GMV/ISON COMBINED OPTICAL CAMPAIGNS

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ABSTRACT

This paper reports on the results of several optical campaigns performed by GMV and ISON together. These campaigns have focused on various aspects, including ranging station calibration, collision avoidance, and end-of-life operations. Special focus is given to a very recent end-of-life activity, devoted to the deorbiting of Meteosat-7.

1 INTRODUCTION

GMV is currently providing SST services to GEO operators using third-party optical sensor data. These services include **conjunction analysis and refinement, calibration capabilities** for ranging stations, and end-of-life operations. For the provision of these services GMV cooperates with a set of optical data providers, being the ISON network one of the largest ones.

ISON has been working already for more than 10 years now and is using adjusted technology for space object observations that has been tested with GLONASS and GPS satellites observations and the accuracy of the measurements obtained for GEO objects has been checked by independent experts. ISON represents now one of largest and most powerful ground systems specialized in observation of space objects. Observatories of the ISON network provide coverage for the whole GEO belt (i.e., telescopes are installed in all four Earth's hemispheres). The **ISON optical network** counts now with 73 telescopes in 33 observation points of 13 countries.

This paper is devoted to describe the results of the combined activities between GMV and ISON in various aspects (conjunction analysis, calibration of ranging stations, end of life operations) and that those three tasks can be performed successfully with GMV's software and the ISON network.

A battery of observation campaigns has been executed during 2016 in order to analyse and to characterise the results using actual observations from the ISON telescope network and ranging data from satellite-operators.

This paper can be considered as a report of all the campaigns and it is focused on the following topics:

- **Orbit determination capabilities and accuracy**: devoted to analyse the orbit determination performances, including the following particular cases:
    - Accuracy of optical-only orbits depending on various aspects: number of telescopes, number of passes, length of passes, etc
    - Station and transponder calibration through the combination of optical data and ranging data.
    - Manoeuvre estimation and orbit accuracy in periods with manoeuvres.
    - Survey activities and achieved performances with survey-only data
- **Collision risk assessment**: devoted to conjunction analyses between operational satellites and debris.
- **End of life operations**: devoted to prove that the telescope network can also be used for special mission support operations such as end of life operations.

The following table shows a summary of the tracking campaigns executed indicating an anonymous satellite identifier. For confidentiality reasons the real satellite identifier is not indicated.

- April 2016
    - A1: 07/04/2016-18/04/2016
    - B1: 07/04/2016-18/04/2016
    - B2: 15/04/2016-20/04/2016
- May 2016
    - C2: 09/05/2016-17/05/2016
    - D2: 06/05/2016-17/05/2016
    - D3: 06/05/2016-17/05/2016
    - F1: 31/05/2016-08/06/2016
    - B3: 08/06/2016-16/06/2016
- July 2016
    - D1: 26/06/2016-08/07/2016
    - D4: 26/06/2016-08/07/2016
    - G1: 01/07/2016-08/07/2016
    - G2: 01/07/2016-08/07/2016
- August 2017
    - M: 01/04/2017-10/04/2017

Proc. 7th European Conference on Space Debris, Darmstadt, Germany, 18–21 April 2017, published by the ESA Space Debris Office
Ed. T. Flohrer & F. Schmitz, (http://spacedebris2017.sdo.esoc.esa.int, June 2017)

2 ORBIT DETERMINATION

This section is devoted to show the orbit determination and ranging station calibration results obtained by processing the **optical data** received from the ISON telescopes network and the **ranging data** received from some of the satellite operators. The processing has been performed by GMV with its some of the elements of its SST software suite, including, ***catmai***, for catalogue maintenance (initial orbit determination, correlation and sequential orbit determination), and ***sstod***, for batch-least squares orbit determination. Some of the satellites have performed several manoeuvres during the observation campaigns and additionally several ISON survey telescopes have also provided survey data during the campaigns. Hence the need to use ***sstod*** for the estimation of manoeuvres and ranging station biases and to use ***catmai*** for observation-to-orbit correlation so that observations not corresponding to the satellite under analysis are filtered out.

