EUMETSAT POLAR SYSTEM	**EPS Program** **DJD Appendix A7-3** **OBT-to-UTC Correlation**	**EUMETSAT** Ref.: EPS.SYS.TEN.990036 Issue: 01 Rev. 05 WBS number: 230000 Date: 04 October 2004

EPS Program
DJD Appendix A7-3
OBT-to-UTC Correlation

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DOCUMENT CHANGE LOG

Issue	Revision	Date	DCN no.	Pages para. Affected	Reason for change
01	00	26/11/01	N/A	All	First Release
01	01	12/11/02	EUM.EPS.SYS. DCR.02.202	2.1.4	Changed concept about usage of on-board UTC data.
01	02	06/03/03	EUM.EPS.SYS. DCR.03.063	10 and 11	Formula Items clarified for easier understanding. Also minor typo in Equation 4 resolved.
01	03	13/01/04	EUM.EPS.SYS. DCR.03.063	All	Description of on-board and on-ground OBT-UTC correlation process including contributions for the generation of an error budget. These contributions were used to update the simulation of time data processing.
01	04	08/09/04	EUM.SYS.DCR. 04.0112 issue 1 (EPS.DCR.EUM. 553)	1,2,3,4 11,18	Requirements baseline clarified, traceability to FDF implementation and modelling as well as for validation tests
01	05	04/10/04	EUM.SYS.DCR. 04.0112 issue 2 (EPS.DCR.EUM. 573) .	10	With reference to EUM.EPS.GSE.FAX.04.209: Implementation of wrap around handling in FDF V 2.2

TABLE OF CONTENT

1 INTRODUCTION

The purpose of this document is to identify and assess the requirements on the correlation between the satellite-onboard-time (OBT) and "Coordinated Universal Time" (UTC). This will be achieved by first describing the steps required for the generation of OBT-UTC correlation and listing the relevant performance requirements. All the factors that influence the OBT-UTC correlation will be used to estimate the error budget. Background and Assumptions

The original version of this document (issue 1.0 dated 17/12/1999) has been thoroughly re-worked in order to analyse the effects of the oscillator drift. This has been implemented by running numerical simulations based on values provided by the spacecraft manufacturer and from values suggested by the experience with existing satellites having the same bus as METOP.

The current issue includes the light time and on ground errors and delays that influence the OBT-UTC correlation. This budget is intended to collect and quantify all factors which influence the OBT/UTC conversion as specified by the requirements. An estimate of the total expected error can be given for the point in time at which the correlation is being determined as well as for the evolution of the OBT/UTC accuracy over a period of 36 hours.

It should be mentioned that only a requirement for the OBT/UTC correlation accuracy at the time of determination is available:

CGSRD requirement CGS-MCF-5.2.6.5-0420:

"*The CGS shall compute the coefficients of a linear model allowing to maintain the OBT/UTC correlation with an accuracy better than 2 ms at the time of computation…*"

For any other time (i.e. 36 hours evolution), there is no requirement available.

In order to demonstrate the capability of the FDF to correctly estimate the OBT/UTC correlation, dedicated tests have been defined in EUMETSAT V&V Plan (see AD18, test cases 01-41a and 01-41c). For this tests real ENVISAT data as well as simulated OBT/UTC data generated by the ESOC FDF simulator will be processed by EUMETSAT FDF. These data will be converted to the MCS format and ingested to FDF for computing the OBT/UTC correlation. Visual comparison with ESOC results will finally be performed.

An estimate of the total expected error for the evolution of the OBT/UTC accuracy over a period of 36 hours based on the performed error budget is given in 3.1.2 and summarised in chapter 5.

EPS system features like time tagged command timing requirements or geolocation requirements do not constrain the OBT/UTC accuracy to values of 2 or 4 ms, rather to values much more relaxed than those (see chapter 4)

1.1 Open Issues

- Physical delay path in the ground station is known but electrical path delay is still to be numerically confirmed. Anyway its contribution to the budget should be negligible (nanoseconds, compared with 1 ms due to the time stamping unit).

1.2 Reference Documents

RD.1 METOP Satellite Technical Description MO.DD.MMT.SY.0001 issue 4 rev 0 dated 30/06/01

RD.2 EURD, EPS/MIS/REQ/93001, Issue 4, Rev 2.

RD.3 LRPT/HRPT Specification, EPS/SYS/SPE/95413.

1.3 Applicable Documents

AD1. Satellite System Requirements Document, MO-RS-ESA-SY-0023

AD2. Amendment Fax to AD.1 as far as overall time resolution is concerned Archive Code: C06946 (Correspondence) page 24 item R8

AD3. EPS Programme DJD Appendix A3-1 RAMS Requirements Justification issue 1 rev 0 21/06/01

AD4. Satellite System Requirements Document, MO-RS-ESA-SY-0023, Issue 7.

