STUDY OF AN INNOVATIVE SYSTEM FOR DEBRIS SURVEILLANCE IN LEO REGIME

Jaime Fernández[1], Alberto Águeda[1], James Dick[2], Claude Jamar[3], Paul Jorden[4], Pier Mario Besso [5] , Gian Maria Pinna[6]

[1] *GMV, Isaac Newton 11, 28760 Tres Cantos, Spain*
jfernandez@gmv.com, aagueda@gmv.com
[2] *Space Insight Ltd, PO BOX 2993, Eastbourne, BN21 9BD, United Kingdom*
info@spaceinsight.co.uk
[3] *AMOS, LIEGE science park, Rue des Chasseurs Ardennais, B-4031 Angleur (Liège) - Belgium*
c.jamar@amos.be
[4] *e2v, 106 Waterhouse Lane, Chelmsford, CM1 2QU, United Kingdom*
paul.jorden@e2v.com
[5] *ESA/ESOC, Robert-Bosch-Strasse, 5, 64293, Darmstadt, Germany*
pier.mario.besso@esa.int
[6] *ESA/ESAC, Camino bajo del Castillo, s/n, Villanueva de la Cañada, E-28692 Madrid, Spain*
gianmaria.pinna@esa.int

INTRODUCTION

Typically, debris in LEO (200 to 2000 km altitude) has been surveyed using radars. ESA is preparing a Space Surveillance Awareness (SSA) system that contains both optical telescopes and radars. In the surveillance of space the roles of these two sensor types are well established: optical telescopes are used for the higher Earth orbits; radars are used for the low Earth orbits. This division of labour, between optical and radar sensors, is optimal for their different characteristics: high-orbit slow-moving sunlit objects are easy targets for optical sensors but are difficult for radars because the signal budget prescribes expensive high power designs; low-orbit objects are often in shadow or overpass in daylight and so are unobservable by optical systems but are easier targets for radars. For LEO especially, phased-array radars have a short-range signal budget which can be met at lower cost.

Given the significant cost of high-power cm-wavelength radars there is a clear need to establish at what orbital height the radar/optics transition zone can be set. The lower the transition zone, the less costly will be the radar system; the higher the transition zone, the less costly will be the optics.

This paper presents an innovative system to survey LEO by optical sensors. Developed by GMV, Space Insight, AMOS, and e2v, under contract to ESA, the study addresses the optical visibility constraints for LEOs, suitable survey strategies, and analyses the cataloguing capability and capacity of the system. A preliminary design of appropriate telescope systems is presented which meets the dual challenges of the requirements for a large field of view and the high astrometric accuracy needed by the cataloguing process.

THE REQUIREMENT

ESA's requirement for the SSA sensor system is focussed on the ability to provide conjunction prediction services. Critical to those services are the timeliness, completeness, and temporal continuity of the orbit catalogue on which they are based. The detection size requirement was specified by ESA as a result of a probabilistic analysis and the size vs. height relationship is shown in Fig. 1. The timeliness criterion was set by the need to maintain a current orbit to an accuracy of 30 m along-track, 4 m out-of-plane, and 20 m radial.

To meet ESA's requirement the consortium divided the problem into five stages:

i) to meet the detection size limit, what sensor attributes (like aperture) are needed?
ii) for orbit coverage (but mindful of ambient conditions), where do sensor groups need to be located?
iii) driven by catalogue maintenance needs, what is the topology of the network of sensor groups?
iv) given the sensor, site, and network specification, what is the catalogue maintenance performance?
v) based on the sensor attributes (and mindful of costs), what specific optical system and focal plane detector is needed?

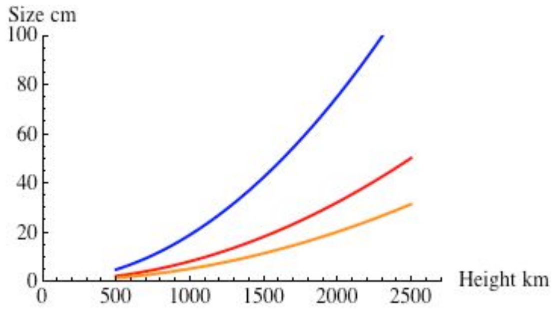

Fig. 1 ESA detection size vs. height specification (based on a specific size at 2000km); blue line: 75 cm, red line: 32 cm, orange line: 20cm (goal for a future upgraded sensor).

SENSOR ATTRIBUTES

The principal sensor attributes are aperture, focal ratio, field of view, exposure time, sky and detector noise characteristics, and image cycle interval. For LEO objects, which have angular velocities (up to $2^{o}\ s^{-1}$), the time that an object spends in a pixel has a significant effect in the signal-to-noise ratio (SNR) equation; signal from the object is only present while its point-like image is on a pixel (the pixel dwell time) – after that, further exposure merely injects sky and detector thermal noise into the pixel.

