All-Sky Electro-Optical Tracking of Mega-Constellations in Low Earth Orbit

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ABSTRACT

We investigate the utility of all-sky electro-optical (EO) sensor systems for enhancing space domain awareness (SDA) and space traffic management (STM) with respect to mega-constellations in low Earth orbit (LEO). We derive results using actual sensor system performance and real weather data, and we focus on the extent to which a network of such EO sensor systems can be used for tracking both the primary and secondary resident space objects (RSOs) involved in a particular conjunction event in order to better inform operator action. Particular attention is given to conjunctions involving Starlink and OneWeb constellations with other objects in LEO. Through detailed simulations, we demonstrate that a network of all-sky EO sensor systems offer an effective approach to mega-constellation tracking and conjunction assessment at scale.

1. INTRODUCTION

The low Earth orbit (LEO) satellite population is burgeoning. Commercial, academic, and government programs continue to see proliferated LEO constellations as a key to success across applications ranging from communications to Earth observation. This large and growing population necessitates and complicates the need for space domain awareness (SDA) and space traffic management (STM) at scale. As the LEO population grows, so do situations that pose risk to spacecraft and the relevant missions that they serve. Some examples include rendezvous and proximity operations (RPOs), orbital insertions, reentries, and, most relevant to the present work, conjunction events.

Radars have historically been the sensor phenomenology of choice for LEO SDA/STM at scale. A single radar system can observe thousands of objects daily and is immune to lighting conditions (day/night), cloud cover, and object illumination conditions. However, these systems are costly to build and operate, limiting the number of sites in operation around the world and the ease with which new systems can be deployed to meet increasing SDA/STM needs.

The Slingshot Global Sensor Network (SGSN), formerly the Numerica telescope network (NTN), comprises an optical sensor network of 20+ sites across five continents along with a custom-tailored data processing and calibration infrastructure. The SGSN has operated 24/7 for the past five years while undergoing continual improvement and expansion. The network provides global geographic coverage (including 8 sites in the southern hemisphere at the time of writing) across all orbital regimes (LEO, MEO, GEO, HEO, GTO, X-GEO). The SGSN is comprised mainly of medium-aperture robotic telescopes that provide precise astrometry and photometry, good detectability, and support on-demand tasking with optional "ASAP" requests [1]. Further, the telescopes use high-speed professional-grade robotic mounts that enable rate tracking for objects moving at high angular speeds (e.g., objects in LEO). Several of these telescopes permit daytime tracking through infrared-optimized optics and patented image processing routines, making such telescopes "cathemeral" (active during day and night) [2]. The SGSN also includes several wide field-of-view robotic sensor arrays that exchange breadth for depth and operate in a staring mode to collect continuous observations on all objects in GEO (or across a given swath of sky). Like the medium-aperture telescopes, the sensor arrays provide high-quality astrometric and photometric observations, thus enabling object characterization and persistent monitoring beyond the typical scope of catalog maintenance missions. The capabilities of these two system types complement one another, and given their global distribution, provide a powerful, innovative, and flexible system for situational awareness and space control. The network has produced over 500 million observations to date, and data quality has been vetted and validated by multiple external organizations. SGSN data products continue to be used operationally by a myriad of government and commercial entities.

Cathemeral electro-optical systems have been demonstrated as a viable complement to radar-based tracking for increasing revisit rates on certain objects in LEO [3]. Such systems are low cost, making them well-suited for worldwide deployment to provide superb tracking on a high-interest subset of LEO objects. These systems leverage daytime capability to circumvent the inherent challenges of observing LEO objects during local night—occlusion due

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to the Earth's shadow. Occlusion limits nighttime viewing of typical mega-constellations to 4-6 hours per night from a typical site. Meanwhile, LEO objects are routinely trackable through daytime hours, allowing a cathemeral optical system roughly 5 times more LEO viewing opportunity than a night-only system. Cathemeral optical systems, however, are typically limited to tracking one object at a time, making them scale poorly for tracking large numbers of LEO objects simultaneously.

Ultra-wide field-of-view (UWFoV) optical sensor systems offer one possible solution to the limitations of cathemeral electro-optical for large-scale LEO object tracking. Such systems can observe most of the visible sky from a site simultaneously and persistently, allowing them to track all sufficiently bright objects overhead. This allows UWFoV optical sensor systems to potentially observe hundreds to thousands of LEO RSOs per hour from a given location. However, their limitations to night-only viewing and reduced detectability create a potential barrier for practical use. Through combining custom hardware and advanced algorithms, Slingshot Aerospace has fielded such a system that, in the present work, we show is able to overcome these barriers at scale, thereby enabling LEO object tracking at scale for SDA/STM applications including mega-constellation conjunction assessment.