AD5. MMS, METOP System Requirement, MO.RS.MMT.SY.0001

AD6. MO-FX-MMT-166-96; CCU oscillator stability

AD7. CGSRD, EPS/GGS/REQ/95327.

AD8. Time drift caused by the onboard oscillator specified for METOP, EPS/SYS/TN/96275, issue 1, 19/04/96

AD9. NOAA Ground Segment (G/S) Interface Specification EPS.ASPI.IR.0260 version 1 issue 2

AD10. Metop Space to Ground ICD MO-IF-MMT-SY0001 issue 6 rev. 0

AD11. Frequency and Time Architecture Document EPS-IE-DD-0007- issue 2 rev. 1 January 2002

AD12. Command Ranging and Telemetry Unit Cortex ICD STI 100013-TTC- issue 1 rev. 2 January 2001

AD13. MCS Interfaces Specification EPS-ASPI-IR-0063 issue 4.1 09/04/03

AD14. EPS FDF Architectural Design Document EPS-GMV-DD-2405/01 issue 1.2 19/11/03

AD15. FDF Interfaces Specification EPS-ASPI-IR-0057 issue 1.3 27/02/02

AD16. Core MCS System Design Document ISI.383.0033.01 issue 1.0 02/04/02

AD17 OBT/UTC Correlation Model Description EPS-ASPI-SW-055 (EPS-GMV-TN-20589/04 Issue 1.1)

AD18 EPS Verification and Validation Plan EUM.EPS.SYS.PLN.01.003 Iss. 03 Rev 1

AD19 EUM.EPS.GSE.FAX.04.209

2 DESCRIPTION OF OBT/UTC CORRELATION PROCESS

All TM and mission data are time stamped on board with OBT provided by an on board free running clock.

Time information is generated in the Metop Central Computer Unit (CCU) of the Service Module, in the Payload Module Computer (PMC) and in the Instrument Control Units (ICUs for most instruments, MPU for MHS or NIU for the US Instruments).

In general each of those units derives the time reference from a counter incremented by means of a stable signal, which can either be generated inside the unit or derived from other units. Signal generation is actually achieved by using stable oscillators. Due to oscillator drifts or to problem in transferring the signals used to increment the various counters, the various time references are not synchronised among each other and therefore they do not provide the same value. Additionally, all time references on-board are, in general, not connected with the standard reference time used for all ground segment activities. This reference is the Co-ordinated Universal Time (UTC).

Onboard MetOp the timer of each instrument is synchronised to the OBT master clock, without influencing other users connected to the OBT bus. The instrument on-board time is also used for command block execution scheduling as well as for housekeeping and measurements datation. All on-board units are synchronised to this clock within an accuracy of 100 microseconds. (specified in AD.1 section 5.4).

In order to allow the correlation of the on-board time to UTC the ground station writes the earth-received time (ERT) into the header of each telemetry frame. This time corresponds to the UTC time of the reception of the leading edge of the first bit of the sync word in the S-Band telemetry frame. The reference for the ground station clock is a GPS receiver. (Specified as AD.11 section.4).

The Frequency & Time (F&T) subsystem at the groundstation provides GPS based time and frequency. The F&T subsystem uses GPS signals to obtain the precise time reference. The GPS signals also provide long term stability for the frequency reference. It is assumed that the GPS signal is always available with sufficient quality. The IRIG-B Time Distribution Unit extracts the IRIG-B time signal from the GPS signal received at the ground station and feeds it to the Cortex Units (Command Ranging and Telemetry Unit) and to the Time Server for further distribution to the Front End Processor (FEP) and other computers and workstations. The S-Band packets are time-stamped by the Cortex unit. For the X-Band packets the time tagging is performed via the FEP (Front End Processor).

The time-tag format can be selected in the Windows NT registry (i.e. numbers of seconds elapsed since 1-January of current year; as specified in AD.12) and the packets are sent to the MCS (Mission Control System).

The MCS generates a HKTM file to be used by FDF to retrieve information for calculating OBT/UTC time correlation coefficients. The file containing the time information (OBT transmission time and associated ERT, the time-stamp at TM reception on ground) is archived in the MCS in a directory available for Flight Dynamics (Specified as AD.13 section 3.5.2). These two times are then correlated to produce a relationship between the on-board time and the UTC time. The corrected on-board time represents the ground station UTC time at which the OBT is generated.

The FD OBT/UTC Time Correlation product is generated for each pass (about every 100 minutes) and sent to MCS.

