Increasing Capabilities in a Growing Radar Network

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ABSTRACT

LeoLabs, Inc. maintains and expands a network of radars for tracking objects in Low Earth Orbit. Careful planning for the extension of the radar network is necessary and the choice of site locations and other characteristics (mainly field of view orientation of the 1D-radar) are critical to the development of a network that gives good coverage at an acceptable cost. In this paper, different studies are shown to estimate the impact of extending the existing radar network from two S-band sites to seven by the end of 2023. Each of those analyses considers a different use case for the radar network and all have to be considered to evaluate the future performance improvements. We discuss impacts of site selection on (1) incidental detection of uncatalogued objects, (2) revisit rates for tracking catalogued objects, and (3) analysing the impact on operational support using launch and early operations support as an example. The conclusions are that the future capabilities provide a good coverage over typical LEO orbits for both object discovery and regular tracking. In case of the launch support, having multiple additional sites will reduce the expected mean update times and also avoid very long outages without data. Overall, this improves the quality and reliability of LeoLabs products for conjunction assessment and space safety.

1. INTRODUCTION

LeoLabs, Inc. is providing tracking data and conjuction alerts for satellites in Low Earth Orbit (LEO) based on their own radar data. Satellite operators use LeoLabs' services for collision avoidance, launch and early operations (LEOP) support and contingency management. The data is produced by the LeoLabs radar network which currently consists of 6 S-band radars, see Tab. 1 and Fig. 1, at three locations (New Zealand, Costa Rica, Azores). One more location with two radars will be added by the end of this year in Western Australia. At least three additional radar sites are expected to become operational in 2023. Additionally, two UHF-radars are contributing, namely the Midland Space Radar (MSR) in Texas, US and the Poker Flat Incoherent Scatter Radar (PFISR) in Alaska, US.

The S-band radars have the advantage of a higher sensitivity for smaller objects due to their shorter wavelength and they are the focus of the studies presented in this paper. Those radars are designed as one-dimensional steerable phased arrays. Fig. 2 shows the radar field of view (FoV) in three dimensional space, focusing on CRSR and AZSR1 but also showing MSR and PFISR. Such a one-dimensional radar can be approximated as a fence-like detection plane, where all objects passing through this plane can be tracked.

This paper focuses on the expected improvements generated by the extension of the radar network at a raw data level, i.e. passes and measurements. All further improvements further down the processing chain, e.g. creation of higher quality Conjunction Data Messages (CDMs), are not explicitly modeled here. The impact is evaluated regarding different use cases. In Section 3 the focus is on the process to discover new, formerly uncatalogued object, which is followed by a general analysis of the improvement of passes in Section 4. Finally, Section 5 shows LEOP support as an operational example outside of routine operations.

2. METHODOLOGY

A complete computational model of a radar network is prohibitively complex. Instead, here we perform studies using a simplified model which is sufficiently close to the real world to give insights at an acceptable computational cost.

In principle, the orbits of potential objects (satellites) for discovery and tracking are described by six parameters. To simplify the analysis, objects are assumed to be on circular orbits. Under this assumption, orbits can be specified

Radar Name	Location	Year of Inauguration
KSR 1/2	New Zealand	2019
CRSR 1/2	Costa Rica	2021
AZSR 1/2	Azores, Portugal	2022
WASR 1/2	Western Australia	2022
FS5	Future Site 5 (TBA)	2023
FS6	Future Site 6 (TBA)	2023
FS7	Future Site 7 (TBA)	2023

Table 1: Existing and future LeoLabs S-band radar sites.

