OPTICAL TRACKING IN SUPPORT TO ROUTINE OPERATIONS AND CONJUNCTIONS ANALYSIS FOR THE EUMETSAT GEOSYNCHRONOUS FLEET

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Abstract: *As part of an internal technological investigation, EUMETSAT has completed different tracking campaigns based on optical data, processing the measurements from multiple service providers.*
The telescope data have been collected for both the geosynchronous satellites of the organisation (Meteosat), and for space debris. The Meteosat on-ground Flight Dynamics software has been upgraded to ingest CCSDS Tracking Data Messages, thus allowing compatibility with any service provider exchanging tracking data in this standard format. The optical data have been successfully processed in batch orbit determination runs, in combination or comparison with the operational 2-way ranging measurements from the EUMETSAT ground stations. Various trials have been performed, to evaluate the potential support of these data sets for conjunction handling; the data have been also used in actual operations, to assist the planning and execution of the first collision avoidance manoeuvre for the EUMETSAT geosynchronous fleet.
In addition, the telescope measurements have been also collected on a regular routine basis to test their potential in: supporting the operational ranging activity (in case of ground station outages), reducing the ground-stations' load, improving orbit determination accuracy and also providing independent assessment of ground-station biases.

Keywords: *Optical tracking data, telescope, geostationary, orbit determination, conjunction analysis.*

1. Introduction

This paper presents the results of the EUMETSAT independent assessment of the use of optical data in support to both routine operations and conjunction handling, from multiple sensors. The ingestion of the data was based on standard CCSDS interfaces. The assessment of the optical tracking data accuracy was done by comparing the obtained solutions to Meteosat operational orbits, determined using 2-way ranging data from 2 alternating ground stations. Trials were performed also in support to conjunction handling, with one case of actual operational use in assisting active risk mitigation operations. The paper is of specific interest for any operator of geosynchronous satellites, and of general interest for orbit determination based on combined observable sources.

2. EUMETSAT Geosynchronous Fleet and Operational Orbit Determination

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 operational meteorological satellites. It currently operates a system of meteorological satellites, monitoring the atmosphere, ocean and land surfaces, delivering weather and climate-related satellite data, images and products.

EUMETSAT currently operates both low-earth orbit (LEO) and geosynchronous (GEO) weather satellites. The satellites in GEO are called Meteosat.There are two generations of active Meteosat satellites, all spin stabilised: Meteosat-7 is the last of the Meteosat first generation series, while the other four satellites belong to the Meteosat Second Generation (MSG) series. The last satellite of the second generation, launched in July 2015, is MSG-4 (that will be re-named Meteosat-11 after successful in-orbit commissioning). A third generation (MTG) series of satellites is currently being procured, with first launch scheduled in 2019. Differently than their predecessors, they will use a three-axis stabilised platform.

For the MSG satellites in orbit, the operational concept for orbit determination is based on 2-way ranging from two alternating ground-stations. The EUMETSAT GEO ground-stations for ranging are located in Usingen (Germany, near Frankfurt), Maspalomas (Spain, on the Canary Islands) and Fucino (Italy, near Rome). The same concept will apply in future for MTG that will use antennas in Fucino and in Cheia (Romania). The required accuracy for the dual-stations ranging for MSG is 1000m/1000m/100m in along-track/cross-track/radial direction at 1-sigma confidence level.

The operational use of optical observations is currently under evaluation: it has been decided to perform a technological investigation, based on regular collection of optical data from various telescopes, to evaluate their potential benefit in support to both routine operations and conjunction analyses.

To allow these analyses, the Flight Dynamics sub-system currently used on-ground to operate the MSG satellites has been upgraded, to ingest angular data in the CCSDS 503 standard Tracking Data Messages (TDM), not originally foreseen for the mission (see RD.1 and RD.2). The same has been done for the Flight Dynamics sub-system for the MTG satellites, currently in the critical design phase, to allow potential future use of this interface.

3. Optical Data Collection and Accuracy Assessment

So far, EUMETSAT completed various optical tracking campaigns, both on Meteosat satellites and space debris, using in total data from 6 different telescopes: 2 in Cyprus, 2 in South France, 2 in Spain (Canary Islands and South Spain). More campaigns are planned for the future, with some of the sensors above, and also testing new telescopes in Switzerland and South Africa.

One of the tested telescopes is a wide-field surveying sensor; this was employed for a longer period of time, according to a bi-weekly regular schedule, pending weather conditions. All the other telescopes were employed asynchronously in shorter but more concentrated tracking campaigns, either for cross-comparison or for specific needs driven by conjunction warnings.

The basic requirements for the regular provision of observations data over were:

- One night of optical measurements every 2 weeks
- Tracking data provided for all EUMETSAT GEO satellites, or any other Space Debris coming from specific request
- Minimum of 2 slots of measurements per object on the same night
- Minimum separation of slots for the same satellite of 2 hours
- Minimum frequency of measurements in a slot of 0.1 Hz
- Minimum slot duration of 10 minutes
- Data formatted according to CCSDS 503 TDM, in local horizon angular coordinates (azimuth/elevation), delivered within 24hours after collection
- Objects to be tracked communicated by EUMETSAT 48 hours before data collection

The assessment of the collected optical tracking data was performed carrying out a series of orbit determination runs, comparing the results of the operational dual-stations ranging solution, with other solutions, either based on optical observations only, or on optical/ranging data fusion.

Of particular interest to EUMETSAT was the study of optical/ranging measurement schemes, aimed to avoid the need of two ground stations to support orbit determination for each satellite. This paper will present the results of the evaluation of these orbit determination schemes for the Meteosat satellites, for potential routine operations support.

An example of conjunction analysis (involving actual operational use of the collected optical observations for independent assessments) will be provided for the case of a Meteosat-10 collision avoidance manoeuvre, executed in May 2013.

4. Wide-Field Surveying Sensor: Testing Results

The telescope which was employed on a regular basis over a prolonged period of time was originally optimized by its operator to be suitable for a general space-surveying role. The sensor located in Cyprus is fully robotic and operated remotely, resulting in relatively limited costs per activation. However, the obtained measurement accuracy is certainly lower than the one offered by small-field sensors which deliver higher accuracy position fixes – but less often and only for a smaller number of satellites each night.

