Disseminating GNSS satellite attitude for improved clock correction consistency

S. Loyer (1), S. Banville (2), F. Perosanz (3), F. Mercier (3)

(1) Collecte Localisation Satellites (CLS), Ramonville Saint Agne, France; (2) Natural Resources Canada (NRCan), Ottawa, Canada; (3) Centre National d'Etudes Spatiales(CNES), Toulouse, France

cnes CLS Natural Resources Canada Ressources naturelles Canada

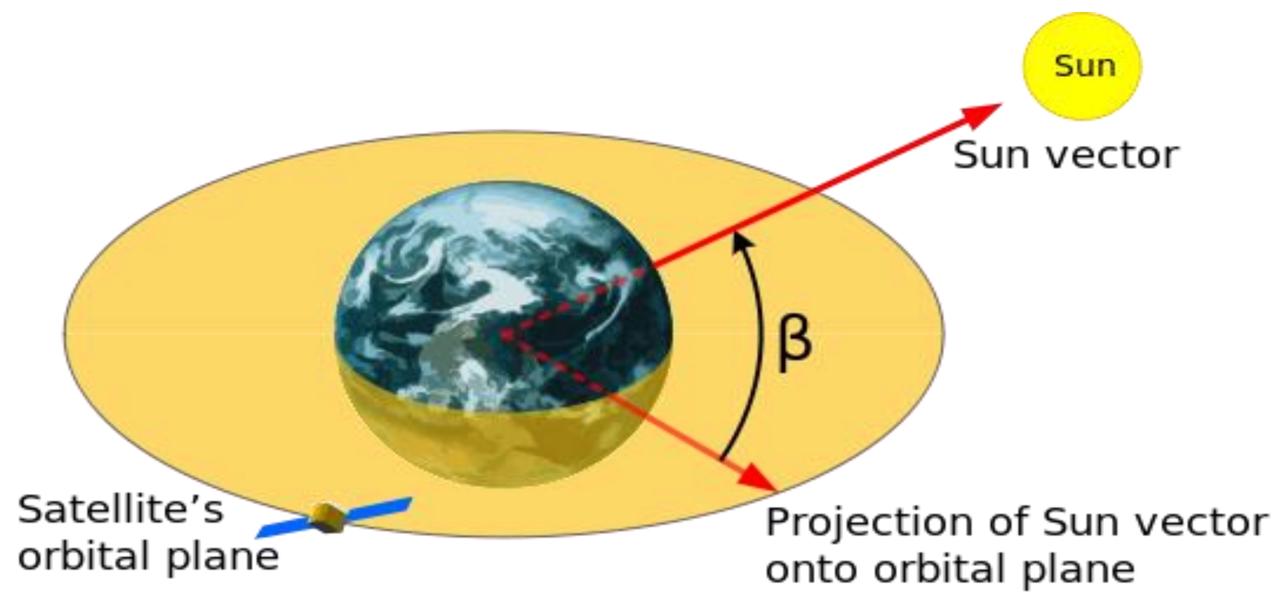
IGSWORKSHOP2017 PARIS PATHWAYS TO IMPROVED PRECISION

Abstract

It is well known that the attitude of GNSS satellites during eclipse seasons suffers from inexact or deficient modeling. The consequences of these errors are limited but there is some impact on the measurement residuals and this partly affects the orbit quality of eclipsing satellites. In addition, it is important to have consistent models between the different Analysis Centers (ACs) in order to construct reliable combined solutions, specifically for the clocks. The IGS ACs have generally adopted specific and as realistic as possible attitude modeling to lower the effects of these errors (e.g., Kouba's attitude laws, Dilssner's estimated yaw rate from measurements,…). Still, we observe today noticeable differences in the clock estimates provided by the ACs during eclipses. The situation is complicated by the combination with new constellations (MGEX) and the increasing number of different attitude laws for all these GNSS. At the IGS Multi-GNSS Working Group Splinter Meeting of the EGU this year, it was decided to propose a format to exchange the attitude quaternions used to build the other delivered products (orbits/clocks). This work presents the proposed exchange format as well as a comparison of attitude laws used by different ACs. This format allows disseminating, together with the classical orbit and clock products, the attitude used to generate the products instead of leaving this assumption to users for PPP and other applications. Importantly, this format would allow comparison and future improvement of GNSS attitude modeling for all ACs and IGS users.