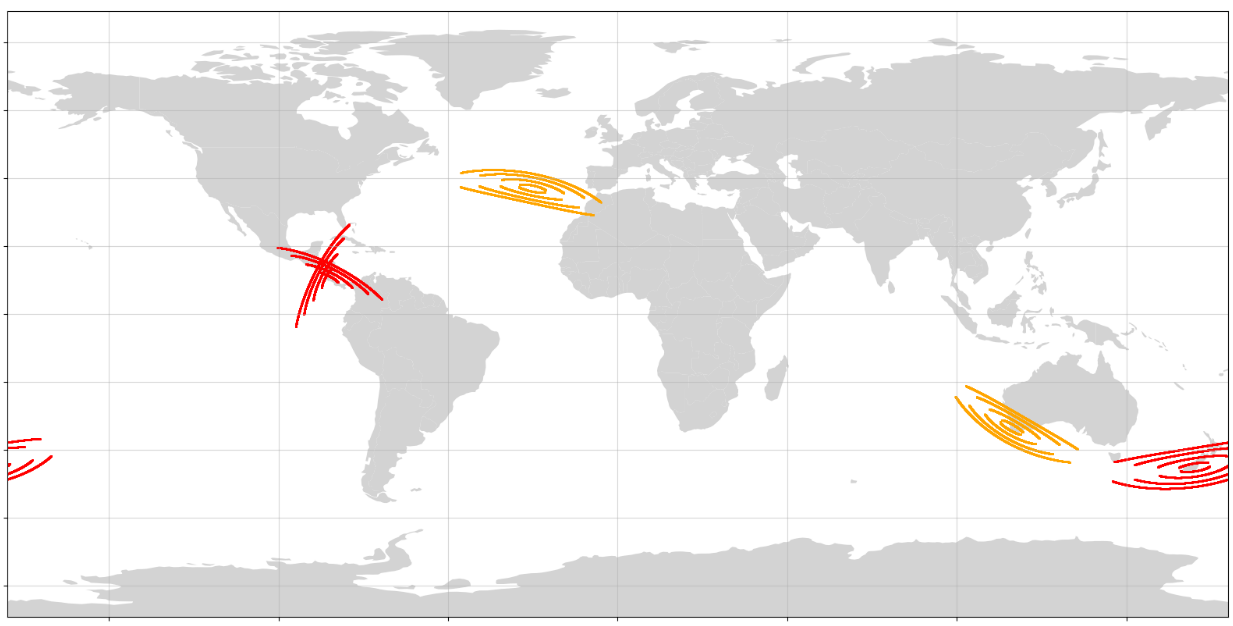


Fig. 1: LeoLabs S-band radars by the end of 2022. (plotted are the field of views, red: built, orange: under construction)

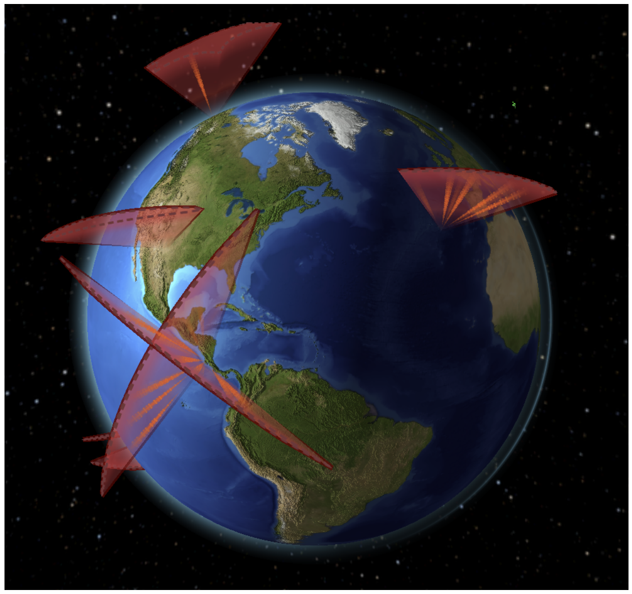


Fig. 2: 3D-View of LeoLabs Radars with a focus on Costa Rica.

by only four parameters: altitude, inclination, right ascension of the ascending node, and mean anomaly. In general, altitude and inclination are fixed, while the orbital plane, gradually precesses due to the torques induced by the Earth's oblateness. The mean anomaly is propagated using the J_2-perturbed mean motion derived from the semi-major axis. On this four-dimensional grid, test particles can be defined to sample the entire orbital space. For each test particle, the crossing through a radar's FoV during the propagation time is detected and the time of crossing is stored together with the observation geometry, i.e. range, azimuth and elevation.

