SURVEYING FOR DEBRIS IN MEO WITH OPTICAL SENSORS

Dick, J. (1)**, Herridge, P.** (1)**, Tremayne-Smith, R.** (2)**, Davey, J.** (3)**, Crowther, R.** (4)

(1) *Space Insight Ltd., PO Box 2993, Eastbourne, BN21 9BD, UK, Email: info@spaceinsight.co.uk*
(2) *Out of Space, c/o PO Box 2993, Eastbourne, BN21 9BD, UK, Email: info@spaceinsight.co.uk*
(3) *British National Space Centre, Polaris House, Swindon, SN2 1SZ, UK, Email: john.davey@bnsc.gsi.gov.uk*
(4) *Science & Technology Facilities Council, RAL, Didcot, OX11 0QX, UK, Email: richard.crowther@stfc.ac.uk*

ABSTRACT

To date, most measurements of the debris population have been carried out in the LEO and GEO-GTO regions, using radars and optical sensors, respectively. The remaining orbital space (which includes MEO) has been sampled only minimally. Given the size of the MEO population and the typical mechanisms for on-orbit fragmentation it is statistically likely that there exists in MEO a debris population with a similar payload-to-debris ratio as for other high Earth orbits such as GEO. This paper reviews the reasons for the poor coverage of MEO, discusses the utility of surveying (*cf.* tracking) and sensor cueing for the surveillance of space, and reports on a MEO debris observation campaign.

1. DETECTING HIGH EARTH ORBIT DEBRIS

The volume of near-Earth space which the space population occupies is approximately $2.7\text{x}10^{14}$ km^3; by exposing a 1°x1° image every 10^s the hemisphere viewable by an optical sensor would take just under 60^h – about 6 nights – to survey in a single pass. The physical size of near-Earth space and the six-dimensional diversity of orbits thus present a significant technical challenge to space surveillance systems.

With optical sensors the task of detecting objects in GEO and quasi-GEO is especially simple because the objects co-rotate with the Earth, making their images almost static on an Earth-fixed sensor's focal plane. A similar advantage exists for objects near apogee in Molniya orbits.

All other objects as seen by an optical sensor have much greater magnitude and dispersion in their apparent angular velocity vectors. For a sensor staring with an Earth-fixed strategy, the high angular rate reduces the in-pixel dwell time of an object's image and thus the signal-to-noise ratio. The high angular rate also means that sensors with a small field of view (<1°) cannot establish leak-proof detection fences and may have difficulty producing observations which can generate an orbit because they may only see an object once or twice.

Radar detection of objects in the higher Earth orbits is made difficult by the long range. The inverse-square law applies on both transmit and receive paths so most radars which can detect objects at long range are dish tracking radars with small (<0.2°) fields of view.

Thus the general high Earth orbit regime is caught between the excellent radar coverage at LEO and the simplicity of optical detection at GEO. In addition, this regime's population has a large range of inclinations (compared to GEO, say) and so has a much lower surface density – and thus detection probability – on the sky. There is, therefore, very little known about the debris population outside the LEO and GEO-GTO regions. The paucity of debris information is demonstrated by analysis of the populations recorded in the US SSN catalogue. Fig. 1 shows all non-transfer orbit objects in the catalogue (x-axis: inclination (°), y-axis: semi-major axis (10^3 km); unpopulated regions are green, most populated in red, and intermediate population densities in blue and magenta) whereas Fig. 2 shows only objects which have a COSPAR launch part "G" or above, assumed to be fragmentation debris. Inspection of these figures shows no significant fragmentation debris population in MEO.

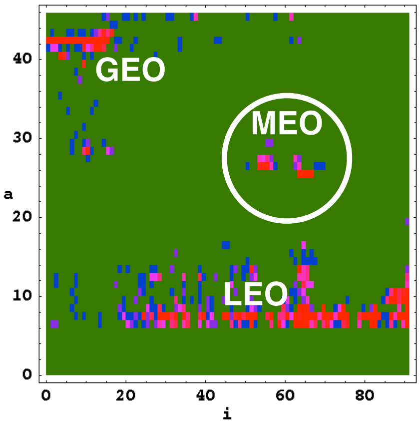

Figure 1. Population density for all objects

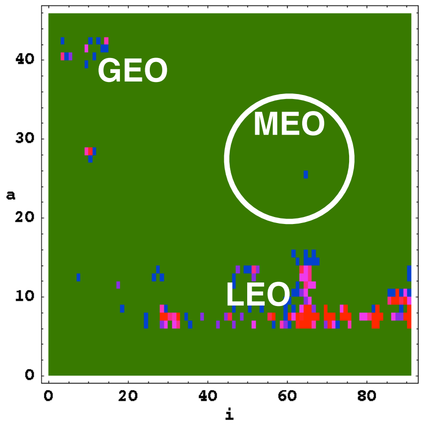

Figure 2. Population density for G+ objects

2. SPACE SURVEILLANCE BY SURVEYING

The growth in the higher Earth orbit space population makes it difficult for tracking optical sensors to keep up with the surveillance workload. In 2006, to investigate other observing techniques, the British National Space Centre (BNSC) initiated a trial into the use of surveying as a method for the surveillance of space.