The process of choosing the principal sensor attributes, therefore, is one of optimisation. Given likely values for the sky noise (taking into account the bright night sky seen around full Moon) and detector noise, and given the expected signal from an object (taking into account range, albedo, and illumination phase angle), what aperture and pixel angular size (equivalent to consideration of the focal ratio) will result in a detection (SNR≥3)?

Sensor pointing is also important because the proximity to the sensor of an object's ground trace sets the zenith distance at which the object may be detected. Because the Earth shadow height is a dynamic function of geographic location, time of night, and calendar date, sensors must be able to point at almost any location of the sky. Although being able to relocate any sensor's field of view to a new sky position is important, the use of open-loop tracking was discounted because it injects biases into surveys: objects moving in the opposite direction to the tracking are disadvantaged in SNR and thus detection probability.

Various trade-offs have to be made. Large pixels give long dwell times but collect more sky noise; wider bandwidth increases the SNR but has implications for the optical design and detector chemistry; sensors pointing at higher zenith distances have better orbit coverage and in-pixel dwell time but lose signal owing to range and phase angle issues.

A 75 cm aperture, 7.5 arcsec $pixel^{-1}$ optical design was identified as having the required sensitivity to meet the detection size criterion above an orbital height of ~1200 km.

SENSOR SITE CONFIGURATION AND LOCATION

For visible-wavelength sensors, objects in space are detectable most easily when they are sunlit and visible against a dark and cloudless sky. Sites have to be chosen pragmatically to meet these needs, to be realisable, and to meet the orbit coverage requirement. For example, equatorial sites have long periods each night when the Earth shadow height is too high for LEO coverage; sites further than ~45º from the equator have long periods during their summer when there is little or no observing time (because the zenith distance of the Sun is never large enough to give a dark sky) and, furthermore, cannot see low-inclination low-altitude orbits.

At each site, several sensors are deployed to form a fence which covers an arc 150º in azimuth and 5º in elevation. The centre of the arc is maintained at the same azimuth as the Sun to provide symmetric coverage of the optimal (that is, lowest) shadow height zone. As objects rise through the fence, a further set of narrow field of view sensors is used to track those objects while they are still visible, to provide more observations for orbit determination. The sensor coverage fence and the tracking sensors' narrow beams are shown schematically in Fig. 2. An example of two co-added fence images, with a LEO object in transit, is shown in Fig. 3.

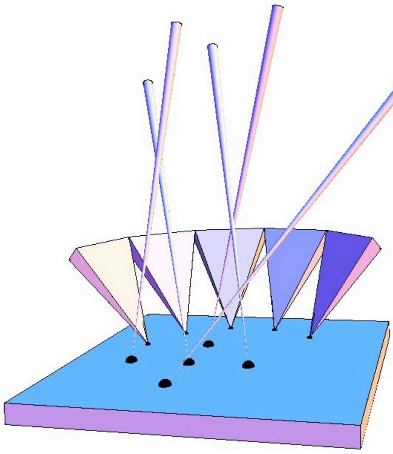

Fig. 2 Schematic sensor coverage for fence and tracking sensors

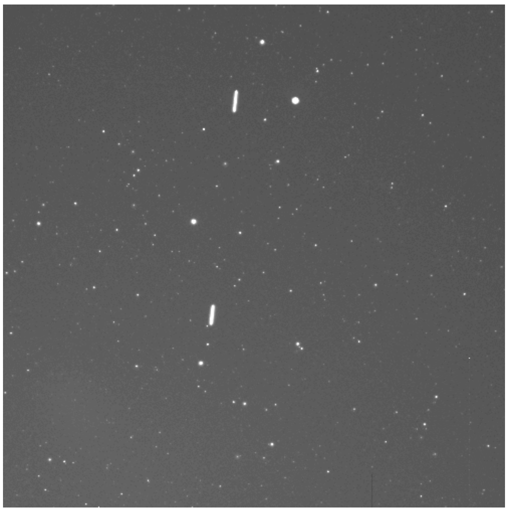

Fig. 3 Two co-added sidereally-tracked images from one of Space Insight's Starbrook sensors provide a visualisation of two fence-crossing detections by a LEO object

From a weather perspective, the tropics are the preferred zones for cloudless skies (as indicated by the World's deserts) although many other (mostly mountainous) locations might be suitable, subject to site testing. Additionally, ESA expressed a preference for use of existing ESA sites (such as tracking/telemetry facilities) and sites administered by ESA member states.