In the remaining sections, we explore the merits of such UWFoV optical sensor systems as a low-cost alternative to radar for LEO tracking at scale, with particular attention given to the tracking of secondary objects involved in potential collisions with Starlink and OneWeb mega-constellations. Leveraging on-sky performance data from Slingshot's UWFoV optical system, codenamed Horus, combined with a decade of global historical weather data from NOAA, we compute the overall performance and scalability of a global network of UWFoV optical sensor systems.

2. SIMULATING HYPOTHETICAL NETWORKS AND THEIR CONSTRAINTS

To explore the utility of UWFoV Horus systems deployed at scale for mega-constellation conjunction assessment (CA), we chose to focus on the two largest (as of 2022) LEO constellations, Starlink and OneWeb, as well as a set of candidate objects that have intersecting orbits (i.e. objects posing potential collision risk to these constellations). Throughout the paper, we will refer to the active constellation objects (Starlink and OneWeb) as 'primary' objects, and objects posing a collision risk as 'secondary' objects. To identify a representative set of secondary candidate secondaries, we performed a high-fidelity conjunction screening using Slingshot's conjunction screening software, described in detail in references [4] and [5]. This software was configured to screen for all possible conjunctions with a miss distance of 10 km or less within the non-debris RSO population. We chose to exclude debris for computational tractability of the simulations underlying the remainder of the study.

In order to account for seasonal trends and achieve accurate statistical performance metrics, we chose to assess hypothetical Horus network performance over the entirety of 2021. We broke the simulation into 1-week intervals, with one week chosen per month of the year to achieve sufficient temporal sampling while maintaining tractability of the simulation. SpaceTrack states for the candidate constellations and their secondaries were propagated between epochs such that the propagation of the most recent state at a given time was used as the object's position at that time.

We then applied a viewability calculator to each object's propagated ephemeris to identify viewability windows from a hypothetical network of Horus systems across 61 feasible candidate sites. Candidate sites were chosen manually for geographic diversity, dark skies, access to infrastructure, and favorable weather patterns. Viewing from each site was limited to 20 degrees above the horizon, sun elevation at least 12 degrees below the horizon, and RSO/time-dependent conditions under which a given object was well-illuminated by the sun (i.e. not in Earth's shadow, either partially or completely). We note that these constraints are conservative; objects are routinely visible by such systems below 20 degrees and when the sun is not yet below -12 degrees. However, the degree to which objects are visible under such conditions is highly dependent on local atmospheric conditions, the quantification of which across the 61 candidate sites we consider out of scope for the present study.

To generate simulated observations from each viewing window, we used the methods outlined in [3] coupled with a much higher fidelity weather model. To model weather, we used a decade of NOAA [6] historical cloud cover data, from which we computed per-site cloud cover distributions by hour of night and by month of year. Fig. 1, for instance, demonstrates mean cloud cover values for a cloudy and seasonally varying site. In this example, cloud cover is high most of the year and has a relatively uniform mean over the course of the local night. Since nighttime viewing of LEOs is constrained to a short number (4-6) hours from a typical site, we found it especially important to use such a high-fidelity weather model, as many sites had weather patterns such that cloud cover was heavier in the early and

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late local night when LEOs are most visible, despite having, on average, low cloud cover. Instead of drawing from the fixed-mean distribution described in [3], we determined cloud cover fraction by sampling from these site- and time-dependent distributions instead on a per-pass basis.

To assess scalability of system performance, we first needed to choose representative networks of N sensors for which to compute performance statistics. Finding the optimal 20-site (for instance) network would take prohibitively long due to the high computational cost of enumerating and simulating all 20-site combinations. We instead chose to take a greedy approach, starting with the most-performant site in isolation, simulating it in combination with all remaining sites, and choosing the best site to add to form a 2-site network. We repeated this process to form networks with site counts ranging from 1 to 20, each of which is a superset of all smaller networks simulated. In all, these networks are almost certainly non-optimal for their size but give a representative example of what can be achieved with a typical Horus network of a given size and moderate optimization of site placement. We found that at least some degree of coupled site selection was necessary to achieve good revisit rates year-round, especially for low site counts, since seasonal weather trends tend to dominate network performance if not mitigated in selection.

