Operational Orbit Determination for the Eumetsat GEO fleet based on optical observations.

Raul Domínguez González [1], Jaime Nomen Torres [1], Dario Oliviero [1], Noelia Sánchez Ortiz [1], Milan Klinc [2], and Stefano Pessina [3]

[1]Elecnor Deimos, Ronda de Poniente 19-22, 28760, Tres Cantos, Spain
[2]WGS Workgroup Solutions GmbH, Brüder Knauß Str. 6, 64285 Darmstadt, Germany
[3]Eumetsat, Eumetsat Allee 1, 64295 Darmstadt, Germany
{*raul.dominguez, jaime.nomen, dario.oliviero, noelia.sanchez*}*@deimos-space.com*
milan.klinc@external.eumetsat.int
stefano.pessina@eumetsat.int

Abstract

The Eumetsat GEO fleet is operated based on orbital determination using ranging-only data from three different ground-based tracking stations. Data from two different ground stations is used for each of the satellites. For more than 15 years, these results have been used for manoeuvre planning, after manoeuvre calibration and collision risk assessment. Since June 2018, an effort has been undertaken to enhance the orbit determination procedures with optical observations, with the objective of assessing the suitability of using optical data to perform the operational orbit determination, and determining the suitability of routine orbit determination and manoeuvre calibration using mixed data from ranging stations and telescopes. The optical measurements are provided currently by the Deimos Sky Survey (DeSS) telescopes, using additional sensors (coordinated by Deimos Space) as a backup in case of adverse weather conditions or technical issues. The processing of the measurement data is being performed by two separate teams at Eumetsat and at Deimos. This paper describes the processing chain put in place at Deimos for performing the observations and the processing of measurement data, and summarises the findings related to the aforementioned objectives after several months of routine observations.

Each spacecraft in the fleet is observed with optical sensors at least twice every week (in two observation slots), with each slot spanning at least 15 minutes, and with a minimum separation of two hours between slots. A software processing chain based around several Deimos tools has been put in place to plan the observations and perform the observations (ITOX), automatically resolve and process the images (TRAX), split tracks (TRACA), and finally perform the orbit determination (TRADE).

The orbit determination is automatically performed weekly with the TRADE by means of a Batch Least Squares approach with a two-week rolling window. In absence of manoeuvres, this allows determining the solar radiation pressure coefficient while maintaining consistency with the previously computed orbits. When a manoeuvre is scheduled, optical observations are taken as soon as possible after the manoeuvre itself. In this case, the paper shows that the orbit determination with optical information only provides results comparable with the nominal range-only orbits.

Finally, the TRADE tool is modified to process range-only measurements from ground-based ranging stations along with optical measurements. A comparison of the quality of the solutions obtained with different combinations of measurements from different sensors is provided.

1 Introduction

Operations on a fleet of spacecraft require routine orbit determination in order to support its routine operations, perform collision avoidance, determine and calibrate station keeping manoeuvres and to generate products to support payload(s) operations and the related on-ground data processing. The Eumetsat GEO fleet is operated with orbit determinations based on ranging measurements taken from a primary ranging station (PRS) and a backup ranging station (BRS). This approach has proven adequate with respect to mission requirements for the nominal operations of the GEO constellation. However, it is known that, when observations are taken always with similar observational geometries, there can be biases that cannot be eliminated. These biases can also arise when performing orbit determination using homogeneous sensors and observables. Eumetsat has been active in the past evaluating different options for complementing the ranging observations [1] [2]. As a result of this evaluation, a supplementary service of optical observations and orbit determination has been put in place in partnership with Deimos, with the objective of evaluating a robust solution fully integrated in the operational system. The optical observations provide not only observations with different geometries, but also different observables (angles instead of ranges), and generated by independent systems. Figure 1 shows the ranging stations located in Italy and Spain (Canary Islands) and the optical locations around the globe. Optical observations are taken nominally from the primary location (the Deimos Sky Survey (DeSS) facilities in Puertollano, Spain. Reference [3] includes a description of the DeSS facilities. The remaining optical facilities are activated only when the weather forecasts in the primary site do not allow fulfilling the objective.

A minimum of two optical observations (slots) per week is required for each of the four satellites in the Eumetsat GEO constellation. The slots must include 15 minutes of observations, and at least 60 regularly spaced measurements. The two slots need to be separated at least 2 hours. This objective can be usually fulfilled by the DeSS sensor. In addition to this, when a manoeuvre is performed, it is necessary to perform observations the night after in case of manoeuvre in daylight, or the same night otherwise. In both cases, if the weather conditions are not adequate in DeSS and there is risk of not fulfilling the objectives, one or several of the backup optical sensors are activated. The optical measurements obtained by this network complement the ranging measurements that are taken routinely from the Eumetsat ranging stations. Figure 2 shows an overview of all the entities involved in the process.

