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Commercial Space Tracking Services for Small Satellites

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ABSTRACT

LeoLabs demonstrates that small satellites, including 1U CubeSats and smaller, are well-tracked to high accuracy by its worldwide network of phased array radars. With its network of two operations radars (valid as of June 2019), LeoLabs is able to provide high-precision ephemeris services for 1U and sub-1U satellites. Roughly 95% of the time, tracking is maintained to better than 1 km at time of estimation (these uncertainties grow when propagating the states). Approximately 50% of the time, these state estimates are better than 200 meters. The quality of the fitted orbits will improve as new LeoLabs radar sites are brought online. Precision tracking services are provided by LeoLabs as a commercial service to small spacecraft operators. Such services are also valuable for regulatory purposes (where detectability and trackability are concerns), for providing backup tracking should GPS not be available, and for safety enhancements by having smaller covariances in instances of potential conjunctions with other satellites.

INTRODUCTION

Recent years have seen a proliferation of CubeSats sized 1U (10x10x10 cm) or smaller in low earth orbit (LEO). LeoLabs[2], with its global sensor network and data platform, aims to support operators of small CubeSats such as these in multiple contexts including navigation and space situational awareness (SSA).

High-precision orbital information obtained from the LeoLabs Data Platform[3] has advantages over the more traditional two-line element set (TLE) format, which represent only approximations to the true orbit and may have errors of several kilometers. In addition, high-precision ephemerides include propagated covariances, and measurements (which are used as inputs to LeoLabs' own orbit determinations) are also made available. Conjunction alerts and assessments (including screening against an input propagation) are also available from LeoLabs, complete with probability of collision calculations and covariances for all involved targets. LeoLabs conjunction screening service allows the user to upload an ephemeris and screen against the catalog, which is especially valuable within the context of risk assessment during mission pre-planning or for on-orbit maneuver planning.

LEOLABS RADAR NETWORK

At the core of the LeoLabs Data Platform is a global network of phased array radars. Unburdened by the overhead of mechanical slew times, phased array radars are well suited to tracking dozens of objects simultaneously using a beam that can be reoriented hundreds of times per second. Currently, the LeoLabs network is comprised of two radars—the Poker Flat Incoherent Scatter Radar (PFISR) near Fairbanks, Alaska and the Midland Space Radar (MSR) near Midland, Texas (Figure 1). PFISR uses a more traditional 2-dimensional phased array, while MSR uses a proprietary 1-dimensional design, achieving nearly identical measurement fidelity at a significant reduction to cost and complexity. Together these radars are capable of collecting measurements on a catalog of over 10,000 objects 10 centimeters in size or greater, with each object passing through a LeoLabs sensor about 1-4 times a day.

Figure 1: Locations of LeoLabs radars—a third location is under construction in New Zealand (Credit: Google Maps)

Construction of a third LeoLabs radar is currently underway in New Zealand. This radar (also based on 1-dimensional array technology), will operate at a higher frequency and permit the detection of resident space objects (RSOs) as small as 2 centimeters in LEO. This added capability will allow for the construction of a catalog that integrates small debris, increasing the number of RSOs that LeoLabs can provide data for by an estimated factor of ten.

LEOLABS DATA PLATFORM

The LeoLabs Data Platform offers data and analyses which enable engagement with the LEO environment at a number of different levels, including:

- Radar measurements
- Object state estimations
- Object propagations
- Conjunction screening and alerts

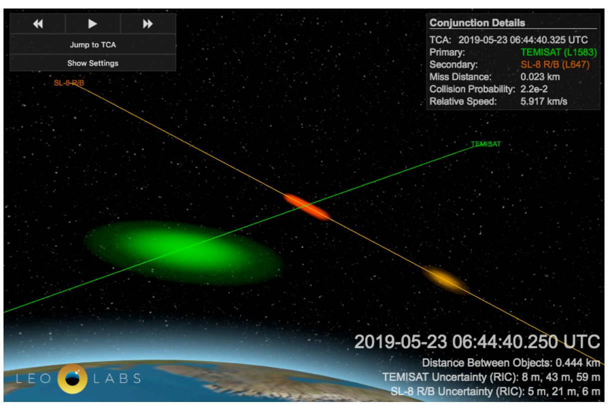

Figure 2: Example of a conjunction visualization on the LeoLabs Platform site

This platform is accessible via two primary interfaces: a web-based API (suitable for custom analysis scripts and automation tasks), and a graphically oriented web application (focused on intuitive plots and visualizations of the available data). Some target use cases for the LeoLabs Platform include:

- Regulatory (rendering the LEO environment within the context of national or agency guidelines)
- Backup navigation (to augment or supplement existing on-board or ground based systems such as GPS)
- SSA (as a source of upcoming conjunctions, maneuvers, and orbit change alerts—See Figure 2)