Evidence for discrepancies in attitude modeling in MGEX clock solutions for low β angle.

Outside eclipse seasons, the well-defined nominal attitude is used by all ACs and software[1]. But during eclipse seasons, i.e. for small beta angles (i.e. the sun elevation angle above the orbital plane), the true attitude is not well known and different strategies and models are used[2][3]. In practice, nearly all ACs have different and more or less incorrect attitude laws and the situation is complicated by the increasing number of existing attitude laws with the increasing number of constellations (MGEX) and the multiple generations of satellites (IIR/IIF, IOV/FOC,…).
The attitude of GNSS satellites have a geometrical effect on the CoM-PCO vector and on the computation of phase wind-up corrections, and these errors map into the clock estimates. Differences in modeling induce visible differences on the estimated clocks. Several examples for three constellations are presented here.



Method:
Orbit and clock solutions are taken from sp3 files of MGEX contributions available on IGS Data Centers. For each comparison, we compute raw clock differences between two analysis center solutions (green) and we correct then with the radial orbit differences delays Δh=Δr/c (red). As a example, we have selected three satellites with a small beta angle, although similar differences can be observed for most eclipsing satellites.

We observe differences of a few tenths of a nanosecond at the time of night and/or noon turns for the three constellations (Figure 1, Figure 2 and Figure 4).
Currently, the GRM solution uses the nominal attitude for Galileo satellites even during eclipses. Signatures of ~0.1 nanoseconds associated with eclipse periods are clearly visible in clock estimates (Figure 3). The models used seem to be the same for GRM & WUM solutions. On Figure 4, we see that COM and TUM use the same laws as GRM and WUM for night turns but different ones for noon turns (right top). These plots also prove that none of the tested ACs have the correct modeling either for noon or midnight turns. Steps of 0.33 nanoseconds in clocks like the one observed on COM-GRM and TUM-GRM differences (Figure 4) represent 1 cycle in orientation (1 narrowlane wavelength). This step is not seen on clock estimates; such errors do not allow correct integer ambiguity fixing at the undifferenced level.

Clock differences for selected MGEX solutions
(raw, and Δradial/c correction ())