Conversion of the OBT contained in the measurement data source packets to UTC is then performed according to the Time Correlation Product (Specified as AD.15 section 4.12) generated by Flight Dynamics and distributed by the (MCS) to the data processors. (Specified as AD.16).

The Time Correlation Product contains the constants of time correlation formula, which is of the form:

$$T_{UTC} = T_s * (OBT_K - OBT_0) + UTC_0$$

Equation 1 Correlation Formula

Where

- T_s is the duration of the OBT lsb (number of microseconds between two OBT ticks (1/256 seconds)
- OBT_k is the OBT value taken from the Instrument Source Packet (ISP) that needs to be converted to UTC
- OBT_0 is the Reference OBT.
- UTC_0 is the Reference UTC

The values of OBT_0, UTC_0 and T_S are those provided by Flight Dynamics. The UTC_0 timestamp is internally stored as standard Unix time, that is the number of standard[1] seconds and microseconds since midnight, January 1, 1970. Therefore T_{UTC} will also be expressed in standard UNIX time accordingly.

The time correlation information is then generated and uploaded via the DELTATIME macro command. The ICU on-board ensures that for UTC calculation consistent delta-time data is used, e.g., the DELTATIME macro command is loaded at the same time as the UTC calculation is due.

Descriptions of the main errors and delays for each individual contribution, both on-board and on-ground, are described in more detail in the following sections.

[1] Standard seconds do not include Leap seconds, i.e., each day is accounted for as 86400 seconds.

2.1 On-Board Time

Several units on Metop manage time information. Time references are used for the following purposes:

1. Synchronise activities among the various units of Metop SVM and PLM
2. Synchronise the data exchange between SVM and PLM
3. Provide an absolute reference for all events occurring in the service module
4. Provide an absolute reference for the generation of science data

Time information is generated in the Metop Central Computer Unit (CCU) of the Service Module, in the Payload Module Computer (PMC) and in the Instrument Control Units (ICUs for most instruments, MPU for MHS or NIU for the US Instruments).

Therefore two basic operational activities must be performed to maintain a unique and accurate reference time on board the satellite:

a) Achieve the correlation among all on-board times in order to remove the drift effects of individual clocks (time synchronisation)

b) Achieve the correlation between on-board time (OBT) and the UTC as computed on-ground (OBT/UTC correlation)

2.1.1 Description of CCU OBT

The CCU OBT is the main reference time on-board Metop and is also the only reference time available within the SVM. It is implemented by a series of hardware units and software functions.

The CCU carries a stable oscillator having a master oscillator frequency of 12.582912 MHz and an associated circuitry that generates a series of signals synchronised with the master oscillator signal. The signals affecting the determination of the CCU reference time are the H20 frequency (1 Hz) and the H12 frequency (256 Hz).

H12 is the signal used to increment a 16-bit register inside the CCU hardware.

H20 is used by the CCU Central flight Software (CFS) for two important reasons:

- Generate a broadcast (BCP2) into the SVM OBDH bus that is used by all remaining SVM units.
- Generate an interrupt (TM IT) used to synchronise all CCU software and hardware functions and to synchronise frame generation and frame transmission activities.
- Stamp each TM frame with an OBT that is within 100 µs of the transmission time of the at TM frame.

Updating the CCU OBT is triggered by the H20-driven TM IT signal. The TM IT causes the CCU to increment the OBT by 16 and to reset the CCU Time Register content.

2.1.2 OBT Synchronisation

It is important to note that the CCU OBT is always downlinked, since it is stored in the header of each S-Band TM frame generated by the CCU. The correlation of the on-board time to UTC is done based on the UTC stamp that is generated in the TT&C ground station and which corresponds to the reception of the leading edge of the first bit of the sync word in the S-Band telemetry frame. The jitter introduced by the Metop on-board systems to this correlation shall be less than 100 µs.

A time of 2 seconds is added to the acquired value by the CFS onboard to take into account the time delay between the creation of the frame and the actual frame transmission time.

2.2 On-Board Clock Drift

The drift of the on board oscillator, located in the Central Computer Unit, causes the On Board Time (OBT) to drift relative to Universal Time (UTC). Due to the high speed of the satellite and the stringent requirements of navigation accuracy, the OBT accuracy has to be well known. The satellite moves ~7.4 meters in 1 ms.

The oscillator drift can be divided into two components, one that is linear and one caused by the temperature variation and therefore having a period equal to the orbital period.

For the oscillator suggested by MMS, the following drift rates have been given:

Linear (long-term) drift: $5*10^{-8}$/day [AD1] (=$0.5787*10^{-12}$ 1/s)

Cyclic (thermal) drift: $2*10^{-7}$/deg [RD1]

This note shows that the drift between OBT and UTC can be compensated using a linear correlation function in the user stations with parameters updated daily.

