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TRACKING THE DARK SIDE ON A SHOESTRING BUDGET

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ABSTRACT

A lot of SSA work on earth-orbiting satellites can be done with modest, off the shelf equipment. This has been shown by an informal group of *Independent Space Observers* ("ISO's") organized around the *Seesat-L* mailing list. They optically track some 200 "classified" objects – objects for which orbital elements are not provided in the public orbital catalogues – using very simple equipment: from binoculars and stopwatch on the 'old skool' end to DSLR's or sensitive CCTV or CMOS/CCD cameras with fast photographic lenses and GPS time management on the sophisticated end. In this paper, a brief outline is provided on the techniques and equipment used by Seesat-L members and an example is given of how a new launch is located and tracked. It is discussed why the whole concept of keeping the orbits of certain space assets "classified" is problematic: not only is it unrealistic, but it also goes against core notions of transparency and accountability regarding activities in space.

1 INTRODUCTION

In 1983, the US Government decided to classify the orbits of certain military satellites and their associated rocket stages [1]. As a result, orbital elements for these objects are no longer part of the published orbital catalogues, such as the CSpOC catalogue at Space-Track [2] and derivate catalogues such as Celestrak.

Nevertheless, orbital elements are available for the majority of these objects from non-Governmental organisations. Specifically, from the 1980's onwards a group of 'amateur' satellite observers (from here on: *Independent Space Observers*, or ISO's), many of whom were trained in Project *Moonwatch* and similar *ad hoc* tracking projects from the 1960's [3], have started to track and catalogue these objects. These independent observers are loosely organized around a mailing list (*SeeSat-L* [4]), where they exchange observational data and analysis. The active core of the group is currently based in the UK and the Netherlands, but there are also active contributors from amongst others the USA, Canada, South Africa, Germany and Italy. The number of active observers in this group varies over time, but is typically somewhere around 15 people.

In this paper it is outlined how these ISO's track objects, using relatively simple equipment. They do this on shoestring budgets. It is discussed what professional tracking networks might learn from this, and why the whole concept of keeping the orbits of certain space assets "classified" is problematic: not only is it unrealistic (as the successful tracking activities of Independent Space Observers underline), but it also goes against core notions of transparency and accountability regarding activities in space.

2 CATALOGUE

The current orbital catalogue of 'classified' objects created by Independent Space Observers [5] contains orbital elements for some 200 objects that are otherwise not available in public catalogues. These objects are not all operational payloads. A lot of them are defunct satellites (that are still kept 'classified') and rocket stages and other debris from classified launches. The catalogue covers objects in LEO, MEO, HEO and GEO.

Coverage is not complete: some objects are observed only sporadically, and especially the coverage of geosynchronous objects is spotty due to the uneven distribution of observers around the globe (concentrating in Europe and North America). As almost all observers are located in the Northern Hemisphere, several objects in LEO are optically temporarily lost during wintertime. Some of these objects nevertheless are being tracked by radio throughout the winter, using Doppler curve fitting

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techniques, after which they are optically recovered again in spring. In general, the LEO population of 'classified' objects is better covered in the catalogue than the MEO, HEO and GEO population (Tab 1).

Table 1. Number of "classified" objects tracked per orbital class (status mid-January 2023).

Orbit type		n objects
LEO	(a)	140
MEO	(b)	8
HEO	(c)	20
GEO	(d)	48
GTO	(e)	6
TOTAL		222

a. *Low Earth Orbit* (Mean Motion > 11.25 and eccentricity < 0.25)
b. *Medium Earth Orbit* (600 min < orbital period < 800 min and eccentricity < 0.25
c. *Highly Elliptical Orbit* (Mean Motion ~2.0 rev/day, eccentricity > 0.25)
d. *Geosynchronous Orbit* (0.99 < Mean Motion < 1.01 rev/day and eccentricity < 0.01)
e. *Geosynchronous Transfer Orbit* (eccentricity > 0.25 and orbital inclination < 50 degrees)

