RADAR AND OPTICAL SENSOR DATA FUSION FOR ORBIT DETERMINATION OF HEO OBJECTS

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ABSTRACT

The paper presents the results of a GSTP project led by GMV for ESA/ESOC to define and experimentally analyse orbit determination techniques for the cataloguing of objects in Highly Eccentric Orbits (HEO), such as the Geostationary Transfer Orbits (GTO) and Molniya-type orbits, using a combination, or fusion, of observations acquired by ground-based radars and optical telescopes. An experimental tracking campaign was scheduled and performed to test the evaluated concepts.

Additionally, the needs of a future tracking network in terms of topology and sensors characteristics for the coverage of the population of HEO object were assessed and formulated.

It is shown that acceptable orbit determination results for objects on eccentric orbits can only be expected when a longer arc of the orbit is covered with observations. As a result, the orbit determination of such objects would highly benefit from the combination of observations from optical telescopes and radars.

1 OVERVIEW OF THE STUDY

The study encompasses the following topics:

1. The analysis of the different suitable orbit determination techniques and algorithms for initial and final orbit determination. (§ 2)

2. The analysis of the characteristics of later used sensors for the implementation of tracking campaigns. (§ 3)

3. The selection of exemplary HEO and MEO (for verification) objects, which are suitable for tracking during the planned campaign. (§ 4)

4. The analysis of the observations to assess the quality of the data and the subsequent orbit determination of the objects using both initial and statistical orbit determination. Finally, the comparison of the estimated orbit with external sources (accurate operational orbit and TLE data) was carried out. (§ 5)

5. The analysis of trade-off with the space surveillance and tracking system architecture in terms of observation strategy, network topology and sensor requirements. (§ 6)

2 ORBIT DETERMINATION TECHNIQUES

Orbit determination is one of the key elements of the space surveillance operations. The estimation of the orbital state of the different space objects being tracked and the propagation of its evolution are one of the primary tasks to be performed to maintain a catalogue of space objects and, consequently, provide other space surveillance services such as the analysis and assessment of conjunction events, analysis of orbit decay and prediction of re-entry etc.

Orbit determination accuracy mainly depends on the tracking data accuracy, its density and frequency, on the orbit determination methodologies and propagation methods. The constraints in our particular study are:

- Optical sensors angular accuracy
- Radar sensors range and angular accuracy
- Optical and radar sensors availability and share in order to make the most of the benefits of the two different sensors
- Observation strategy: minimise revisit time, maximise length of passes, obtain passes in diverse regions of the orbits.
- Precise orbit propagation models including solar and lunar perturbation, air drag, solar radiation pressure and geopotential of 15x15 (30x30 recommended)
- Measurements reconstruction patterns including applied corrections such as for tropospheric and ionospheric refraction.
- Robust orbit determination approaches and algorithms. Possibility to estimate the initial state vector near available tracking to avoid propagation errors leading to non-convergence, possibility to estimate the initial state vector near apogee to avoid strong dynamics near perigee that provoke non-convergence, possibility to use long enough

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estimation arcs to a better characterisation of the long orbital period HEO orbits and possibility to set-up proper weighting according to expected/known measurement noise level.

3 ANALYSIS OF SENSORS

Radar and optical systems are both used for space surveillance. Nevertheless, their performance and application area is quite different. On one hand, optical telescopes can observe objects at large distance if the conditions are well suited and the angular velocities are low, but their biggest drawback is that their operation strongly depends on good weather conditions at the observing station and suitable illumination during night-time. On the other hand, radars are able to track objects with bigger angular velocities, they are in principle available round the clock and have no restriction w.r.t. the weather. However, their sensitivity is inversely dependant to the fourth power of the distance; it is not suitable to use radar to track objects at positions higher than lower-MEO region.

The fusion of measurements from optical telescopes and radar is supposed to give highly acceptable orbit determination results since the advantage of both systems can be exploited while the disadvantages can largely be suppressed.

3.1 Optical Telescope: OGS

The instruments requirements for satellite observations are very specific. Then, satellite observations from ground with optical sensors could be done today just by a few instruments in the world.