2.2.1 Linear component

We introduce three constants:

To time

Po the period of the on board counter at *To*

Mo the counter value at *To*

A linear approximation of how time is evolving could be given by: $T = (M - Mo)Po + To$

Without loss of generality one can assume that the counter M was zero at T_0 (M_0=$M(T_0)$=0) which gives the simplified formula: $T = MP\mathrm{o}$

The frequency of the on board counter is affected by a linear drift: $f(t) = f_0(1 + \frac{df}{dt} * t)$

and P varies with time: $P(t) = \frac{1}{f(t)} \cong P_0(1 - \frac{df}{dt} * t)$. Assuming that $\frac{df}{dt}$ is small and that $P_0 = \frac{1}{f_0}$

The value of the on board counter M correspond to a true elapsed time:

$$T = \sum_{0}^{M} P(t) = \sum_{0}^{M} P_0 - \sum_{0}^{M} P_0 \frac{df}{dt} * t$$

$$T \cong \mathrm{T} - \int_{0}^{T} (\frac{1}{f_0}) * (\frac{df}{dt}) * t * dt$$

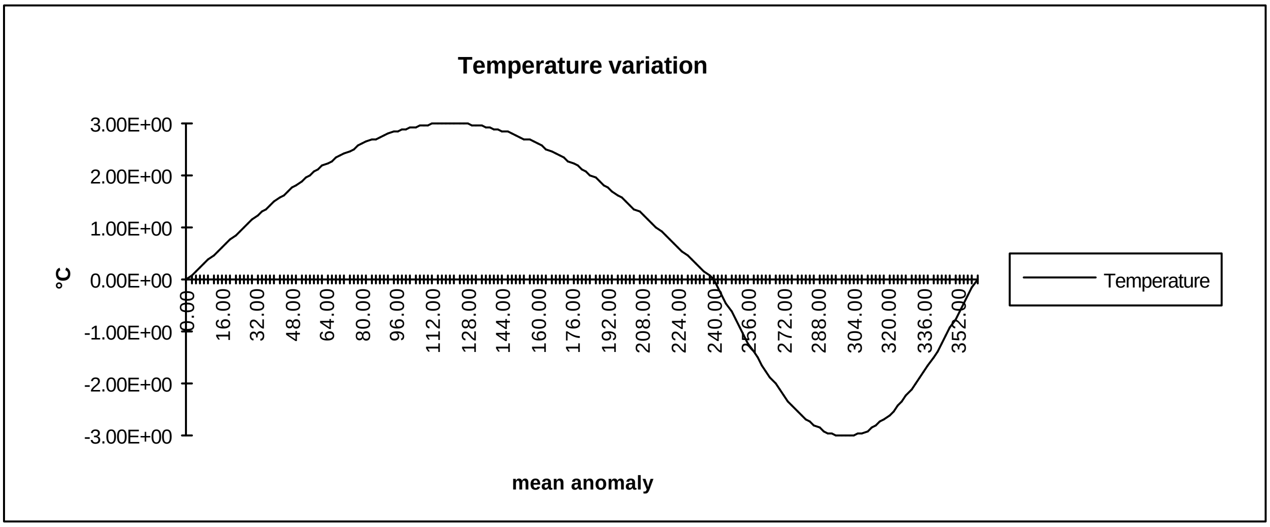
the integral then becomes:

$$\Delta T = \left[(\frac{1}{fo})(\frac{df}{dt}) * \frac{t^2}{2} \right]$$

$df/(f_0 * dt) = 5*10^{-8}$ 1/day = $0.5787*10^{-12}$ 1/s. This amounts to a ΔT of 2.2 ms in one day, after 3 days it builds up to almost 20 ms.

2.2.2 Periodic Component of the Drift

According to The spacecraft Manufacturer, the temperature variation looks as given below:



The shape of the cyclic variation can be explained by the time the satellite spends in sunlight and shadow, respectively. The uneven distribution contributes significantly to the OBT drift.

Generally, we have a sinusoidal variation of the frequency: $f(t) = f_0(1 + \Delta f \sin(\Omega t))$