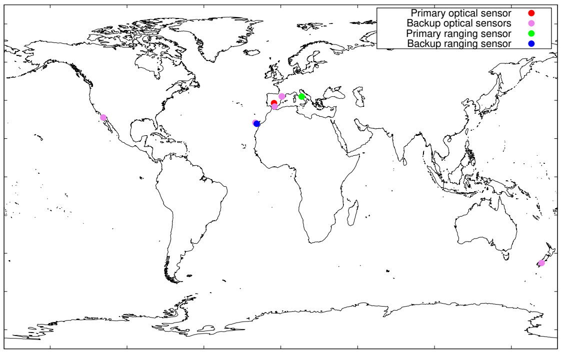

Figure 1: Location of ground stations

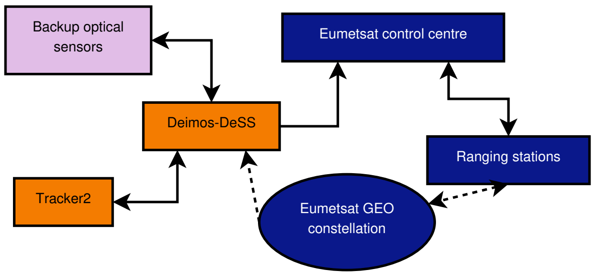

Figure 2: Systems and entities involved in the optical orbit determination

The optical products are gathered at Deimos premises and made available to Eumetsat weekly. Each week, the following products are delivered:

- Optical tracks (one per object and slot).
- Orbits computed from optical observations (one per object).
- Automatically computed summary of the delivered data.

Name	NORAD id	mass (kg)
MSG1	27509	1083.0
MSG2	28912	1090.0
MSG3	38552	1120.2
MSG4	40732	1192.7

Table 1: Eumetsat fleet information as of October 2018 [4]

1.1 Eumetsat geostationary fleet

At the date of this document, Eumetsat operates four geostationary satellites. These four spacecraft belong to the Meteosat Second Generation (MSG) family. Physically, they are spin stabilized satellites with their rotation axes perpendicular to the orbit plane. Rotation is nominally 100 rpm. Table 1 summarises the characteristics of the fleet at the date of this document.

1.2 DeSS

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 optical sensors were specifically designed and built with the objective of observing natural and artifical space objects near the Earth. This includes Near Earth Objects (NEOs), satellites and space debris. The observatory is operated remotely from the control centre via a dedicated 37-km radio link.

At the date of this document, DeSS comprises four optical sensors: *Centu 1* for surveillance, *Tracker 1* and *Tracker 2* for tracking, and *Antsy* for tracking (including LEO tracking). The observatory is used daily to perform SST services for several customers.

The Tracker 2 sensor is dedicated to this activity. Table 2 summarises the characteristics of this optical sensor.

Optical design	Schmidt Cassegrain Coma-Free (ACF)
Aperture	400 mm
Focal length	3251 mm
Focal relation (f/R)	8 (5.5 with focal reducer)
FOV	21' x 21'
Resolution arcsec/pix	1.19
CCD chip	EMCCD 201 e2v Back-illuminated
CCD array	1024 x 1024
Pixel size microns	13 x 13
Quantum efficiency	90%
Colling temp	-95°

Table 2: Tracker 2 characteristics

1.3 Backup optical sensors

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 Astrofísica 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 Astrofísica de Andalucía, comprises three available sensors at different longitudes.

2 Description of the software processing chain

The software processing chain at Deimos can be broadly divided in three categories: telescope control, telescope raw data processing and data processing chain. Each of the categories is described in a subsection below.

2.1 Telescope control

ITOX is a developed software tool for locally or remotely controlling the sensors. It takes control of the dome, sensor mount, CCD camera, dew removers, focusing, auto-synchronization, slewing, guiding, and the execution of all the observing sequences. It integrates the functionality to evaluate observation opportunities in the basis of live satellite ephemerides and prioritization functions. This is a hardware dependent tool, since it requires to control and integrate many devices together with computing accurate pointing and UTC time registry under millisecond.

The system works under a fully robotic procedure. For Eumetsat observations, OEM ephemeris provided by the operator are utilized for pointing the sensors, and they are called for the time and interval scheduled according a graphical planner in the same tool. Scheduling task shuffles the sorting and time of the slots of the observations for the four satellites in order to avoid repeating it on consecutive nights while avoiding the Earth shadow.

2.2 Telescope raw data processing

TRAX takes care of the image processing for extracting and measuring moving objects against the stars background, all in close to real time as images are being produced by the sensor. It requires a minimum of single detections or ”loners”, shown as trails or point sources to generate ”movers” or object candidates with their astrometric and photometric measurements. The main steps on this procedure require calibration of the images, solving them against a catalogue by Word Coordinate System, find coherence on images before combining them, by extracting sources, loners and movers.

Due to the large amount of images generated by the sensors, the processing of the images requires powerful resources for maintaining close to real time processing, redundancy and robustness. A parallel processing is executed distributed on several identical computation nodes. For tracking Eumetsat satellites, which are quite bright targets, TRAX is configured to combine triplets of loners filtered by RMS, speed and angle of motion (that is previously known).

2.3 Processing chain

The processing chain is responsible of acting as interface between Deimos and Eumetsat and to perform orbit determination based on the optical products obtained by the Deimos Tracker 2 sensor, and the secondary sensors (whenever required). The interface functionality involves taking care of several different data fluxes. The processing chain itself is deployed in a single Linux machine. Several FTP accounts are made available to Eumetsat and to secondary sensors, they are used for data exchange in both directions, with directory structure and naming conventions to be used agreed with each of the entities beforehand. This schema allows exchanging the information manually or automatically. Currently, all the processes within Deimos related to the nominal service are performed in an unattended manner.

