Normal Paper

Meteosat ranging antennas relocation: performance assessment and compensation using telescopes data service

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Abstract

EUMETSAT operates four Meteosat imaging satellites, in geosynchronous regime, for weather monitoring and climate studies (see [1]). Their orbit is determined using traditional two-way ranging measurements from two different antennas per each satellite, with regular stations swaps. For the majority of the mission, 13-metres antennas were located in Usingen (Germany), each assigned as primary ground stations to different satellites. The single antenna in Maspalomas (Canary Islands, Spain) was in shared-use, for ranging only.
The wide separation in latitude/longitude allowed in the past fulfilment of the orbit-determination requirements, to achieve the target quality of image processing and weather products.

In the last 2 years, different changes took place: the last first-generation Meteosat was decommissioned, making available an extra antenna in Fucino (Italy). Then, it was decided to cease the use of the Usingen site, and to physically relocate the three antennas: one was moved to Fucino, other two in Cheia (Romania). Finally, the discontinuation of the Maspalomas antenna was considered. The target final configuration foresees therefore ranging antennas in Fucino/Cheia only, with a much smaller separation than the initial baseline Usingen/Maspalomas.

To assess the change in orbit-determination performance due to antennas relocation, the Flight Dynamics team performed various studies. First step was a series of covariance analyses, allowing the theoretical performance estimation based on typical modelling errors, both on the measurement chain (noise, bias, coordinates errors) and in the processing chain (ionospheric/tropospheric delay, initial covariance), for given tracking schedules.

When the performance loss was characterised, it was decided to test the effects of an augmented observability, using telescope(s) data on a routine base, and to actually implement the solution with a service. After various trials with different service providers and operational concepts in the last years (see [2] and [3]), a multi-year service contract was established in 2018 for the use of the primary DeSS robotic telescope (Spain) and other cooperative sensors. Purpose of the service was the parallel independent monitoring of the dual-stations´ orbit solutions and manoeuvre calibration, and eventual compensation of the eventual antenna contingency or performance loss.

The paper will describe all the steps of the analyses, till the conclusion on the use of data-fusion techniques with dual stations’ ranging and optical data: this allowed mitigation of the accuracy loss due to ground stations relocation, and minimisation of the impact on the reference quality of the weather products.

Keywords: geosynchronous, orbit-determination, telescope, ranging, data-fusion.

Introduction

EUMETSAT is the “EUropean organisation for the exploitation of METeorological SATellites”. It is an independent intergovernmental organisation created in 1986 to establish, maintain and exploit European systems of meteorological satellites. It currently operates a system, monitoring the atmosphere and ocean and land surfaces, which delivers weather and climate-related satellite data, images and products – 24 hours a day, 365 days a year. EUMETSAT currently has eight operational weather satellites: Meteosat-8, -9, -10, -11, Jason-3, and Metop-A, -B, -C. Meteosat are the satellites of the geosynchronous (GEO) fleet. Metop are the Low-Earth-Orbit (LEO) polar meteorological satellites, which form the space segment component of the overall EUMETSAT Polar System (EPS). Jason-3 delivers oceanographic data from not-Sunsynchronous LEO at 1336km altitude.

The present generation of GEO satellites is the Meteosat Second Generation (MSG, see [2]), providing real time imagery of the Earth with Full-Disk Service (FDS, images every 15 minutes) and Rapid-Scan Service reduce areas (RSS, every 5 minutes) from geosynchronous orbit (see Table 1, Fig. 1), with additional support to Indian Ocean Data Coverage and in-orbit back-up capabilities.
The programme foresees 4 satellites of this kind, spin-stabilised, rotating at around 100 rpm. All of them are operational: MSG-1 launched in 2002, MSG-2 in 2005, MSG-3 in 2012. MSG-4 in 2015, completes the programme, before the third generation (MTG) will take over the service.

Table 1: Current Meteosat satellites

Satellite	Launch => End-of-Life(*)	Position	Services
Meteosat-11 (MSG4)	15/07/2015 => 2033	0°	Earth Full-Disk Service (FDS)
Meteosat-10 (MSG3)	05/07/2012 => 2030	9.5°E	Rapid Scanning Service (RSS)
Meteosat-9 (MSG2)	22/12/2005 => 2024	3.5° E	RSS gap filling & in-orbit back-up
Meteosat-8 (MSG1)	28/08/2002 => 2022	41.5° E	Indian Ocean Data Coverage Service

(*)EOL figures are based on propellant considerations only (no reliability analysis)

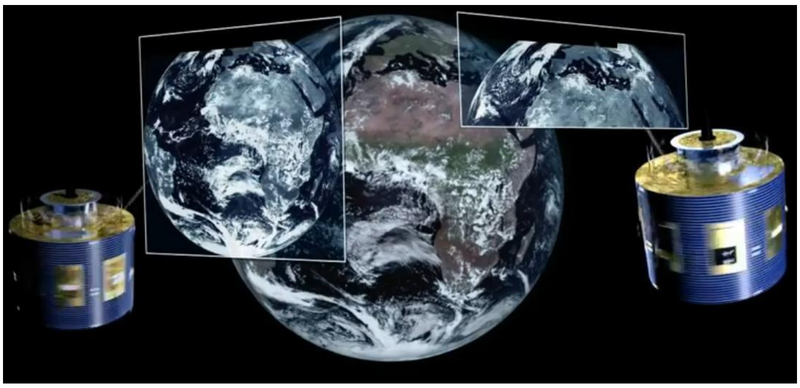


Fig. 1: MSG satellites, Earth Full-Disk (left) and Rapid-Scan (right) services

Initial and Target ground-stations configuration for ranging

Operationally, for the previous first generation of Meteosat, the Orbit Determination (OD) was performed by means of ranging from a single station. For the last 2 of these satellite series, the Antenna-1 and Antenna-2 in Fucino (Italy) were used.

Due to more stringent orbit requirements for the Meteosat of Second Generation (MSG, the 4 spacecraft presently in-flight), their orbit is determined using traditional two-way ranging measurements from two different antennas per each satellite, with regular stations swaps.
For the majority of the mission, three antennas were located in Usingen (Germany), each assigned as primary ground stations to different satellites, and labelled internally Antenna-18, -19, -20. These 3 antennas are EUMETSAT property. The single antenna in Maspalomas (Canary Islands, Spain) has been in shared-use via service contract, for ranging purposes only, from the beginning of the programme till nowadays. The wide separation in latitude/longitude allowed in the past fulfilment of the orbit-determination requirements, to achieve the target quality of image processing and weather products.

For the Meteosat of Third Generation (MTG, 3-axis stabilised satellites, first to be launched in 2021), two new S-Band antennas have been already procured, installed and validated in Fucino and Cheia (respectively TTC1 and TTC2, also EUMETSAT propriety).

In the last years, different changes took place:

- The last Meteosat of last first-generation were decommissioned, making available extra antennas in Fucino, belonging to EUMETSAT. Last 2 satellites were re-orbited in 2011 and 2017.
- It was decided to cease the use of the site in Usingen (due to blocking points for contractual extensions for the 2018-2035 period).
- Due to the point before, the three EUMESAT proprietary antennas in Usingen were to be physically relocated:
    - Antenna-20 to Fucino
    - Antenna-18 and -19 to Cheia

The discontinuation of the service for the use of Maspalomas antenna is being considered (principally for cost saving reasons), to be replaced by relocated Antenna-18 and -19 in Cheia.