The analyses performed for each one of the satellites is composed of the following orbit determination tasks:

- **Optical only:** orbit determination based only on optical observations coming from the ISON telescopes.
- **Data fusion:** orbit determination based on optical observations coming from the telescopes and ranging data provided by satellite-operators. A range bias for each station/transponder combination is estimated.
- **Orbit comparison** between both orbits, optical-only and data fusion to characterize the accuracy of the optical-only solution.

The following table shows the residuals obtained from each orbit determination process. Satellites noted with "*" contain manoeuvres during the orbit determination period. For these satellites, manoeuvres are estimated during the orbit determination process.

Table 1: Orbit determination residuals.

Satellite ID	Optical		Range		Only-optical residuals		Data fusion residuals		
	Sensors	Obs. #	Stations	Obs. #	R. A. RMS [mDeg]	Dec. RMS [mDeg]	R. A. RMS [mDeg]	Dec. RMS [mDeg]	Range RMS [m]
A1	4	1184	2	408	0.267	0.221	0.282	0.221	3.6
B1	4	989	2	144	0.265	0.231	0.277	0.231	5.2
B2*	4	460	2	94	0.253	0.221	0.268	0.221	2.2
C2	9	2024	4	176	0.270	0.254	0.270	0.254	7.453
D2	7	3281	2	239	0.216	0.180	0.217	0.180	1.9
D3	7	3671	2	241	0.207	0.189	0.208	0.189	1.0
F1*	8	1028	2	215	0.245	0.247	0.271	0.290	5.161
D1	9	1302	2	251	0.247	0.213	0.248	0.209	0.9
D4	7	1472	2	286	0.223	0.197	0.221	0.197	1.8

Taking into account the previous results, it is possible to state the following conclusions:

- **Small pointing residuals** on the optical observations are achieved (less than 0.3 mdeg ~ 200 meters for all cases)
- **Telescopes are correctly calibrated** as no large biases are observed
- Taking into account the low residuals observed, the great number of observations and the number of telescopes involved, the excellent quality of the telescope data and of the resulting orbits is confirmed.
- There is **no difference** on pointing **residuals between the two orbit** determinations, ranging data is correctly ingested by the orbit determination process, and the final range residuals obtained are reasonable.

The **small pointing residuals** for both orbit determinations allow us to assume that the orbit determined using only telescopes observations is very close to the data fusion one, and **no radial biases** are appreciated. To demonstrate this last hypothesis the resulting orbits are compared during the whole orbit determination arc (i.e. several days) in terms of error on the orbital frame in the following table:

Table 2: Optical-only vs Data fusion comparison

Satellite ID	Orbit Errors Mean [m]			Orbit Errors RMS [m]		
	Radial	Along-track	Cross-track	Radial	Along-track	Cross-track
A1	0.6	94.9	0.1	58.2	152.1	14.3
B1	1.0	-4.9	0.2	41.6	87.7	10.1
B2*	**1.5**	**-7.0**	**0.4**	**42.1**	**88.9**	**11.3**
C2	-0.7	21.7	0.2	16.5	60.5	1.3
D2	0.1	52.6	-0.2	24.4	76.7	3.3
D3	0.0	13.5	0.0	18.9	41.7	5.0
F1*	**24.4**	**-113.4**	**114.2**	**279.4**	**785.9**	**330.8**
D1	0.2	-42.6	-103.7	64.4	224.6	569.0
D4	0.0	142.9	0.6	63.1	200.4	11.9

As it can be observed in most of the cases, the main **bias** is in the **along-track** direction and is normally below **100 meters**. For the particular case **F1**, larger biases are observed, which are justified by the **presence of daily manoeuvres** during the orbit determination arc. Even if those manoeuvres are **estimated**, the increase of the orbital errors is unavoidable. However, even in that stringent scenario, the comparison against data-fusion orbits, which are quite accurate as they are based on ranging data as well, shows that optical only solutions can be computed with good accuracy even during periods of daily manoeuvres.

The following plot shows the orbital differences between the optical-only and the data fusion orbits for two of the satellites, **B1** and **F1**, the first one without manoeuvres during the campaign period and the second one with manoeuvres every 12 hours until the 7th day.

