EUMETSAT

POLAR SYSTEM

EPS Mission Conventions Document

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DOCUMENT CHANGE RECORD

Issue/Revision	Date	DCR No.	Changed Pages/Paragraphs
Issue 1 Draft A	23/4/99		Updated from "ENVISAT –1 Mission CFI Software – Mission Conventions Document", PO-IS-ESA-GS-0561 Modified for Metop as "Metop Mission CFI Software – Mission Conventions Document", MO.TN.ESA.SY.0131 First EUMETSAT issue for working meeting with SSST.
Issue 1 Draft B	7/5/99		Additional EUMETSAT inputs
Issue 1 Draft C	13/7/99		Harmonised draft output of SSST/EUM working meeting, ESTEC 13/7/99.
Issue 1 Draft D	27/7/99		Additional SSST/EUMETSAT inputs
Issue 1 Draft E	18/09/01		Chapter 4.3 "NOAA Time Definitions" reference inserted pointing to NOAA-provided documentation. Chapter 5.1.1 "MetOp Reference Orbit" changed from 5d/71 revs to 29d/412 revs Chapter 5.1.2 Incorrect Formula for Eccentric Anomaly on page 14 corrected.
Issue 1 Rev 00	25/09/01		First Release.
Issue 1 Rev 01	29/01/03	DCR.03.040	Chapter 2.3: NOAA-provided Local Orbital Reference Frame inserted (thus TBC eliminated)

			Chapter 5.3.1: Reference to TN added in order to supply and educated guess for NOAA-N, -N' orbits (NOAA official data still outstanding). Chapter numbering at level 5.1.* re-organised to improve readability. Chapter 5.1.2:minor typo corrected ("nhanced SPOT model")
Issue 1 rev 2	02DEC2004	EUM.SYS.DCR.04.0098 and EUM.SYS.DCR.04.0182 EUM.SYS.DCR.05.226	2. Metop Naming Convention inserted. Reworking of the ref. frame descriptions: 3.2.1 3.2.2 3.2.3 3.2.5 3.2.10 3.3.1 4.1 5.1.3 (PSO definition range inserted). Same for true latitude. 5.1.6 (ANX definition and range inserted) Chapter 6 (Time Reference Systems): some clarifications added. 7.1.1 Metop Reference Orbit 7.3 NOAA Orbit inserted. Cross-references updated in entire doc.Typo corrected in par. 7.6.3: MJD2000 instead of JD2000. Chapter 6 re-written (Date & Time References and Formats). Figure 1 corrected. SSST requested changes inserted. Caption numbering re-worked.

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1 INTRODUCTION

1.1 Scope

This document describes in detail the time references and formats, co-ordinate systems, parameters, models, and units that will be used by the EPS Mission.

1.2 Reference Documents

RD. 1 EPS System Requirements Document EUM.EPS.SYS.REQ.93001 issue 4.4 06/11/2003

RD. 2 OAD Standards: Time and Coordinate Systems for ESOC Flight Dynamics Operations. Orbit Attitude Division, ESOC. Issue 1. May 1994.

RD. 3 Explanatory Supplement to the Astronomical Almanac for the year 1992

RD. 4 GPS Theory and Practice, B. Hofmann-Wellenhof, H. Lichtenegger and J. Collins, Springer Verlag, New York.

RD. 5 NOAA KLM User's Guide Appendix B, http://www2.ncdc.noaa.gov/docs/klm/html/b/app-b.htm

RD. 6 MISSION CFI SOFTWARE – CFI CONVENTIONS DOCUMENT, MO.TN.ESA.SY.0194, issue 1.1, 16/08/99.

RD. 7 EPS/Metop Technical Note on Orbit Prediction, GMV-EPSFDS-TN-002

RD. 8 Celestrak WWW, a Web page by Dr TS Kelso containing detailed description of the TLE format and the SGP4 orbit propagation model. http://www.celestrak.com.

RD. 9 U.S. Standard Atmosphere 1976, National Oceanic and Atmosphere Administration

RD. 10 Handbook of geophysics and the space environment, Adolph S. Jursa. Air Force Geophysics Laboratory. 1985.

RD. 11 Low precision formulae for planetary positions in Astrophysical Journal Supplement Series: 41, p391-411. T.C. Van Flandern, K.F. Pulkkinen. November 1979.

RD. 12 Optical Properties of the Atmosphere, R. McClatchey, R. Fenn, J. Selby, J. Garing and F. Volz, AFCRL Environ. Res.pap 331,US Air Force Cambridge Res Lab, Bedford Mass.

RD. 13 Global 30-Arc-Second Elevation Data, http://edcwww.cr.usgs.gov/Webglis/glisbin/guide.pl/glis/hyper/guide/gtopo_30.

RD. 14 World Geodetic System 1984 DMA-TR-8350.2. The Defense Mapping Agency. Second Edition. 1 Sept 1991.

RD. 15 Method of Bowring NGT Geodesia 93-7, p333-335, 1993.

RD. 16 Dennis McCarthy and Gerard Petit, "IERS Conventions 2003", IERS Technical Note No. 32, 2004

RD. 17 Physical Geodesy. Weikko A. Heiskanen, Helmut Moritz, Graz, 1987

RD. 18 NOAA Satellites Time and Clocks Definitions; Section 16.0 16.1 General Description. NOAA/TIROS Program EUM.EPS.SYS.TEN.01.010.*.

RD. 19 Technical Note on NOAA-N and NOAA-N' Reference Orbit. EUM.EPS.SYS.TEN.02.021 issue 1 rev. 0 dated 18NOV2002.

RD. 20 GENERIC PRODUCT FORMATSPECIFICATION, EPS.GGS.SPE.96167, issue 6.4 dated 11/02/03

RD. 21 J.J.F. Liu and R.L. Alford, "Semianalytic Theory for a Close-Earth Artificial Satellite", Jour. Of Guidance and Control, 79-0123R, Vol. 3, No. 4, Jan. 15-17, 1979.

1.3 Applicable Documents

None.

2 METOP NAMING CONVENTION

The EPS space segment elements (Metop satellites) are named according to their launch sequence as:

Metop-A (first element to be launched)
Metop-B (second element to be launched)
Metop-C (third element to be launched)

For internal data processing purposes, the satellite acronyms are M01, M02, and M03, where the sequential number refers to the satellite production number. In the EPS programme, the candidate for the first launch is the second Metop built, therefore the first Metop to be launched shall be known as Metop-A for all external correspondence and M02 in the data processing and operational chains.

3 COORDINATE FRAME DEFINITIONS

3.1 General Coordinate Frames

This section provides descriptions of the reference co-ordinate systems that are used in the EPS context. In general a detailed description of those co-ordinate systems are described in RD. 3

3.1.1 Barycentric Mean-of-2000.0

It is based, according to the recommendations of the International Astronomical Union (IAU), on the star catalogue FK5 for the epoch J2000.0. The directions of co-ordinate axes are defined relative to a given number of star catalogue positions and proper motions.

The accuracy of this reference system, realised through the FK5 star catalogue, is approximately 0.1’’.

The center of this co-ordinate system is the barycenter of the Solar system. The x-y plane coincides with the predicted mean Earth equatorial plane at the epoch of J2000.0, and the x-axis points towards the predicted mean *vernal equinox*, the ascending node of the ecliptic on the Earth’s equator. The ecliptic is the mean plane of the Earth’s orbit around the Sun. The z-axis points towards north.

The word *mean* indicates that the relatively short periodic nutations of the Earth are smoothed out in the calculation of parameters for the reference epoch J2000.0.

3.1.2 Heliocentric Mean-of-2000.0

It is obtained by a parallel translation of the Barycentric Mean-of-2000.0 co-ordinate system from the barycenter of the Solar system to the center of the Sun.

3.1.3 Geocentric Mean-of-2000.0

It is obtained by a parallel translation of the Barycentric Mean-of-2000.0 co-ordinate system from the barycenter of the Solar system to the center of the Earth. The Cartesian co-ordinates in the Mean-of-2000.0 co-ordinate system refer to the mean equinox of J2000.0 and mean equator of J2000.0.

3.1.4 Mean-of-Date

The centre of this co-ordinate system is the centre of the Earth. The x-y plane coincides with the predicted mean Earth equatorial plane and the x-axis points towards the predicted mean *vernal equinox of date*, the ascending node of the ecliptic on the Earth's equator. The ecliptic is the mean plane of the Earth's orbit around the Sun. The z-axis is perpendicular to the mean Earth equatorial plane. The Mean-of-2000.0 cartesian co-ordinates are transformed into the mean equator and equinox of date (or epoch) by correcting only for the effects of precession which is the secular effect of the gravitational attraction of the Sun and Moon on the equatorial bulge of the Earth.
All co-ordinate systems are inertial ones, excluding of course the Earth-fixed and topocentric systems.

3.1.5 True-of-Date

The centre of this co-ordinate system is the centre of the Earth. The x-y plane and the x-axis are defined by the true (or instantaneous) Earth equatorial plane and the true (or instantaneous) vernal equinox-of-Date. The transformation from the mean equator and equinox of date to the true-of-date co-ordinate system involves correcting for the nutation effect defined by the adopted model of the nutation of the Earth which comprises of the short periodic gravitational perturbations due to the Moon and planets acting on the Earth's equatorial bulge.

3.1.6 True Equator and Mean Equinox-of-Date

The centre of this co-ordinate system is the centre of the Earth. The x-y plane and the x-axis are defined by the true Earth equatorial plane and the mean vernal equinox-of-Date.
The expression *true equator and mean equinox-of-Date* indicates the usage of the instantaneous Earth equatorial plane and mean vernal equinox. Thus, the relatively short periodic nutations of the Earth are used in the specification of the x-y plane. However, the direction of the x-axis, which in this case coincides with the mean vernal equinox, is defined by taking into account the precession of the vernal equinox but ignoring the nutation of the Earth's obliquity.

3.1.7 IERS Terrestrial Reference Frame (ITRF)

The Earth fixed co-ordinate system in use is the *IERS Terrestrial Reference Frame* (ITRF), RD. 16 The zero longitude, or IERS Reference Meridian (IRM), as well as the IERS Reference Pole (IRP), are maintained by the International Earth Rotation Service (IERS), based on a large number of observing stations, and define the IERS Terrestrial Reference Frame (ITRF).
This co-ordinate system is body-fixed and rotates with the Earth, therefore velocities expressed in this co-ordinate system include the rotation of the Earth.

3.1.8 Topocentric

Its z-axis coincides with the normal vector to the Earth's Reference Ellipsoid, positive towards zenith. The x-y plane is the plane orthogonal to the z-axis, and the x-axis and y-axis point positive, respectively, towards east and north.

