FLIGHT DYNAMICS PERFORMANCES OF THE METOP A SATELLITE DURING THE FIRST MONTHS OF OPERATIONS

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ABSTRACT

The 19th of October 2006 at 16:28 UTC the first MetOp satellite (MetOp A) was successfully launched from the Baykonur cosmodrome by a Soyuz/Fregat launcher. After only three days of LEOP operations, performed by ESOC, the satellite was handed over to EUMETSAT, who is since then taking care of all satellite operations.

MetOp A is the first European operational satellite for meteorology flying in a Low Earth Orbit (LEO), all previous satellites operated by EUMETSAT, belonging to the METEOSAT family, being located in the Geo-stationary orbit.

To ensure safe operations for a LEO satellite accurate and continuous commanding from ground of the on-board AOCS is required. That makes the operational transition at the end of the LEOP quite challenging, as the continuity of the Flight Dynamics operations is to be maintained.

That means that the main functions of the Flight Dynamics have to be fully validated on-flight during the LEOP, before taking over the operational responsibility on the spacecraft, and continuously monitored during the entire mission.

Due to the nature of a meteorological operational mission, very stringent requirements in terms of overall service availability (99 % of the collected data), timeliness of processing of the observation data (3 hours after sensing) and accuracy of the geo-location of the meteorological products (1 km) are to be fulfilled.

That translates in tight requirements imposed to the Flight Dynamics facility (FDF) in terms of accuracy, timeliness and availability of the generated orbit and clock solutions; a detailed monitoring of the quality of these products is thus mandatory.

Besides, being the accuracy of the image geo-location strongly related with the pointing performance of the platform and with the on-board timing stability, monitoring from ground of the behaviour of the on-board sensors and clock is needed.

This paper presents an overview of the Flight Dynamics operations performed during the different phases of the MetOp A mission up to routine.
The activities performed to validate all the Flight Dynamics functions, characterise the behaviour of the satellite and monitor the performances of the Flight Dynamics facility will be highlighted.

The MetOp Flight Dynamics Operations team is led by Anders Meier Soerensen and composed by Pier Luigi Righetti, Francisco Sancho, Antimo Damiano and David Lazaro.
The team is supported by Hilda Meixner, responsible for all Flight Dynamics validation activities.

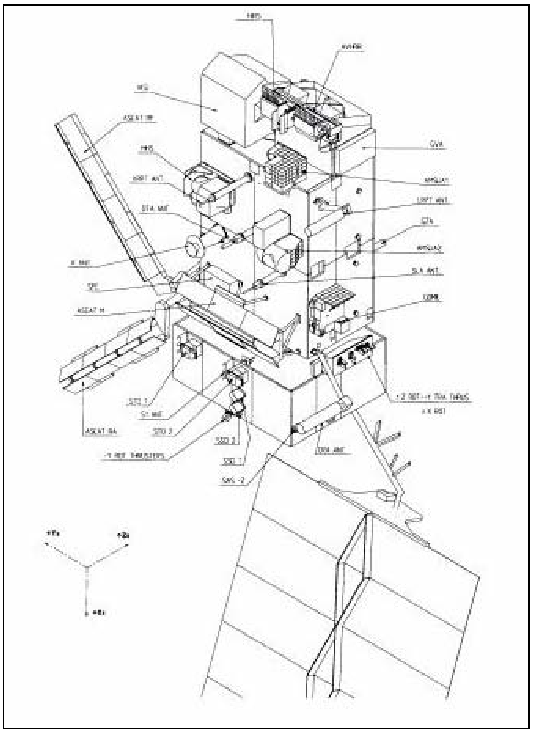

Figure 1: MetOp Satellite

1. THE METOP MISSION

MetOp constitutes the space segment of the EUMETSAT Polar System (EPS). The EPS is the European contribution to a joint European-US polar satellite system called the Initial Joint Polar System IJPS).

EUMETSAT has the operational responsibility for the morning (local time) orbit, where the MetOp A satellite is located, while its US counterpart, the National Oceanic and Atmospheric Administration (NOAA) is responsible the afternoon orbit, covered by the NOAA N satellite.

The MetOp satellite flies on a sun-synchronous orbit with local time of the descending node of 9:30 (± 2 minutes) maintaining a repeat cycle of 29 days and 412 orbits (dead-band of ± 5 km).
Frozen eccentricity conditions are moreover to be kept in order to maintain optimal observation conditions for the calibration and the following exploitation of the on-board instruments.

1.1. The MetOp Satellite

The satellite platform is directly derived from the one used for SPOT, ERS and ENVISAT (figure 1).
Automatic attitude control is based on one Digital Sun Sensor (DSSA, for yaw de-pointing) one Digital Earth Sensor (DESA, for pitch and roll de-pointing) and two bi-axial gyros (gyro1, 2, for angular rates).
Orbit control is performed on-command by hydrazine thrusters (two plates with one pair for propulsion and yaw control and two pairs for roll and pitch control).
Hot redundancy of all units is ensured.

The satellite carries on board 13 instruments for meteorological observation.
Among those the ones of particular interest for the flight dynamics operations are:

- GRAS (GNSS Receiver for Atmospheric Sounding): provision of precise navigation data.
- ASCAT (Advanced Scatterometer): constraint to repeat cycle and frozen eccentricity maintenance.
- GOME (Global Ozone Monitoring): constraint in the local time maintenance.
- AVHRR (Advancer high resolution radiometer): constraint in the geolocation accuracy.

1.2. MetOp Ground Operations

All instrument data collected during one orbit are dumped in X-band to one of the two Command and Data Acquisition (CDA) ground stations, located in Svalbard, sent to the Central Site (CS) in EUMETSAT head quarter and there processed in near real time (NRT).

Furthermore, continuous transmission of the sensed data via high and low rate links is performed. Local users can collect those data while the satellite is in visibility and process them locally.

Operational support has to be warranted also in case of severe contingency either in the CDA or in the CS:

- Emergency satellite control capabilities are available from the Back-Up Control Centre (BUCC) in Madrid.
- Ranging/Doppler and TM/TC emergency support is provided by ESOC through a dedicated stations network (XTTC).

Auxiliary data are provided by ESOC (NRT precise GPS ephemerides) and NOAA/USNO (Earth orientation parameters and solar magnetic activity).

Moreover, a daily N18 4LE is received from NOAA to provide, when requested, TM/TC and data dump support to the satellite in case of no visibility from the Fairbanks and Wallops ground stations (blind orbits). Similar support can be provided to MetOp through Fairbanks.

1.3. FDF Mission Tasks

During routine operations the FDF is responsible for the routinely generation and distribution of specific products needed for:

- Service module (SVM) operations: tele-commands (TCH) for AOCS programming.
- Payload module (PLM) operations: geometric events prediction (visibilities of GPS in GRAS, transponder sites in ASCAT, sun-moon in GOME) for instrument operations planning.
- Ground station operations: satellite visibilities prediction and pointing information for proper satellite acquisition and data dump.
- Global mission: orbit and clock information for geolocation of the instrument data.
- Local mission: orbital data in SPOT and TBUS format for distribution via admin message to the local users.

Due to the stringent timeliness requirement, the generation of all FD products is based on propagated orbit and clock.
Considered the large amount of products to be routinely generated and distributed, an as high as possible level of automation of the FD operations is required.

The integration of the MetOp FDF in the overall EPS system is depicted in figure 2.