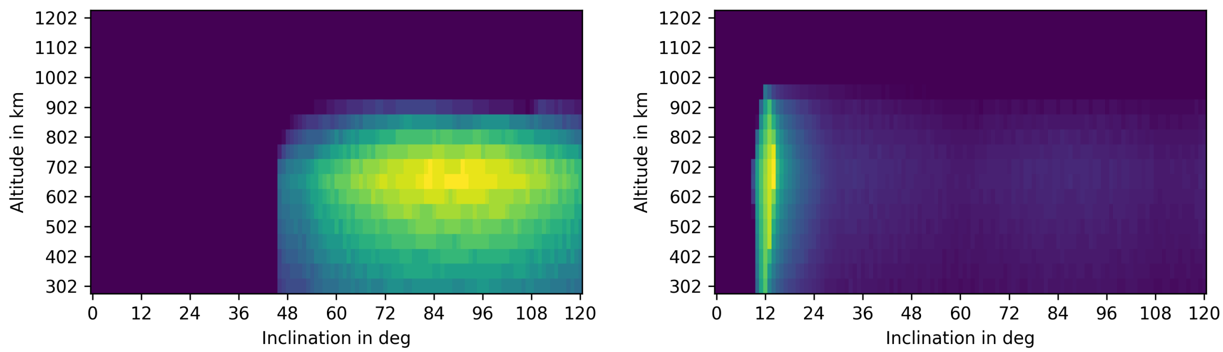
The radars are modeled as pie-shaped planes with a minimum elevation and a maximum range. For many analysis tasks the definition of a minimum elevation and maximum range is sufficient to define measurable passes and all passes fulfilling those conditions are counted. For in-depth studies, a more advanced statistical model can be applied to calculate the probability of detection based on range, elevation and size of the object, i.e. Radar Cross Section (RCS). In this model the received backscattered signal power from the object in combination with the expected instrument performance can be used to get an estimate of the signal-to-noise ratio and probability of detection [1].

In the scope of this paper, the terms *revisit* or *revisit rate* are used to refer to all passes which pass through the radars' FoVs without considering limitations by detection capabilities or scheduling, except if explicitly mentioned.

3. OBJECT DISCOVERY

3.1 Overview

The object discovery process is LeoLabs' approach to find new, formerly uncatalogued space objects. The radars are not actively searching for new objects, but the discovery process is based on serendipitous detections of objects during regular tracking. For example if an object is tracked at a given range and a second tracklet appears at a different range / doppler combination, it is processed separately as an Uncorrelated Tracket (UCT). An initial circular orbit is fitted to the UCT and it is tested whether this orbit crosses the second radar on site during the same pass, typically 1-2 minutes later. If this is the case, the closest beams in the second radar can be scheduled to look for a potential follow-up measurement. In case a second detection is made, a full six parameter initial orbit is calculated and used to schedule future observations at all radars. Two specific analyses for this object discovery process are presented in the following. The first is the estimation of the contribution of dual radar sites based on FoV orientations and location. The second one is an estimation of the results of the discovery process and will be explained further in its dedicated subsection.



(a) Kiwi Space Radar (KSR), New Zealand.

(b) Costa Rica Space Radar (CRSR).

Fig. 3: Percentage of orbital planes which can contribute to object discovery over altitude and inclination.

3.2 Single Site Impact

As explained previously, an object has to pass through both radars at a single site during a single pass to be available for serendipitous discovery if is detected in the first radar. To consider detectability for potentially small objects, the acceptable observation conditions are constrained to a maximum range of 1000 km and a minimum elevation of 40°. Based on simple geometry, one can imagine that for a given site with two radars, only a subset of orbits will cross through both radars on a single pass, which means that each two-radar site has a footprint for its contribution to object discovery in orbital space. To quantify this footprint, sample objects on circular orbits in altitudes from 300 km to 1,200 km are used in steps of 50 km and inclinations are sampled from 0° to 120° in steps of 2°. Each orbit has 360 orbital planes equally spaced in right ascension of the ascending node (RAAN) by 1°. A total of 827,640 orbits has been simulated. The results are reported as a percentage of objects in an altitude-inclination bin which gave two valid radar crossings at the same site during a single pass. Because all test objects start at the same value of the mean anomaly and argument of perigee (both 0°), this result in terms of percentage is equivalent to any other common start point of the objects, although different orbital planes would be detected. This extrapolation allows it to generalize the result to give the percentage of the entire altitude/inclination band which is passing through both radars at observation geometries which enable object discovery. However, it has to be noted that this is not equivalent to the percentage of objects which are discovered, because this is limited by the number of beams which are scheduled and whether the initial detection is made while passing through the first radar instead of the second one to have a follow-up chance.

