Argus: A UK citizen science study in support of the surveillance of space

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ABSTRACT

Space debris poses a collisional risk to satellites that are essential to everyday life here on Earth. This issue is not, however, always appreciated by the wider public outside the space tracking domain. Dstl initiated the Argus experiment (named after the Greek god known as "the all-seeing one") with the aim of harnessing the enthusiasm of amateur astronomers within the UK to bring space debris tracking to the masses.

Argus was a Citizen Science project, involving scientists at the United Kingdom's (UK) Ministry of Defence's Defence Science and Technology Laboratory (Dstl) working with members of the Basingstoke Astronomical Society (BAS). Argus examined the potential utility of employing a distributed array of amateur-grade astronomical imaging systems to inform the development of an indigenous UK Space Situational Awareness (SSA) capability. BAS members used their equipment to take observations of low-Earth orbit (LEO) satellites selected from those routinely tracked by the International Laser-Ranging Service (ILRS). Dstl extracted satellite positions from the resulting images and used in-house software to determine an orbit fit to the data. The results were critically compared to published ILRS measurements.

This activity highlighted shortcomings in our existing image processing software and orbital dynamics modelling software, and provided an opportunity to ingest a large dataset from a heterogeneous architecture and test the performance of Dstl's software. This emphasised the criticality of timing accuracy.

Comparison by Dstl of initial measurements to ILRS predictions revealed significant timestamp accuracy issues with the commercially-available astronomical software used by BAS members in the control of their cameras. BAS developed both hardware and software solutions to significantly increase the timestamp accuracy. These techniques included characterisation of camera timing delays and clock synchronisation, ultimately achieving synchronisation to within approximately 2 milliseconds.

The project prompted significant development of Dstl's in-house software. Dstl's image processing software automatically detects and measures satellite trails in optical images. The image processing software has been ported from two independent IDL and MATLAB instances into a Python implementation which includes a number of improvements. These include improved rejection of false positives, a lower detection threshold and the automatic association of related trails. The robustness and utility of Dstl's orbit determination software, Mission Planner, was improved by the implementation of timing bias estimation and a Levenberg-Marquardt algorithm.

Argus has highlighted infrastructure issues which would have to be addressed by any operational SSA system such as automation and remote operation, connectivity, data standardisation, sensor availability and sensor tasking. Additionally, it provided a better appreciation of the benefits and difficulties associated with Citizen Science collaborations. The experiment also determined the capabilities and limitations of using amateur-grade equipment for SSA.

This experiment marks the first time that Dstl has conducted a citizen science project. The technical expertise and enthusiasm of BAS for the project played a significant role in its success. Argus has demonstrated that amateur-grade equipment is capable of observing a reasonable proportion of the LEO satellite population. An SSA system

based on such equipment could be a very cost-effective solution if associated issues such as infrastructure can be successfully addressed.

1. INTRODUCTION

The Royal Air Force (RAF) and the United Kingdom Space Agency (UKSA) have been directed to enhance the UK's indigenous Space Situational Awareness (SSA) capability beyond current levels. RAF mission areas include a satellite warning service (overflight), cataloguing, conjunction assessment, re-entry warning and fragmentation analysis. Additionally, the UKSA has a requirement to maintain custody of UK-licensed satellites for both national liability and licence compliance purposes. Significant development of the UK's SSA capability is planned to enable the UK to retain access to space services critical to both the military and civil domain; this includes management of the increasing risk posed by space debris to active satellites. To support this modernisation programme, Dstl has an SSA project which has been assessing sensor and data processing options. This aims to identify ways to augment the SSA data currently available to the UK.

The US Space Surveillance Network (SSN) comprises a network of high-quality radars and optical telescopes distributed around the world, and is the primary source of the UK's SSA data. Small-aperture optical telescopes can, however, detect many satellites and offer the prospect of a very cost-effective solution to some parts of the UK's SSA requirements. Indeed, several commercial companies are currently offering SSA products based on this model. These commercial offerings are in general concerned with the observation of higher orbital regimes such as geosynchronous orbit (GEO).