Figure 3 shows the outbound fluxes and figure 4 shows the inbound fluxes. In order to work with these fluxes several processes are executed automatically at scheduled intervals. The data storage is set up in a PostgreSQL database and a dedicated storage folder. All the automated processes make use the database and the storage. The most relevant information that is stored includes:

- Definition of the Eumetsat GEO fleet, including all the relevant details required for observations and orbit determination.
- Optical sensors information (location, typical noise in measurements, known biases and whether they provide tracks corrected by annual aberration).
- Nominal manoeuvres provided by Eumetsat (start and end time, Delta-V and direction).
- Track files generated by the system (file metadata is stored in the database, and the files themselves are stored in the storage folder).
- Incoming and outgoing OEM files (file metadata is stored in the database, and the files themselves are stored in the storage folder).

This schema allows daily offsite backups to be taken easily, by storing the database itself and the storage folder.

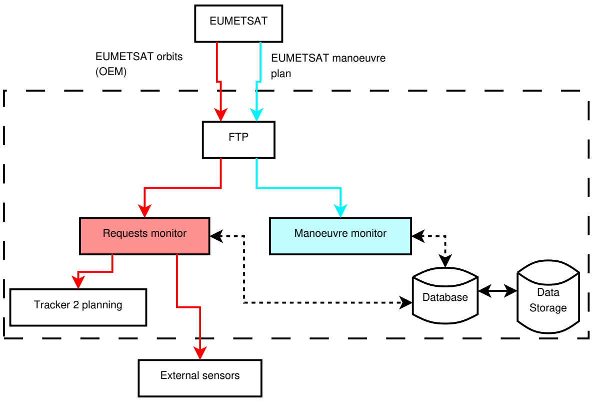

Figure 3: Inbound data fluxes managed by the processing chain

2.3.1 Observations planning

The objective of this flux is to retrieve the primary operational orbits from Eumetsat, in order to use them for the optical sensor planning and pointing.

Observations planning is depicted as the red path in figure 3. The *Requests monitor* process polls the FTP for new orbits uploaded by Eumetsat. Whenever a new orbit is found, it is registered in the database and automatically copied to the Tracker 2 planning machine. In addition to this, an email is sent to the Deimos operators, with the file itself attached. This information is agreed to be exchanged once per week.

Nominally, observations are planned at the beginning of the week, attempting to use only the primary sensor (Tracker 2). Observations must fulfil the conditions mentioned in section 1. Depending on the weather forecast and the remaining opportunities for observation, one or several of the secondary sensors are activated.

2.3.2 Manoeuvre processing

The objective of this flux is to ingest the manoeuvre schedules for the GEO constallaion and make this information available to the other subsystems that require it.

The optical processing needs to take into account the manoeuvres performed by the satellites for the orbital determination process. For the routine orbit determination, which is performed by means of a Batch Least Squares (BLS) algorithm, the system selects the batches ensuring that no manoeuvre happens within a batch. The *Manoeuvre monitor* process polls the FTP for manoeuvre files provided by Eumetsat. These files contain information of each of the scheduled manoeuvres. From these, the manoeuvre epoch and Delta-V are extracted and registered in the database. This action is depicted as the cyan path in figure 3.

2.3.3 Track submission

Tracks meeting the conditions mentioned in section 1 are made available to Eumetsat once per week through the shared FTP in a batch. In addition to this, each individual track is made available the morning after it was taken, These processes are depicted as the green path in figure 4.

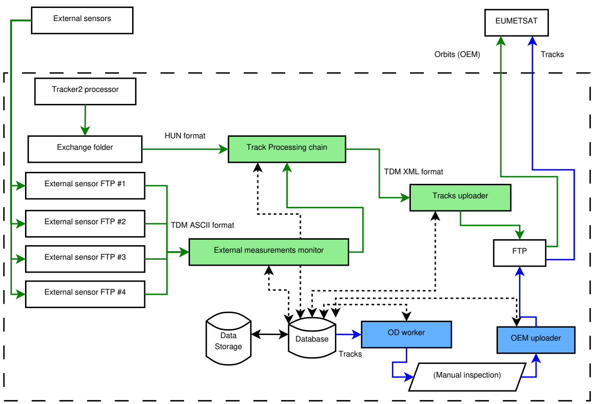

Figure 4: Outbound data fluxes managed by the processing chain

When the secondary sensors are used, the *External measurements monitor* polls each of the FTPs for incoming tracks. When new tracks are found, they are registered in the database and converted. They are converted to the same format as output by Tracker 2 processor, as part of the ingestion process.

The main track processing is performed by the *Track processing chain*. It polls for tracks generated by the Tracker 2 sensor or made available by *External measurements monitor*. In the case of Tracker

2, there is a single HUN file per night, which contains all the observations performed by Tracker 2 in that particular night. The HUN format is a format used internally within DeSS. It contains all the relevant astrometric data along with metadata.