It should be noted that the semi-automated systems used by some ISO's also record astrometric data on large numbers of *non-classified* objects. And apart from astrometric data, they also provide information on optical behaviours. Members of the ISO community have recently for example provided data on the optical characteristics of Starlink satellites and the Bluewalker 3 prototype (2022-111AL) in support of the efforts by the International Astronomical Union Center for the Protection of the Dark and Quiet Sky from Satellite Constellation Interference (IAU-CPS) to assess the impact of satellite constellations on the night sky [6].

3 EQUIPMENT AND PROCESS

ISO's track with simple equipment on a shoestring budget. Their equipment ranges from simple binoculars and stopwatch on the 'old skool' end, to DSLR's or sensitive CCTV or CMOS/CCD cameras with fast photographic lenses and GPS time management on the sophisticated end.

3.1 Astrometry

Astrometric processing of the observations is done with a variety of software suites and scripts, some specifically developed for this kind of observations (e.g. the *STVID* suite for video observations, or the *ObsReduce* program for optical observations with binoculars), some originally developed for other purposes (e.g. TANGRA which was originally developed for astrometry on video observations of fast moving Near Earth Asteroids). The astrometric data are posted on the Seesat-L list or directly sent to analysts, and are processed by a member who runs them through orbit determination software and maintains and publishes the orbital element catalogue [5] derived from the data. Various other analysts frequently step in with orbital determinations and analysis as well, especially after initial observations of new launches, or following the detection of orbital manoeuvres or interesting proximity operations.

3.2 Camera systems used

Fig. 1 and fig. 2 show two examples of camera equipment used within the group.

Example A in fig. 1, the setup operated by station 4353 (Marco Langbroek, Leiden, the Netherlands), consists of a sensitive WATEC 902H2 Supreme Low-Light-Level CCTV camera, which can be equipped with a variety of photographic lenses. The author uses this camera with (depending on the type of target) either a 1.2/50 mm Pentax, a 1.4/85 mm Samyang, or a 2.0/135 mm Samyang lens. These lenses provide a field of view of respectively 7.4 x 5.5 degrees (50 mm), 4.4 x 3.3 degrees (85 mm), and 2.7 x 2.0 degrees (135 mm).

Figure 1. Example (A) of a camera system used by ISO's: the camera setup of station 4353 in Leiden, the Netherlands, operated by M. Langbroek. This is a WATEC 902H2 Supreme Low Light Level CCTV camera, with time management by GPSBoxsprite-2 GPS time inserter. The lens shown is a Pentax 1.2/50 mm lens, but a Samyang 1.4/85 mm and a Samyang 2.0/135 mm lens are used as well..

The analogue output signal of the camera is fed through a GPSBoxSprite-2 GPS time inserter, which marks each video frame with a 1PPS based time stamp. The video signal is then digitized by an EZCap dongle and recorded on a laptop, in AAV-format, using OccuRec software [7]. The recorded video frames are astrometrically solved after the observational session using TANGRA software [8].

Depending on the optics used, this system can record, at 25 frames/second, satellites up to magnitude +7 to +10, occasionally even capturing 3U cubesats (fig 3). For fainter distant objects in HEO, MEO and GEO, a Canon EOS DSLR photographic camera with a 2.0/135 mm lens is used which reaches well beyond mag +10 for slow moving objects when using multi-second exposures. This system has a 25 x 17 degrees field of view.

Example B in fig. 2, the setup operated by station 4171 (Cees Bassa, Dwingeloo, the Netherlands), consists of a ZWO ASI 1600MM PRO CMOS camera equipped with a 1.4/85 mm lens. It is used with a computer-controlled Alt-Az mount. This system is semi-automated.. The digital output of the camera is directly processed on a PC using the STVID software suite Bassa developed for the purpose [9]. This same suite controls the mount.