Fig. 3 compares the discovery footprints for the first two S-band radar sites in New Zealand and Costa Rica, which are significantly different in their FoV-orientation designs, see Fig. 1. This difference is also clear in their distribution of orbits for object discovery. For KSR, Fig. 3a, all inclinations above 46° inclination have at least a part of the altitude samples passing through both radars. The cut-off at 1,000 km altitude is due to the maximum range. This parameter also leads to the diamond shape around the overall maximum at approximately 90° inclination and 700 km altitude. Objects in higher or lower orbits are more likely to violate the range or elevation condition on either of their passes.

For the site in Costa Rica, the peak of discoveries is centered at much lower inclinations which is close to the latitude of the site where the two FoVs cross. Nevertheless, discoveries are also possible for larger inclinations, only that it involves less orbital planes compared to a parallel-FoV site like KSR. To build an independent small object catalogue, coverage across all orbital regions is necessary and thus sites like Costa Rica are as important as New Zealand. The results from this analysis are used to strategically grow the LeoLabs radar network and obtain a good coverage. In general, it is expected that many more objects can be found in polar orbits, thus it makes sense to have more resources for discovery there compared to low inclinations.

3.3 Search Completeness

The search completeness simulation is a tool which simulates the object discovery process to a higher degree of detail. The term *search completeness* refers to the percentage of objects in a given orbital region which have been catalogued via the described object discovery process. For each radar in the simulation, the daily tracking with multiple beams is simulated. Additionally, a number of orbits are defined for which the search completeness values are estimated. Each simulated beam can be tested whether it intercepts an orbit. If this is the case, it can be further checked whether an object at this location on the orbit would also cross the next radar at the same site to allow for an IOD. Afterwards, all passes at other radar sites are considered as potential follow-up passes to confirm and consolidate the initial orbit. This simulation uses the aforementioned probability of detection to scale the observed portion of the orbit. This is done by assuming a spherical shape of the objects and calculating the theoretical RCS value from that. Simulating this process over an increasing time interval, would lead to more and more parts of the orbits being covered by the discovery process and thus increasing the completeness of objects. Certainly, this simulation is based on a number of assumptions and simplifications but it gives a general insight into the feasibility of the object discovery process and can be used to estimate the scaling of the results by changing different parameters, such as the number of sites or the detection capabilities of the radars. Due to this, the results are mainly used to estimate sensitivity to certain parameters and see relative changes between assumptions and orbital regions.

Internally, this simulation is used to understand the drivers of future performance improvements. For example, if the simulation is run once under the assumption of an increased sensitivity and once with more radars at the baseline sensitivity, it can be understood which improvement has the larger impact which can be used to assign priorities and resources to projects.