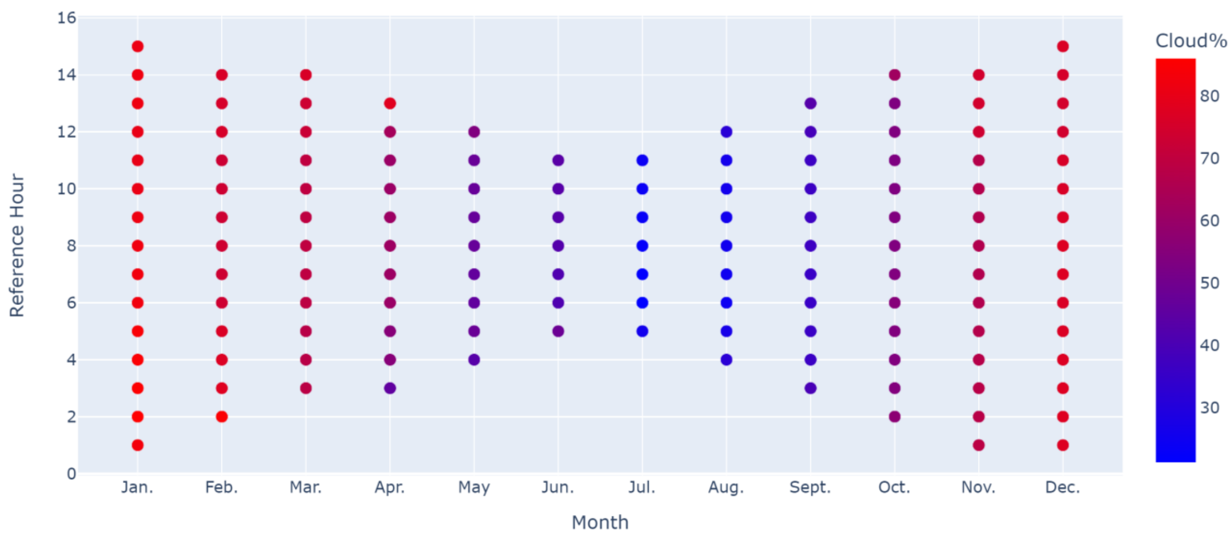

Fig. 1. Mean cloud cover values for an example site showing seasonal variation and intra-night trends. Reference hour describes hour of the longest night (kept consistent throughout the year) for comparison.

3. PERFORMANCE STATISTICS AND SCALING

We first examined the average time since last observation (ATSLO) as a salient revisit-rate statistic to quantify custody scaling of the simulated networks. We chose the ATSLO metric for several reasons. ATSLO itself, for a particular object, answers the question "at any time, how long on average has it been since I last saw the object I care about?" Unlike revisit metrics like average gap time, this metric is robust to short-term observation cadence and requires no ambiguous choice of how to group observations for computing aggregate statistics. To aggregate ATSLO values across objects, we applied the median to most reasonably compute a 'typical' value while ignoring outliers with unnaturally high or low ATSLO values (for instance objects in elliptical orbits that happen to pass through the Starlink constellation). In practice, outliers with atypically low revisit rates are few and could be better served by cathemeral optical systems [3].

Fig. 2 shows median ATSLO values with respect to the number of deployed Horus systems in the simulated network. Overall network performance achieves an approximate 3- to 5-hour median ATSLO by the time sixteen sites are deployed, depending on which LEO population was examined.

