RESULTS AND ANALYSIS OF THE ESA SSA RADAR TRACKING CAMPAIGNS

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ABSTRACT

Following the decision at the Ministerial Council 2008 to initiate a Preparatory Programme on Space Situational Awareness (SSA), the European Space Agency started a series of activities together with industry, implementing both classical design approaches: bottom-up and top-down. For the Space Surveillance and Tracking segment of the programme, the bottom-up approach was initially addressed through various activities to evaluate the potential performance of contemporary European resources.

One element of this investigation was the assessment of the existing European assets that can be used to generate tracking data on Earth orbiting objects at all altitudes between LEO and the GEO graveyard orbits. The study addressed both the technical performances of the assets and the identification of the operational constraints characteristic for each sensor. In this context, a paper was presented at the 2011 European Space Surveillance Conference in Madrid, Spain that discussed the results obtained using two existing European radars: EISCAT and Chilbolton. The emphasis of this new paper is to analyse the results obtained from a third asset: the BEM Monge, a measurement and test vessel of the French Navy operated for the French Direction Générale de l'Armement (DGA).

The Monge's three primary radars were designed with the specific mission to detect and characterise the trajectory of missiles as part of France's national missile defence programme, however the radar on-board the Monge are also able to detect and track Earth-orbiting objects. Even though this role is not the primary one for the system, the achieved accuracy of the orbital tracks and resulting orbit determination is several orders of magnitude better than radars that have been developed for other uses. The evaluation carried out in the frame of the SSA programme helped demonstrate that the systems provided by the Monge are able to perform orbital tracking within the performance requirements of a federated SSA system. During the campaigns, the radars on the Monge were used to track several known satellites, pre-selected so as to cover a wide range of altitudes and inclinations in the LEO region. Several separate campaigns were done to track the satellites. Upon receipts of the resulting tracking data, orbit restitution was performed in order to characterise the significance and influence of the distinct observation parameters and to indicate the optimum procedure to improve the orbit estimation performance with a single asset or with a combination of the different assets used within the study. This paper describes the preparation of the campaigns as well as the results obtained. The campaigns were mainly driven by the availability of radar assets and the visibilities of the satellites. The precise orbit determination enabled the comparison of the performance of the different assets.

1 INTRODUCTION

1.1 The ESA SSA programme

The objective of the SSA programme [Ref.2] is to support Europe's independent utilisation of, and access to, space through the provision of timely and accurate information, data and services regarding the space environment, and particularly regarding hazards to infrastructure in orbit and on the ground. In general, these hazards stem from possible collisions between objects in orbit, harmful space weather and potential strikes by natural objects that cross Earth's orbit. The SSA programme will, ultimately, enable Europe to autonomously detect, predict and assess the risk to life and property due to remnant man-made space objects, re-entries, in-orbit explosions and release events, in-orbit collisions, disruption of missions and satellite-based service capabilities, potential impacts of Near Earth Objects, and the effects of space weather phenomena on space- and ground-based infrastructure.

Activities in the initial SSA Preparatory Programme (2009-11) are addressing the consolidation of requirements and the architectural study and design of the complete SSA system. But precursor SSA services will also be established through the use of existing national facilities, when possible. In parallel, essential components of the complete SSA system are being designed, including radars, sensors, networks and data centres.

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The programme is active in the following three main areas:

- Survey and tracking of objects in Earth orbit - comprising active and inactive satellites, discarded launch stages and fragmentation debris that orbit the Earth;
- Monitoring space weather - comprising particles and radiation coming from the Sun that can affect communications, navigation systems and other networks in space and on the ground;
- Watching for near-Earth objects - comprising natural objects that can potentially impact Earth and cause damage and assessing their impact risk and potential mitigation measures.

Under the SSA Preparatory Programme, one of the objectives of the Space Survey and Tracking (SST) element is to provide an independent ability to promptly acquire and catalogue precise information on objects orbiting Earth. Using these data, a wide range of services will be provided by the future European SSA System, such as warning of potential collisions and alerting when and where debris re-enters Earth's atmosphere. These data will be stored in a catalogue and made available to SSA customers across Europe.

The infrastructure required to provide these capabilities is referred to as the '‘SST Segment'. It comprises surveillance and tracking sensors, which could use radar or optical technology, to acquire raw data, which are then processed to correlate (or link) each observed object with the ones already known, or to indicate a new object. Initially, the SST Segment will obtain data using existing sensors. When the full SSA programme begins, additional systems may be developed and deployed as required to achieve the objective of European autonomy in this area. In that context, tracking campaigns have been conducted in the frame of the ESA CO-VI study, on satellites for which accurate orbital information exists, in order to start investigating the possibility to integrate European Sensors and data into the SSA System.