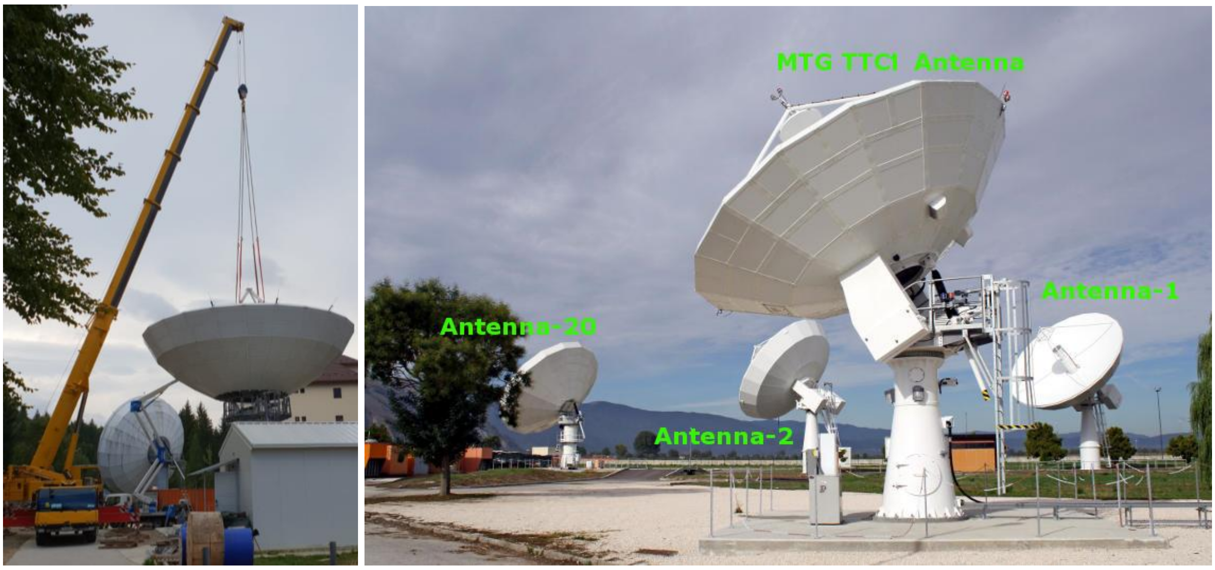


Fig. 2: Antennas relocation on-going in Cheia (left) and completed in Fucino (right)

The target final configuration foresees therefore ranging antennas in Fucino/Cheia only for the MSG operational satellites (with an intermediate phase using also Fucino/Maspalomas); this has a much smaller separation than the initial baseline of Usingen /Maspalomas, and subsequent impact on orbit determination accuracy.
The launch of the first MTG being in 2021, the MTG antennas TTC1&2 have been meanwhile made available for MSG: TTC1 passed already the operational readiness, while TTC2 can be currently used for test purposes only.
The target final solution (base-line “C” in Table 2 and Fig. 3) would allow the use of two sites only for a very long time period (the launch the operational life time of the MTG programme is of at least 20 years), augmenting synergies between the MSG and MTG satellites programmes for operations.

Table 2: Current and Future sites for Meteosat ranging ground-stations

Site ID	Antenna(s) ID	Site Latitude [°]	Site Longitude[°]	Site Name Country	Base-lines
1	Antenna-18, -19,-20	50.334	8.4833	Usingen, Germany	A
2	BRGS(**)	27.682	-15.429	Maspalomas, Spain	B
3	Antenna-1, -2, -20(*), TTC1	41.97747	13.59873	Fucino, Italy	C
4	Antenna-18(*), -19(*), TTC2	45.45732	25.94602	Cheia, Romania	

(*) after antenna relocation *(**) external service*

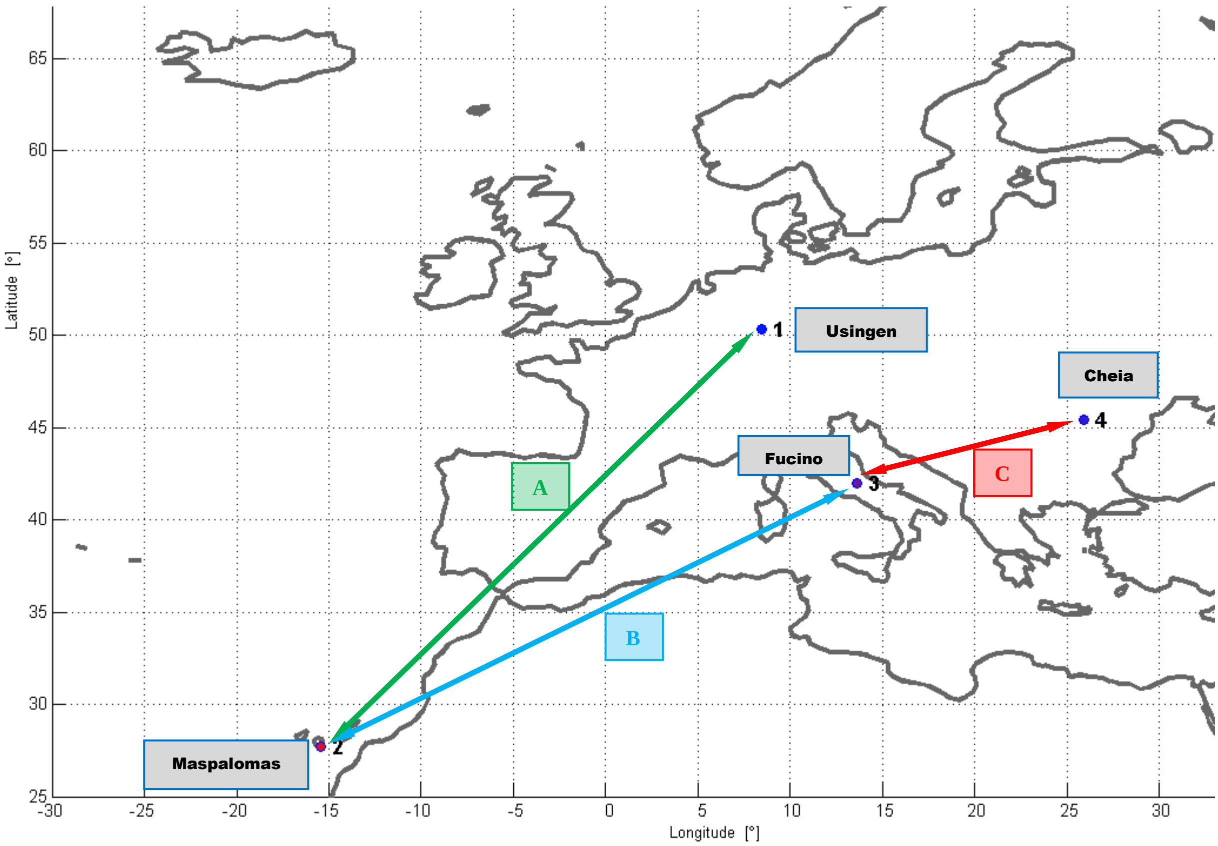


Fig. 3: Current and Future ranging sites for Meteosat (equi-rectangular map)

Orbit-determination accuracy prediction for planned antennas relocation

As mentioned, the final configuration could have several practical advantages from logistic and economical point of view. But what could be anticipated is an overall degradation of the Orbit Determination (OD) accuracy due to shortening and rotation of the OD base-line with respect to the configuration used in the initial part of the MSG programme. The first step was the quantification of the performance loss, by means of covariance analysis.

Covariance analysis Tool

For the purpose of the analysis, it is necessary to use a tool that simulates the orbit determination process in a representative way, giving a reliable statistical content in the results. TRAMOS (TRacking Analysis with MOnte-carlo Simulations) is proprietary software, procured by EUMETSAT. The simulation concept foresees the use of high accuracy models for orbit propagation and measurements generation.
As part of the "Real world" simulation, the tool allows generation of a reference trajectory, simulating the spacecraft "real" orbit based on high fidelity model (GEMT3 50x50 Earth gravity field, Solid tides from IERS conventions, third body gravitational attraction with NASA DE405 ephemerides, solar radiation pressure with flat plate model). One can select the geographical location of the tracking stations, the scheduling of the tracking measurements (and eventual stations swaps in case of ranging) in the measurements generation module, with addition of assumed measurements' errors; then, the "Estimated World" simulation is run (see top-level architecture in Fig. 4).

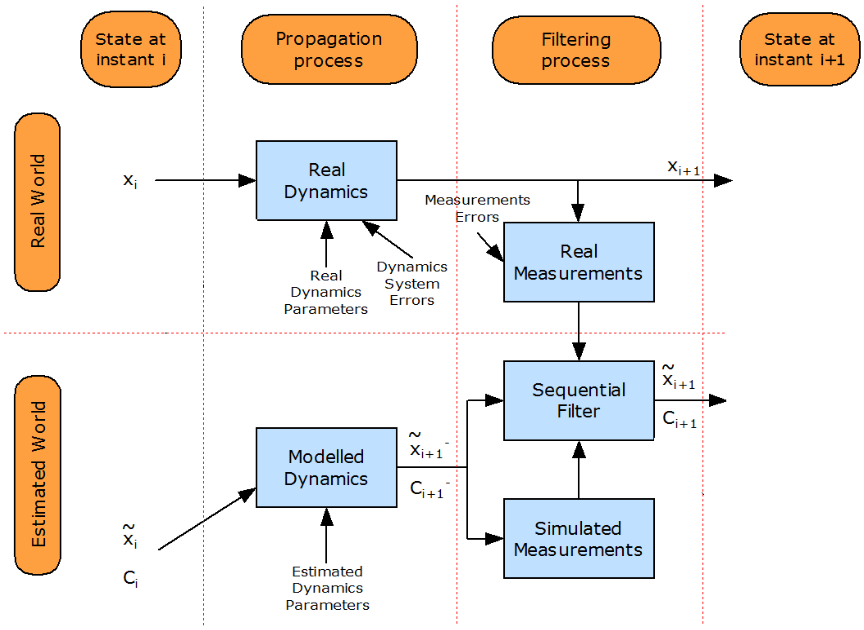


Fig. 4: TRAMOS top-level simulation/OD architecture

The covariance-analysis module (see Fig. 5) allows for simulating various uncertainties of the orbit determination process, such as local terrain displacement of stations, effects of the troposphere and ionosphere (including periodic variations), measurements noise, ground stations and spacecraft transponder delays, uncertainties in the solar radiation pressure or geopotential coefficients. Partial derivatives are computed over the nominal dynamics and measurements by discrete differences