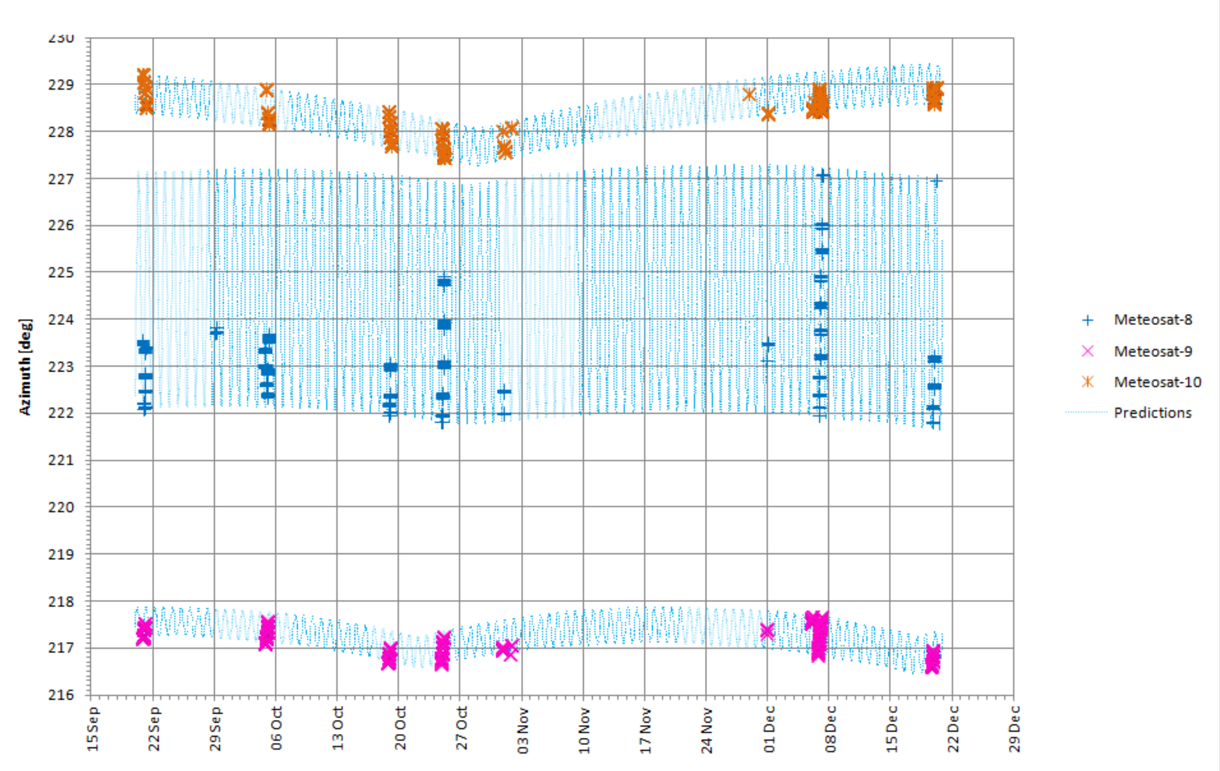

Figure 1: Overview of the covered period and satellites by the surveying sensor observations for the period September-December 2014.

An overview of the covered arcs between September and December 2014 by the employed wide-field surveying sensor for MSG satellites is given in Figure 1; this plot shows the predicted azimuth for Meteosat-8/9/10 as function of time, together with the one measured by the telescope in the various tracking campaign. A noticeable gap, due to bad weather conditions at the sensor site, can be seen during the month of November.

1 provides the list of routine orbit determination runs (performed weekly, on Mondays), where optical tracking data could be found within the standard 8-day measurement interval, used in the batch least-squares estimation (in this table, λ is the longitude slot and i the inclination of the various spacecrafts). Optical tracking was normally scheduled to be performed one night during the weekend (typically on the night starting on Saturday) for the operational MSG satellites in orbit. In some cases however, no observation was possible over a scheduled weekend. Depending on the weather conditions, the coverage was sometimes also only partial (spanning less than 3 hours), or sparse (very few measurements, but more than 3 hours apart).

Table 1: Nights of surveying sensor tracking within the 8-day measurement interval.

Data Retrieval		**Nights of Tracking**		
Routine OD Run	**Date**	**Meteosat-8** λ**=3.5°E,** i**=3°**	**Meteosat-9** λ**=9.5°E,** i**=0.5°**	**Meteosat-10** λ**=0°E,** i**=0.5°**
OD_14_265	22/09/2014	1	1	1
OD_14_279	06/10/2014	1 + 1 (partial)	1	1
OD_14_293	20/10/2014	1	1	1
OD_14_300	27/10/2014	1	1	1
OD_14_307	03/11/2014	1 (partial)	1 (partial) + 1 (sparse)	1 + 1 (partial)
OD_14_342	08/12/2014	1 + 1 (partial)	2	2
OD_14_356	22/12/2014	1	1	1

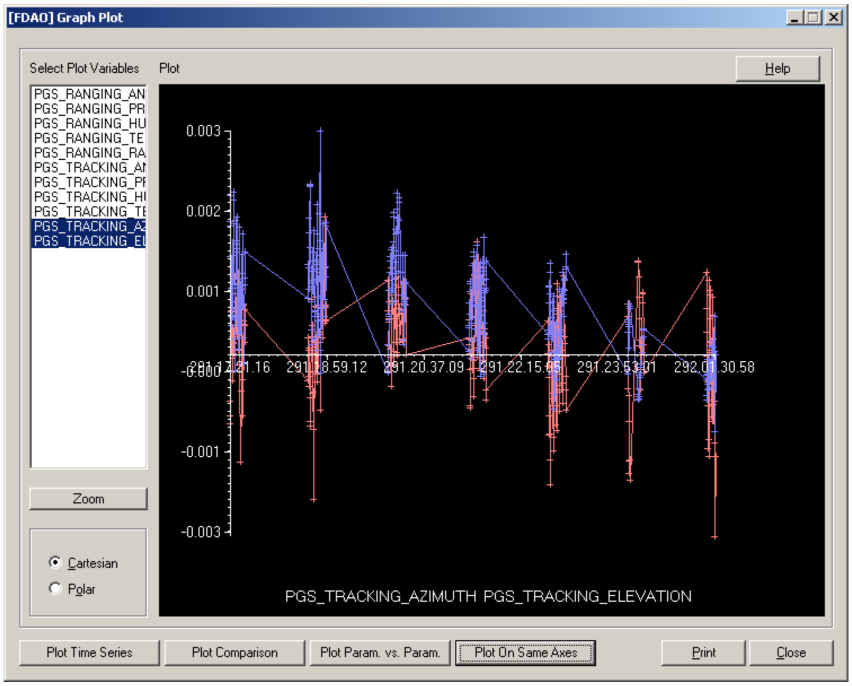

Figure 2: Surveying sensor data residuals plotted by the operational orbit determination software in a Meteosat-10 orbit determination ([deg], red=Azimuth, blue=Elevation)

For all the routine orbit-determinations, including measurements from the surveying sensor within the standard 8-day retrieval interval, three runs were executed for comparison, with respectively the following measurement sets:

- Ranging data from the Usingen and Maspalomas ground-stations (reference run)
- Ranging data from the Usingen ground-station only
- Ranging data from the Usingen ground-station and surveying sensor observations

Figure 2 is an example of the final residuals for the surveying sensor tracking data, obtained after a Meteosat-10 orbit determination.

The orbit determination results obtained with the Usingen ground-station ranging data only and the results obtained, merging the Usingen ranging data with the surveying sensor observations, were compared to the reference solution, obtained with the nominal dual ranging coverage (Usingen+Maspalomas). Figures 3 to 6 show the obtained deltas in the orbital elements *a*, *e*, i and *RAAN*, for the comparison runs making use of Usingen ranging only (labelled as PGS only, standing for Primary Ground Station) and Usingen ranging + surveying sensor observations (PGS+Opt), performed respectively for Meteosat-8, Meteosat-9 and Meteosat-10.

