Astronomical Observatories as Tools for Space Object Characterization

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Abstract

Rapid growth in commercial space activity has brought space sustainability to the forefront of Space Situational Awareness (SSA) and Space Domain Awareness (SDA). Currently, the safety and sustainability of operations in the near-Earth environment require consideration in this ever more crowded space. In addition to satellite operations, astronomical observatories are facing the challenge of minimizing the impact of the increase in satellite numbers on their operations and services. Optical and radio facilities are particularly affected in dealing with the interference this poses to astronomical data. However, this contamination in optical observations, while troublesome for astronomy, can be used as a source of high-quality satellite observations, expanding the current data sources used in SSA observations.

NOIRLab is a facility which is a partner in and runs many of the large telescopes in the world, including the Gemini Observatory, Cerro Tololo and, soon, the Vera C. Rubin Observatory. These optical telescopes encounter the bright signatures of satellites within observations, especially satellites in Low Earth Orbit. This can leave a bright streak in the image, much brighter than any other light source. To navigate this, the affected images may be disregarded or the satellite is removed in post-processing, a procedure which may lead to a loss of data. As part of ongoing work at NOIRLab, we are exploring methods to exploit these opportunistic observations of satellites with astronomical observatories which are equipped with instruments that are not routinely employed in SSA observations.

Using this unconventional astronomical data, we investigate the capabilities of these observatories to observe, identify and characterize satellites. As with many observatories, NOIRLab possesses databases of legacy observations from the various telescopes. Combining these legacy data with contemporary observations shows potential for expanding upon the data sources we can use to observe satellites and their properties, such as position, brightness and materials. This analysis presents the capabilities and drawbacks of using astronomical observatories and observations to complement current SSA observation methods. Varied instrumentation is utilized in this investigation as many data are acquired through unintentional observation and the instrument used is the one chosen for a specific astronomical observation. These are examined for their current and future utility for satellite characterization.

From this assessment, we can better understand the impact of satellite interference on optical observatories. The potential present in using these publicly available data to further characterize satellites is discussed to ascertain the advantages of various instrumentation and telescopes. Improved insight on this issue can aid in creating equitable methods for satellite operators and astronomers to minimize satellite interference in imaging.

1. Introduction

The rapid growth of the space economy has led to unprecedented increases in the number of satellites launched and planned. Currently, there are over 10,000 active satellites in orbit, with that number predicted to exceed tens of thousands in the coming decade [1,2]. While this expansion supports communications, Earth observations and new space services, it also creates challenges for space sustainability and astronomical research.

1.1 Space sustainability

A growing number of satellites equates to more traffic to contend with, not just in physical space, but also within the electromagnetic spectrum for radio and the contamination of the starry sky in the optical wavelengths by satellite reflections. This population increase has prompted suggestions and studies around orbital carrying capacities and the regulatory structures required to enforce them [3]. At the same time, astronomers experience the visible consequences of this growth by way of satellite contamination as streaks within images.

1.2 Astronomy

The presence of satellite streaks in images, appearing as extremely bright pixels, taken by professional observatories is now a well-known phenomenon, with the most catastrophic impacts seen from constellation launches. As can be seen in Fig. 1, the streaks in the background of the leftmost image show the general visibility to the naked eye of satellites from the summit of Cerro Pachon. The other two images depict what the contamination is like soon after the

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launch of a batch of Starlink satellites. Although these effects can also be caused by rocket bodies or other Resident Space Objects (RSOs), we focus here on satellites as they cause the most contamination by number.