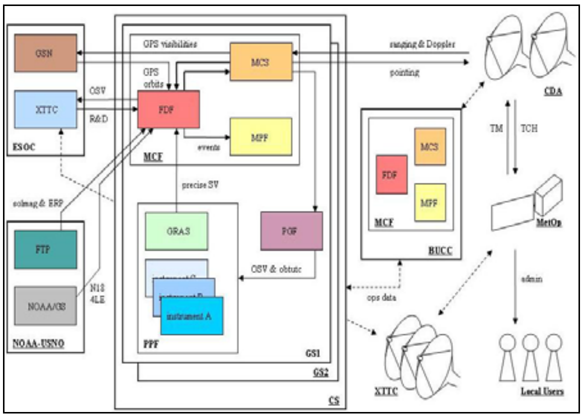

Figure 2: FDF integration in EPS system

1.4. FDF Operations

Different Flight Dynamics operations were needed during the different phases of the MetOp A mission (LEOP, SIOV, commissioning, routine), to cope with the different scenario and mission needs.
Moreover special activities, required to characterise the behaviour of the satellite, validate the performances of the FDF and achieve the target operational configuration, were performed.

2. LEOP OPERATIONS

During the entire Launch and Early Operation Phase (LEOP), lasting 3 days from launch, the operational responsibility of the MetOp A satellite was fully entrusted to ESOC.
Operations were executed through a dedicated network of 6 ground stations (Kerguelen, Malindi, Kiruna, Alaska, Hawaii and Perth).

The goal of this phase was to bring the satellite from the separation conditions into a stable status where the operational responsibility could be safely handed-over to EUMETSAT, as from hand over plan:

- Nominal pointing is acquired.
- Solar panel and all antennas are deployed.
- No major anomaly on-board is present.
- Satellite is on an orbit drifting smoothly toward the operational one (target time14 days).
- Routine TCH are on-board.

More details on the LEOP operations performed by ESOC is provided by the paper "The METOP-A Orbit Acquisition Strategy and its LEOP" presented by ESOC in the 20th ISSFD.

EUMETSAT activities were limited to the monitoring of the satellite status from TM, acquired by the LEOP stations and Svalbard CDA (CDA2 used during LEOP).
Acquisition of radiometric measurements on selected passes not in conflict with ESOC operations (orbits 22, 23 and 24) was also performed to allow an early validation of the tracking capabilities of CDA2.
The last orbit before hand-over was tracked from CDA2 as well, to insure its operational readiness.

Moreover, in order to provide to EUMETSAT full visibility of Flight Dynamics status, regular deliveries of FD products were performed by ESOC after each main operational step:

D1. 1st orbit determination (OD) in FAM2; around 8:00 mission elapsed time (MET): tracking measurements, determined and propagated orbit, orbit ground-track (GT) evolution, OBTUTC correlation, AOCS TCH and geometric events.
D2. 1st OD in Fine Pointing mode (FPM); around 19:15 MET: as D1 plus mass at FPM entry.
D3. 2nd OD in FPM; around 31:30 MET: as D1.
D4. 3rd OD in FPM; around 40:00 MET: as D1.
D5. 1st manoeuvre preparation; around 46:30 MET: as D1 plus planned 1st manoeuvre DV and TCH.
D6. 2nd manoeuvre preparation; around 61:15 MET: as D1 plus planned 2nd manoeuvre DV and TCH, calibrated 1st manoeuvre DV and mass update.
D7. Final OD; around 68:30 MET: as D1 plus calibrated 2nd manoeuvre and mass update; TCH time-tagged at 72 MET for maximum on-board autonomy.
D8. Final tracking; around 72:00 MET: tracking measurements.

These data were used by FDF in a twofold manner:

- Maintenance of the operational context consistently with the ESOC one.
  All operational products needed for satellite acquisition in both CDA and MPF operations are based on that context.
- End-to-end processing of all collected data (both via ESOC stations and CDA2).
  That permits on one side to validate the capability of the FDF to generate operational products compatible with the ESOC context and on the other the suitability of the CDA2 data for operational support.
  Moreover the achievement of the hand-over conditions can be validated.

Continuity of the Flight Dynamics operation could therefore be fully ensured.

2.1. FDF Architecture for LEOP

In order to avoid interferences between these activities, a clear separation of tasks was defined:

- The maintenance of the operational context and the generation and distribution of the operational products was carried-out in a dedicated server.

1.5. All data processing activities were executed in parallel on 3 work stations (clients), having read-only access to the operational context, SW, database and configuration but no delivery capabilities.

In this manner concurrent access to the operational data was granted with no risk of interference with the operational support.

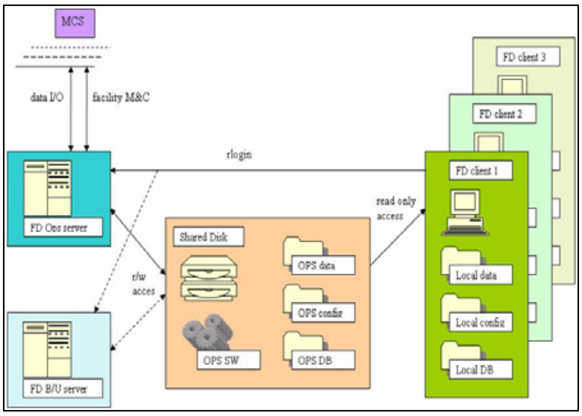

Figure 3: MetOp FDF Client/Server architecture

The client/server architecture is depicted in figure 3.

Each client was used for specific validation activities:

- Client 1: OBTUTC and HKTM processing.
- Client 2: orbit determination and GT evolution.
- Client 3: TCH and products generation.

2.2. FDF Operation during LEOP

The following operations were performed during LEOP:

- Before launch:
  On server: initialisation of operational orbit (propagated launcher trajectory), OBTUTC correlation (flight SW reset time on launch-pad) and mass (launch-pad HKTM); generation and delivery of init products for MPF and antenna.
- HKTM reception from ESA or CDA station:
  On server: ingestion of HKTM.
  On client 1: computation of fuel mass and comparison with operational value; OBTUTC correlation for LEOP and CDA stations and comparison with operational correlation (LEOP and CDA ground delay calibration); HKTM processing and residual analysis.
- After D1; OD in FAM2:
  On server: ingestion of tracking measurements; maintenance of operational orbit and OBTUTC correlation; generation and delivery of products for MPF and antenna.
  On client 2: tracking measurement residual analysis against operational orbit (LEOP stations measurements biases calibration); GT evolution and comparison with ESOC results.
  On client 3: generation of products and TCH based on operational context and comparison with ESOC results.
- After D2; 1^{st} OD in FPM:
  On server: as after D1 plus maintenance of operational fuel mass.
  On client 2: as after D1 plus orbit determination with data in FPM and comparison with operational orbit.
  On client 3: as after D1.
- After D3; 2^{nd} OD in FPM:
  On server and client 2 and 3: as after D1.
- After tracking from CDA2 (orbit 22, 23, 24):
  On server: ingestion of tracking measurements.
  On client 2: tracking measurement residual analysis against operational orbit (CDA measurements biases calibration); orbit determination with data (from LEOP and CDA) in FPM and comparison with operational orbit.
- After D4; 3^{rd} OD in FPM:
  On server, client 1 and 3: as after D1.
- After D5; 1^{st} manoeuvre preparation:
  On server, as after D1; planned manoeuvre effect considered in the operational orbit.
  On client 2; as after D2; manoeuvre effect observed on GT evolution.
  On client 3: as after D1 plus generation of manoeuvre TCH and comparison with ESOC one.
- After D6; 2^{nd} manoeuvre preparation:
  On server: as after D5 plus maintenance of operational fuel mass.
  On client 2: as after D5; manoeuvre calibration performed and compared with ESOC results.
  On client 3: as after D5.
- After D7; final OD
  On server: as after D2.
  On client 2: as after D6. Hand-over orbital condition observed in GT evolution.
  On client 3: as after D1. Products and TCH generation performed also using estimated orbit and OBTUTC correlation from CDA (end-to-end) and compared with previous generation.
- After D8; final tracking
  On server: as after D1.