The Optical Ground Station (OGS) is equipped with a 1-meter optical telescope of 0.7º FOV and it is located in the Teide observatory (Spain) at an altitude of 2395 meters above sea level. Its main characteristics are shown in Tab 1. This sensor is fully qualified to perform the required astrometric measurements from the upper MEO to GEO and the more eccentric orbits. The OGS has already been used for space objects optical surveillance and tracking.

Table 1: Characteristics of OGS

Field of view	42.5' x 42.5'
Accuracy of epoch	<5 ms
Tracking accuracy	Sidereal tracking better than 2"/h and pointing better than 10" anywhere at sky
Typical exposure time	2-7 seconds
Readout duration	7 seconds
Sensitivity	Up to magnitude 21 at 2 seconds of exposure
Spatial Scale	1.44arcs/px at 2x2 binning
Tracking object (low limits)	1/3 MEO orbit interval (>13000 km)
Tracking object (high limits)	Without restrictions
Data output	Astrometric parameters (RA, DEC, Epoch and Magnitude) and orbital parameters

Conditions on the Canary Islands for astronomical observations are very good. Moreover, the altitude of the observatory allows a great amount of clear skies along the year, with 75% of observation time available in good weather.

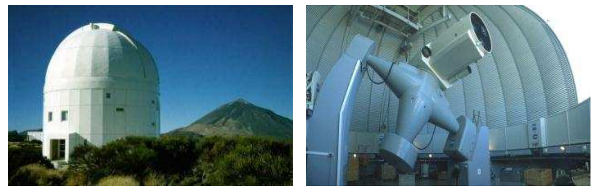

Figure 1: OGS. Teide observatory (left) English mount and 1m telescope (right)

3.2 Radar: TIRA

TIRA is one of the largest and most powerful radar systems for space observation in the world. Since TIRA is a research platform to support the development of radar systems and techniques to detect, track, and analyse space objects, the sensor typically is working non-continuous. Quasi-operational tasks are performed on demand.

Figure 2: TIRA radar system

Fig *2* shows the 34 m parabolic antenna protected by a rigid 49m-diameter radome. This Cassegrain-feed antenna is mounted on a pedestal that allows pointing velocities of 24º/s in azimuth and 6º/s in elevation.

TIRA contains a L-band tracking radar and a Ku-band imaging radar. However, only the L-band subsystem is of interest in this study because it is the one used for the detection and tracking of space objects. The L-band's amplitude monopulse system operates at a centre frequency of 1333 MHz, with 250 kHz bandwidth (utilized), and with a pulse length of up to 2 ms. The TLE supported tracking process is initiated when the object of interest passes the initially fixed radar beam within a predefined range and time window. The tracking direct results are the measurements of range, Doppler, azimuthal and elevation deviation.

4 SELECTION OF OBJECTS

One experimental observation campaign using one telescope (OGS) and one radar (TIRA) is included in the frame of this project. In order to obtain the maximal information of this observation campaign, it is important to elaborate an observation planning taking into account not only the characteristics of the objects to be tracked, but also the limitations and characteristics of the sensors to be used.

HEO (main goal of the project) and MEO objects (for verification) have been chosen by analysing their visibilities from the available sensors and following the next observation strategy:

- Overlapping observation opportunities from the different sensors
- Long observation opportunities
- Good observation conditions
- Spread observation opportunities
- Precise orbits availability to assess the accuracy of the obtained orbit determination.
- Big radar cross sections

Candidate objects were chosen for every population group, and finally the objects tracked were: XMM and Molniya 3-40 in HEO and GPS BIIR-3 in MEO.

5 EXPERIMENTAL TRACKING CAMPAIGN

Taking into consideration all the issues exposed regarding sensors used and objects selected, the campaign plan was scheduled.

5.1 Preparation of observation plan

Due to availability and budgetary issues, the observation planning took place only during June 2011, specifically from 4th to 6th June from OGS and on the 6th June from TIRA. Moreover, available optical observation duration was limited to 2 observation units (OU; 15 minutes each) per object during the 2 first nights and 4 OU during the last OGS observation night, while 4 tracking hours were available for TIRA

Radar tracking are intended to be done, whenever possible, as close as possible to the perigee because it enables to track the object with higher accuracy. Meanwhile, optical observations are intended to be done, whenever possible, far from the perigee in order to avoid high relative angular velocities that makes object tracking from the telescope very difficult, or even impossible.

