Upcoming satellite detection and tracking capabilities of the Australian National University

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ABSTRACT

With ever rising amounts of satellites and debris in orbit, tracking capabilities need to be increased and upgraded on a global scale to keep up with the continuous growth of objects to be tracked in orbit. It is important to have more sensors distributed all over the world to support space traffic management (STM) and space situational awareness (SSA) efforts. Also needed is a variety of sensors with different capabilities accommodating the different characteristics of different satellites in different orbits, so that different features of satellites can be measured. Telescope facilities solely dedicated for the purpose of STM and SSA are expensive to build and mostly not yet commercially viable, especially when new techniques are being developed to improve detection and extent tracking times.

The Australian National University has identified how their existing and future optical telescopes can be repurposed for space situational awareness and is putting considerable effort into implementing SSA detection and tracking capability into established and newly developed facilities.

We are presenting three optical telescope facilities in this paper and show how their capability can be harnessed for SSA applications:

- SkyMapper, an already established optical telescope dedicated to a Southern sky survey in the visible, but also capable of geostationary satellite detection; this is a 1.3m class wide-field telescope originally designed to conduct astronomical surveys and is therefore capable of detecting satellites and debris in its field of view.
- the Dynamic REd All-sky Monitoring Survey (DREAMS) telescope suitable for satellite detection in low Earth orbit in the short wave infrared (SWIR); the DREAMS telescope is a 0.5m astronomical telescope that is capable of detecting low Earth orbit objects and performing follow-up tracking.
- The third telescope is a 0.7m class telescope situated in an optical communications ground station dedicated to developing and operating satellite laser communication technology, but also capable of hosting a satellite detection and tracking service in both visible and infrared wavelengths.

In this paper, we provide an overview of the capabilities of the telescopes described above. We showcase detection performance for SkyMapper who has been in operation for astronomical purposes since 2014, provide an update on the installation and expected tracking performance with the DREAMS telescope which is scheduled to be commissioned in the first half of 2023 and provide an overview on the status of the optical communications ground station and its planned SSA capability.

1. INTRODUCTION

The growing number of satellites and space debris object in orbit poses an increasing risk on the sustainability of the space environment. The number of space debris objects regularly tracked by the U.S. space surveillance network alone sits at 25,209 as of 4 May 2022 [1] and this number will increase rapidly over the next few years. Accessibility to space has become more affordable over the last years and rocket launches with smaller but more satellites on board are now offered by several launch companies. The biggest threat to a sustainable operation of satellites within this environment is the planning and commissioning of mega constellations. Several constellations are being planned and some have already started to be launched. There will be as many satellites launched into orbit over the next few years as there are currently in orbit, or even more [2]. Rocket bodies, mission related objects, dead satellites and other fragmentation objects are causing debris that is uncontrollable. Despite increasing efforts of sustainable behavior in space, researchers are in agreement that the current debris situation is unsustainable and that the amount of debris in orbit will get to a point where collisions are causing an exponential, irreversible growth of debris objects (a.k.a. the Kessler syndrome) [3]. It is clear however, that both detection and tracking capabilities as well as capacities need to be increased globally to cater for current and future detection and tracking demands.

To cater for this growing demand in tracking capacity and diverse capabilities, the Research School of Astronomy and Astrophysics (RSAA) at the Australian National University (ANU) has started upgrading existing and planned optical telescope facilities to be capable of tracking satellites throughout various orbital regimes.

Upgrading telescope is often not feasible, mostly because of financial reasons due to necessary major mechanical or electronic upgrades. Additionally, high resolution, small field-of-view astronomical instrumentation are often designed and optimized with long exposure times leaving them unsuitable for space situational or space domain awareness (SSA and SDA respectively) applications. Astronomical all-sky survey telescopes, however, are usually designed with faster detectors and have a bigger field of view. Additionally, different instruments are optimized for different wavelength regimes, which can be useful to gain additional information about the detected objects. Furthermore, observations in the short wave infrared (SWIR) during twilight hours extend the amount of time available for detections.