Time registration is from the PC clock, synchronized through NTP. This system records objects to magnitude +10. The field of view of this camera is 11.85 x 8.95 degrees. Several other ISO’s operate similar systems using STVID.

3.3 Accuracy

Depending on what camera-lens combination is used, the astrometric accuracy of these systems is in the order of 30” to 5”. For an object observed at a range of 500 km, this corresponds to positional accuracies in the order of ~75 to ~15 meter. As the actual positional accuracy is not only dependent on astrometric accuracy but also on timing accuracy, a GPS- or NTP-based timing accuracy of 0.001 to 0.01 second introduces an extra inaccuracy in the order of 10-100 meters.

Figure 2. Example (B) of a camera system used by ISO’s: the camera setup of station 4171 in Dwingeloo, the Netherlands, operated by C. Bassa. This is a ZWO ASI 1600MM PRO CMOS camera, fitted with a Samyang 1.4/85 mm lens.

Figure 3. Video capture of a 3U Cubesat: the Stork 4 satellite (2021-058C) imaged at a range of 552 km on 17 July 2021 by station 4353 in Leiden, the Netherlands. Stack of 25 frames obtained with a WATEC 902H2 Supreme (see fig. 1). The camera was fitted with a Samyang 2.0/135 mm lens for the occasion.

4 TRACKING NEW LAUNCHES

The tracking of ‘classified’ objects by this group usually starts at launch. Even before launch, a general idea often exists of the orbital plane and altitude aimed for. This information is derived from the locations of the parts of airspace and maritime space that are closed for the launch, e.g. the splash-down and deorbit areas of rocket stages, which is public information published in Maritime Navigational Warnings [13] and NOTAM’s. The relative locations of these areas define a direction of launch, and from that the orbital plane aimed for, via the relations [10]:

$$\beta = \beta_1 \pm \lambda \qquad (1)$$

$$\sin \beta_1 = \cos i / \cos L \qquad (2)$$

$$\tan \lambda = (V_L \cos \beta_1) / (V_0 - V_{eq} \cos i) \qquad (3)$$

(where β is the launch azimuth, β_1 the inertial launch azimuth, λ the correction due to the velocity of the earth’s rotation, i is the resulting orbital inclination, L is the launch site latitude, V_L is the inertial velocity of the launch site and V_{eq} is the velocity of the earth's rotation at the equator).

Directly after launch, observers start to scan the predicted orbital plane for new objects, and quite often the newly launched object is located on-orbit within the first few revolutions.

4.1 Example: NROL-91

Case in point, and a by no means exceptional example of this, is the recent NROL-91 launch. This launch of a classified satellite (USA 338, COSPAR 2022-117A) for the National Reconnaissance Office (NRO), took place from Vandenberg Space Force Base on 24 September 2022 at 22:25 UTC [11]. It is believed by some analysts to be an improved ADVANCED CRYSTAL electro-optical reconnaissance satellite, even though it was not launched into a sun-synchronous orbit [12].

A Maritime Navigational Warning (HYDROPAC 2592/22 [13]) was published for this launch establishing four hazard areas in the Northeast Pacific Ocean (areas A to D in fig 4). These defined a launch direction corresponding to a 73.6 degree inclined, Low Earth Orbit (the latter underlined by the position and time window of the upper stage deorbit area, one full revolution after launch). From the similarity of the orbital inclination to that of an earlier launch, NROL-71 (USA 290) launched on 19 January 2019, and the location and general time window for the upper stage deorbit hazard zone (area D in fig 4), an orbital altitude near 400 km was initially guessed.

An object in this rough orbit estimate would make a visible pass over Northwest Europe some six hours (four orbital revolutions) after launch. Indeed, around 4:17 UTC on September 25 on the fourth revolution, Marco Langbroek in downtown Leiden (the Netherlands) and Cees Bassa in Dwingeloo (the Netherlands) observed and imaged a previously unknown object with movement conforming to the pre-launch orbital plane estimate. It was bright and at magnitude +2.5 to +3 easily visible to the naked eye, even from Leiden town center.