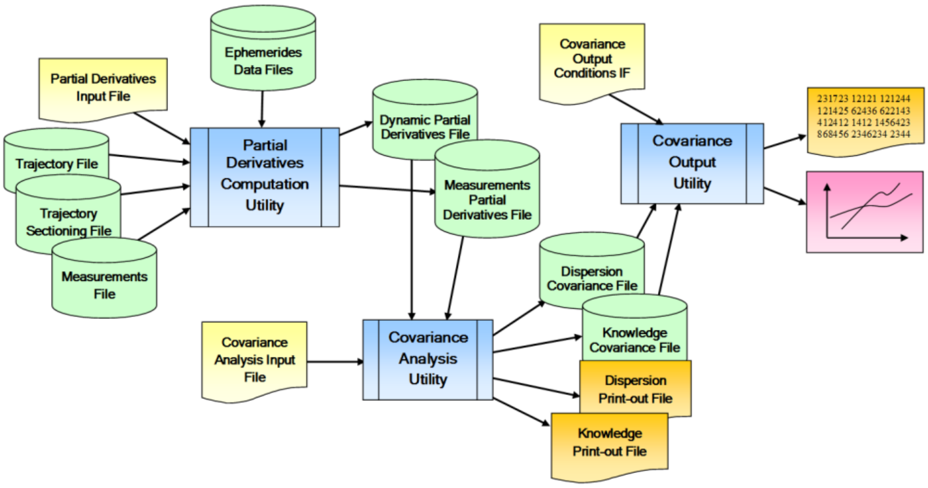


Fig. 5: Schematic functionality of the TRAMOS covariance-module

The solution for the trajectory determination is implemented by means of covariance analysis with a square root information filter (SRIF); the orbit determination performances are obtained in time intervals, during which a batch of measurements is processed altogether, to obtain an update in the knowledge of the system state. The use of SRIF allows obtaining an estimated deviation in the state vector at the beginning of the mapping time interval. This is done by merging the a-priori accuracy information with those provided by the associated dynamics and the measurements in a mapping time interval. Then, the augmented state and the covariance matrix are propagated to the next mapping time. This approach allows including in the estimation process not only the modelling of the dynamic variables, as defined by their equations, but also the effect of exponentially correlated random variables and considered biases. The output of the covariance-module gives the evolution of the 1-sigma position (and velocity) accuracy as function of time. A successive arc of pure propagation is used, starting from the acquired orbit determination accuracy, to evaluate the final accuracy at the end of tracking, also considering the typical oscillating uncertainty in along-track, cross-track and radial direction (due to errors in determination of the eccentricity).
To improve simulation results in case of correlated errors or non-Gaussian errors, the estimation process can be simulated also in Monte Carlo sense, with a traditional statistical analysis process for final statistics attainment (elimination of outliers).

Covariance analysis set-up

As mentioned, the shared use of Maspalomas antenna and related stations' swap are necessary to achieve the MSG orbit determination accuracy requirements.
At the time of writing, Antenna-20 was moved to Fucino and passed already its operational readiness review; same for MTG TTC-1, they are both used in operations together with Antenna-1 and 2 as primary stations, all in the Fucino site. Maspalomas is still providing the shared service for ranging support as secondary station, with higher frequency of ranging measurements to compensate for the shorter tracking arc.
An example of operational ranging schedule and stations' swap for this configuration is showed Table 3. Based on this, and assuming a tracking arc of 8 days (as done in routine operations for the operational orbit update), the following tracking schedule is established for the covariance analysis.

- Primary station: Day 1/2/3 and Day 6/7/8, ranging measurement every 60 minutes
- Secondary station: Day 4/5, ranging measurement every 30 minutes

Table 3: Example of operational ranging schedule

	Mon	Tues	Wed	Thurs	Fri	Sat	Sun	Mon	Tues	Wed	Thurs	Fri	Sat	Sun
MSG2	00:00 TTC1 24:00	00:00 TTC1 24:00	00:00 TTC1 24:00	00:00 TTC1 24:00	00:00 TTC1 08:00 BRGS 24:00	00:00 BRGS 16:00 16:00 TTC1 24:00	00:00 TTC1 24:00	00:00 TTC1 24:00	00:00 TTC1 24:00	00:00 TTC1 24:00	00:00 TTC1 24:00	00:00 TTC1 08:00 BRGS 24:00	00:00 BRGS 16:00 TTC1 24:00	00:00 TTC1 24:00
MSG3	00:00 Ant.20 24:00	00:00 Ant.20 24:00	00:00 Ant.20 12:00 12:00 BRGS 24:00	00:00 BRGS 24:00	00:00 BRGS 08:00 08:00 Ant.20 24:00	00:00 Ant.20 24:00	00:00 Ant.20 24:00	00:00 Ant.20 24:00	00:00 Ant.20 24:00	00:00 Ant.20 12:00 BRGS 24:00	00:00 BRGS 24:00	00:00 BRGS 08:00 Ant.20 24:00	00:00 Ant.20 24:00	00:00 Ant.20 24:00
MSG1	00:00 Ant.1 08:00 08:00 BRGS 24:00	00:00 BRGS 24:00	00:00 BRGS 08:00 08:00 Ant.1 24:00	00:00 Ant.1 24:00	00:00 Ant.1 24:00	00:00 Ant.1 24:00	00:00 Ant.1 24:00	00:00 Ant.1 08:00 BRGS 24:00	00:00 BRGS 24:00	00:00 BRGS 08:00 Ant.1 24:00	00:00 Ant.1 24:00	00:00 Ant.1 24:00	00:00 Ant.1 24:00	00:00 Ant.1 24:00
MSG4	00:00 BRGS 08:00 08:00 Ant.2 24:00	00:00 Ant.2 24:00	00:00 Ant.2 24:00	00:00 Ant.2 24:00	00:00 Ant.2 24:00	00:00 Ant.2 16:00 BRGS 24:00	00:00 BRGS 24:00	00:00 BRGS 08:00 08:00 Ant.2 24:00	00:00 Ant.2 24:00	00:00 Ant.2 24:00	00:00 Ant.2 24:00	00:00 Ant.2 24:00	00:00 Ant.2 16:00 BRGS 24:00	00:00 BRGS 24:00

In all simulations, the ranging noise is assumed 2 meters 1-sigma. The reference orbit is assumed at 9.5Edeg longitude with 0deg inclination (worst case for orbit determination, given the base-lines). The initial covariance is in line with 1-sigma position requirements for orbit determination as from MSG system requirements (1 km /1 km / 0.1 km in along-track / cross-track / radial).

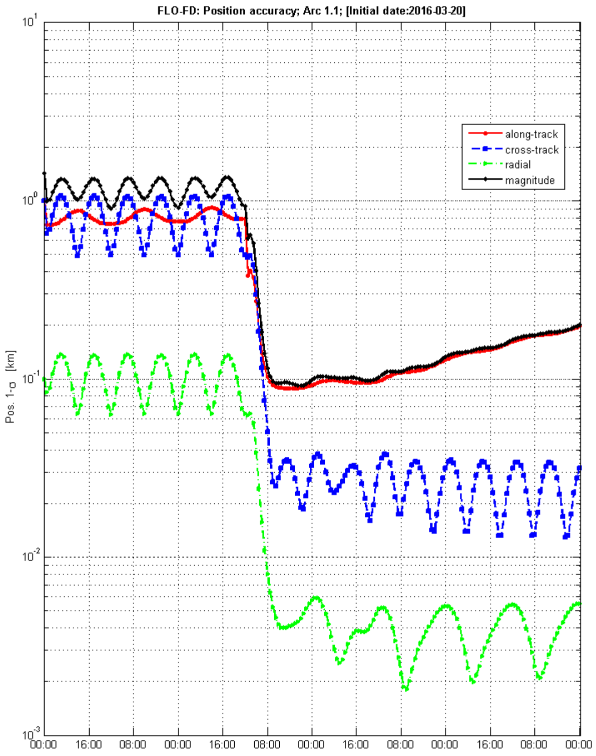
Results of Covariance analysis with ranging only for 3 base-lines

In each analyses reported in the following sections, the results show the evolution of the covariance in along-track/cross-track/radial/magnitude, as function of time, for the selected measurements and tracking schedule, see Fig.6 to Fig.8, showing the covariance (1-sigma) on position in local-orbital frame, in logarithmic scale as function of time .

