AUGMENTATION OF UK SPACE DEBRIS OBSERVING CAPABILITIES USING UNIVERSITY OPTICAL TELESCOPES

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ABSTRACT

The study of space debris requires a range of different sensors. Debris population monitoring requires survey, follow-on and characterisation capable sensors. In order to fully participate in space debris measurement the range of sensors available to the UK Space Agency needs to be augmented with additional capability. One source of untapped resource resides within the UK university sector.

This paper discusses investigation into extending the optical sensor diversity available to the UK for participation in study of the debris environment through a collaboration between Space Insight Limited, a commercial company providing Space Situational Awareness (SSA) services to the UK Space Agency, and the Astronomy Group at the University of St Andrews.

1 INTRODUCTION

The space resident population of man-made objects occupies a wide range of differing orbits each with different issues relating to its observation.

For low Earth orbit (LEO) objects, the range to the object is such that active illumination is the preferred option. Radar sensors, like the Chilbolton Observatory (Fig. 1), can undertake fence and tracking observations without the transmitted power requirements becoming unduly large. For passive optical sensors, however, the rate of motion of LEO objects makes survey and tracking problematic. The rapid motion of the target across a static sensor causes illumination issues and tracklet acquisition requires large fields of view. Tracking requires sophisticated and expensive drive systems.

For higher Earth orbit objects, the on-sky motion is much smaller, as shown in the Starbrook image in Fig. 2. The low on-sky motion and large range make observations with passive optical sensors more appropriate. The range to the target makes the power requirements of radar sensors very large and, in order to detect at the desired range, the radar beam is usually focussed into a small field of regard.

Figure 1. Chilbolton Observatory 25 m radar antenna

Highly elliptical orbit objects may benefit from a fusion of radar observations near perigee and optical observations near apogee, but their orbits may mean that perigee or apogee occurs where there is sparse sensor coverage. Because the apogee of highly elliptical orbit objects often occurs over higher latitudes, the phase angle with respect to the Sun can be unhelpful, making smaller and darker objects hard to detect with optical sensors. From an optical sensor perspective the motion of elliptical and medium Earth orbit objects is not supported by a traditional astronomical telescope mount system. Specialist drive systems are needed to provide the necessary arbitrary rate tracking across the sky.

Furthermore, it is often the case that controlled and uncontrolled objects need to be treated as separate classes. The operational payload population consists of objects whose orbits are maintained. Regular updates are needed to the position and motion to keep these orbits current. The non-operational population is considerably more numerous, but each object needs less frequent observations for orbit maintenance. The non-operational population can be further sub-divided into larger intact objects and smaller debris from a variety of sources including explosively and collision generated, and

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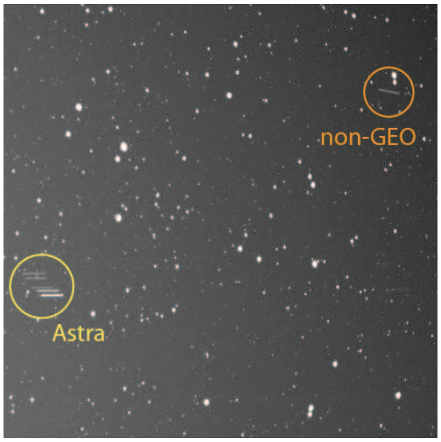

Figure 2. Starbrook image of streaks of the Astra Cluster (left, yellow) and a non-GEO object (right, orange)

mission-related debris. The study of the debris element of the population requires a range of sensors for discovery, orbit determination and characterisation.

2 OPTICAL OBSERVING

Optical observing consists of three main phases: discovery, orbit determination and maintenance, and characterisation. The sensor requirements differ for each phase. The discovery phase is carried out using survey sensors which scan areas of space to detect any object that occurs within the sensor field of view. No knowledge of the orbit of the objects is required but a catalogue is used to identify known and new objects. In post processing, approximate initial orbits, using basic assumptions such as a fixed eccentricity, are calculated for any unknown objects. In order to cover sufficient sky a survey sensor requires as large a field of view as possible.

Once objects have been discovered by a survey sensor it is advantageous to be able to hand off the observation workload to a follow-on sensor to undertake the observations required to generate and maintain an accurate orbit. This frees up the survey sensor to maintain its survey pattern and also allows a more appropriate optical configuration sensor to be utilised. The follow-on sensor can then determine the evolution of the orbit and provide accurate ephemerides to specialised sensors.