This processing chain performs these actions:

1. Filter the HUN file, 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. This is performed with the TRACA tool (described in section 2.3.5).
4. Apply corrections to the tracks that require it. As each sensor provides tracks with different corrections applied, we make all the tracks homogeneous at this stage.
5. Apply time biases to sensors that require it.
6. Convert the remainig 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. When it is executed, it verifies the database, checking for new files to be submitted. When there are new files to be submitted, and 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. When the daily uploads are performed, an automatic email is sent to the Deimos operator. Figure 5 shows an example of the information that is forwarded. For the weekly deliveries, the same information is provided for each of the files comprising the weekly batch. In addition to this, a summary of the total observation time and measurements for each of the satellites in the constellation is provided. In this case, the automatic email is sent to both the Deimos and Eumetsat operators.

```
File: FUCPGSA3_OPE_TDM_MSG1_20181014T082025_20181013T220035_20181013T221724.tdm
MD5: af6b6039c86a3d2d4aac66d2fe62b44f
Target: MSG1 [METEOSAT-8 (MSG-1)]
Sensor: TRCKR2
Slot duration: 2018-10-13 22:00:35 - 2018-10-13 22:17:24 (16 minutes 49.0 seconds)
Number of measurements: 1212
Measurement rate: 1.20118929633 measurements/second
```

Figure 5: Example of data sent for individual track files

2.3.4 Orbit determination

Orbit determination is performed routinely with the optical tracks, and the results are made available in a weekly basis. The process is shown in figure 4, in blue. The *OD worker* retrieves from the database all the optical tracks within two weeks before the execution date. In case there is a manoeuvre within that period, only the tracks after the manoeuvre are considered for the Orbit Determination batch. Then, the TRADE tool (described in section 2.3.6) is executed. This tool performs the orbit determination and generates an OEM file 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 TRADE 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 about the computed orbits. Subsequent sections devoted to the orbit determination contain several examples of the data present in that email.

2.3.5 TRACA

TRACA is a tool meant to determine if individual optical observations can be assigned to the same physical Earth orbiting object. To do so, it implements an algorithm that attempts to build tracks with individual measurements, considering their compatibility. In order to check the compatibility, the apparent motion of the candidate tracks is considered (this is, the apparent motion is required to be smooth), as well as the compatibility of the apparent motion with an Earth orbit.

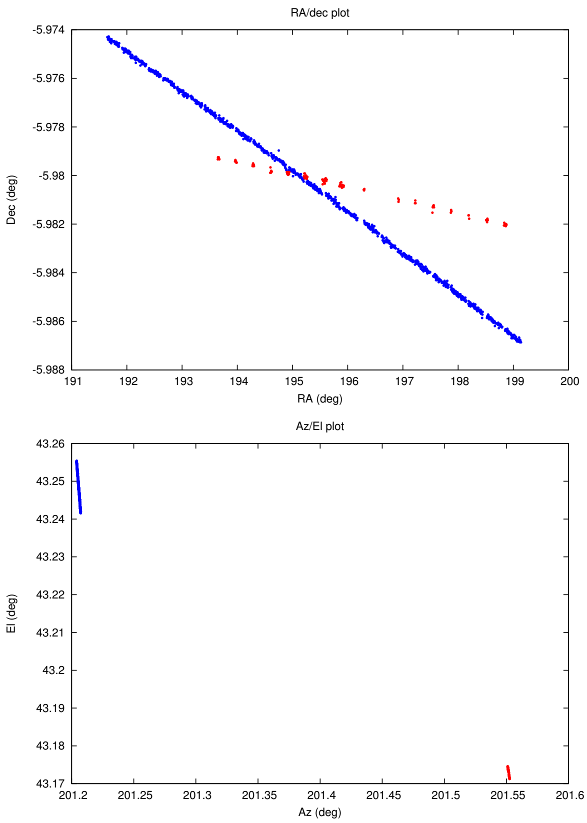

Figure 6: Example track separation performed by TRACA

Figure 6 presents an example of the task performed by TRACA. The individual observations depicted in the figure were taken independently by the system. This is, each measurement was taken without making use of any information of previous measurements. An intruder object (red points) appeared in the sensor field of view during the slot time. Moreover, this intruder appears intermittently. This suggests that the intruder is spinning, and is probably a smaller object. In this case, TRACA is able to discern the two objects, because even though their individual measurements are all very similar, the apparent motions are not compatible. TRACA splits the observations into two tracks. Within the frame of this activity we discard the track related to the intruder, but in other SST related activities, intruder tracks are usually kept, as they correspond to real objects, and can be therefore relevant information for an SST system.

2.3.6 TRADE

TRADE is a tool developed by Deimos focused for performing offline orbit determination with different algorithms. It implements an Square Root Information Filter (SRIF) [6] and Batch Least Squares (BLS) and Bayes filter [7]. TRADE supports optical telescopes, monostatic radars. For the activity described in this work, it has been updated to support ranging stations for the BLS mode. It is capable of processing tracks from different sensors (and of different types) simultaneously. It includes a numerical propagator with a detailed set of perturbations: Non-spheric Earth, third bodies, solar radiation pressure (SRP), atmoshpheric drag, albedo effect and solid tides. These perturbations are toggleable.

TRADE computes the adjusted orbit at the epoch of the first measurement in the batch or at an user-defined epoch. It allows providing an initial estimation of the solution by means of TLEs, by interpolating over an user-provided OEM file or by manually inserting the value. It also implements initial orbit determination (IOD) algorithms for telescope and monostatic radars, so it is possible to obtain solutions without initial estimations (as long as the input data allows for a good IOD). As outputs, it provides per-sensor plots of the estimated residuals, as well as plots of the optical measurements in Right Ascension/Declination and Azimuth/Elevation. It also provides standard-compliant OEM orbits with or without covariances. Finally, it has the possibility of computing pointing opportunities for the determined orbits and the configured sensors network. The version used in this activity also includes the possibility of calibrating manoeuvres, this implementation is described with detail in section 4.