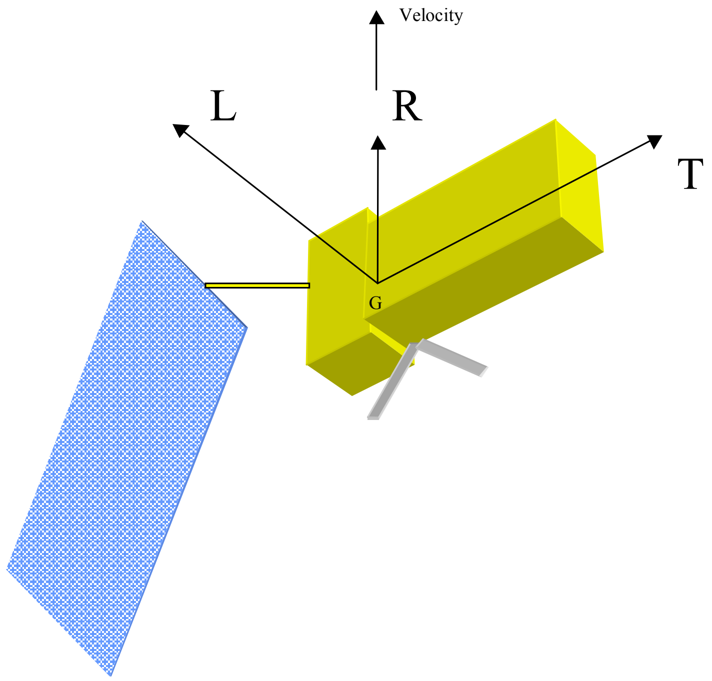
3.2 MetOp Coordinate Frames

Section 2.2 describes the co-ordinate frames that relate directly to the Metop spacecraft and its instruments.

3.2.1 Local Orbital Reference Frame (T, R, L)

The origin of the Local Orbital Reference Frame is the satellite in-flight centre of mass G.

The unit vector **L** is in the direction opposite to the Earth's centre, [Geocentre].
The unit vector **T** is normal to the plane defined by **L** and the satellite inertial velocity vector V, such that **T** is parallel to (V x L)
The unit vector R completes the right-hand reference frame: R = (LxT).
R lays on the plane defined by L and V.



[T: Tangage, R: Roulis, L: Lacet]

3.2.2 Local Relative Orbital Reference Frame (T_1, R_1, L_1)

The Local Relative Orbital Reference Frame ($\mathbf{T_1}$, $\mathbf{R_1}$, $\mathbf{L_1}$) has the same definition as the Local Orbital Reference Frame (**T**, **R**, **L**) except for the local normal pointing as follows.

The unit vector **L** is parallel to the local normal of the Earth's reference ellipsoid (WGS84 model, RD. 14) directed upward and crossing the spacecraft centre of mass G.

The Local Relative Orbital Reference frame defines the absolute pointing of the satellite for the Local Normal Pointing Mode with T1, $\mathbf{R_1}$, $\mathbf{L_1}$ being the pitch roll and yaw axes respectively.

3.2.3 Local Relative Yaw Steering Orbital Reference Frame (T', R', L')

The Local Relative Yaw Steering Orbital Reference Frame is applicable to the Yaw Steering Mode (YSM). It has the same definition as the Local Orbital Reference Frame (**T**, **R**, **L**) except for the local normal pointing and for its orientation with respect to the spacecraft velocity vector as follows.

Local Normal Pointing **L'** = $\mathbf{L_1}$.
The unit vector **R'** perpendicular to **L'** is in the direction of **V'** which is the velocity vector of the sub-satellite point relative to the earth model surface (relative ground trace velocity vector) taking into account a plane elliptical orbit with the orbital elements specified in paragraph 7.1.1.

The Local Relative Yaw Steering Orbital Reference Frame defines the absolute pointing of the satellite for the Yaw Steering mode (YSM) with **T'**, **R'**, **L'** being the pitch, roll and yaw axes respectively.

3.2.4 Satellite Reference Frames (X_s, Y_s, Z_s)

The origin of the Satellite Reference Frame ($\mathbf{X_s}$, $\mathbf{Y_s}$, $\mathbf{Z_s}$) is on the centre-line of the spacecraft at its intersection with the satellite launcher adapter interface plane. The $\mathbf{X_s}$ axis coincides with the longitudinal (downward vertical) axis of the satellite on the launch vehicle. The $\mathbf{Z_s}$ axis coincides with the outward normal to the surface carrying the stowed solar array and the $\mathbf{Y_s}$ axis forms a right-handed orthogonal set.
In orbit, when the satellite is being yaw steered, the satellite orientation shall be such that the $-\mathbf{Z_s}$ axis is aligned close to the downward local normal (Nadir), the $-\mathbf{Y_s}$ axis is aligned close to the ground track velocity direction and the $\mathbf{X_s}$ axis completes a right-handed orthogonal set.

3.2.5 Piloting Reference Frame (X_{PIL}, Y_{PIL}, Z_{PIL})

The Piloting Reference Frame is the frame to which the attitude control is performed and is normally aligned with an instrument line-of-sight. The angle between the unit vectors of the reference frame ($\mathbf{X_A}$, $\mathbf{Y_A}$, $\mathbf{Z_A}$) and the local Relative Yaw Steering Orbital Reference Frame (**T'**, **R'**, **L'**) are the pointing errors due to the AOCS in yaw steering mode (YSM) after a 180° rotation around the spacecraft $\mathbf{Z_A}$ axis (i.e. positive pitch and roll errors in the attitude reference frame are negative with respect to the Local Relative Yaw Steering Orbital Reference Frame).
The origin of the frame is the satellite centre of mass. The approximate direction of the Piloting Reference Frame axes are:
Pitch axis parallel to $\mathbf{X_{PIL}} = +\mathbf{X_S}$
Roll axis parallel to $\mathbf{Y_{PIL}} = +\mathbf{Y_S}$
Yaw axis parallel to $\mathbf{Z_{PIL}} = +\mathbf{Z_S}$
Note: This frame shall be characterised with respect to the satellite mirror cube defined in section 3.2.7.

3.2.6 Attitude Reference Frames (X_A, Y_A, Z_A)

The Attitude Reference Frame ($\mathbf{X_A}$, $\mathbf{Y_A}$, $\mathbf{Z_A}$) is that frame to which the attitude measurement is performed.
This frame is obtained by translation of the Piloting Reference Frame ($\mathbf{X_{PIL}}$, $\mathbf{Y_{PIL}}$, $\mathbf{Z_{PIL}}$) origin to the position of the AOCS optical sensor which ensures the AOCS performances.

3.2.7 Satellite Optical Reference Frames (X_{SO}, Y_{SO}, Z_{SO})

The Satellite Optical Reference Frame is defined by a reference mirror cube located at a stable position on the payload module.
Note 1: It shall remain visible throught the AIT phase and pre-launch check out.
Note 2: A secondary reference mirror cube shall be installed as a backup.
The unit vectors ($\mathbf{X_{SO}}$, $\mathbf{Y_{SO}}$, $\mathbf{Z_{SO}}$) shall be nominally parallel, and in the same sense to the unit vectors ($\mathbf{X_s}$, $\mathbf{Y_s}$, $\mathbf{Z_s}$).
The Satellite Optical Reference Frame shall be used for payload and satellite level alignments.

3.2.8 Instrument or Antenna Mounting Reference Frames (X_{AMP}, Y_{AMP}, Z_{AMP})

The Instrument or Antenna Mounting Reference Frame is defined for each physically separated unit (or antenna) which composes the instrument. The origin of the frame is the centre of the reference datum point which is physically represented by the centre of the mounting hole in the reference . One couple of axes will lie on the datum plane, defined as the plane of the instrument unit lugs. The axes of the Instrument or Antenna Mounting Reference Frame ($\mathbf{X_{AMP}}$, $\mathbf{Y_{AMP}}$, $\mathbf{Z_{AMP}}$) shall be nominally parallel to the Satellite Reference Frame ($\mathbf{X_s}$, $\mathbf{Y_s}$, $\mathbf{Z_s}$).

3.2.9 Instrument or Antenna Mirror Cube Reference Frames (X_{AMC}, Y_{AMC}, Z_{AMC})

For each instrument or antenna with identified alignment requirements the Mirror Cube Frame shall be realised through a mirror cube located near the mounting plane of the instrument/antenna.

3.2.10 Geocentric and Yaw Steering Mode definition

The geocentric commanded reference frame is the same as the fine acquisition mode commanded reference frame defined as follows (related to section 3.2.1):

- $\mathbf{Z_{sg}}$ is aligned with the direction from the Earth centre to the satellite centre of mass.
- $\mathbf{Y_{sg}}$ is in the orbit plane perpendicular to $\mathbf{Z_{sg}}$ closely aligned to the velocity vector direction.
- $\mathbf{X_{sg}} = \mathbf{Y_{sg}} \times \mathbf{Z_{sg}}$
  where $\mathbf{X_{sg}}$, $\mathbf{Y_{sg}}$, $\mathbf{Z_{sg}}$ is the satellite reference frame translated to the actual centre of mass.

The yaw steering mode provides the following change to the fine pointing mode (s. section 3.2.3):

- $\mathbf{Z_{sg}}$ (yaw) is aligned to the local normal (outward direction) of the Earth reference ellipsoid, WGS84.

- Compensation of Earth rotation effects is achieved by yaw steering the satellite so that the satellite roll axis projected on the tangential plane on the earth model surface at the geodetic sub-satellite point coincides with the projected relative velocity vector (relative ground trace velocity vector) between the geodetic subsatellite point and the earth model surface.

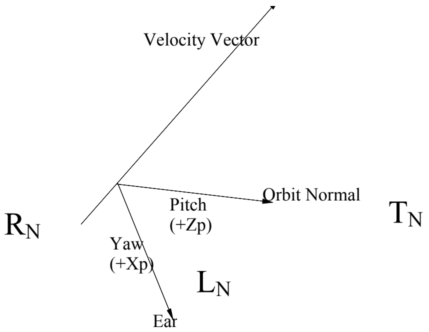
- The local orbital reference frame and the local relative yaw steering orbital reference frame applicable for the control law are defined in sections 3.2.1, “Local Relative Orbital Reference Frame (T, R, L)” and 3.2.3 “Local Relative Yaw Steering Orbital Reference Frame (T’, R’, L’)” respectively.

3.3 NOAA Coordinate Frames

3.3.1 Local Orbital Reference Frame

The NOAA local orbital reference frame definition is (see Appendix 2):
Unit vector L_N in the direction to Earth centre

Unit vector R_N in the opposite direction to the spacecraft velocity
Unit vector T_N completes the right-handed frame
($T_N = R_N$ x L_N)
where
T_N=Pitch axis
R_N=Roll axis
L_N=Yaw axis



Note that the positive direction for L_N is the opposite of the positive direction for the Metop L and the positive direction of R_N is opposite to the positive direction of the Metop R (which is aligned with spacecraft velocity)
The above-mentioned definitions are those followed by NOAA. The conversions between the NOAA local orbital Reference Frame [T_N R_N L_N] and the [T, R, L] frame used in the EPS Programme are given below (the "x" symbol denotes the cross-product operand):

R_N = -R
L_N = -L
$T_N = R_N$ x L_N =(-R) x (-L)=R x L

3.4 Coordinate System transformations

This section of the document identifies the co-ordinate system transformations that are relevant for MetOp.
Note that whenever a transformation is expressed as a sequence of rotations, the following expressions apply (the angle *w* is regarded positive clockwise):

$$R_x(w) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos w & \sin w \\ 0 & -\sin w & \cos w \end{bmatrix} \qquad R_y(w) = \begin{bmatrix} \cos w & 0 & -\sin w \\ 0 & 1 & 0 \\ \sin w & 0 & \cos w \end{bmatrix} \qquad R_z(w) = \begin{bmatrix} \cos w & \sin w & 0 \\ -\sin w & \cos w & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

where x, y and z are the respective axes of rotation.