For the computation of the final covariance values, a pure propagation (24hours) is run, this allows computing the worst case figures for the orbit determination accuracy, also coping with orbital pulsations. These results are presented alphanumerically (see Table 4), giving the statistics on the position 1-sigma error, during the pure-propagation arc of 24 hours following the orbit determination, for comparison among the various combinations of tracking sites (geographically represented in Fig. 3).

Table 4: Maximum 1-sigma position errors, after OD based on dual stations' ranging

Base-line	Along-Tr.[m]	Cross-Tr.[m]	Radial[m]	Magnitude[m]
A) Usingen + Maspalomas	295.219	33.5203	5.45099	296.992
B) Fucino + Maspalomas	206.625	39.4582	4.84035	209.751
C) Fucino + Cheia	187.447	206.478	27.1699	255.643



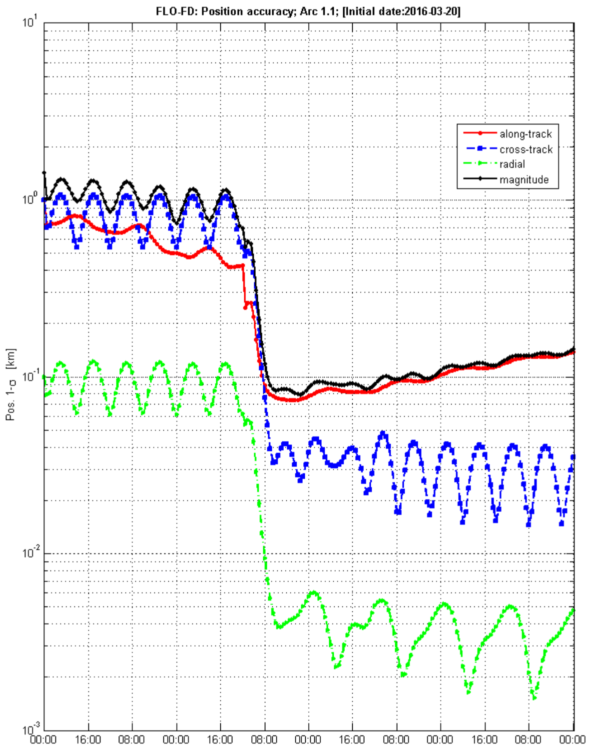


Fig.6:Usingen/Maspalomas, covariance results;Fig.7:Fucino/Maspalomas, covariance results

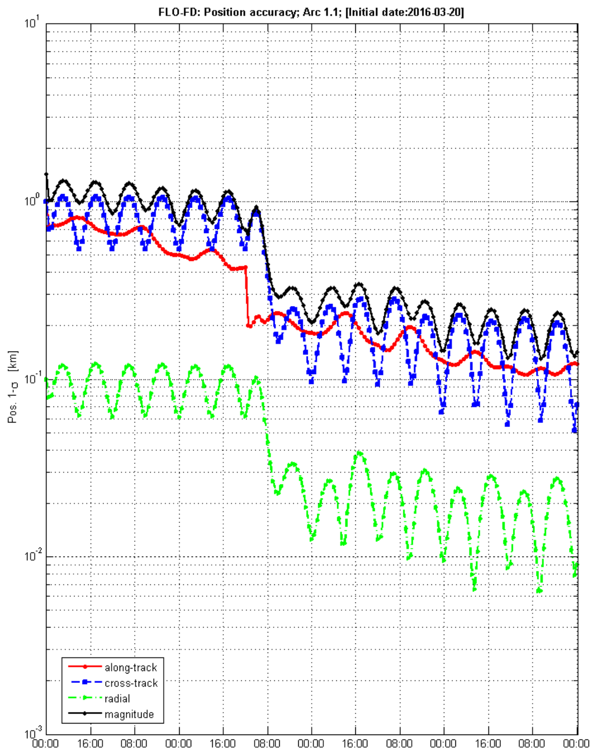


Fig.8: Fucino/Cheia, covariance results

In the envelop of the simulated scenarios, the combination of tracking sites' using ranging measurements from Maspalomas, either with Usingen (former primary site) or with Fucino (current one primary site), are very similar in performances. The Fucino/Maspalomas case has a slightly better along-track accuracy due to a greater longitude separation of the primary station with the sub-satellite point (along-track error is known to go to infinite, for tracking with a single station at same longitude of tracked spacecraft). This has been confirmed also by the operational orbit determination results, after the switch from the initial base-line to the intermediate one.

When considering the target final base-line (Fucino as primary site and Cheia as secondary), it can be noted that:

- the along-track accuracy is slightly improved; in fact, the minimum error in the mean longitude drift occurs in the future (while it happens in the past, i.e. within the determination arc for the first 2 cases). This is due to Earth rotation and to the relative positioning of the subsatellite point West of the base-line midpoint, as known for theory (see [4]).
- the cross-track and radial accuracy get both notably worse, of a factor ~6 and ~5 respectively, due to much shorter geographical separation of the stations, and subsequent observability impact.

Accuracy recovery with Optical-Data augmented tracking

As potential mitigation of the accuracy worsening, the use of optical data from ground telescopes was investigated, especially based on the promising results of the short-term trial campaigns performed by EUMETSAT in the past years (see [2] and [3]) about data-fusion: the orbit determination processes together both optical data and ranging data.

Another covariance analysis was set up, based on typical performance of the telescope used for tracking (instead of survey sensors), assuming an azimuth/elevation noise of the telescope data of 0.33 millideg 1-sigma, and a telescope located in South Spain.
Furthermore, the previous trials showed that good orbit determination results can be obtained with 2 or 3 slots of telescope measurements of 15 minutes each, in a single or two consecutive nights, each with 60 measurements (therefore with measurements every 15 seconds), that is a solution typically achievable by many telescope data providers.
Anyway, due to a limitation of the tool for covariance analysis (minimum time-separation between measurements is 1 min), the slots are extended to allow the same number of measurements (e.g. 60 min slots).

The following different types of telescope scheduling were analysed, with the same 8 days tracking arc used in the previous step:
a) Two slots of 1 hour in consecutive nights (Day 7&8), separated by 24 hours
b) Two slots of 1 hour in consecutive nights (Day 7&8), separated by 24+3=27 hours
c) Two slots of 1 hour in consecutive nights (Day 7&8), separated by 24+6=30 hours
d) Two slots of 1 hour in consecutive nights (Day 7&8), separated by 24+9=33 hours
e) Two slots of 2 hours in consecutive nights (Day 7&8), separated by 24 hours
f) Two slots of 1 hour in the same night (Day 8), separated by 6 hours
g) Three slots of 1 hour in the same night (Day 8), separated by 3 hours

An example of the covariance evolution in time is shown for the schedule type d) in Fig. 9 while the summary of numerical results is reported in Table 5.

Table 5: Maximum 1-sigma position errors, after OD based on Fucino-Cheia & Optical Data

Base-line C) Fucino + Cheia & Optical data with:	Along-Tr.	Cross-Tr.	Radial	Magnitude
Schedule a)	166.82	189.54	25.0531	240.936
Schedule b)	157.368	91.9998	13.5491	176.178
Schedule c)	160.397	79.2183	12.6888	169.794
Schedule d)	174.188	137.442	19.5518	204.203
Schedule e)	158.463	69.2991	11.606	163.846
Schedule f)	161.639	72.2005	9.98866	175.748
Schedule g)	154.73	52.2145	8.58728	157.561

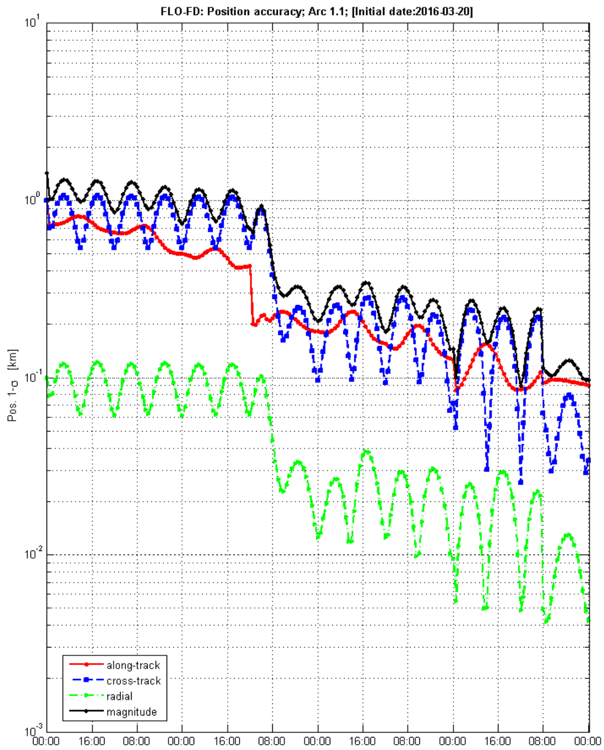


Fig. 9: Base-line C), Fucino-Cheia dual stations ranging, with optical data schedule type d)

As shown, the scheduling of the telescope data has an impact on the overall accuracy: in case multiple slots of observations are possible, for greater accuracy the 2nd slot should be scheduled, with ideally a 6 hours separation in local start time of the slots (on the same night, or in the following night). The optional use of telescope data with this kind of schedule, in support to Fucino/Cheia ranging, allows an improvement in the orbit determination accuracy, limiting the above mentioned cross-track and radial worsening.

