Optical Observation Campaign in the Framework of the ESA Space Surveillance System Precursor Services

European Space Surveillance Conference
7-9 June 2011

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ABSTRACT

The ESA SSA CO-VI study *Space Surveillance Precursor Services* is evaluating the conditions to implement an operational European Space Surveillance network and is establishing first precursor services. In the framework of this study seven European optical sensors were tasked to provide quasi simultaneous observations of operational GEO and MEO spacecraft. GPS and GLONASS navigation satellites served as calibration targets. The observations were organized in three one-week campaigns in December 2010, January and February 2011.

The paper presents the overall campaign planning including the target selection, the detailed sensor coordination activities during the campaigns, the data reduction and processing, as well as the results. The astrometric accuracy and possible epoch biases of the observations provided by the sensors were estimated by comparing the measurements of the calibration objects with precise ephemerides. Orbits were determined for all target objects using the acquired optical measurements. The lessons learned are discussed and suggestions concerning the further development of an operational European optical space surveillance sensor network are made.

INTRODUCTION

In a future European Space Surveillance System, space around the earth is closely monitored to provide and keep a save environment for operational spacecrafts. For altitudes higher than 20´000 kilometres optical ground based sensors are cost efficient means to survey the near earth space, e.g. the geostationary ring, which is used by many operational spacecrafts due to its unique properties.

In the precursor service phase, existing European facilities shall be organized for a test campaign into a sensor network. Feasibility of space surveillance measurements shall be evaluated. The sensors use different optical systems, parts of them are involved in space debris observations since many years, others were involved in surveillance of near earth objects or gamma ray bursts. None of the sensors had been adjusted to the newly developed requirements for a future SSA system, which will be explained in detail in the next section. The differences of the sensors had to be incorporated and have to be taken into account when judging the results. An observation scenario suitable for an evaluation of the very different sensors within very limited observation time had to be developed.

SENSORS AND PLANNING PHASE

SSA Aims

For a future European SSA sensor network, following requirements have been defined by ESA:

- Availability of the system and staff with a response time within 72 hours after reception for 97% of all requests (SP8.0-05).
- Accuracy of one sigma angular error of below 0.0002degree = 0.7 arcseconds (SP8.0-08).

The first aspect of availability and response time can only insufficiently answered with a prescheduled campaign. All sensors, which delivered data, were able to react within few hours to a decision that observations take place and could adapt without difficulties to a new observation plan. But it has to be taken into account that the general seven day slots of the campaigns were previously assigned and the general observation plan and data delivery procedures were agreed with the sensors beforehand. In the following especially the accuracy of the measurements is evaluated and the feasibility of successful orbit determination.

Participating Sensors of the Precursor Campaign

The precursor campaign consisted of three single observation campaigns in December 2010, January and February 2011, in the new moon phase. In total seven different sensors participated; four of them participated in all three campaigns, two sensors were joined during the second and one joined in the third campaign. The sensors are located in central and southern Europe (Switzerland, France, Spain, Cyprus) and South America (Chile).

Unfortunately one sensor only delivered very few data of fewer nights than scheduled, another one not at all. Both of those sensors were scheduled during all the time of their official participation, and were fully included in the planning. All other sensors delivered their data timely during the day following the observation night.

Every sensor had a different setup, optimized for its intended purpose. Two of the telescopes have a one meter aperture, with 0.7 degrees and 0.4 degrees field of view (FOV), respectively. The other participating sensors are wide-field telescopes: the apertures are 0.5 meter with 4.4 degrees FOV, 0.45 meter with 0.68 degrees, two times 0.25 meters with 1.86 degrees, and 0.15 meters with 4 degrees FOV.

As specific aims of the three different campaigns, the AIUB planning team chose the following additional aims, in order to be able to compare the sensors and to evaluate their accuracy:

- maximize the observation arc with minimum observation time
- parallel observations for best comparability of sensors
- calibration measurements at the beginning and end of each observation night for high precision accuracy evaluation

A minimum of three fully successful nights per campaign and sensor was foreseen within each seven day campaign interval (entire nights required in order to maximize arc lengths).