1.2 The tracking radar assets

The campaigns were planned commonly between three different European assets, it is: Eiscat, Cam-Ra/STFC-Chilbolton, and Monge assets. The interest of using these three assets is their very different conception and current use. Since Chilbolton was conceived for meteorology, EISCAT is mainly a scientific radar for the study of the interaction between the Sun and the Earth, and the Monge is a ship dedicated to the tracking of missiles and satellites.

A detailed description of Cam-Ra is given in [3], while a complete description of EISCAT can be found in [4]. A short summary of the characteristics of EISCAT and CamRa assets was given in the introduction of the previous paper [1].

The Monge, named after the 18th century mathematician Gaspard Monge, is a Missile Range Instrumentation Ship of the French Navy dedicated to tracking and measuring rocket trajectories. It was built for the trials of the Submarine-launched ballistic missiles of the Navy, and is also used to monitor the launch of Ariane rockets.

Figure 1-1: View of the Monge ship (source: Marine Nationale – Pascal DAGOIS)

The measurements gathered during these campaigns have been processed in order to assess in particular the accuracy of the data supplied by the different European assets and in the end, their interest for the improvement of orbital parameters (e.g. needed in case of a high collision probability). This information combined with other types related to availability and operational process will contribute to the reflections for the creation of the most suitable Service Licence Agreement (SLA) for the use of European Assets in the SSA system, in the next phases of the program.

2 CAMPAIGN ORGANISATION AND EXECUTION

Because of the several operational constraints of the different assets, it was not possible to realize the measurements with all of them simultaneously, but, they were done during the same periods when feasible.

2.1 The tracked satellites

The observed satellites were chosen in order to have a complete range of altitudes and inclinations. The retained list of observed satellites is the following: PROBA-1, CRYOSAT-2, ENVISAT, JASON-2, METOP-A, GRACE-1 and STARLETTE.

The distribution of these satellites in terms of semi-major axis and inclination is given in Figure 1.

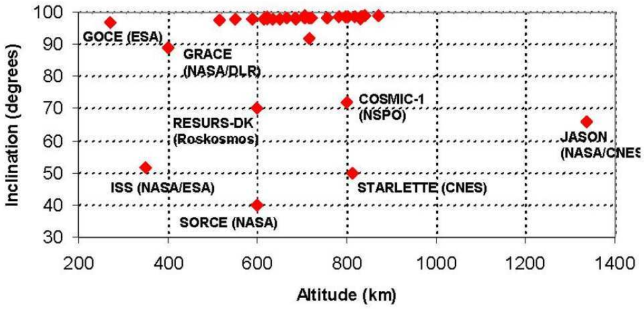

Figure 2-1: Distribution of tracked satellites over an altitude-inclination graph

Due to the commonalty of Monge observations with other on-going campaigns, the list of satellites that were observed by the Monge, was slightly different. It was: SPOT-5, ENVISAT, STARLETTE, EXPLORER-27, STELLA, GRACE, and JASON.

EXPLORER-27 had a specific interest because of being on an eccentric orbit with a low inclination, thus providing different characteristics than other satellites. Nevertheless, its low inclination prevented it from being detected by CAMRa most of the time.

The characteristics of the orbits of all the satellites are summarized on Table 2-1:

Satellite	***Altitude (km)***	***Inclination (deg)***
PROBA-1	615	97.9
CRYOSAT-2	717	92
ENVISAT	782	98.5
JASON-2	1336	66
METOP-A	840	98.8
GRACE-1	400	89
STARLETTE	812	49.8
SPOT-5	830	98.7
EXPLORER27	941/1304	41.18
STELLA	803/812	98.55

Table 2-1: Characteristics of the orbits of the tracked satellites

2.2 The tracking campaigns

The observations were organized in two separate campaigns, one at the end of 2010, and the second one by the spring 2011.

The details of the 2010 campaign are given in [1]. This first campaign used EISCAT and CamRa radars, getting a total of a hundred passes of the selected satellites (Chilbolton observed other additional satellites). The details of the passes are given in Table 2-2.

Satellite	***CAMRa passes***	***EISCAT***
Metop-A	9	8
Envisat	5	7
Proba-1	5	9
Jason-2	4	12
Cryosat-2	7	12
Starlette	15	0
Grace-1	7	0
TOTAL	**52**	**48**

Table 2-2: Synthesis of the acquired passes for the two sensing assets during the first tracking campaign

The second observation campaign was scheduled by April/May 2011. Since the availability of the Monge was more limited than Chilbolton, it was the main factor to fix the dates.