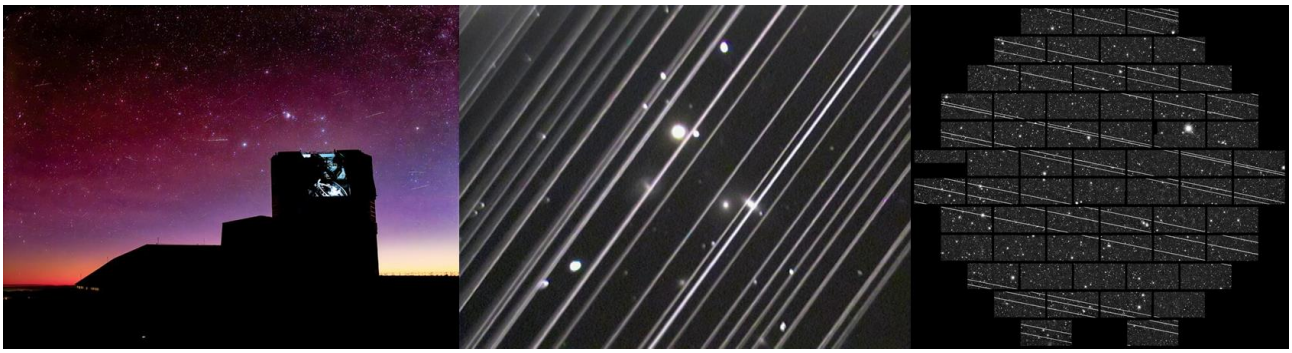

Fig. 1. Examples of satellite streaks contaminating astronomical imagery. *Left*: Naked eye visibility of satellites seen over the Vera C. Rubin Observatory. *Center & Right*: Satellite streaks as seen in astronomical images soon after a Starlink launch.

These streaks can be innocuous, not having a major impact on the target object as it may not overlap with the target object in the field. However, they are capable of resulting in bleeding into other pixels or a loss of the entire observation. Removing this contamination also creates a higher computational overhead to reduce the impact of the streaks through post-processing. This can result in degradation in the image quality as a result [4].

Mitigation strategies have been developed for operations at telescopes affecting how the observatories plan and operate their observations. Point away protocols have been developed to avoid areas during the night that may have overlap with satellites. Although these measures cannot fully mitigate the impact of satellites, particularly for survey telescopes that cannot adapt their cadence. Yet, while unintentional, these observations of satellites potentially contain scientifically valuable data that can be explored for characterization.

1.3 NOIRLab

This paper investigates how optical observatories can contribute to Space Situational Awareness (SSA) through utilizing these incidental observations, particularly the observatories operated by the National Science Foundation (NSF) National Optical Infrared Laboratory (NOIRLab). NOIRLab operates several world-class observatories across the United States and Chile, including Gemini, Cerro Tololo, SOAR and, recently, the Vera C. Rubin Observatory. These observatories observe a broad range of astrophysical phenomena and, therefore, are equipped with a large range of instrumentation providing a novel source of data for SSA observations [5].

Fig. 2. Images of NOIRLab facilities in Chile. *Left*: Cerro Tololo with the Victor Blanco 4-m telescope in the foreground. *Right*: Cerro Pachon with SOAR on the left, GEMINI-South on the right.

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In the upcoming sections, the main goals of SSA observations are determined and their input data identified. These are then used as criteria against which to assess the capabilities and limitations of astronomical facilities in providing data relevant to characterization, including orbit determination, attitude and material properties.

2. Methods

2.1 SSA Observation Goals

Different satellite operators require a variety of observation services for the various missions and applications for which satellites are used. This necessitates multiple modes of observation to accomplish the goals of every type of operator. As such, there are many data products that can be obtained through optical observations which, for SSA, is typically performed with small cameras and telescopes.

To assess what is required to use astronomical telescopes for SSA observations, we first determine the various main types of observations that are used in SSA to create useful information. This study is concentrating primarily on optical methods; therefore, the focus is on parameters that can be obtained from optical observations. These measurement parameters will form the basis of the criteria for assessing the utility of astronomical facilities.

Orbit determination is where the orbit of an RSO is determined from multiple observations. This is important to maintain custody over objects and to ensure catalogs are updated accurately. To perform orbit determination, it is necessary to identify the object, observe it over multiple passes and also to have accurate timing information. This data, along with the observer information, can then be used to calculate a precise orbit [6].