Compared with tracking, surveying has important advantages. The surveying method has minimal detection biases, sensor workload is invariant with the size of the population, and the sensor hardware and control system are simpler. Surveying covers diverse orbits by default, is better at discovering new objects, automatically produces follow-up observations for newly discovered objects, gives better object re-visit intervals, and requires no sensor scheduling. Surveying is a common radar technique (especially for phased-array radars) but has only recently been possible for optical sensors.

The critical technology needed for optical surveying to work is a large field of view optics and detector package which delivers an appropriate sky coverage rate: surveying is technology-enabled by large format CCDs and GHz-class CPUs.

3. STARBROOK

In 2006 BNSC contracted Space Insight to install and use its Starbrook space surveillance sensor for a trial of the surveying method. Starbrook uses a fast optical system and a 10 megapixel CCD to deliver a 10°x6° field of view and a sky coverage rate of 1,440 sq° hr^{-1}.

Space Insight designed Starbrook *ab initio* to be a fully robotic surveying sensor. Images taken with Starbrook are processed using an algorithm which allows the sensor to detect objects in a wide range of high Earth orbits. Although designed only to be sufficient for the purposes of the BNSC survey method trial, during its first 30 nights of operation the sensor detected ~40% of the high Earth orbit objects in the US SSN catalogue. This figure is commensurate with a limiting detection size of about 1.5 m and is a consequence only of the sensor's small 10 cm aperture.

Starbrook is installed at a UK facility in Cyprus (which has excellent nocturnal sky conditions) and is now used routinely to service a number of UK government military and civil programmes.

This paper reports on using Starbrook to survey for debris in MEO. Because of Starbrook's wide field of view, the field transit time for MEO objects is long (up to 10 minutes) and surveys of significant volumes of orbital space are possible: a leak-proof ascending node detection fence of 20° width can be established. The sensor's large pixels and ability to blind track combine to give good detections of fast-moving MEO objects; during tests, Starbrook detected 100% of US SSN catalogued MEO objects which were predicted to pass through the sensor's field of view.

4. SENSOR CUEING FOR BETTER ORBITS

A key task for a proper understanding of the debris population is the determination of full six-parameter elliptical orbits. Historically, many debris surveys have assumed that debris were in circular orbits. Where observations of debris in elliptical orbits are processed using the circular orbit assumption the orbits determined contain serious errors which prevent re-acquisition of the objects. Long-term observations of debris are important because evolution of the orbits can be monitored and the effect of solar radiation pressure determined; such studies lead to the discovery of the high area-to-mass ratio objects [1].

Although Starbrook can acquire observations of an object spanning ~10 minutes (during a MEO object's transit through the field of view) this is not long enough to provide even an initial six-parameter orbit. One solution to this problem is to have a sensor provide follow-up observations over a period of an hour or so after the initial discovery.

The Starbrook information processing system reduces observations in near real time so celestial position fixes and magnitude estimates are available within about 3 minutes of the discovery observations being taken. All observations are passed to a correlator which determines whether the observations are of known or unknown objects. Observations which do not correlate with a known object are then used to generate a follow-up cue which can be used to obtain, over a longer period of time, more observations to enable determination of a full six-parameter orbit.

The cueing process (which is, like other elements of the sensor operation, fully automatic) can hand off cues to Starbrook itself, or a remote sensor, or the companion sensor, Starbrook North.

5. STARBROOK NORTH

Starbrook North was installed on the same site in 2007, has a field of view of 4ºx4º, a more sensitive but smaller (1 megapixel) CCD, and a 15 cm aperture (Fig. 3).

Figure 3. Starbrook North sensor head

Housed separately (left dome, Fig. 4), Starbrook North works independently from Starbrook but uses identical control and information handling software.

6. MEO DEBRIS SURVEY

Starbrook and Starbrook North have been used to carry out a series of MEO surveys. The mode of operation for these surveys has Starbrook follow, throughout the night, a MEO ascending node position. During exposures, the Starbrook mount control system nods the sensor in declination to blind track at an approximate MEO rate to improve the detection limit.

Two strategies have been used: *i*) for surveying ascending nodes only, positive nodding is active and two fields of view can be sampled so maintaining a leak-proof fence 20º in extent in right ascension; *ii*) alternate positive and negative nodding can be used to sample one field of view to maintain a leak-proof fence 10º in extent but covering objects in transit through either their ascending or descending node.