After a few iterations, the observations were planned on the following dates:

- 8th + 11-13th April, 11-13th May: on these dates, both assets, CAMRa and MONGE tracked the satellites
- April 23-25th: these extra dates were added specifically to track the satellites Jason-2 and Grace with Monge. CAMRa did not track any satellites during these two days.

During the realization of the campaigns, the slot of April 24th for GRACE satellite had to be cancelled and a new slot was rescheduled on April 26th.

The passes that were finally acquired during the second tracking campaign are summarized on Table 2-3.

Satellite	***CAMRa passes***	***MONGE***
Spot-5	12	9
Envisat	5	8
Starlette	3	4
Explorer-27	6	4
Stella	7	8
Grace	9	6
Jason	1	6
TOTAL	43	45

Table 2-3: Synthesis of the acquired passes for the two sensing assets during the second tracking campaign

3 CAMPAIGN DATA PROCESSING

Since the operational orbits are accessible, it was possible to process the data in two steps: first, the residuals were computed and the characteristics of the assets, and second, the orbits were restituted using a Kalman filter.

3.1 Computation of the residuals

The results for EISCAT and Chilbolton were detailed on previous paper [1] and as follows there are the residuals for a few passes obtained with the Monge asset.

It is worth noting that the residuals are computed without the correction of ionosphere propagation delay (the effect was of course introduced for orbit restitution), so the signature of ionosphere is expected to be visible (mainly on the low elevation measurements, and depending on the band of the radar).

Only the information on the range has been used for the orbit determination, the information on angular variables is given only in sake of completion.

Envisat residuals

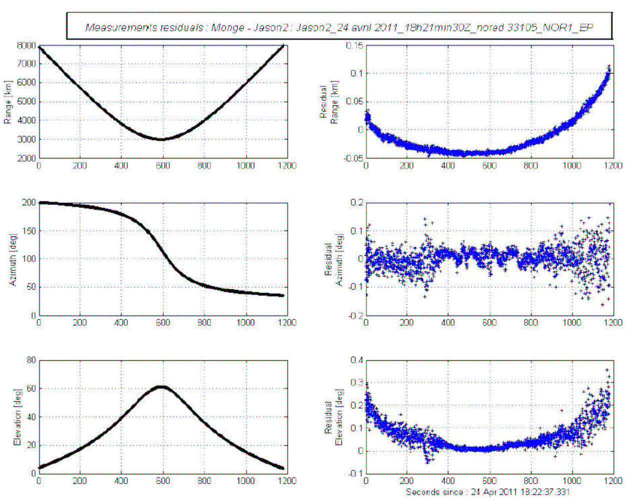

Figure 3-1: Example of measurement residuals for JASON-2 pass taken with a Monge asset the 24th April (range is the way-back distance)

Jason-2 residuals

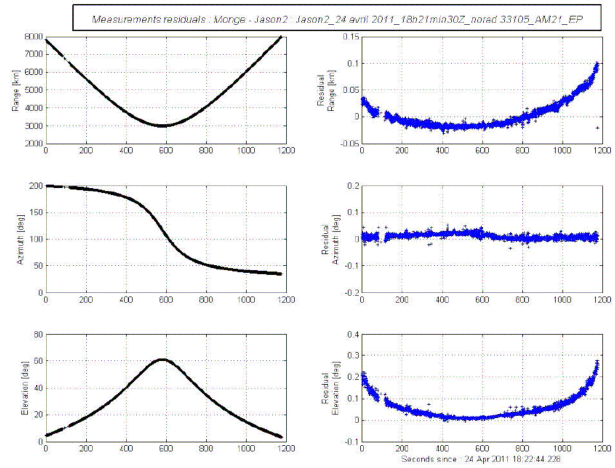

Figure 3-2: Example of measurement residuals for Jason-2 pass taken with Monge asset the 24th of April (range is the way-back distance)

3.2 Orbit Determination

The orbit determination consists in fitting the data into a dynamical model of the orbit in order to minimize the difference between the expected measurements and real. This process requires an extremely detailed description of the environment model and the forces acting on the satellite.

For this study, he orbit determination was realized using commercial software STK/ODTK, which is described, for example, in [6].