4. TRACKING PERFORMANCE

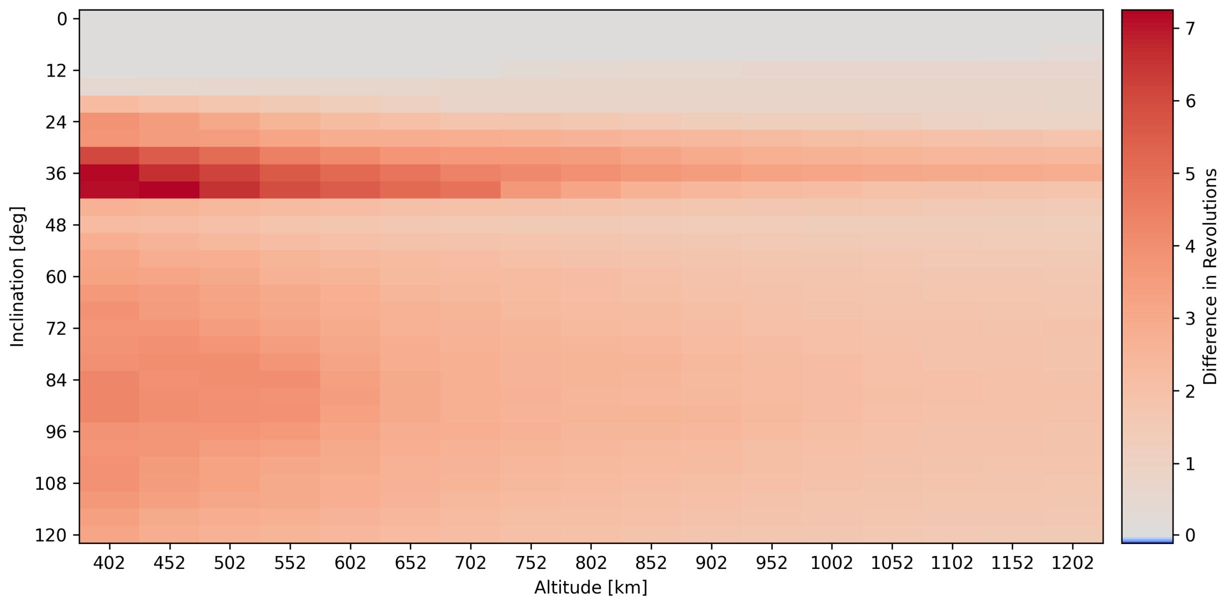
Increasing the size of the radar network will significantly improve the routine tracking operations. For the reduction of revisit rates, it is not important whether it is a dual-radar site like the discovery sites or a single radar site. To calculate the revisit rates, only passes at elevation higher than 25° are used as a detection cut-off, but no other model using probability of detection is used and all passes above that threshold are counted. The four-dimensional orbit space which was described in Section 2 is reduced for the analysis to two dimension by calculating values for mean and maximum time between passes over all orbital planes and mean anomalies for a given combination of altitude and inclination.

Certainly, the number of radars at the site impacts its capacity and overall contribution of measurements, but the time between passes is only marginally affected by the opposite pointing directions of two radars at a single site. The revisit rates of objects in the radar network is the main parameter which improves and depends on the orbit. The change in revisit rates can be quantified with a focus on different measures. Fig. 4a shows the difference in mean revisit rate between two radar sites (KSR, CRSR) and the 7 sites listed in Tab. 1. The difference in time is normalized by revolution time and thus shown in orbital revolutions. From the figure, it can be seen that the average time between two revisits will reduce by 4-6 revolutions with the seven site network. The peak for low altitudes at around 36° inclination occurs because for the two site combination, this inclination is too low for KSR but too high for CRSR to reliably have good passes. Another observation is that the improvements are larger at low altitudes. This happens mainly because low orbits have a tendency to go below the minimum elevation and thus have worse revisit rates than orbits at higher altitudes in general. The mean revisit rates can be used as a general approximation of increased measurement data and thus reduced uncertainty throughout the catalogue. More regular passes across all objects in the catalogue also allow a better scheduling approach to maintain a consistent level of uncertainty over all objects.