Interestingly, for Meteosat-8, which was in a 3° inclined orbit, the contribution of the surveying sensor observations was found to be very marginal. Regarding this inclined orbit case, it must be noted also that, with the exception of the semi-major axis value, this special case presented already significantly smaller degradations of the single ranging station solutions, compared to the nominal dual ranging station coverage. No significant further advantage was then observed when adding the surveying sensor tracking data. Only in the first of the considered runs, the semi-major axis value could be considerably improved. However, this was simply due to the fact that for that specific run, the available Usingen ranging measurements were significantly less than normal, as the ground-station antenna needed to be put out of service for maintenance for most of the assumed measurement interval. In practice, this case provided an example of how, during mission extension phases (after the end of active inclination control), orbit determination performance can be expected to remain satisfactory, when using a single-station ranging solution. The slightly degraded determination of the Semi-major axis value would be then only partially recoverable with the addition of the tested surveying sensor tracking data.

The results for Meteosat-9 and Meteosat-10 show instead a clear advantage of the solutions that included the surveying sensor data. In particular for Meteosat-9, for which the nominal sub-satellite point is within 1 degree from the longitude of Usingen, the surveying sensor observations become crucial, as the Semi-major Axis is then very poorly observable with the Usingen ranging data alone.

Figures 7 to 9 summarise the surveying sensor tracking data residual statistics on Azimuth and Elevation for the performed runs based on data fusion (making use of the Usingen ranging data and the surveying sensor observations).

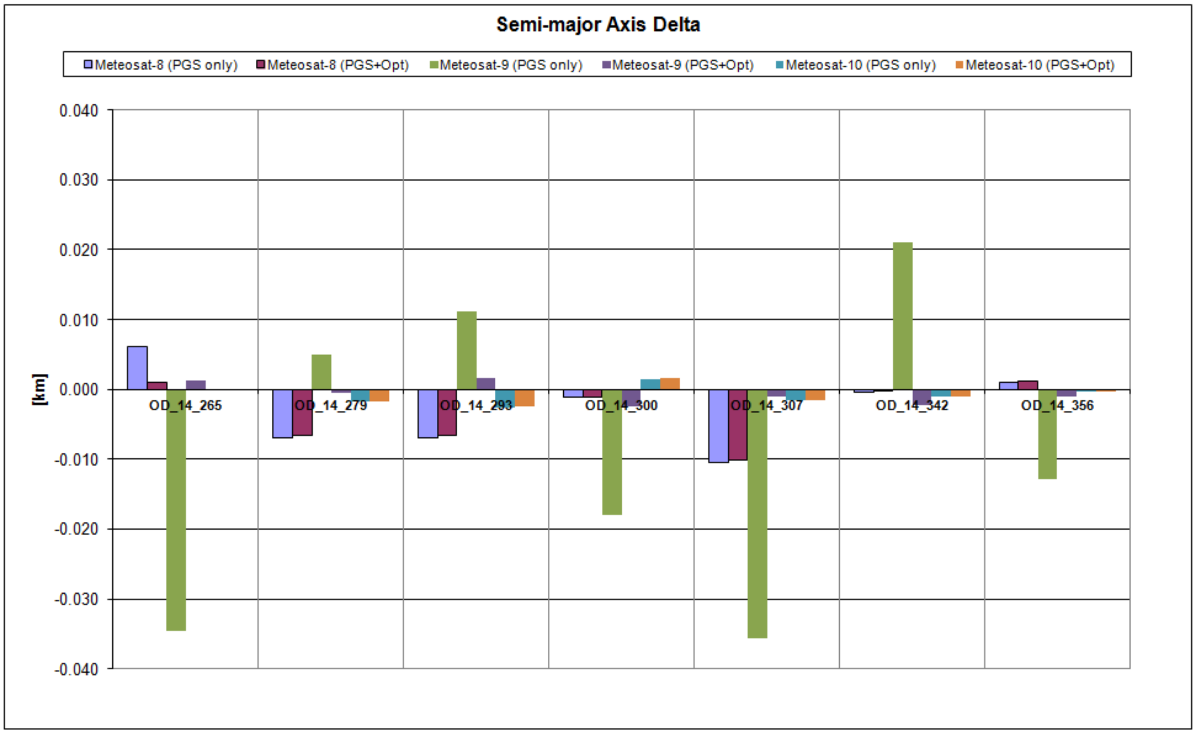

Figure 3. Orbit determination results: Semi-major axis delta compared to the reference solution (nominal dual ranging coverage Usingen+Maspalomas).

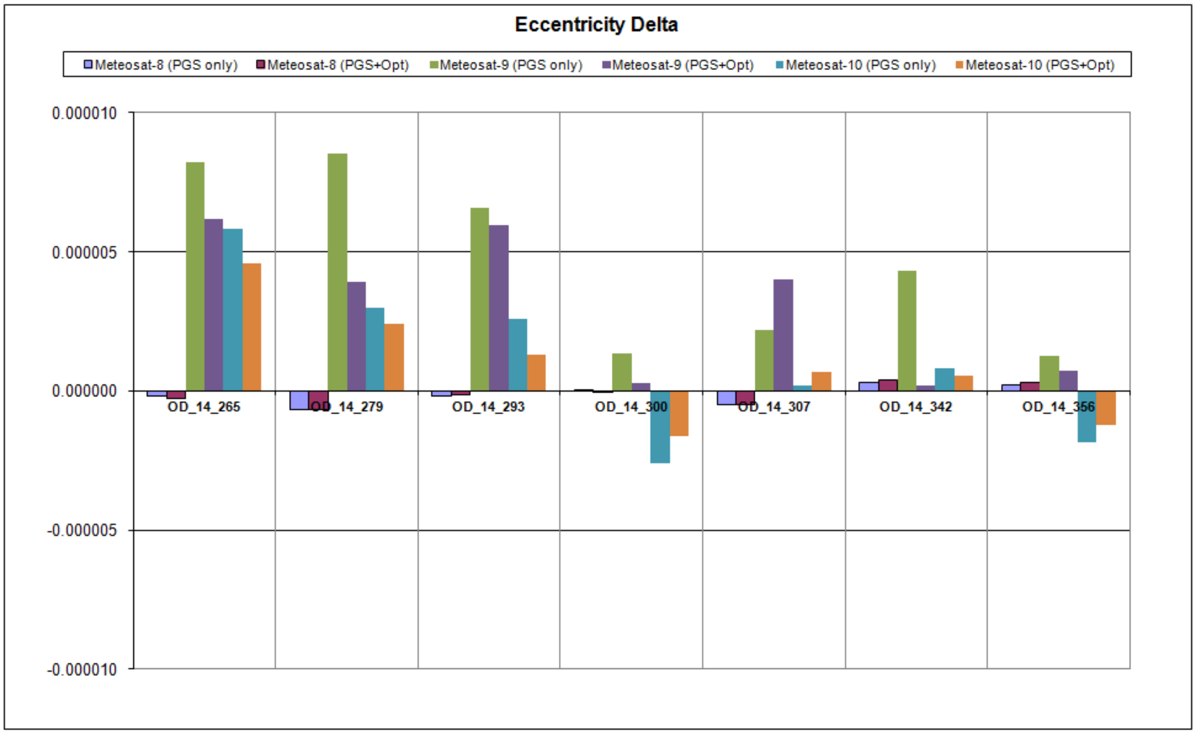

Figure 4. Orbit determination results: Eccentricity delta compared to the reference solution (nominal dual ranging coverage Usingen+Maspalomas).