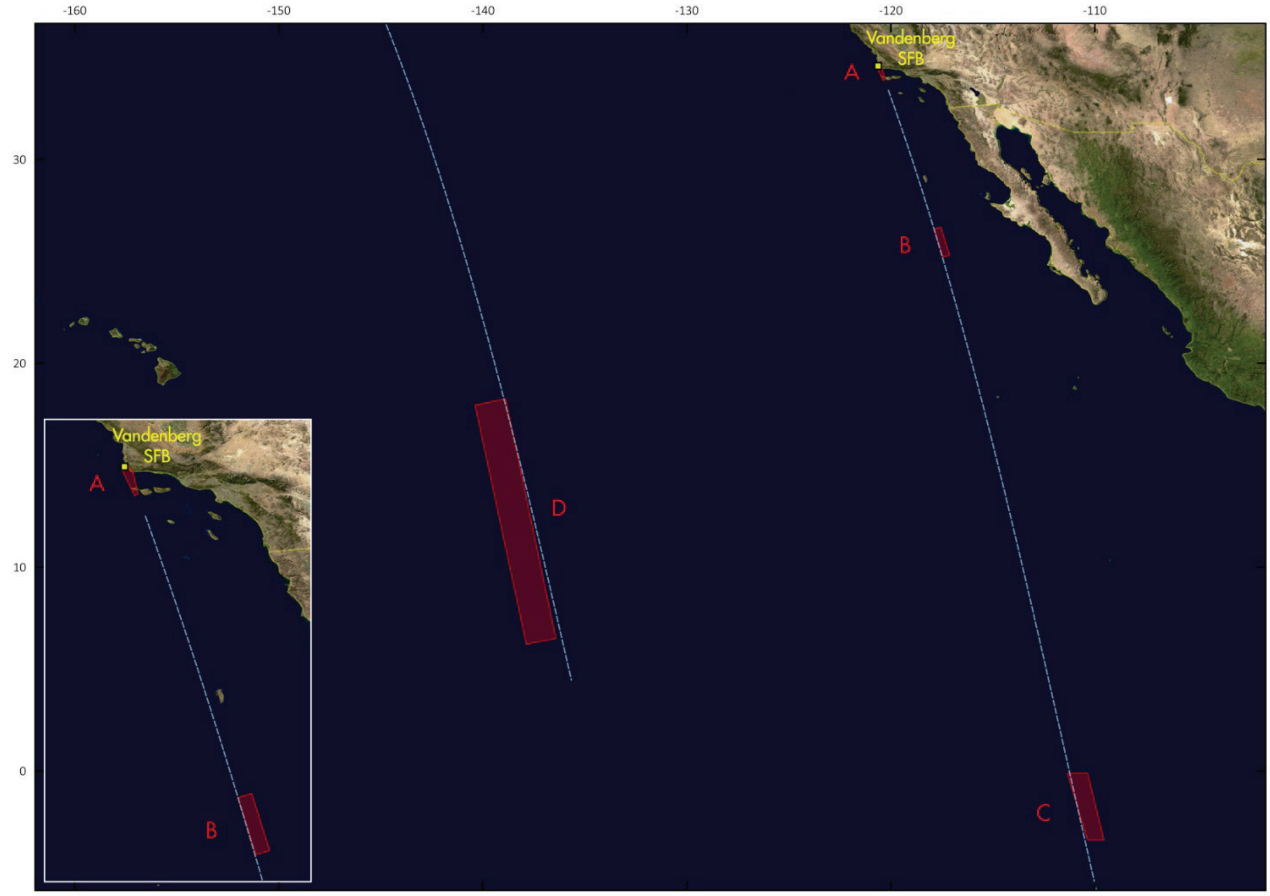

Figure 4. Hazard areas from Maritime Navigational Warning HYDROPAC 2592/22 [13] for the classified NROL-91 launch plotted, defining the launch direction. NROL-91 was the launch of the USA 338 satellite on 24 September 2022.