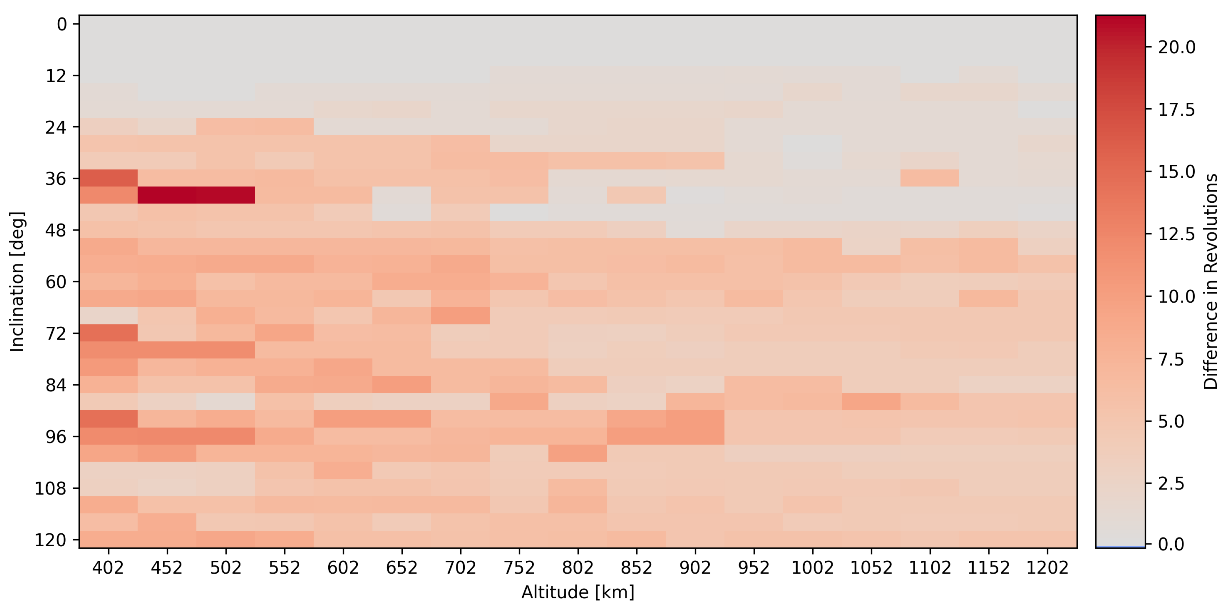
The second parameter to consider for the analysis is the maximum time between two passes. This figure is especially interesting in the context of event monitoring or tracking objects of high-interest. In those cases, the maximum time without a revisit is a limiting factor to provide updated information on a regular basis. The change of this parameter is shown in Fig. 4b. The distribution of those changes is much less smooth than for the mean times because it shows the largest single change for all orbital planes of a given altitude inclination combination. Most orbits show improvements of approximately 5-10 revolutions which is on the order of half a day.

The changes in these parameters are also analyzed and evaluated for the selection of the radar orientation at a new site. An optimization can be performed over multiple potential orientations to estimate the improvement provided by the different orientations. For such an optimization, it has to be considered that the total changes over the plotted altitude / inclination range are not directly proportional to the impact. The objects in space have a distribution in both inclination and altitude which gives some orbits more weight than others. To consider this, each orbit is given a weighting based on the number of objects in that bin in the current space debris environment. This avoids optimizing an orientation for an orbital region where only a very small number of objects can be found. Weighting by the object distribution gives a comparison for the improvement in tracking operations.

Fig. 5 shows the improvements in mean revisit rates after adding each additional site for two example orbits. It is

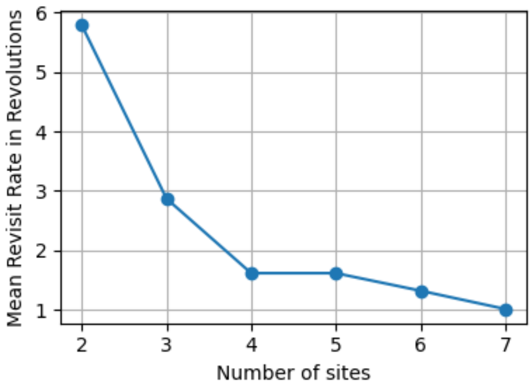


(a) Improvement in mean number of revolutions between two revisits.

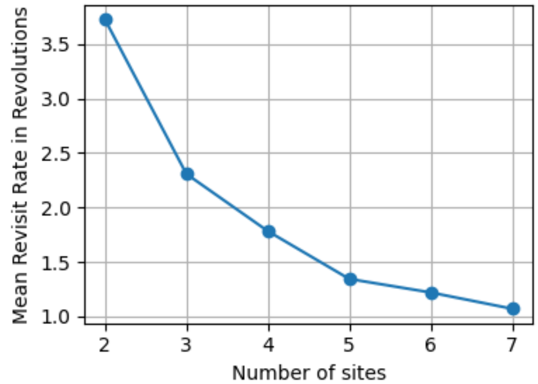


(b) Improvement in maximum number of revolutions between two revisits.

Fig. 4: Improvements in mean and maximum time between revisits for objects in LEO after upgrading from two radar sites to seven by the end of 2023.



(a) Altitude: 652 km, inclination: 36°.



(b) Altitude: 752 km, inclination: 88°.