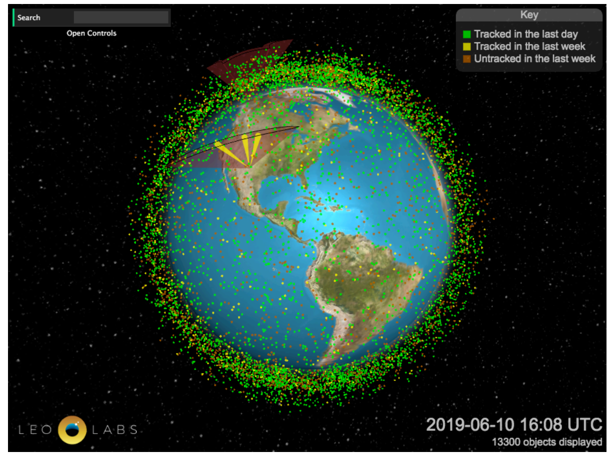

Fig 3: Visualization of objects in the LeoLabs catalog, color coded by how recently they have been tracked

MEASUREMENT CALIBRATION

In order to fully characterize the performance of sensors in the LeoLabs radar network, including sensor bias and uncertainty, comparisons to an external source of truth must be made. For these purposes LeoLabs employs data from the International Laser Ranging Service[4]. The ILRS distributes orbit propagations for targets of interest which are computed by a number of different providers. Since they are derived from laser-based measurements, these propagations are of a high fidelity and suitable to be processed for predicted measurements, which are then used as truth data.

Comparisons to these predicted values are made multiple times a day, deriving the bias and uncertainty which should be associated with the range and doppler measurements made at PFISR and MSR. These parameters are automatically incorporated into measurements provided by the LeoLabs API, and reported in a dashboard on the LeoLabs Platform page. At present, range uncertainties for both radars are typically near 15 meters, with doppler uncertainty near a value of 3 meters per second on PFISR, and 25 centimeters per second on MSR (see Figure 4).

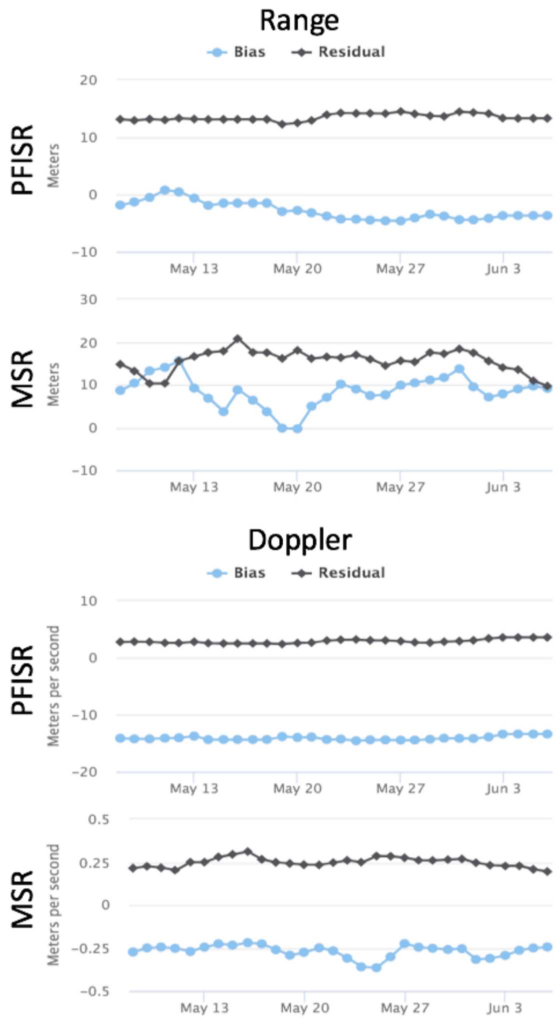

Figure 4: Daily summaries (available via the LeoLabs Platform site) of measurement biases and uncertainties (residuals) for PFISR and MSR radars.

ORBIT DETERMINATION

Orbital state estimations at LeoLabs are achieved via an unscented Kalman filter (UKF). This class of algorithm pairs the computational efficiency of a Kalman filter with the unscented transform (UT), which attempts to more accurately render covariance evolution in nonlinear systems by propagating a set of sample points using the full physical model. Both orbit determinations and propagations provided by LeoLabs make use of the Orekit open source orbital dynamics library[5], with the following forces considered:

- Non-uniform gravity (to degree and order 42)
- Atmospheric drag (using the NRLMSISE-00 model)
- Solar radiation pressure
- Third body forces from the Sun and Moon

Computations of new orbital state estimations are initiated by a transit of the target through a LeoLabs radar, and are performed at most once per hour in a cloud-based computer cluster. For targets in polar orbits new estimations are calculated as often as four times per day. Each estimation is coupled to an eight-day propagation window that looks one day backward from state epoch and seven days forward.