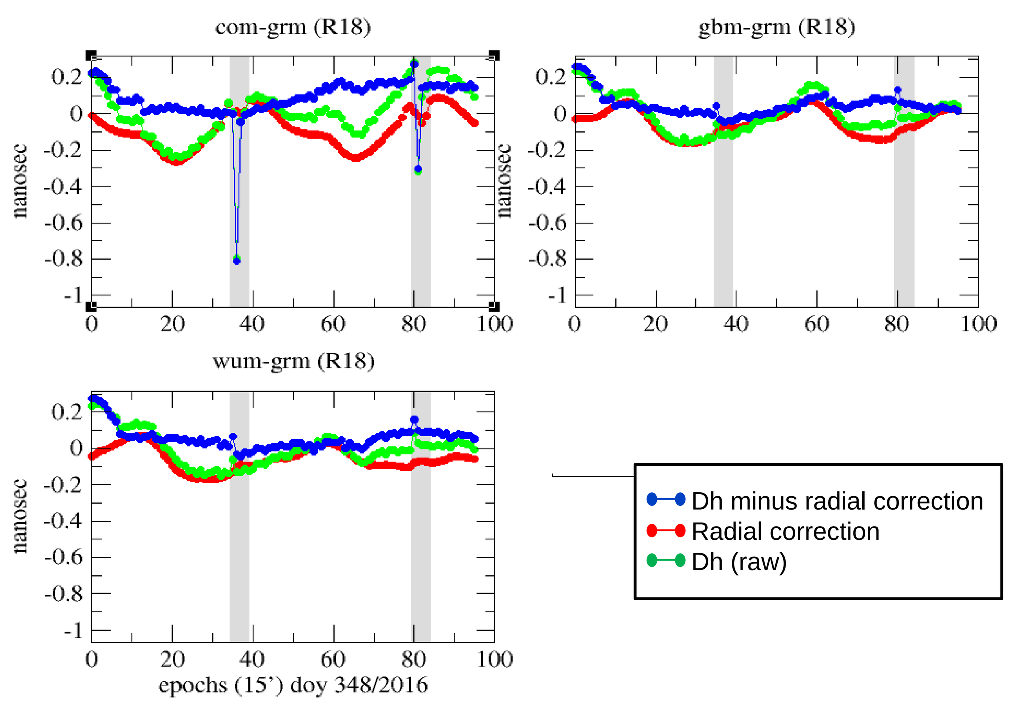


Figure 1: Glonass (doy 348/2016, β = -0.9 deg.)
=> differences up to 0.8 nanoseconds

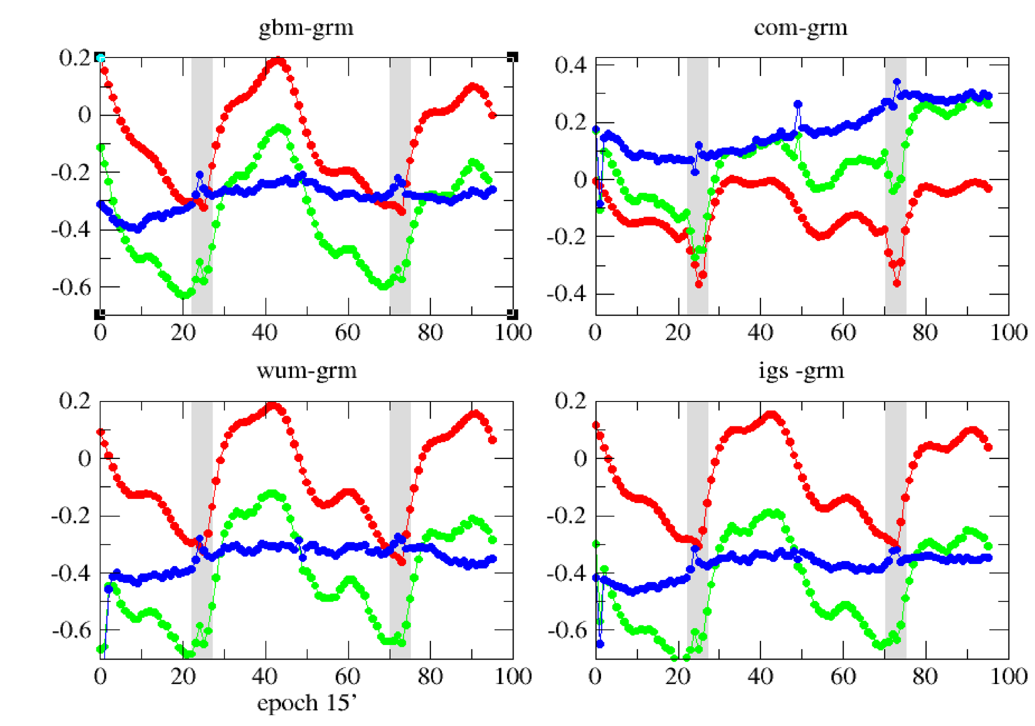


Figure 2: GPS (PRN30 IIF doy 360/2016, β = -1 deg)
=> differences up to 0.2 nanoseconds