The Argus experimental concept originated from a February 2018 outreach briefing to Basingstoke Astronomical Society (BAS) members by Dstl following a speculative request by BAS who had seen a recent Dstl space programme press release related to the Dstl Daedalus experiment [1]. The BAS has a membership of approximately 60 with a wide range of interests, skills and equipment. Seven BAS members became full participants in the experiment. Of these seven, several have highly technical backgrounds and all quickly proved themselves very useful collaborators. Most BAS participants used laptop-controlled, tripod-mounted DSLR or astronomical CCD/CMOS cameras located in their back gardens in the Basingstoke area. In addition, Grant Privett from Dstl also contributed data from his home in Wiltshire and the Dstl observatory at Dstl Porton Down.

Fig. 1: Location of participating observers. Imagery & map data ©2019 Google.

The Argus experiment focused on low Earth orbit (LEO) satellites as relatively little work has been done on optical measurement and analysis compared to GEO satellites due to the prevalence of radar data in this orbital regime and the high slew rates required to physically track the high angular rates of LEO satellites. Wide field of view sensors were chosen for the Argus experiment to ensure adequate quantities of data could be obtained from staring the sensors at a fixed azimuth and elevation relative to the horizon.

Satellites were selected on the basis of their observability and the availability of high-quality orbital ephemerides to calibrate against and facilitate quantitative analysis. The three objects selected were the International Space Station (ISS; Space-Track #25544), Remove Debris (RD; #43510), and Cryosat 2 (#36508).

The ISS was of interest as it is the brightest satellite in the sky, has extremely precise orbital ephemerides available to support calibration, and has a high priority due to human space flight safety management. It was chosen as an initial target as it is the easiest satellite to observe. The ISS observations were made during initial shakedown testing and were used to assess the feasibility of further observations, de-risk tasking between BAS and Dstl, and refine the measurement and analysis processes. Detailed analysis was not performed and therefore results are not presented here.

RD had several payloads of interest to SSA. RD was co-funded by the European Commission, was built by a consortium led by Surrey Space Centre (SSC) and aimed to demonstrate several active debris removal technologies. These comprised: a cubesat captured by a net fired from the main satellite; a cubesat which was tracked by an optical camera and LIDAR (Light Detection And Ranging) hosted on the main spacecraft; a harpoon fired at a deployed target; and a de-orbit drag sail [2]. Telemetry was made available to Dstl from SSC to support analysis of Argus data.

Cryosat 2 is an International Laser Ranging Service (ILRS, [3]) mission. This means that the ILRS network of terrestrial laser stations routinely measure its location and produce extremely high-precision orbits (the measurements are accurate to a few millimetres) which could be used by the Argus experiment to calibrate observational data. Of all the ILRS missions available, Cryosat 2 was selected because it is visually bright and was visible from Basingstoke during the experiment.

2. METHODOLOGY OVERVIEW

The experimental process can be summarised as follows, with the responsible organisation indicated in square brackets:

- Produce a short list of targets of interest [Dstl]
- Identify an upcoming period of suitable weather (clear skies). [BAS/Dstl]
- Select a suitable target(s) for this period and predict its position. [Dstl/BAS]
- Photograph satellite as it passes through the field of view of the sensor. [BAS/Dstl]
- Transform between the image co-ordinates (x,y) and celestial co-ordinates right ascension and declination (α,δ). The open source Astrometry.net service [4] was used to determine the parameters of the image transformation between (x,y) and (α,δ). [Dstl]
- Detect streak made by satellite in each image and record the start and end positions in celestial co-ordinates. Dstl is developing software to perform this step automatically, but at that time it was not yet entirely robust so this was done manually using the SAOimage DS9 software and the image transformation parameters determined in the previous step. [Dstl]
- Confirm satellite identification. The in-house Dstl software Mission Planner was used to correlate observations against the Space-Track catalogue. [Dstl]
- Use available data to calculate an orbit. The in-house Dstl software Mission Planner was used to perform this step. Mission Planner has both SGP4 and Special Perturbations models; special perturbations mode was used throughout this work. [Dstl]
- Provide feedback to Argus observers on their data quality. [Dstl]
- Refine process based on feedback. [Dstl/BAS]

The above process is reliant upon external data sources to cue sensors and to provide a start vector (an initial estimate) for orbit determination. The Space-Track.org website was used to provide two-line element sets (TLEs) and high-precision orbital ephemerides for Cryosat 2 were obtained from the ILRS website [2].