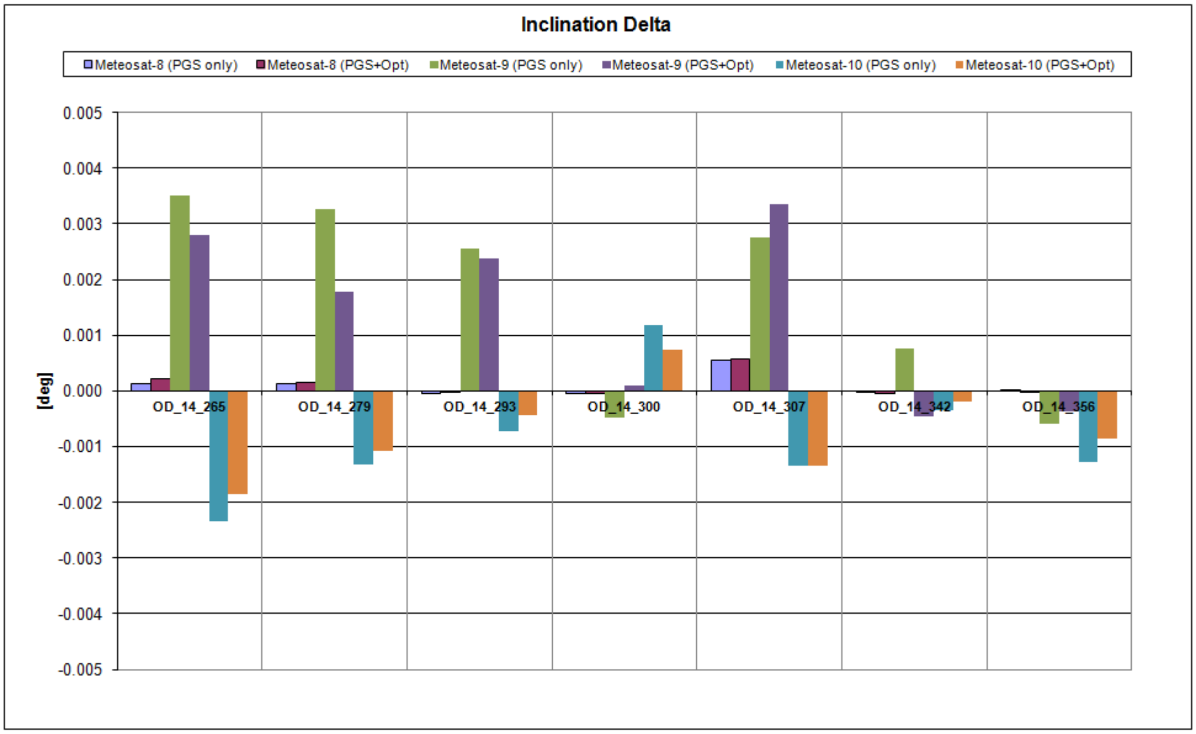

Figure 5. Orbit determination results: Inclination delta compared to the reference solution, (nominal dual ranging coverage Usingen+Maspalomas).

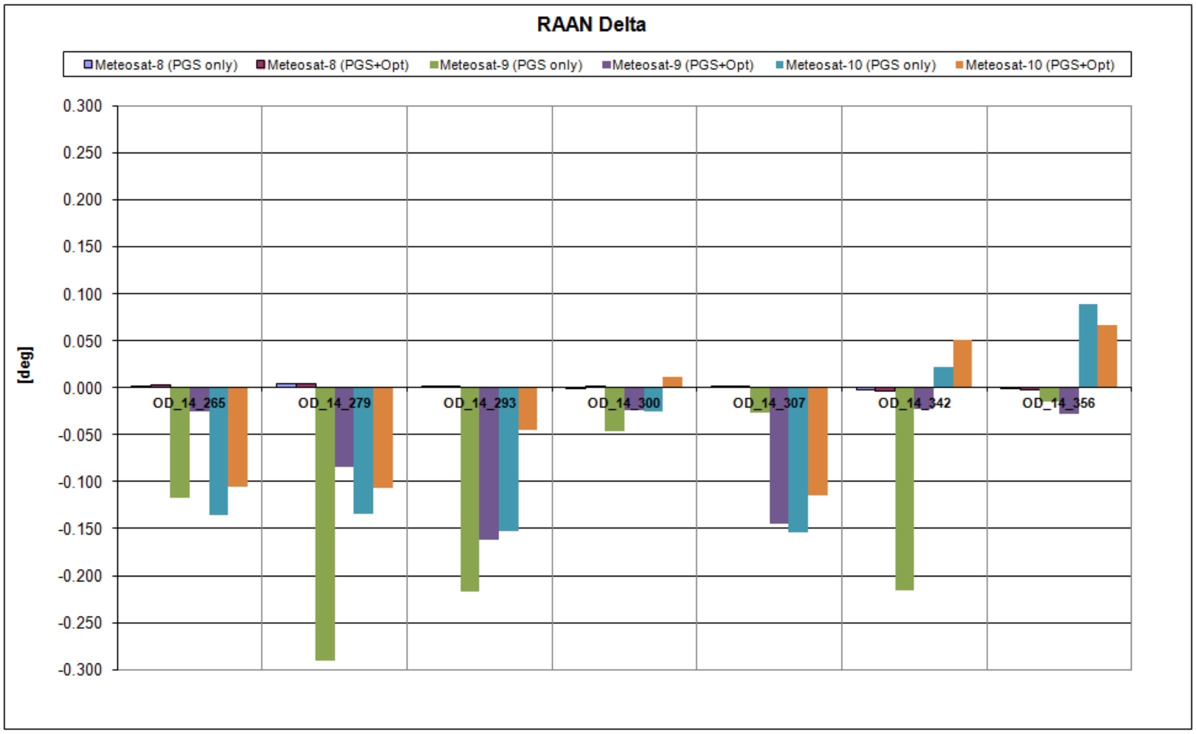

Figure 6. Orbit determination results: Right-Ascension of Ascending Node delta compared to the reference solution (nominal dual ranging coverage Usingen+Maspalomas).