Then the period of the counter would vary as:

$$P(t) = \frac{1}{f(t)} \cong P_0(1 - \Delta f \sin(\Omega t)),$$

Equation 1 Change in Clock Period

The model is: $T = MP_0$ which gives:

$$T = \sum^{M} P(t) = MP_0 - \sum^{M} P_0 \Delta f \sin(\Omega t) dt$$

Equation 2 Change of Clock Period per Rev

The full orbit is assumed to take 100 min = 6000 sec

The sunlit part is set to 4000 s

The time in shadow is 2000 s

We now define two angular speeds

$\Omega 1 = p/4000$

$\Omega 2 = p/2000$

The first half cycle would give a time contribution of:

$$\Delta T = T - T \cong \int_0^{p/\Omega 1} \frac{\Delta f}{f_0} \sin(\Omega_1 t) dt \text{ with } u = \Omega_1 * t \text{ and } dt = \frac{du}{\Omega_1}$$

$$\Delta T = T - T \cong \int_0^{p} \frac{\Delta f}{f_0 * \Omega_1} \sin(u) du$$

$$\Delta T = \frac{\Delta f}{f_0 * \Omega_1} [-\cos u] = 0.001528 \text{ seconds}$$

with a value of $\frac{\Delta f}{f_0} = 2*10^{-7}*3$, assuming a temperature amplitude of 3 Kelvin.

A similar integration over the second half cycle gives a negative value of 0.000764 sec so the result is a total time increase of 0.000764 sec for each orbit.

Although this adds up to about 11 ms per day it does not adversely affect the OBT/UTC correlation since this is a linear term and as such will be corrected for by the linear model used in the OBT/UTC correlation. It will, however, add an additional asymmetric uncertainty of up to about +1.53 ms/-0.0 (with a modulation of the orbital frequency). This means that the calculated UTC using the OBT timer and the linear correlation (from FDF) can be up to 1.53 ms ahead of the true UTC, but very little or nothing behind. This asymmetry is caused by the circumstance that only the S-band telemetry can be used in the OBT/UTC correlation process and it is always sampled at the end of the night period at which the clock supposedly runs slower (due to lower average temperature) than during sunlit periods.

2.3 Activities needed to correlate OBT with UTC

In general, the OBT is not correlated to the UTC due to on-board oscillator drifts. Therefore the ground needs to perform the activity of OBT/UTC correlation.

The correlation between the OBT contained in the TM frame and the UTC is achieved on ground by calculating the UTC corresponding to the first bit of the first byte of the TM frame when transmitted. This is done by subtracting all the modelled delays from the UTC time that is recorded when the frame has been received on-ground. In this way the time sampling is done on the same event.

Comparing the UTC and the OBT values of the TM frame transmitted at every pass it is possible to evaluate the OBT/UTC correlation by means of a least squares algorithm. Assuming a slow drift in the oscillator, a linear model shall suffice. Hence only two parameters have to be computed:

a) the line slope, representing the average "velocity" of the on-board clock OBT versus UTC

b) the line offset, indicating the UTC time of the most recent OBT rollover (UTC_0, see equation in section 2). Any delays in the transmission of the telemetry frames will directly affect this offset. Therefore it is prone to systematic errors.

An additional aspect of the OBT/UTC correlation is that the TM IT on-board register is 32 bits long, i.e. after 2^32 updates the register is re-set to zero. In other words, every 6.47 months an OBT wrap-around takes places. The algorithm has therefore to take into account at least 10 wrap-around events during the lifetime of each Metop flight model.

It should be noted that OBT is the primary source of timing information in the TM downlink. In particular OBT is used in the general product processing of the CGS. However, on board UTC is also made available and this may be used by HRPT / LRPT users. However, even in this case it is preferable to use the OBT instead, and apply the OBT-UTC time correlation coefficients uploaded by the MCS and broadcast as part of the Admin message.

The OBT/UTC correlation process between FDF is specified in AD.14 section 3.5.4. A detailed description of the OBT/UTC algorithm as implemented in FDF is given in AD17. Especially those aspects related to the design and implementation in FDF for the generation of the correlation function, OBT/UTC propagation model as well as detection and handling of outlier and wrap-around between passes.

For the handling of wrap-around, outlier and clock count anomalies, the following suggestions were added by EUMETSAT (via FAX to Alcatel AD.19). They are expected to be included in the next version of AD17 and implemented in the FDF version 2.2

Regular counter wrap-around

- Step 1.

  A wrap-around (WA) is detected inside FDF by monitoring the CCU counter transition from FFFFFFFF to 00000000. In this case, for TM frames after WA the OBT is modified in such a way that:

  OBTnew=OBTTM+1.0000.0000 (HEX) (Equation 1)

  This action corresponds to temporarily "extending" the straight line used before the WA occurrence also to the TM frames after the WA.

- Step 2

  The linear fit is applied to all the data including those after WA, thus determining for the entire data-set a single OBT/UTC correlation described by the two parameters:

  a slope, corresponding to A_STEP in RD.2

  b intercept for OBT ° 0 corresponding to B_OFFSET in RD.2

- Step 3

  Afterwards, the determined fit is translated "downwards" to the actual OBT after WA:

  The new intercept value (b) is thus:

  bnew = b + a*1.0000.0000 (HEX) (Equation 2)

  OBT0 must be non-negative. This means that an origin point after WA must be given.