Planning

Before the observation campaigns, a specific planning and data delivering schedule was agreed with each sensor by EARLY-SPACE. A routine schedule was elaborated in order to ensure a smooth campaign. The expert knowledge on local weather pattern of the sensor operators were taken into account, to be able to react to short term changes to gain as many parallel observations as possible. Simultaneous 1.5-hour intervals, in which all sensors would observe the same targets and gaps of 30 minutes between these intervals were foreseen to facilitate ‘re-synchronisation’ of the stations in case of any delays or problems.

GEO and MEO satellites were chosen as target satellites. The target GEO satellites were chosen under the visibility constraints of the different sensors. The objects, which were chosen, were selected to be well separated in longitude from any neighbour satellites in order to prevent confusions. All Astra spacecraft in clusters were excluded. Moreover, objects were preferred for which it was likely to have operator data available, from ESA, EUMETSAT or SES Astra. In order to provide objects visible by all sensors, in particular being visible from Europe and South America at similar times, a few controlled objects had to be selected were no operator orbit data is available. The GEO objects selected are given in Tab. 1. Some of these objects may sometimes become faint and difficult to observe for the small-aperture sensors due to their small size (MSG 1, MSG 2) and/or large phase angles (e.g. Astra 1F). Also a GEO object in drift orbit (METEOSAT 4) was selected for the third campaign to observe an object with a limited visibility and to simulate a hand-over of such an object between the different sensors.

After consulting with ESA it was decided to observe MEO satellites primarily as calibrators. High-precision orbits for all GPS and GLONASS satellites are publicly available from the International GNSS Service (IGS) or from the Center for Orbit Determination in Europe (CODE) located at the AIUB. The calibration targets were selected for each sensor independently and due to visibility constraints differently each day.

Tab. 1: Selected GEO objects.

Satellite	COSPAR	SSN	Long. [°]	Drift [°/d]	Incl. [°]	Operator/Comment
NSS 5 (INTELSAT 803)	97053A	24957	340.01	-0.02	0.03	-
SKYNET 5C	08030A	33055	342.21	-0.01	0.11	-
EXPRESS 4A	02029A	27441	345.99	-0.02	1.00	-
MSG 2	05049B	28912	0.08	-0.02	0.46	Eumetsat
ASTRA 1D	94070A	23331	1.77	-0.02	2.72	SES Astra
ASTRA 1C	93031A	22653	2.02	0.00	3.61	SES Astra
MSG 1	02040B	27509	9.16	-0.02	0.81	Eumetsat
ARTEMIS	01029A	26863	21.40	-0.01	8.46	ESA
ASTRA 1F	96021A	23842	51.00	0.00	0.05	SES Astra
METEOSAT 4	89020B	19876	14.1 – 54.1	11.4	13.3	Drift object

Tab. 3: Observations per target object.

Sensor	MGS-1	MSG-2	MSG-4	Artemis	Astra 1C	Astra 1D	Astra 1F	Skynet 5	NSS -5	Express A4	Calibra-tion
G	822	686	300	375	445	366	129	369	587	863	582
H	256	494	112	296	158	224		80	112	107	99
I	619	585	26	1078	1484	1173	691	269	423	355	607
J	4648	6887	1513	5509	2958	3173		2203	2034	477	908
K											
L								63	104	64	
M	179	186	116	196	55	99	13	86	75		119

EVALUATION OF THE CAMPAIGNS

Weather

It turned out that the weather constraints were the limiting factor with the most severe impact for the optical observation campaigns. Especially the coordination of quasi-parallel observation in order to maximize the comparability and quality of the orbits of the different observations sites, posed a major challenge. The large spread of sites in central and southern Europe is clearly not enough to escape larger weather pattern. During the first campaign in December, not many observations could be gained at all. More nights were scheduled in the subsequent campaigns. In total, with sensor G observations were gained during 10 nights, but not in all nights observations could be taken during the whole night, so in total an equivalent of the observation time of 8 full nights could be gained. Observations were possible with sensor H in nine full nights. With sensor I observations at 11 nights were taken, but because of weather constraints and a minor technical failure not the full nights could be used, an equivalent of nine full nights could be gained. Sensor J operated during 12 nights and gained an observation time of equivalent of nine full nights. No information on the observation nights of sensor K is available, sensor L delivered data of three nights. Sensor M was operated during 5 nights, half a night was lost because of weather conditions.

