# GNSS Attitude quaternions exchange using ORBEX (Version 30/04/2019)

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**Introduction:**

This document is a proposal for exchanging attitude data information within IGS based on the ORBEX format[1] as discussed initially in Vienna at the EGU "IGS Multi-GNSS Working Group Splinter Meeting" (April 2017)[2,3] and decided at the IGS AC meeting of Potsdam (April 2019)[4].

**History of changes in this document:**

1. June 2017: Initial version
2. April 2019 (S. Loyer): Corrected version with clarifications on the use of the ORBEX format, precisions on the frames related to the quaternion transformation and modified Example of appendix 2.

**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 use the ORBEX format version 0.09 with the following guidelines:

1. The "Header Lines" and "FILE/DESCRIPTION block" are mandatory and follow the description of ORBEX 0.09 (p 9).
2. The SATELLITE/ID_AND_DESCRIPTION Block is "Mandatory" and must list the satellites appearing in the file (with the 3 characters of the satellites IDs). Other information (Satellite Description) can be omitted.
3. The time system to be used is the GPS time as in the sp3 and the clk files (Then the TIME_SYSTEM label of the FILE/DESCRIPTION block should be "GPS")
4. The stepsize shall be fixed and preferably coherent with the clocks one used in .clk files. Epochs containing no information at all must be given even if the data block is not populated.
5. We recommend limiting the content of the EPHEMERIS/DATA block to attitude records (ATT) using the fixed format given in 0RBEX 0.09 (p 32). This will avoid redundancy with the content of sp3/clk files but

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[1] The complete description of the ORBEX file format is available at: ftp://ftp.ngs.noaa.gov/pub/ORBEX/ORBEX009.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.
[4] Workshop 2019 recommendations: https://s3-ap-southeast-2.amazonaws.com/igs-acc-web/igs-acc-website/workshop2019/Workshop_Findings.pdf

other records like PCS, VCS, POS, CLK, etc. are allowed (if specified in the LIST_OF_REC_TYPES lines of the FILE/DESCRIPTION block).

6. Unknown or invalid ATT data for any satellite can be omitted. ORBEX (section 2.3) allows a variable number of satellites at each epoch.
7. We follow the recommendation of the Vienna MGEX meeting (2017) to give the attitude quaternions between ITRF and Body-Frame of the satellite. The four parts of the quaternion (q0 being the scalar part of the Quaternion) will provide the transformation from the terrestrial frame to the spacecraft body frame. ORBEX follow the quaternion notation (q0,q1,q2,q3) outlined in [Kuipers 1999][5] and [Montenbruck 2000][6] and the ECEF frame involved in the transformation must be specified in the COORD_SYSTEM LABEL field of the FILE/DESCRIPTION block. The transformation can also be described with comments lines at the start of EPHEMERIS/DATA block. An example of file, limited to attitude data, is given in Appendix 2.

**Name of the files:**

Names of ORBEX ATT files will follow the general rules in place within IGS with extension .obx or .OBX (e.g. GRG0MGXFIN_20190020000_01D_30s_ATT.OBX or gbm20343.obx).

**Detailed definitions 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 <u>between the Terrestrial Frame and the Satellite Body-Frame</u> such that the coordinates of a vector ($x_1$,$x_2$,$x_3$) in the Satellite Body-Frame and ($X_1$,$X_2$,$X_3$) in the Terrestrial frame are related to each other by the following relationship:

$$(0,x_1,x_2,x_3) = q.(0,X_1,X_2,X_3).\bar{q} \qquad (1)$$

5 Kuipers, J. B. 1999: Quaternions and Rotation Sequences: A primer with Applications to Orbits, Aerospace and Virtual Reality, Princeton University Press, Princeton, New Jersey. 47
6 Montenbruck, O., 2000: Quaternion Representation of BIRD Orientation and Reference System Transformations, DLR-GSOC TN00-03,www.weblab.dlr.de/rbrt/pdf/TN_0003.pdf

$\bar{q}$ being the transposed quaternion such as $\bar{q}$ = (q0,-q1,-q2,-q3) and the 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):

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

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.