RSAA has used its wide-field survey telescope SkyMapper to track geostationary satellites. Its capability is showcased in Section 2 of this paper. We are also in the process of commissioning a wide-field telescope that operates in the infrared wavelength regime and is equipped with a low Earth orbit (LEO) tracking capable mount. Its envisioned use for SSA/SDA applications is explored in Section 3.

Furthermore, telescopes for laser communication purposes bring along already the capability to detect and track LEO satellites. They are usually not fully used to capacity, because free space optical communication technology is not yet fully commercialized and the space segments are not fully developed yet. We are building an optical communication ground station (OCGS) as a testbed for optical communication that will also provide opportunities for SSA and SDA applications. These are explored in Section 4 before a summary is provided in section 5.

2. THE SKYMAPPER TELESCOPE AS SATELLITE DETECTION TELESCOPE

The first telescope we present in this paper is the SkyMapper Telescope. The SkyMapper Telescope [4] is a robotic 1.3 m optical telescope at Siding Spring Observatory at 1170 m elevation near Coonabarabran in rural New South Wales, Australia and it is operated by the Australian National University. Since 2014, it has been conducting the SkyMapper Southern Sky Survey, the SkyMapper Transient Survey [5], and optical follow-up of gravitational wave events [6].

As the telescope was designed for astronomical purposes, the dome and telescope drives cannot operate fast enough for LEO objects. Hence, the telescope is restricted to observe satellites in and near geosynchronous orbits (GEO). However, due to the telescope's developed telescope control software (TCS), upgrades necessary to operate the telescope to track geostationary objects were manageable. To accommodate observations in and around GEO and the integration of publicly available three line elements (TLE), some changes were made to software components and data pipelines that were originally developed for sidereal tracking.

SkyMapper is a *f*/4.8 telescope operated and it has a 5.7 deg^2 field of view, covering a square 2.4 deg × 2.4 deg area with a fill factor of 91%. The installed instrument is a 268-Mpix imager with a pixel scale of 0.5 arcsec/pix.

The spatial resolution of SkyMapper images is limited by atmospheric turbulence to typically 2 to 3 arcseconds FWHM (4 to 6 pixels) corresponding to a physical scale of 350 to 525 metres at the distance of a geostationary object. Given the fast survey mode that SkyMapper is capable of, the telescope can scan the entire visible GEO belt in one night.

Fig. 1 exhibits an example of a detection made of object in GEO. It shows an image of two detected and identified Australian GEO satellites, Optus D3 and Optus 10 and an unidentified, much fainter object moving at 3.7deg per hour relative to the two Optus satellites in Geostationary orbit. A sequence of five consecutive images with exposure times between 10 and 60 seconds are taken at fixed telescope position resulting in most GEO satellites staying in the same pixel position in contrast to the stars. The repeat images therefore useful to differentiate satellites from star trails.

Work has since been undertaken to identify how data pipeline and data analysis processes can be improved to automate telescope operation and detection of GEO objects.