Measurements

Tab. 3 shows the number of measurements of the different target satellites in all three observation campaigns and the calibration measurements of the second and the third campaign. During the first campaign, very few observation nights took place and incomplete nights were gained by most of the sensors, resulting in small number of calibration measurements. Those were used to give feedback to the sensors for improvements and are not regarded further here. The number of measurements gained is highly dependent on the sampling rate of the different sensors, rather than on the total observation time. For example sensor J has a sampling rate of three to four seconds, sensor H of 30 seconds to one minute.

Accuracy

The accuracy of the measurements was evaluated. For accuracy estimates precise ephemerides, as provided by the IGS for the GNSS satellites were used. The accuracy of these orbits is of the order of 1-2cm, which corresponds at a distance of 20’000km to 0.0001 – 0.0002 arcseconds. Operator data is of inferior quality. Topocentric ephemerides in the geocentric J2000 equator and equinox system were generated for the actual observation epochs and compared with the observations. The differences (observed minus computed) were evaluated.

In the evaluation of the observations, outliers, which belonged obviously not to the observed objects, have been excluded. Some observations with negative declinations provided by sensor J during the 3rd campaign were excluded. Those observations were wrongly corrected for the annual aberration by the operator. Tab. 4 shows the corrections applied by the AIUB which lead to smaller residuals in all cases. Time corrections had to be applied for observations of all sensors. Those were very small in case of sensor G and up to 100 milliseconds and 4400 milliseconds for sensor J and I, respectively. Sensor L only provided very few observations, no time correction could be estimated there. In the data of sensors J, L and M the annual aberration needed to be applied correctly.

Tab. 4: Corrections applied to observations.

Sensor	G	H	I	J	L	M
camp1	8 ms	80 ms	100 ms	100 ms annual Aberration	- - -	- - -
camp2	8 ms	80 ms	5. Jan: 3650 ms 7. Jan: 4000 ms 8. Jan: 4200 ms 9. Jan: 4350 ms	100 ms annual Aberration	annual Aberration	- - - -
camp3	3 ms	80 ms	-100 ms	50 ms	- - -	50 ms annual Aberration

Fig. 1 shows the residuals (observed minus computed) of the observations of the second campaign with respect to IGS precise ephemerides of sensor J in arcseconds, first without any corrections as provided directly by the operator, with aberration correction only and with additional time correction. Fig. 2 shows the time corrected residuals (observed minus computed) in right ascension and declination in arcseconds of all sensors except L, for which only very few observations are available, which prevent a further evaluation. The root mean square of the residuals of the corrected measurements and the precise ephemerides are shown in Tab. 6.

For sensor I a higher accuracy is not possible because of the optics used, which is perfectly suitable for its prime purpose but prevents of being compliant with SSA requirements. For sensor M improvements are possible and can be aided by using a camera with smaller pixel size. For sensor H only small adjustments would be needed to be compliant with accuracy requirements, e.g. by implementing a high precision star catalogue and using an improved mapping model. Only sensor G and J are below the required threshold of 0.7 arcseconds, sensor J reached this accuracy only with the corrections applied by AIUB of the data provided by the operator. It has to be noted that accuracy even for those two sensors can only be guaranteed if calibration measurements are evaluated on a regular basis.

Tab. 6: Accuracy determined in calibration

	campaign	number of observations	accuracy in arcsec
H	camp2	325	0.26
	camp3	257	0.201
		average	**0.2305**
I	camp2	61	0.959
	camp3	38	0.766
		average	**0.8625**
J	camp2	110	0.55
	camp3	798	0.55
		average	**0.55**
K	camp2	466	4.385
	camp3	141	5.816
		average	**5.1005**
M	camp3	119	**2.92**