**Link between matrix and quaternion:**

To make the coordinate transformation between the two frames, one can use either formula (1) or use the equivalent matrix transformation:

$$\vec{x} = M\ \vec{X}$$

$$\text{with M} = \begin{pmatrix} q0^2 + q1^2 - q2^2 - q3^2 & 2(q1q2 - q0q3) & 2(q1q3 + q0q2) \\ 2(q1q2 + q0q3) & q0^2 - q1^2 + q2^2 - q3^2 & 2(q2q3 - q0q1) \\ 2(q1q3 - q0q2) & 2(q2q3 + q0q1) & q0^2 - q1^2 - q2^2 + q3^2 \end{pmatrix}$$

The above transformation (from quaternion to matrix) is straightforward to compute but the inverse one (from matrix to quaternion) can be numerically problematic in some cases; we provide an example of a Fortran program that avoids numerical problems in Appendix 1.

## Appendix 1: Example Fortran routine to compute the transformation from matrix to quaternion:

```
subroutine mat2quater(xmat,quater)
!
! ----------------------------------------------------------------------
!
! This subroutine is an example of a possible algorithm to avoid
! numerical instabilities when computing a quaternion of rotation
! from the elements of the corresponding matrix of rotation.
! The matrix given in entry have to be a rotation matrix (i.e.
! having a determinant equal to 1). This is not checked here!
!
! INPUT  : xmat (3,3) : matrix of rotation
! OUTPUT : quater(4)  : corresponding quaternion of rotation
!                       (with a positive scalar part)
!     quater=(q0,q1,q2,q3)       q0: scalar part
!                          q1,q2,q3: vectorial part
!
!   example:
!
!       |  0.0000000000000000 -0.5000000000000001 -0.8660254037844386 |
! xmat= |  0.9238795325112867 -0.3314135740355917  0.1913417161825449 |
!       | -0.3826834323650897 -0.8001031451912655  0.4619397662556435 |
! gives:
!
!  quater = ( 0.5316310262343734       ! q0
!            -0.4662278970042302       ! q1
!            -0.2272920256568435       ! q2
!             0.6695807158758448 )     ! q3
!
! ----------------------------------------------------------------------
implicit none
double precision , dimension(3,3) :: xmat
double precision , dimension(4)   :: quater , qsquare
double precision :: xtr, xs , max , denominator
integer :: imax , i
!
! computation of the squares of the quadriplet:
xtr = xmat(1,1)+xmat(2,2)+xmat(3,3)
qsquare(1) = (xtr + 1.d0)/4.d0
xs = 0.5d0 - qsquare(1)
qsquare(2) = xs + xmat(1,1)/2.d0
qsquare(3) = xs + xmat(2,2)/2.d0
qsquare(4) = xs + xmat(3,3)/2.d0
!
! we cannot take as it is the square root of these squares since this
! gives numerical errors for nearly vanishing values.
!
! selection of the max of the values (to be used like pivot):
!
max = -1.d0
do i=1,4
  if (qsquare(i) > max ) then
    max = qsquare(i)
    imax = i
  end if
end do
quater(imax) = sqrt(qsquare(imax))
denominator=4.d0*quater(imax)
!
! quaternion values now computed using extra diagonal terms
! of the matrix
!
if (imax == 1) then
  quater(2)=(xmat(3,2)-xmat(2,3) )/denominator
  quater(3)=(xmat(1,3)-xmat(3,1) )/denominator
  quater(4)=(xmat(2,1)-xmat(1,2) )/denominator
else if (imax == 2) then
```

```
    quater(1)= (xmat(3,2)-xmat(2,3))/denominator
    quater(3)= (xmat(1,2)+xmat(2,1))/denominator
    quater(4)= (xmat(1,3)+xmat(3,1))/denominator
  else if (imax == 3) then
    quater(1)= (xmat(1,3)-xmat(3,1))/denominator
    quater(2)= (xmat(1,2)+xmat(2,1))/denominator
    quater(4)= (xmat(2,3)+xmat(3,2))/denominator
  else if (imax == 4) then
    quater(1)= (xmat(2,1)-xmat(1,2))/denominator
    quater(2)= (xmat(1,3)+xmat(3,1))/denominator
    quater(3)= (xmat(2,3)+xmat(3,2))/denominator
  end if
  !
  ! as quater  and -quater are equivalent this subroutine always return
  ! the one of the two having a positive scalar part.
  ! warning: this procedure does not imply that two successive call
  ! will give two quaternions that can be interpolated.
  !
  if (quater(1)<0.d0) quater(1:4)=-quater(1:4)
  !
  return
  end
```