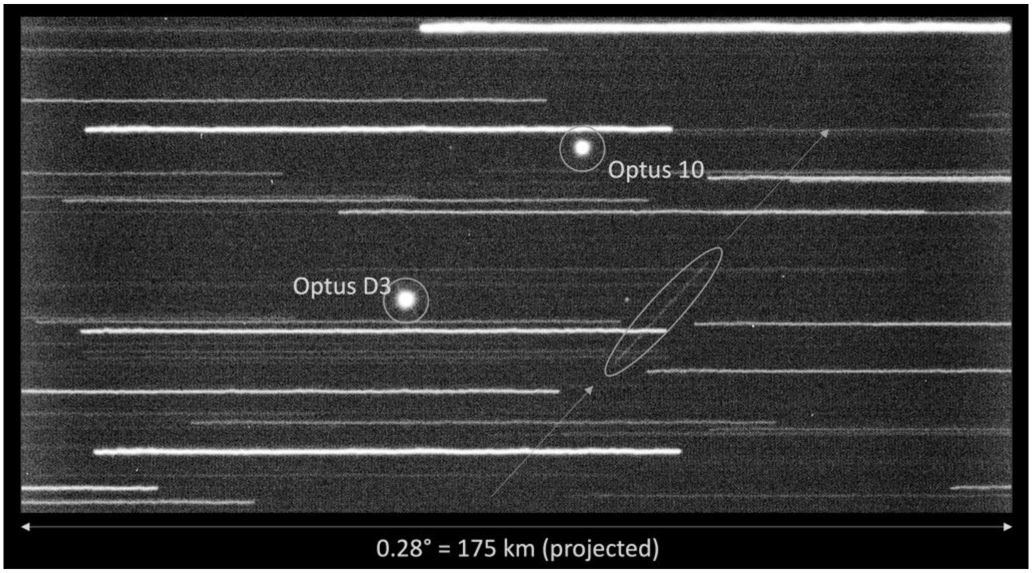

Fig. 1: Image of Optus D3 and 10 satellites and an unidentified object taken with SkyMapper

3. THE DREAMS TELESCOPE AS SATELLITE TRACKING TELESCOPE

The second telescope we would like to present in this paper is the DREAMS telescope. Similar to the SkyMapper telescope, the DREAMS (Dynamic Red All-sky Monitoring Survey) telescope [7] is an astronomical optical telescope, and it is also being developed to perform all sky surveys. In contrast to SkyMapper, DREAMS is a smaller (0.5 m) optical telescope with a field-of-view of 3.75 deg^2, and is capable of slewing at much higher rates to accommodate LEO satellite detection. DREAMS is designed to operate in the infrared wavelengths at 1 - 1.65 μm. Fig. 2 shows a model of the telescope. The telescope is mounted on an equatorial mount from ASA Astrosysteme Austria. The telescope uses a novel modular camera design resulting in a field-of-view of 3.75 square degree. The pixel size on the sky is 2.48 arcsec square covered by six 1280 x 1024 Indium Gallium Arsenide (InGasAs) detectors. It will operate robotically, performing a complete survey of the sky in J- (centred on 1.25 μm) and H-bands (centred on 1.65 μm) with a depth of 17.2M_{AB} (AB magnitude) on a weekly cadence. The operation model will also support a “Target of Opportunity” mode to perform specialized searches such as gravitational wave follow-up, high-energy neutrino follow-up and fast radio bursts.

During its regular survey operation, DREAMS will be capable of capturing a large number of satellites and near-earth objects. In each of its 8 second exposure, a plethora of GEO and LEO targets will appear as short trails from which orbits can be deduced. Thanks to a fast German equatorial mount, the DDM500, the telescope is capable of speeds of 2 deg/sec and accelerations of 2 deg/sec^2 which are sufficient to track some of the lowest, hence fastest, LEO targets – not usual for most Astronomical telescopes that tend to sit and stare for long periods of time in comparison. With this capability, our goal is to add such observations in our “Target of Opportunity” model and dedicate telescope time to observe SSA target that require particular attention. In addition, and perhaps even more exciting, we have conducted a study into the feasibility of using DREAMS to carry out SSA observations at twilight. Until now, optical SSA observations are overwhelmingly done at visible wavelengths [9, 10]. This is largely due to the cost effectiveness of the instrumentation.

There are, however, substantial advantages in adding short wave infrared observations to the visible arsenal for SSA, all of which result from the properties of the twilight sky. Geostationary satellites, that appear roughly constant in position above the same location, that is close to zenith in Australia, become rapidly faint in the visible once sky brightness changes during twilight conditions. However, at short wave infrared wavelengths, such as the astronomical ‘H’ band, centred around 1.65 μm, the infrared sky itself is sufficiently dim to enable satellite tracking.

Fig. 2 The DREAMS telescope consists of a 0.5m optical telescope assembly that feeds a six-channel infrared camera payload [8]

For LEO satellites, night observations cannot be made easily at visible wavelengths as they are fully obscured by the Earth, i.e. pointing in the direction of Earth's shadow. The advantage of twilight in this case is that satellites can be observed in full solar reflectance near zenith, making these low altitude objects fully observable by DREAMS even before civil twilight conditions are established. More importantly, twilight observations can be done on astronomical telescopes like DREAMS which are not otherwise used during those hours for astronomical purposes.

To quantify the potential of using DREAMS for dedicated SSA observations during the twilight hours, we have made sky background measurements in the H-band during those hours using a prototype system. Fig. 3 shows the brightness of the sky obtained using the DREAMS camera on a smaller telescope as a function of solar angle. The change in brightness is fitted to a piecewise twilight function used by [11, 12] to refer to the different slopes during early and late twilight.