When attempting to understand the rotation rate or tumbling motion of a satellite, a light curve is used. This is the variation in brightness of the satellite over time, from which periodic variation can be inferred. Although, this method cannot determine directly the rotational motion of an RSO without including the solar phase angle of the satellite with respect to the observer. Information about the tumbling motion of a satellite is necessary when attempting to rendezvous with another object to determine the feasibility of approach [7].

Other properties that are of interest to be observed are to check for deployments of various hardware, anomalies with the spacecraft or for maneuver detection. These properties can be derived from direct imaging, assessing the material properties or can be inferred from a light curve. These observation goals and their observation criteria are shown in Table 1.

Table 1. Goals of SSA imaging and the required inputs to achieve them.

SSA Goal	**Observation Criteria**
Initial Orbit determination	• Angular position (RA/Dec) • Apparent motion/Streak length • Distance / range • Precise timestamps
Light curves	• Apparent brightness (time-series) • Orientation / rotation (attitude, solar phase angle) • Color / spectral info
Material properties	• Spectral/multi-filter data • Apparent brightness • Material / surface properties • Physical size
Maneuver detection	• Angular position (time series) • Full orbital parameters • Apparent motion • Distance / range

2.2 Astronomy

Astronomical observatories are also capable of observing satellites, although this is mainly through coincidental observations. Within astronomy, observatories are built with the goal of studying a particular astrophysical phenomenon and are thus equipped with highly specialized equipment for achieving this aim. This paper is focusing

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on optical observatories, which are typically comprised of a telescope and some array of instrumentation that can include a wide range of cameras, filters and spectrographs. The types of incidental observations that can be exploited for SSA are investigated here. With respect to SSA observations, there is a major distinction to be made when investigating the applicability of a certain observatory; whether the main mission of the observatory is to image specific targets that can be requested by observers or if the main mission is to perform a survey.

Telescopes that operate using targeted observations point specifically at the requested objects using the requested instrumentation, for example Gemini and SOAR. There are a range of capabilities within this type of telescope and their fields of view can vary drastically. In the course of normal operations, when observations for a night of observing are planned, this is also checked against what satellites may appear in the field of view over the entire duration of the observation.

Typical exposure times for astronomy images can range from 5 to 10 minutes, although can vary based on the science being performed, and usually require multiple images of the one target that will then be stacked to increase the signal-to-noise ratio. Therefore, the presence of satellites in a region is assessed over the entire period, which may be more than an hour [8]. If many bright satellites are present in the field, the schedule may be rearranged to point away from the potential contamination [2].

The other type of observatory to consider is survey telescopes, where the objective is to observe the same patch of sky or objects repeatedly over a given period of time. As shown in Fig. 3, the survey is made up of many small regions connected together to form a larger spatial image and the period of the survey adds the temporal dimension. For the Vera C. Rubin Observatory, this period is ten years. Typically, these telescopes do not observe any requested targets. With these telescopes, the impact of satellite interference can be seen more directly as they cannot employ point away strategies or any other remediations for satellites while observing.

