Modelling the GLONASS-M satellite yaw-attitude during eclipse seasons

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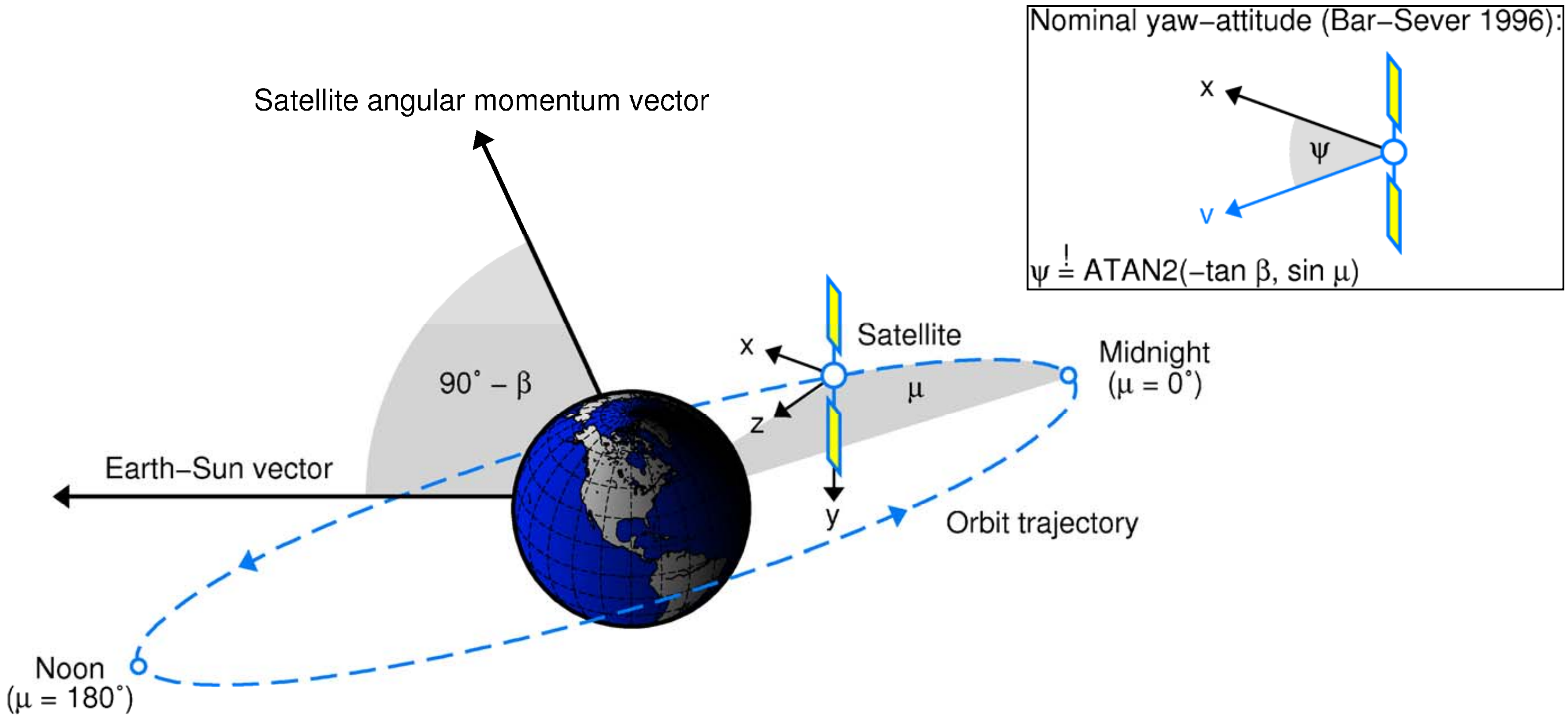
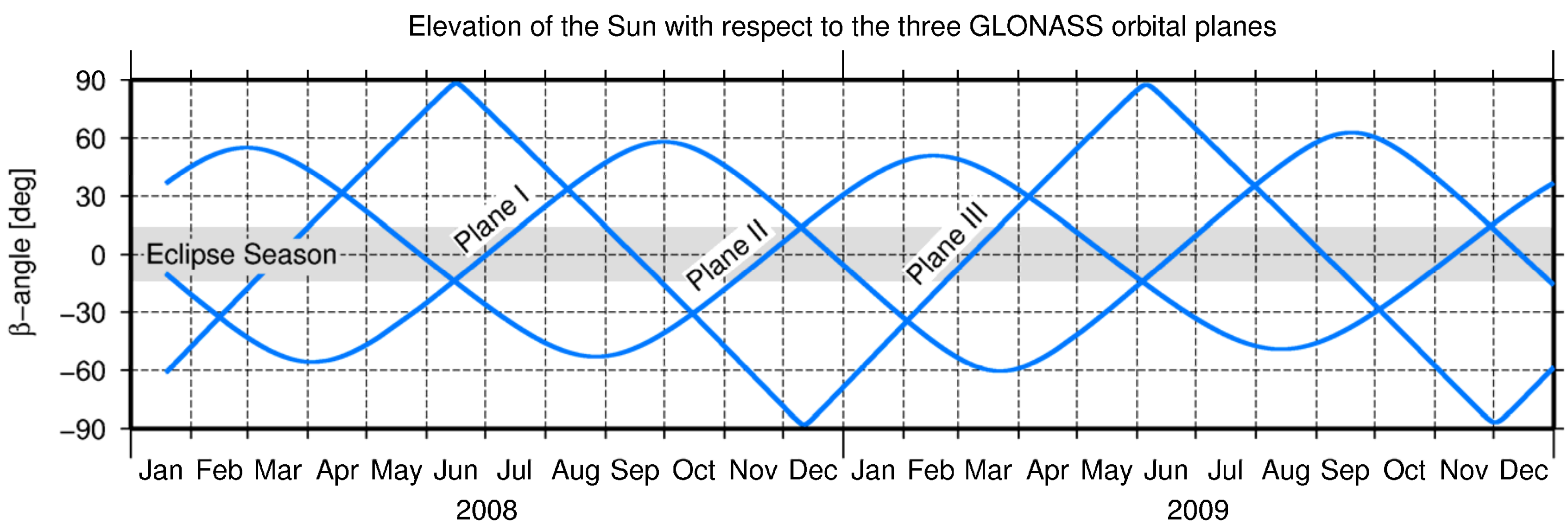
Attitude constraint: Sun-Earth-pointing