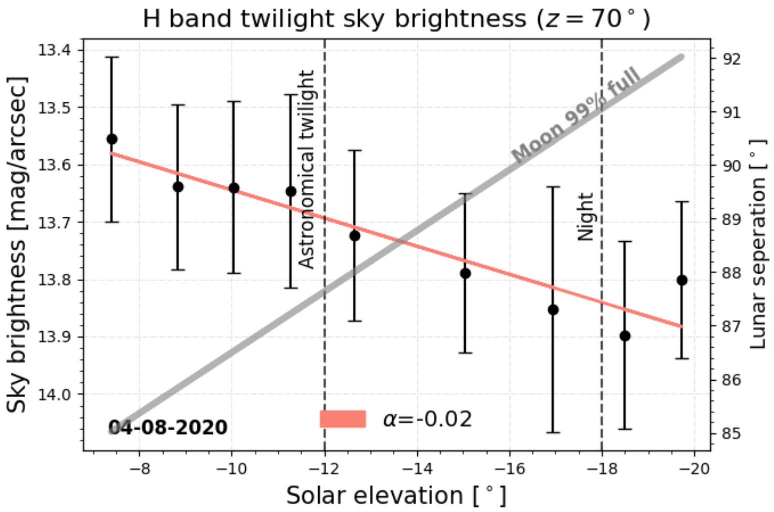

Fig. 3 SWIR sky brightness in H at twilight measured with one of the DREAMS detectors 1280SCICAM and 0.25m Bintel telescope. Separation angle between telescope pointing and moon is shown as grey solid line and labelled on the right y-axis. α refers to the linear slope of the twilight function [11].

In addition, we can calculate the signal-to-noise ratio (SNR) of the satellite brightness and the sky brightness. We take the visual magnitudes at a variety of orbital heights from [13] and calculate the magnitude ratio in H-band (m_H) and the visible (m_V) from the solar spectral flux density after atmospheric transmission (approximately 1.6W/m^2/nm in V and 0.2W/m^2/nm in H) [14,15] with the equation 3.1:

$$m_H = m_V + 2.5\log\frac{f_H}{f_V} \qquad (3.1)$$

to be m_H-m_V=2.3 assuming reflectivity is uniform across the visible and near infrared (NIR) [16,17]. Combining these calculations with our sky brightness measurements, we can predict when a detection of a LEO satellite could feasibly be made at this wavelength with DREAMS. Fig. 4 shows the SNR for observations of multiple LEO orbits as a function of sky background in H, suggesting low to medium height LEO objects, where the majority reside, should be observable very early. It is also worth noting that early twilight can also facilitate observations in the east or west at sunset and sunrise respectively.

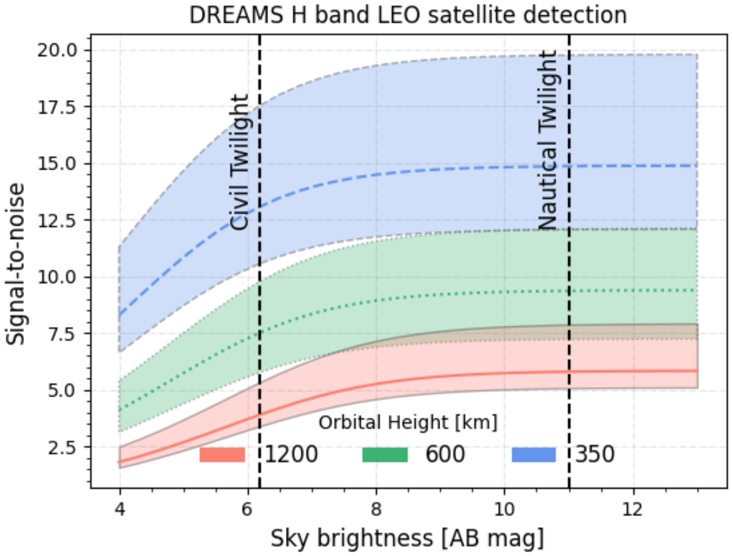

Fig. 4 Calculated signal-to-noise ratio of satellites detections in multiple LEO orbits as a function of sky brightness during twilight.