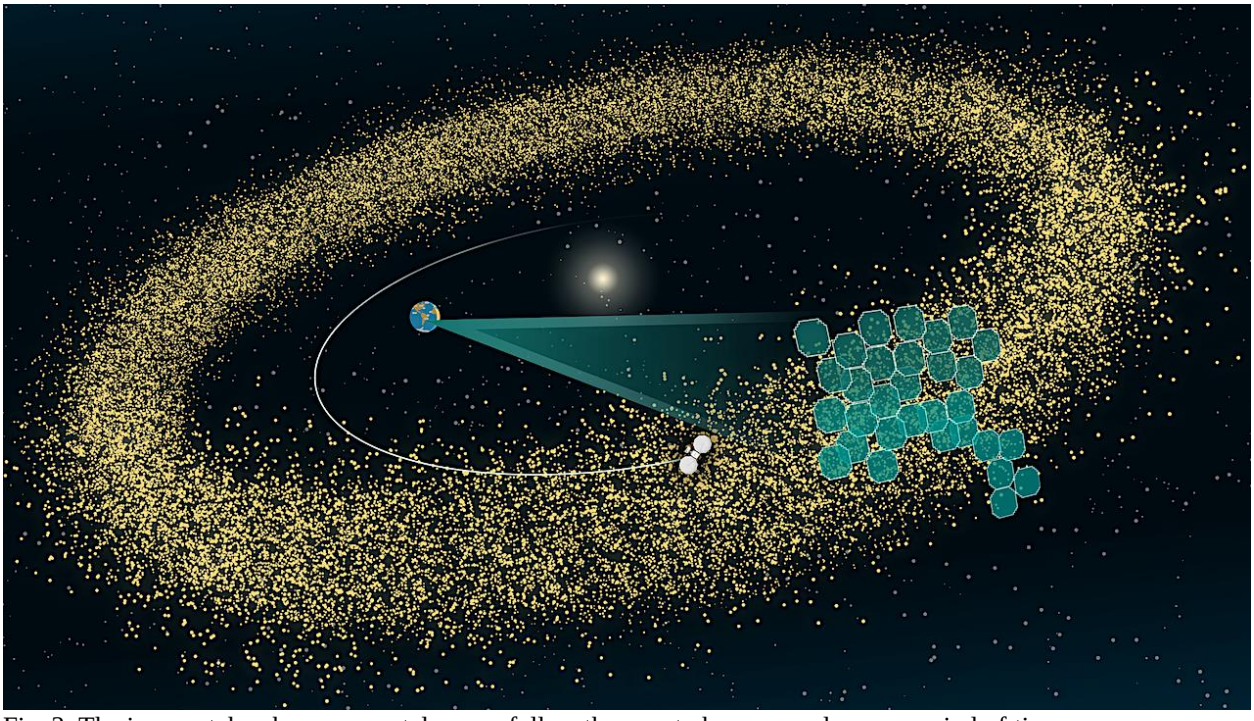

Fig. 3. The images taken by a survey telescope follow the area to be surveyed over a period of time.

Their only option for minimizing the interference created by satellites is by removing their presence through post processing in some manner. This can have varying effects on the image utility and quality depending on the telescope and the level of interference experienced in these images.

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Astronomical surveys create large databases of the observations taken over the course of the survey period. As many of these surveys are publicly funded, their data is often made publicly available. This provides a large repository of images and data that can be explored for its utility for SSA purposes.

A recent initiative that highlights this potential is the Trailblazer project, which provides an open-access repository of satellite-streaked images collected by major sky surveys [9]. Trailblazer aggregates examples of streak-contaminated images and also standardizes metadata for analysis of brightness, length, and frequency of streaks. Although, other databases, the images have usually undergone some form of post-processing, meaning that satellite streaks present in images may have been removed [10].

In this study, the capabilities of both targeted and survey observatories are assessed against the SSA goals outlined previously. We also explore how those capabilities may be improved when changes to the operations of the telescopes are considered.

3. Results & Discussion

For both types of telescopes, targeted and survey, different types of SSA observations can be ruled out immediately by the nature of how astronomical observatories are constructed. Firstly, there can be no fast observations such as tracking an object across the sky as, even though in astronomical terms some of these observatories are considered to move "fast," for SSA they are much too slow [11]. Secondly, observations at astronomical facilities do not prioritize SSA observation and almost all observations are coincidental, hence timely follow-ups or multiple observations of the same object are highly unlikely. However, due to astronomical requirements, the angular position of any object within an image and the timestamps are easily obtained.

Both the targeted observation and survey telescope capabilities are compared against the required criteria for obtaining the SSA observation goals and are presented in Table 2. The targeted observation telescope is taken to be a single optical observation including any other instrumentation normally available at these observatories. For example, the Victor Blanco 4-m Telescope has DECam (a wide-field imager), COSMOS (optical spectrograph) and NEWFIRM (infrared imager) [5]. Survey telescopes generate a large amount of data and it is made available through a database, thus we term the data from these observations as database or legacy data. Similar to the single optical observation, survey data, while observing the same portion of the sky repeatedly, does not ensure that the same satellites will be within the field. Therefore, we assume there is some possibility that a repeat observation may occur.