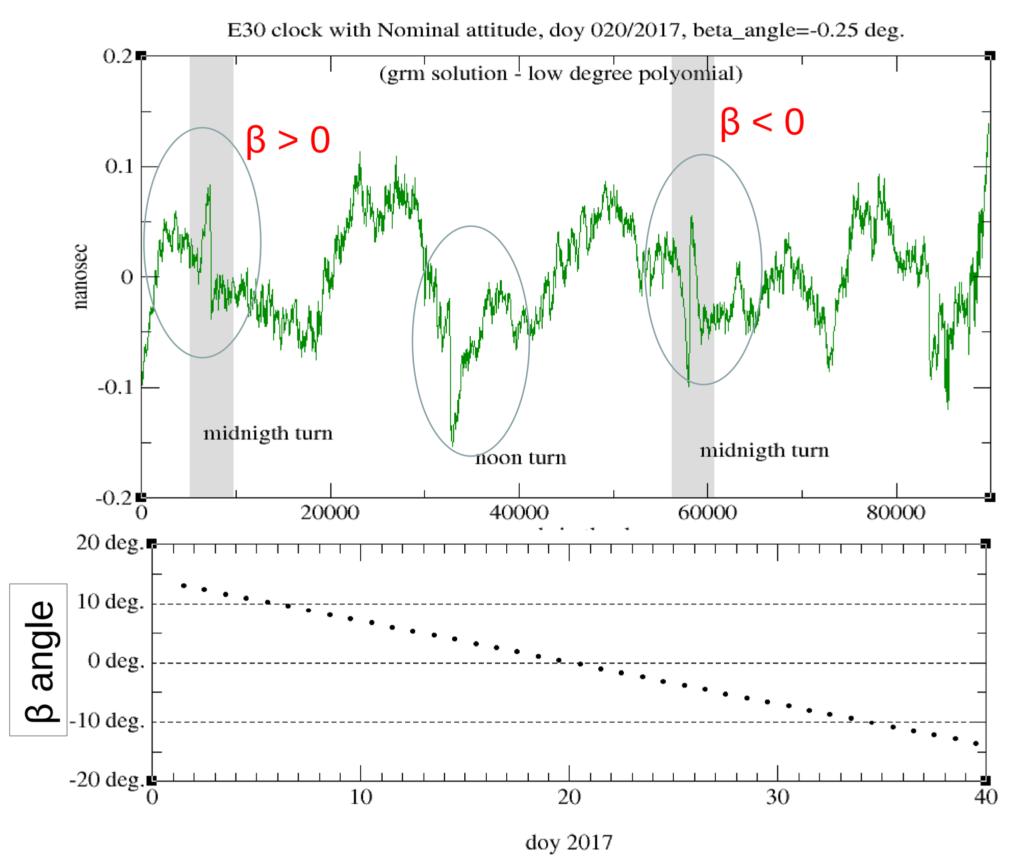


Figure 3: direct observations of eclipse signatures in GRM clocks (same period and satellite as in Figure 2)