As technological investigation, the implementation of an optical data provision service was therefore recommended, based on regular collection of optical data from various telescopes, to evaluate their potential benefit in support to routine operations.

Operational service for optical data support to operational orbit determination

Optical data service top level description

The new optical data service procurement was initiated in open tender in 2017, with the target to demonstrate the robustness of a technical solution, fully integrated in a EUMETSAT formal operational environment. The contract was granted to Elecnor Deimos, and started in July 2018. The operational uses of the data involve:

- Complement of ground stations' scheduled/contingency outages (e.g. antenna move)
- Calibration of ground-stations
- Manoeuvre support
- Orbit determination, analysis and comparisons.

The service consists of the following operational modes: Routine Mode and Manoeuvre mode: both providing telescope optical data in CCSDS Tracking Data Message (TDM) , and orbit ephemeris data in CCSDS Orbit Ephemeris Message (OEM). In routine mode, the provision of the optical data is regular and it is triggered without direct input from EUMETSAT. The manoeuvre mode is on-demand: when it is activated by EUMETSAT, the same sequence of events is performed for the provision of data, but with additional restrictions for the telescope(s) scheduling. An example sequence diagram of the service is shown in Fig. 10. The generation of ephemeris by the optical data provider is done based on independent orbit determination software with the delivered sets of optical data.

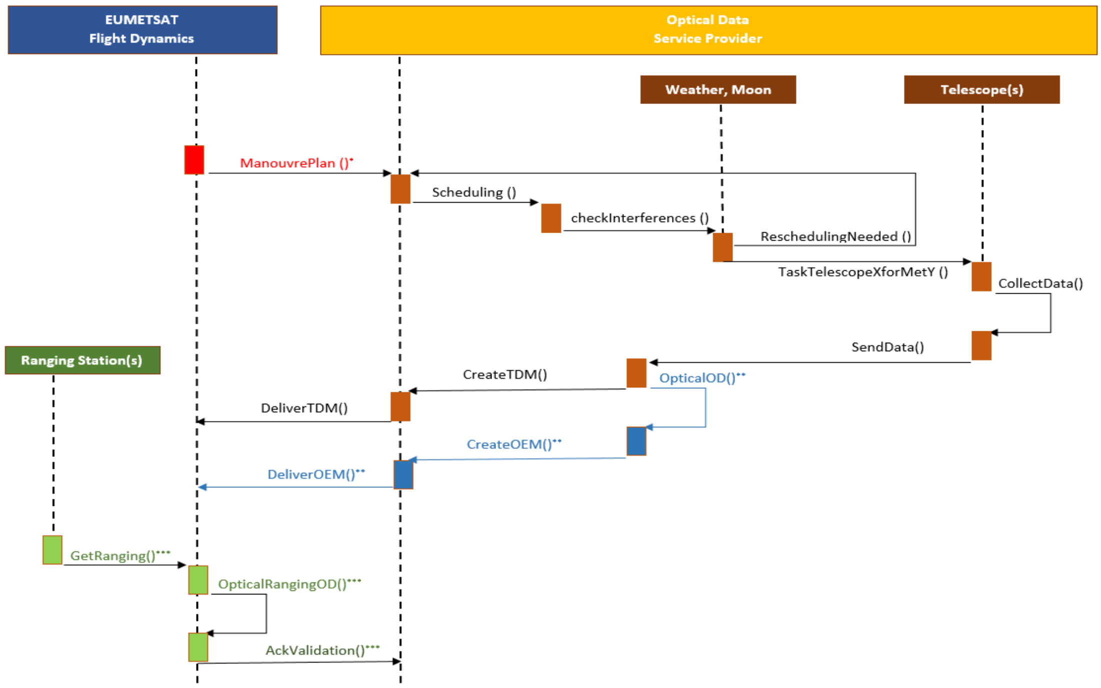


*Fig. 10: Optical Data Service, example of sequence diagram; * = Manoeuvre mode only, ** = Ephemerides Service, *** = Validation phase only*

The service successfully completed an initial contractual period for validation of two-week by an Operational Readiness Review. The operations were then authorised to start, with 52 weekly Routine Mode regular deliveries (each week) and 12 Manoeuvre mode deliveries (to be activated on demand) for the first year, with options for extension of the service for 2

following years. Each delivery is subject to integrity checks on the delivery content, as reported by email from the contractor, together with quality checks.
In order to check the Optical data TDMs quality, for every weekly delivery EUMETSAT performs an orbit determination based on data fusion (optical data and dual stations' ranging). As a quality indicator, the residuals of the optical data are required to have a mean value and standard-deviation (Azimuth and Elevation) both below 0.75 millideg (in absolute value) for 97% of the measurements.
Another quality indicator, the results of the EUMETSAT ephemerides from data fusion OD are compared with those provided as part of the Service. For the whole time arc between 2 consecutive tracking periods, the differences in position (along-track, cross-track, radial) are required to be:

a) less than 500m/300m/35m in case of "Routine Mode"
b) less than 1200m/350m/350m in case of "Manoeuvre Mode"

In case the quality indicators are below the respective thresholds, the delivery is not accepted.

Optical data service, required functionalities

Routine Mode is possible for all MSG spacecrafts, while the Manoeuvre Mode has a maximum of 1 spacecraft per week, if activated. The optical measurements are delivered in TDM format every week per spacecraft, based on a scheduled tracking period. Tracking periods for different spacecrafts are not bound to be on the same night, they can be on different nights. For a single spacecraft, tracking on multiple nights is also possible. The measurements are single triplets (e.g. {time, right ascension, declination}) of a specific target object. The tracking period contains a minimum of 2 slots of measurements; these slots can be separated in different nights. Each slot of measurements has a minimum duration of 15 minutes duration, with slots separated by at least 2 hours, and containing at least 60 measurements regularly spaced (this means: for a slot of 15min, this implies 15 seconds maximum separation among measurements).

All the measurements are collected in night or twilight, without clouds or Moon interferences. In routine mode, due to weather conditions, the service provides short term re-scheduling and it has the flexibility to change tracking period in a week, as long as the required slots are guaranteed. In manoeuvre mode there is less flexibility in choosing the tracking periods, due to higher availability needs. The "Manoeuvre Mode" tracking period is scheduled within 24 hours of manoeuvre execution. For executed manoeuvres during the night-time at the selected telescope site(s), the tracking period is in the same night (this assumes the manoeuvre execution time allows the scheduling of tracking period as required). For executed manoeuvres during the day at the selected telescope site(s), the tracking period occurs in the night immediately following the manoeuvre.
This means that to cope with adverse weather condition in a single site, the service provides site diversity and telescope redundancy. For scheduling purposes, the prediction of the spacecraft trajectory is based on orbit ephemerides delivered weekly, covering 30 days and containing eventual effects of manoeuvres in same time horizon.

The Service also provides OEM ephemerides obtained from the orbit-determination process, based on optical data only. This OD for ephemeris generation is run weekly by the service providers, using optical data collected in the current and previous week. In "Routine Mode", the Solar Radiation Pressure coefficient (cannon-ball model) and the telescope(s) Azimuth and Elevation bias are determined. In "Manoeuvre Mode", manoeuvre calibration factors (magnitude and direction) are determined and compared to the planned value provided by EUMETSAT. The orbit determination function of the service computes also statistics on measurements (residuals mean, residuals standard deviation, number of used/rejected measurements), as well as computed and propagated covariance.