ODTK performs the treatment of data in three steps:

- First, a least square methods is used to obtain a good first guest to be introduced on the Kalman filter (the Kalman filter is particularly sensitive to the quality of initial conditions). The initial guest for the least square method is the initial state issued from the available two-line elements.
- Second, a forward Kalman filtering is used to obtain a raw determined orbit.
- Third, a backwards Kalman filtering is used to refine previous orbit and get the final precise orbit.

The dynamical model that have been used is the following:

- Gravity model to the order 70x70
- Solid Earth Tides
- Ocean Tides
- Third body gravity effect

The first step when treating new data consists on characterising the asset using well-known measurements. Thanks to the operational orbits that were provided by satellite operators, it was possible to calibrate the sensors in terms of bias and noise.

Once this task concluded, the orbits were restituted using real measurements. Several parameters of the restitution were tested in order to evaluate its impact. Namely, the following parameters were tested:

- The influence of the gravity field harmonics
- The estimation of the S/m ratio and its variability
- The atmospheric and ionospheric model
- The initial covariance matrix

All these parameters were adjusted in order to obtain optimal results. The whole set of parameters that have to be tuned for optimal orbit determination are listed in Figure 3-3.

	Parameters	Description
Dynamic model	Gravity	Order and level of gravity potential
	Gravitational perturbations	Planets used for potential perturbations
	Air drag	F10.7 file, Mass, cross-sectional area and drag coefficient
	Solar Pressure	Cross-sectional area, pressure coefficient
	Ionospheric & tropospheric delay	Signal frequency
	Albedo & Thermal Radiation Pressure	Cross-sectional area and pressure coefficient
Satellite initial position	Initial orbital position	Satellite initial state vector
Covariance of initial position	Radial_sigma	A priori initial position sigma in radial direction
	Intrack_sigma	A priori initial position sigma in the along track direction
	CrossTrack_sigma	A priori initial position sigma in the across track direction
	Radial_dot_sigma	A priori initial velocity sigma in radial direction
	Intrack_dot_sigma	A priori initial velocity sigma in the along track direction
	CrossTrack_dot_sigma	A priori initial velocity sigma in the across track direction
Covariance of measurements	Bias	Value of the a priori measurement Bias
	BiasSigma	Value of the a priori measurement bias sigma
	BiasHalfLife	Bias decaying by 2 when no measurements
	WhiteNoiseSigma	Value of the a priori sigma of the Bias
	TropoSigma	Value of the a priori sigma of Tropospheric delay

Figure 3-3: Orbit determination parameters

3.3 Results exploitation

Results of Orbit Determination are provided in terms of residuals with respect to measurements and in terms of distance to the reference orbit.

For synthetic results, the distance to reference orbit is provided in RMS (Root Mean Square) of the along-tack, cross-track, radial stand-off vector between reference and determined orbit in 1 minutes time steps over a 24h arc centred in the Orbit Determination epoch.

The definition of the results is visually explained in Figure 3-4.

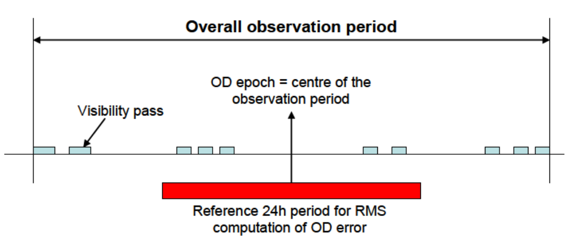

Figure 3-4: Definition of the error that has been used to evaluate the performances of the radars.

Using this definition, the errors obtained with the Monge measurements are the following:

	Along track RMS (m)	Cross track RMS (m)	Radial RMS (m)
Spot-5	210	14	6
Stella	245	34	16
Jason-2	17	72	6
Grace-1	175	11	31
Envisat	100	14	8

Table 3-1: Summary of the precision of the orbits determined using Monge measurements

The orbits were also determined using all the available data, including Chilbolton passes, but due to the difference of accuracy between the measurements of the two radars, no improvement was detected.

4 CONCLUSIONS

This paper presents the scheduling and the execution of the several radar tracking campaign as well as the processing of the obtained data that were performed in the frame of the ESA CO-VI study.
The campaign was defined in order to allow tracking experiments on objects spanning a wide altitude vs inclination window, covering the LEO domain. Beside the assessment of the existing radar means capability to realize tracking campaigns, the important number of passes successfully recovered from the CAMRa, EISCAT and the Monge have permitted to perform a parametric investigation of orbit restitution performance, considering combinations of passes over time, and over the three assets.
The results show heterogeneous performance on the asset considered. CAMRa and EISCAT shows lower accuracy with respect to Monge dedicated asset. However, foreseen improvements should help providing enhanced performances.

Acnowledegment

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