3 Optical-only orbit determination with no manoeuvres

The orbit determination with optical measurements and no manoeuvres is able to provide valid results (consistent with themselves) in the absence of manoeuvres. TRADE is used to determine the orbital elements and solar radiation pressure coefficient. Experience has shown that if the batch does not cover at the very least 1 week of tracks, the estimated solar radiation pressure is not correct. Therefore, the system is configured to attempt to determine this coefficient only when the available measurements span at least 1 week.

Figure 7 shows the percentage of removed residuals during the system operation. Each batch comprises between 10000 and 20000 individual measurements, so we consider these percentages reasonably significant. It can be seen that the behaviour is good for all the four satellites, and extremely good for the MSG4 in particular. For all cases the resulting orbit determination results are consistent, and allow further tracking of the object.

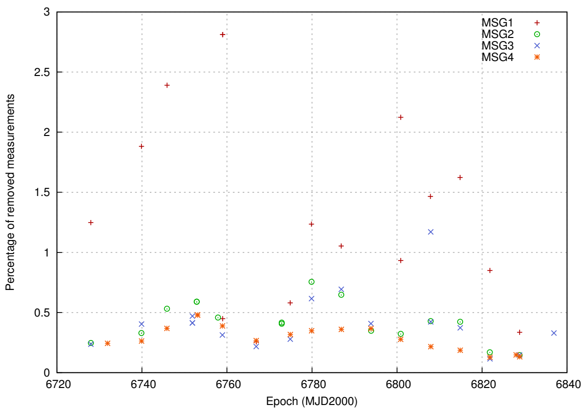

Figure 7: Percentage of removed measurements as a function of time

Figure 8 presents an example of the plots that are sent along with the orbits, showing the orbit determination residuals. Figure 9 presents a comparison

Epoch	**Cross section (m^2)**
Equinox	8.6
Solstice	10.54

Table 3: Geometric cross sections of MSG spacecraft from the Sun at different epochs of year

of the computed orbit (in terms of cartesian state vectors) with the one computed the previous week. We have observed that these comparisons are consistently below 1 km in the absence of manoeuvres. Finally, figure 11 presents this same comparison along with the combined covariances at 1σ level. This shows that there is good agreement between two orbits of the same object computed in different weeks, as the components of the state vector are well within the combined covariance.

Using batches of two-week data it is possible to estimate a the solar radiation pressure coefficient. TRADE implements solar radiation pressure using a cannonball model (thus, independent from attitude). The parameter estimated by TRADE is $c_r \cdot \frac{A}{m}$ where c_r is the solar radiation pressure coefficient (typical values are around 1.1), A the cross section area in square meters (m^2) and m the mass in kilograms. It is expectable that this estimated parameter will not be constant in different batches for several reasons: the mass of the satellites slowly decreases as they spend fuel, thus increasing the value of the parameter. In addition to this, the magnitude of the solar radiation pressure is expected to be the lowest during equinoxes and largest during solstices because the cross section area exposed to the Sun varies with time. Table 3 (computed with ESA DRAMA CROC tool [5]) shows the extreme values reached by this cross section area. Figure 10 shows the results provided by the system during approximately four months, going from a solstice to an equinox. According to table 3, this should result in the effective cross section area reducing with time, and this explains the descending trend for all MSG satellites.