5.2 Analysis of the obtained measurements

Tracking of the selected objects has been done according to the elaborated schedule and the obtained measurements are shown in Fig. 3 (optical data) and in Fig. *4* (radar data). Both sensors have shown their capabilities to track multiple space objects in parallel. The observation campaign was considered successful.

Optical measurements (right ascension and declination) have been compared to reference orbits (precise orbits for XMM and GPS BIIR-03, and propagated TLE for Molniya 3-40) to find the offsets per pass, at around 4 millidegrees in right ascension and 1 millidegree in declination. Before orbit determination measurements were corrected for that apparent bias. Larger residuals between reference orbits and acquired observations have been found in right ascension in high elevation passes.

Range measurements acquired by TIRA are shown in Fig. *4*. Operating at the cutting edge of sensitivity, one can observe disruptions in some follow-up tracking cases for XMM and GPS. Potential errors have been identified for tracks #4 and #6 of XMM as loss of the track due to tracking perturbations caused by very weak radar echoes. A track distraction was observed in the second part of track #3 of GPS. The reason was another object in the beam moving in close vicinity to the object of interest.

A big offset (around 275km) has been found for XMM. GPS tracking showed no bias and the sigma of these residuals was similar to the one obtained during the XMM contingency campaign [1]. Finally, Molniya tracking showed a bias of ca. 20km.

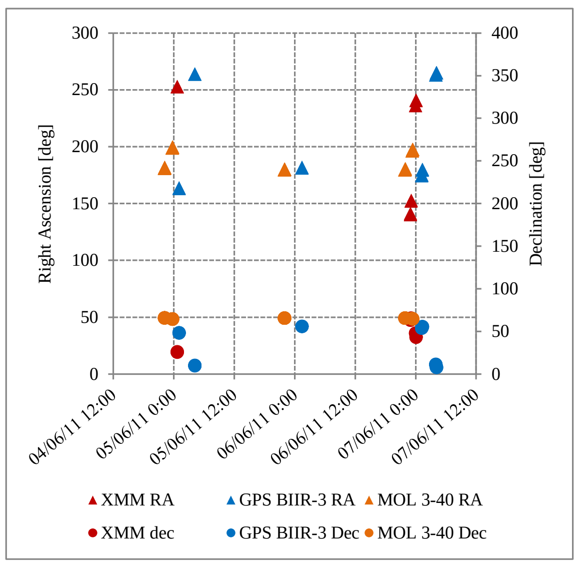

Figure 3: Observed right ascension and declination of the OGS measurements

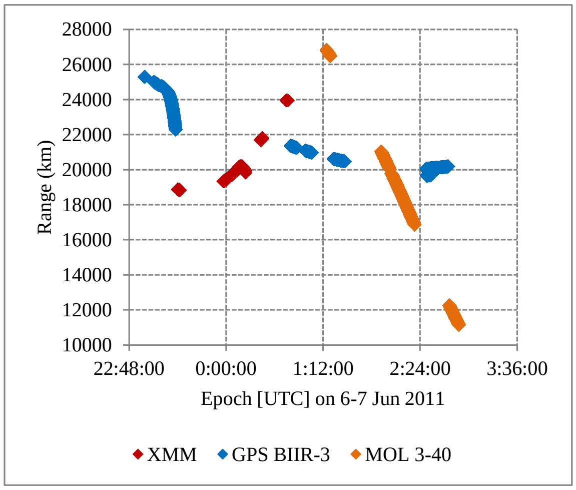

Figure 4: Observed ranges of TIRA measurements

5.3 Initial orbit determination using the obtained measurements

The process of object orbital state initialisation is particularly complex in cases where only angular observations from passive devices are available. GMV had developed PREOD, software that estimates a range from 3 optical tracklet (or 4 depending on the chosen algorithm) using three different algorithms: Gauss, Gooding and Baker-Jacoby [3]. In order to assess the accuracy of the obtained orbit, the estimated ranges are compared to ranges simulated (without noise) from reference orbits. In most of the cases, where the algorithm has reached a solution, these differences are of the order of 100 km. Then, it is considered that these results cannot be used to start the process of precise orbit determination because the big differences between the computed state vectors and those corresponding to the reference orbit, causes that the obtained measurements do not fit at all. This fact must be taken into account in the definition of a sensor network architecture, because some extra tracking after a first detection, which would provide more information for determining the initial orbit, will be needed.