3.4.1 Barycentric Mean-of-2000.0 to Geocentric Mean-of-2000.0

The transformation from the Barycentric Mean-of-2000.0 to the Geocentric Mean-of-2000.0 co-ordinate system is a translation, to move the co-ordinate system origin from the solar system barycentre to the earth centre. It is calculated with the following expressions:

$$\bar{r}_E = \bar{r}_B - \bar{r}_{B,Earth}$$
$$\bar{v}_E = \bar{v}_B - \bar{v}_{B,Earth}$$

where $\bar{r}_E$ and $\bar{v}_E$ are the position and velocity vectors in the Geocentric Mean-of-2000.0 co-ordinate system, $\bar{r}_B$ and $\bar{v}_B$ are the position and velocity vectors in the Barycentric Mean-of-

2000.0 co-ordinate system, and $\bar{r}_{B,Earth}$ and $\bar{v}_{B,Earth}$ are the position and velocity vectors of the Earth in the Barycentric Mean-of-2000.0 co-ordinate system.
$\bar{r}_{B,Earth}$ and $\bar{v}_{B,Earth}$ are calculated according to RD. 11.

3.4.2 Heliocentric Mean-of-2000.0 to Geocentric Mean-of-2000.0

The transformation from the Heliocentric Mean-of-2000.0 to the Geocentric Mean-of-2000.0 co-ordinate system is a translation, to move the co-ordinate system origin from the sun centre to the earth centre. It is calculated with the following expressions:

$$\bar{r}_E = \bar{r}_H - \bar{r}_{H,Earth}$$

$$\bar{v}_E = \bar{v}_H - \bar{v}_{H,Earth}$$

where $\bar{r}_E$ and $\bar{v}_E$ are the position and velocity vectors in the Geocentric Mean-of-2000.0 co-ordinate system, $\bar{r}_H$ and $\bar{v}_H$ are the position and velocity vectors in the Heliocentric Mean-of-2000.0 co-ordinate system, and $\bar{r}_{H,Earth}$ and $\bar{v}_{H,Earth}$ are the position and velocity vectors of the Earth in the Heliocentric Mean-of-2000.0 co-ordinate system.
$\bar{r}_{H,Earth}$ and $\bar{v}_{H,Earth}$ are calculated according to RD. 10

3.4.3 Geocentric Mean-of-2000.0 to Mean-of-Date

The transformation from the Geocentric Mean-of-2000.0 to the Mean-of-Date co-ordinate system is a rotation, to take into account the precession of the earth rotation axis. It is performed with the following expression:

$$\bar{r}_m = R_z\left(-\frac{\pi}{2} - z\right) R_x(\theta) R_z\left(\frac{\pi}{2} - \zeta\right) \bar{r}_{J2000}$$

where $\bar{r}_m$ and $\bar{r}_{J2000}$ are the position vector in the Mean-of-Date and the Mean-of-2000.0 co-ordinate system, respectively.

3.4.4 Mean-of-Date to True-of-Date

The transformation from the Mean-of-Date to the True-of-Date co-ordinate system is a rotation, to take into account the nutation of the earth rotation axis. It is performed with the following expression:

$$\bar{r}_t = R_z(-\delta\mu) R_x(-\delta\varepsilon) R_y(\delta\upsilon) \bar{r}_m$$

where $\bar{r}_t$ and $\bar{r}_m$ are, respectively, the position vector in the True-of-Date and the Mean-of-Date co-ordinate system.

3.4.5 Mean-of-Date to True Equator and Mean Equinox-of-Date

The transformation from the Mean-of-Date to the True Equator and Mean Equinox-of-Date co-ordinate system is a rotation, to take into account the nutation of the earth rotation axis for the calculation of the instantaneous equatorial plane.
The formulae to perform this transformation are given in RD. 3.

3.4.6 True Equator and Mean Equinox-of-Date to True-of-Date

The transformation from the True Equator and Mean Equinox-of-Date to the True-of-Date co-ordinate system is a rotation, to take into account the nutation of the Earth's obliquity (the angle between the equatorial plane and the ecliptic).
The formulae to perform this transformation are given in RD. 3

3.4.7 True-of-Date to Earth fixed

The transformation from the True-of-Date to the Earth fixed co-ordinate system is a rotation, to take into account the earth rotation. It is performed with the following expression:

$$\bar{r}_e = R_z(H)\bar{r}_t$$

where $\bar{r}_e$ and $\bar{r}_t$ are, respectively, the position vector in the Earth fixed and in the True-of-Date co-ordinate systems. H = Greenwich hour angle of the true equinox of date (see chapter7.6.3).

4 EPS-SPECIFIC DEFINITIONS

The orbital state vectors (OSV) are computed and made available by Flight Dynamics Facility (FDF) to the rest of Core Ground Segment (CGS) in any one of the following co-ordinates systems:

A. Geocentric True of Date
   X points toward the true vernal equinox and Z points along the true rotation axis of the Earth at the Orbit Epoch.
B. Geocentric Mean-of-Date
   X points toward the mean vernal equinox and Z points along the mean rotation axis of the Earth at the Orbit Epoch.
C. Geocentric Mean Equatorial of J2000
   X points toward the mean vernal equinox and Z points along the mean rotation axis of the Earth on 1 Jan 2000 at 12:00:00.00 TDB, which corresponds to JD 2451545.0 TDB (see also RD. 3 page 55-56). For TDB definition, please see Appendix 1
D. Geocentric True Equator and Mean Equinox of Date
   X points toward the mean vernal equinox and Z points along the true rotation axis of the Orbit Epoch.
E. ITRF Earth fixed frame
   X is fixed at 0 degrees longitude, Y is fixed at 90 degrees longitude, and Z is directed toward the north pole.

Inside the CGS the Cartesian state vector shall be expressed in Earth-fixed frame (case E above) and the Keplerian state vector shall be expressed in True of Date frame (case A above). Moreover, the generated products and other output data shall follow this convention. The reference frames used are also described in the document “Generic Product Convention Document” [RD. 20].

For a detailed description of the OSV structure, please see 5.1

The ANX information and the geometric event file contain the state vector in Earth-fixed co-ordinate system for the first record in the file.

Other elements of the EPS system shall follow the same convention for their generated data, unless otherwise specified in the Interface Requirements Document and in the Interface Control Document.

4.1 Longitude Convention.

Inside the CGS, longitudes range from 0° to 180° for the hemisphere east of Greenwich and -179.999° to 0° for the hemisphere west of Greenwich. Products forwarded by CGS and other CGS output shall follow this convention.

Other elements in the EPS System shall follow the same convention for their output data, unless otherwise specified in Interface Requirements and/or Interface Control Documents.

5 SYSTEM PARAMETER AND CONSTANTS DEFINITION

5.1 Orbit Parameters

5.1.1 Cartesian state vector

It comprises the cartesian components of the position and velocity vectors of the satellite expressed in one of the Metop co-ordinate systems at a given epoch.

5.1.2 Orbit radius, velocity magnitude and components

The satellite **orbit radius,** *R***,** is the absolute magnitude of the satellite position vector $\overline{r}_{sc}$:

$$R = \left|\overline{r}_{sc}\right|$$

The **velocity magnitude,** *V***,** is the absolute magnitude of the satellite inertial velocity vector $\overline{v}_{sc}$:

$$V = \left|\overline{v}_{sc}\right|$$

The satellite **velocity** vector when is expressed in the True-of-Date co-ordinate system can be split into two **components**:

- Radial component: $\overline{v}_r = \overline{v}_{sc} \bullet \overline{Z}$
- Transversal component: $\overline{v}_t = -\overline{v}_{sc} \bullet \overline{Y}$

The radial component is the component along the **L** unit vector. The transverse component is the component along the **R** unit vector of the Local Orbital Reference co-ordinate system.

Where $\overline{Y}$ and $\overline{Z}$ are the direction vectors of the Satellite Reference co-ordinate system.

5.1.3 Osculating Kepler state vector

The osculating Kepler elements are equivalent to the cartesian state vector, at the corresponding time, expressed in the True-of-Date co-ordinate system.

The six Kepler elements, which define unambiguously the state vector, are:

- Semi-major axis (a)
- Eccentricity (e)
- Inclination (i)
- Argument of perigee (ω)
- Mean anomaly (M)
- Right ascension of the ascending node (Ω)

Other auxiliary elements, which are derived from the above six elements, are:

- Eccentric anomaly (E)
- True anomaly (υ)
- Mean latitude (β)

The relationships between these auxiliary elements and the six Kepler elements are:

$$\tan\frac{E}{2} = \sqrt{\frac{1-e}{1+e}}\tan\frac{\upsilon}{2}$$

$$\mathrm{M} = E - e\sin E \qquad \text{(Kepler's equation)}$$

$$\beta = \omega + \mathrm{M}$$

β is also known as PSO ("Position sur l' Orbite"). It is the angle marking the satellite position along the orbit and on the satellite orbital plane. PSO ranges from 0° (zero) at the ascending node to 359.999°. PSO is different from the satellite geodetic latitude. The above-mentioned PSO definition is also the definition contained in the Metop Flight Operations Manual for the angle used by the

Metop SVM as an independent variable for yaw steering laws implemented in the Central Flight Software. Other sources call this independent variable "mean latitude". For all platform guidance purposes in the EPS Programme, PSO is therefore the same as "mean latitude"

5.1.4 Mean Kepler state vector

The six osculating Kepler elements in the True-of-Date co-ordinate system can be averaged w.r.t. time from one ascending node to the next or one nodal period (or w.r.t. mean anomaly over 2Π radians, which is equivalent), to obtain the mean Kepler elements:

$$\bar{a}, \bar{e}, \bar{i}, \bar{\omega}, \bar{\Omega}, \bar{M}$$

A reference for defining the osculating Kepler elements with respect to the mean Kepler elements is RDXXX:

5.1.5 Equinoctial state vector

The osculating Kepler elements are usually replaced by the equivalent osculating equinoctial elements for quasi-equatorial and quasi-circular orbits:

$x_1 = a$
$x_2 = e_x = e \cos(\Omega+\omega)$
$x_3 = e_y = e \sin(\Omega+\omega)$
$x_4 = i_x = +2 \sin(i/2) \sin(\Omega)$
$x_5 = i_y = -2 \sin(i/2) \cos(\Omega)$
$x_6 = \Omega + \omega + M$

5.1.6 Ascending node, descending node, ascending node time, nodal period, absolute orbit number

The Metop orbit trajectory intersects the equatorial plane of the geocentric co-ordinate at two points. The intersection point at which the satellite moves from the Southern Hemisphere into the Northern Hemisphere at the equator is called the **ascending node.**
The intersection point at which the satellite moves from the Northern Hemisphere into the Southern Hemisphere at the equator is called the **descending node.**
The **ascending node time** is the UTC time of that ascending node.
The **descending node time** is the UTC time of that descending node.
The **relative time** is the time elapsed since the last ascending node until the current point in the orbit.
The **nodal period** of an orbit is the interval of time between two consecutive crossings of the ascending node.
Absolute orbital number: after a SOYUZ/Fregat launch from Baikonur, the Metop/Fregat composite shall follow an elliptical transfer orbit before Metop is injected into its reference orbit over Antarctica, approximately 69 minutes after lift-off. This Metop path after release from Fregat and before the first ascending node crossing is regarded as **absolute orbital number** zero (0). From then on, each time a new ascending node is crossed, the absolute orbit number is incremented by one.