2.3. FDF Validation during LEOP

At the end of the LEOP, only slight discrepancies with ESOC results were identified.

Figure 4 shows the performances of the range and Doppler measurement processing.

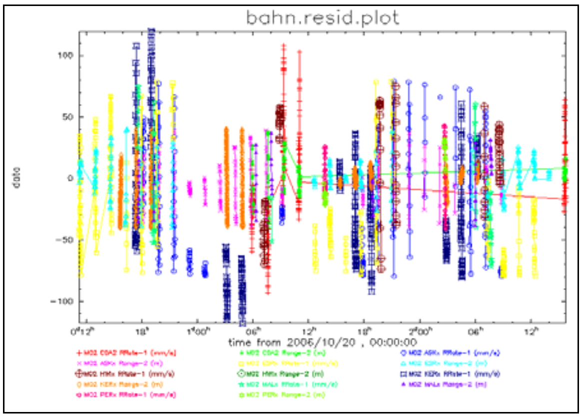

Figure 4: Residual against fix operational orbit

The residuals values are well within expectations, considering that are computed with respect to a propagated orbit. Problems are only identified in Hawaii ranging (all data rejected due to bad lock) and Kerguelen Doppler (large integration time impact in range-rate measurement generation). CDA2 range and Doppler residuals are more than satisfactory.

Figure 5 depicts the performances and of the orbit determination.
An along-track difference of 300 meters is observed after 2 days of propagation, more than sufficient for safe satellite operations.
The initial relatively large error is due to propagation at the exit from FAM2 (fine acquisition mode 2), during which attitude control with thrusters is performed.

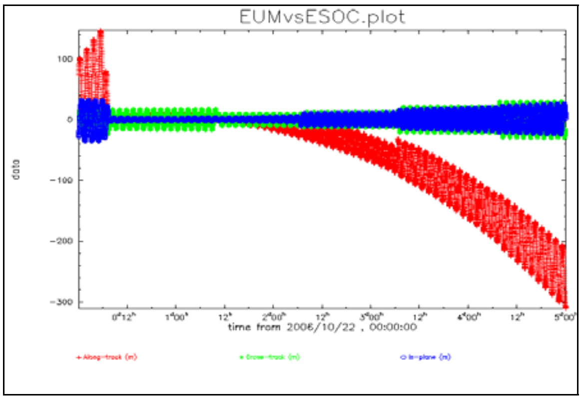

Figure 5: Operational orbit versus LEOP determined

Similarly the capability of all other FD functions for safe satellite operations was considered as validated:

- OBTUTC correlation: differences in slope below 1 PPM and in OBT0 not larger than 1 count for CDA2 and Hawaii stations.
- Routine TCH: differences below 0.01 degrees in the on-board model and the DSS programming. DES masking full covering ESA masking.
- Routine products generation: differences largely below 1 second in the event computation.

Moreover the following activities were performed:

- Verification of the hand-over orbital conditions, as shown in picture 6 (foreseen drift stop manoeuvre is considered),
- Verification of SVM commanding continuity; ESOC TCH on-board time-stamp at 72:00 MET.
- Preliminary validation of manoeuvre generation and calibration against ESOC results.
- Preliminary validation of HKTM acquisition and processing: residual in line with expectations.

Figure 6: Ground-track evolution at hand-over

Immediately after hand-over (MET 72) FDF started maintaining the operational context with estimated orbit and clock based on CDA2 measurement and generating operational products based on it.
The first TCH uplink after having formally handed-over the operational responsibility to EUMETSAT was performed during the night of the 22nd October and SIOV was started the following morning.

3. SIOV OPERATIONS

During the System in Orbit Validation (SIOV) phase the main goal was to validate all on-ground and on-board equipments and functions to ensure their full readiness; for FDF that implied to validate:

- Quality of radiometric data from CDA2 and accuracy of orbit determination.
- Behaviour of the on-board clock and accuracy of OBTUTC correlation.
- Behaviour of the sensors and pointing stability of the satellite.

Moreover, the operational readiness of all the back-up units was validated; for FDF that means:

- FDF functions in BUCC.
- Processing of data (HKTM and radiometric) provided by the on-ground back-up systems (CDA1 and XTTC).
- Processing of HKTM from back-up on-board sensors (gyro3 and 4, Earth sensor B).

A drift stop manoeuvre was executed within the second week of SIOV (2nd of November) to acquire the reference ground-track for commissioning.
That permitted to fully validate the manoeuvring capabilities in FDF.

Due to the high complexity of the PLM SIOV operations, extended satellite visibility was continuously provided by the XTTC network, composed by 3 ground stations operated via ESOC (Alaska, Kourou and Perth).
Moreover, during the first two weeks, the option of handing-back the operational responsibility on the satellite to ESOC, in case of major anomalies, was maintained.
To provide ESOC with a clear picture of the satellite status, orbital data were provided daily and SVM TCH after each up-link. Fortunately, no hand-back was needed.

FDF operations ware performed in the server according to the nominal routine operation scheme:

- Once a day: orbit determination and orbit product generation.
- Twice a day: OBTUCT correlation and SVM TCH generation.
- Once a day HKTM processing.

After one week of manual operations, needed to validate the reliability of the system and to accumulate a batch of enough CDA data, automatic operations were started: manual check of products before distribution was however maintained.

In this phase the assessment of the FDF performances was achieved through the detailed analysis of the operational runs in the server.
Dedicated campaigns were carried out to assess the readiness of the back-up units.

3.1. Orbit Determination

During SIOV an arc of 3 days of CDA2 radiometric data was used for orbit determination.
3 days after hand-over enough data were available to compute the orbit in the routine configuration.

The following was observed on the estimated status:

- Very good consistency with the orbit computed including the LEOP stations data (< 50 m).
- A systematic Doppler bias of 2.4 m/s, due to truncation to the kHz of the uplink frequency.
- 30 meters of residual range bias, probably due to an inaccurate estimation of the on-board delay.

The measurements residuals for this case are shown in figure 7.

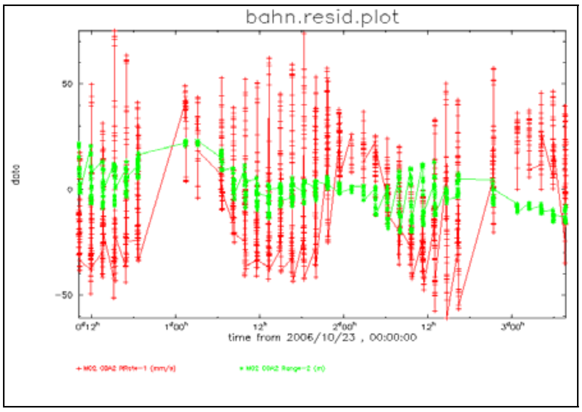

Figure 7: CDA range and Doppler residuals

It can be noticed that the level of noise, of the order of 8 meters RMS for the range and 25 mm/s RMS for the Doppler, is a bit higher than the expectations.
Moreover, its daily evolution makes clear that a systematic error is present in the estimation process; possible causes may be:

- Inaccurate station coordinates.
- Insufficient measurement model (relativistic or tropospheric correction).
- Insufficient dynamics model (solid tides).
- Timestamp truncation to millisecond.