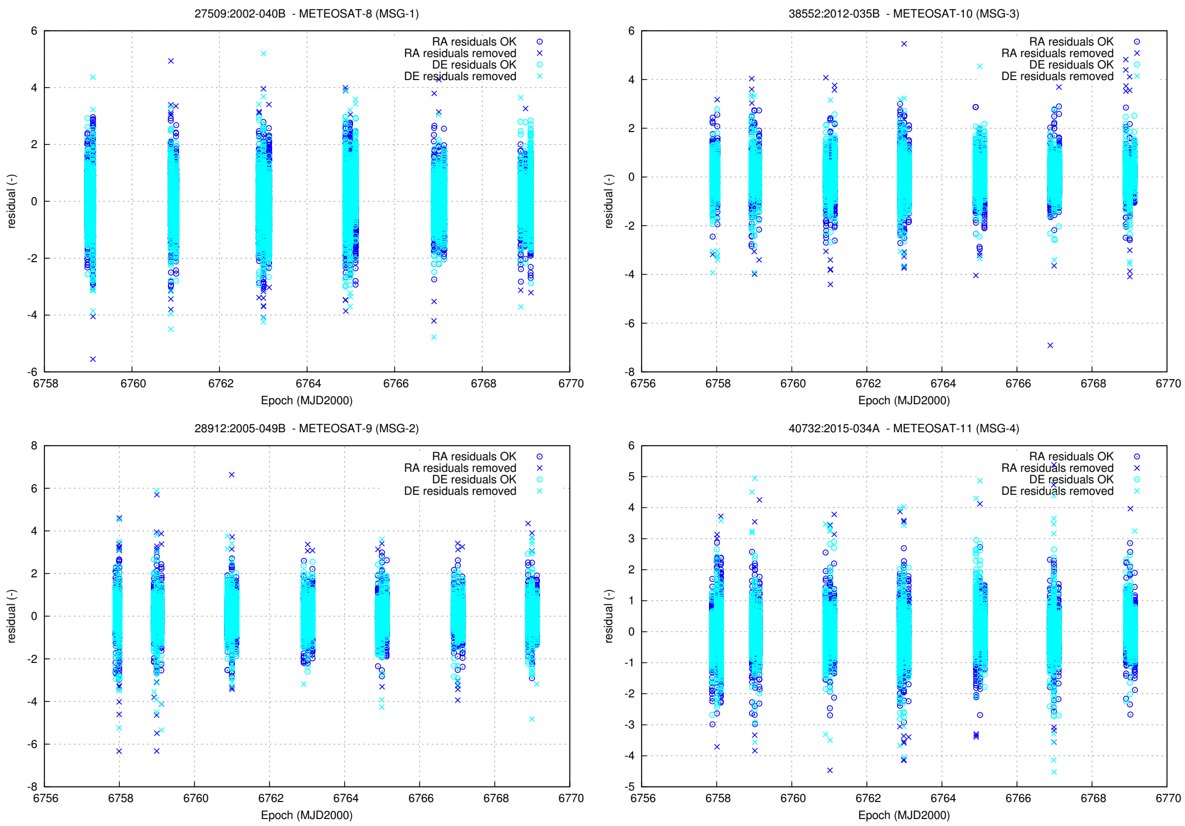

Figure 8: Example of orbit determination residuals of a weekly delivery for the whole constellation

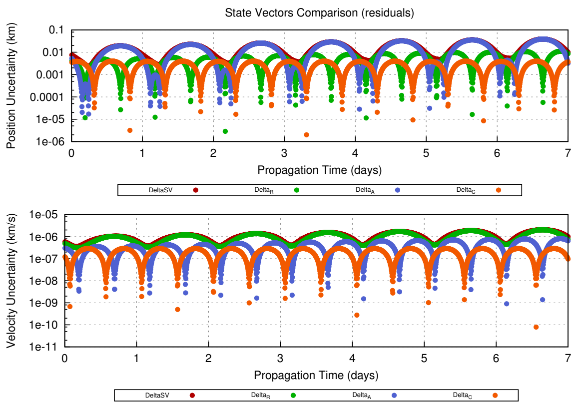

Figure 9: Comparison of MSG4 orbit and the orbit obtained one week before

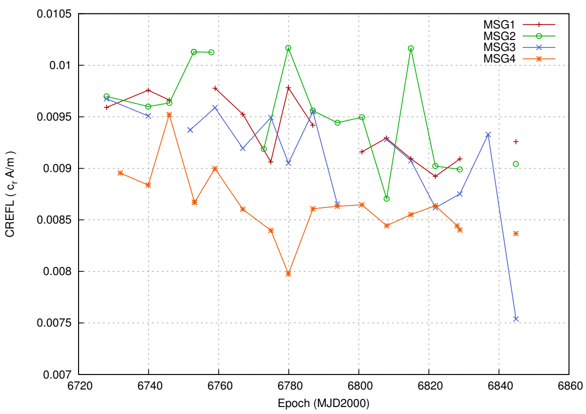

Figure 10: Solar radiation presure coefficent $c_r \cdot A/m$ for MSG spacecraft

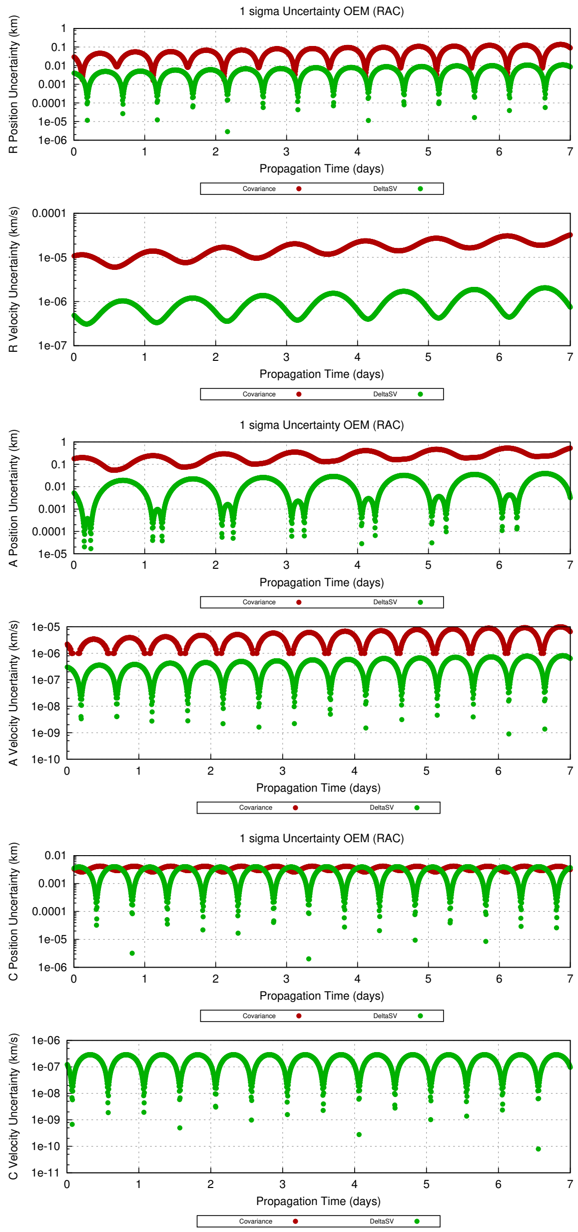

Figure 11: Comparison of determined covariance with state vector differences

4 Optical-only orbit determination and manoeuvre calibration

In addition to the regular orbit determination service which is carried out in absence of manoeuvres, an additional service for calibrating manoeuvres based on optical data has been set up. When a manoeuvre is scheduled, the sensors network performs observations at the first opportunity after the manoeuvre time. Optical observations after the manoeuvre are submitted immediately after being captured, and later in the next weekly delivery. Eumetsat fleet performs three kinds of manoeuvres during the nominal operations: North-South Stationkeeping manoeuvres (NSSK), East-West Stationkeeping manoeuvres (EWSK) and slew manoeuvres (SLEW). Table 4 presents a summary of the manoeuvres that have been carried out since begining of service.