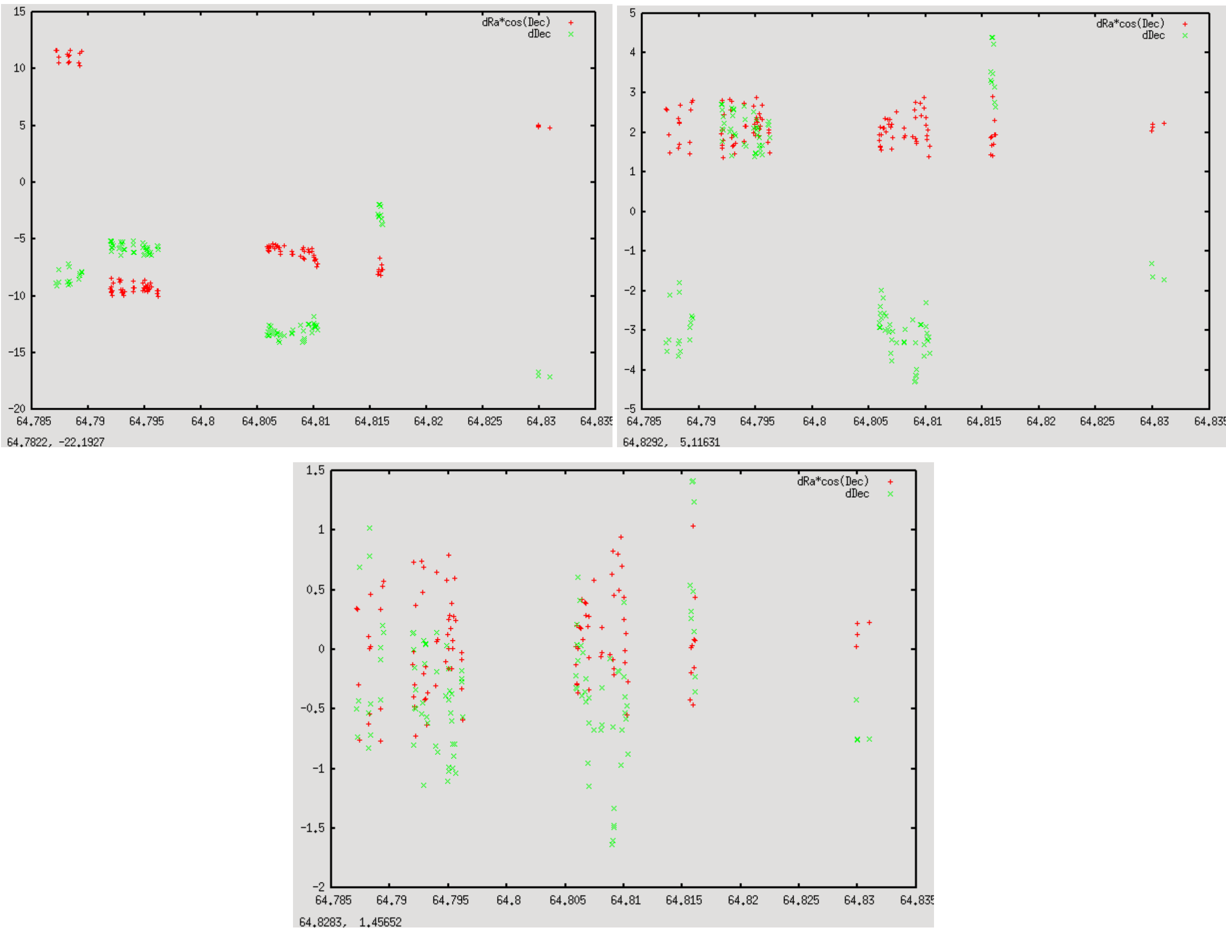

Fig 1: Residuals of calibration measurements (obs. - comp.) of the second campaign of sensor J in right ascension and declination in arcseconds: Without corrections applied (top left), with annual aberration corrected (top right), with corrected annual aberration and corrected time offset (bottom).