The analysis of the impact of these errors in the orbit determination and propagation accuracy was performed in commissioning (paragraph 4.1).

3.2. OBTUTC Correlation

During SIOV an arc of 1 day of S-band TM data received in CDA was used for OBTUTC correlation.
The day after hand-over enough data were available to compute the correlation in routine configuration.

The following was observed on the estimated status:

- Very good consistency with the correlation computed in LEOP (< 1 PPM in slope)
- No delay in the on-ground time-stamp.

The data residuals for this case are shown in figure 8.

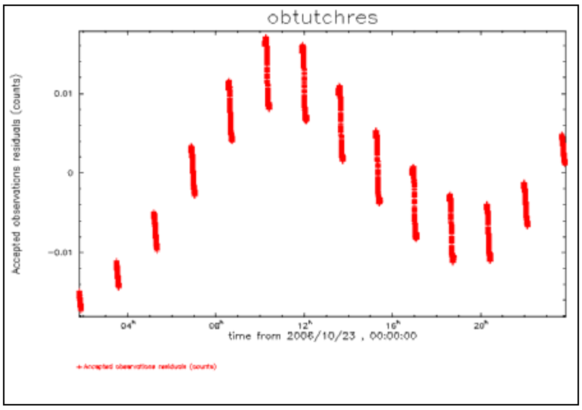

Figure 8: CDA OBTUTC data residuals

The evolution of the residuals shows a large orbital and daily evolution, consistent with the limited thermal stability of the clock. A long arc of data is therefore needed for ensuring a stable solution.
The impact of the arc length on the accuracy was performed in commissioning (paragraph 4.7).

3.3. Sensor HKTM Processing

Sensor data are available in the HKTM when the routine TM format is selected.
During the SIOV, a non-routine format, optimising the monitoring of the PLM, was selected during the most of the time. Therefore only 10 minutes of sensor data per orbit where available for platform monitoring in FDF (routine TM format).

The processing on the HKTM consists in the estimation of the optical measurement biases and gyro drift with respect to the nominal pointing.

For the first estimation after hand-over the following is computed:

- DSS Z bias: -0.007 deg
- DES X bias: 0.018 deg
- DES Y bias: -0.037 deg
- Gyro drift X = 0.000014 deg/sec
- Gyro drift Y = -0.000083 deg/sec
- Gyro drift Z = 0.000047 deg/sec

A good consistence with the on board gyro drift estimation was moreover observed.

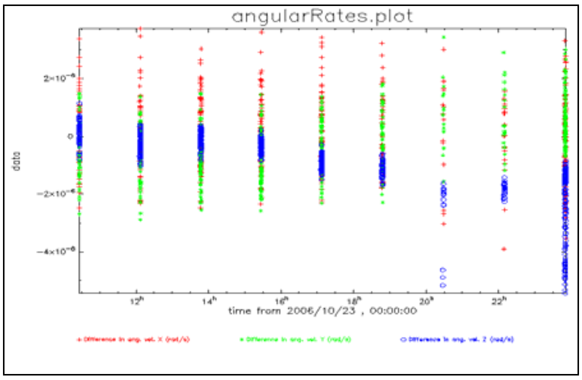

Figure 9a: Angular velocity drift daily evolution

Figure 9b: Angular velocity drift short term evolution

Figure 9a and 9b shows the gyro data residuals (no drift removed) in satellite frame, which is equivalent to the angular velocity drift.

The optical sensor data residuals (no bias removed) are presented in figure 10a, 10b and 10c.

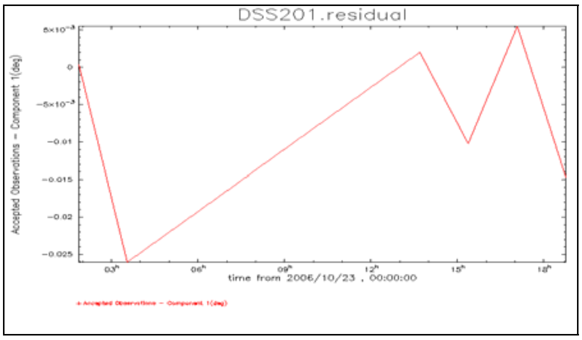

Figure 10a: DSS data residuals

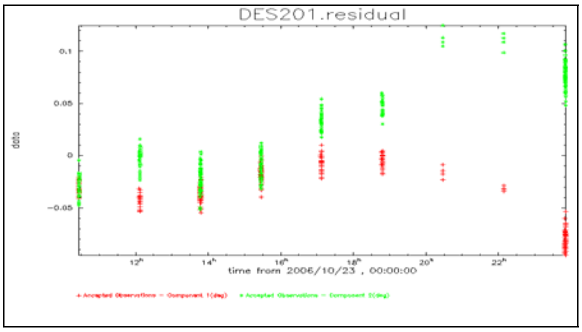

Figure 10b: DES data daily residuals

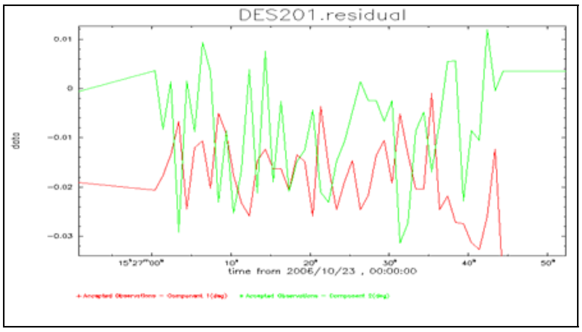

Figure 10c: DES data short-term residuals

The angular velocity drift shows in the Z direction a large bias and remarkable variations during the day.

Furthermore, the Earth sensor Y bias presents a clear correlation through the orbital pulsation with the Z gyro drift.
That shows that a large roll bias of around 0.04 degrees was implemented on board; a significant roll oscillation of around 0.02 degrees can be observed.
This bias was caused by an error in the uplink sequence of the DES mounting bias values: the Y bias for the prime sensor was swapped with the X bias for the back-up sensor.
The bias oscillation was analysed in detail during commissioning (paragraph 4.10)
A large value of the gyro drift was also observed in the Y direction with small daily oscillation.
However, no clear cross-coupling was observed with the Sun sensor Z bias.
A relative mounting bias of 0.08 degrees could explain this behaviour. The impact in the yaw pointing of the satellite can be understood only through image geolocation.

Larges gaps and quite large residual oscillations are observed for the Sun sensor data.
That is caused by the under-sampling of the instrument HKTM to 1/16 Hertz.
Being the sun visible in the DSS around 10 seconds per orbit and being the signal stable only during few seconds in the middle of the visibility, the probability to receive either bad or no data is very high.
The impact of that problem in the ground monitoring was analysed in commissioning (paragraph 4.10).

From the short term residuals analysis a good stability of the gyro measurement, mainly affected by measurement quantization, and of the platform (oscillations below 0.001degrees) is observed.

The Earth sensor measurements present oscillations of the order of 0.01 degrees, much higher than what would be expected from the instrument performances and from the short term attitude evolution.
That is mainly due to the fact that no infra red compensation, to take into account the variation of the earth limb apparent locations from the orbit, is applied to the measurements.