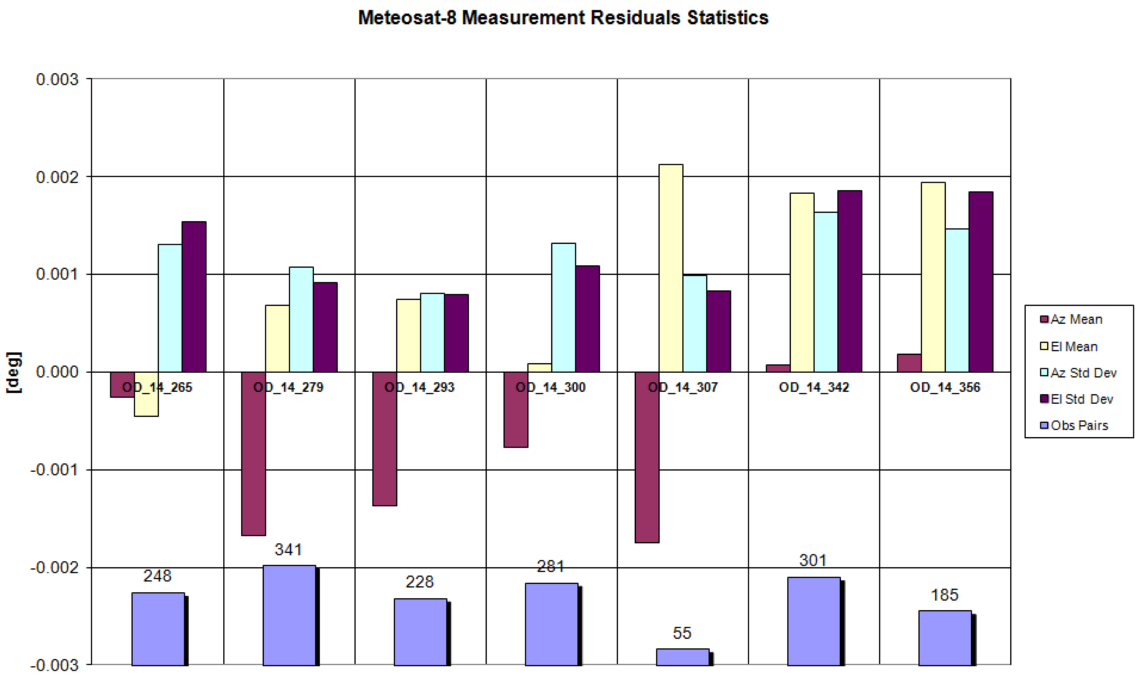

Figure 7: Met8 Surveying sensor measurements residual statistics, number of observations

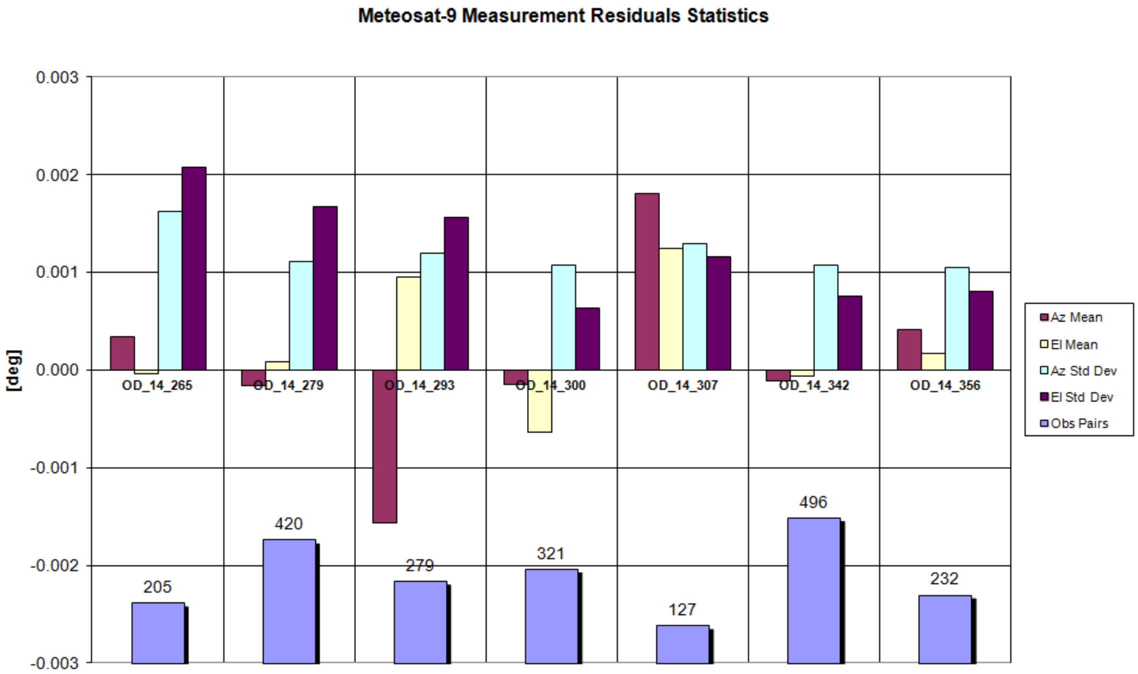

Figure 8: Met9 Surveying sensor measurement residual statistics, number of observations

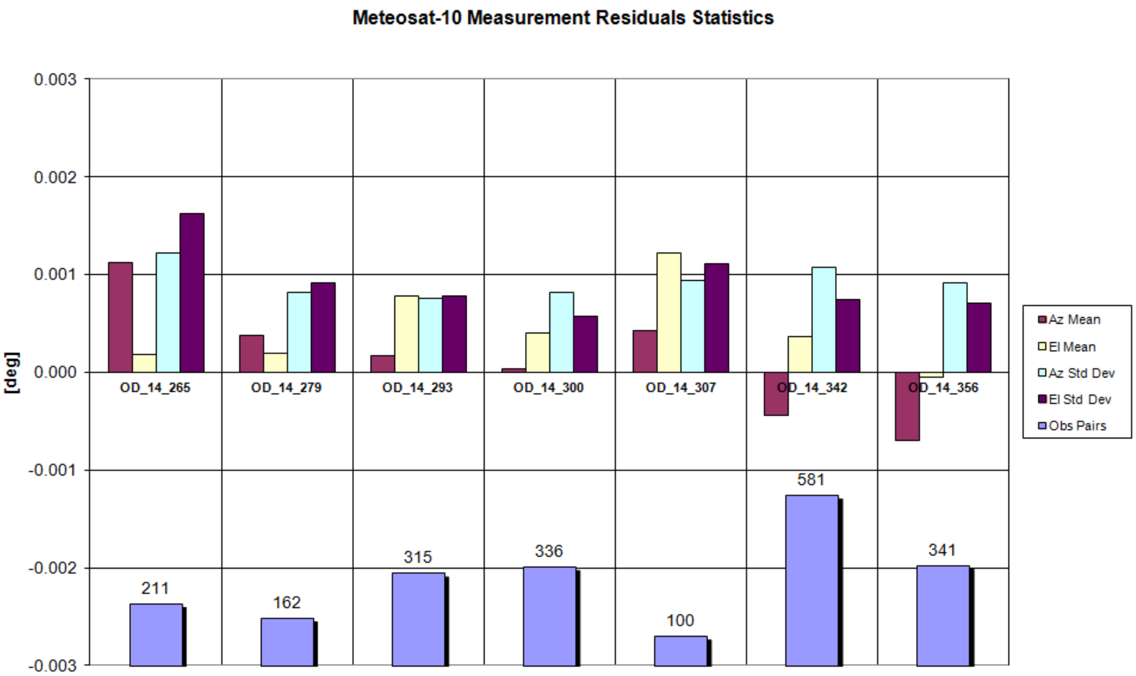

Figure 9: Met10 Surveying sensor measurement residual statistics, number of observations

5. Dedicated Tracking Sensor Observation Campaign Results

During a limited period of time, between 24 and 31 October 2014, the MSG satellites in orbit were tracked every night by an additional telescope in South Spain, with a dedicated GPS calibration, providing higher precision tracking data compared to the wide-field surveying sensor