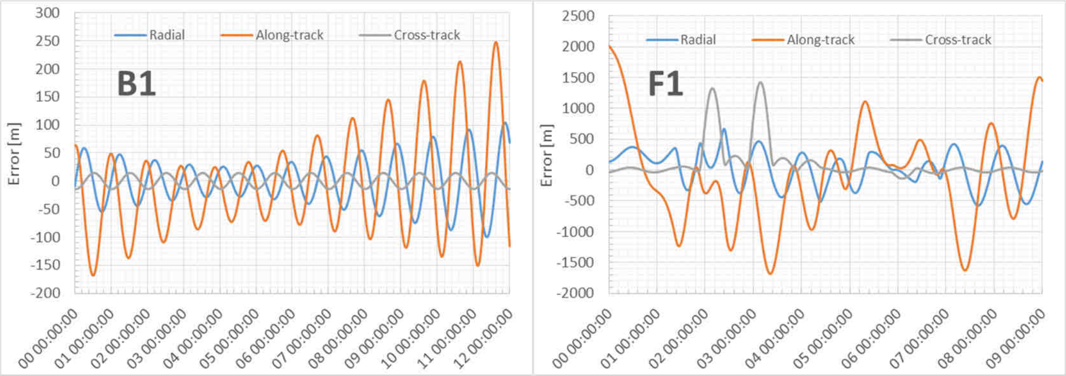

Figure 1: Orbital errors comparison

The previous results allow us to confirm the hypotheses made before, the **orbit determination** performed **only** using **optical** observations is **accurate**, in terms of orbital errors, compared to the orbit determination based on the **fusion** of these optical observations with the ranging data provided by the operators. This is particularly important in the case of **non-collaborative objects**, demonstrating the capability of the GMV / ISON solution to compute **accurate orbits** even for this kind of objects.

2.1 Station / Transponder bias calibration

GEO satellite operators compute their operational orbits based mainly on range observations from one or two ranging stations. These kind of observations are normally affected by biases on the time tagging of the signal, and by unknown delays on the satellite transponder and station receiver. The pointing observations derived from these stations are rough and do not provide useful information for the orbit determination process. Thus it is very important to have well-calibrated ranging stations.

The objective of this subsection is to estimate the errors introduced on the orbit determination caused by the biases mentioned above and to demonstrate the calibration capabilities with the observations coming from the ISON network.

The analysis performed consists in the execution of orbit determinations for the following cases:

a) Using data fusion of range data from ranging stations and pointing observations from telescopes, estimating additionally the range biases for each station.

b) Using only range observations considering the transponder/station bias provided by the operator.

c) Using only range observations considering the estimated bias on the case a).

Case “***a***” corresponds to the best estimation of the orbit with the available data, then orbits from cases “***b***” and “***c***” are both compared against the orbit from case “***a***”. The comparison “c vs a” shows that after proper calibration the along-track error is considerably reduced.

Table 3 contains a summary of the results of these comparisons.

At this point, it shall be remarked that biases provided by the satellite-operator are computed with different algorithms and models than the ones implemented on ***sstod***, then it is not possible to state conclusions about the actual orbital biases of the orbits when doing comparisons “b vs a”. However, some qualitative results can be obtained from the previous table:

- Radial components of the orbit are accurately determined thanks to the range observations.
- Along-track biases introduced due to station biases are roughly 500 m in mean.
- The use of the estimated bias on the orbit determination with only range observations allow to reduce these along-track biases by a factor of 10, given roughly ~ 50 m in average.
- The case of the **F1** satellite shall be carefully treated, as explained on the previous subsections, because it is a satellite with two manoeuvres every day. Then the orbit determination process needs to estimate additionally all the manoeuvres, and as consequence the orbit accuracy is degraded.