LEO satellites have typical orbital velocities of ~17,500 mph, which translates to apparent angular rates of around 1°/sec, depending upon the geometry. From previous Dstl studies on orbital estimates, the timing accuracy must be such that the corresponding positional error is no larger than the sensor spatial resolution [5]. To enable fusion of data from multiple sensors error estimates must be consistent between sensors – whether they are consistently over or underestimated is less important. Timing accuracy to better than 50 milliseconds is therefore essential and better than 10 milliseconds is highly desirable. BAS members were instrumental in designing an appropriate solution, an issue which is discussed in detail in section 5.

Lines of communication between BAS and Dstl presented a significant issue. The quantity of email traffic to Dstl staff led to a significant workload increase – this was in part due to the success of the collaboration, but was exacerbated by the centralisation of the image processing task within Dstl. Communications were also the subject of single-points-of-failure due to the limited number of Dstl staff involved. Emails from the BAS team tended to be sent during observing periods, i.e. in the evenings and weekends, whereas Dstl staff typically check emails during normal working hours. The Dstl SSA team has recently set up a group email account and a similar solution could be considered for similar future collaborations. The use of mobile phones for out-of-hours emails should also be considered for future work.

3. IMAGE PROCESSING

The format of the BAS images varied significantly between observers due to the different cameras used: manufacturers typically use their own proprietary formats. These were converted by the BAS observers to the FITS (Flexible Image Transport System) standard. Differences persisted, however – for example, if the image required debayering[1] or not. Header data (containing information about the timing and image parameters) was recorded in different formats by each observer's image capture software. These issues were all surmountable but slowed progress. Standardisation is clearly desirable for future activities.

Analysis of the images was conceptually simple, but practically challenging. Dstl have developed software to automatically detect and characterise the streaks from satellites [5], but this is not yet entirely robust: false negatives and especially false positives need to be minimised; and the start and end points of the line need to be accurate to approximately the pixel scale, or preferably sub-pixel, which is not trivial for faint satellite detections in noisy images. Due to these issues the satellite detection and analysis was conducted manually, which proved very time consuming and significantly delayed the provision of feedback to BAS.

4. EQUIPMENT

The BAS and Dstl observers used high-grade amateur quality equipment to make observations. The observing sites were all in the south of England (see Fig. 1) and as such suffer from light pollution (typically 20 mag/arc sec or worse), relatively poor seeing and non-ideal weather. The equipment used is summarised in Table 1. To anonymise the data processing and reporting, each observer was assigned a unique observer identifier.

[1] A typical colour sensor records red, green and blue intensities on separate pixels arranged in a grid, so that when viewed in greyscale a checkerboard effect – a Bayer pattern – is seen.

Table 1: Summary of equipment used.

Observer	CCD/camera	Aperture / mm	Focal ratio	Pixel scale / "/px
1	Canon 500D	50	1.8	19
2	QHY168C	305	7.9	0.4
3	Starlight Xpress Lodestar	50	1.7	35
4	Starlight Xpress Ultrastar	50	1.8	26
5	Canon 5D Mk ii	85	1.8	16
6	Canon 600D	50	1.8	18
7	Starlight Xpress Lodestar	50	1.4	14
8	Starlight Xpress SXVF-H9	50	1.8	25

Fig. 2: Examples of equipment used by the BAS observers.

5. TIMING SYNCHRONISATION

During initial testing using the ISS as a test target it was discovered that the commercial image capture software used to trigger the Canon DSLRs used by BAS members gave large and variable random timing errors of up to approximately two seconds. The software developer was contacted but unfortunately proved unable to offer a solution.

The issue was overcome by BAS who developed a Java program to communicate with the serial port and open/close the shutter using a simple USB relay purchased for approximately GBP12. This reduced the random timing error to 70 – 120ms. BAS measured the mechanical relay delay (bias) to be consistently 4ms. Each camera model behaved differently in terms of shutter lag and exposure length; mirror flip-up delay was a significant contributor and on most cameras it was highly inconsistent from shot to shot. A mirror up option was therefore added to the camera control application. Further, the camera memory card speed influences the achievable frame rate before buffering delays image capture, so high-speed memory cards were used.