5.1.7 Sub-satellite point, satellite nadir and ground track

The **sub-satellite point (SSP)** is the normal projection of the position of the satellite in the orbit on to the surface of the Earth's Reference Ellipsoid.
The **satellite nadir** is equivalent to the **sub-satellite point**.
The projection of the satellite motion along its orbit onto the Earth's Reference Ellipsoid is called the **ground track**.

5.1.8 Repeat cycle and cycle length

In sun-synchronous orbits, such as the MetOp orbit, ground track repeats its trace on the Earth's surface precisely after a constant integer number of orbits and days. The number of days of that period is called the **repeat cycle**, whereas the corresponding number of orbits is called the **cycle length.** After one repeat cycle, the satellite ground tracks form a grid over the surface of the earth. The number of days between one ground track in the grid and an adjacent one is referred to as a **sub-cycle**. A detailed description of the repeat cycles and cycle lengths pertaining to MetOp orbit constraints is given in (RD. 6).

5.1.9 Mean Local Solar Time and True Local Solar Time

The **Mean Local Solar Time** (MLST) is the difference between the right ascension of the selected point in the orbit, and the *mean longitude of the Sun*, L. This normally defines an angle, but is expressed in hours assuming 24 hours is a full circumference (2π).

$$MLST = (RA - L + \pi)\frac{24}{2\pi} \text{ [hours]}$$

The **True Local Solar Time** (TLST) is the difference between the right ascension of the selected point in the orbit and the right ascension of the Sun, RA_{Sun}, expressed in hours.

$$TLST = (RA - RA_{Sun} + \pi)\frac{24}{2\pi} \text{ [hours]}$$

The RA_{Sun} is calculated, in the Mean-of-Date co-ordinate system, according to RD. 11

5.2 Earth Related Parameters

Note that altitude refers always to geodetic altitude except when the contrary is explicitly said.

5.2.1 Geodetic position

The geodetic co-ordinates of a point, related to the Earth´s Reference Ellipsoid, are the **geocentric longitude** λ, **geodetic latitude** φ, and **geodetic altitude** h, represented in the following drawing:

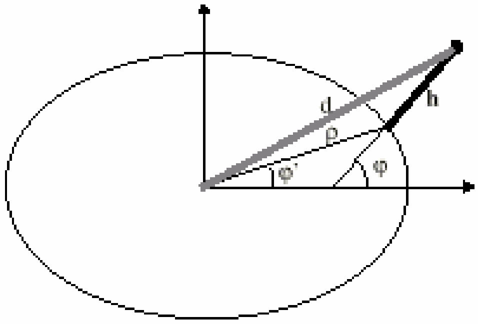


Figure 2: Geodetic position

The **geocentric latitude** φ', **geocentric radius** ρ and the **geocentric distance** d are also represented in that drawing.

The parameters **a**, **e** and **f**, i.e. the semi-major axis, the eccentricity and the flattening of the Earth's Reference Ellipsoid (see 5.4.1), define the equations that express these other parameters

The geocentric latitude φ' and the geodetic latitude φ are related by the expression:

$$\tan\varphi = \frac{1}{(1-f)^2}\tan\varphi'$$

The geocentric radius ρ is calculated with:

$$\rho = \frac{a\sqrt{1-e^2}}{\sqrt{1-e^2\cos^2\varphi'}}$$

The relationship between the cartesian co-ordinates of a point and its geodetic co-ordinates is:

$x = (N + h)\cos\varphi \cos\lambda$

$y = (N + h)\cos\varphi \sin\lambda$

$z = [(1-e^2)N + h]\sin\varphi$

where N is the **East-West radius of curvature**:

$$N = \frac{a}{\sqrt{1-e^2\sin^2\varphi}}$$

The inverse transformation, from the Cartesian to the geodetic co-ordinates, cannot be performed analytically. The iterative method that will be used will be initialised according to RD. 14.

The normal projection of a point on the surface of the Earth's Reference Ellipsoid is called **Nadir**, and when that point corresponds to the position of the satellite, the projection is called subsatellite point.

Another important radius of curvature is M, the **North-South radius of curvature** (unit is m):

$$M = \frac{a(1-e^2)}{\sqrt{(1-e^2\sin^2\varphi)^3}}$$

The **radius of curvature** in any selected direction R_{Az} can be calculated with the expression (unit is m^{-1}):

$$\frac{1}{R_{Az}} = \frac{\cos^2 Az}{M} + \frac{\sin^2 Az}{N}$$

where Az is the angle of the selected direction expressed in the Topocentric co-ordinate system.

The **satellite centred aspect angle** $\alpha_{s/c}$ is the angle measured at the satellite between the *geometric direction*[1] from the satellite to the subsatellite point and the geometric direction from the satellite to the centre of the Earth.

The **geocentric aspect angle** α_g is the angle measured at the centre of the Earth between the geometric direction from the Earth centre to the subsatellite point and the geometric direction from the Earth centre to the satellite.

The **subsatellite point centred aspect angle** α_{ssp} is the angle measured at the subsatellite point between the geometric direction from the subsatellite point to the satellite and the geometric direction from the subsatellite point to the centre of the Earth.

The geodesic **distance** or **ground range** between two points that lie on an ellipsoid is by definition the minimum distance between those two points measured over that ellipsoid.

The **velocity** $\bar{v}_E$ **and** $\bar{a}_E$ **acceleration relative to the Earth**, i.e the Earth's Reference Ellipsoid, of a point that lays on its surface can be split into different components.

- Northward component, $\bar{v}_E \bullet \bar{N}$ or $\bar{a}_E \bullet \bar{N}$
- Eastward component, $\bar{v}_E \bullet \bar{E}$ or $\bar{a}_E \bullet \bar{E}$
- Groundtrack tangential component, $\bar{v}_E \bullet \bar{t}$ or $\bar{a}_E \bullet \bar{t}$
- Magnitude, $v_E = \left|\bar{v}_E\right|$ or $a_E = \left|\bar{a}_E\right|$
- Azimuth = the azimuth of the $\bar{v}_E$ or $\bar{a}_E$ vectors measured in the Topocentric co-ordinate system

where $\bar{N}$ and $\bar{E}$ are the North and East direction axes of the Topocentric co-ordinate system centred on that point, and $\bar{t}$ is the unitary vector tangent to the ground track at that point.

5.2.2 Ray path parameters

The path followed by the electromagnetic radiation, from its source, an observation target, to the proper instrument mounted on MetOp, is bent due to the atmospheric refraction when it crosses the Earth atmosphere.

The magnitude of the bending of that path is a function of the value of the relative refraction index along the path that crosses the atmosphere.

Some parameters related to the path are the **range** S, which is the length of that path, and the signal **roundtrip time** T_r , which is the time needed by the radiation to travel twice that distance (unit is s):

$$T_r = 2\frac{S}{c}$$

where c = 299792458 [ms^{-1}] is the velocity of the radiation in a vacuum.

The one-way travel time,$T_{one\text{-}way}$, is the time taken for a signal to travel the distance S.

$$T_{one-way} = \frac{S}{c}$$

[1] The geometric direction is defined by the straight line that connects the initial and the final point.

The **incidence angle** i of that path when it intersects an ellipsoid is the angle formed between the vector tangent at the path u, at the target from the target to MetOp, and the normal vector to that ellipsoid at the incidence point.

$$\cos i = u \bullet \overline{N}$$

The **tangent altitude** h_T is the minimum distance, i.e the geodetic altitude, between that path and the Earth´s Reference Ellipsoid, and the corresponding point in the path is called the **tangent point** $\overline{r}_T$:

The **two way Doppler shift** of the signal D_s reflected by a target, is a function of the frequency of the transmitted signal f_s , and of the change in the length of the path travelled by that signal in its roundtrip, namely twice the range-rate from the corresponding Earth fixed target to the satellite (unit is Hz)

$$D_{2s} = -2 f_s \frac{S}{c}$$

The **one way Doppler shift** is, obviously (unit is Hz):

$$D_{1s} = -f_s \frac{S}{c}$$

All these parameters are calculated according to the selected ray tracing model .

5.2.3 Earth centred direction

The parameters that define a direction from the centre of the Earth to a point in the True-of-Date co-ordinate system are the right ascension (α) and the declination (δ), shown in next figure

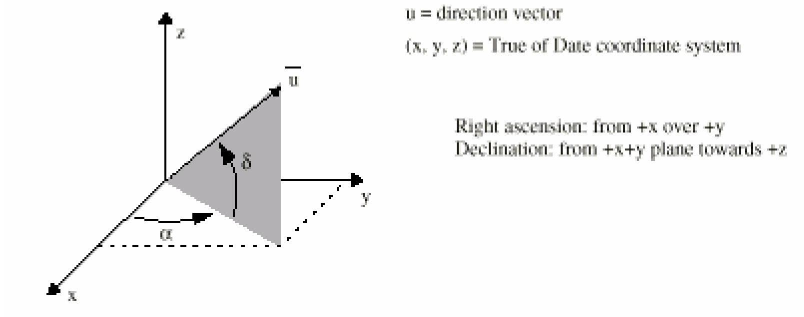


Figure 3: Earth centred direction

The same definitions can be used to define Earth centred direction in Mean of 2000 and Mean-of-Date co-ordinate systems.

5.2.4 Topocentric direction

The parameters that define a direction in the Topocentric co-ordinate system are the topocentric azimuth (Az) and the topocentric elevation (El), represented in the following drawing:

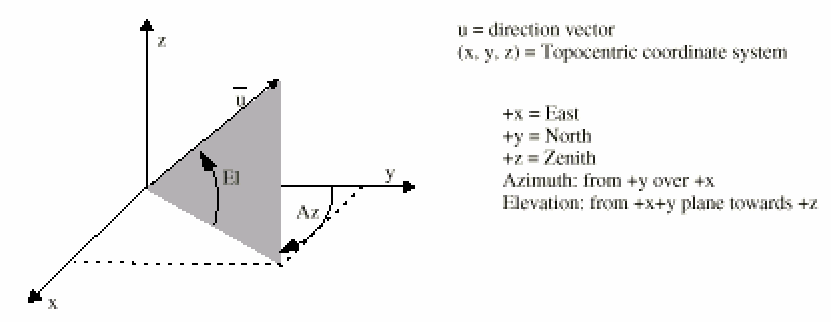


Figure 4: Topocentric direction

5.3 Ground Station Location Parameters

5.3.1 Ground station location

The **location** of a **Ground Station** is defined by its geodetic parameters: i.e. geocentric longitude λ, geodetic latitude φ, and geodetic altitude h wrt the Earth's Reference Ellipsoid.

5.3.2 Ground station visibility

The visibility of a point from a Ground Station is limited by the **minimum link elevation** at which that point must be in order for the link between that Ground Station and that point to be established. That minimum topocentric elevation is expressed in the Topocentric co-ordinate system centred at that Ground Station *(see section 5.2.4),* and although it is ideally a constant, in fact a real Ground Station usually has a physical mask that makes the minimum topocentric elevation be a function of the topocentric azimuth.

5.4 Scene and Target Parameters

5.4.1 Moving and Earth fixed targets

A **target** $\bar{r}_t$ is a point that is observed from the satellite and that satisfies certain conditions.

The **look direction**, or **line of sight** (LOS), $\bar{u}_0$ is the light direction, at the satellite, of the path followed by the light in its travel from the target to the satellite.
If the target moves wrt the Earth, as a result of a change in the satellite position or a change in the look direction, it is called the **moving target**.
If the target is fixed wrt the Earth, which implies that if the satellite position changes then the look direction has to change in the precise way to keep looking to that particular point fixed to the Earth, it is called the **Earth fixed target**.
In other words, the velocity of the moving target is the result of the motion of the satellite and the change in the look direction, or in the conditions that define it, with time. On the other hand, the velocity of the Earth fixed target is only a function of the position of that point wrt the Earth's Reference Ellipsoid and the rotation of the Earth fixed co-ordinate system.