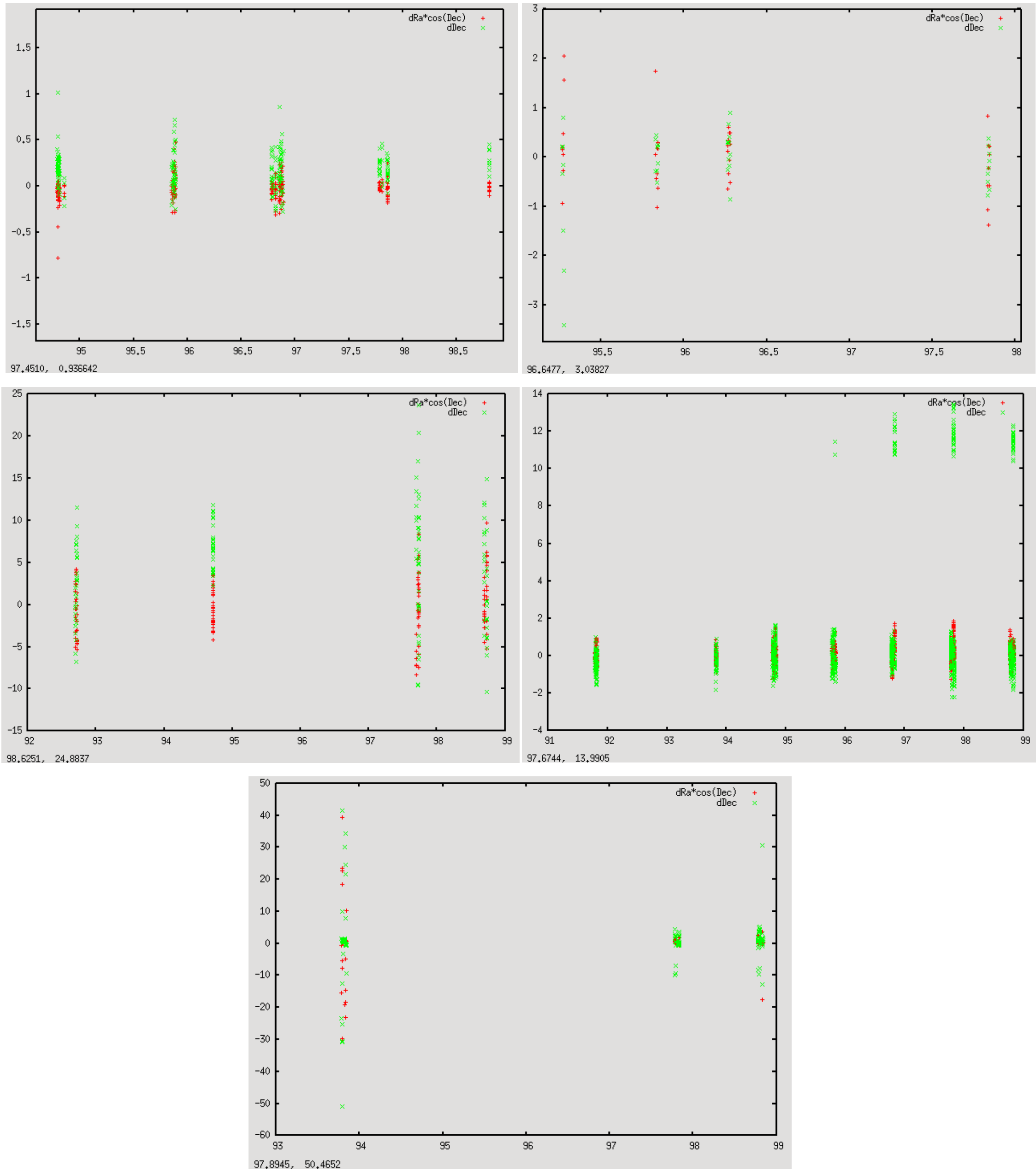

Fig. 2: Residuals (obs. - comp.) in right ascension and declination in arcseconds of sensor G (top left), H (top right), I (middle left), J (middle right), M (bottom) of the third observation campaign.

Orbit

Orbits of all data have been determined with the CelMech tool [1]. Orbits are determined with a least squares approach, including the Earth's potential coefficients up to terms of degree and order 12, perturbations due to the Earth tides, the corrections due to general relativity, and a simple model for the direct radiation pressure (DRP). The results from the calibration measurements were used to add the time offsets and annual aberration determined by the analysis of the calibration measurements also to the observations of the target satellites. Moreover, the overall accuracies determined in the calibration measurements have been used to weight the observations of the different sensors. Otherwise a successful orbit determination of the joint observations would not have been possible. All orbit determinations for each object have been done only for a single campaign with a resulting arc length of 3 days (1^{st} campaign) to 7 days (3^{rd} campaign). Fig. 3 shows the residuals of the orbit determination in right ascension and declination for the object MSG-1 and Express-4A of joint observations of all sensors in the third campaign. The large residuals of Express-4A correspond to the observations of one station only.