Fig. 5: Improvement of mean revisit rates for two different example orbits when increasing the number of radar sites.

visible that there are diminishing returns for adding more sites and the curve clearly flattens after 5 sites. However, this does not mean that there is already a sufficient number of radar sites at that time. It still has to be considered that a radar has limited capacity to track all objects passing through the FoV. More sophisticated analysis would be necessary to estimate the number of radars which can regularly track a certain object population.

5. OPERATIONAL SUPPORT

LeoLabs is regularly supporting launch operators and satellite operators during their Launch and Early Operations (LEOP) phase, which typically is the first week after the launch for LEO. During these events, the radars are scheduled in a special mode in which the radar beams are selected such that they follow the orbital plane while the radar site rotates below it. With this approach, it is possible to screen the target orbit of the launch. Due to the typical deployment of multiple payloads from a single upper stage, not much delta velocity is given to the released satellites and thus it is expected that the released satellites are slowly dispersing along the same orbital plane, before potentially starting to manoeuvre. Depending on e.g., the launch orbit, the number of released satellites and the time after the launch, good passes where the entire batch of new satellites can be detected are limited, because not single objects are considered like in the previous sections but the entire group. One of the typical tasks during such a launch support is to identify the individual satellites based on the prior launch information and thus help satellite operators to make contact. This provides an extremely valuable service to operators as it reduces the risk of a failing mission due to the failure to make contact with the satellite early after the launch. In theory, it could also be used to evaluate distances between satellites if another payload wants to release smaller satellites. The clearance for this release could be given when other satellites have separated sufficiently.

For the analysis of the improved revisit rates, five different launches are considered going into three different inclinations, namely 97° (based on the SpaceX missions Transporter 3/4/5), 45° and 66°. For each simulation, the targeted launch orbit for each satellite is known and this allows it to simulate all passes for all individual objects from a single launch. Again due to sensitivity considerations, we declare a *good pass* to be a pass during which all payloads are crossing the radar's FoV at an elevation above 40°. It would also be possible to use the size of the objects to have a better anticipation of the probability of detection, but for generality we focus only on elevation. It should also be clarified that passes which do not fulfil this condition may still be used operationally. Depending on the distribution of good passes, a sub-optimal pass can also be used to provide at least partial information. Additionally, the plots in this section refer to the number of S-band sites like before, but the analysis includes passes at the UHF radar MSR because it is also used during operational support. As an initial analysis, Fig. 6 shows the number of such good passes over the typical support window of one week. One important aspect is that the number of good passes is mainly driven by orbit inclination. For the 45° mission, the number of good passes is more than doubled already for 2 sites compared to T3/T5. Increasing the sites has a significant effect. Going to seven sites by the end of 2023 will more than double the good pass opportunities for both mission profiles. The roughly linear scaling relation in this plot is not surprising

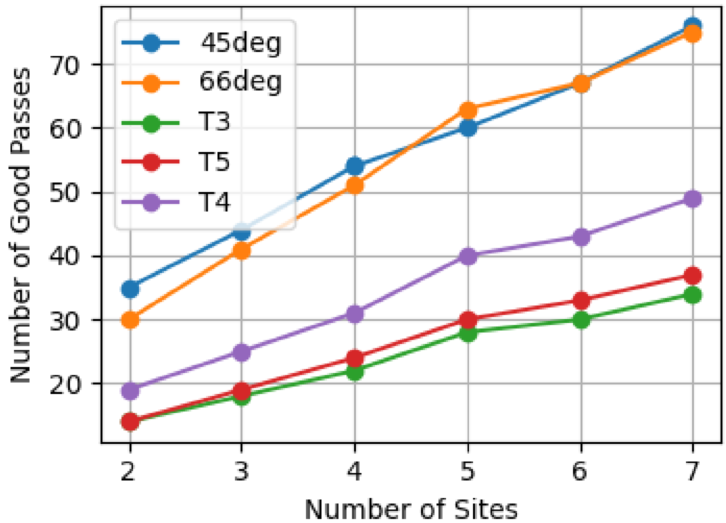


Fig. 6: Number of good passes (all elevations above 40°) over one week for the different missions.