In assessing the attitude of a satellite or any tumbling motion, this can be done using the brightness variation over time. While it can be performed on a single image, to obtain an estimation of the tumble rate many images over the course of a satellite pass are required, as noted in Table 2.

Apparent motion, or streak length, is dependent on the individual observations. In general, the exposure time of astronomy images, around 5 minutes, is too long for obtaining the start and end points of a streak. Although, for the Vera C. Rubin Observatory, the concept of operations is to take two images with an exposure time of 15 seconds for each visit to a field giving a median visit time of 39s [12]. Therefore, there is a higher likelihood of capturing the full streak of a LEO satellite. As this is a survey telescope, this data will likely be pre-processed before being made publicly available, potentially removing any streaks present.

There are a range of filters that are always employed in astronomical observatories and almost every observatory has a basic range of filters. Using these, it is possible to infer certain properties about various materials on the satellite if it is particularly bright in a given filter. However, for more specific knowledge on the materials, it is necessary to observe a given target with multiple filters, which requires multiple observations. The range to an object and full orbital parameters cannot be calculated from a single image, although it may be possible with survey data if there are observations taken of the same object across multiple epochs.

As can be seen in Table 2, utilizing single incidental observations has less potential to meet the criteria required for the previously defined SSA goals than mining an astronomical database. There is a degree of uncertainty in the legacy data as it is highly dependent on if the data contains repeat observations of the same object.

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Table 2. Comparison of the capability of meeting the criteria required for SSA observations for both targeted, single observation and the database of various surveys.

Criteria	**Single Optical Observation**	**Astronomical Database / Legacy Data**
Angular position (RA/ Dec)	Yes	Yes
Apparent brightness (magnitude)	Yes	Yes
Orientation / rotation (attitude)	Not directly	Possibly (if light curves over time exist)
Apparent motion / streak length	Yes (if exposure captures motion)	Yes, over multiple epochs
Spectral/Material Properties	Yes	Yes, if database includes multifilter / spectral observations
Full orbital parameters	No	Yes (if enough historical observations exist)
Distance / range	No	Possibly (if combined with parallax from multiple epochs)

4. Future Work

The properties presented here are those that could be measured directly by current observatories without much change to their normal operations. While still prioritizing astronomical observation time and hardware, there are some opportunities to improve the quality of observations or expand upon the parameters that are measurable.

A major challenge in using opportunistic data is the minimal or lack of repeat observations of a specific object. Improvements could be made if a targeted observation campaign was run to take repeat observations of a given object. Observations for LEO satellites can nominally be performed shortly after sunset or before sunrise. These times are generally too bright for clearly imaging astronomical objects with a suitable signal-to-noise ratio and, as such, are opportune times to maximize the observing potential of these facilities without greatly impacting science operations.

Another avenue for exploration is the observatory all sky cameras which are used for monitoring weather conditions at the sites. Almost every professional observatory is equipped with an all sky camera, if not multiple, or other sensors for climate data. Sometimes this data is a live stream and not stored, but other facilities have the capabilities to store the images. This creates databases of imagery at ideal astronomical locations which are comprised of all sky imagery taken every night.

Some companies currently use similar all sky cameras to perform their SSA observations [13]. If the data from all sky cameras could be adapted and used for SSA, this would improve the potential measurements that are available as multiple observation epochs could then become available. Using these cameras has the potential to have large geographic diversity, as seen in Fig. 4, and increase the potential for maintaining custody of objects. A current limitation of this is that there does not currently exist a robust framework for collecting and sharing this information.