Finally, once an accurate orbit is being maintained, sensors can be deployed to characterise the object in terms of its area-to-mass ratio, albedo, shape, tumbling rate, material composition, physical size and other attributes of interest. Some of the sensors needed to do this will be specialised, like spectrometers and multicolour photometers, and because of the high illumination demands are likely to have large apertures and hence small fields of view.

3 UK AIMS AND REQUIREMENTS

It is the intention of the UK Space Agency that the UK should play as full a part in debris monitoring and research as is practical. In order to do this the Agency funds a number of facilities to carry out related tasks. Amongst the observing facilities, the Agency provides funding for the Starbrook sensors operated by Space Insight Limited. These are dedicated optical space surveillance sensors which carry out a national programme of work as well as providing a UK contribution to the European Space Agency's (ESA) SSA Preparatory Programme and to international collaborations and observing campaigns. However, because their design is tailored for observing the active payload population, the Starbrook sensors are not well configured for observations of the small debris population. The UK is therefore investigating means of bridging the capability gaps and extending observations towards fainter objects for which a larger aperture sensor is required in addition to the existing and planned Starbrook sensors.

4 UK UNIVERSITY OBSERVATORIES

Many of the UK universities that run astronomy or astrophysics courses have their own observatories. Often these are relatively small affairs used predominantly for undergraduate teaching purposes and university astronomical societies. For some departments, however, the instruments in their observatories are used for work on various topics of current astronomical research. The instruments range from high-end commercial off-the-shelf telescopes and detectors to large custom built sensors. Publicly available information on the sensors at UK universities suggests that many have aperture/field of view configurations that offer little additional capability to existing and planned space surveillance sensors, but there are some that offer particular features of interest for the study of debris. A sensor that was known by the principal author to offer a configuration that might provide a useful enhancement to UK capability was selected and the head of the university department responsible for it was contacted with a view to carrying out an investigative trial, the results of which form the remainder of this paper.

5 ST ANDREWS UNIVERSITY OBSERVATORY JAMES GREGORY TELESCOPE

The University of St Andrews was founded in 1413 making it the oldest university in Scotland and the third oldest in the English-speaking world. The university has been involved in astronomy since the seventeenth century when, as Regius Chair of Mathematics, James Gregory established the UK's first meridian line and first university astronomical observatory. The present University Observatory was founded and opened by Erwin

Freundlich in 1939 and occupies a relatively dark site in the middle of the university's playing fields on the edge of the town where a number of telescopes are installed.

The town of St Andrews is located 50 miles (80 km) to the northeast of Edinburgh on the east coast of Fife in Scotland and is best known for its association with golf. It is one of the driest and sunniest places in Scotland, with an average of over 1500 sunshine hours per year [1].

The largest telescope in St Andrews is named after the Observatory's founder. Built in 1962, the James Gregory Telescope (JGT), shown in Fig. 3, is the largest operational optical telescope in the UK. It is a Schmidt-Cassegrain design with a 0.94 m primary mirror and 0.86 m clear aperture. The telescope has a focal ratio of ~ 3. In its original configuration images were made onto photographic plates mounted within the telescope body. In its present configuration the light is refocussed through the primary mirror to a CCD detector mounted at the rear of the telescope. The CCD detector is based around an e2v 1k x 1k chip with 13 µm pixels giving an unvignetted field of view of ~ 15' diameter.

Figure 3. The James Gregory Telescope seen through its dome

The JGT has been used in a range of research studies since its installation including research into active galaxies, transiting planets and stellar variability. At present it is predominantly used for research into extra-solar planets and St Andrews Astronomy Department is an active participant in the Super-WASP project.

6 OPTIONS FOR USE OF THE JAMES GREGORY TELESCOPE

For observations in pursuit of its research on extra-solar planets the JGT takes a series of exposures for up to five hours at a given RA and declination. Typically each exposure ranges from ~ 30 s to ~ 120 s depending on the nature of the target parent star. Most of the targets' regions of interest studied at the JGT are at low to moderate northern declinations. The telescope is used for observations on ~ 60 nights during the autumn, winter and spring seasons. Due to the northern latitude of St Andrews the telescope is not used for observations during the short summer months which are dedicated to carrying out any required maintenance or upgrades.