3.4. BUCC and CDA1 Readiness

3 days after hand-over the first operational activation of the BUCC was carried out.
For this activity the CDA1 station was used, permitting to validate both elements at the same time.
The activation was performed in three phases:

- Passive monitoring of the satellite from HKTM collected through CDA1.
- End-to-end processing of data collected from CDA1 and generation of FD prods and TCH.
- Sending of not-operational TCH to the satellite (not affecting FDF).

The readiness was assessed using the same criteria considered in LEOP for the CS and the CDA2.

3.5. XTTC Readiness

During the first week after hand-over several XTTC passes were requested in order to accelerate the operation of PLM activation, which provided a large base of data for validation of the service.

Both ranging and Doppler measurements and HKTM data for OBTUTC were processed, using the same approach used for the LEOP stations:

- Coherence of the residuals of the radiometric measurements against the operational orbit.
- Orbit determination and comparison with the operational orbit (based on CDA).
- OBTUTC correlation and comparison with the operational correlation (based on CDA).

A common bias of around 25 meters in the range measurements was identified, as for the CDA.
That confirmed the suspected inaccurate on-ground estimation of the on-board transponder delay, whose value was therefore corrected in the FD database.

Quite large variations were observed in the Doppler bias (over 50 mm/s) for the Perth station.
That may be related with a bias in the uplink frequency, as no return to zero offset with respect to the nominal frequency was performed.

The residual level and signature was similar to the one observed for the LEOP stations and for the CDA, both in the fixed arc and the orbit determination.
That confirmed the suspect that inaccurate handling of the radiometric data may be present in FDF.

Nevertheless the quality of the orbit determined using XTTC data only is quite satisfactory, being very close to the LEOP case.

On what concern the generation of an OBTUTC correlation using the XTTC stations time-stamp on the HKTM, solutions equivalent to the one from CDA were computed with all stations
Larger residuals were observed for Perth and Alaska, due to the truncation to the millisecond of the on-ground time-stamping.
Furthermore, a delay of 15625 microseconds was computed for Kourou and updated in the FD database.

3.6. Gyro3, Gyro4 and DESB Activation

Within the first weeks after hand-over the back-up on board AOCS sensors were activated.
Gyro 3 was de-stored while gyro 1 and 2 were kept as operational units for AOCS.
Afterwards the same activity was repeated for gyro 4.

The behaviour of the gyro in terms of transition and convergence times as well as of computed angular rate against the operational gyro was analysed.

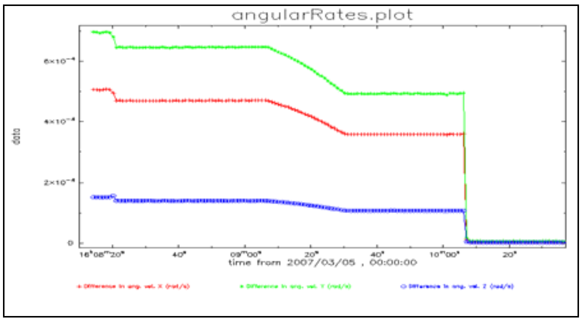

Figure 11: Gyro 3 transitions

Figure 11 shows the typical transitions curve. Gyro data are pre-processed considering calibration curve for fine measurements. Therefore the periods where the real measurement mode is very-coarse and coarse are well observable.

The differences observed between the operational angular velocity, computed with gyro 1 and 2 (G12), and the one computed using one of the operational gyros (A) and either gyro 3 or 4 (B) are (deg/s; in satellite X, Y, Z axes):

G12 - G13 = 0.000019, 0.000002, 0.000025
G12 - G23 = -0.000011, 0.000009, 0.000032
G12 - G14 = -0.000005, -0.000045, -0.000013
G12 - G24 = -0.000001, -0.000019, 0.000022

The variability in the gyro drift estimation is of the order of the 50% of the largest gyro drift (on Y), mainly due to the results of the couple gyro1, gyro 4 (G14), which differs significantly from all others.
Therefore the attitude de-pointing information that can be derived is strongly affected by that.
Nonetheless, the large Y gyro is observed with all couples; that confirms the relative misalignment with the DSS observed with the G12 couple.

For the activation of the back-up Earth sensor (DESB) it was necessary to declare the prime unit (DESA) as faulty and set DESB as operational.
Only the HKTM of one gyro was available on ground at a time, therefore no direct comparison of the output of the two units was possible.

The analysis of the DESB HKTM provided results very similar to the one of the DESA in terms of estimated biases and residual evolutions. Moreover, no variation was observed in the Z gyro drift.

The back-up Sun sensor (DSSB) was never activated as the procedure needed, similar to the DES one, was considered too dangerous operationally by the flight control team.

3.7. Manoeuvring Capabilities

On the second of November a drift stop manoeuvre was performed to acquire the operational orbit and the frozen eccentricity status.

The manoeuvre was successfully executed, even a non-calibrated thruster plate was used (all LEOP manoeuvre performed with the same plate).

Several problems were identified in the preparation and execution of that manoeuvre:

- A large cross-coupling between the main thrusting direction and the radial and cross-track direction is present, due to the plate mounting; that causes undesired effects on the target orbit evolution. That problem is treated in the paper "Coupled inclination and eccentricity control for Metop" presented in the 19th ISSFD.
- A large cross-coupling between the main propulsion thruster and the attitude control thruster is present due to the large parasitic torques; that causes a very large and systematic under or over performance depending on the used plate.
- A very long stabilisation phase is observed due to the large excitation of flexible modes. The effect is similar to the one immediately above.
- The accuracy in the pressure reading is very rough, affecting not only the estimation of the foreseen thruster performances but also the computation of the used fuel and the reconstruction of the executed manoeuvre from HKTM.

A detailed analysis of the manoeuvring capabilities for Metop will be presented, when consolidated, in a future symposium.

4. COMMISSIONING OPERATIONS

During the commissioning phase the main goal was the monitoring of the quality of the products against the mission requirements; for flight dynamics that implies to assess the accuracy of:

- Orbit determination and propagation.
- OBTUTC correlation
- Satellite pointing
- AOCS TCH
- Geometric and vector products

Operations needed to continuously perform these monitoring activities during routine were moreover developed.

Dedicated analyses were performed to characterize the generation processes in terms of minimum data amount needed for the estimation processes and optimal configuration for AOCS TCH and vector products generation.
Other analyses were focussed on further investigation of the problems identified in the SIOV.

4.1. Orbit Determination and Propagation

A preliminary estimation of the orbit determination accuracy was obtained by computing the differences of consecutive orbit determination on the common segment of estimation arc: as each arc spans three days, two days of overlap are present.

Figure 12 depicts the evolution of the max difference in the overlap for the month of January.
The values, always below 30 meters, were however a bit higher than expected, probably due to the not perfect processing of the radiometric data, as reported in SIOV.

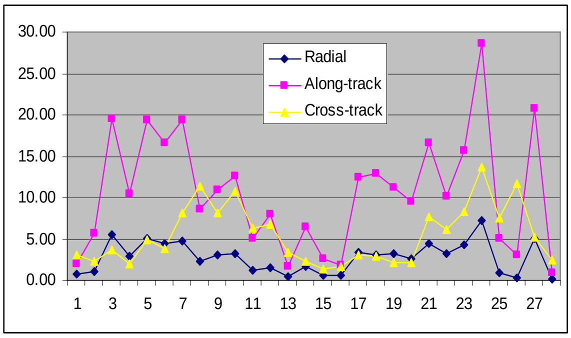

Figure 12: Orbit determination overlap error (m)

A direct comparison with the precise orbit generated with GRAS for the period 19-26 February gave similar results (meters; RMS, max):

- Radial error 5.75 14.72
- Along-track error 12.15 28.93
- Cross-track error 7.50 16.67

The accuracy in propagation was computed comparing the propagated orbit at N days with the determined computed N afterwards.