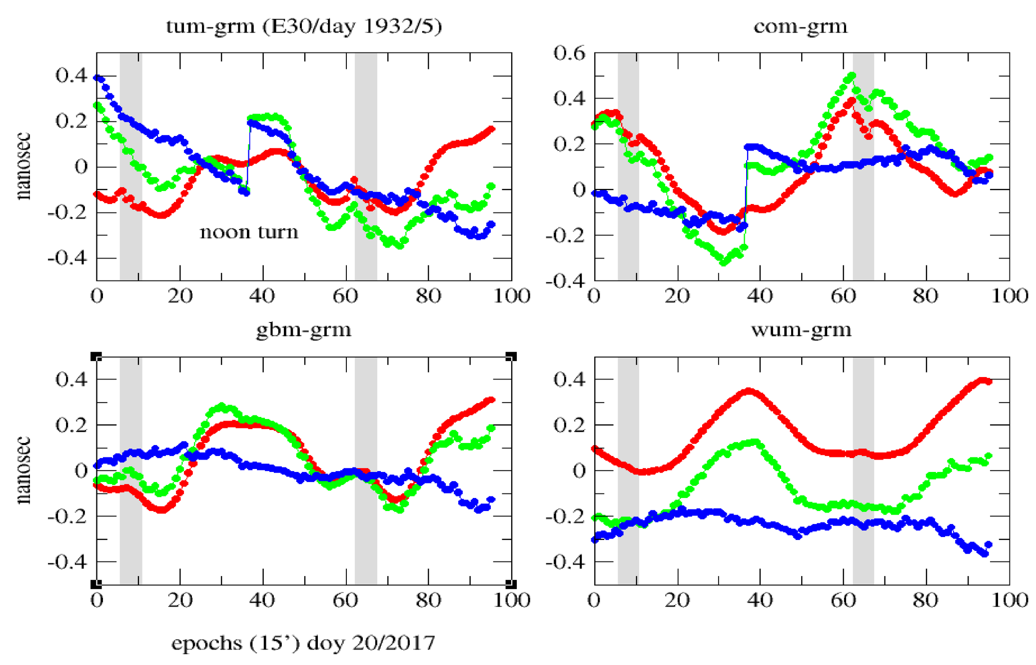


Figure 4: Galileo E30 FOC-6 (doy 020/2017, β= -1 deg)
=> differences up to 0.4 nanoseconds

(1) Montenbruck et al., 2015, O. Montenbruck, R. Schmid, F. Mercier, et al. GNSS satellite geometry and attitude models, Adv. Space Res., 56 (6) (2015), pp. 1015–1029 http://dx.doi.org/10.1016/j.asr.2015.06.019
(2) Kouba, J (2008) A simplified yaw-attitude model for eclipsing GPS satellites GPS Solutions 2008: DOI:10.1007/s10291-008-0092-1
(3) 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

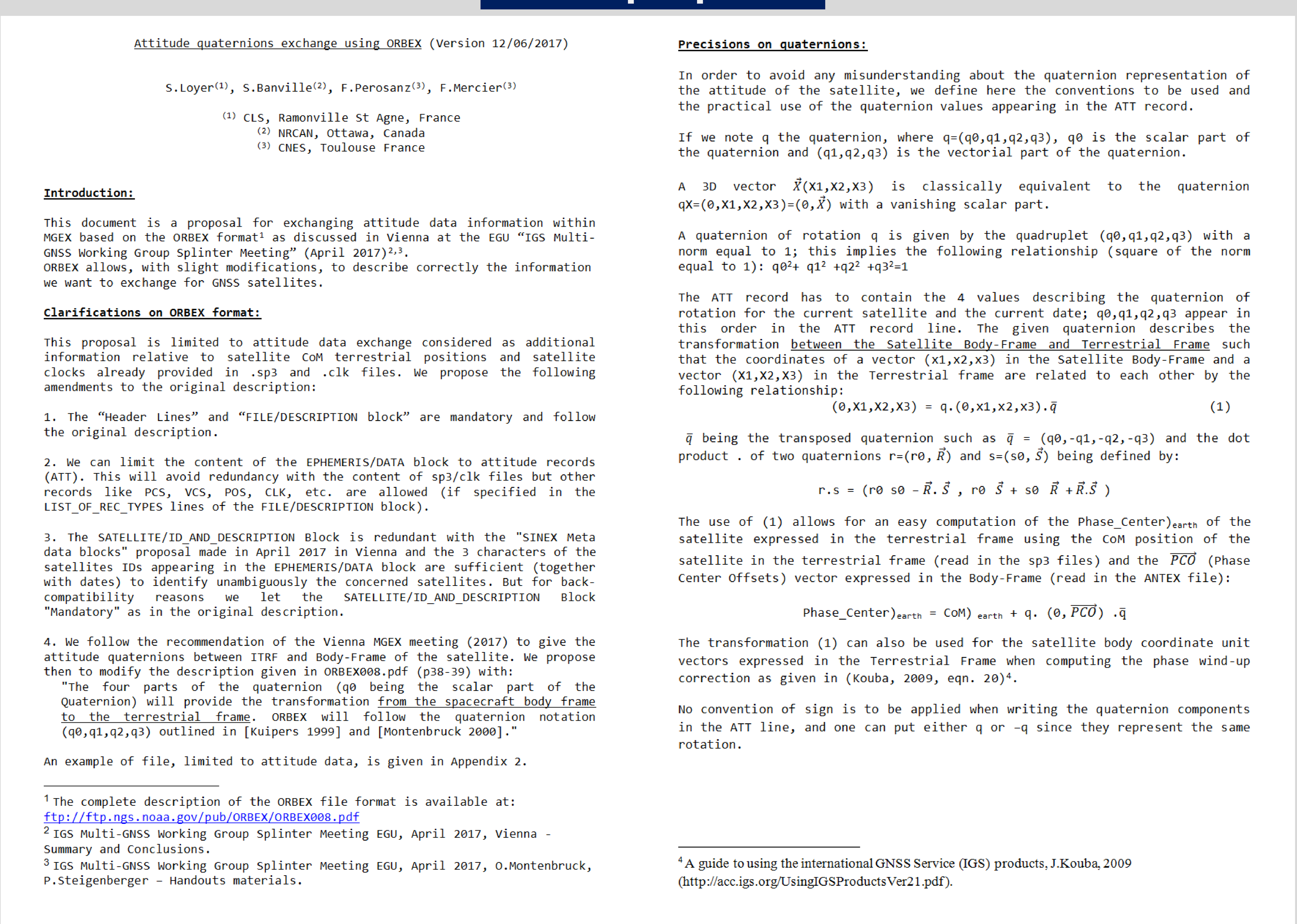
Is common modeling for GNSS attitude possible?