5.4 Final Orbit Determination

Orbit determination has been done with NAPEOS (Navigation Package for Earth Orbiting Satellites) that is a well-known operational ESA software used extensively along Europe for Flight Dynamics and Orbit Determination, specifically NAPEOS-BAHN, a software that determines precise orbits from the observations and a-priori information. It performs a Batch Orbit Determination, all measurements are incorporated simultaneously and a one-shot solution is obtained after an iterative algorithm over the whole dataset is performed by a Least Squares fitting algorithm.

The a-priori orbits used to initialize the process are different in each case; operational orbit provided by the Flight Dynamics Team at ESOC for XMM, TLE propagated orbit for Molniya3-40 and IGS precise orbit for GPS BIIR-3. The reference epoch, in which the state vector is determined, is fixed to be close to the first measurement. The determined orbit is propagated back and forward from the reference epoch during 14 days using a propagation model that contains geopotential (up to 30 degrees), Sun and Moon as third bodies and solar radiation perturbation.

Results of orbit determination obtained for Molniya 3-40 and GPS BIIR-03 are shown next [1]

Right ascension and declination noise sigma are both fixed to 1 millidegree. As these measurements are obtained from differential astrometry, data is not needed to be corrected for parallactic refraction. Weights for radar tracking were set to equivalents of 200 meters in range, 250 millidegrees in azimuth and 90 millidegrees in elevation.

A filtering criterion is also defined in order to eliminate the outliers of the orbit determination procedure. Whereas all the astrometric measurements are considered, not all the radar observations have been taken into account because they may drift considerably from the reference orbit.

As the reference orbit used for Molniya is not a precise one but a propagated TLE, the differences are not only caused by errors in the orbit determination procedure, but also by the nature of the TLE orbit by itself, as it can be seen when results for both objects are compared

Tab. 2 shows the obtained residuals in the orbit determination procedure for the 3 different scenarios taken into consideration (optical-only, radar-only, optical and radar fusion).

Table 2: Residuals from the orbit determination using acquired data separately or together (data fusion). T stands for TIRA and O for OGS. Upper results of each cell correspond to Molniya 3-40 and lower results to GPS BIIR-03

TO	r[m]	a[mdeg]	e[mdeg]	α[mdeg]	δ[mdeg]
X				0.148 0.597	0.145 0.446
X	178.912 280.712	235.943 362.169	84.913 92.729		
XX	188.616 158.001			0.278 0.750	0.269 0.445

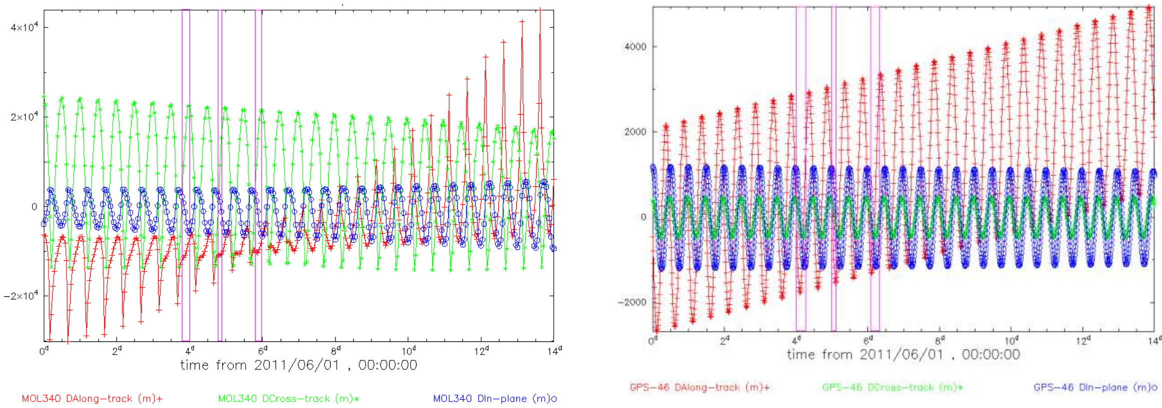

Figure 5: Comparison between determined orbit considering just optical measurements and the reference orbit (TLE) along 14 days. Molniya 3-40 results are on the left and GPS BIIR-03 results on the right.