The evolution in January of the maximum propagation error at 2 days is presented in figure 13.

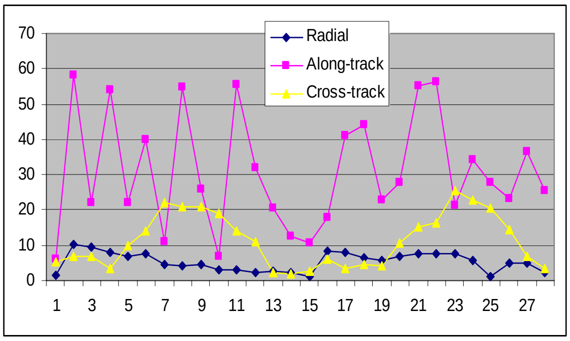

Figure 13: Orbit propagation error at 2 days (m)

It can be observed that the impact of the inaccuracy in the determination has little impact on the propagation, where the main error source remains the uncertainty of used drag model.
The achieved accuracy is of the order of 5 times better than the geolocation requirements of 250 meters after 36 hours.
The mean propagation error after 7 days for January was of the order of 200 meters, with a maximum of 600 meters, 10 times smaller than the required 6 km.

Those large margins come from the highly stable atmospheric drag due to the very low solar activity.

A fully automatic procedure was developed on a dedicated FDF client to compute daily overlap errors against the previous day solution and propagation errors against the solution of 2 and 7 days before.

4.2. OBTUTC Correlation

The accuracy of the OBTUTC correlation can be computed from the difference of the estimated on-board clock frequency with respect to the average frequency observed on a propagation span.
The linear propagation of that difference gives the clock error at the end of the propagation.

Figure 14 shows the evolution of the estimated on-board clock frequency in January (2 values per day).

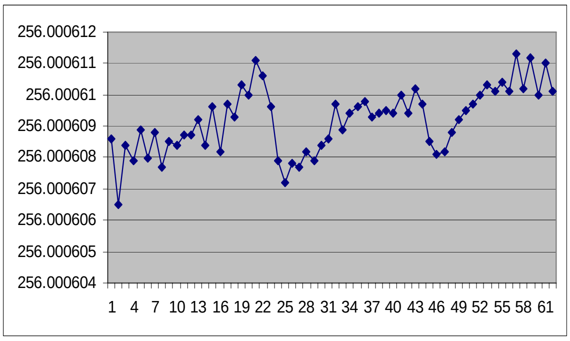

Figure 14: Estimated on-board frequency evolution

Oscillations of the order of 2 micro-Hz with respect to the average monthly value are caused by the thermal variations due to the activation of the instruments. That translates into a timing accuracy of less than 1 millisecond after 36 hours (corresponding to a geolocation error of 7 meters).
Larger oscillations were observed in case of gyro de-storage or switch-off of all instruments. Also in these cases sufficient margin was available with respect to the required 4 milliseconds of accuracy at 36 hours.

A procedure for automatic monitoring of the on-board frequency was implemented before entering in routine.

4.3. Satellite Pointing Monitoring

The assessment of the satellite pointing was performed by monitoring the stability of the estimated gyro drift and optical sensors off-pointing.
January evolution is shown in figures 15a and 15b.

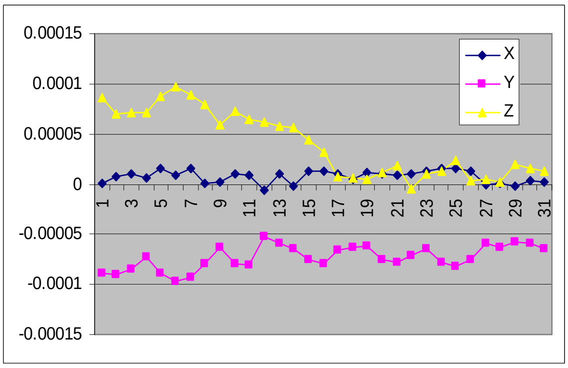

Figure 15a: Estimated gyro drift evolution (deg/s)

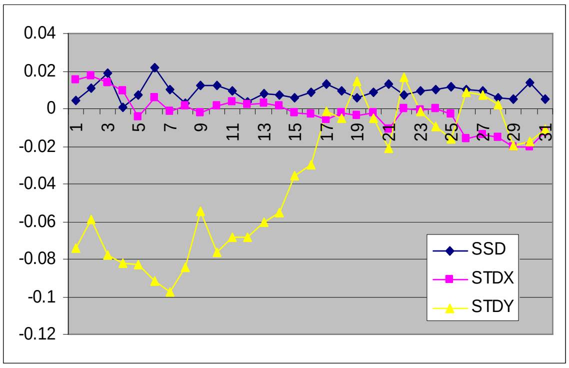

Figure 15b: Estimated off-pointing evolution (deg)

The behaviour before day 15 of the month corresponds to the case of inversion of the a-priori mounting bias command, discovered in SIOV.
After correction both the DES Y off-pointing and the gyro drift in the Z direction decreased clearly.
Nonetheless, remarkable and correlated variations, equivalent to a roll bias oscillation of 0.02 degrees, were still visible.
The margin with respect to the required accuracy in roll of 0.1 degrees remained in any case acceptable.

A stable gyro drift on the Y axis was observed during the entire month, confirming the suspected relative misalignment of the gyros and the DSS.

4.4. AOCS TCH Accuracy

The two TCH, for which the accuracy needs to be monitored, are the on-board orbit model (OBOM) and the DSS programming.
The accuracy is computed by comparing the last TCH with the previous one propagated to the execution time of the last one.

Figure 16a and 16b present the results obtained in January (2 comparisons per day).

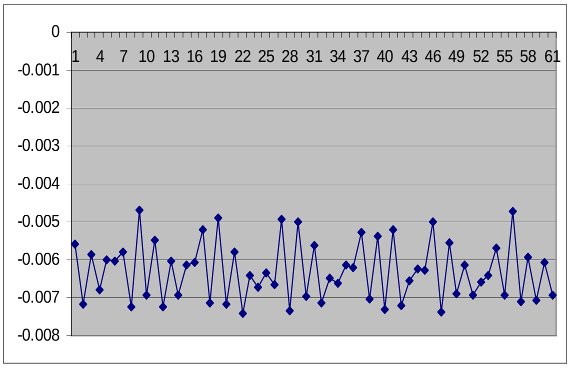

Figure 16a: OBOM TCH error at execution (deg)

From the OBOM TCH error evolution a constant bias of 0.006 degrees is observed. That was linked to a mishandling of the effect of the on-board clock offset with respect to the nominal frequency, corrected immediately by the FDF on-site support.

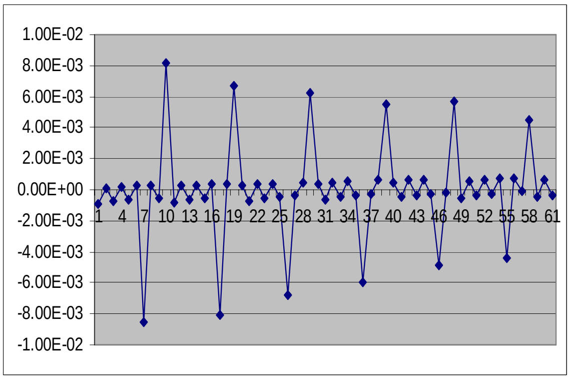

Figure 16b: DSS TCH error at execution (deg)

A clear anomalous behaviour can be observed in the DSS TCH evolution. That was caused by a bad definition of the TCH execution time in case of time-tag between the ascending node and the sun visibility, corrected immediately by the FDF on-site support.