## Appendix 2: Example of ORBEX file limited to attitude data

```
%=ORBEX  0.09
%%
+FILE/DESCRIPTION
 DESCRIPTION         Attitude quaternions for grg/grm products
 CREATED_BY          CNES-CLS IGS-AC
 CREATION_DATE       2019 05 02 12 34 54
 INPUT_DATA          u+U
 CONTACT             igs-ac@cls.fr
 TIME_SYSTEM         GPS
 START_TIME          2018 10 21 00 00  0.000000000000
 END_TIME            2018 10 21 00 01  0.000000000000
 EPOCH_INTERVAL         30.000
 COORD_SYSTEM        IGS14
 FRAME_TYPE          ECEF
 LIST_OF_REC_TYPES   ATT
-FILE/DESCRIPTION
+SATELLITE/ID_AND_DESCRIPTION
 E01
 E02
 E03
 R01
 R02
 R03
 G01
 G02
 G03
-SATELLITE/ID_AND_DESCRIPTION
+EPHEMERIS/DATA
*ATT RECORDS: TRANSFORMATION FROM TERRESTRIAL FRAME COORDINATES (T) TO SAT. BODY FRAME ONES (B) SUCH AS
*                                 (0,B) = q.(0,T).trans(q)
*REC ID_                  N ___q0_(scalar)_____ ____q1__x__________ ____q2__y__________ ____q3__z__________
## 2018 10 21 00 00  0.000000000000  09
 ATT E01                  4  0.2796988739859625  0.0767732228075297  0.9535493300680007 -0.0813516273813716
 ATT E02                  4 -0.0763832709942057  0.2798108239960775  0.0805438903508286  0.9536163696235584
 ATT E03                  4  0.5051654088446309 -0.0123667305508339 -0.8608432558942428  0.0600321785688232
 ATT R01                  4  0.3929179843903584  0.1771727389613362 -0.7035390216886975  0.5650293116935323
 ATT R02                  4  0.1005541208221312  0.1166037923840662 -0.3880332242101842  0.9086928200973037
 ATT R03                  4 -0.0278325195218448 -0.1619139938829182 -0.1519125633400278  0.9746444390347746
 ATT G01                  4  0.4062502437634697 -0.0970122592581474 -0.8694030375664159 -0.2639843163258768
 ATT G02                  4 -0.1496681237335243 -0.2530795077026955 -0.7371638931910669  0.6083910009972509
 ATT G03                  4  0.3203878356598950 -0.0321052432048551 -0.9467398141198986  0.0021476685370511
## 2018 10 21 00 00 30.000000000000  09
 ATT E01                  4  0.2794666584952466  0.0788926857131641  0.9532771962325394 -0.0832881628654021
 ATT E02                  4 -0.0785052158963970  0.2795801729714974  0.0824831455053343  0.9533458914086921
 ATT E03                  4  0.5041284994648602 -0.0141082233717651 -0.8615253227849633  0.0585622084698466
 ATT R01                  4  0.3936182419914179  0.1754501671718069 -0.7054536941674464  0.5626873055227684
 ATT R02                  4  0.1007699680301561  0.1175295119858701 -0.3895677507545111  0.9078927221470803
 ATT R03                  4 -0.0285733933451835 -0.1603295276881839 -0.1532496228213486  0.9746756162175904
 ATT G01                  4  0.4065921190368229 -0.0986582811099466 -0.8684206983132919 -0.2660730783950743
 ATT G02                  4 -0.1496939903353548 -0.2526908562350616 -0.7384408338917909  0.6069960257479998
 ATT G03                  4  0.3197072840913043 -0.0334593005685304 -0.9469253855505140  0.0002047057334085
## 2018 10 21 00 01  0.000000000000  09
 ATT E01                  4  0.2792315418951427  0.0810077144798338  0.9529976390208150 -0.0852232141283546
 ATT E02                  4 -0.0806227445862077  0.2793466020796836  0.0844209198940245  0.9530679709475965
 ATT E03                  4  0.5030876207653896 -0.0158419216213776 -0.8622015285941634  0.0570999425730834
 ATT R01                  4  0.3943114626522111  0.1737119189156034 -0.7073624054387999  0.5603401351139925
 ATT R02                  4  0.1009931412040600  0.1184458879020473 -0.3911061152064730  0.9070870761492159
 ATT R03                  4 -0.0293088796883079 -0.1587475977271824 -0.1545879463757490  0.9747013679187043
 ATT G01                  4  0.4069287788973764 -0.1003018648871554 -0.8674315645499522 -0.2681622375124261
 ATT G02                  4 -0.1497097542061216 -0.2523063427000890 -0.7397124347680939  0.6056021902026991
 ATT G03                  4  0.3190254690192300 -0.0348094961213492 -0.9471050800871627 -0.0017367699695737
-EPHEMERIS/DATA
%END_ORBEX
```