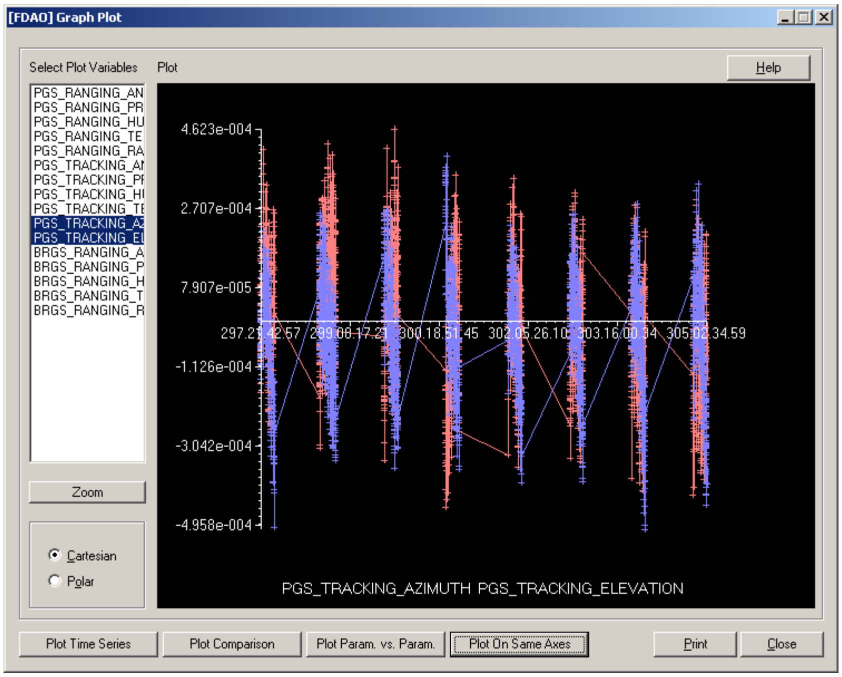

Figure 10. Tracking sensor measurement residuals plotted by the operational software after a Meteosat-9 orbit determination run ([deg], red=Azimuth, blue=Elevation).

Figure 10 is an example of the measurement final residuals, obtained for the dedicated tracking sensor data; this plot is related to a Meteosat-9 orbit determination run, spanning the complete period of the eight consecutive nights of observations.

The improved precision of the sensor data can be seen directly by comparing the plot in Figure 10 with the one in Figure 2 (note that the scaling is different). Also the measurement statistical results of Figure 11 can be compared to the ones in Figures 7-9.

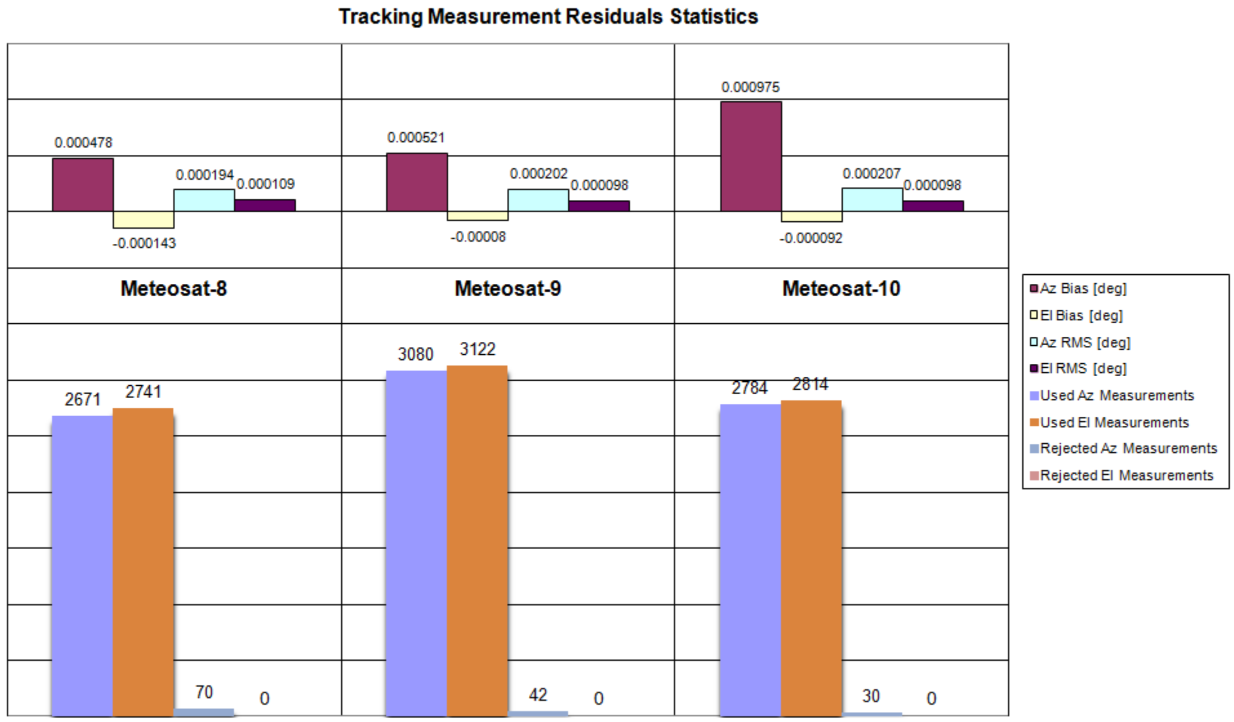

Figure 11. Tracking sensor data residual statistics and number of observations.

Despite determining a significantly reduced jitter in the tracking sensor measurement data, the obtained orbit determination results did not however show an equivalently strong reduction of the solution errors, compared to the runs performed using the data of the surveying sensor. Figure 12 shows the position errors in the Meteosat-9 ephemeris data, generated from solutions obtained with different data sets, using the dual ranging station solution as the underlying reference. An interesting finding was in any case that, using the tracking sensor optical observations alone, collected over at least two consecutive nights, the ranging data could be completely removed, without essentially affecting the errors in the obtained solution. Figure 13 is a comparison of the solutions based only on optical tracking observations, spanning across arcs of 2, 4, 6 and 8 consecutive nights.