Those TCH continuity checks are needed to ensure a smooth feeding to the on-board system, avoiding the AOCS transient needed to absorb the discontinuity in the commanding.

Procedures for in-line automatic check before delivery were implemented before the start of the routine phase.

4.5. Vector Products Accuracy

Vector products of 3 types have to be generated by the FDF:

- TLE orbit model, needed for CDA antenna steering: 1 vector for the next 36 hours.
- TBUS and SPOT orbit models, needed for distribution through admin message to the local users: 3 vectors of 12 hours each for the next 36 hours.

The quality of those products was computed by comparing with the operational orbit the orbits obtained with the propagator provided by NORAD (TLE), NOAA (TBUS) and CNES (SPOT) using the FDF vectors as input.

Figure 17 shows the results obtained for February.

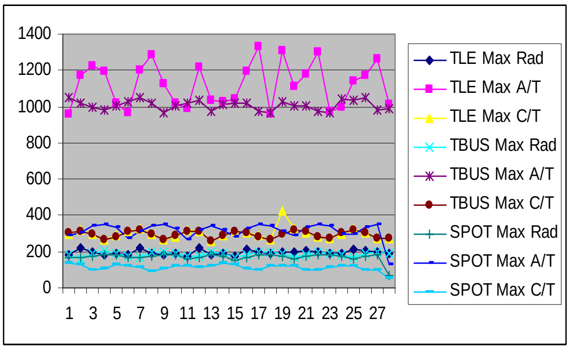

Figure 17: Vector product max error (m)

It can be observed that the maximum along-track error for the TBUS is so high that the geolocation target accuracy of 1 km cannot be achieved.
Unfortunately, little can be done, as the TBUS generation configuration, which is the same used for the NOAA satellites, cannot be changed.

As far as the TLE is concerned, the along-track error is large enough to cause a remarkable misalignment of the CDA antenna (0.07 degrees) in case of operations in program-track.
That may lead to data losses in the X-band; such losses were really observed in commissioning.
Therefore an optimisation of the TLE generation scheme was needed. Its implementation is presented below (paragraph 4.8 and 5).

Automatic procedures were implemented on a client to monitor the accuracy of the generated vector products.

4.6. Geometric Products Accuracy

The geometric products, whose accuracy needs to be monitored, are the start and end of visibility of the satellite from the CDA stations and the start and end of visibility of a particular target in the field of view (FOV) of determined instrument:

- GPS entry in the GRAS FOV
- Moon entry in the GOME FOV
- Ground transponder entry in the ASCAT FOV

Those events are used at mission planning level to trigger operational procedures, as for instance start and end of carrier lock to the satellite and instrument calibrations.

The assessment of the accuracy of the FDF prediction was performed by direct comparison of the foreseen and the observed event times.

Differences of several seconds were observed for the start and end of satellite visibility.

Those differences were consistent with the TM bending due to tropospheric refraction.

For GRAS, shorter events were predicted by FDF than observed in the TM.
For GOME a common time shift of the start and end of the event was observed.
For ASCAT a good match was observed for the mid beam, whereas large but not systematic discrepancies were observed for the fore and aft beams.

It was possible to cancel the discrepancy for GRAS and GOME by modifying in the FDF database the instrument FOV description to match the observed events time. Further comparison presented a nearly perfect agreement.
On the contrary it was impossible to have the ASCAT discrepancies corrected in the same manner. A direct comparison with the ASCAT event prediction tool of ESTEC showed a perfect match, leading to the conclusion that the problem was in the transponder itself.

4.7. Orbit Determination and OBTUTC Correlation Characterisation

Several analyses were performed to characterise the performances of the orbit determination and OBTUTC estimation processes in terms of:

- Minimum length of the estimation arc for achieving sufficient accuracy for satellite commanding.
- Minimum length of the estimation arc for achieving sufficient accuracy for products geolocation.

The goal of those analyses was to understand how fast the operational accuracy could be retrieved after a major contingency, causing a significant gap or deterioration in the observation data: satellite safe mode, CDA unavailability, BUCC activation.

The following was observed for the orbit determination:

- After three passes it is possible to compute an orbit with less than 1 km of error after 36 hours, therefore sufficient for satellite operations.
- After 7 passes it is possible to compute an orbit fulfilling the geolocation requirements.

For the OBTUTC correlation:

- After only one pass it is possible to compute a correlation with less than 1 count of error after 36 hours, thus sufficient for satellite operations.
- After 2 passes it is possible to compute a correlation that fulfills the geolocation requirements (orbital thermal effect cancelled).

Those analyses were performed assuming the availability of all the data.

The impact of a reduced availability of the data was analysed too.
That information was needed to quantify the impact of CDA problems (several losses were observed in commissioning) on the FDF service.

The conclusions of the analysis are that, for generating products with accuracy sufficient for geolocation, the following is needed:

- Four CDA passes per day on a three days arc for the orbit determination.
- Two CDA passes per day on a one day arc for the OBTUTC correlation.

Other investigations are still on going to determine the optimal arc for orbit determination and OBTUTC.
It was also foreseen to optimise the dynamic and measurement processing models for orbit determination.
Those activities were however not performed during commissioning and are currently being carried out in routine (paragraph 5.1)

4.8. Vector Products Characterisation

As described above, the accuracy of the TLE generated at the beginning of the commissioning was not sufficient to ensure proper X-band dump in case of operation of the CDA in command track.
Furthermore it was noticed that the accuracy of the TLE was not sufficient for visibility prediction planning far in the future (1 week).

The impact of the orbit arc length used for the TLE estimation on the orbit accuracy after N days was analysed: the results are presented in figure 18.

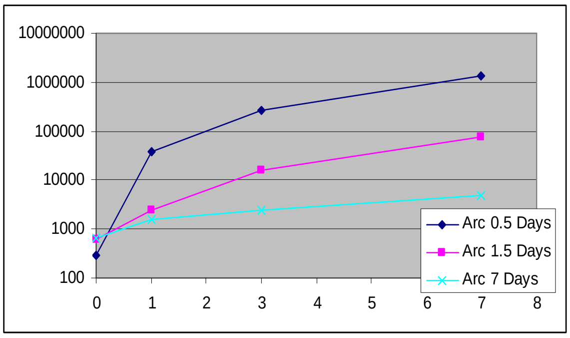

Figure 18: TLE accuracy in propagation (m)

The 1.5 days arc TLE presents poor performances both in the short term (around 0.6 km of accuracy RMS at day 0) and in the long term (nearly 100 km max error after a week).

The 0.5 days arc TLE improves of a factor two the short term accuracy and the 7 days arc TLE of a factor 20 the long term.

The operational generation of TLE was therefore modified to generate a short term product for CDA commanding and a long term product for visibilities prediction.

4.9. TCH generation characterisation

One day of orbit arc is considered for the generation of the OBOM and the DSS TCH.
That ensures proper commanding both in the 12 hours of nominal usage (two TCH uplinks per day are performed) and in the 36 hours in case of contingency (on-board autonomy requirement).