β = elevation of the Sun with respect to orbital plane; μ = geocentric orbital angle between satellite and midnight

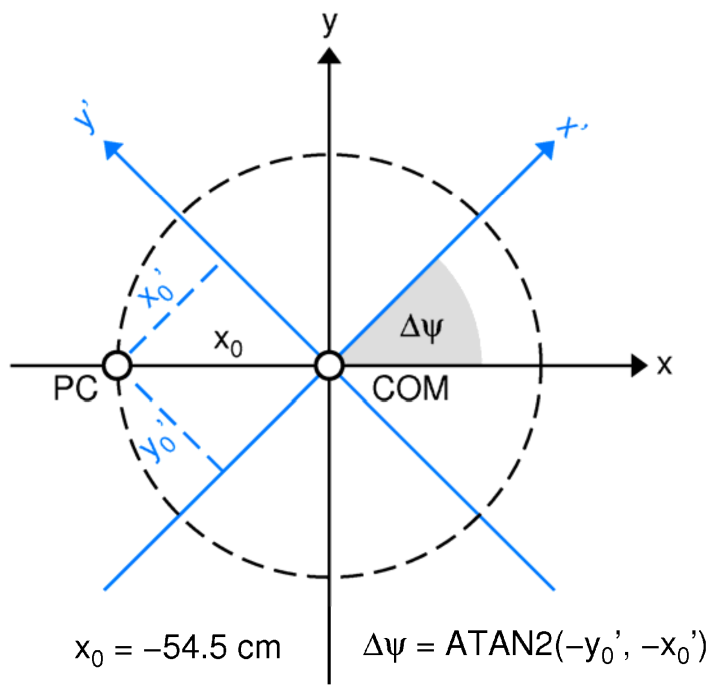
Eclipse season



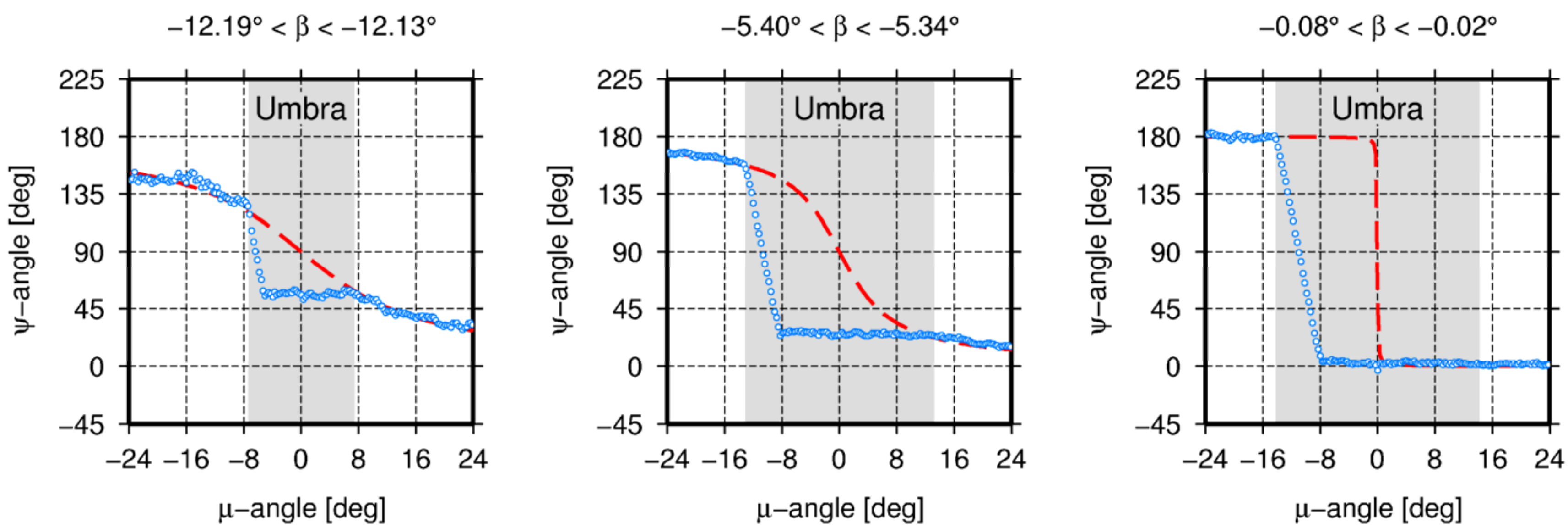
- ß-angle varies while the Earth revolves around the Sun
- Modelling of yaw-motion challenging during eclipse season (|ß| < 14.2º)
- Solar sensors can no longer control attitude due to absence of sunlight
- GLONASS-M attitude control in Earth's shadow? Noon-turn manoeuvre?

Processing strategy

- Lack of telemetry data
- 30-second code & phase measurements from global GPS/GLONASS network
- 1^{st} step: IGS-like multi-GNSS analysis
- 2^{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