SENSOR NETWORK TOPOLOGY

The network topology has implications for object detection, orbit accuracy, and catalogue maintenance. The seasonal change in the configuration of Earth shadow height is exploited better by a network which has both northern and southern hemisphere sites. For orbit accuracy and catalogue maintenance, multiple sites are necessary so that objects can be observed on a number of consecutive orbits – a mode of operation which is particularly important for semi-major axis determination. To enable consecutive orbit detection, the network needs to be located to exploit the orbit-to-orbit change in ground-track longitude.

Fig. 4 shows one possible network of sites which is compliant with ESA's site administration requirement as well as providing consecutive-orbit cover. This particular network also uses sites which are likely to have good weather and are in both northern and southern hemispheres.

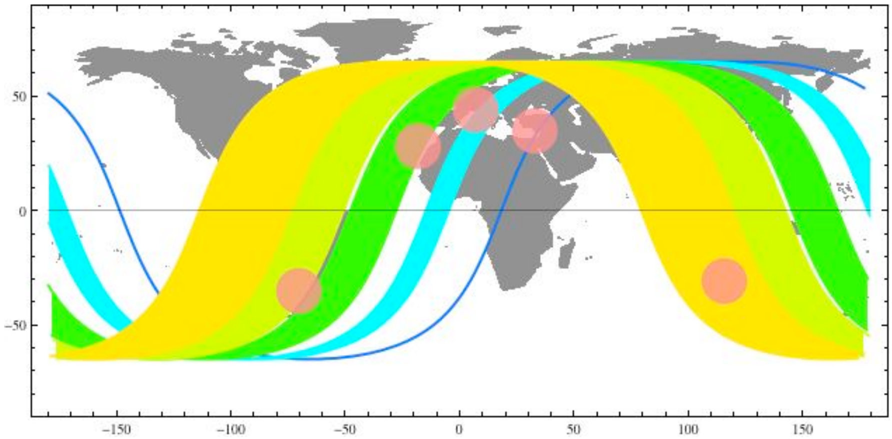

Fig. 4 Illustration of five sites (red disks) covering successive orbits (blue, cyan, green, yellow, orange).

CATALOGUING PERFORMANCE

The performance of the sensor network in terms of its ability to deliver orbits of the required accuracy and to maintain a catalogue of objects was analysed. Using the ESA POP3 catalogue, simulations were carried out to determine frequency of observation, typical pass duration, maximum detection gap duration, and (given the expected number and time of detections) the orbit accuracy which could be achieved. The simulations took account of the sky conditions (earth shadow height, Moon interference, night length, phase angle, weather); simulation results were grouped into four orbital height ranges (800–1000, 1000–1200, 1200–1500, and 1500–2000 km) with results sub-grouped by season (winter, summer, and equinox) and by orbital inclination.

Fig. 5 shows the simulation results for the 1200–1500 km height band, for a seven-site network. The fraction of the population which cannot be maintained in a catalogue is in green; the fraction which can be successfully maintained is in red (without cloud) and blue (with weather taken into account). Catalogue maintenance becomes problematic for lower orbits (especially below 1200 km) and for Sun-synchronous orbit objects (especially near the equinoxes). Introducing more sites reduces the uncatalogued fraction but at considerable incremental cost.

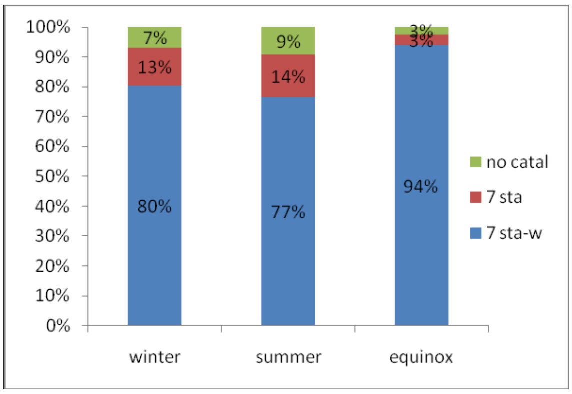

Fig. 5 Population fraction able to be maintained in a catalogue, 1200–1500 km height band.

For each site, the operational concept is that an object is detected as its transits the fence and has a preliminary orbit calculated. For ascending transits, the preliminary orbit is used as input to the tracking sensors which then follow the object until it enters Earth shadow. The typical duration of a pass is important to determine as this limits the arc over which the orbit determination can be made; a modal pass duration is ~30 s.

The observations (including measurement position noise) from the fence transit and the subsequent tracking phase were fed into the orbit determination phase of the simulation. The effect of solar activity on the orbit accuracy was also considered. For 8-day arcs the accuracy requirement is met providing the revisit time on the object is no more than

24 hr (Fig. 6). The ability to detect manoeuvres and fragmentation events was confirmed, with a detection timescale of two revisits after the event.