The length of the exposures taken for extra-solar planet studies is not ideal for searching for or studying debris objects. It is expected that some of the low declination fields observed will contain "contamination" by objects moving through the field of view at non-celestial rates. Given appropriate resources, it should be possible to data mine these images to obtain position fixes on these contamination objects. The size of the unvignetted field of view of the current configuration presents some possible difficulties at the longer end of the exposure range since the streak of a potential debris object will extend beyond the edges of the frame.

For the shorter exposures, however, a geosynchronous Earth orbit (GEO) or near-GEO object can be expected to appear on more than one consecutive image, allowing a number of position fixes to be determined. Even for faster moving objects, such as medium Earth orbits (MEO) and GEO transfer orbits (GTO), the trail of the object may be sufficient to allow the position and direction of motion to be determined. Data mining of the shorter duration exposures therefore would seem to be a tenable proposition, particularly at the lower declinations equating to the GEO inclination evolutionary range.

There may also be some observing time, not required for extra-solar planet research, when the JGT would otherwise lie idle. This time could potentially be profitably used for debris searches or follow-on observations. The unvignetted field of view available with the current configuration is at the lower limit desirable for use for survey operations, but the aperture would imply that the telescope should be useful for follow-on and characterisation studies of debris objects. Also, the high northern latitude of the sensor, a disadvantage in terms of the length of summer night observing, may mean that objects in the relatively poorly studied Molniya orbits have better phase angles and on-sky positions than sensors on sites at lower latitudes.

7 INITIAL TRIAL AIMS

An initial trial of using the JGT to observe man-made space resident objects was arranged. The aims were deliberately kept modest and the definition of the trial method was such as to ensure that there were positive results to evaluate. The principal aim of the trial was to establish the capability of the JGT to observe the targets of interest with its existing optical configuration and alongside its existing observing workload. The trial would allow the potential of the telescope for use within the UK's work programme to be explored. It would provide indications of the feasibility of data mining the telescope's observing archive and would help to direct future targeted observing.

8 TRIAL DEFINITION AND OBSERVING

In order to ensure positive results it was decided to concentrate initial observations on the zero inclination GEO belt. A GEO longitude was chosen that contained a number of GEO payloads and, because of the latitude of the site, was within a few degrees of south as seen from St Andrews so that the telescope could be pointed at reasonable elevation. It was decided that observations should be attempted at a celestial declination of – 7.75° in the hour angle range 176° – 178°. The hour angle and declination of the target region would then be passed to the telescope observers who would fit the observations in as weather and observing schedules allowed.

Over the course of two nights during November 2012 a series of exposures was taken at the target location. On the first night 1, 3 and 5 s exposures were taken continuously with the telescope terrestrially parked at the target location. The gap between exposures was 1.3 s and the observing procedure was set to take 300, 200 and 120 images, respectively, for the three exposure times. Altogether 620 images were obtained over a period of 40 minutes.

For the second night, two sets of 100 observations were taken, each with 3 s exposures. During the first set of 100 observations the telescope was tracked sidereally at RA $4^h47.6^m$ from an hour angle of 0^h19^m to $0^h26.6^m$. During the second set it was tracked at RA $5^h1.9^m$ from hour angle 0^h15^m to $0^h22.3^m$. Following the sidereal tracking exposures, three further sets of 100 3 s exposures were taken with the telescope static at 0^h18^m, 0^h19^m and 0^h20^m hour angles respectively.

The images were then processed at the University of St Andrews before being transferred to Space Insight for further analysis.

9 TRIAL OUTCOME

Altogether, for the trial, over 1000 images were obtained during two observing sessions, each lasting around 40 minutes, on two consecutive evenings in November 2012. An example of the images obtained during the trial is shown in Fig. 4. An initial visual inspection of the images showed that all of the terrestrially static observations contained at least one geostationary object. A number of geostationary objects crossed the frames of the sidereally tracked images.

A non-geostationary object was also noted in a number of the 1 s exposure images taken during the first night's observing.

The images sent to Space Insight from St Andrews did not contain the position of the images in the image headers. This information is not automatically recorded at source but is manually noted in the observer's log for the night. The lack of position in the image header does not present an issue in the Observatory's normal work since the RA and declination of the region of interest does not change frequently because the telescope is only pointed at a small number of celestial targets during the observing session. However for terrestrially stationary observing this is a little more problematic. It was therefore necessary to identify the exact stars in the field so that an analysis of the limiting brightness detected by the telescope could be identified.