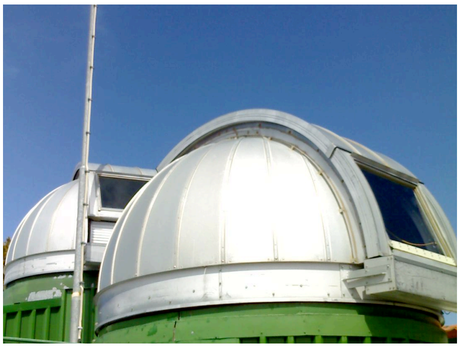

Figure 4. Domes of the Starbrook sensor cluster

For the surveys, the right ascension was chosen to cover a populated MEO plane at small solar illumination phase angle; a populated MEO plane was chosen to detect any debris in that plane and, by detecting known objects, to provide a check on system performance.

During the survey, detections by Starbrook of uncorrelated objects were processed and handed off as interrupting cues to Starbrook North (which was carrying out other duties). As the more sensitive sensor, Starbrook North receives cues from Starbrook because this cue flow direction provides a better guarantee that follow-up cues will be serviced productively.

The MEO debris surveys were carried out around the new Moon in October and November 2008: 21st to 29th October, and 26th November to 3rd December. Tab. 1 gives the right ascension (RA) targeted for each night and whether the survey mode used was for ascending (a) and/or descending node (d) transit.

Table 1. Nightly survey location and mode

Date (2008)	RA	Mode
21/10 to 23/10	325.5º	a+d
24/10 to 29/10	325.5º	d
26/11 to 28/11	50.6º	a
29/11 to 3/12	46.5º+54.5º	a

During the surveys, the clarity of the night sky was monitored by measuring the sky radiative temperature and the ambient air temperature.

It is well established that the difference between these two temperatures is correlated strongly with the clarity of the sky [2, 3]. Fig. 5 and Fig. 6 show the inferred sky state during the survey and are colour-coded as follows: turquoise for clear sky, grey for poor transparency or some clouds, and magenta for cloudy; a blank date line indicates the sensor was not used on that night.

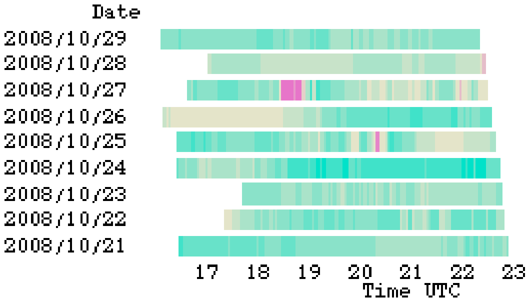

Figure 5. Sky state for the October survey

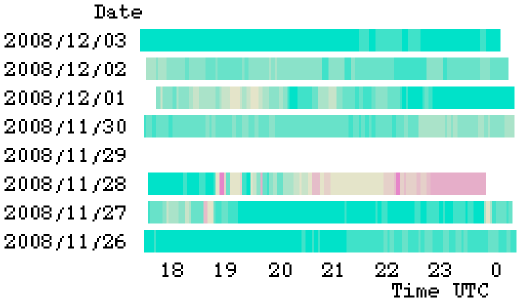

Figure 6. Sky state for the November-December survey

Analysing the sky state observations shows that 25% of the survey had good clear skies and 25% had very poor sky conditions due to local mountain cloud or high-altitude cirrus. Illumination phase angles were evenly distributed between 25° and 55°.

7. MEO DEBRIS SURVEY RESULTS

The survey demonstrated that the Starbrook sensor cluster was effective in detecting unknown MEO objects. During the October survey various unknown objects near old Glonass satellites were detected by Starbrook and these triggered hand-off cues which were processed by Starbrook North. On further analysis all these objects were identified as members of a recent Glonass launch which took place on September 25th (COSPAR identifier 2008-046). At the time of the survey these objects were being manoeuvred into their operational locations and so could not be correctly identified by the correlation process.

After careful analysis of the observations no debris was detected during either of the two survey periods.

The lack of detections of unknown debris may be due to the sensor's lack of sensitivity to small objects (Starbrook was not designed as a debris research tool) and the imperfect weather conditions. The use of blind tracking imposes a selection effect which would have discriminated against objects out of the search plane, or with different orbital periods.

The debris population in MEO may be less numerous than that in, say, GEO. This difference may be due to the younger age of the MEO population (there are no launches to MEO prior to ~1977 [4]); objects in MEO will have benefited from the improvements in satellite construction methods and passivation measures which postdate the early launches to GEO. Also, in MEO there are no lost objects; an object is considered lost if its TLE has an out of date epoch in the US SSN catalogue. There are lost objects in GEO and these may be lost because they have fragmented. Although the absence of lost objects in MEO does not prove that no fragmentations have taken place it may indicate that no catastrophic fragmentation events have happened.

The work reported here covered ~0.2% of the $\{\Omega, m, i\}$ MEO orbit parameter space and so the null result obtained is not statistically significant. Building on the detection and cueing capability successfully demonstrated so far, further surveys of MEO will be carried out with the Starbrook sensor cluster as part of BNSC's contribution to the IADC.

8. ACKNOWLEDGMENTS

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