The Java program attempted to calibrate out the various timing errors described above. The exposure start time calibration used the LED on the USB relay switch. The calibration results were accurate and repeatable to within 10ms. For the exposure length calibration we used a computer simulated LED grid. This was less accurate because the computer screen only updates once every 16ms. A full description and a download of the software is available from [6].

The Starlight Xpress cameras were controlled by freeware software – SXcon – which can acquire images using almost any Starlight Xpress monochrome CCD camera and is based upon the software development kit (SDK) supplied by Starlight Xpress. Unusually, image capture is triggered on the toggling of the integer second and so timing accuracy is limited only by the accuracy of the system clock. The images created are entirely FITS compatible.

To ensure a nominal timing accuracy of the order of 2ms, the system clocks on the laptops used were corrected during each observational run by either an network time protocol (NTP) server (at sites where a reliable internet connection was available) or the NMEATIME shareware interpreting data from a USB GPS dongle. A better long-term solution would have been to employ a full GPS clock at each laptop.

6. IMAGE PROCESSING PIPELINE DEVELOPMENT

The automated processing pipeline is written entirely in Python 3.6 and is based upon previously described MATLAB and IDL code [5].

Images are first sorted into chronological order, and then each has the appropriate dark frames, flat fields and a defect mask applied. These corrections are only undertaken if the required calibration frames are available. (For the position estimation process described here, the effect of the absence of these calibration frames has not been investigated but is likely to decrease detection sensitivity and to decrease positional accuracy for faint objects.) The images are then normalised relative to each other based upon their sky background count.

Once the images have been calibrated and normalised, a Python implementation of DAOFIND taken from the software suite DAOPHOT [7] & [8] is used to extract the star positions. The star positions are then used to align the image in groups (currently 3) of images which are then median stacked. The resulting median image is then subtracted from each calibrated image in turn to greatly diminish the signal from stars, clouds, the Zodiacal light, light pollution and the Milky Way, thereby highlighting transient features such as satellite streaks.

The median subtracted images are then adaptively thresholded to highlight pixels with a brightness more than 3 standard deviations above the image background count. The resulting image is formed into “clumps” on the basis of simple spatial association. Each clump is examined to test if its size and shape are suggestive of a satellite streak via the coefficient of determination of a simple linear regression fit and downselected on that basis. For the clumps deemed sufficiently linear, a straight line is then fitted to provide a better assessment of the streak orientation and position. This uses a weighted linear regression which is then refined using a weighted orthogonal distance regression. An optional step further refines the streak position by fitting a 2D Gaussian convolved with a straight line to the image using the orthogonal distance regression fit as a starting point. This uses the Nelder-Mead simplex method [9].

The preceding and succeeding images are then checked for the presence of streaks corresponding to those identified in the test image. The trail length, exposure time and time between images is used to determine how far a streak would be expected to move while the shutter is closed and streaks are matched based on comparing an expected position to the streak’s measured position. Any streak that does not correspond to one in a neighbouring image is rejected.

Once the streak endpoints are found an installed instance of astrometry.net is used to plate-solve the subsections of the calibration images around each streak and the Astropy Python package is used to transform between the (x,y) and (α,δ). Finally, the time and (α,δ) of the solved streaks are written into text files readable by the Dstl Mission Planner software.

7. RESULTS

Cryosat 2:

To assess the accuracy of the Argus measurements of Cryosat 2 a special perturbations orbit was fitted to 14 nights' of ILRS measurements between 2018-10-26 and 2018-11-08, inclusive. The residuals between this fit and the ILRS measurements (which were used to constrain the solution) were a mean residual of -0.38m with a standard deviation of 2.1m. These figures exclude a small number of obviously spurious measurements which were rejected by the fitting algorithm. The small residuals to the ILRS measurements indicate a satisfactory orbital solution.

Table 2: Residuals between the Argus measurements and the fit to the ILRS measurements in degrees and multiples of the estimated measurement errors (n_delta).