A wrong attitude model could do partly the job if we have coherent clocks, orbits and attitude but for other reasons (force models, code-phase biases, clocks studies) it is preferable to use as realistic models as possible.
A common yaw/attitude modeling for all satellites/ACs (including eclipse seasons) seems impossible for the following reasons:

- Some ACs have specific attitude yaw modeling linked to their processing strategy.
- Even if ACs agree "on paper," new models are implemented at various times in the software.
- In case of changes in attitude law models and/or for new satellites with new attitude laws, the new models should be adopted simultaneously by all ACs (like for the ITRF14/igs14.atx switch for reference frame). Not easy to handle in practice…
- Even if all IGS ACs have the same attitude laws and checked their respective software, the same models should also be implemented on the user side (implying many more different software to be checked/modified).

Today, it is not the case and the users have a large probability to not use the same attitude modelling as the one used to compute the clocks. For IGS-like mixed products it is worse since nobody can even define the attitude law to be used.

Orbex proposal



Attitude quaternions exchange using ORBEX (Version 12/06/2017)

S.Loyer(1), S.Banville(2), F.Perosanz(3), F.Mercier(3)

(1) CLS, Ramonville St Agne, France
(2) NRCAN, Ottawa, Canada
(3) CNES, Toulouse France

Introduction:

This document is a proposal for exchanging attitude data information within MGEX based on the ORBEX format[1] as discussed in Vienna at the EGU "IGS Multi-GNSS Working Group Splinter Meeting" (April 2017)[2,3].
ORBEX allows, with slight modifications, to describe correctly the information we want to exchange for GNSS satellites.

Clarifications on ORBEX format:

This proposal is limited to attitude data exchange considered as additional information relative to satellite CoM terrestrial positions and satellite clocks already provided in .sp3 and .clk files. We propose the following amendments to the original description:

1. The "Header Lines" and "FILE/DESCRIPTION block" are mandatory and follow the original description.

2. We can limit the content of the EPHEMERIS/DATA block to attitude records (ATT). This will avoid redundancy with the content of sp3/clk files but other records like PCS, VCS, POS, CLK, etc. are allowed (if specified in the LIST_OF_REC_TYPES lines of the FILE/DESCRIPTION block).

3. The SATELLITE/ID_AND_DESCRIPTION Block is redundant with the "SINEX Meta data blocks" proposal made in April 2017 in Vienna and the 3 characters of the satellites IDs appearing in the EPHEMERIS/DATA block are sufficient (together with dates) to identify unambiguously the concerned satellites. But for back-compatibility reasons we let the SATELLITE/ID_AND_DESCRIPTION Block "Mandatory" as in the original description.