5.4.2 Location parameters

The **location** of a **Target** is defined by its geodetic parameters: i.e. geocentric longitude λ, geodetic latitude φ, and geodetic altitude h wrt the Earth's Reference Ellipsoid, although it also can be defined by its cartesian position vector (x, y, z) expressed in the Earth fixed co-ordinate system.

5.5 Sun and Moon Parameters

The **Sun semi-diameter** D_{Sun} is the apparent semi-diameter of the Sun, expressed in degrees, as seen from the satellite, and is calculated with the equation:

$$D_{Sun} = \frac{d_{Sun}}{R_{Sun-SC}}$$

where $d_{Sun} = 6.96 \times 10^8$ [m] is the semi-diameter of the Sun, and R_{Sun-SC} is the geometric distance between the satellite and the Sun centre.
The **Moon semi-diameter** D_{Moon} is the apparent semi-diameter of the Moon, expressed in degrees, as seen from the satellite, and is calculated with the equation:

$$D_{Moon} = \frac{d_{Moon}}{R_{Moon-SC}}$$

where $d_{Moon} = 1738000$ [m] is the semi-diameter of the Moon, and $R_{Moon-SC}$ is the geometric distance between the satellite and the Moon centre.

The **area of the Moon lit by the Sun** $A_{Moon-Sun}$ is calculated with the expression:

$$A_{Moon-Sun} = \frac{1+\cos\theta_{Sun-Moon-SC}}{2}$$

where $\theta_{Moon-Sun-SC}$ is the angle measured at the centre of the Moon between the geometric direction from the centre of the Moon to the centre of the Sun and the geometric direction from the centre of the Moon to the satellite.

If $A_{Moon-Sun} = 0$ it is a new Moon, and if $A_{Moon-Sun} = 1$ it is a full Moon

The **satellite eclipse condition** exists when the path followed by the light from the centre of the Sun to the satellite intersects the Earth´s Reference Ellipsoid. The path is calculated according to the selected ray-tracing model.

The **satellite to Moon visibility condition** exists when the path followed by the light from the centre of the Moon to the satellite intersects the Earth´s Reference Ellipsoid along a path that is calculated according to the selected ray-tracing model.

The **target to Sun visibility condition** exists when the path followed by the light from the centre of the Sun to the target intersects the Earth´s Reference Ellipsoid, the path is calculated according to the selected ray-tracing model.

6 DATE AND TIME REFERENCES AND FORMATS

6.1 Time Reference Systems

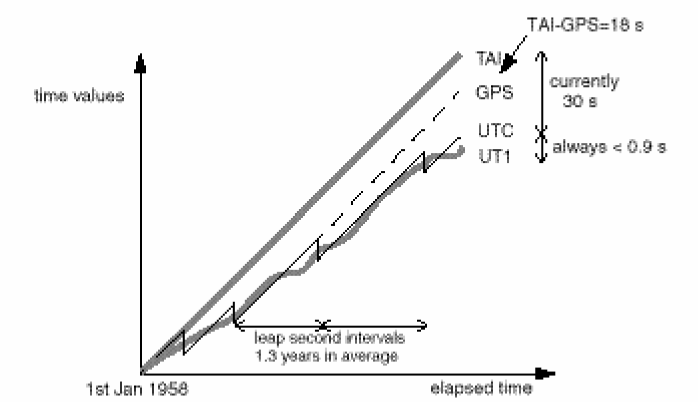
The following table identifies the time references that are used in the context of EPS.

Time Reference	EPS Usage
Universal Time 1 (UT1)	Used as time reference by the orbit propagator.
Universal Time Coordinated (UTC)	Used as time reference for all products datation, for the auxiliary files and for the orbit state vector.
International Atomic Time (TAI)	Not used directly, but it is related to GPS time
GPS Time	Used by the Global Positioning System (GPS).

Table 1: EPS time references

The relationships between UT1 and UTC are illustrated in the following drawing:

Figure 5: Relationships between UT1, UTC and TAI



Universal Time (UT1) is a time reference that conforms, within a close approximation, to the mean diurnal motion of the Earth. It is determined from observations of the diurnal motions of the stars, and then corrected for the shift in the longitude of the observing stations caused by the polar motion.

The time system generally used is the *Coordinated Universal Time* (UTC), previously called *Greenwich Mean Time*. UTC is the standard time for 0-degree longitude. The UTC is piecewise uniform and continuous, i.e. the time difference between UTC and TAI is equal to an integer number of seconds and is constant except for occasional jumps from inserted integer *leap seconds*. The leap seconds are inserted to cause UTC to follow the rotation of the Earth, i.e. to follow UT1. This is performed in the following way:

If UT1 is predicted to lag behind UTC by more than 0.9 seconds, a leap second is inserted. The message is distributed in a *Special Bulletin C* by the International Earth Rotation Service (IERS). The insertion of leap seconds is scheduled to occur with first preference at July 1st and January 1st at 00:00:00 UTC, and with second preference at April 1st and October 1st at 00:00:00 UTC.

DUT1 = UT1 - UTC is the increment to be applied to UTC to give UT1, expressed with a precision of 0.1 seconds, and which is broadcast, and any change announced in a *Bulletin D*, by the IERS[2].

[2] ΔUT1 usually changes 1-2 ms per day

DUT1 is the predicted value of UT1. Predictions of UT1 - UTC daily up to ninety days, and at month-ly intervals up to a year in advance, are included in a *Bulletin A,* which is published weekly by the IERS.
International Atomic Time (TAI) represents the mean of readings of several atomic clocks, and its fundamental unit is exactly one SI second at mean sea level and, therefore, evolves continuously at a constant rate.

GPS time has a constant offset of 19 seconds with the TAI and was coincident with UTC at the GPS standard epoch 1980, January $6.^{d}0$, [RD. 3 Explanatory Supplement to the Astronomical Almanac for the year 1992

RD. 4 GPS Theory and Practice, B. Hofmann-Wellenhof, H. Lichtenegger and J. Collins, Springer Verlag, New York.

RD. 5 NOAA KLM User's Guide Appendix B, http://www2.ncdc.noaa.gov/docs/klm/html/b/app-b.htm

RD. 6].

6.2 Time Parameters

6.2.1 Time Formats

The time formats for data exchanged between elements of the EPS system shall be described in Interface Requirements Documents, Interface Control Documents or Product Format Specification Documents.

6.2.2 Definition of Time Parameters

The following time parameters are defined in the EPS system. All of them refer to the UTC reference system.

ERT

Earth Received Time; the UTC time at which a TM frame has been received by the tracking station

TMUTC

Telemetered UTC (see 1); the UTC time calculated onboard the spacecraft. On Metop TMUTC is calculated from the OBT using the OBT/UTC correlation (that has been uploaded to the satellite). TMUTC can be found in the instrument source packets (ISP). Its value relies on the careful maintenance of the OBT/UTC coefficients onboard. Since these coefficients may not exactly reflect each OBT rollover or any unforeseen reset, the value of TMUTC is considered unreliable. Therefore this parameter is for information only and shall not be used in any data processing.

SCET

Spacecraft Event Time; the UTC time of an event onboard the spacecraft reconstructed on-ground. For Metop the SCET is calculated from the onboard time counters (CCU_OBT and ISP_OBT, see

6.3.1) using the OBT/UTC correlation. Ground operations will take care to ensure the correct reconstruction of SCET.

SCET = A_STEP * (OBT - OBT_0) + UTC_0

With:

OBT := CCU_OBT; CCU_OBT count is produced by a 2^8 Hz counter, see 6.3.1

or

OBT := ISP_OBT/256; ISP_OBT count is produced by a 2^16 Hz counter, see 6.3.1

and

A_STEP, OBT0, UTC0 are provided by the FDF in the so called OBT/UTC auxiliary file

Data processing in the CGS shall use SCET, i.e., the UTC generated on-ground via the OBT/UTC correlation provided by the FDF. This applies in particular to the generation of products (see 6.3.3). For NOAA, SCET is calculated on-ground by correcting the TMUTC (see 6.4.2).

6.3 Metop Time Data

6.3.1 Metop Onboard Clocks

The on-board times used in the context of MetOp are:

Time Reference and Format	Description	EPS usage
CCU_OBT	32-bit integer number: • 256 Hz counter	Processing of satellite housekeeping data
ISP_OBT	48-bit integer numbers: • 65536 Hz counter	Processing of instrument data

Table 2: MetOp On-board time

The On-Board Time (OBT) in the central communication unit (CCU) of Metop (a.k.a CCU_OBT, however, shown as "Satellite Binary Time (SBT)") is a 32 bit counter, incremented by 1 at a frequency of about 256 Hz. It varies from **00000000** (Hexadecimal) to **FFFFFFFF** (Hexadecimal), the next value being again **00000000** (Hexadecimal) and so on. This reset of the counter after **FFFFFFFF** (Hexadecimal) is called the **wrap-around** and occurs every 2^{32} counts (i.e. 4294967296 counts / 256 counts per second = 16777216 seconds) or 194.2 days. The reference time (or epoch) of the CCU_OBT is known and determined by the Satellite Control Centre. The **wraparound** or the **rollover** is equivalent to a modification of the epoch.

The On Board Time in the Instrument Source Packets (ISP_OBT in Figure 6, a.k.a. OBT_{48}) is a generic term used to represent any of the instrument counters to date their source packets. In MetOp, this counter is a 48 bit counter which includes 8 leading bits set to “0” for compatibility with the NOAA satellite onboard systems and where the 32 most significant bits not including the 8 leading 0’s are exactly synchronised with the CCU_OBT. The ISP_OBT is a 2^{16} Hz counter.

The following figure shows the relationship between CCU_OBT and ISP_OBT.

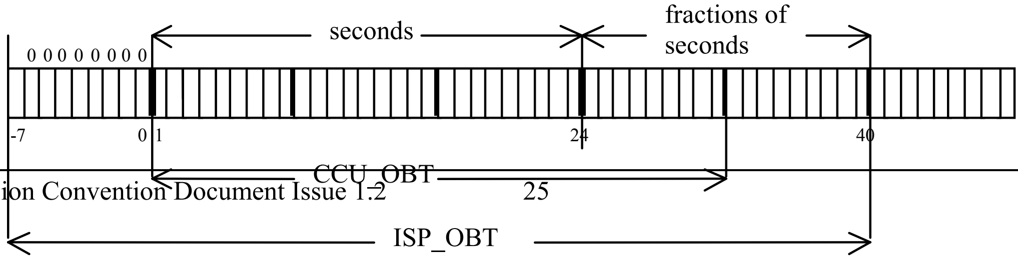


Figure 6: CCU_OBT and ISP_OBT relationship

6.3.2 Metop Onboard Calculated Time Data

TMUTC is calculated onboard based on the ISP_OBT count and the OBT/UTC coefficients that are regularly uploaded to the satellite. The relationship is:

TMUTC = A_STEP * (ISP_OBT/256 - OBT0) + UTC0

A_STEP, OBT0, UTC0 are calculated by the FDF and uploaded via telecommand to the satellite. The format of TMUTC in the instrument source packets is given in form of three integer numbers:

1. Integer days since 1-Jan-2000 (16 bit)
2. millisecond of the day (32 bit)
3. micro-seconds within the millisecond (16 bit)

6.3.3 Time Data in Metop Products

The time information given in the Metop products will correspond to SCET (see 6.2.2).