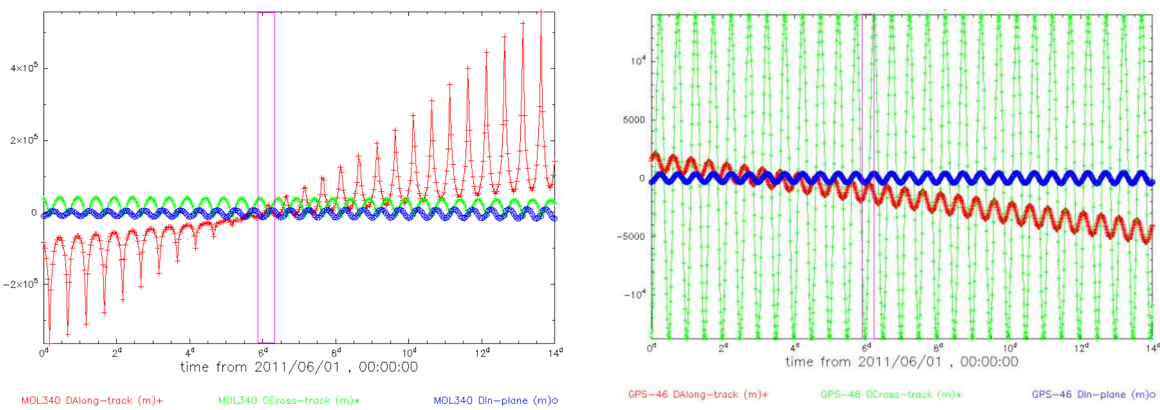

Figure 6: Comparison between determined orbit considering just radar measurements and the reference orbit (TLE) along 14 days. Molniya 3-40 results are on the left and GPS BIIR-03 results on the right.

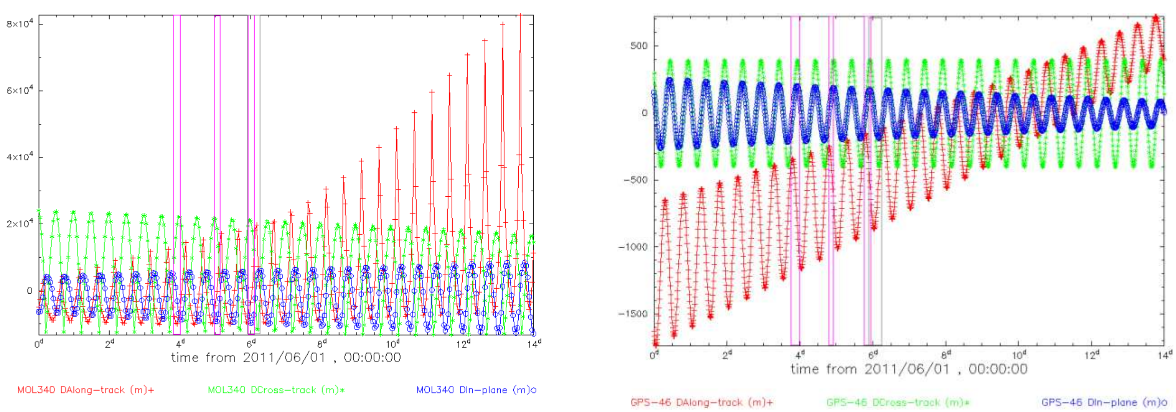

Figure 7: Comparison between determined orbit considering both optical and radar measurements and the reference orbit (TLE) along 14 days. Molniya 3-40 results are on the left and GPS BIIR-03 results on the right.

The determined orbits (propagated back and forward from the reference epoch during 14 days) have been compared to the reference one; differences are shown in Fig. 5 to Fig. 7 where the time intervals of the observation campaigns are highlighted as pink boxes.