Optical data service ground hardware and organisation

All details about the technical solution implemented by Deimos to fulfil the EUMETSAT requirements for the optical data service are reported in [5] and [6], the following is a summary. The network of telescope employed by the service is shown in Fig. 11.

Fig. 11: Optical data service: primary and backup sensors

Tracker-2 of DeSS is used as primary sensor for the service, with other telescope allocated as back-up in case data from the primary are not available for manoeuvres of for long outage period. DeSS is owned and operated by Elecnor Deimos. It comprises an optical observatory, its related control centre, hardware, software and personnel. All the facilities are located in Castilla-La Mancha (Spain). The optical sensors are located near Niefla mountain pass, while the control centre is located in the Deimos premises in Puertollano. The observatory is operated remotely from the control centre via a dedicated 37-km radio link. The main characteristics of the DeSS Tracker-2 telescope are shown in Fig. 12.

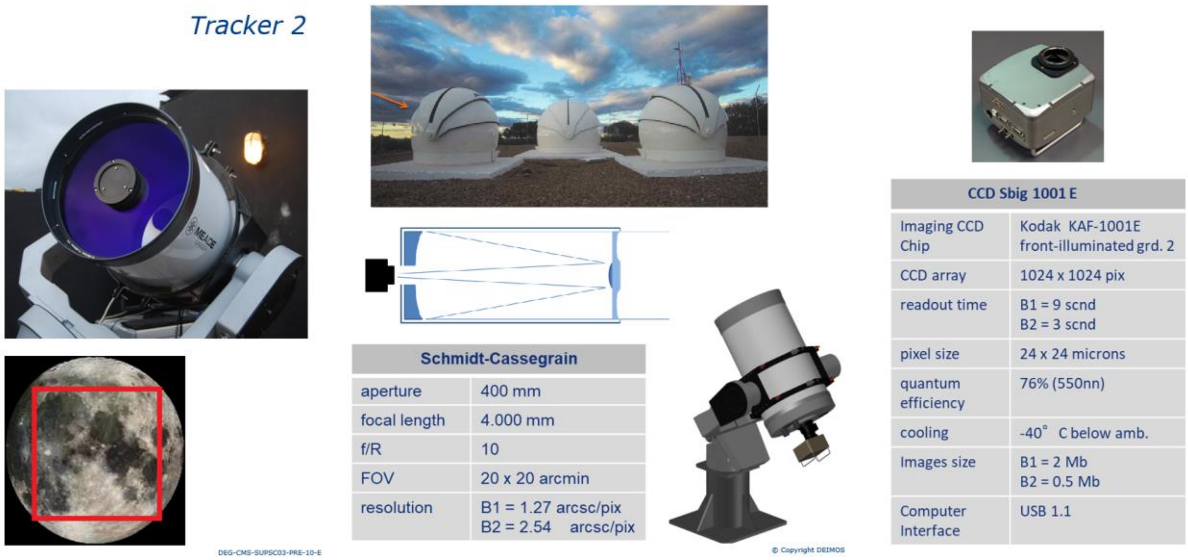


Fig. 12: DeSS Tracker-2 primary sensor, main characteristics

The backup sensors are activated only in case of technical failures or bad weather conditions in the primary site. When they are activated, their respective operators perform the requested observations on the Eumetsat GEO satellites and submit the results to DeSS.

- TJO is a tracking sensor operated by the Institut d'Estudis Espacials de Catalunya.
- IAC80 is a tracking sensor operated by the Instituto Astrofisica de Canarias.
- TFRM is a surveillance sensor with tracking capabilities operated by the Real Academia de Ciencias de Barcelona.
- The Bootes network operated by the Instituto de Astrofisica de Andalucía, comprises three available sensors at different longitudes

After optical data collection by the sensors (HUM files), the main track processing is performed by a dedicated chain. It polls for tracks generated by the Tracker2 sensor or made available by External measurements sources. In this case, there is a single HUN file per night, containing all the observations performed by that telescope in that particular night. The HUN is a format used internally within DeSS, with all relevant astrometric data along with metadata.
This processing chain (see Fig. 13) performs these actions:

1. Filter the HUN, keeping only the observations tagged for EUMETSAT.
2. Split the remaining measurements into groups, each group corresponding to a different observations slot.
3. Remove intruders in the groups. Intruders are observations of secondary objects that happen to be in the same field of view of the target object at the time of observation.
4. Apply corrections to the tracks that require it. As each sensor provides tracks with different corrections applied, Deimos makes all the tracks homogeneous at this stage.
5. Apply time biases to sensors that require it.
6. Convert the remaining tracks into the format agreed for data exchange (in this case, ASCII TDM).
7. Register the tracks in the database.

Finally, the track uploader is executed upon schedule: it verifies the database, checking for new files to be submitted. In this case and when the agreed timeliness conditions are met, the files are uploaded to the FTP, and thus made available to EUMETSAT, as well as registered as already uploaded in the database.

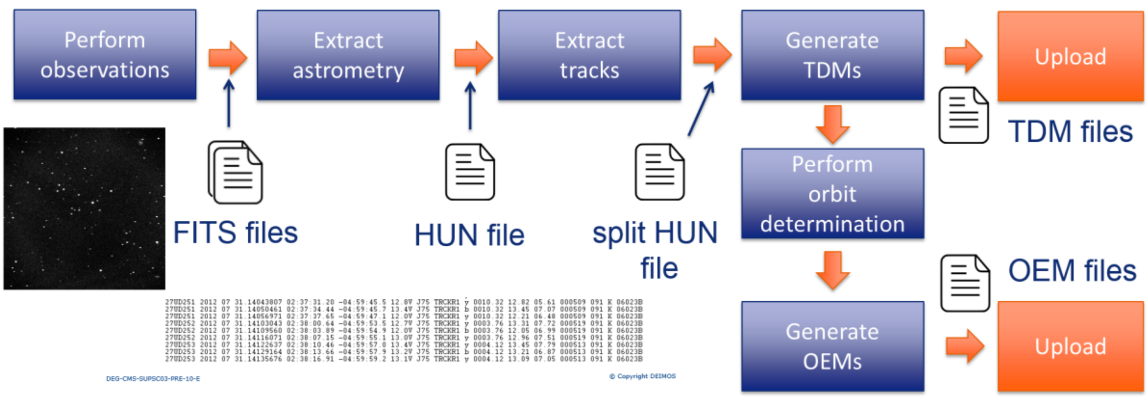


Fig. 13: Optical service track processing and orbit determination

The service orbit determination is performed routinely with the optical tracks. An OD worker retrieves all the optical tracks from the database, within two weeks before the execution date. When there is a manoeuvre within that period, only the tracks after the manoeuvre are considered for the Orbit Determination batch in a dedicated tool that also generates an OEM with the determined orbit. Finally, the resulting orbit is compared with the orbit that was obtained the previous week. This OD worker task is executed daily for each of the satellites and the results provided by it submitted once per week. This is achieved by the OEM uploader. This process just uploads the latest orbits computed by the system to the FTP and registers them in the database. There is a time window between the execution of OD worker and OEM uploader. During that time window, the Deimos operators can manually check the orbit determination results. The system allows the operators to re-execute the OD tool, replacing the results of the manual execution. This design was devised in order to allow manually repeating the orbit determination in case some problem arises, while working fully automatically. Generally, the operators do not need to perform any action, and therefore, when the time window expires, OEM uploader uploads the orbits without further action. Upon uploading the orbits, an automatic email is issued with information and statistics about the computed orbits.

There are four + one data fluxes, with data exchanged by secure ftp:

- Nominal orbits from EUMETSAT for observations planning.
- Manoeuvres plan from EUMETSAT for manoeuvre calibration
- Optical observations from Deimos to EUMETSAT for orbit determination.
- Orbits from Deimos to EUMETSAT for cross checking, with auxiliary information to quickly monitor the quality of the Deimos determined orbit and its self –consistency with the previous delivery (see Fig. 14)
- The fifth data flux is ranging measurements from EUMETSAT for orbit determination. It is used to perform data fusion (ranging + optical) orbit determination at Deimos, but this interface and functionality was added after the service started and it is still in trial phase.