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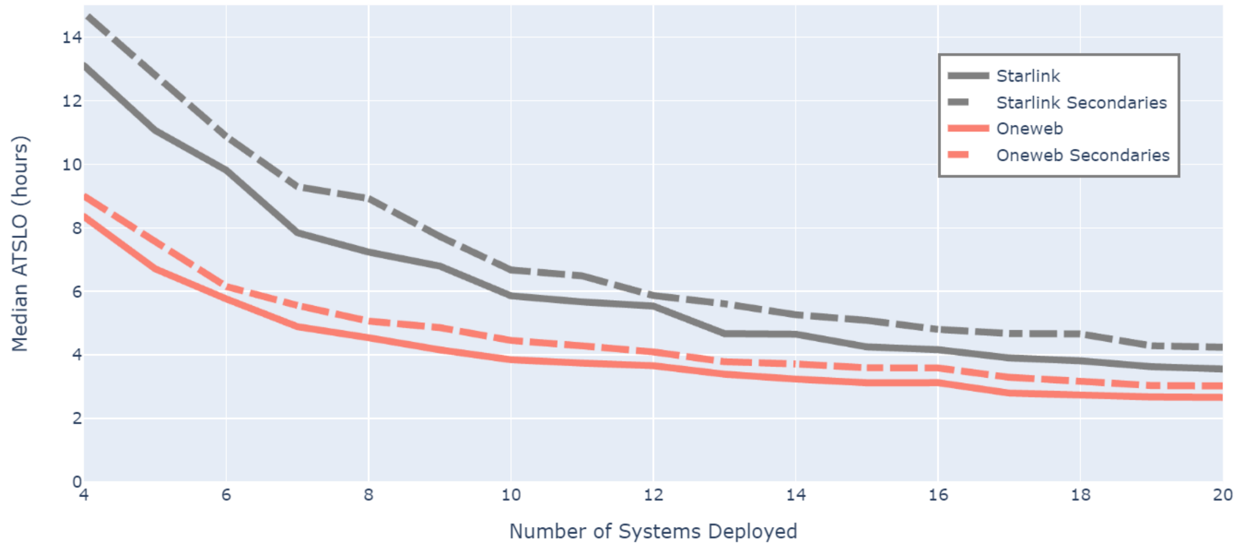

Fig. 2. Median ATSLO, accounting for weather and sensor limitations, on two LEO satellite populations along with corresponding collision-risk secondaries, graphed with respect to the number of deployed Horus systems.

Overall, two trends are apparent. OneWeb and its secondaries are easier to track with such systems than Starlink, and ATSLO scaling with increasing system count suffers from diminishing returns. The first of these is somewhat intuitive: OneWeb tends to operate at a higher altitude than Starlink. This has two effects that drive changes in the ATSLO metric between the two constellations and their secondaries. First, as shown in Fig. 3, a given LEO tracking site has a larger effective viewing area for higher-altitude RSOs, meaning more OneWebs are typically visible overhead than Starlinks. This is not unique to UWFoV or electro-optical sensors, but rather a simple geometric consequence of observing space-based objects from a ground-based site with fixed horizon limits (in this case 20 degrees above the horizon). The second trend is also intuitive and is a direct consequence of the ATSLO metric. Since ATSLO for an object is computed by taking a mean time since last observation over all times in the simulation window, a new observation that evenly divides a large observation gap improves the metric far more than a new observation dividing a shorter observation gap. As more sites are added to the hypothetical network, the gap times necessarily become shorter, decreasing the marginal utility of additional sites for ATSLO-based custody needs.

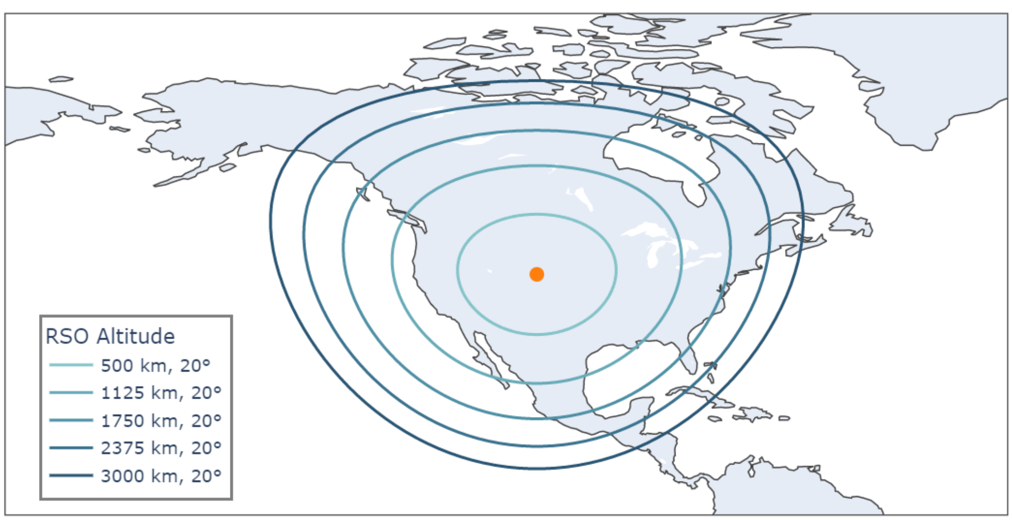

Fig. 3. Viewing area by altitude for a LEO tracking site with 20-degree horizon limits located in Colorado.