Although measurements are from different nature, the comparison between the two first figures shows that it is possible to conclude not only that the number of measurements is important (number of radar measurements is significantly bigger than optical ones) but also the frequency of these observations (optical measurements were acquired during 3 consecutive night whereas radar tracking was performed during 4 hours).

Optical observations usually give good information about cross-track, whereas radar tracking, mainly ranging, gives reliable information in the in-plane component. It is possible to see that Fig. 7 (both optical and radar tracking) has the same behaviour than Fig. 5 (only optical observations) but improving the in-plane component due to the information added by the radar measurements.

It should be mentioned that considering the nature of observations (real, not simulated), and that they have not been pre-filtered before being inserted in NAPEOS-BAHN, it can be conclude that the NAPEOS-BAHN software is robust enough to determine orbits from radar observation that represents a real-wold scenario. Furthermore, taking the comparison figures as reference, it could be stated that NAPEOS-BAHN does not only determines an orbit but this orbit is accurate enough around the epoch when the observations were taken. The accuracy of the obtained orbits mainly depends on the observation strategy followed. The growing differences along time could be caused by the used propagation model in the process or even by the propagation model of the TLEs that have been taken as reference orbits.

6 SSA ARCHITECTURE

6.1 Observation concepts for catalogue build-up and maintenance for HEO

There are two key parameters to design space surveillance architecture: the percentage of objects tracked for cataloguing purposes and the accuracy of the orbits of these objects. The requirements on the orbit determination performances are specified by ESA in a SRD document [4]. However, as HEO population should not be the driver for the design of the requirements, because they are a minority population, there is currently no special accuracy requirement for a transient population passing through GEO, MEO, or LEO. We assumed a general population requirements derived for LEO objects, which shall be catalogued with an accuracy of 200meters (TBC) and 2km (TBC) for MEO/GEO objects after 48 hours of the object detection.

The simulated scenarios consider a worldwide network of telescopes, corresponding to the currently considered baseline for the future European SSA system, and a radar that could be located in a European site as Fig. 8 shows.

An analysis of the accuracy achieved in the orbit determination after one observation pass is performed. The aim of this analysis is to assess whether the satellite will be reacquired again during the next observation opportunity taking into consideration the field of view of telescopes. Furthermore, once the object is detected more observations/tracking are needed to have more information available in order to determinate a more precise orbit that will make the catalogue maintenance possible.

Figure 8: Radar in blue and telescope network in red. From left to right: Marquises Islands, Tenerife, radar, Cyprus and New Norcia (Perth)

If the object is detected by a telescope, a minimum a 15-minute pass is required to reacquire the object again (assure to find the object inside the FOV of the telescope during the next observation opportunity). Taking in mind the proposed GEO survey strategies [5], where the FOV changes every 15 seconds, the detected object must be tracked from a telescope located in the same site within 15 minute immediately after the object is detected.

In terms of catalogue maintenance, if the object is observed just with telescopes during their apogees it is possible to fulfil the accuracy requirements provided by the SRD, but only in the apogee regions (GEO/MEO criteria). However, the fact of adding just one radar tracking in the perigee (or close to this orbit region) contributes significantly to the accuracy of the determined orbit, making the catalogue maintenance during the whole orbit possible in some of the simulated scenarios.

6.2 Required characteristics of optical sensors for HEO observation

The main limitations to follow up the objects of the reference population are the FOV and the maximum tracking speed of the telescope. The instrument should be equipped with a great FOV which enable detection of 3 consecutive images in the same inertial space, including the time required to do two readings of the CCD and also two establishments to the original position. Considering the FOV dimensions of the proposed optical sensors (2.5º) and the interval of time to get a triple detection (15 s per picture), the maximum angular velocity that it can be admitted would be around 300’’/s. Unfortunately, a large distribution of objects would be limited by FOV since the objects exceed 300’’/s near its perigee, leaving aside illumination constraints.

On the other hand, the instrument should be equipped with a mount capable of offering accurate tracking of the inertial space with an error less than 0.5 pixels within the maximum time of exposure and with the sensor moving between 0 and 60”/s. Considering this limitation in the design of the sensor, we can establish 75”/s as the maximum relative velocity of the instrument (sky moves to 15”/s due to the Earth rotation). This speed can be considered like the limitation to track the objects of the reference population.