The maneuver information provided by the operators of Astra-1C and Astra-1D for the second campaign could be confirmed. The orbit determinations of the joint observations suggests a further maneuver for NSS-5 at January 8^{th}, and

Artemis at 3rd February or February 5th, the data is not finally conclusive, since it is not dense enough. No information from the operator side on Artemis has been provided so far for confirmation; no operator data is available for NSS-5.

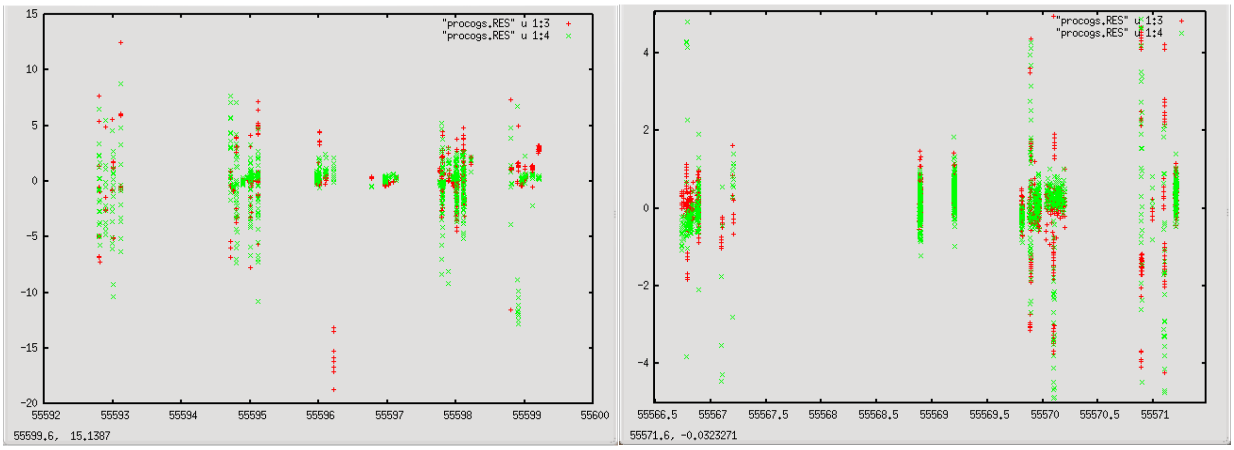

Fig. 3: Residuals (obs.- comp.) in right ascension (red) and declination (green) in arcseconds of object 02040B MSG-1 (left) and 02029A Express-4A (right).

CONCLUSIONS

The joint optical observation campaign within the framework of the Space Surveillance Precursor Services of the European Space Agency can be judged successful. The largest limitation on taking more measurements was imposed by the weather conditions. The spread of the European sensors in central and southern Europe was not enough to escape the general large scale weather patterns.

The different sensors have not been developed and optimized for space surveillance measurements and are in general used for other experiments, their different setups were optimized for their primary use. All sensors could be used for space surveillance measurements but evaluation of observations of calibration targets showed, that the accuracies of almost all sensors need to improve to be compliant with ESA SSA requirements. To ensure the accuracy at the sensors already compliant, regular calibration observations and their evaluation are absolutely necessary. Software enhancements are necessary for the quality control and to improve the accuracy of the other sensors. In one case, a hardware change is necessary to be compliant with accuracy requirements; in one other case hardware changes are recommended. The calibration measurements were necessary to eliminate time offsets and reference system errors.

The accuracies determined via the calibration measurements were used to weight the observations properly when determining orbits from combined observations of all sensors. Only with the different weights successful orbit determination is possible. Manoeuvre times could be confirmed, further manoeuvres are visible in the data, but information is not provided by the operators for eventual confirmation yet.

ACKNOWLEDGEMENTS

The work of this paper was gained under the ESA Contract CO-VI AO/1-6260/09/D/HK.

REFERENCES

[1] G. Beutler. *Methods of Celestial Mechanics*. two volumes. Springer-Verlag, Heidelberg, 2005. ISBN: 3-540-40749-9 and 3-540-40750-1.