The TRADE tool has been modified within the scope of the activity described in this paper in order to estimate the following magnitudes by means of a BLS.

- Cartesian state vector at the epoch of the first track in the batch (km and km/s)
- Solar radiation pressure coefficient ($c_r \cdot \frac{A}{m}$)
- Manoeuvre Delta-V vector at the epoch of the manoeuvre centroid (km/s)

The manoeuvre is modelled as an impulsive manoeuvre. According to table 4, this approach can be considered acceptable for EWSK and SLEW. For the NSSK manoeuvres, this approach can lead to determining a ficticious Delta-V that is equivalent to the true manoeuvre, and it is feasible as long as the observations are not carried out during the manoeuvre duration. The BLS process atempts to adjust an orbit to a trajectory that includes an impulsive manoeuvre at a fixed time (this is, the manoeuvre time is not determined nor adjusted).

#	Sat.	Start date (UTC) (seconds)	Type
1	MSG4	2018/06/05 15:44	NSSK
2	MSG3	2018/06/26 11:47	NSSK
3	MSG1	2018/07/03 21:28	EWSK
4	MSG2	2018/07/17 08:28	EWSK
5	MSG1	2018/08/14 05:28	EWSK
6	MSG3	2018/08/21 19:58	EWSK
7	MSG1	2018/09/25 17:58	EWSK
8	MSG2	2018/09/26 04:13	EWSK
9	MSG4	2018/09/24 20:28	EWSK
10	MSG1	2018/10/16 12:28	SLEW
11	MSG3	2018/10/16 15:58	EWSK
12	MSG2	2018/10/23 13:57	SLEW

Table 4: Manoeuvres performed by Eumetsat fleet from June 2018

#	Duration (s)	$\lvert\Delta V\rvert(m/s)$	C	$\alpha(deg)$
1	2643.08600	45.428	1.0058	0.0068
2	2787.17400	49.062	0.9931	0.0004
3	76.91100	0.2111	0.9911	0.8611
4	59.70500	0.1655	0.9982	0.2386
6	75.75200	0.2074	0.9989	0.5314
7	80.51500	0.2208	1.0001	1.3057
11	52.91000	0.1448	1.0024	0.6880

Table 5: Results of manoeuvre calibration

In order to calibrate the manoeuvre, we consider two figures of merit. On the first place, we define the manoeuvre calibration factor (C) as:

$$C = \frac{|\Delta V|}{|\Delta V_{nominal}|} \quad (1)$$

We also evaluate the angular difference (α) between the nominal manoeuvre and the determined manoeuvre. Table 5 shows these figures of merit for all the manoeuvres for which calibration was performed. It can be seen that the magnitude of the manoeuvre is always estimated within 1%. The angular difference is noticable better determined for the NSSK manoeuvres. We consider that this is caused by the magnitude of the NSSK manoeuvres (the Delta V is two orders of magnitude larger than for the other kinds of manoeuvres. Overall, the results show good agreement between the nominal and actual manoeuvres. The differences could be explained by small inaccuracies of the model and/or by the fact that the real manoeuvre will be slightly different from the nominal manoeuvre.

5 Data fusion

We are currently investigating the performance of orbit determination with merged ranging and optical sensors. In order to perform this investigation, we have undertaken a modification of the

TRADE tool to cover ranging stations and include the transponder delay in the parameters to be estimated. The ranging stations are modeled as a two-way ranging. The round-trip time is modeleded as:

$$T_{roundtrip} = T_{TX->T} + T_{delay} + T_{T->RX} \quad (2)$$

where T_{delay} is the transponder delay, and the two other times are the two travel times. The transponder delay is not a fixed parameter, as it depends slightly on the temperature of the equipment. For this activity, however, we neglect those variations and consider the transponder delay constant for each satellite for the whole batch duration. $T_{TX->T}$ is modelled as the time taken for a signal moving at the speed of light to travel from the ground station at departure time to the position of the satellite at arrival time. $T_{T->RX}$ is modelled as the time taken for the signal to travel from the satellite at departure time to the ground station at arrival time. As the transponder delay is taken into account, the arrival time to the satellite and the subsequent departure time are different by the transponder delay.

In addition to this, it is necessary to consider the delays induced by the atmosphere. Reference [8] mentions that ionospheric and tropospheric corrections should be taken into account for high precision applications. For the ionospheric model, the International Reference Ionosphere (IRI) [9] has been implemented. For the tropospheric correction, the model described in [10] and [11] has been implemented. Both effects are considered as delays to both the outgoing and incoming signals.

Finally, a station-dependant fixed bias has been introduced. This bias is associated to the time-tagging at the tracking station.

After all corrections are applied, the one-way range is computed as:

$$R = \frac{T_{roundtrip}}{2} \quad (3)$$

Ranging data is taken regularly at the primary and secondary ground stations shown in 1. These data is retrieved weekly at Deimos premises and processed together with the optical data.

Figures 12 and 13 present an example of the results provided by the system with range-only and range and optical measurements.