4. We follow the recommendation of the Vienna MGEX meeting (2017) to give the attitude quaternions between ITRF and Body-Frame of the satellite. We propose then to modify the description given in ORBEX008.pdf (p38-39) with:
"The four parts of the quaternion (q0 being the scalar part of the Quaternion) will provide the transformation from the spacecraft body frame to the terrestrial frame. ORBEX will follow the quaternion notation (q0,q1,q2,q3) outlined in [Kuipers 1999] and [Montenbruck 2000]."

An example of file, limited to attitude data, is given in Appendix 2.

[1] The complete description of the ORBEX file format is available at: ftp://ftp.ngs.noaa.gov/pub/ORBEX/ORBEX008.pdf
[2] IGS Multi-GNSS Working Group Splinter Meeting EGU, April 2017, Vienna - Summary and Conclusions.
[3] IGS Multi-GNSS Working Group Splinter Meeting EGU, April 2017, O.Montenbruck, P.Steigenberger – Handouts materials.

Precisions on quaternions:

In order to avoid any misunderstanding about the quaternion representation of the attitude of the satellite, we define here the conventions to be used and the practical use of the quaternion values appearing in the ATT record.

If we note q the quaternion, where q=(q0,q1,q2,q3), q0 is the scalar part of the quaternion and (q1,q2,q3) is the vectorial part of the quaternion.

A 3D vector $\vec{X}$(X1,X2,X3) is classically equivalent to the quaternion qX=(0,X1,X2,X3)=(0,$\vec{X}$) with a vanishing scalar part.

A quaternion of rotation q is given by the quadruplet (q0,q1,q2,q3) with a norm equal to 1; this implies the following relationship (square of the norm equal to 1): $q0^2 + q1^2 + q2^2 + q3^2 = 1$

The ATT record has to contain the 4 values describing the quaternion of rotation for the current satellite and the current date; q0,q1,q2,q3 appear in this order in the ATT record line. The given quaternion describes the transformation between the Satellite Body-Frame and Terrestrial Frame such that the coordinates of a vector (x1,x2,x3) in the Satellite Body-Frame and a vector (X1,X2,X3) in the Terrestrial frame are related to each other by the following relationship:

$$(0,X1,X2,X3) = q.(0,x1,x2,x3).\bar{q} \qquad (1)$$

$\bar{q}$ being the transposed quaternion such as $\bar{q}$ = (q0,-q1,-q2,-q3) and the dot product . of two quaternions r=(r0, $\vec{R}$) and s=(s0, $\vec{S}$) being defined by:

$$r.s = (r0\, s0 - \vec{R}.\vec{S}\ ,\ r0\, \vec{S} + s0\, \vec{R} + \vec{R}.\vec{S}\ )$$

The use of (1) allows for an easy computation of the $Phase\_Center)_{earth}$ of the satellite expressed in the terrestrial frame using the CoM position of the satellite in the terrestrial frame (read in the sp3 files) and the $\overrightarrow{PCO}$ (Phase Center Offsets) vector expressed in the Body-Frame (read in the ANTEX file):

$$Phase\_Center)_{earth} = CoM)_{earth} + q.\ (0, \overrightarrow{PCO})\ .\bar{q}$$

The transformation (1) can also be used for the satellite body coordinate unit vectors expressed in the Terrestrial Frame when computing the phase wind-up correction as given in (Kouba, 2009, eqn. 20)[4].

No convention of sign is to be applied when writing the quaternion components in the ATT line, and one can put either q or –q since they represent the same rotation.

[4] A guide to using the international GNSS Service (IGS) products, J.Kouba, 2009 (http://acc.igs.org/UsingIGSProductsVer21.pdf).

To quantify the impact of deficient attitude modeling, we performed various 30s-PPP solutions using the GRM products but with different attitude modeling. We compared these solutions to the solution using consistent attitude modeling with the GRM products. As seen on Fig. 5, errors can reach several centimeters in the three directions (North/East/Up).