  It is suggested to take the very first point after WA, namely:

  OBT0 = 0 (Equation 3)

  UTC0 = b

Leap seconds.

All internal computations in the FDF OBTUTC application shall be performed in TAI. In this way all leap seconds discontinuities are automatically taken into account by the application.

Outlier.

FDF shall allow the user to define the minimum deviation of a data point from the linear fit that qualifies that data-point as an outlier (e.g. beyond 4 sigma). To be clear, those data are not to be taken into account for the correlation.

Clock Counter Anomalies.

Spurious clock resets (wrap-around before the due time) are only caused by spacecraft entry into safe mode. No automatic action is required by FDF to handle this kind of discontinuities. Rather, human intervention will be performed in the following way:

a new correlation starting after the entry in safe mode is computed by manually defining the OBT/UTC correlation span. The option of constraining an a- priory value for A_STEP around a certain value (derived from previous correlation) is operationally extremely useful and shall be implemented.

The OBT/UTC correlation process will be performed following the following steps:

- TM reading from MCS: accumulation and reading of MCS data into an internal FDF file.
- Application of corrections due to light path, troposphere and delays: In order to correlate the on-board time and the ground station reception time, the most important factors to consider are:
  - The inherent differences between the on-board and the ground station clock due to clock offsets and drifts
  - The time stamping delay at groundstation due to used HW/SW
  - The path transmission delay
- Filtering: there are initial computations of the correlation to detect possible jumps and wrap-around. This filtering is based on thresholds defined by the user. Basically there are two types of jumps: local glitches and real jumps. Each real jump will define a new data segment to be correlated, while the glitches are not taken into account for the computation.
- The correlation process: over the period defined by the different data segments, the correlation is performed following the formulation of the linear regression. These correlations are stored in the OBT/UTC history file and the latest one is exported by the FDF to MCS.

2.4 Ground Station Master Clock errors

The F&T subsystem at the groundstation provides GPS based time and frequency reference for time tagging and synchronisation.

A GPS antenna receives the signals from the GPS constellation. These signals are fed to the receiver itself by means of a 50 meter antenna download cable.

The receiver contains a high stability quartz oscillator OCXO that provides the 10MHz reference to the rest of the station. This reference is locked to the GPS reference to provide long-term stability.

The receiver is manufactured by RAPCO providing the following time code reference characteristics:

Time Code IRIG B

Accuracy to UTC	+/- 300 ns
Long Term Stability	$3*10^{-10}$/ day (GPS unlocked)

2.5 Time tagged accuracy

The Cortex Units at the ground station generate the reference time for the S-Band packets.

The telemetry messages are time tagged with a resolution of 1 millisecond, as specified in AD.12, thus resulting into an uncertainty of ±0.5 ms.

2.6 Transmission delay Time analysis

When correlating the onboard clock time with the UTC time of the packet reception time, the time necessary for the packets to travel to the groundstation needs to be included in the model.

The transmission delay time is equal to the one way light time, which is dependent on the range of the spacecraft and the effects of the ionosphere and troposphere.

The requirements (FDF-0150/CGS-SYS-4.2.4-0350) specify that the spacecraft orbit will be accurate to 50m/50m/10m in along track/ cross track/ radial direction. Assuming the range is of similar accuracy, i.e. 10 m, then the transmission delay due to the range error is

Range error in nanoseconds = 10 m / $3x10^{8}$ ms –1) = 33.3 ns

The requirements (FDF-0410/CGS-SYS-5.2.6.3-0260) specify that the spacecraft orbit prediction will be accurate to 250m/100m/50m in along track/ cross track/ radial direction after a period of 36 hours. Taking into account the spacecraft autonomy requirement of 36 hours, we can expect the range to suffer from a propagation error of 50 m.

Range error due to orbit propagation over 36 hours in nanoseconds = 166 ns

Now consider the troposphere delay. A variety of refraction models for spacecraft tracking data has been established in the past, ranging from simple exponential formulas to sophisticated and numerically expensive algorithms that account for the light path curvature in the atmosphere. The refraction correction given for representative meteorological conditions as derived from the elaborate Hopfield-Goald model (Two-Quartic Tropospheric Refractivity Profile for correcting Satellite Data, Journal of Geophysical Research, Vol. 74) gives a range correction of 34 m for the very worst case of 5 degrees elevation. The effect of 34m in the range corresponds to an error in the timing of

Troposphere error in nanoseconds = 23 m / $3x10^{8}$ m/s = 76.6 ns

The ionosphere exhibits a normal dispersion with a frequency dependency that is the inverse to the square of the frequency. For signals in the S-Band frequency regime at 2053.4 MHz a range correction of about 22 m is expected for the worst case of an elevation value of 5 degrees.