There were no faint Earth orbiting objects visible in any of the frames obtained by the JGT. All the man-made objects were relatively bright, intact objects. When correlated with the Hubble Guide Star Catalogue stars with streaks fainter than ~ 14.3 magnitude could not be consistently identified in the terrestrially static images. There was no discernible difference in the faintest magnitude stars detected in the 1, 3 or 5 s exposures. No difference in limiting magnitude was expected since the stars cross multiple pixels during a 1 s exposure; the in-pixel time is the same regardless of the length of the exposure.

For the sidereally tracked images the starlight falling on each pixel is a function of the exposure time. Since only a single length exposure was carried out in sidereal tracking mode the variation of limiting magnitude with exposure cannot be evaluated. For the 3 s exposure the limiting magnitude of a static object was ~ 15.5 magnitude.

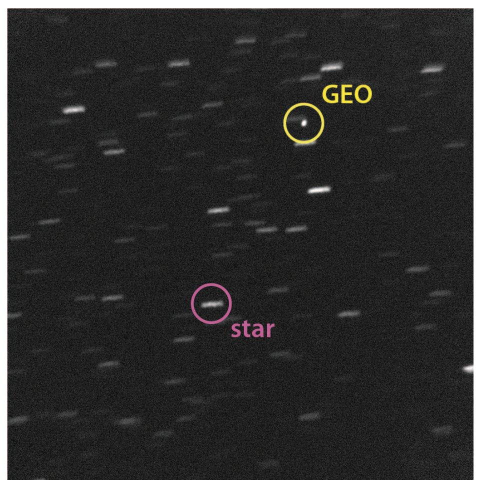

Figure 4. Sample image from the JGT. The telescope was terrestrially stationary, the GEO object (top right, yellow) remains static, stars (pink) trail across image

If a standard size estimation model had been adopted for the limiting magnitude, an approximate equivalent smallest object size could have been derived for the JGT. Such calculations are highly uncertain and were not felt to give a useful measure for the purposes of this trial given the rather broad assumptions that would be required. The stellar magnitudes used in the calculations of limiting magnitudes do not take into account the colour of the stars or the filter used on the telescope. The limiting magnitudes are only intended to be an indicative measure of the capabilities of the telescope.

Once the background stars had been identified the scale of the images could be calculated. The detector used on the JGT is manufactured by Andor Technology with an e2v 1k x 1k, 13 µm pixel CCD chip. From the background stars it was calculated that the angular scale of the detector was 1.1” per pixel. This implies that the field of view of the detector is approximately 18’ which is in close agreement with the 15’ unvignetted field of view estimated by St Andrews University Observatory for their detector.

Once the field centres and image field of view of the observations had been determined it was possible to search the US public domain catalogue [2] for objects that could be expected to have crossed the field of view during the two observing periods. The catalogue was restricted to exclude objects with periods of less than 4 hours (6 revolutions/day) as it was felt that these moved too fast to be usefully visible using a telescope such as the JGT. This catalogue was then analysed for visible targets. There was a small number of frames during the sidereally tracked runs for which an object was predicted to be seen at the extreme edge of the field of view but was not visible in that particular image. It is likely that, in these cases, the discrepancies result from errors in the estimation of the position from the propagation of the orbit in the public domain catalogue. A number of additional objects were seen to have passed close to but outside the field of view. In no case did an object that was predicted to be within the central 950 pixels of the 1k x 1k field of view fail to be detected within the image.

10 TRIAL ASSESSMENT

This initial observing trial using the JGT at the St Andrews University Observatory met all of its trial aims.

Observers at St Andrews University successfully captured a number of geostationary objects using the sensor.

The observations thereby obtained were reduced locally at the telescope site, where the behaviour of the detector is best understood, and then transferred to Space Insight for further analysis to extract information of interest for the detection of debris objects.

The objects detected showed that the telescope could be used to observe debris objects in both sidereal tracking and terrestrially static modes.

Both geostationary and non-geostationary objects were observed.

There were sufficient stars in the field of view to identify the plate centre, and hence the position of the target man-made objects, at a range of exposure times from the very shortest tested.

The limiting brightness, plate scale and field of view of the telescope were successfully determined for both static objects and those moving at sidereal rates with respect to the field centre.

All objects passing through the field of view of the telescope were detected.

The trial did however encounter a number of issues that need to be further investigated and considered before it makes practical sense to continue with debris observations using the JGT. The two most important of these issues relate to how the telescope in its present configuration can be used to make a useful contribution to debris studies.