Obs. Date		Right Ascension (deg)		Declination (deg)		Right Ascension (n_delta)		Declination (n_delta)		
YYYYMMDD	Observer	mean	SD	mean	SD	mean	SD	mean	SD	Comments
20181026	1	0.048	0.067	-0.026	0.038	2.22	3.07	-3.49	5.17	
20181028	1	-0.045	0.035	-0.045	0.038	-2.45	1.92	-6.71	5.67	
20181029	1	0.001	0.012	0.004	0.014	0.08	1.08	0.48	1.70	
20181101	1	0.017	0.018	-0.004	0.042	1.94	1.99	-0.75	7.86	
20181102	1	0.012	0.034	-0.016	0.033	1.21	3.59	-2.36	4.95	
20181103	1	0.003	0.038	-0.021	0.051	0.29	4.12	-3.92	9.56	
20181029	4	-0.073	0.018	0.050	0.015	-3.41	0.87	3.22	1.00	
20181029	7	-0.046	0.040	0.038	0.026	-3.76	3.26	3.84	2.59	
20181102	7	-0.041	0.029	0.038	0.032	-3.57	2.61	3.85	3.22	
20181103	7	0.015	0.008	0.075	0.032	0.78	0.44	7.43	3.14	
20181028	8	-2.15	0.16	-6.25	0.13	-633	47	-885	18	~12 sec timing offset
20181029	8	-0.023	0.027	-0.003	0.003	-1.77	2.08	-0.37	0.47	
20181102	8	-0.82	0.03	-0.27	0.04	-73.7	2.5	-38.6	6.3	Pass 1; ~2 sec timing offset
20181102	8	0.87	0.05	-0.05	0.04	74.7	4.7	-7.1	6.1	Pass 2; ~2 sec timing offset
All		-0.010	0.035	0.002	0.032	-0.66	2.54	-0.53	4.98	excluding serials with large time offsets

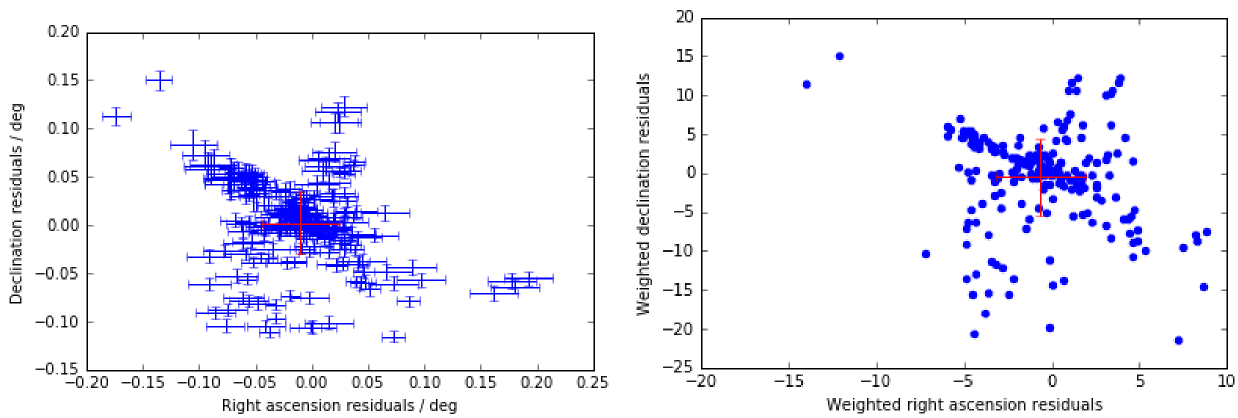

Fig. 3: Left: Residuals between the Argus measurements and the orbit fitted only to the ILRS measurements in degrees. The red cross shows the mean residuals and the standard deviation. Right: As left, but showing the weighted residuals (i.e. the residuals divided by the estimated measurement errors).

The residuals between the Argus observations of Cryosat 2 (which were not used to constrain the solution) and the fit to the ILRS measurements are shown in Table 2 and Fig. 3[2]. The residuals indicate that the observations are typically accurate to approximately 2 arc min. The standard deviation of the weighted residuals (i.e. relative to the estimated measurement errors) is larger than unity, indicating that the measurement errors have been underestimated. Three data sets (observer 8 on 2018-10-28 and both passes on 2018-11-02) show very large discrepancies which are almost certainly timing errors.