The effect of 22 m in the range corresponds to an error in the timing of

Ionosphere error in nanoseconds = 22 m / 3x10 ^{8} m/s) = 73.3 ns

Leap Seconds

Leap seconds occur in the ground station time but not in the on-board time, which causes a discontinuity in the corrected on-board. The filtering should detect such jumps in time, which then will lead to defining a new data segment in the correlation process.

3 OBT/UTC BUDGET

Summarising the results of the analysis before, the OBT/UTC worst case error budget can be broken down as:

Clock Errors and Drift Rates:

Clock	Oscillator Frequency	Drift	Accuracy
On-Board	12582912 MHz	+/- $5*10^{-8}$/day +/- $2*10^{-7}$/degree	100 µs
G/S Master	10MHz	$3*10^{-10}$/day (GPS unlocked)	300 ns

Delays	Uncertainty
Range	±0.0000333 ms
Range Propagation error over 36 hours	±0.000166 ms
Troposphere correction	±0.0000766 ms
Ionosphere correction	±0.0000733 ms
Ground Station Physical Path Delay	±0.000267 ms
Ground station time stamping (Cortex resolution)	±0.500 ms
Onboard datation requirement	±0.100 ms
TOTAL Uncertainty (RSS)	±0.510 ms

This represents the total uncertainty of the OBT/UTC correlation at the time of determining this relation (not including the drift effect as time progresses). This error meets the CGS requirement of being less than 2 ms (CGS-MCF-5.2.6.5-0420).

3.1 Time Accuracy

3.1.1 Requirements

The on-board time accuracy relative to UTC is driven by a *desire* to meet the different product requirements of a UTC time stamp synchronisation, but constrained by the overriding system requirement for 36 hours of satellite autonomy.

From the error budget shown before it can be seen that the major contribution of the error comes from the Cortex Unit datation error at the groundstation.

3.1.2 Analysis

Known drift requirements provided in [AD1] provide characteristics that can be modelled to result in the frequency of updates by EUMETSAT. Each pass of Metop will result in an estimation of the correlation error and through linear modelling [AD7] update rates can be estimated.

Three factors have been identified to contribute to the error: the S/C, the CDA time stamping function and the modelling error due to the fact that the model is linear whereas the on board clock drift is cumulating a cyclic and a quadratic term.

A simulation was performed using the following assumptions:

- a random measurement error of 600 µs (assuming 50% error for the ground station datation)
- a orbital temperature variation of ±3 °

The simulation shows the single contributions to the oscillator drift within 36 hours.