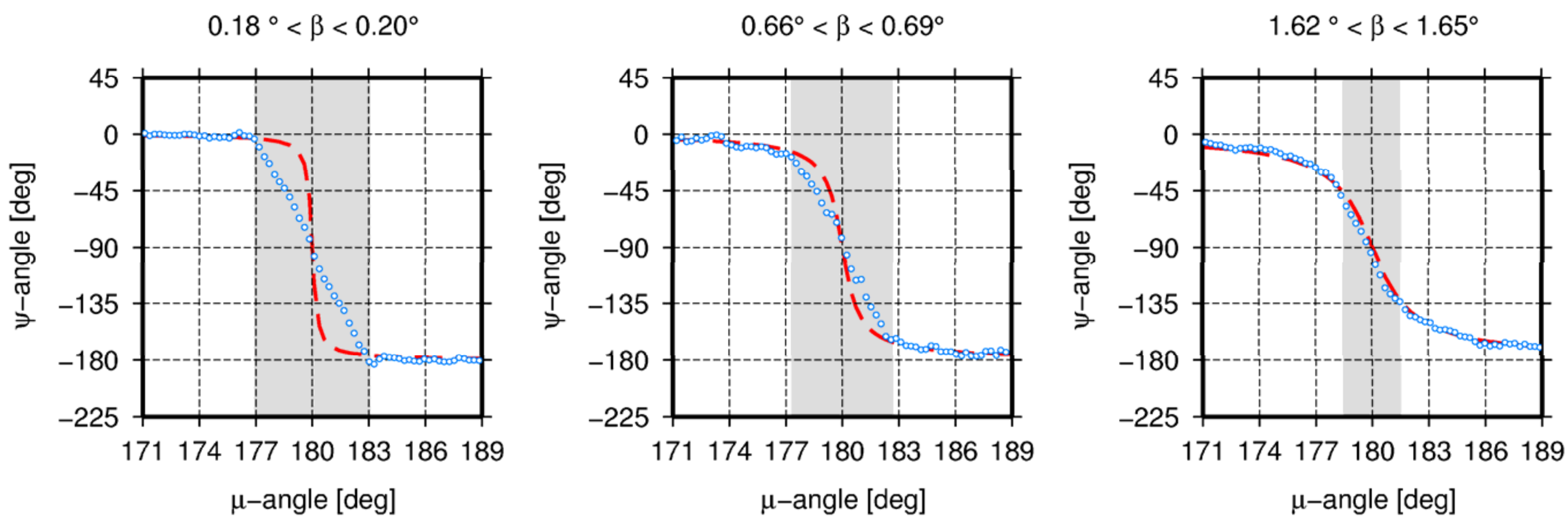


Shadow-crossing manoeuvre



- Linear drift in estimated yaw-angle as soon as s/c enters umbra
- S/c is spinning around its z-axis with maximum rate (R ≈ 0.25°/s)
- Sense of rotation is equivalent to nominal rotation direction
- S/c switches into fixed-yaw mode at the end of required midnight-turn

Noon-turn manoeuvre



- S/c is spinning its z-axis with maximum rate (R ≈ 0.25°/s)
- Maximum duration 12 min; maximum yaw error ±90º