6.4 NOAA Time Data

NOAA uses time definitions that are different from the ones used on Metop. This section is devoted to the NOAA time definitions.

6.4.1 NOAA On-Board Times

There are several onboard clocks and counters onboard the NOAA spacecrafts (see “NOAA Satellites Time and Clocks Definitions; Section 16.0 NOAA/TIROS Program EUM.EPS.SYS.TEN.01.010*), but only the time code provided in the TIP frames and in the GAC frames are relevant for EPS. Both frames contain a 40-bit time code, which is identical in format and represents the UTC time onboard (TMUTC). Based on the time format the resolution of the onboard time is greater or equal to 1 ms.

	Designation	*Description*	*Numerical range*
9 bit	TimeCode_day	the day of year count (TimeCode_day = 1, means 1-Jan)	1 to 366 days
4 bit	Spare bits ("0101")		n/a
27 bit	TimeCode_millisecond	Millisecond of day count	0 to 86,399,999 ms

6.4.2 Time Data in NOAA Products

During product processing the UTC time found the telemetry (TMUTC) is corrected by any known inaccuracies. The corrected time (SCET) is then put into the products.

There are two sources reporting any offsets or drifts of the onboard clock.

1. the NOAA Clock Drift (CLKD) File

This file is sent by NOAA to the CGS. It contains offset and drift of the onboard clock allowing the correction of the time information received in the telemetry. The EPS products will contain the corrected time data.

2. the NOAA TBUS Bulletin

7 THE BULLETINS ARE PREPARED BY NESDIS (DAILY) AND TRANSMITTED THROUGH THE NATIONAL WEATHER SERVICE TELECOMMUNICATIONS GATEWAY (KWBC) TO MAJOR METEOROLOGICAL CENTERS AND RELAY POINTS AROUND THE WORLD, WHICH COMPRISE THE GLOBAL TELECOMMUNICATIONS SERVICE (GTS). THE GTS PRIMARILY SERVES THE INTERNATIONAL METEOROLOGICAL COMMUNITY. HOWEVER, THE TBUS BULLETIN RECEIVES FURTHER DISTRIBUTION VIA THE INTERNET, ELECTRONIC MAIL, HIGH FREQUENCY RADIO BROADCASTS AND COMMERCIAL DATA SERVICES.

7 MODELS

7.1.1 Metop Reference orbit

The orbit parameters for the reference orbit, with respect to the inertial Mean-of-Date System J2000.0 are given below:

Mean Element	Notation	Value
Semi-major axis	a	7195,605.347 m
Eccentricity	e	0.001165
Inclination	i	98.702198 deg
Ascending node	Ω	62.4731 + 0.98564735 * N Where N = number of Julian days from 1 Jan 2000
Argument of Perigee	ω	90.0 deg
Mean anomaly	M	270.133359 deg
MLST at ascending node	$MLST_{AN}$	21:30

Table 3: MetOp Nominal Orbit Elements

Note (1): The given Right Ascension of the Ascending Node corresponds to a longitude of the ascending node of 0.0 degrees on 01 Jan. 2000. This is equivalent to 09:30 hours mean local solar time of the descending node or 21:30 hours mean local solar time of the ascending node.

The mean period of this orbit is 6081.5534 seconds, therefore the number of orbits per day is 14.2068.

This leads to a repeat cycle of 29 days and a cycle length of 412 orbits. This a change from the original cycle of 5 days and cycle length of 71 orbits and was introduced to allow a more uniform ASCAT transponder coverage during the ASCAT calibration phases. Those phases take place for one month every year.

7.1.2 MetOp Orbit propagators

There are two orbit propagation models applicable to MetOp.

7.1.3 CFI Orbit Propagator

The CFI orbit propagation model can be used to calculate the spacecraft state vector (position and velocity) at any specified time (or epoch). It requires as input, the spacecraft cartesian state vector expressed in Earth fixed co-ordinates at a certain time in the initialization mode. The user can then propagate the spacecraft state vector to any desired time using either of two propagation modes depending on the level of accuracy required [RD. 6]

7.1.4 Enhanced SPOT orbit model

The Enhanced SPOT model [RD. 7] is used to calculate the orbit position of the spacecraft at a requested time. The user shall be able to extract the required input parameters from the MetOp administrative message.

7.2 MetOp attitude modes

The MetOp spacecraft operate in several attitude control modes whose purpose and (nominal) attitude are described in the following table:

Mode	Purpose	Attitude
Rate Reduction Mode (RRM)	Used during initial acquisition after the solar array secondary deployment, in re-acquisition case after failures, and also returning to nominal operations from safe mode. The RRM is intended to reduce the angular rates down to values lower than 0.3° / sec on each of the 3 axes using the thrusters.	Arbitrary attitude.
Coarse Acquisition Mode (CAM)	Allows to acquire a coarse geocentric pointing of the pitch and roll axis with an accuracy of the order of 5 degrees, while maintaining a small angular rate on the yaw axis	Arbitrary to Geocentric, rotating
Fine Acquisition Mode 1 (FAM1)	Performs yaw acquisition while maintaining a geocentric pointing on the pitch and roll axis. An automatic transition to FAM2 is initiated when the angles are accurate to less than 2 deg and the angular rates are less than 0.05 deg/sec on each axis.	Geocentric, rotating to FAM2 attitude.
Fine Acquisition Mode 2 (FAM2)	Stable waiting mode, ending the acquisition phase; it maintains satisfactory pointing performances while minimizing the hydrazine consumption.	The satellite attitude is aligned parallel to the Local Orbital Reference Frame.
Fine Acquisition Mode 3 (FAM3)	Transient mode between FAM2 and FPM. The main objective is to set up the wheel velocity to adequate initial value such that the wheel kinetic momentum transient is reduced when entering OPM.	Identical to FAM2 and FPM
Operational Mode (OPM)	This mode is automatically entered from FAM3. It results from the grouping of the FPM and YSM modes. This mode uses wheels and magnetotorquers for the fine control of the satellite.	
Fine Pointing Mode (FPM)	Steady-state transition mode between some thruster control modes and YSM.	The satellite attitude is aligned parallel to the Local Orbital Reference Frame (geocentric pointing). The FPM acronym is used for Envisat, but is retained in the Metop documentation for historical reasons. It is equivalent to Geocentric Mode.
Yaw Steering Mode (YSM)	Primary AOCS operational mode of MetOp. This mode is activated automatically after the FCM. This mode ensures local normal pointing and yaw steering of MetOp	The satellite attitude is aligned parallel to the Local Relative Yaw Steering Reference Frame. It moves wrt the Local Orbital Reference Frame according to the Local Normal Pointing and Yaw Steering laws.

Mode	Purpose	Attitude
Orbit Control Mode (OCM)	This mode is used for in-plane (semi-major axis and eccentricity updating) and out-of-plane (inclination updating) manoeuvres with long thrust durations.	For in-plane corrections, the commanded attitude is geocentric. For out-of-plane corrections, a rotation about the Z_s axis of $\pm 90^o$ from the geocentric pointing is performed.
Fine Control Mode (FCM)	It is used for in-plane orbit corrections with small amplitude. It can be entered only from the YSM mode.	Identical to YSM
Safe Mode	Ensures a survival state after a major service module anomaly	Heliocentric pointing of the $+Z_s$ face for the satellite, plus a spin motion around about the Z_s axis

Table 4: Attitude Control Modes

A description of the attitude rotation angles (roll, pitch and yaw) and the corresponding mispointing is given in [RD. 6]

7.3 NOAA orbits

7.3.1 Injection orbit

The orbit parameters for the NOAA-N reference orbit have been provided by NOAA in a private communication [Appendix 2] .
They refer to the orbit at injection (Beginning of Life).

SPACECRAFT NOAA-N (1234567)
THE FOLLOWING ORBITAL ELEMENTS ARE BROUWER MEAN TYPE
COMPUTED AND ISSUED BY GODDARD SPACE FLIGHT CENTER.
COORDINATE SYSTEM IS INERTIAL EARTH-CENTERED
TRUE OF DATE EQUATORIAL

EPOCH (YY MM DD HH MM SS.SSS)	4 6 30 11 27 41.000
SEMI-MAJOR AXIS	7230.2161 KM
ECCENTRICITY	00138866
INCLINATION	98.7347 DEG
R.A. OF ASC. NODE	128.8727 DEG
LONG. ASC. NODE DOT	9756 DEG/DAY
ARGUMENT OF PERIGEE	260.3966 DEG
ARG. PERI. DOT	-2.8418 DEG/DAY
MEAN ANOMALY	114.7061 DEG
PERIOD	101.9733 MIN
PERIGEE HGT	842.0394 KM
APOGEE HGT	862.1201 KM
VELOCITY AT PERIGEE	7.4353 KM/SEC
VELOCITY AT APOGEE	7.4146 KM/SEC
LATITUDE OF PERIGEE	-77.0461 DEG
EAST LONGITUDE	35.7282 DEG
GEODETIC LATITUDE	15.0343 DEG
HGT	861.1863 KM
X	-4161.51366426 KM
Y	5619.84369192 KM
Z	1867.15493749 KM
X DOT	2.06202207 KM/SEC
Y DOT	-.82561490 KM/SEC
Z DOT	7.08080482 KM/SEC

The NOAA-N and N’ operational orbit will be allowed to drift due to natural perturbations: there will be no orbit maintenance manoeuvres performed for either satellite.

7.3.2 NOAA orbit propagation models

Three NOAA specific orbit propagation models shall be used within the EPS System: Brouwer-Lydane Model, Two Line Element Model and Four Line Element Model.
To generate orbit information for ground antenna pointing purposes, where only moderate orbit accuracy is required, either the Brouwer-Lydane or the Two Line Element Model may be used. When higher orbit accuracy is required, such as in the processing of satellite instrument data, the more accurate Four Line Element Model should be used.

7.3.2.1 Brouwer-Lydane Model

The TBUS [RD. 5]is a national practice code form used by the United States to transmit information for predicting the path or locating the position of polar orbiting environmental satellites. It is transmitted daily, at about 1900Z, by KWBC Washington, DC, on the Global Telecommunications Service network.

In the TBUS message the orbital elements are provided in the form of Brouwer mean elements. They can be used as input to the Brouwer-Lydane orbit prediction model to determine the orbit position at a user requested time. The Brouwer-Lydane algorithm is an analytical solution of satellite motion for a simplified disturbing potential field that is limited to zonal harmonic coefficients J2 through J5.

The Brouwer-Lyddane orbit prediction algorithm is available on the Internet at http://www2.ncdc.noaa.gov/docs/klm/html/b/app-b.htm.