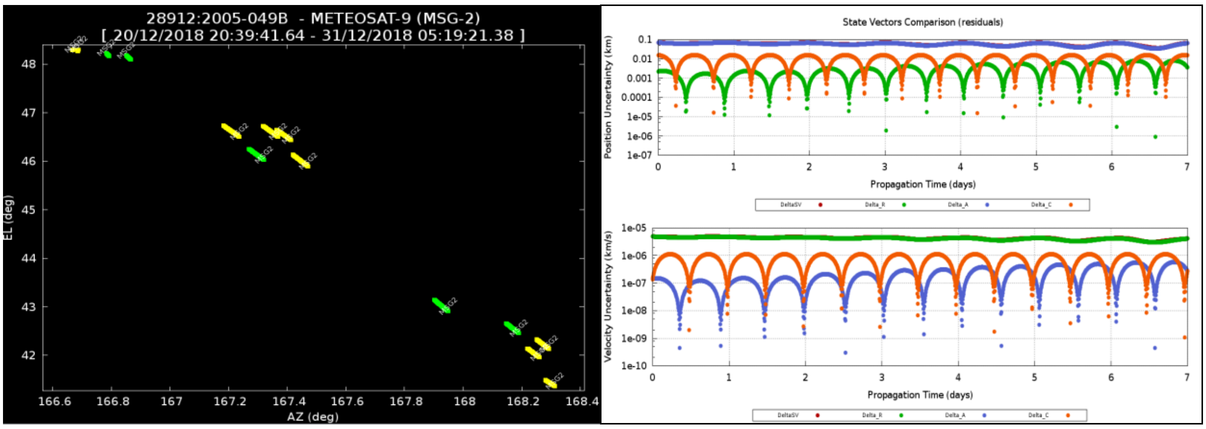


Fig. 14: Example of auxiliary data in support to Orbit products from Deimos to EUMETSAT

The weekly organisation of the tasks of the service is detailed in Fig. 15

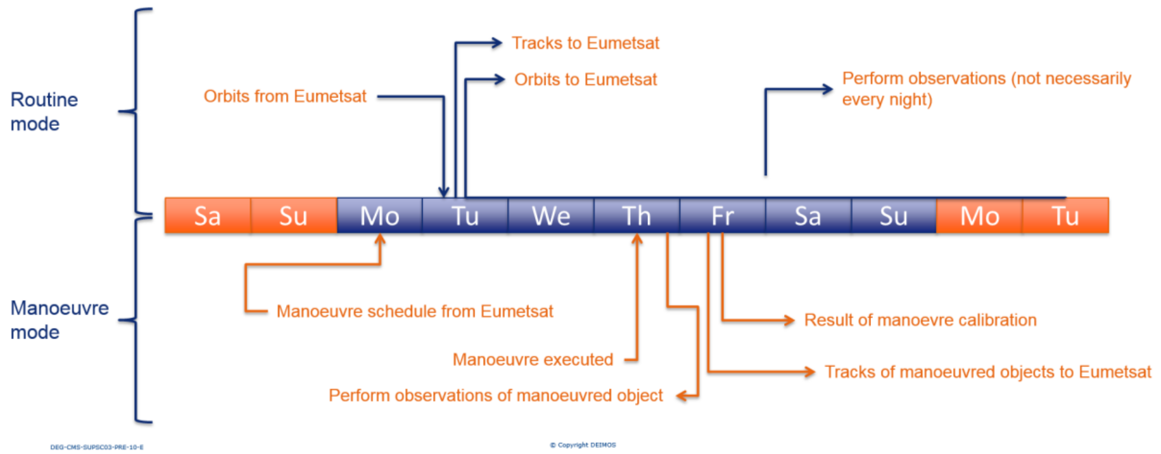


Fig. 15: Weekly scheduling of the service "Routine Mode" and activated "Manoeuvre mode"

Operational execution of Fucino-Cheia-Optical OD

As an early opportunity to assess the orbit determination performance using range measurements from Fucino+Cheia stations, a test with real data was organised, involving the use of the already available MTG TTC2 antenna in Cheia and the regular optical observations from the DeSS Tracker-2 sensor.
The satellite used in the orbit determination test was Meteosat-9 (MSG2), located at a longitude of 3.5°East, as a stand-by satellite and in-orbit back-up.
To reproduce the routine weekly orbit determination (including data from 2 stations, with 2 swaps a week, see Table 3), 48h slots of ranging coverage from the MTG TTC2 antenna in Cheia were inserted within the regular scheme of ranging stations swaps, and a sequence of orbit determinations was run (see Fig. 16).

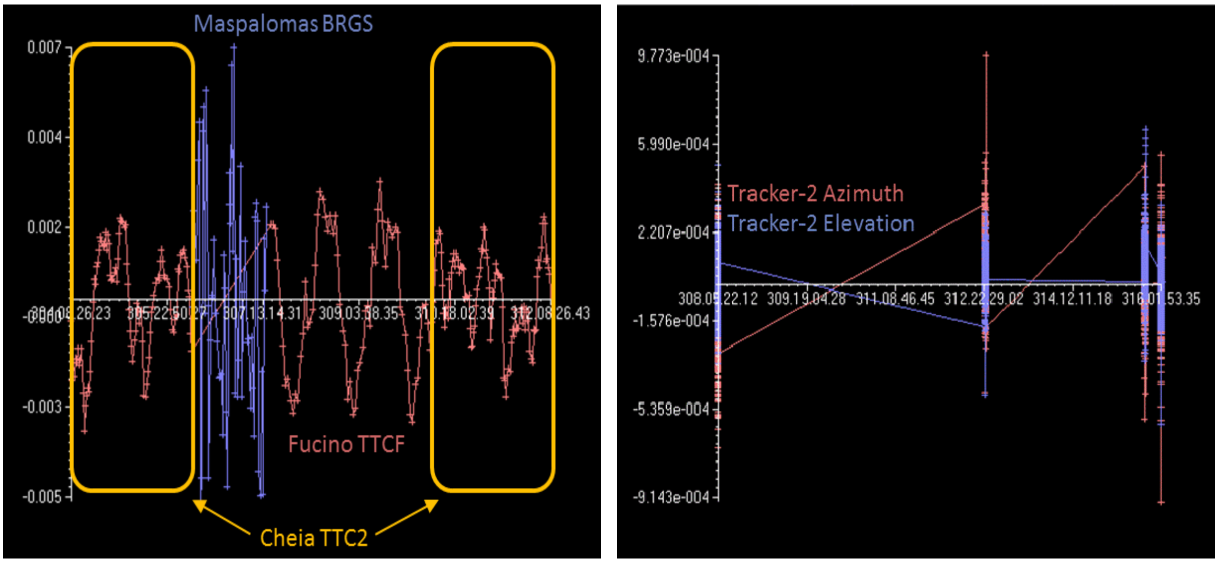


Fig. 16: OD final residuals (Range [km] on the left, Azimuth/Elevation [deg] on the right as function of calendar day/time (DOY.HH.MM.SS)

The Meteosat-9 orbit determinations were repeated separately, to make use of different antenna pairs for the ranging data, with and without using the additional optical tracking data, as follows:

- Case-1: using ranging data from Fucino+Maspalomas and DeSS optical tracking data
- Case-2: using ranging data from Fucino+Cheia
- Case-3: using ranging data from Fucino+Cheia & DeSS Tracker2 optical tracking data

Case1 is the configuration known to have the better OD accuracy, due to the widest stations base-line and the additional support of optical data, so it is used as a reference to compare the orbit solutions and assess their consistency. The routine schedule type g) is used (see Table 5).

The results determined in the tracking campaigns were essentially well aligned with the expectations from the earlier covariance analysis. A sample of obtained orbit comparison charts is provided in Fig. 17 and Fig. 18. In particular, the positive effect of the addition of optical tracking measurements to the data set was observed, significantly reducing the cross-track and radial error, as also anticipated by the same study.