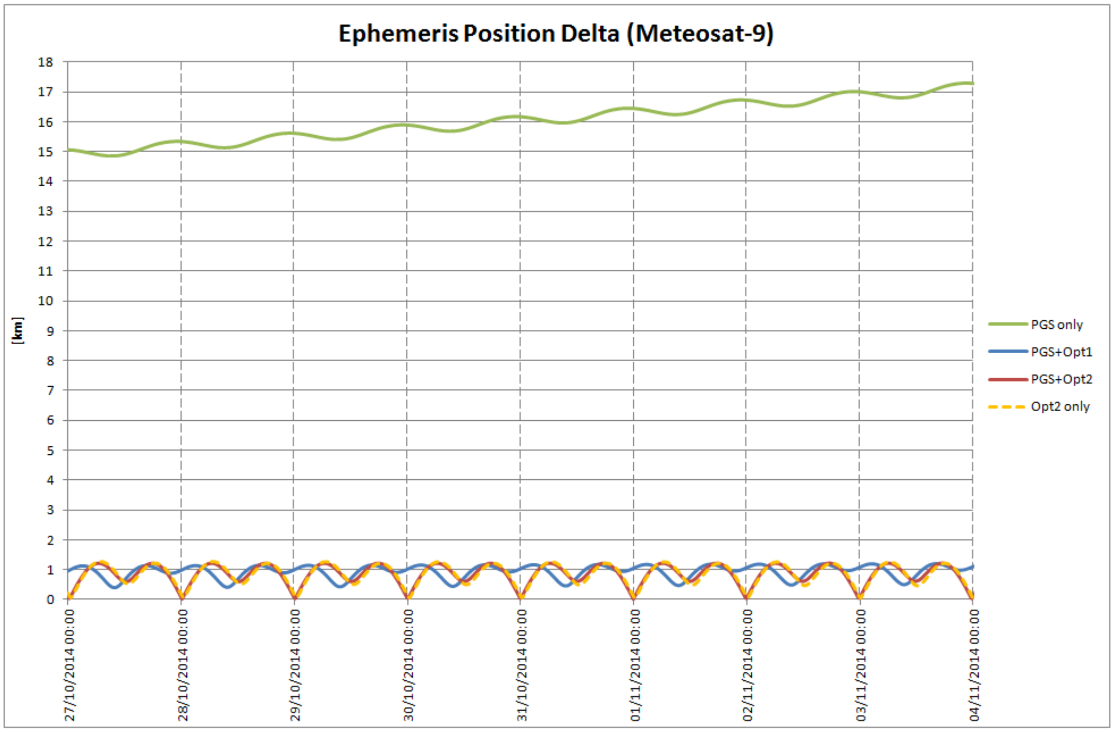

Figure 12. Met9 example of the comparison of OD solutions: Usingen ranging data only (PGS only), Usingen ranging + wide-field surveying sensor data (PGS+Opt1), Usingen ranging + dedicated sensor data (PGS+Opt2), dedicated sensor data alone (Opt2 only).

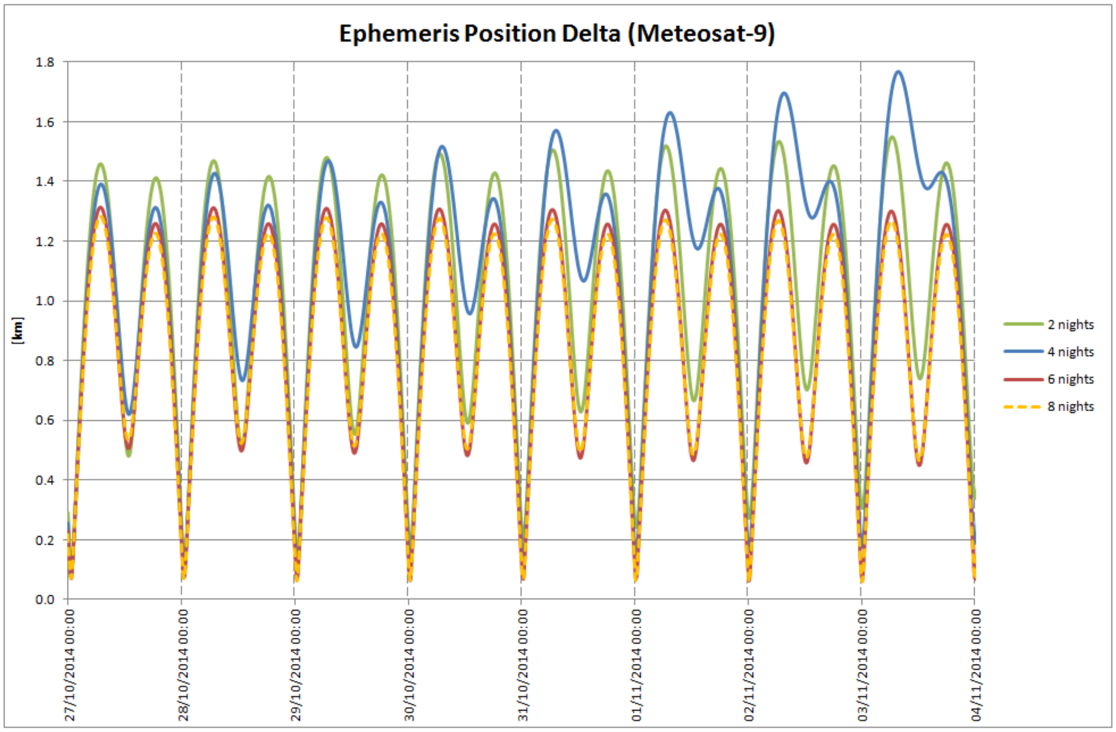

Figure 13. Meteosat-9 example of the comparison of OD solutions obtained from the dedicated tracking sensor observations alone, using increasing arc lengths of consecutive observation nights (2, 4, 6 and 8 nights).

6. Optical Tracking in Support of Conjunction Warning: Verification and Avoidance Manoeuvre Decision

During May 2013, a conjunction warning was received by EUMETSAT concerning Meteosat-10 and the abandoned free-drifting object GORIZONT-22. The alert was issued only days after the execution of a routine East/West Station-Keeping manoeuvre for Meteosat-10 and predicted the closest approach to be within 0.562 km, to occur in less than 3 days. The conjunction could not be predicted before, because it was just outside the 3-day screening window, systematically requested to JSpOC before each manoeuvre, which used a set of provided post-manoeuvre ephemeris. As the information about the predicted conjunction arrived at short notice, immediate steps were taken to try to confirm the high risk of the close encounter. Thanks to the prompt response of the sensor operator, a tracking campaign could be set up with the wide-field surveying sensor, which acquired data for both Meteosat-10 and the approaching free-drifting object (Figure 12) during the two nights before the predicted closest approach.