Firstly, the field of view of the JGT is smaller than anticipated. The telescope operates at *f*/3 and would be expected to have a larger field of view than that seen in this study. Historically when the telescope operated using photographic plates the field of view was ~ 4° x 4°. However, at that time, the focus of the telescope was inside the telescope tube. Having the focus inside the telescope tube was untenable for the use of CCD based detectors, in the early days following their introduction, due to the required electronics and the removal of excess heat. In order to fit a CCD detector to the rear of the telescope a set of transfer optics was introduced to refocus the telescope. These transfer optics introduced vignetting of the telescope beam to the CCD, reducing the field of view to that available today. If it were possible to increase the field of view of the telescope then it would become much more useful as a survey instrument for fainter debris objects.

Secondly, in its main role in the study of exoplanets, most of the work of the JGT involves taking photometry on stellar targets. As such it has been found useful to operate the telescope slightly defocussed to improve the photometric signature-gathering capabilities. The disadvantageous aspect of this for debris studies is that the limiting magnitude of the telescope is degraded as the available light from the targets is spread over a larger number of pixels. Therefore, the usefulness of the JGT for the study of faint items of debris is limited by this feature of the telescope’s standard mode of use.

In the sidereal images the full width at half maximum (FWHM) of those stars not saturating the CCD is approximately 10 pixels. If the telescope were refocussed for space debris observing such that the FWHM could be reduced, the limiting would be reduced accordingly. To a first approximation the background noise can be assumed to remain constant, allowing an estimate of the limiting brightness that could be expected if the signal was concentrated into various image circles. Taking a 5 pixel spread of the light from the stars as a reasonable expectation, the calculated improvement in limiting magnitude is ~ 1.5 magnitudes. This would suggest that a properly refocussed telescope could be expected to see debris objects down to a limit of 17 – 17.5 magnitudes. This kind of improvement to the limiting magnitude available on the JGT would make the telescope significantly more useful for the search for and the characterisation of faint debris.

These two aspects of the configuration of the JGT have resulted in further work on this collaboration awaiting the formulation of a suitable manner of using the sensor in discussion between Space Insight, the University of St Andrews and the UK Space Agency.

11 SUMMARY

A successful trial of observing high Earth orbit objects has been carried out, with the support of the UK Space Agency, between Space Insight Limited and the University of St Andrews using the JGT. The trial demonstrated that the JGT was capable of observing man-made space debris objects in both terrestrial and sidereal tracking modes. A number of objects were detected, both geostationary and non-geostationary, and these objects were successfully correlated against the US public domain catalogue. No objects that were predicted to be in the field of view of the telescope went unobserved although there were some issues, most likely resulting from errors in the propagated positions of the catalogued objects, at the extreme edges of the telescope's field of view.

The relevant parameters to describe the capabilities of the JGT to undertake space debris research observations have been determined. Certain issues regarding the configuration of the telescope for its present tasks have been identified and need to be more fully considered and discussed between the various parties in the collaboration before additional work is carried out.

It is clear from this trial that the JGT has the potential for use in a space debris context. There are a number of possible modes of use for the JGT and the most appropriate should be considered for taking the collaboration forward.

The telescope could be used for targeted observations of particular objects of interest, such as the brighter high area-to-mass ratio objects or debris objects in Molniya orbits, on an available time allocation basis. Such observations, possibly including photometry on appropriate targets of opportunity, would fit well with the existing capabilities of the telescope and its present workload.

Whilst the existing field of view is smaller than would be ideally desirable, the telescope could be used for survey observations, particularly in areas such as the Molniya apogee ring where its northern latitude is advantageous. The increase in limiting magnitude available if the telescope can be refocussed to accommodate targeted space debris observations would significantly decrease the smallest object visible using the JGT. This would enable faint object surveys to be carried out in addition to the surveying options available without refocussing.

The possibility of undertaking serendipitous data mining of observations taken during the existing schedule should be investigated. The main use of the JGT at present is targeted towards low northern declinations some of which will coincide with the geostationary debris inclination evolution band, 15 degrees above and below the geostationary belt. It is anticipated that more of the upcoming extra-solar planet observing will be made at high declination and may coincide with navigation satellite or Molniya culmination. An investigation on whether the JGT's existing exoplanet observations can be successfully mined for debris object observations should be considered.

Finally, there is an investigation being carried out at the St Andrews University Observatory into the possibility of reconfiguring the JGT to use the original focus position. If this proves possible the option of adjusting the telescope's configuration to better suit a space debris role should also be considered.

12 ACKNOWLEDGEMENTS

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