- Required yaw rate around noon exceeds hardware rate R, if |ß| < 2.0º
- Manoeuvre already starts before required yaw rate exceeds R (≠ GPS)

The new GLONASS-M yaw-attitude model

- Shadow-crossing regime:

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

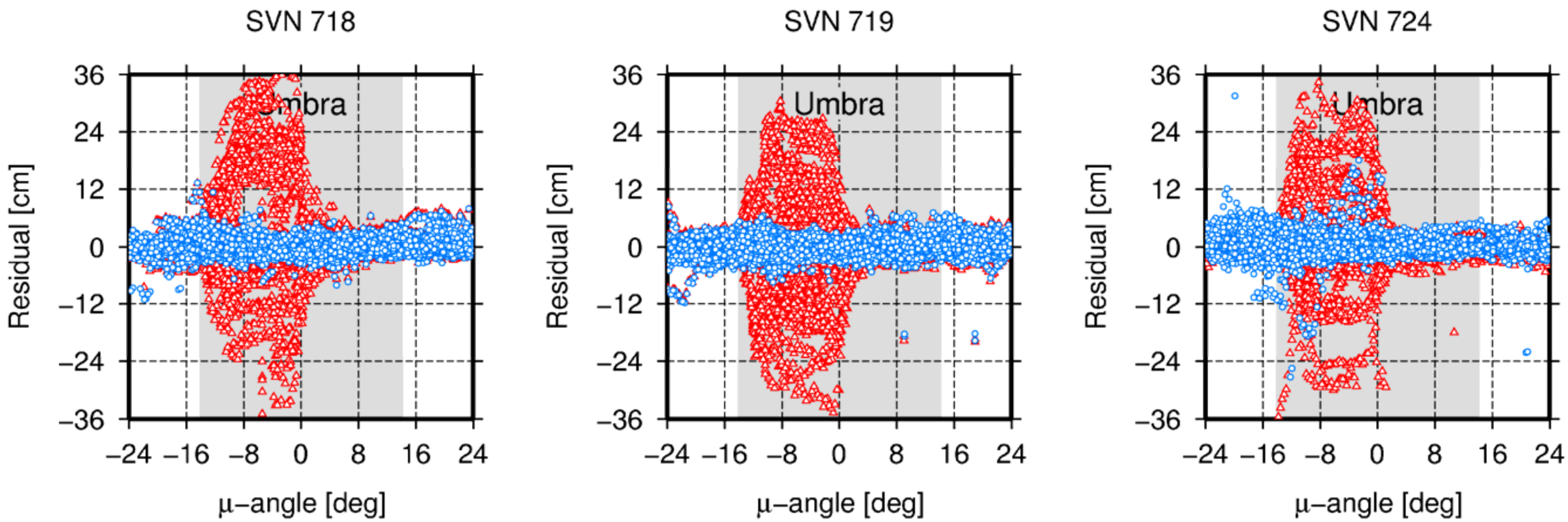
$$\mu_f = \frac{\dot{\mu} \cdot [\mathrm{ATAN2}(-\tan\beta, \sin\mu_e) - \mathrm{ATAN2}(-\tan\beta, \sin\mu_s)]}{\mathrm{SIGN}[R, \dot{\psi}(\mu_s)]} + \mu_s, \qquad \mu_e = -\mu_s = \arccos(\cos\beta_0 / \cos\beta)$$

- Noon-turn regime:

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

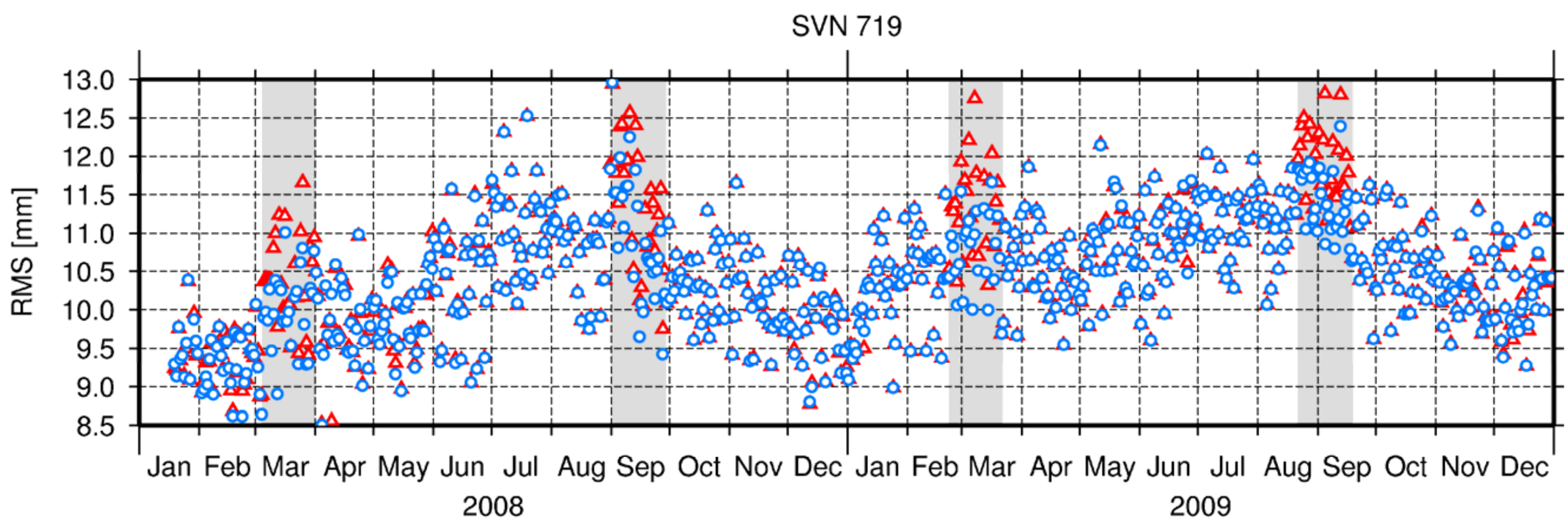
$$\mu_s = \frac{\arctan(|\beta| / \sin\mu_0) + |\beta|\mu_0 \cos\mu_0 / (\beta^2 + \sin^2\mu_0) + \pi R/\dot{\mu} - \pi/2}{R/\dot{\mu} + |\beta| \cos\mu_0 / (\beta^2 + \sin^2\mu_0)}, \qquad \mu_e = 2\pi - \mu_s$$