The sensor requirements are enough to detect an object around 20th magnitude during the nights with the best observation´s conditions, and around 17th magnitude in worst conditions, considering the maximum time of exposure in both cases (2 seconds). However, if this magnitude is sufficiently bright, the exposure time would be reduced

6.3 Required characteristics of radar sensors for HEO observation

In principle, radar can be used to detect and track all relevant objects on eccentric orbits with an accuracy required by the customer. However, this demands to the set-up of an adequate radar sensor with well-defined characteristics.

Depending on environmental restrictions one may not be able to increase the energy transmitted within a single-pulse without limits. Moreover international regulations lead to a set of radar bands which may be used for the foreseen purpose, only.

The application of highly elaborated pulse processing techniques is for most of the systems in operation the only way to sail round the above mentioned constraints without a need for major hardware modifications. However, existing systems may also be optimized and upgraded with regard to HEO observations. New systems shall carefully be placed to take both, regional advantages and restrictions into account.

In consequence one has to state that one is not able to derive optimal sensor characteristics without prior knowledge of the sensor(s) location and restrictions to be considered in that place.

Although there are open issues regarding the radar design in terms of operational demands, it is concluded that the tracking radar should be used as a follow-up system with initial pointing information coming from an optical site.

6.4 SSA Architecture performance simulations

The reference population chosen for this study consist on the objects of the US SSN catalogue (epoch 14/10/2011 a.m.) whose eccentricity was larger than 0.5. The 1285 remaining objects (out of initially 14680) comprise mainly Molniya, GTO and scientific objects.

The baseline telescope architecture is composed by 4 identical 2.5ºx2.5ºFOV telescopes per site shown in Fig. 8. The survey strategy used in these simulations is the one proposed in the PDAOSSS [5], which was developed for GEO objects; HEO objects will be observed as a by-product of these surveillance tasks. Moreover, these simulations have been done without considering weather restriction or any other possible unavailability.

The proposed architecture also contains a surveillance radar that is developed for LEO region as proposed in [6]. The maximum detection range has been considered to be 2000km. Location for this radar has not yet been defined, then for this analysis it has been considered to be located in Spain.

So as to consider that an object is detected, inclusion in the catalogue, one minimum pass of 15 seconds (duration fixed by the GEO surveillance strategy) and a maximum revisit time of 1 day are necessary. Moreover, in order to maintain the object in the catalogue, another extra pass of 15 seconds with a maximum revisit time of 48 hours is required. Nevertheless, these are simple assumptions because the tracking required immediately after detection is not considered and every observable object can be tracked and enters the catalogue instantly, so the obtained results are quite optimistic.

As Fig. 9 shows, using the PDAOSSS network configuration and survey strategy developed for GEO population (O_S), it is possible to detect 2/3 of the HEO reference population as a by-product of surveillance tasks after 4 observation weeks. When the LEO surveillance radar is added to the simulation (OR_S), the percentage of detected HEO objects grows up to 75%.

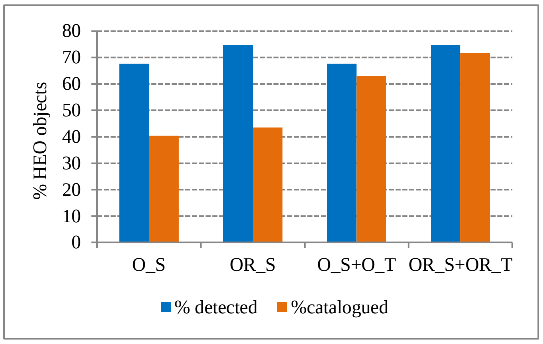

Figure 9: HEO objects cataloguing performances using different scenarios. O_S stands for optical surveillance, OR_S stands for optical and radar surveillance, O_S+O_T stands for optical surveillance and tracking and OR_S+OR_T stands for optical and radar surveillance and tracking

A dedicated HEO surveillance strategy should be developed in order to close the surveillance gap found in these scenarios (more than 20% of objects are not detected during one month). Moreover, the fact that the HEO objects are detected as by-product of other population surveillance strategies could entail data processing problems.