It was foreseen to analyse the impact of the length of the orbit arc on the accuracy of these TCH.
However, considered the excellent performances of these TCH, that activity was not carried out during commissioning and has being postponed to the routine phase (paragraph 5.1)

The number of commanded Earth sensor masking was compared with the foreseen number, according to the real sun and moon visibilities in the sensor.

Around 3000 events requiring mask were detected in one year, whereas around 10000 masking were commanded.
Furthermore the duration of these masking was significantly larger than the duration of the event.

These large differences are due to:

- The very large margins used for the generation of the TCH, both in FOV and on orbit position.
- The oversimplified way the masking transitions are handled in the TCH: if an event is detected in a fraction of a day, the masking is applied for the entire day.

Optimisation activities for that TCH are foreseen in routine phase (paragraph 5.1).

4.10. Attitude Monitoring Characterisation

A special TM campaign was organised during the commissioning to analyse in detail:

- The roll oscillation observed in the HKTM during SIOV and in the monthly trend analysis.
- The loss of accuracy in the Sun sensor HKTM due to data under-sampling.

During an entire day routine TM format was used during 90 minutes a day (instead of 10 in SIOV).
Moreover high frequency TM of the DSS was collected through a special TM format (TDIF).

Figure 19 depict the orbital evolution of the roll off-pointing computed from the Earth sensor and the equivalent roll off-pointing from the gyro drift on Z.

A clear correlation can be observed also in this case. Earth sensor oscillations are larger than the Z drift ones due to the missing infra-red compensation.

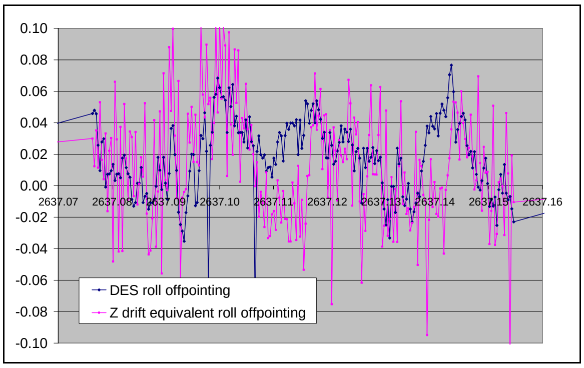

Figure 19: Roll off-pointing orbital evolution (deg)

The most probable cause of these oscillations is a imperfect compensation on-board of the variations of the Earth infra-red shape.
Because of that the Earth sensor commands an inaccurate roll pointing which is then observed in the Z gyro drift.

The compensation tables used are derived from the Envisat ones; the impact of the difference in local time of the ascending node is analytically added.
Improved compensation tables should be computed and loaded on board to reduce the oscillation.

In figure 20 the typical evolution of the DSS signal as from TDIF is provided.

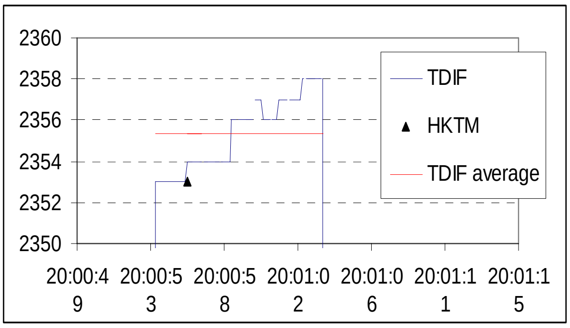

Figure 20: DSS HKTM accuracy (m)

Due to the under-sampling in the HKTM, the value returned on ground differs significantly from the real Sun position (average value)
Therefore the inaccuracy of the measurement is of the order of several mdeg, and thus comparable with the residuals observed in SIOV; that makes the measurement useless for on-ground monitoring.

5. ROUTINE OPERATIONS

During routine operations a continuous monitoring of all Flight Dynamics functions, based on the monitoring activities developed in SIOV and commissioning, is performed. That ensures the maintenance of the achieved performances.
Furthermore, standard activities of monitoring of the orbital evolution and implementation of orbital maintenance manoeuvres are carried out.

The generation of routine products needed for fulfilling the FDF mission requirement (paragraph 1.3) is performed in the server according to the following operational drivers:

- 3 operational sequences are executed daily to fulfil with the need of updating the SVM TCH twice a day and to update the mission planning and GRAS support network (GSN) products once a day.
- Events for mission planning are generated weekly and re-synchronised daily to the latest values of the ascending node crossing time.
- SVM TCH must be generated considering geocentric pointing and not considering any manoeuvre in the future up to the day of the manoeuvre itself.
- Mission planning and GSN products are generated considering estimated attitude (nominally Yaw Steering Mode - YSM) and manoeuvre prediction 3 days in the future.

Table 1 summarises the processes executed in each sequence as well as the execution time and the generation conditions

Routine (AM) *Geocentric pointing; late manoeuvre*	Aux (noon) *YSM pointing; early manoeuvre*	Second TCH (PM) *Geocentric pointing; late manoeuvre*
• OD and OBTUTC • SVM TCH and QA • Admin message • Antenna pointing • OSV for processing	• Attitude monitoring • Mission plan ANX • GSN events • Long term pointing • Attitude for processing	• OBTUTC • SVM TCH and QA • Admin message • Antenna pointing

Table 1: MetOp FDF Routine Automatic Operations

5.1. Routine FDF Monitoring

Auxiliary operations as well as monitoring operations are performed on the 3 clients on regular basis:

FDF client 1:

- XTTC data quality assessment: evaluation of timeliness, bias stability and noise of provided ranging and Doppler data.
- Assessment of FDF process quality: orbit determination and propagation accuracy, TBUS/SPOT vector accuracy, per-pass range and Doppler residuals analysis…
- Trend analysis of parameters in the routine runs: CD, station and gyro biases, clock frequency…

FDF client 2:

- TM special processing: gyro de-storage monitoring, gyro spectra computation, long arc TM re-processing, TM campaign data processing...

FDF client 3:

- Generation of extra products for special operations: special events generation for calibrations campaign and early detection of critical events…
- Early detection of dead-band violation and manoeuvre preliminary computation.
- On-line support to anomaly investigations and contingencies.
- Maintenance of precise orbit from GRAS L1A

The availability of a GRAS precise orbit permitted to start, on the same client where the precise orbit is maintained, the optimisation of set-up of the orbit determination:

- Dynamic model optimisation is performed using SV pseudo observations from POD.
- Observation modelling optimisation is performed using the POD orbit as fixed reference.

Other activities, not performed in commissioning, are foreseen to be carried out in routine:

- Optimisation of the estimation arc for orbit determination and OBTUTC correlation.
- Optimisation of the orbit arc for OBOM and DSS TCH generation.
- Optimisation of the DES masking TCH.

The results of these activities, once completed, will be presented in a future symposium.

6. CONCLUSIONS

Flight Dynamics operations for MetOp were designed on one side to provide full operational support during the different phases of the mission and on the other to evaluate at the same time the performances of the FDF itself and of the satellite.

A gradual evolution of the operations, from fully manual during LEOP and early SIOV to fully automatic in routine, was therefore implemented.
At the same time a gradual evolution of the depth of validation of the FD functionalities, from the mission critical capabilities during LEOP to continuous monitoring of the products quality during routine, was performed.

That permitted to have problems identified and thus solved quite early, improving the overall quality of the service.
Up to now FD products with the required accuracy and timeliness were provided in nearly the 100% of the routine time and TCH availability outages were limited to very few cases.

7. ACKNOWLEDGMENTS

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