Carrier phase residuals



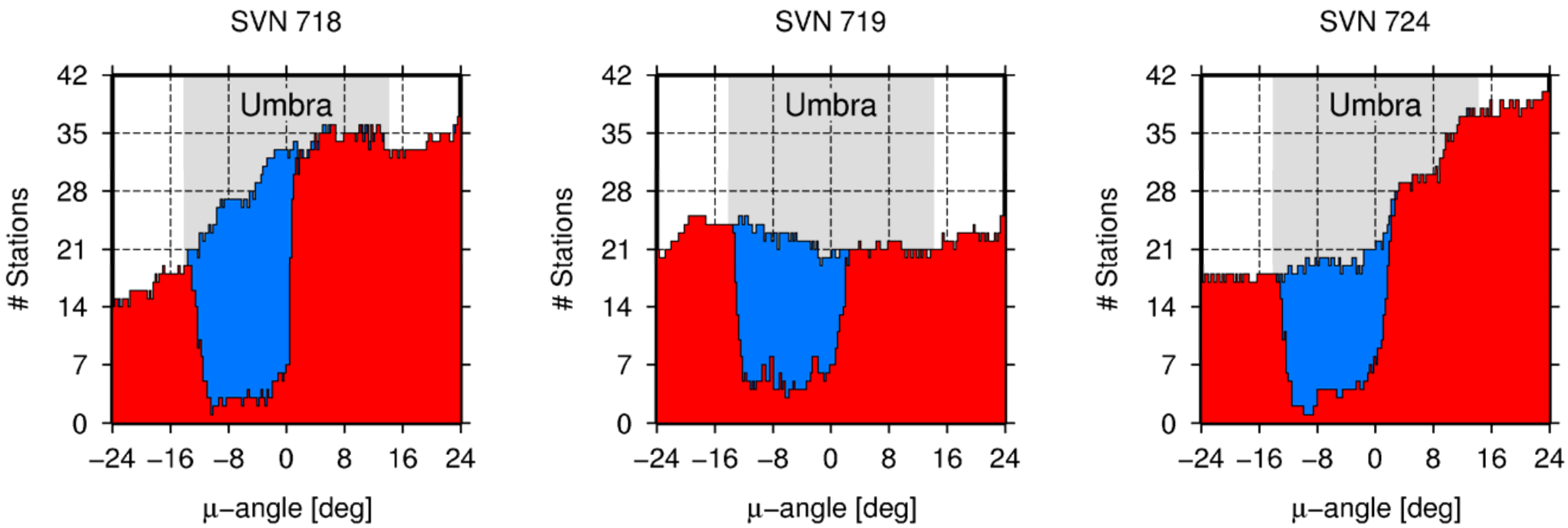
- Reprocessing of 30-second satellite clock solutions w/o solving for PCOs
- Nominal attitude model (*red*) vs. new attitude model (*blue*)
- Range error due to mismodelling of satellite APC correction during noon and midnight may amount to ±19 cm and ±27 cm, respectively

Daily carrier phase RMS



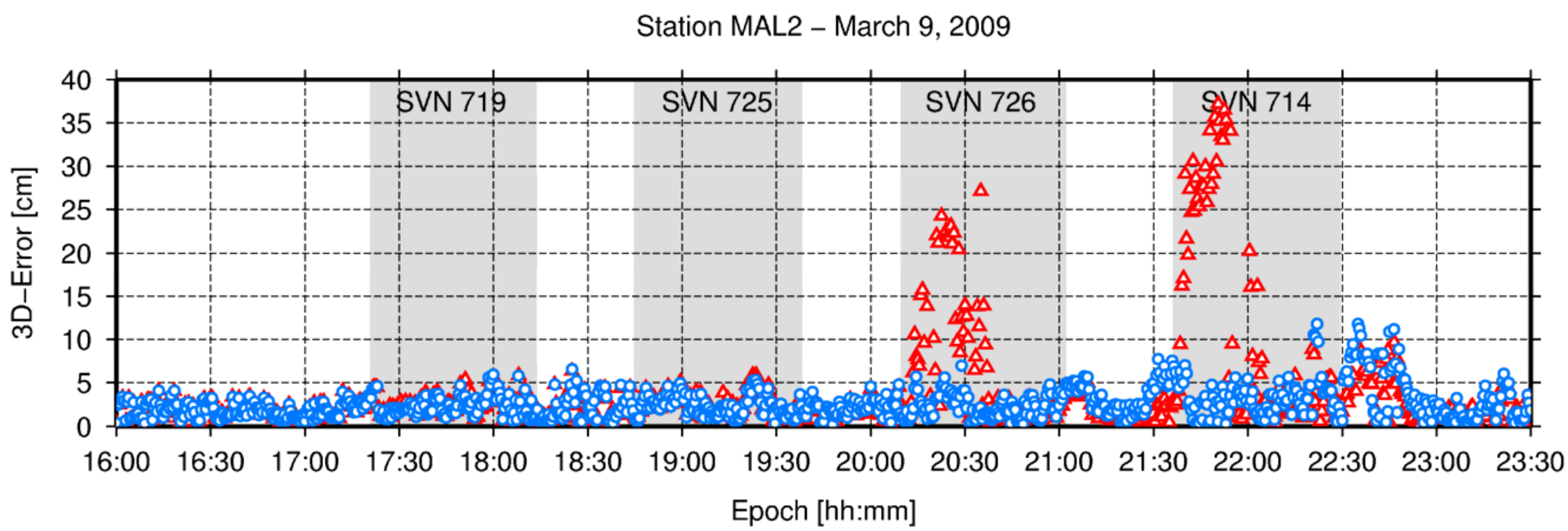
- Nominal attitude model (*red*) vs. new attitude model (*blue*)
- RMS values during eclipse seasons ~10% higher (*red*)
- Reduction to "normal" level when employing new attitude model
- Improvement goes along with increased number of observations (~2.5%)