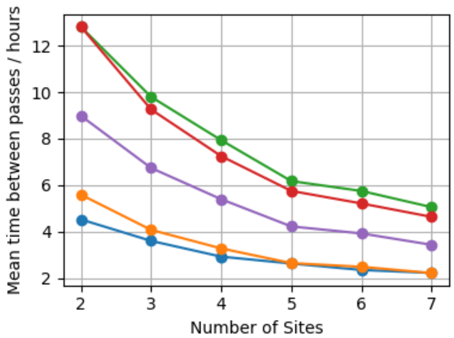
as it would be expected that each site contributes with a similar number of additional good passes based on orbit and site location.

However, the number of good passes is only one aspect of a successful LEOP support. It is also important to consider the rate at which new information is received. Fig. 7 shows the mean and maximum time between good passes. Certainly, the mean in Fig. 7a is closely related to the previously shown number of passes. The mean time gives an impression of a typical interval operators have to wait for a new update, ideally a new state estimate. Even for the worse orbit geometry, it is expected to be reduced to 4-5 hours. In addition to the mean, there is another important value for LEOP analysts which is the maximum time without a good pass. If such a no-pass interval happens early during the support, this makes the work more difficult for analysts and operators. The scaling of this no-pass interval is much less linear and also much more dependent on single missions. It also depends a lot more on the specific locations of radars. Fig. 7b shows that the maximum time without a good pass would reduce for a seven site network to about 15 hours from previously 24 hours for T4, whereas the other missions have smaller reductions to a maximum value of 24 hours. As mentioned before, this does not mean that there is no data for 24 hours but analysts will select multiple sub-optimal passes which may only show parts of the launched objects at one pass and then get measurements for the rest at another pass. The chance of getting good passes also depends on the rate at which the objects disperse along the orbit. The quicker the group of objects grows in their along-track separation, the more difficult it is to measure them all on the same site pass with a good geometry.

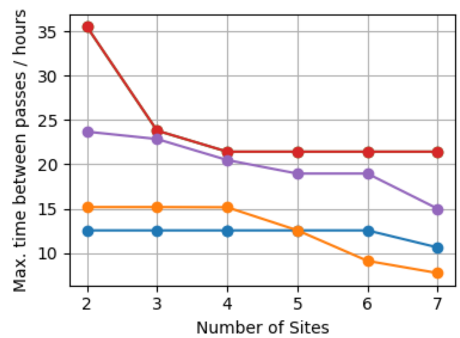
6. CONCLUSION

The extension of the LeoLabs radar network is expected to lead to various improvements in current service levels and enable new products. In general, objects will have more passes over radar sites with opportunities to collect measurements. This improves both the overall mean revisit rate as well as the maximum time between two passes. With decreased mean revisit times and more measurements per day, overall uncertainties in the catalogue will be reduced and lead to the creation of more actionable conjunction warnings. Reducing the maximum time between passes allows LeoLabs to better monitor orbits of interest or further improve the discussed LEOP support. Apart from pure revisits, more radars are also necessary to maintain a large catalogue because a single radar has a limited capacity of objects to track in parallel. In order to achieve better orbit quality, more radars enable more measured passes.

For LEOP specifically, the most obvious benefit is certainly the increased number of measurements in total, which makes it easier to fit orbits and also perform association between measurements from different passes. From LeoLabs' perspective, more radars also allow a more targeted approach to schedule launch passes. It has to be considered that



(a) Reduction in mean time between two good passes.



(b) Reduction in maximum time between two good passes.

Fig. 7: Reduction in times between passes when increasing the number of sites. This only accounts for passes defined as good although more passes can be used, thus it shows the minimum expected improvement.

running a LEOP measurement of the orbital plane takes approximately 1 hour and blocks the radar from performing nominal tracking operations which has an impact on the overall catalogue. With more sites, it will be easier to select good passes at regular intervals to provide high-quality data at a smaller impact for LeoLabs' other services. A similar scenario as LEOP is the reaction to catastrophic break-up events in orbit like the Cosmos-1408 ASAT in 2021.

More radar sites also increase the reliability of the LeoLabs services as an unexpected failure of a site, e.g. due to a loss of power, does not affect operations as much as for a smaller total number of sites. This is true for LEOP as well as normal operations. At the same time, LeoLabs will start to build their own catalogue of formerly untracked objects to further increase space safety.

[1] Merrill Skolnik. *Radar Handbook*. McGraw-Hill Professional, New York, NY, 3 edition, January 2008.