Table 3: Range bias calibration

Satellite ID	Provided Range Bias vs Data Fusion (b vs a) RMS Mean [m]			Estimated Range Bias vs Data Fusion (c vs a) RMS Mean [m]		
	Radial	Along-track	Cross-track	Radial	Along-track	Cross-track
A1	0.0	410.2	0.5	0.1	3.6	-0.5
B1	-1.5	-862.6	0.1	1.5	32.9	-0.1
B2*	**-0.1**	**2598.0**	**1.5**	**0.5**	**16.3**	**-2.1**
C2	6.5	-784.0	0.3	-6.6	229.2	-0.5
D2	0.2	583.8	0.6	0.0	31.0	-0.6
D3	-4.3	727.5	0.2	0.0	1.9	-0.3
F1*	**-1.1**	**465.1**	**-28.6**	**1.5**	**9.6**	**29.4**
D1	-5.9	843.9	10.1	-0.1	-7.0	0.7
D4	0.0	590.2	0.2	-0.3	-2.5	-0.3
Mean	-1.1	515.9	-24.4	-2.4	45.2	25.0

Table 4: Accuracy obtained with different combinations of survey telescopes

D2, Telescopes combination	RMS (m)
0292 0509 0536 0963 0964	497
0292 0509 0536 0963	272
0292 0509 0536 0964	911
0292 0509 0963 0964	441
0292 0536 0963 0964	566
0509 0536 0963 0964	511
0292 0509 0536	585
0509 0536 0963	278
0536 0963 0964	219
0509 0536 0964	486
0509 0963 0964	174
0509 0963	186
0292 0963	801
0292 0536	1322
0509 0536	501
0536 0963	232
0509	309
0536	2354
0963	155
0964	5931

D3, Telescopes combination	RMS (m)
0292 0509 0536 0963 0964	97
0292 0509 0536 0963	100
0292 0509 0963 0964	100
0292 0509 0536 0964	102
0292 0509 0536	105
0509 0536 0963	109
0536 0963 0964	147
0509 0536 0964	216
0509 0963 0964	144
0536 0963	111
0509 0963	127
0292 0963	163
0292 0536	812
0509 0536	228
0536 0964	857
0292	634
0509	2128
0536	150
0963	79
0964	800

D4, telescopes combination	RMS (m)
0114 0292 0509 0963 0964	320
0292 0509 0114 0963	362
0292 0509 0963 0964	341
0292 0509 0114 0964	204
0292 0509 0114	208
0509 0114 0963	470
0114 0963 0964	553
0509 0114 0964	206
0509 0963 0964	412
0114 0963	680
0509 0963	474
0292 0963	444
0292 0509	257
0509 0114	290
0509 0964	296
0292	1038
0509	347
0114	N/A
0963	601
0964	7872

2.2 Accuracy in survey activities

This section is intended to show the accuracy achieved only with real survey optical data for orbit determination purposes. To this end, several orbit determination processes have been executed for three of the satellites above varying the number of used survey telescopes. The time interval of the campaigns correspond to around 2 weeks for all three satellites. The resulting orbits are compared against a reference orbit generated from data fusion with all available optical data (tracking+survey) and ranging data from the satellite operator itself.

Table 4 proves shows that as long as **three survey telescopes** observe a given object it is possible to maintain a typical accuracy below 500 metres RMS.

2.3 Orbital bias detection

Another aspect that has been tested during the tracking campaigns is the orbital biases detection. The process is the following:

- Operational orbit of the operator is available.
- Observations-to-orbit correlation of observations from survey telescopes is carried out with ***catmai***
- A full independent orbit determination process is executed with ***sstod*** using the pointing observations from the ISON telescopes network.
- Both orbits can be then compared in order to estimate the bias between them.

Results for satellites whose operational orbits are available are found in the following table:

Table 5: Orbit bias calibration

Predicted Orbital Biases [m]		
Radial	**Along-track**	**Cross-track**
1.4	352.8	-2.8
2.2	238.9	-2.9
-6.6	472.5	-6.6
3.0	221.0	-4.2

As it can be observed, the results are coherent with the previous subsection, an important bias in along-track is shown, around ~300 m in all cases, which is lower than previous one but confirms the conclusions explained before.

3 COLLISION RISK ASSESSMENT

This section is devoted to show the results obtained for the collision risk campaigns with tracking and survey data from the ISON sensor network. Some conjunctions have been detected with ***closeap*** for selected satellites and analysed as part of some of the previously defined tracking campaigns. The analysed conjunctions do not pose any actual risk to the involved satellites, and thus they shall be considered only as functional examples profiting on the data available for each campaign.