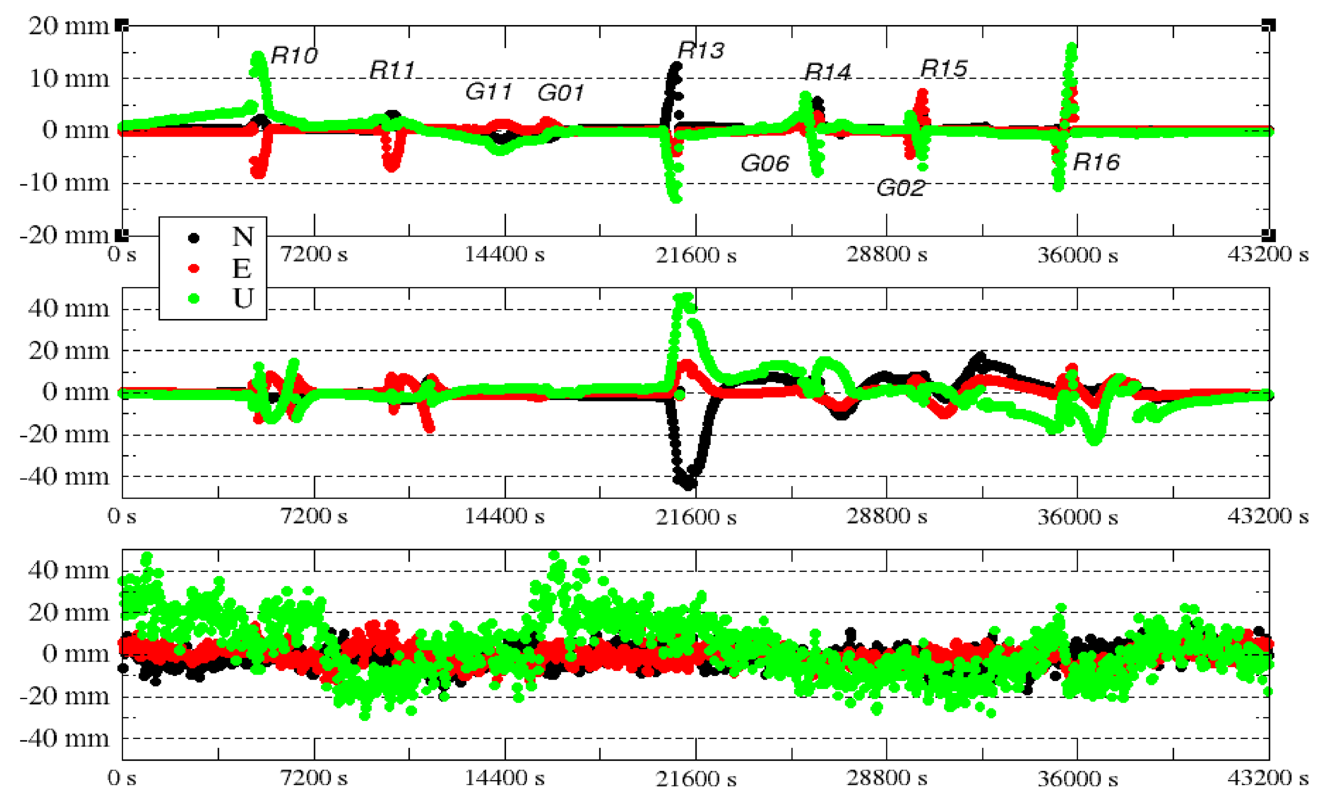


Figure 5: NRCan 30s-PPP solution using station ALGO on 13/01/2017. The reference solution is using the GRM products with consistent attitude (bottom). The top panel shows position differences when using an internal attitude modeling, while the middle panel shows position differences when ignoring eclipsing satellites.

Disseminating GNSS attitude

To make progress in this area we re-activate the possibility to exchange attitude data within IGS. A proposal using ORBEX has been written and distributed (see left). In case of agreement between ACs, we could start sharing the attitude used to derive the products.

As illustrated in this presentation, this could help improving the models for eclipsing satellites and the clock comparison/combination; this will also help users to obtain full consistency with IGS products.