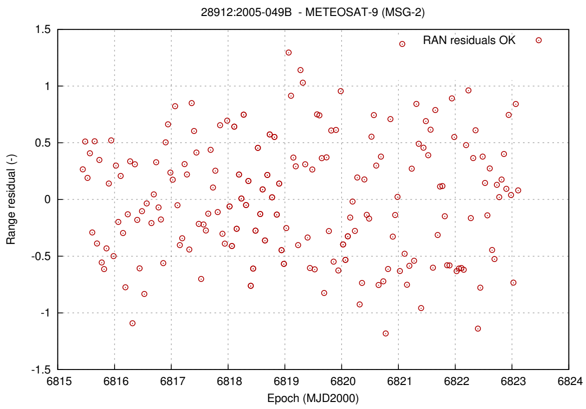

Figure 12: Orbit determination residuals of a case with only range measurements.

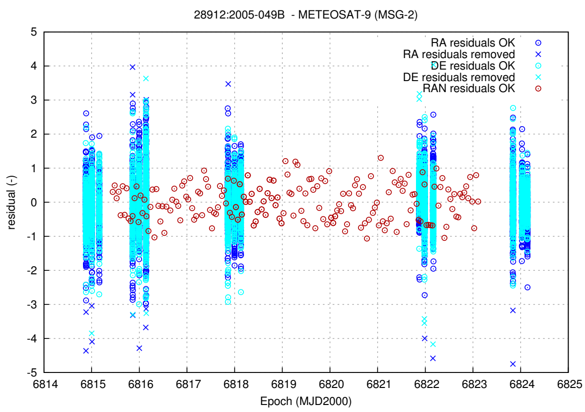

Figure 13: Orbit determination residuals of a case with optical and range measurements.

It can be seen that processing the measurements together has the effect of displacing the ranging residuals. However, the results are very similar for all cases (table 6). This is expectable, as measurements are all weighted equal, and optical measurements are more numerous (13942 optical measurements against 210 ranging measurements in this particular case). Even though the ranging measurements contribute to the solution, the solution is mostly the one provided by the optical measurements.

Kind	X	Y	Z
Range	-33415.06187	25688.38954	-833.82612
Range	-1.8741362	-2.4381764	-0.0084856
Optical	-33415.06924	25688.37148	-833.84694
Optical	-1.8741342	-2.4381782	-0.0084926
Fusion	-33415.08398	25688.34946	-833.84695
Fusion	-1.8741331	-2.4381791	-0.0084927

Table 6: Determined cartesian state vector (km and km/s) at 29/09/2018 11:00 UTC

6 Conclusions

In this paper we have described an operational system that provides optical measurements for operational orbit determination of a GEO fleet comprising four satellites in a regular basis since June 2018. We have also shown an orbit determination processing chain that is able to provide accurate orbits based exclusively on the optical data. The feasibility of using optical only data for manoeuvre calibration has been shown as well, with all the cases being exercised resulting in good agreement with the nominal orbits. Finally, we have shown on-going work to perform data fusion of optical and ranging data.

The system we describe here has been operational for 4 months (June to October 2018). During that time, the secondary sensors had to be used a single time, in order to fulfill observations after a manoeuvre.

For future work, we are considering the following lines of investigation:

- It is possible to model the solar radiation pressure more accurately. Leveraging the simple geometry and attitude control of the MSG satellites, it would be possible to accurately include the true cross section for solar radiation pressure at each time.

- Manoeuvres of MSG type satellites consist in a series of short engine firings for EWSK and SLEW manoeuvres (due to the spin stabilization) and a single continuous firing for NSSK manoeuvres. Currently, we are modelling those manoeuvres as a single impulsive manoeuvre. The model could be refined to model the individual firings.

- Consider different weighting schemas to have optical and ranging measurements contribute evenly to the solution.

- Automatically perform tracking of the satellites based on their current accuracy. This is, instead of considering a fixed observations schema, perform observation tasks automatically whenever the accuracy of the satellites in the constellation falls below a given threshold.

References

[1] Milan Klinc, Stefano Pessina *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)

[2] Milan Klinc, Stefano Pessina *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

[3] Jaime Nomen Torres, Noelia Sánchez-Ortiz, Raúl Domínguez-González, Nuria Guijarro López, Pablo A. Quiles Ibernon *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

[4] Eumetsat website.
https://www.eumetsat.int/website/home/Data/ServiceStatus/MeteosatOrbitalParameters/
Retrieved on October 2018

[5] Johannes Gelhaus, Christopher Kebschull, Vitali Braun, Noelia Sanchez-Ortiz, Esther Parrilla-Endrino, Joaquim Morgado Correia de Oliveira, Raul Domínguez-Gonzalez, Holger Krag *Upgrade of ESA's Space Debris Mitigation Analysis Tool Suite, Final Report.* 2013

[6] G.J. Bierman *Factorization methods for discrete sequential estimation.* 1977

[7] William E. Wiesel *Modern orbit determination.* 2003

[8] E. M. Soop *Handbook of geostationary orbits.* 1994

[9] International Reference Ionosphere

www.irimodel.org

[10] J. Collins *Assessment and Development of a Tropospheric Delay Model for Aircraft Users of the Global Positioning System. M.Sc.E. thesis, Department of Geodesy and Geomatics Engineering Technical Report No. 203* University of New Brunswick, Fredericton, New Brunswick, Canada. 1999

[11] ESA navipedia *https://gssc.esa.int/navipedia/index.php/Tropospheric_Delay* Retrieved on August 2018