The procedure followed on the different campaigns is the following:

- Selected the operational satellite, a conjunction analysis is performed based on external TLEs for the satellite and all potential chasers. From the selected conjunctions it is possible to compute a predicted time of closest approach (TCA) and miss distance.
- Once the conjunction is selected, a tracking campaign for both objects is requested, then the orbit can be determined based on both survey and tracking data. From this orbit determination, orbits are propagated to the future in order to cover the TCA.
- Finally, using the previously propagated orbits based on optical-data, the conjunction analysis is repeated in order to compute a more accurate TCA, miss distance and probability.

The results of the orbit determination for the targets have been analysed on the previous section. The following table contains the orbit determinations results for the selected chasers.

Table 6: Chasers OD Residuals

Chaser ID	Optical		Optical residual	
	Sensors	Obs. #	R. A. RMS [mDeg]	Dec. RMS [mDeg]
03431	3	116	0.335	0.416
20693	7	769	0.300	0.270
02717	2	650	0.219	0.203

As it can be observed, these residuals are similar to the ones obtained for the operational satellites, then it is possible to assume that the resulting orbits are of similar accuracy to those obtained for the operational satellites.

Results for the whole process on three different conjunctions are shown on the following table.

Table 7: Collision Risk Analysis

Chaser Norad Id	Target RMS [m]	Chaser RMS [m]	TLE Prediction TCA	Estimated TCA	TLE Prediction Miss Distance [km]	Estimated Miss Distance [km]
03431	142.0	178.1	20:15:00	20:15:14	50	36.5
20693	181.8	213.4	02:53:33	02:53:31	20	32.6
02717	144.2	133.9	15:58:40	15:58:35	14.5	15.7

Some considerations shall be taken into account about those results:

- Target and Chaser RMS are computed using only the optical measurements retrieved from the ISON telescope network. These RMS correspond to the residuals obtained in the orbit determination process expressed in terms of distance, instead of millidegrees.
- The accuracy of the determined orbit is expected to be better than those RMS, thanks to the great number of observations and sensors used.
- Even if it is not shown in the table, during the determination process the covariance evolution for both objects, target and chaser, is computed allowing us to perform probability computations.

As it can be observed, the precision achieved with the orbit determination has a sigma error less than 250m for all cases, enough to compute accurate collision risks on geostationary orbits.

On the conjunction analysis, predicted TCAs based on optical-only orbits differ in seconds from the predicted TCAs based on TLEs and the miss distances roughly in 10 km, which is in line with the accuracy of TLEs.

4 END OF LIFE OPERATIONS

Eumetsat, the European Organization for Meteorological Satellites, has recently performed deorbiting operations of Meteosat-7, which recently reached its end-of-life. As part of these operations, Eumetsat has identified the need for support from optical telescopes to complement the data from ranging stations. In relation to this, a contract has been awarded to GMV and ISON for the provision of optical data as well for orbit determination and manoeuvre estimation. This section reports on the activities performed as part of that contract from the point of view of the optical data and orbit determination services provided to Eumetsat by GMV and ISON.

As part of these activities, Eumetsat has provided GMV with the following input data:

- **Ranging data** both before and during the deorbiting operations
- **Manoeuvre plan** in order to have a reasonable estimate of the predicted orbit for sensor tasking

The following tasks have been performed as part of these services:

- **Orbit determination** of Meteosat-7 based on optical data from more than 10 ISON survey telescopes before the deorbiting phase.
- **Tracking campaigns** with more than 10 tracking telescopes of the ISON network located in various longitudes and latitudes with visibility of Meteosat-7.
- **Orbit determination** of Meteosat-7 based on optical data from up to 28 ISON telescopes (both survey and tracking)

As part of these services both ***catmai*** and ***sstod*** GMV's software applications have been used for observation correlation (filtering our observations from other satellites) and batch least squares orbit determination (orbit, station bias and manoeuvre estimation) respectively.