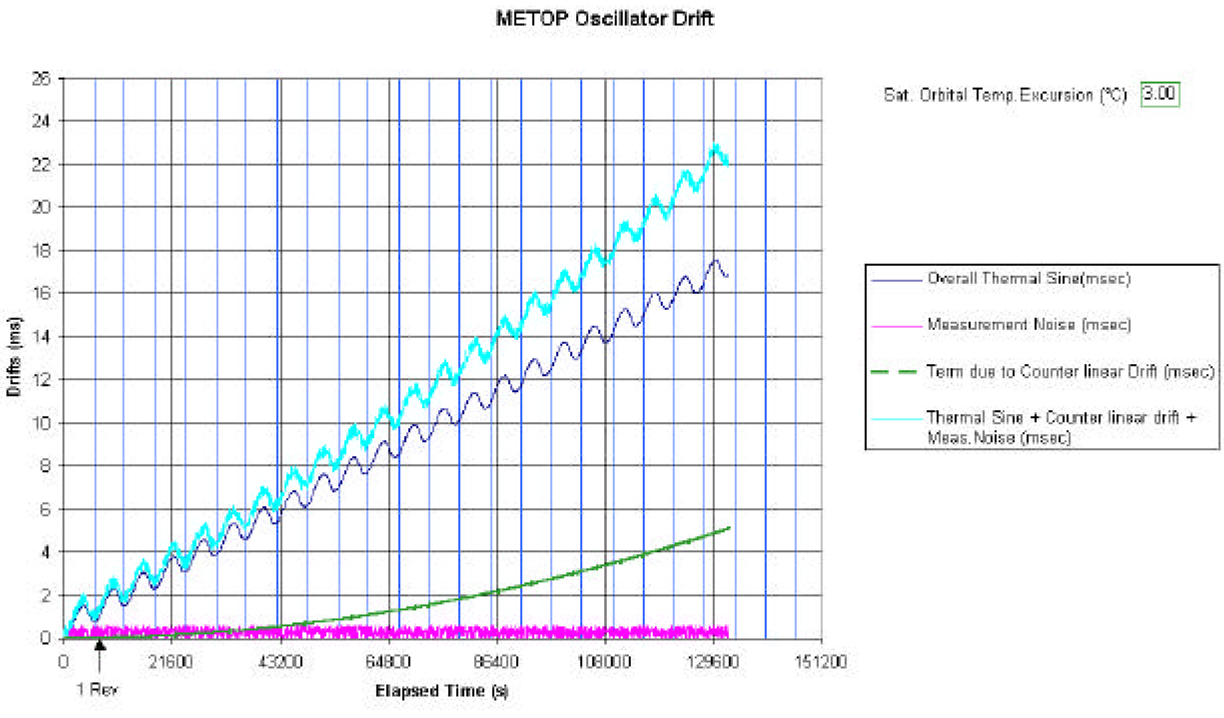


Figure 1 Metop Oscillator Drift.
Curves from Top to Bottom: [Thermal Sine + Counter Linear Drift + Measurement Noise]; Overall Thermal Sine; Counter Linear Drift; Measurement Noise

The contributions are:

a) Linear Drift of the Counter (which maps into a shallow quadratic time function)

b) Thermal Drift (discussed before)

c) Measurement Noise

The uppermost curve in Figure 1 is the sum of the above mentioned three terms, and it represents the observed OBT. Several considerations must be done on this chart.

1) The X-axis is the true elapsed time in seconds. The value 6084 indicates one full rev (marked by means of an arrow), the value 86400 marks 24 hours, and the value 129600 marks 36 hours.
2) The thermal drift term drives the uppermost curve to drifts beyond 4-ms value after approximately 6 hours. It should be noted that the thermal drift is the driving factor for the overall drift during the first 18 hours. Moreover this drift has a strong dependency on the assumed temperature variation at oscillator level during one full orbit.

4 EPS SYSTEM FACTORS CONSTRAINING THE OBT/UTC ACCURACY

The OBT/UTC correlation accuracy must be compared with the time accuracy requested by other EPS system features and must be such as not to jeopardise those features.

4.1 Time tagged Commanding Constraints

The minimum time separation for consecutive time tagged commands is 125 ms. Therefore the OBT/UTC correlation accuracy must be better than that ±62.75 ms.

4.2 Geolocation Constraints

The typical geolocation accuracy is in the order of magnitude of 1 km, which maps into 135 ms.
Therefore the correlation accuracy must be better than ±67.5 ms.

5 SUMMARY

The error due to the on-board clock error drift will increase with time, whereas the drift caused by the thermal cycling of the oscillator is substantially linear and should be fully compensated by the correlation function, provided that enough measurements have been done to make a good linear approximation. The measurement errors will introduce a noise.

As can be seen above, the error up to the CGS level is dominated by the ±0.5 ms datation error in the ground station (see Paragraph 2.5).

This document shows that the required accuracy of 2 ms for determining the OBT/UTC correlation is likely to be met by the FDF whenever it updates the correlation file which is done after each pass (about every 100 minutes). As described here the errors should not amount to more than ±0.51 ms at the time of calculation (see section 3). Propagating the OBT/UTC correlation using a linear model will not be able to account for the following errors:

- The short-term periodic variation due to thermal effects will cause the OBT and therefore the calculated UTC to be ahead by up to 1.5 ms (assuming a ±3 K temperature variation over the course of one orbit) relative to the true UTC. It will be nothing or very little behind.

  ⇒ short-term cyclic error +1.5/-0.0 ms (see Paragraph 2.2.2)

- The long-term OBT clock drift

  The linear drift of the onboard clock speed causes a quadratic term in the counts versus time function. A linear model can not account for this effect. The discrepancy between the UTC calculated using the linear model and the true UTC will build up with time until a new OBT/UTC correlation is re-established.

  The error due to the linear drift effect is about 2.2 ms after 24 hrs and 4.9 ms after 36 hrs (see Figure 1).

All in all, after 36 hours the calculated UTC time based on the linear correlation differs from the true UTC time by up to +6.9 / -5.4 ms.
The following table gives an overview of the individual contributions:

Delays	**Uncertainty [ms]**		
Ground Station	+0.5	-0.5	See Section 3
On Board Oscillator stability	+4.9	-4.9	See Section 3.1.2 figure 1
Thermal Orbital Cycle	+1.5	-0.0	See Section 2.2.2
Total	+6.9	-5.4	

The value of 6.9 ms includes 4.9 ms due to linear drift, +1.5 due to thermal sine effect, +0.5 due to time-stamping inaccuracy.

Depending on the required accuracy for the UTC calculations (on-board or on-ground), it will be decided at what update rate the FDF-generated correlation shall be applied to the rest of the system.