-1 launched on May 27, 2010
- Next 11 IIF satellites are underway; GPS IIF-2 to be launched in June 2011
- Navigation antenna array eccentricity ($x_0 = 39.4$ cm; $y_0 = 0.0$ cm)
S/C is able to keep nominal attitude inside Earth’s shadow (cf. Block IIR)
Midnight-turn manoeuvre must be taken into account for $|\beta| < 8^\circ$
Low yaw rate; slope of straight line fits yields $\sim 0.06^\circ$/s
Maximum duration 54 min; maximum yaw error $\pm 90^\circ$
- Noon-turn manoeuvre must be taken into account for $|\beta| < 4^\circ$
- Yaw rate twice as large as midnight-turn rate (~$0.11^\circ$/s)
- Maximum duration 27 min; maximum yaw error ±180°
- Neglecting manoeuvres causes satellite APC errors up to ±19 cm
- Noon-turn manoeuvre must be taken into account for $|\beta| < 4^\circ$
- Yaw rate twice as large as midnight-turn rate (~0.11°/s)
- Maximum duration 27 min; maximum yaw error ±180°
- Neglecting manoeuvres causes satellite APC errors up to ±19 cm
Conclusions

- Existence of horizontal satellite antenna phase centre eccentricity can be exploited to derive spacecraft’s yaw-attitude
- Method has been successfully applied to study yaw-attitude behaviour of eclipsing GLONASS-M and GPS IIF satellites
- Nominal yaw-attitude model during eclipse seasons causes range errors on decimetre-level due to mis-modelling of satellite APC correction
- GLONASS-M shadow-crossing and noon-turn manoeuvre can be accurately modelled by using a constant yaw rate of 0.25°/s
- Model should also help to improve SLR tracking during eclipse as the centre of the GLONASS-M LRA also exhibits significant horizontal PCO
- GPS IIF-1 recently passed through its 2nd eclipse season; yaw-attitude behaviour in-line with results from initial analysis (1st eclipse season)