Fig 5: USA 338, the NROL-91 payload, imaged in a partly cloudy sky on its fourth revolution, six hours after launch, on 25 September 2023 between 04:17:20.02 – 04:17:25.02 UTC by Marco Langbroek from Leiden, the Netherlands, using a Canon EOS 80D DSLR and Samyang 1.4/35 mm lens. USA 338 has created a trail in this 5-second exposure at 800 ISO.

Fig. 5 shows one of the photographic captures obtained from Leiden, the Netherlands. The object's sky track was close to predictions based on the pre-launch orbit estimate. Continued optical and radio tracking by several observers over the consequent days established it in a 396 x 416 km, 73.5 degrees inclined orbit.

5 WHY CLASSIFYING ORBITS IS WRONG

The reasons why ISO's track these 'classified' objects are varied. Apart from a simple "because we can!", it includes a realization that keeping the orbits of certain satellites 'secret' goes against core notions of transparency and accountability regarding activities in space, such as laid out in Resolution 222 (XXI) of the United Nations (the 'Outer Space Treaty' [14]), specifically Articles X and XI.

Space-based intelligence gathering nowadays plays an important role in shaping geopolitical decision making, which affects us all. Our modern societies and economies have moreover become highly dependent on Space, and hence vulnerable to what happens in space. This translates to a necessity for transparency and accountability when it comes to the activities of Nations and organisations in space, both civil and military.

From the viewpoint of Space traffic management, it is undesirable to have a situation where the presence of certain classes of tracked objects is kept undisclosed. The idea that the orbits of certain (military) space assets can be kept 'secret' is highly unrealistic anyway, given that some of the most prominent of them are easily visible to the naked eye during a pass. Such delusions of secrecy can in fact be dangerous, as unrealistic notions might foster unrealistic decision making.

6 ADVANTAGES OF LOW COST EQUIPMENT

Government-funded tracking networks can learn and benefit from the work of ISO's. Relatively low cost equipment using commercial-off-the-shelf (COTS) components could be a way forward to quickly add optical tracking capacity to increasingly strained tracking networks, especially with the rise of mega-constellations. One advantage in addition to modest cost versus the potential for high quantities, is that this kind of equipment can be made mobile.

This approach was recently taken by the FOTOS consortium of Leiden University, Delft Technical University and the Royal Netherlands Air Force (RNLAF), who are developing a low cost optical SST capacity for the RNLAF using COTS components [14]. Delft Technical University and Leiden Observatory are currently developing and testing a new robotic tracking camera that was inspired by and is basically an improved version of the video equipment used by ISO's, using a higher (industry) grade sensor with a larger field of view.

7 CONCLUSIONS

A group of *Independent Space Observers* (ISO's) has demonstrated that tracking large and medium sized artificial objects in earth orbit, and occasionally even smaller ones such as cubesats, using relatively inexpensive equipment made of commercial-off-the-shelf components is feasible.

Such relatively low cost equipment could be a way forward to quickly add optical tracking capacity to increasingly strained tracking networks, especially with the rise of mega-constellations.

ISO's have also demonstrated that certain objects whose orbits are kept "classified" by the responsible Nations, can often easily be observed using such equipment. This underlines how highly unrealistic it is to expect that the orbits of certain (military) space assets can be kept 'secret'.

From the viewpoint of Space traffic management, it is actually undesirable to have a situation where the presence of certain classes of tracked objects are kept undisclosed. The practise moreover goes against core notions of transparency and accountability regarding activities in space, such as laid out in Resolution 222 (XXI) of the United Nations (the 'Outer Space Treaty' [14]).

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