Observability of satellite clocks



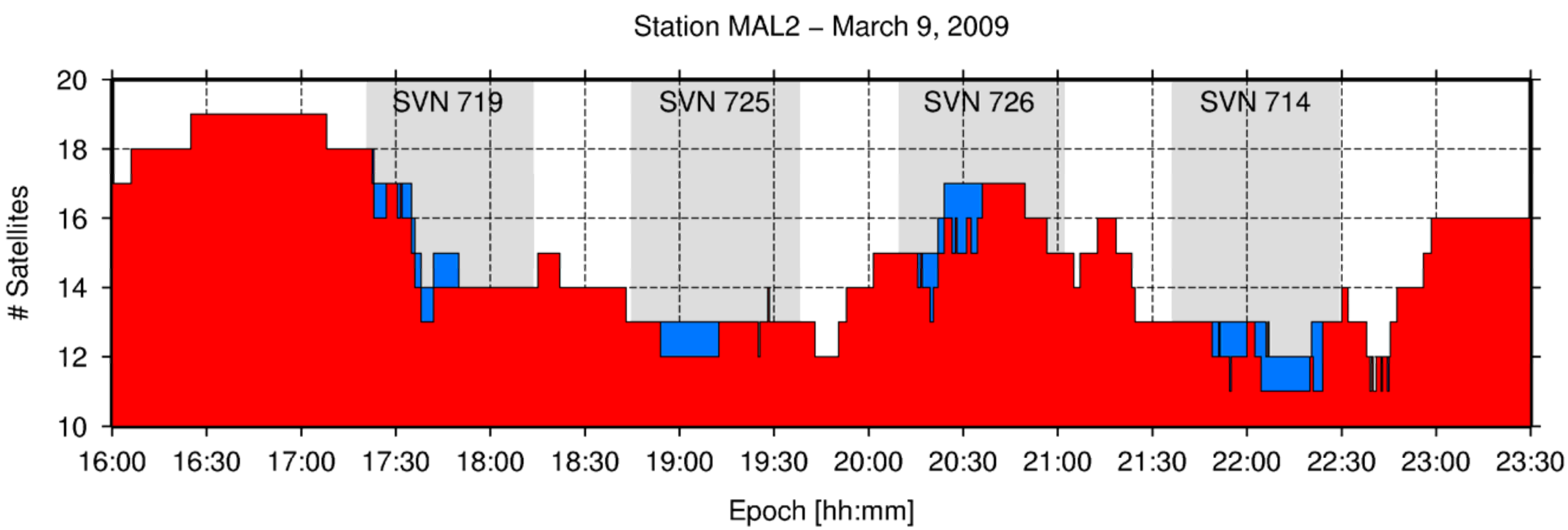
- Nominal attitude model (*red*) vs. new attitude model (*blue*)
- Number of non-rejected ground stations per satellite and epoch
- Drastic decrease in number of stations satisfying outlier test criteria (*red*)
- Significant loss of precision; clock solution even failed in some cases

Kinematic GPS / GLONASS PPP



- 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 ⇒ solution fails
- Problems do not arise when attitude is properly modelled (*blue*)

Kinematic GPS / GLONASS PPP



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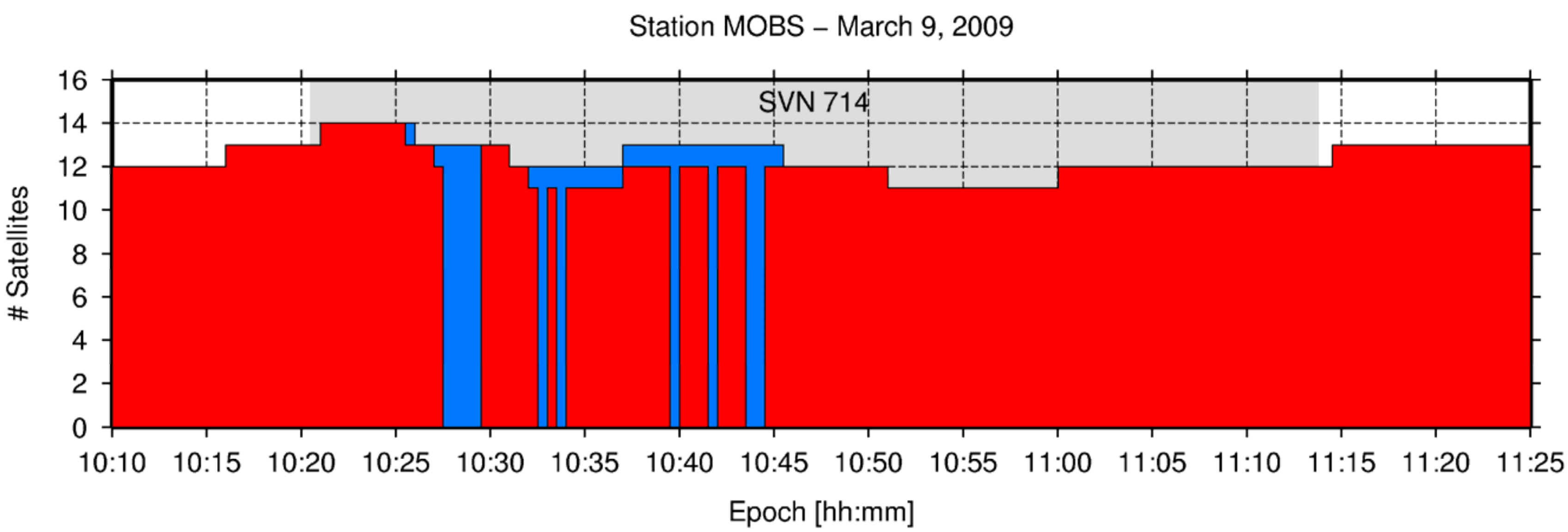