Now, one tracking sensor to each site is added to the scenario in order to improve the cataloguing maintenance performances. These survey and tracking scenarios achieve cataloguing performances higher than 90% of the detected objects. However, a tracking radar located in Spain does not give notable benefits to the catalogue maintenance. Nevertheless, the addition of tracking radars provides accuracy enhancements in the whole orbit and mainly in the perigee area, region where collision probability is higher due to the large LEO population. Taking in mind that most of the eccentric orbit perigees take place in the southern hemisphere, radars should be located in this region.

These scenarios, that consider only HEO population, are already very demanding in terms of telescopes loads. Moreover, real-world system will face additional obstacles, such as considering the rest of objects population or weather outage, prioritized tasks, scheduling, etc, Taking all this into consideration, it is possible to conclude that more tracking sensors are required.

7 CONCLUSIONS

The presented study started with a preliminary theoretical study regarding issues such as orbit determination techniques and characteristics of existing sensors suitable to observe HEO objects. Gathering all these information, an limited experimental observation campaign has been performed. The aim of this campaign was not only to prove the evaluated concepts, but also to extract conclusions that have enabled the derivation of the main characteristics/requirements that the SSA architecture may fulfil in order to cover HEO population.

Taking into consideration the objectives and the resources of the experimental observation campaign, it can be considered successful as data for the 3 selected objects was obtained from the OGS telescope and the TIRA, both observing in parallel. Moreover, the quality of this data was good enough to determine the orbits using NAPEOS-BAHN, software that has been proven to be suitable for this concept.

Optical detection requires an immediate tracking in order to assure the object's reacquisition at least during the next apogee. Tracking by radar or optical means as follow-up after optical detection seems to be one of the most suitable approaches to enhance the detection of HEO objects.

Taking optical observations during apogees make possible to fulfil the accuracy requirements for catalogue maintenance provided by the SSA SRD, but only in the apogee region. However, adding one radar tracking in the perigee contributes significantly to the accuracy of the determined orbit, making the catalogue maintenance during the whole orbit possible.

Detecting HEO as by-products of other population surveys (e.g. GEO) doesn't only cause surveillance gaps in HEO population, but also could entail data processing problems. Consequently, comprehensive surveillance strategies for eccentric orbits are needed. Space-based surveillance strategies could be one possible approach.

It is not possible to catalogue all the detected objects by using only one single tracking telescope per site. Moreover, high telescope loads result from the simulation. Therefore, additional tracking telescopes are needed in each site.

This study demonstrates that fusion of optical and radar data enhances the accuracy of the determined orbit for HEO objects. Then, it is important to take advantage of this benefit for a SSA architecture concept.

8 REFERENCES

[1] L. Aivar, A. Águeda, J. Fernández, A. de Andrés, T. Flohrer, G. Bartsch, D.Abreu, J.Utzmann. SSA Radar and Optical Sensor Data Fusion for Orbit Determination of GTO and GEO objects: Final Report. December 2011.

[2] T. Flohrer, H. Krag, H. Klinkrad, J. Kuusela, L. Leushacke, T. Schildknect & M. Ploner. Orbit determination form combined radar and optical tracks during XMM contingency operations. 5th European Conference on Space Debris, Darmstadt, Germany, 30 March – 2 April 2009

[3] F. Martinez, A. Águeda, J. Jorquera, J. Fernández, L. Aivar, "Comparison of Angles Only Initial Orbit Determination Algorithms For Space Debris Cataloguing", Paper presented at the 22nd International Symposium on Space Flight Dynamics (ISSFD 2011), Sao Jose dos Campos, Brazil, 28 February – 4 March 2011.

[4] Space Situational Awareness – Space Surveillance and Tracking System Requirements Document (SSA-SST-RS-SRD-0001, August 2011)

[5] N.Sánchez-Ortiz, E.Olmedo, N.Guijarro, F.Jiménez and P.Keinänen. PDAOSSS Optical Segment of SSN Requirements Document.29 October 2010.

[6] H.Krag, T.Flohrer, K.Merz, B.Bastida Virgili, H.Klinkrad. Requirements for a LEO surveillance radar in response to collision avoidance user needs. European Space Surveillance. Workshop 211.