7.3.2.2 NORAD Two Line Elements (TLE)

The NORAD Two-line Element datasets contain orbital parameters in a compact form. They are designed to be used with an orbit model SGP4 [RD. 8] Each record for a satellite consists of three lines, the first with the satellite's name, and the next two with the data in a rigid format described in as follows:

Data for each satellite consists of three lines in the following format:

```
AAAAAAAAAAA
1 NNNNNU NNNNNAAA NNNNN.NNNNNNNN +.NNNNNNNN +NNNNN-N +NNNNN-N N NNNNN
2 NNNNN NNN.NNNN NNN.NNNN NNNNNNN NNN.NNNN NNN.NNNN NN.NNNNNNNNNNNNNN

Line 0 is a eleven-character name.
Lines 1 and 2 are the standard Two-Line Orbital Element Set Format identical
to that used by NORAD and NASA.  The format description is:
Line 1
Column     Description
 01-01     Line Number of Element Data
 03-07     Satellite Number
 10-11     International Designator (Last two digits of launch year)
 12-14     International Designator (Launch number of the year)
 15-17     International Designator (Piece of launch)
 19-20     Epoch Year (Last two digits of year)
 21-32     Epoch (Julian Day and fractional portion of the day)
 34-43     First Time Derivative of the Mean Motion
        or Ballistic Coefficient (Depending on ephemeris type)
 45-52     Second Time Derivative of Mean Motion (decimal point assumed;
           blank if N/A)
 54-61     BSTAR drag term if GP4 general perturbation theory was used.
           Otherwise, radiation pressure coefficient.  (Decimal point assumed)
 63-63     Ephemeris type
 65-68     Element number
 69-69     Check Sum (Modulo 10)
           (Letters, blanks, periods, plus signs = 0; minus signs = 1)
Line 2
Column     Description
 01-01     Line Number of Element Data
 03-07     Satellite Number
 09-16     Inclination [Degrees]
 18-25     Right Ascension of the Ascending Node [Degrees]
 27-33     Eccentricity (decimal point assumed)
 35-42     Argument of Perigee [Degrees]
 44-51     Mean Anomaly [Degrees]
 53-63     Mean Motion [Revs per day]
 64-68     Revolution number at epoch [Revs]
 69-69     Check Sum (Modulo 10)
All other columns are blank or fixed.
Example:
NOAA 6
1 11416U          86 50.28438588 0.00000140          67960-4 0  5293
2 11416  98.5105  69.3305 0012788  63.2828 296.9658 14.24899292346978
```

7.3.2.3 Four Line Elements (4LE)

The Four-line Element data sets contain orbital parameters in a compact form that allow a more accurate calculation of the satellite position than the TLEs. Each record for a satellite consists of four lines as follows:

Data for each satellite consists of three lines in the following format:

Line 1

Column	Description
01-05	Satellite Number
07-21	Epoch time
23-27	Epoch Rev Number
29-40	X-component of the position vector at epoch in kilometres
42-50	Y-component of the position vector at epoch in kilometres

Line 2

01-12	Z-component of the position vector at epoch in kilometres
14-26	X-component of the velocity vector at epoch in km/sec
28-40	Y-component of the velocity vector at epoch in km/sec
42-54	Z-component of the velocity vector at epoch in km/sec

Line 3

01-10	Ballistic coefficient ($C_D A/m$) units m^2/kg
12-14	Daily solar flux at 10.7cm (F10) units 10^{-7} W/m^2
16-18	Average solar flux for 90 days at 10.7cm (F10) units 10^{-7} W/m^2
20-22	Planetary magnetic index (AP) units 2 * 10^{-5} gauss
25-29	Drag modulation coefficient (MBETA)
32-42	Radiation pressure coefficient (AGOM)
46-57	Time of ascending node in days since the beginning of the current year, Jan. 0, 0Z
60-64	Rev number corresponding to the ascending node

Line 4

01-10	Universal time correction in seconds
13-22	Universal time correction rate in milliseconds/day

7.4 Earth

7.4.1 Earth geometry

The geometry of the Earth is modelled by a Reference Ellipsoid, namely the WGS84.
The most important parameters of the WGS84 ellipsoid are [RD. 14]:

Mean Element	Notation	Magnitude
Semi-major axis	a	6378137 m
Flattening = (a - b)/a	f	1/298.257223563
Eccentricity = $((a^2 - b^2)/a^2)^{1/2}$	e	0.0818191908426
Semi-minor axis	b	6356752.3142 m

Table 5: WGS84 Ellipsoid Parameters

The minimum distance between two points located on an ellipsoid is the length of the geodesic that crosses those two points. This geodesic distance will be calculated according to [RD. 17]

The surface at a certain **geodetic altitude h** over the Earth's Reference Ellipsoid is defined by:

$$x = (N + h)\cos\varphi \cos\lambda$$
$$y = (N + h)\cos\varphi \sin\lambda$$
$$z = [(1-e^2)N + h]\sin\varphi$$

where N is the radius of curvature parallel to the meridian:

$$N = \frac{a}{\sqrt{1 - e^2 \sin^2 \varphi}}$$

and φ and λ are the geodetic latitude and geocentric longitude of a point on that ellipsoid.
Nevertheless, the surface at a certain geodetic altitude h over the Earth´s Reference Ellipsoid will be modelled as another ellipsoid, *concentric* with it, and with (a+h) and (b+h) as semi-major and semi-minor axis.
This simplification is quite accurate and has the advantage to allow the analytical calculation of the intersection or tangent points with such a surface.

7.4.2 Earth Gravity

The following geopotential constants are used in the orbit propagator models (see Section 5.1.2):

Parameter	Notation	Value
Equatorial radius of the Earth	R_e	6378136 m
Earth's Gravitational constant = GM	μ	$3.98600440 \times 10^{14}$ m^3 s^{-2}
Second zonal harmonic	J2	1082.626×10^{-6}
Third zonal harmonic	J3	-2.536×10^{-6}
Fourth zonal harmonic	J4	-1.623×10^{-6}

Table 6: Propagation Mode Constants

7.4.3 General Earth atmosphere

Standard Earth atmospheres will be used to model the atmoshere (e.g. the U.S Standard Atmosphere 1976, [RD. 8] or the McClatchey atmospheres, [RD. 11].
Specific measurement atmospheric related data products may deviate from this usage.

7.4.4 Refractive index

The refractive index is calculated with the Edlen's law [RD. 9], although neglecting the contribution of the partial pressure of the water vapour.

7.5 Sun and Moon

The Sun and Moon position and velocity in the True-of-Date co-ordinate system will be calculated according to [RD. 11]

7.6 Reference Models

This annex describes in detail the models mentioned throughout the document

7.6.1 Precession

The rotation angles of the precession model are calculated as follows [RD. 3]

$$\zeta = 0.6406161T + 0.0000839T^2 + 0.0000050T^3 \text{ [deg]}$$

$$z = 0.6406161T + 0.0003041T^2 + 0.0000051T^3 \text{ [deg]}$$

$$\theta = 0.5567530T - 0.0001185T^2 - 0.0000116T^3 \text{ [deg]}$$

where T is the TDB time expressed in the Julian centuries format (1 Julian century = 36525 days). However, the precession motion is so slow that the UTC time can be used instead of the TDB time, and therefore T can be calculated from t, the UTC time expressed in the JD2000 format, with the following expression:

$T = (t - 0.5)/36525$ [Julian centuries]

7.6.2 Simplified nutation

The rotation angles of the simplified nutation model are calculated with [RD. 3]

$$\delta\mu = \delta\psi \cos\varepsilon$$

$$\delta\upsilon = \delta\psi \sin\varepsilon$$

where ε is the obliquity of the ecliptic at the epoch J2000.0 (unit is deg):

$$\varepsilon = 23.439291$$

$\delta\varepsilon$ and $\delta\psi$ are expressed by the *Wahr* model taking only the nine largest terms, and <u>using UT1 instead of TDB as the time reference</u>.

7.6.3 Earth rotation

The **Earth rotation angle H** is the sum of the Greenwich sidereal angle and a small term from the nutation in the longitude of the equinox.

The Greenwich sidereal angle moves with the daily rotation of the Earth and is calculated with the Newcomb's formula according to international conventions as a third order polynomial, although the third order term will be neglected in our calculations.

The nutation term is calculated with the simplified nutation model.

$$H = G + \delta\mu$$

$$G = 99.96779469 + 360.9856473662860T + 0.29079 \times 10^{-12}T^2 \text{ [deg]}$$

where T is the UT1 time expressed in MJD2000.

Note that the transformation from the Mean-of-Date to the Earth fixed co-ordinate system can be performed in one step being the $\delta\mu$ rotation term cancelled out:

$$\bar{r}_E = R_z(G)R_x(-\delta\varepsilon)R_y(\delta\upsilon)\bar{r}_{qm}$$

7.6.4 Mean longitude of the Sun

The mean longitude $\bar{L}$ of the Sun represents the motion of the *mean Sun* and is given, in the Mean-of-Date co-ordinate system, by (
RD. 11):

$$\bar{L} = 280.46592 + 0.9856473516(t - 0.5) \text{ [deg]}$$

where *t* is the UT1 time expressed in the MJD2000 format.

The motion of the mean Sun has a constant mean longitude rate, namely = 0.9856473516 [deg/s]

7.6.5 Earth atmosphere

The Earth atmosphere is modelled as the U.S Standard Atmosphere 1976 but modified as follows:

- it ranges from Z = 0 Km to Z = 86 Km.
- the ratio M/M_0 decreases linearly from Z = 80 to Z = 86 Km.
- the linear relationship between T_M and H is replaced by either an arc of a circle or by a polynomial function in the vicinity of the points where the molecular-scale temperature gradient changes, in order to have a continuous and differentiable function $T_M = f(H)$

The U.S Standard Atmosphere 1976 is defined as follows (
RD. 9):
The air is assumed to be dry, and at altitudes sufficiently below 86 Km, the atmosphere is assumed to be homogeneously mixed with a relative-volume composition leading to a constant mean molecular weight M.
The air is treated as if it were a perfect gas, and the total pressure P, temperature T, and total density ρ at any point in the atmosphere are related by the equation of state, i.e. the perfect gas law, one form of which is:

$$P = \frac{\rho R T}{M}$$

where R = 8.31432 x 10^3 [Nm/(KmolK)] is the universal gas constant.
Besides the atmosphere is assumed to be in hydrostatic equilibrium, and to be horizontally stratified so that dP, the differential of pressure, is related to dZ, the differential of geometric altitude, by the relationship:

$$dP = -g\rho dZ$$

where g is the altitude-dependent acceleration of gravity, which can be calculated with the expression:

$$g = g_0\left(\frac{r_0}{r_0 + Z}\right)^2$$

where r_0 = 6356766 [m] and g_0 = 9.80665 [m/s^2], and that yields:

$$H = \frac{r_0 Z}{r_0 + Z}$$

where H is the geopotential altitude.
The molecular-scale temperature T_M at a point is defined as:

$$T_M = T\frac{M_0}{M}$$

where M_0 = 28.9644 [kg/kMol] is the sea-level value of M.
In the region from Z = 0 Km to Z = 80 Km M is constant and M = M_0, whereas between Z = 80 Km and Z = 86 Km, the ratio M/ M_0 is assumed to decrease from 1.000000 to 0.9995788.
Up to altitudes up to 86 Km the function T_M versus H is expressed as a series of seven successive linear equations. The general form of these linear equations is:

$$T_M = T_{M,b} + L_{M,b}(H - H_b)$$

The value of $T_{M,b}$ for the first layer (b = 0) is 288.15 [K], identical to T_0 the sea-level value of T.
The six values of H_b and $L_{M,b}$ are:

Subscript	Geopotential altitude H_b [km]	Molecular-scale temperature gradient LM,b [K/km]
0	0	-6.5
1	11	0.0
2	20	1.0
3	32	2.8
4	47	0.0
5	51	-2.8
6	71	-2.0
7	84.8520 (Z=86)	

Table 7: values of H_b and $L_{M,b}$

Finally, the pressure can be calculated with the following expressions:

$$P = P_b \left(\frac{T_{M,b}}{T_{M,b} + L_{M,b}(H - H_b)} \right)^{\frac{g_0 M_0}{R L_{m,b}}} \quad (L_{M,b} \neq 0)$$

$$P = P_b \cdot \exp\left[\frac{-g_0 M_0 (H - H_b)}{R T_{M,b}} \right] \quad (L_{M,b} = 0)$$

The reference-level value for P_b for b = 0 is the defined sea-level value $P_0 = 101325.0$ N/m^2 . Values of P_b for b = 1 through b ≥ 6 are obtained from the application of the appropriate equation above for the case when $H = H_{b+1}$.