[2] The corresponding figure is not shown for the fit to the Argus measurements because it is visually indistinguishable.

The Argus observations of Cryosat 2 were themselves used to determine an orbital solution for the satellite using the Dstl Mission Planner software. The orbit determination software was modified to estimate constant time bias offsets to allow for any residual un-corrected timing errors in the observation processing pipeline. This required the addition of software routines to compute partial derivatives of the observations with respect to time. Implementation of the Levenberg-Marquardt algorithm was also included to enable more robust convergence than the existing batch least-squares routine. The updated software successfully determined timing biases of -12.9 sec, -2.1 and -2.1 sec for the data sets from observer 8 on 2018-10-28 and both passes on 2018-11-02, respectively. The root cause of these offsets has not been determined. The resulting residuals between this fit and the Argus observations are shown in Table 3, and are very similar to the residuals between the Argus measurements and the orbit fitted to the ILRS measurements. The residuals between the orbit fit to the Argus measurements and the ILRS measurements (not used to constrain the solution) were a mean residual of 0.62m with a standard deviation of 28m, indicative of the lower precision of the Argus measurements. The right ascension and declination residuals appear to be linearly correlated (see Fig. 3); this is probably due to errors in estimating the streak end-point and/or timing errors manifesting as along-track errors which affect both co-ordinates.

Table 3: Residuals between the Argus measurements and the fit to them in degrees and multiples of the estimated measurement errors (n_delta).

Obs. Date		Right Ascension (deg)		Declination (deg)		Right Ascension (n_delta)		Declination (n_delta)		
YYYYMMDD	Observer	mean	SD	mean	SD	mean	SD	mean	SD	Comments
20181026	1	0.048	0.067	-0.026	0.038	2.216	3.069	-3.491	5.169	
20181028	1	-0.044	0.035	-0.044	0.038	-2.402	1.922	-6.611	5.665	
20181029	1	0.00019	0.012	0.005	0.014	0.014	1.076	0.592	1.698	
20181101	1	0.018	0.018	-0.001	0.042	2.080	1.976	-0.210	7.858	
20181102	1	0.010	0.034	-0.014	0.033	1.004	3.588	-2.053	4.952	
20181103	1	0.004	0.038	-0.017	0.051	0.401	4.118	-3.118	9.561	
20181029	4	-0.074	0.018	0.050	0.015	-3.456	0.867	3.273	1.005	
20181029	7	-0.046	0.040	0.039	0.026	-3.825	3.261	3.932	2.587	
20181102	7	-0.043	0.029	0.040	0.032	-3.735	2.613	4.061	3.222	
20181103	7	0.016	0.009	0.079	0.032	0.840	0.436	7.853	3.142	
20181028	8	-0.006	0.006	-0.017	0.020	-1.700	1.758	-2.418	2.882	-12.9 sec timing offset
20181029	8	-0.024	0.027	-0.002	0.003	-1.858	2.086	-0.354	0.472	
20181102	8	-0.00003	0.027	0.00011	0.008	0.0004	2.415	0.016	1.161	Pass 1; -2.1 sec timing offset
20181102	8	-0.00023	0.018	-0.003	0.002	-0.022	1.503	-0.454	0.277	Pass 2; -2.1 sec timing offset
All		-0.008	0.032	0.002	0.029	-0.598	2.420	-0.358	4.452	including serials with corrected time biases

Remove Debris:

Observations of RD were attempted but it proved to be borderline detectable. Visual inspection of the raw images indicated a faint trail consistent with the expected RD profile and position (*e.g.* Fig. 4), but in many cases this was too faint to detect. Image processing may be able to increase the detection sensitivity beyond manual inspection but this has not yet been explored. It was observed that CCD sensors used by the Argus team were more successful in capturing faint objects than the DSLRs. The phase of the Moon can make several magnitudes difference to the sky brightness which can significantly affect the detectability of faint targets. Several attempts at capturing RD were made during times close to full moon and the high sky brightness is suspected to be why many such attempts failed. Several observers detected the combined subsatellite and net (see [1]) deployed by RD and noted that it was significantly brighter than RD itself – probably due to the shape and reflectivity of the inflatable target on the former.