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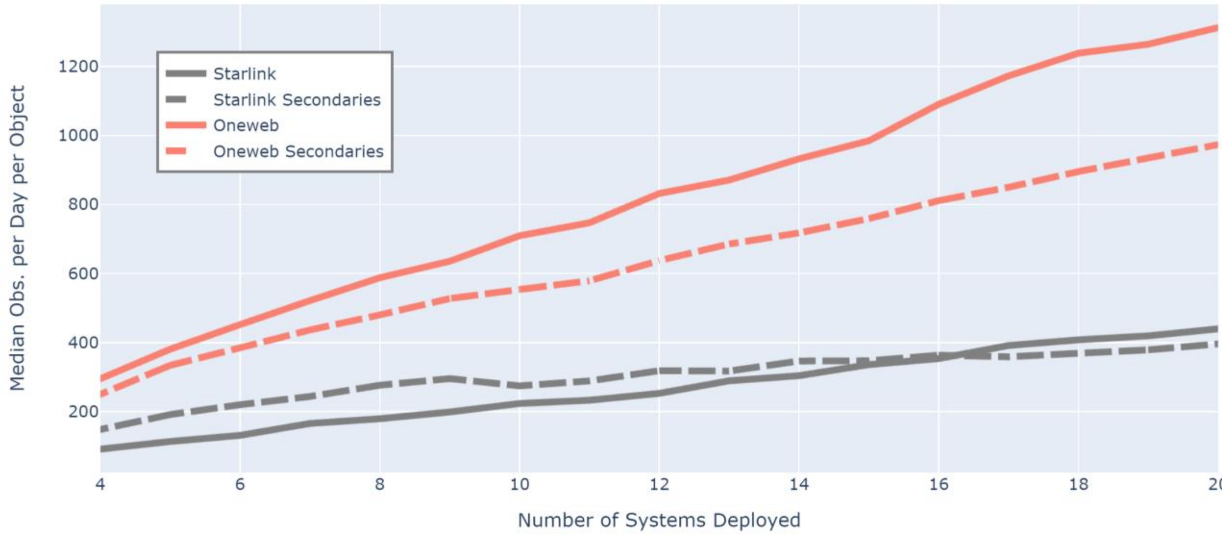

Fig. 4. Median observation count per day per object with respect to number of deployed Horus systems for the four candidate LEO populations studied—accounts for real weather and sensor limits.

We also examined the number of observations per day achievable by the simulated networks, results of which are presented in Fig. 4. Median observation counts across RSOs in each constellation were used to describe typical performance. In other work, we have shown the substantial impact that even a small number of electro-optical observations can have to reducing state uncertainty for states derived from radar observations [3, 7], so we considered observation count an important metric to present. Overall, we note that any reasonable network of Horus systems can be expected to produce at least a few hundred to several thousand observations per day for a typical object in the populations studied. Differences in the observation count between the Starlink and OneWeb is relatively more pronounced than differences in ATSLO. In addition to the altitude-based viewing factor identified as a driver of inter-constellation differences in the ATSLO metric, altitude has a second role to play in observation count: pass length. In essence, higher RSOs are visible overhead for longer, which, for a system like Horus, translates to more observations per pass.

4. CONCLUSIONS

We have provided evidence that a network of low-cost, all-sky (UWFoV) EO sensor systems is capable of producing high revisit rates and high observation counts to support LEO mega-constellation tracking and conjunction assessment at scale. Such performance requires a combination of advanced algorithms, specialized hardware, and the ability to deploy and operate remote sensing systems to produce operationally relevant observational data. As EO observations have been shown to substantially reduce LEO state uncertainty at typical observation cadences [3] and significantly improve collision probability estimates [7], we expect observations derived from a global network of such sensor systems to significantly enhance mega-constellation tracking and conjunction assessment. By supplementing coverage with cathemeral (day/night) optical systems, such as those described in [3], even higher revisit rates are achievable on a subset of LEOs for further-improved tracking and conjunction assessment. Future work will quantify the astrometric and photometric data quality of such systems and its impact on other downstream SDA and STM functions.

5. REFERENCES

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