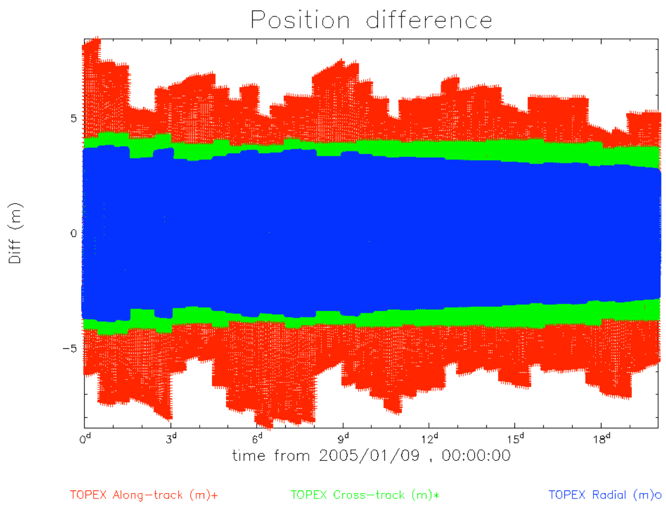

Fig. 6 Example orbit error analysis; long-track (red), cross-track (green), and radial (blue)

SENSOR DESIGN

The large-aperture wide-field requirements of the design (derived from consideration of the signal budget) are demanding for both the optics and the focal surface detector.

For the optical system, various wide field (including Schmidt, Baker-Nunn, and three mirror) designs were evaluated; equatorial, alt–az, and alt–alt mount options were studied. To synthesise the fence, designs which offered 5ºx20º and 5ºx5º fields of view were compared. Fig. 7 shows a schematic of a Schmidt-based design which delivers a rectangular 5ºx20º field of view onto a curved focal surface.

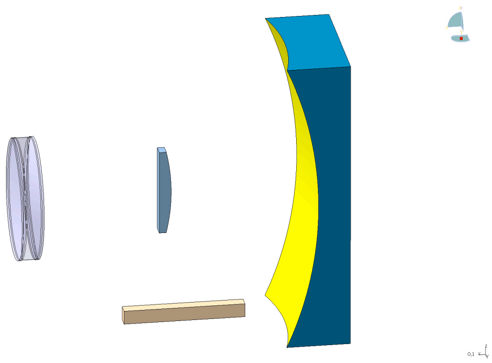

Fig. 7 Schmidt design with a rectangular field of view (1 m brown bar shown for scale)

Each focal plane would be populated with a mosaic of CCD detectors with the size of each mosaic tessera being chosen to enable rapid (few ms) readout of the images, and with ~35µm pixel sizes.

For the tracking sensors, a more conventional approach was adopted to reduce overall system costs. A 1 m diameter telescope with a 1º field of view was proposed.

NETWORK IT DESIGN

Data flow, data volume, and processing requirements were evaluated during the study. Various network architectures were analysed (for example, Fig. 8), subject to the impositions of data policy and the fulfilment latency specifications for end-user information requests.

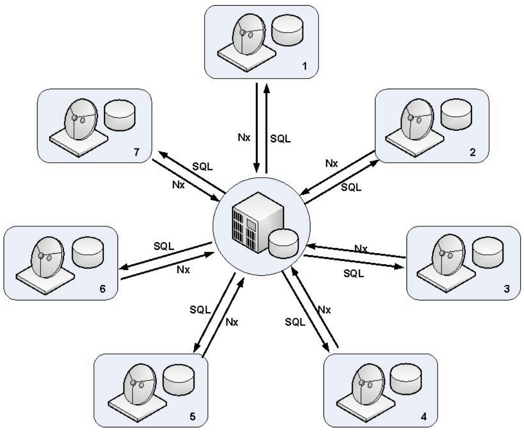

Fig. 8 Example logical network

SYSTEM EXTENSION

The study also considered the extension of the role of the optical system from LEO to the higher Earth orbits. The plan would be to use the wide field of view sensors to conduct surveys of the higher Earth orbits during the period when the Earth shadow height is too high to permit LEO observations. Using the fence sensors for surveying, a detection size ~50 cm in MEO and ~35 cm in GEO can be achieved.

SUMMARY

A network of optical sensors has been designed as a radar augmentation facility for LEO space surveillance. This complex problem was addressed by a multi-disciplinary team which fused experience in space surveillance operations, signal budget analysis, orbit determination and cataloguing, data processing infrastructure, optical design, and large-area scientific detectors.

A multi-site network of sensors was proposed with each site hosting a 5ºx120º optical fence augmented by five 1º field of view tracking telescopes. The network geographical dispersion was chosen to permit consecutive-orbit follow-up observations. The detection size and orbit accuracy specifications were met for orbital heights > 1250 km, at which altitude a catalogue completeness of up to ~95% was achieved.

ACKNOWLEDGMENTS

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