During the deorbiting phase the following products have been provided to Eumetsat in a daily basis before 7:30 UTC in all cases:

- **Tracking optical data** (right ascension and declination) transformed to azimuth and elevation and corrected for tropospheric delay from up to 9 telescopes
- **Estimated orbit and manoeuvre** as a result of the orbit determination process including all the ranging data provided by Eumetsat and all the optical data obtained by ISON telescopes (tracking and survey).
- **Report** on the processing performed by GMV including orbit determination statistics.

Additionally, in order to provide pointing information to the ISON tracking telescopes the predicted orbit of the Meteosat-7 satellite has been provided to the ISON network accounting for the manoeuvre plan.

In terms of numbers, the following figures are worth mentioning:

- 18 survey telescopes providing optical data
- 10 tracking telescopes providing optical data
- 10972 measurements (pairs of right ascension and declination) obtained for Meteosat-7 during the deorbiting operations
- 7 manoeuvres estimated within the same orbit determination process plus two pseudo-manoeuvres due to venting activities
- Provision of tracking data and orbital products to the customer only few hours after local dawn.

One of the main conclusions from the end-of-life operations of Meteosat-7 is that the ISON network is a very reliable system thanks to the availability of tens of telescopes. This ensures that regardless of weather conditions optical data is available from several telescopes every night, including both survey and tracking data. This eliminates one of the usual problems encountered when using a telescope network of very few telescopes, where weather conditions may cause that one or several consecutive nights there is not optical data available.

Figure 2 shows a plot of the optical measurement residuals obtained during the deorbiting phase. Residuals in the order of 0.3 millideg are obtained in all cases despite of the presence of two large manoeuvres every day of the deorbiting operations.

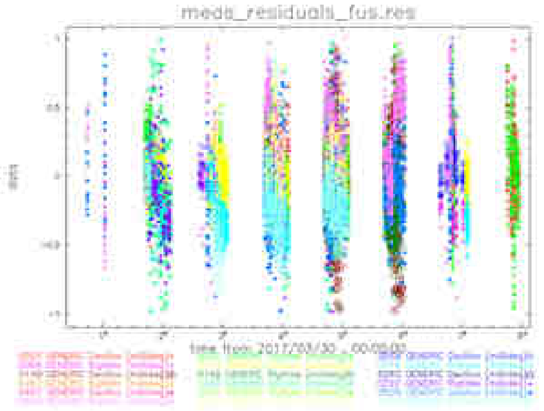

Figure 2: Optical angular data residuals (millideg) from the orbit determination process combining both optical and ranging data

Figure 3 shows an image of the Meteosat-7 satellite obtained during the deorbiting operations by the CrAo observatory, member of the ISON telescope network.

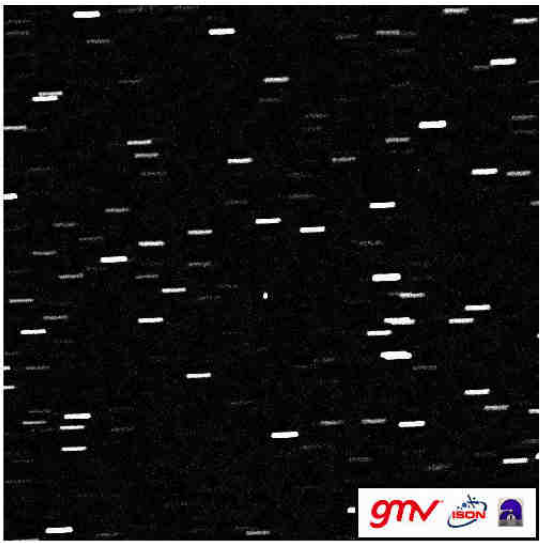

Figure 3: Image of Meteosat-7 taken by CrAo observatory

5 CONCLUSIONS

This paper has presented the results from several optical campaigns executed by GMV and ISON. The use cases covered with these campaigns are:

- Ranging station calibration
- Orbit determination and manoeuvre estimation
- Collision prediction and refinement
- End-of-life operations

The results obtained from these campaigns, both trial and operational ones, show the operational readiness of both the ISON network and GMV SST software suite for the provision of SST services in an operational manner to GEO operators for collision avoidance, ranging station calibration and end-of-life operations.