4. THE OPTICAL COMMUNICATION GROUND STATION AS SATELLITE TRACKING STATION

The SkyMapper and the DREAMS telescope showcased in the previous sections are optical telescopes, designed and built to conduct research in astronomy. Both of these telescopes have been built with the support of the Advanced Instrumentation and Technology Centre (AITC) situated within RSAA at ANU. The AITC has traditionally supported RSAA activities with ground-based optical telescope instrumentation with particular expertise in building infrared detectors, spectrographs and adaptive optics (AO) systems. Over more recent years, AITC activities have also branched out into space based infrared Earth observation systems, ground-based AO systems for satellite and space debris characterization and collision mitigation systems as well as ground-based communications systems for optical satellite communication.

To develop and apply the latter technology further, an optical communications ground station is under development in direct proximity of the AITC at Mt Stromlo Observatory in Canberra [18]. The facility will accommodate and support free space optical communication research for ground to space, space to ground and ground to ground applications. The telescope to be installed in the station will be a RC700, a 0.7 m Ritchey–Chrétien telescope from PlaneWave Instruments. Fig. 5 shows a render of the planned facility. Connected through a coudé path to the telescope, the bottom floor will house a research lab with optical tables for laser communications research. The facility will come online for laser communication operation in 2023. As the facility is capable to detect and track satellites in all orbital regimes including LEO, part of the bench space will be reserved for SSA/SDA research. The ANU is currently devising its strategy with respect to SSA/SDA instrumentation research that can be commissioned and tested at the facility taking advantage of its geographical location and easily accessible and available space for SSA/SDA instrumentation with established power and communication infrastructure. More details about the status of the facility and the telescope's performance can be found in [19].

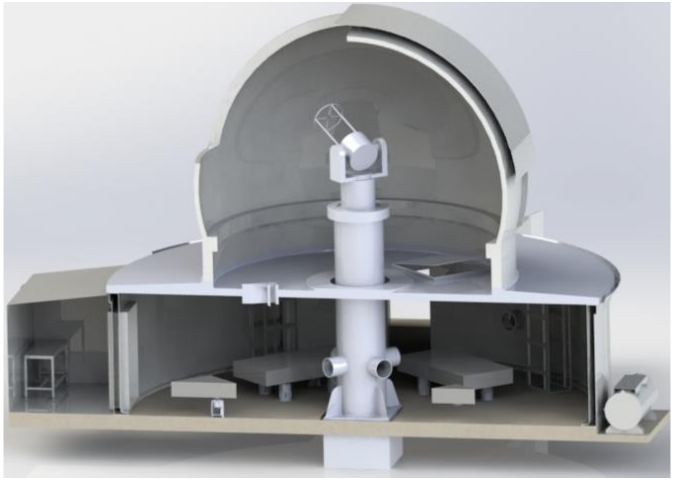

Fig.5 Layout of the Optical Communications Ground Station at Mt Stromlo with a coudé path and optical bench space on the ground floor [18].

The OCGS will also be part of the Australia/New Zealand optical communications ground station network for next generation satellite communications [20]. This network is envisioned to have optical ground stations with 0.7 or 1 m class telescopes in New Zealand, at Mt Stromlo, Canberra in the Australian Capital Territory, in South Australia, the Northern Territory and Western Australia. Discussions have commenced to investigate the potential to use the optical ground station network as an SSA/SDA network. This would provide Australia with a telescope network capable of performing hand over and follow-up tracking creating redundancy to overcome facility down time due to technical issues or cloud coverage.

5. SUMMARY

With the ever increasing number of satellites in orbit the global networks need to be expanded and sensor diversity needs to be increased. ANU has started to upskill their existing and new astronomical telescopes to be capable of satellite and debris tracking to enable diverse sensor development and increase tracking capability in Australia. We have introduced three telescopes owned by ANU: the SkyMapper telescope capable of GEO observations in the visible; the DREAMS telescope capable of LEO satellite detections and tracking in the infrared and the OCGS telescope capable of LEO tracking with the potential to establish an Australian tracking network.

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