7.6.6 Edlen's law

The relative refraction index m at any point in the atmosphere can be calculated with the Edlen's law:

$$m = 1 + N \times 10^{-6}$$

$$N = \left[a_0 + \frac{a_1}{1 - (\upsilon/b_1)^2} + \frac{a_2}{1 - (\upsilon/b_2)^2} \right] \frac{P}{P_0} \frac{(T_0 + 15.0)}{T} - \left[c_0 - (\upsilon/c_1)^2 \right] \frac{P_w}{P_0}$$

where P is the total air pressure in mb, T is the temperature in K, $P_0 = 1013.25$ mb, $T_0 = 273.15$ K, P_w is the partial pressure of water vapour in mb, and $\nu = 10^4/\lambda$ is the wave number in cm^{-1} for the wavelength λ in micrometers (

RD. 10

The constants in that equation are

$a_0 = 83.42$

$a_1 = 185.08$

$a_2 = 4.11$

$b_1 = 1.140 \times 10^5$

$b_2 = 6.24 \times 10^4$

$c_0 = 43.49$

$c_1 = 1.70 \times 10^4$

The total air pressure and the temperature will be the corresponding to the atmosphere previously described, and the term in the last equation that corresponds to the partial pressure of water vapour will be neglected and therefore not calculated.

7.6.7 Terrain Elevation Database

Terrain elevation models with global resolutions of approximately 1 km will be used within EPS. One example of such a model is the 'Global 30-Arc-Second Elevation Data Set' that was developed over a 3-year period through a cooperative effort led by the United States Geological Survey's (USGS) EROS Data Center (RD. 12 Op).

8 UNITS

In general, the units that will be used in the EPS mission will be the SI units, except for the angle that will use the **degree** instead of the **radian**.

Quantity	Unit	Symbol
Length	meter	m
Mass	kilogram	kg
Time	second	s
Thermodynamic temperature	kelvin	K
Amount of substance	mole	mol
Plane angle	degree	deg
Frequency	hertz	Hz
Pressure	pascal	Pa

Table 8: Units

APPENDIX 1: GLOSSARY

A.1 Abbreviations and Acronyms

AOCS Attitude and Orbit Control System

CAM Coarse Acquisition Mode

CFI Customer Furnished Item

CGS Core Ground Segment

FAM Fine Acquisition Mode

FK5 Fifth Fundamental Catalogue

FAM Fine Acquisition Mode

FCM Fine Control Mode

FDF Flight Dynamics Facility

FPM Fine Pointing Mode

IAU International Astronomical Union

IERS International Earth Rotation Service

ITRF IERS Terrestrial Reference Frame.

Julian Day Number: continuous day counter, defined to be 0 on the day starting at Greenwich mean noon on January 01, 4713 b.C. Julian proleptic calendar.

JD Julian Date. Julian day number followed by the fraction of the day elapsed since the last noon (Sun Transit at meridian).

J2000.0 The TDB (see definition) at 1/1/2000 at 12:00:00 or JD=2451545.0 TDB

LOS Line of Sight

LNP Local Normal Pointing

MLST Mean Local Solar Time

MJD2000 Modified Julian Date 2000. It is defined as MJD=JD-2400000.5. Thus a day in MJD begins at midnight of the civil day.

N/A Not Applicable

OBT On Board Time

OCM Orbit Control Mode

OPM Operational Mode

RRM Rate Reduction Mode

RMS Root Mean Square

SR Satellite Reference

SRR Satellite Relative Reference

SRAR Satellite Relative Actual Reference

SBT Satellite Binary Time

S/C Spacecraft

SI International System of Units

SSP Sub Satellite Point

TAI International Atomic Time

TBC To Be Confirmed

TBD To Be Defined

TDB (Barycentric Dynamical Time). It is the independent variable of equations of motion w.r.t. the barycentre of the solar system. TDB is determined from TDT by means of mathematical expressions.

TDT (Terrestrial Dynamical Time). It is theoretical time scale of apparent geocentric ephemerides of bodies in the solar system. It is linked to TAI such that currently TDT=TAI+32.184 seconds. TDT is often abbreviated as TT.

TLST True Local Solar Time

UT1 Universal Time UT1

UTC Co-ordinated Universal Time

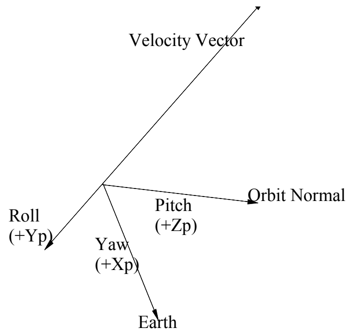
YSM Yaw Steering Mode

Appendix 2 : Applicable Documents

NOAA e-mail communication dated March 11, 2003
1. Can you confirm that all NOAA satellites to be supported by EUMETSAT are not going to perform orbit maintenance? - That is correct. Orbit maintenance will not be performed. The orbits will be maintained as they are today.

2. Can you provide me with the NOAA satellite Local Orbital Reference Frame definition? - NOAA reference frame definition:
Unit vector L in the direction to Earth center
Unit vector R in the opposite direction to the spacecraft velocity
Unit vector T completes the right-handed frame (T=RxL)
where

T=Pitch axis
R=Roll axis
L=Yaw axis



Coordinate system True of Date J1950 (This will be updated to TOD J2000).

3. We are using 1029.3 Kilograms for the spacecraft mass.

4. We are using 10.79 meters**2 for the spacecraft cross-sectional area

5. Drag coefficient and solar pressure coefficient are obtained from information provided in the 4-line message received daily. To stay in sync with the Air Force model we are using WGS-72 earth gravitational model of order 12 and degree 12 (will at some point change to WGS-84) and the Jacchia-Roberts atmospheric density model. The format of the 4-line element set is provided below with a current NOAA-16 4-line message.

```
&TOLIST  &END
26536 012752000 0.    5307  0036.663233 -1405.770849
-7095.799774 -5.74485780  -4.60690784   0.88516363
 .02848090 205 179  14  .9449 .0000500000  276.77135813  5321
-00.039827  -00.440000
ENDM
```

NORAD FOUR LINE MESSAGE

LINE #1: 1. I$SATN ---------- Satellite Number (5-digits)
2. EPOCH ---------- Epoch time in the form YYDDDHHMMSS.SSS
3. I$ERV ---------- Epoch Revolution Number (5 digits)
4. D$X ---------- Epoch X position component in kilometers
5. D$Y ---------- Epoch Y position component in kilometers

LINE #2 1. D$Z ---------- Epoch Z position component in kilometers
2. D$XD ---------- Epoch X velocity component in km/sec
3. D$YD ---------- Epoch Y velocity component in km/sec
4. D$ZD ---------- Epoch Z velocity component in km/sec

LINE #3 1. R$BLCF ---------- Ballistic coefficient in meters squared per kilogram
2. I$F ---------- Solar Flux at 10.7 centimeters
3. I$FAV ---------- Average Solar Flux for 3 months at 10.7 centimeters

4. I$A ---------- Planetary Magnetic Index
5. R$DG ---------- Drag Modulation Coefficient
6. R$SOLR ---------- Solar Radiation Pressure Coefficient in meters squared per kilogram
7. D$ND ---------- Time of Ascending Node in days since the beginning of the year DDD.DDDDDDDDD
8. I$NREV ---------- Revolution Number at ascending node time D$ND

LINE #4 1. D$UTC ---------- Universal Time Correction (seconds)
2. D$UTCD ---------- Universal Time Correction Rate milliseconds/day

Example of a four line message

```
26536 012752000 0.    5307  0036.663233 -1405.770849
-7095.799774 -5.74485780   -4.60690784    0.88516363
 .02848090 205 179  14  .9449  .0000500000   276.77135813    5321
-00.039827  -00.440000
```

LINE #1: 1. I$SATN ---------- 26536
2. EPOCH ---------- 01275200000.000
3. I$ERV ---------- 5307
4. D$X ---------- 0036.663233
5. D$Y ---------- -1405.770849

LINE #2 1. D$Z ---------- -7095.799774
2. D$XD ---------- -5.74485780
3. D$YD ---------- -4.60690784
4. D$ZD ---------- 0.88516363

LINE #3 1. R$BLCF ---------- .02848090
2. I$F ---------- 205
3. I$FAV ---------- 179
4. I$A ---------- 14
5. R$DG ---------- 0.9449 (constant)
6. R$SOLR ---------- .0000500000 (constant) in meters squared per kilogram
7. D$ND ---------- 276.77135813
8. I$NREV ---------- 5321

LINE #4 1. D$UTC ---------- -00.039827
2. D$UTCD ---------- -00.440000

NOAA e-mail communication dated November 07, 2002

Hi Antimo,
Attached is the first set of nominal vectors provided in preparation for the NOAA-N launch. We are checking them out with SOCC now. We normally use the Osculating Keplerian elements rather than the Brouwer Mean.
When there are changes or updates we will provide that information to you.
I will be out of town for the next two weeks. I plan to check my email, however please be sure to include Yan Wang on any emails should you need additional information.
Regards
Emily

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ORBITAL ELEMENTS REPORT

SPACECRAFT NOAA-N (1234567)

THE FOLLOWING ORBITAL ELEMENTS ARE BROUWER MEAN TYPE
COMPUTED AND ISSUED BY GODDARD SPACE FLIGHT CENTER.

COORDINATE SYSTEM IS INERTIAL EARTH-CENTERED
TRUE OF DATE EQUATORIAL

OUTPUT TVHF FRN 26 RECORD NO 429

EPOCH (YY MM DD HH MM SS.SSS)
4 6 30 11 27 41.000

SEMI-MAJOR AXIS	7230.2161 KM
ECCENTRICITY	.00138866
INCLINATION	98.7347 DEG
R.A. OF ASC. NODE	128.8727 DEG
LONG. ASC. NODE DOT	.9756 DEG/DAY
ARGUMENT OF PERIGEE	260.3966 DEG
ARG. PERI. DOT	-2.8418 DEG/DAY
MEAN ANOMALY	114.7061 DEG

PERIOD	101.9733 MIN
PERIGEE HGT	842.0394 KM
APOGEE HGT	862.1201 KM
VELOCITY AT PERIGEE	7.4353 KM/SEC
VELOCITY AT APOGEE	7.4146 KM/SEC
LATITUDE OF PERIGEE	-77.0461 DEG

EAST LONGITUDE	35.7282 DEG

GEODETIC LATITUDE	15.0343 DEG
HGT	861.1863 KM
X	-4161.51366426 KM
Y	5619.84369192 KM
Z	1867.15493749 KM
X DOT	2.06202207 KM/SEC
Y DOT	-.82561490 KM/SEC
Z DOT	7.08080482 KM/SEC