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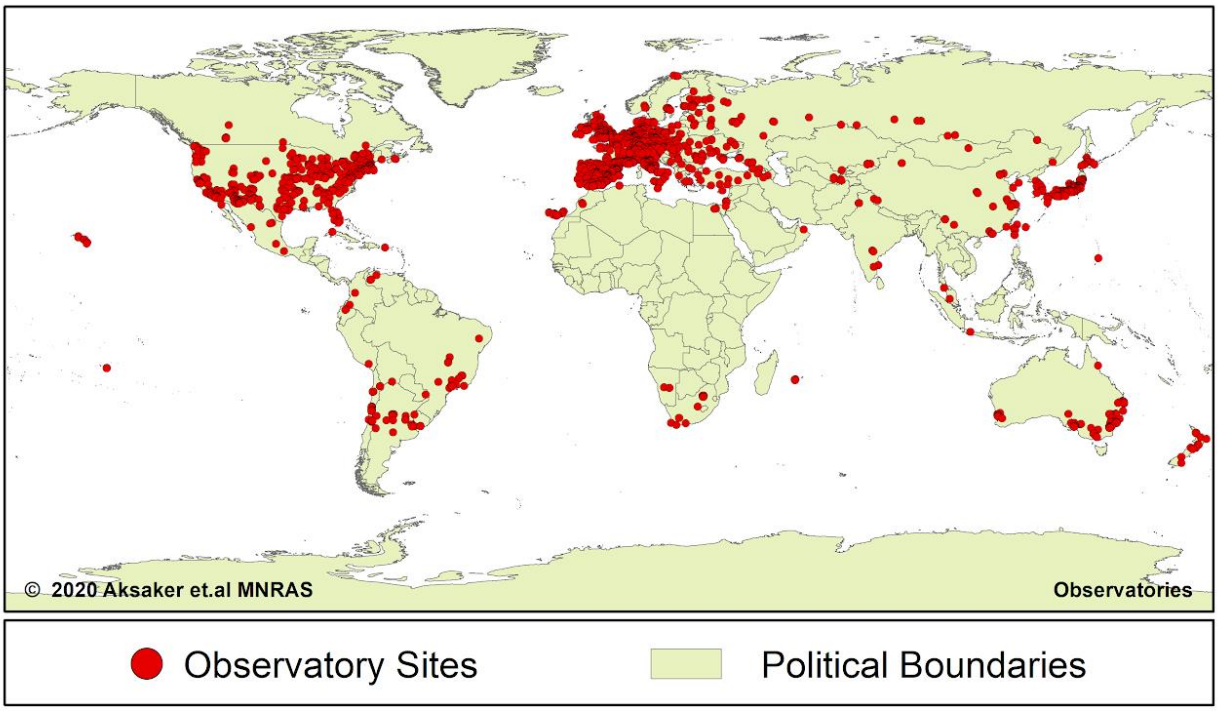

Fig. 4. A map of around 2,100 professional and amateur observatories. These are potential locations of currently operational all sky cameras [14].

Collaborative efforts between astronomers and the satellite industry are improving in recent times, especially with the introduction of initiatives like the IAU Centre for the Protection of the Dark and Quiet Sky (CPS) [15]. As a part of CPS. NOIRLab is helping to drive collaboration across the space sector to minimize the impact of space activities on astronomy and to provide value to the community. Within CPS, there are active outreach and partnership activities between academia and industry to improve communication, knowledge and data sharing across the space sector. As shown in this study, leveraging dedicated astronomical infrastructure for SSA is a complementary approach, expanding observational coverage and adding photometric and spectral capabilities to the community.

5. Conclusion

Astronomical observatories can offer valuable complementary observations to SSA. The benefits of these observatories are in precise astrometry, brightness measurements, and multi-decade archival databases that may have incidentally captured satellites. These datasets can be exploited for orbit refinement, light curve analysis, and material inference. Limiting factors for using these data are the long exposure times, lack of direct range measurements and possibly no repeat observations. There are further opportunities to investigate integration of all-sky cameras and using twilight observations as avenues for obtaining observational data without impacting the nominal operations of the observatory.

Collaboration between astronomers and SSA operators will be vital to progress with any use of astronomical data for SSA. This improvement in our understanding of satellites using astronomical observatories can potentially lead to more effective mitigations in contaminating astronomical imagery and aid in improving the sustainability of Earth's orbital environment.

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