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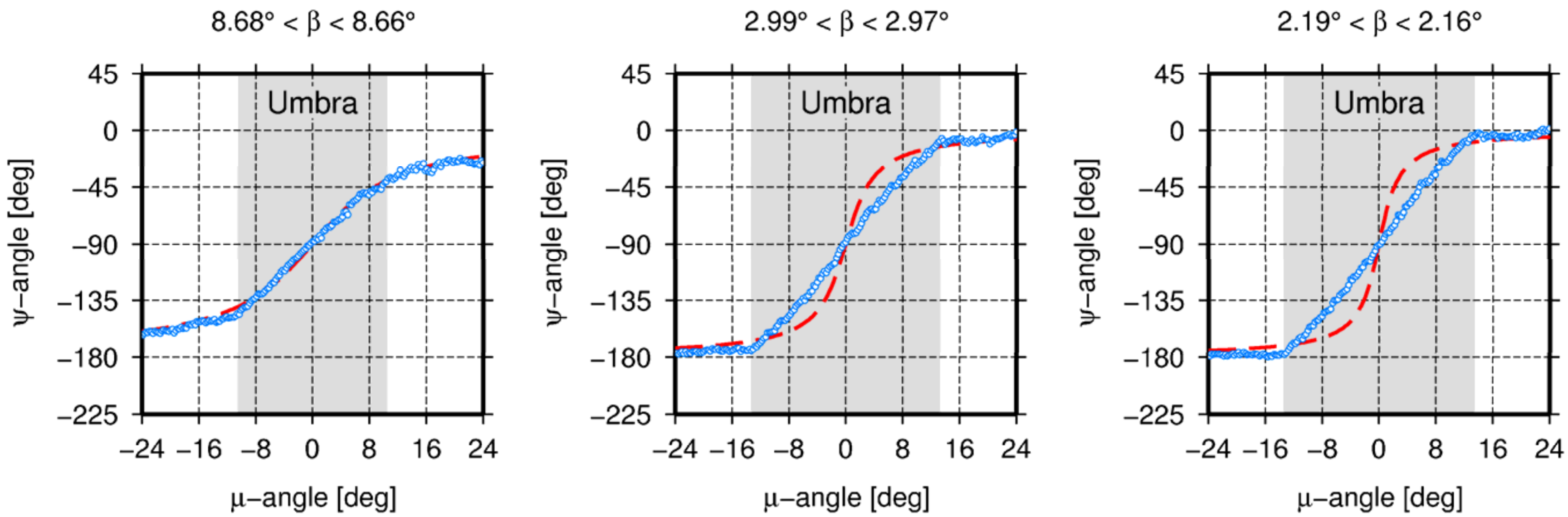
Conclusions

- 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 satellites
- Nominal yaw-attitude model during eclipse seasons causes range errors on decimetre-level due to mismodelling of satellite APC correction
- 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 SV 1 (SVN 62)



- S/c tries to keep nominal attitude in Earth's shadow like Block IIRs
- Low yaw rate; slope of straight line fits yields 0.06º/s
- Midnight-turn manoeuvre must be taken into account for |ß| < 7.9º
- Noon-turn manoeuvre still needs to be investigated