The borderline detectability of RD is a useful result as it can be used to estimate a lower limit on the brightness/size of LEO satellites that can be detected with small aperture (around 50mm) staring sensors: somewhat smaller than RD at around 30cm diameter or approximately 7th magnitude. The exact figure will depend on the satellite's shape, range, reflectivity and Sun angle, as well as the observing conditions and equipment used, however this provides a useful 'rule of thumb' to help assess the contribution of amateur observations of the on-orbit debris population.

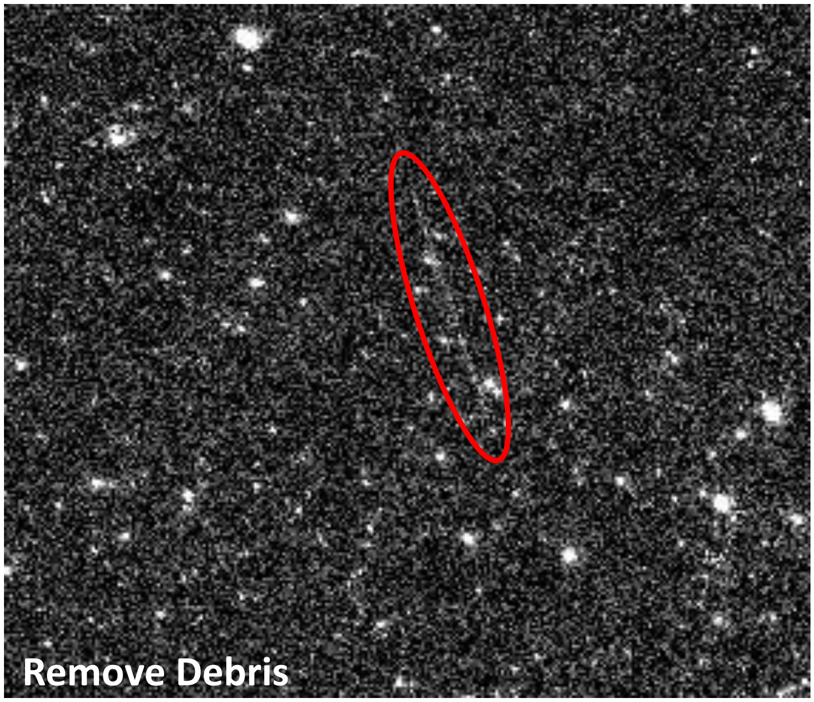

Fig. 4: Borderline detection of RemoveDebris satellite by observer 4 using the Starlight Xpress Ultrastar and a 50mm lens.

8. CONCLUSIONS

We have presented preliminary results of a LEO observation campaign using distributed small-aperture, low-cost astronomical imaging systems operated by members of an amateur astronomy society. Comparison of the results to laser ranging data indicates that such systems can obtain data of adequate precision to determine orbital parameters to a useful degree of accuracy.

It became apparent during the course of the experiment that members of the astronomical society possessed significant technical ability and they developed several techniques to enhance the timing accuracy of their instrumentation. It seems likely that other UK amateur astronomers also possess significant, perhaps untapped, technical expertise.

Data collected during the course of the experiment have been used to help develop a system for the automated processing of satellite trails found on imagery sourced from fixed wide angle optical sensors. The experiment data have also been employed to successfully test methods for correcting for time biases in observational data.
Limits to the utility of the type of hardware used in the experiment have been determined: there is a sensitivity limit of approximately 7^{th} magnitude; and the angular accuracy is currently approximately 2 arc min. It is possible that this angular accuracy could be improved: it may be limited by timing, astrometry and/or angular precision.

Argus has helped to quantify the utility of amateur-grade astronomical imaging systems for SSA, and the findings will inform the assessment of options against the UK's SSA requirements. Such instruments could potentially fulfil part of these requirements by monitoring brighter, lower-priority satellites, with a smaller number of higher-fidelity, more sensitive sensors being tasked against priority targets. One performance aspect not addressed by Argus is the area of sky instantaneously surveyed by such instruments. If required, this could be increased by using co-located groups of similar instruments, each with different fields of view.

Dstl are exploring options for a follow-on activity to this citizen science project and are interested to engage with the wider astronomical community to explore how we best use these un-tapped resources to help ensure the long-term sustainability of space.

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