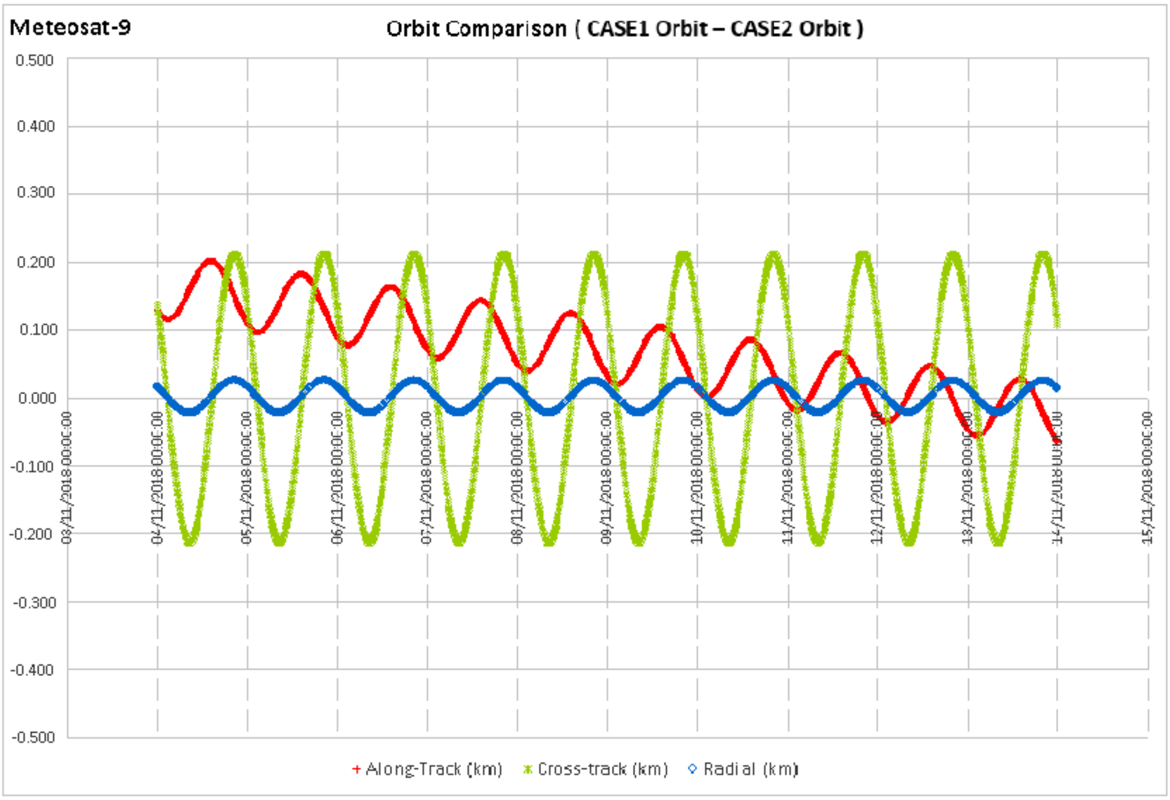


Fig. 17: Determined position deltas, reference vs. Fucino+Cheia

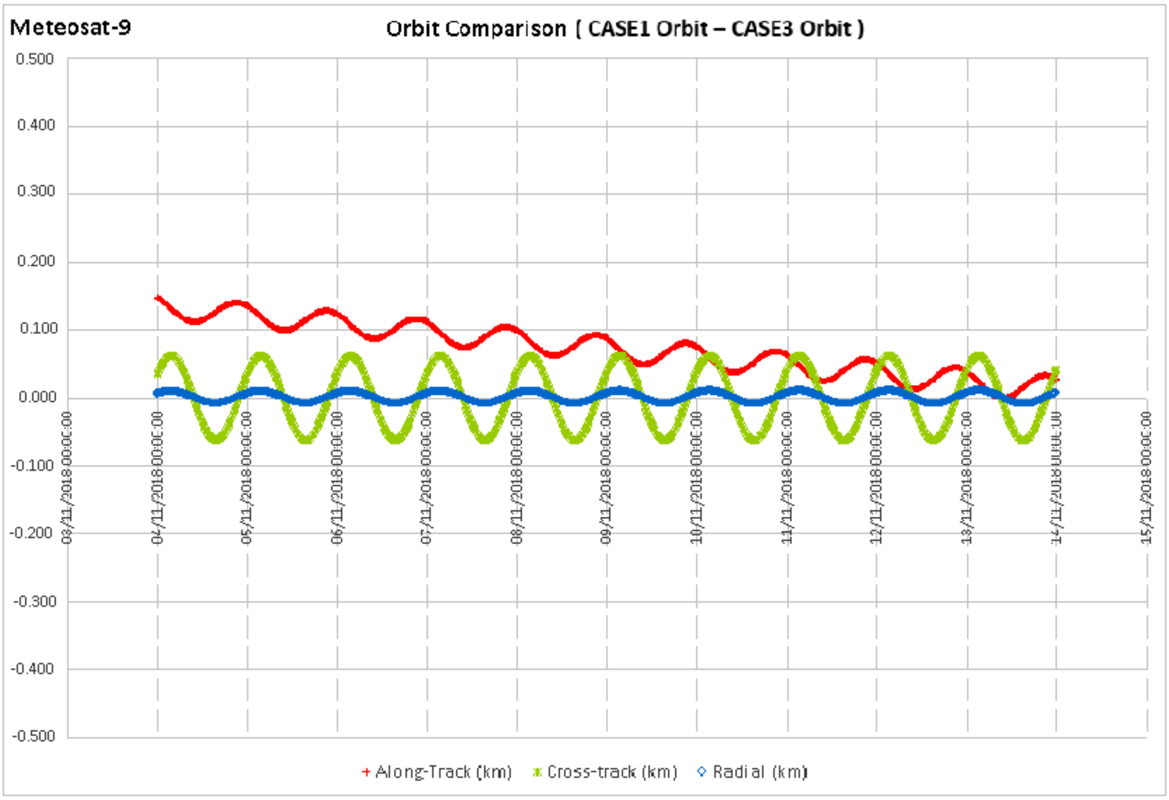


Fig. 18: Determined position deltas, reference vs. Fucino+Cheia & DeSS-T2 Telescope

Conclusions

EUMETSAT is implementing a sequence of ground-stations relocations, with the target to improve the synergies between the current (MSG) and future (MTG) satellites programmes, by using only two sites in Fucino (Italy) and Cheia (Romania) with proprietary antennas.
In addition, the minimisation of the dependency from external services for ranging support by-non-proprietary antennas is being considered.

The shortening of the stations’ geographical base-line for Orbit Determination (based on dual stations’ ranging with regular stations’ swaps) has an impact on the observability, thus on the accuracy of the same process. This has been quantified with a series of covariance analysis. When comparing the initial configuration of tracking sites (Usingen/Maspalomas) with the target base-line (Fucino, Cheia), the results shows that:

- the along-track position accuracy is slightly improved , with an error reduction of ~10%
- the cross-track and radial position accuracy get worse, of a factor ~6 and ~5 respectively

Due to the accuracy loss, the regular use of a telescope was proposed and analysed, showing the potential recovery of the above mentioned cross-track and radial worsening. As also demonstrated, the scheduling of the telescope data has an impact on the overall accuracy: in case multiple slots of observations are possible, for greater accuracy the 2nd slot should be scheduled with ideally 6 hours separation in local time between the slots (on the same night, or in the following night).

After the analysis phase, EUMETSAT started a mid-term project (3 years) for regular provision of optical data by a network of telescopes. The purpose of the service is to support routine and special (e.g. manoeuvres) operations for orbit determination. Furthermore, the service allows the compensation of eventual performance degradation of the ranging antennas, during the relocation of the ground-stations, especially related to the use of the Maspalomas. The details of the optical data service, as implemented and running nowadays, are detailed in this paper, based on the first 6 months of operational experience.

To confirm the preliminary results of the covariance analysis, a dedicated tracking campaign was executed; the actual performances were evaluated in-flight, using actual tracking data from the S-band tracking sites of Fucino and Cheia and from the telescopes, via the optical data service. These results showed good consistency with the theoretical expectations, and confirmed the proposed approach.

Future work will investigate both the relaxation of stations’ swaps for ranging (in favour of extended optical data use), and the effectiveness of the optical data service (and eventual design improvements) to cope with more stringent requirements imposed by the next generation of GEO satellites, specifically the service availability in case of manoeuvres and safe modes.

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References

1. Meteosat Second Generation (MSG) satellites https://www.eumetsat.int/website/home/Satellites/CurrentSatellites/Meteosat/index.html

2. Klinc M., Pessina S., "Optical tracking in support to routine operations and conjunctions analysis for the EUMETSAT geosynchronous fleet", *25th International Symposium on Space Flight Dynamics* (ISSFD at DLR, Munich, Germany)

3. Klinc M., Pessina S., "Optical Tracking Extended Network in Support to Operational Flight Dynamics and Conjunction Analysis for Meteosat" *26th International Symposium on Space Flight Dynamics & 31st International Symposium on Space Technology and Science*, ISTS-2017-d-156/ISSFD-2017-156

4. E.M. Soop, "Handbook of Geostationary Orbits", Publisher *Kluwer Academic Publishers*

5. Dominguez-Gonzalez R., Nomen Torres J., Oliviero D. Sanchez-Ortiz N., Klinc M., and Pessina S. "Operational Orbit Determination for the EUMETSAT GEO fleet based on optical observations" , *7th International Conference on Astrodynamics Tools and Techniques (ICATT)*, DLR Oberpfaffenhofen, Germany, 6-9 November 2018

6. Nomen Torres J., Sanchez-Ortiz N., Dominguez-Gonzalez R., Guijarro Lopez N., Quiles Ibernon P.A. , "Accurate Optical Observations of Space Objects in GEO and applicability to closer LEO regimes" , *7th European Conference on Space Debris*, ESA/ESOC, Darmstadt/Germany, 18 - 21 April 2017