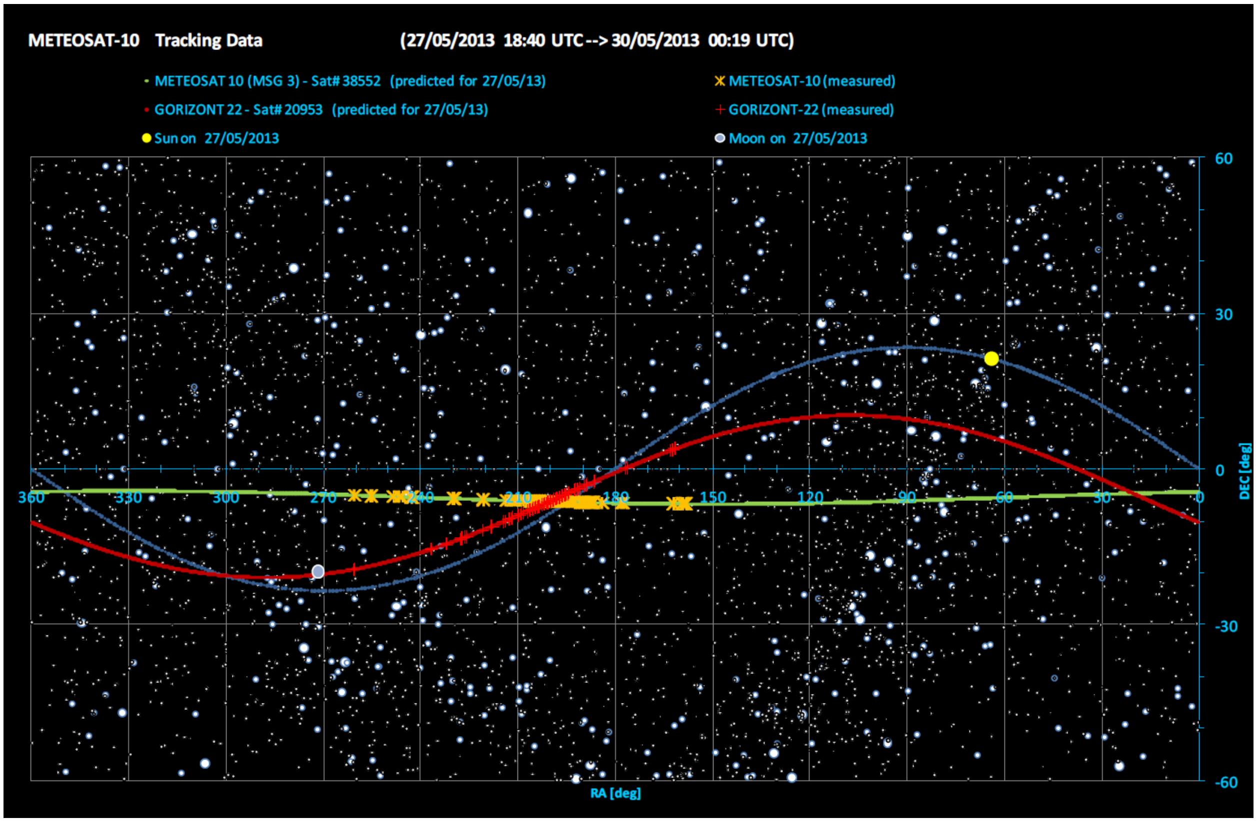

Figure 12. Graphic representation of a subset of surveying sensor fixes in EME2000 intertial frame (RA, DEC) collected around 36h from the predicted closest approach.

To verify the close approach, optical data were collected for both Meteosat-10 and the space debris: the telescope data of Meteosat-10 were initially processed in an orbit determination, together with ranging from two ground-stations, to determine eventual bias of the optical sensor. Then, fixing the a-priori telescope bias previously determined, another orbit determination was done with the optical measurements for the space debris only, using the state vector from the JSpOC conjunction message. The assessment of the measurements residuals provided sufficient evidence that the JSpOC alert was genuine and candidate of requiring active risk mitigation operations. The predicted minimum separation in the radial direction was of -0.318 km, meaning that a Meteosat-10 avoidance manoeuvre would be most effective when providing a positive tangential thrust at an opportune time, to increase the existing altitude separation at closest encounter. However, care had to be taken also to avoid exiting the longitude control dead-band, so the magnitude was restricted to the minimum needed amount, which was determined in 0.009 m/s. The manoeuvre was finally executed with a short 5-pulse burn of a total duration of 3 seconds. A further post-manoeuvre assessment of the optical data estimated that the magnitude of the radial separation at the encounter was successfully increased to 0.7 km.

7. Assessments of Additional Tracking Campaigns

Additional shorter campaigns of optical tracking of Meteosat satellites were performed by a sensor located on the Canary Islands and another in South France. Also for these cases, merged observation/ranging data sets were used to assess the accuracy of the optical tracking data. Tables 2 and 3 summarise the results of the assessment performed for the collected data.

Table 2: Assessment results for observations collected between 24 October 2014 and 01 November 2014 by a sensor located on the Canary Islands.

Tracked Satellite	Measurement	Determined Bias [deg]	Residuals Mean [deg]	Residuals RMS [deg]	Used Meas.	Rejected Meas.
Meteosat-8	Azimuth	-0.001777	-0.000012	0.000457	150	16
	Elevation	-0.000415	-0.000003	0.000292	163	3
Meteosat-9	Azimuth	-0.000778	-0.000017	0.000833	153	18
	Elevation	-0.000371	-0.000002	0.000461	171	0
Meteosat-10	Azimuth	-0.000612	-0.000005	0.000340	119	6
	Elevation	-0.000172	-0.000001	0.000159	121	4

Table 3: Assessment results for observations collected between 31 October 2014 and 03 November 2014 by a sensor located in South France.

Tracked Satellite	Measurement	Determined Bias [deg]	Residuals Mean [deg]	Residuals RMS [deg]	Used Meas.	Rejected Meas.
Meteosat-10	Azimuth	0.002250	0.000013	0.000217	2755	42
	Elevation	-0.000484	-0.000003	0.000133	2789	8

Finally, another tracking sensor located in South Spain performed a series of test tracking campaigns in July 2015, during the MSG-4 LEOP, while the satellite was still in an intermediate tranfer orbit. The number of big orbit manoeuvres implemented in the LEOP required a continuous ephemeris exchange with the telescope operators, to cope with frequent manoeuvres' optimisation and re-planning. Indeed, following a launch from Kourou with Ariane-5 (with a launch window very close to the launcher standard window), the implemented perigee raising manoeuvres to circularise the GTO was based on apogee burns with dual stations coverage over Europe, often in daylight or twilight; this made the possibility of optical observations very difficult till the second part of the LEOP, in near-synchronous orbit, when passes over Europe started to be also overnight. Anyway, the experience proved to be very useful to test frequent ephemeris exchange in a stressful/challenging conditions such as the GTO to GEO transfer.

8. Conclusion

For the EUMETSAT fleet of Meteosat Second Generation (MSG), a recent upgrade of the operational Flight Dynamics System (FDS) allowed to ingest optical tracking observations for orbit determination, beside the ranging data provided operationally by the ground-stations. A series of tracking campaigns have been carried out so far, aiming in particular to test suitable orbit determination schemes, which would allow fewer ground-station antennas to be needed in support of orbit determination of the MSG satellites.

The performed orbit determination runs, in particular for Meteosat-9 and Meteosat-10, revealed that the orbit solution obtained with the Usingen ground-station ranging data alone could be generally improved, when using additionally a night of observations from a wide-field surveying sensor. This was found to be particularly true for the case of Meteosat-9, located on an orbital slot very close to the longitude of the Usingen ground station. In the case of Meteosat-8, where the orbit was inclined by 3°, the addition of the surveying sensor data was less effective and the solutions based on the Usingen ranging data alone (already generally closer to the nominal reference solutions than for the not inclined orbit cases) was not be substantially improved.

The tests performed with a higher precision tracking sensor revealed smaller than expected error reductions for the merged observation/ranging measurement data sets, compared to the solutions obtained when using the wide-field surveying sensor data. An interesting finding obtained with the dedicated tracking sensor data, collected more intensively on several successive nights, was that satisfactory solutions could be obtained even without including any ranging measurements from a ground-station, when using tracking data arcs across at least two observation nights.

The capability to process optical observations for orbit determination in EUMETSAT allows also carrying out independent verifications of alerts, reporting particularly hazardous close encounters, which require consideration for potential active mitigation operations. This was for example the case in May 2013, when optical observations of Meteosat-10 and a space debris object provided useful supporting assessments, leading to the final decision to perform a last-minute collision avoidance manoeuvre.

EUMETSAT plans to continue making use of optical observations also in the future years, to further consolidate the schemes and methods described in this paper. This is to generally improve the robustness of the orbit determination function for the in-flight and also future Meteosat satellites, as well to potentially reduce the requirements in terms of ground stations support and operational load (such as ranging station swaps), simplifying the operational concepts.

9. References

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RD.2 Klinc, M., Lazaro, D., Siemer, A., "Use of optical directional observations for routine METEOSAT orbit determination", European Space Surveillance Conference, ESA, Madrid, June 2011.