To assess the quality of state estimations, comparisons to ILRS-provided propagations are computed automatically for a 48-hour period centered on state epoch and captured in an internal dashboard (see Figure 5 for a similar but manually-created analysis with longer duration comparisons). Each state estimation is also compared to previous (and, if possible future) estimates in terms of both physical distance and Mahalanobis distance (a multi-dimensional statistic similar to standard deviation). These distance comparisons are viewable on the LeoLabs Platform site for each available state estimation and propagation.

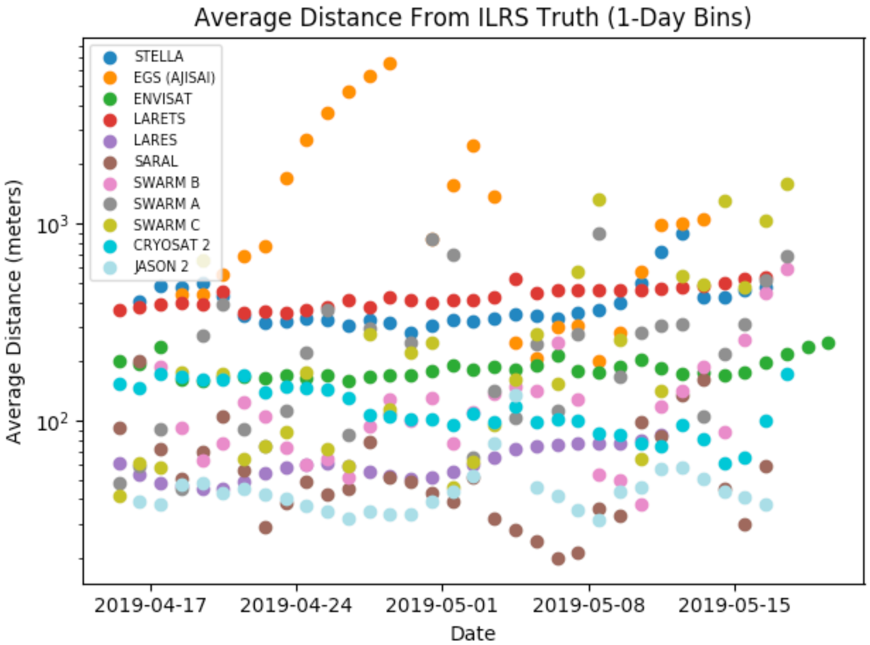

Figure 5: Average distance between propagated state estimates from LeoLabs and truth ephemeris provided by ILRS for 11 satellites in LEO

PERFORMANCE ON SMALL SATELLITES

Of particular interest to the SmallSat community is the performance of the LeoLabs Data Platform against targets sized 1U or smaller. A survey of RMS position uncertainties at state epoch for 68 targets with sizes of 0.25U, 0.5U and 1U is shown in Figure 6. The median of the distribution of these values is found to be below 200 meters, with about 95% of all values falling below one 1 kilometer.

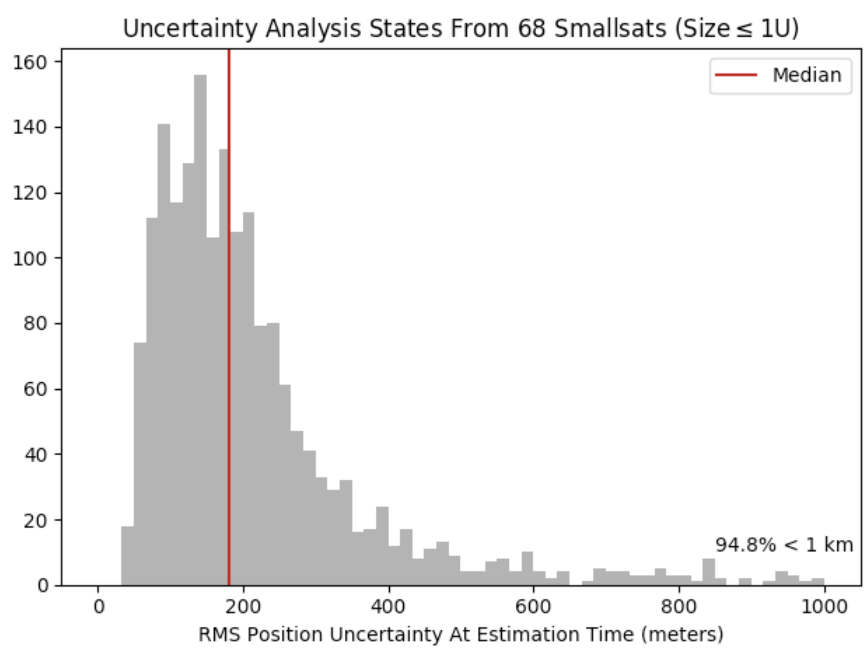

Figure 6: Epoch position uncertainties for a set of 68 smallsats of size 1U or smaller

Only six of the objects in this survey fall in the "sub-1U" category, enabling a detailed time series plot of the evolution of the RMS position uncertainties for these satellites over a one-month interval (see Figure 7). Even under propagation RMS position uncertainties for these targets are usually below 1 kilometer.

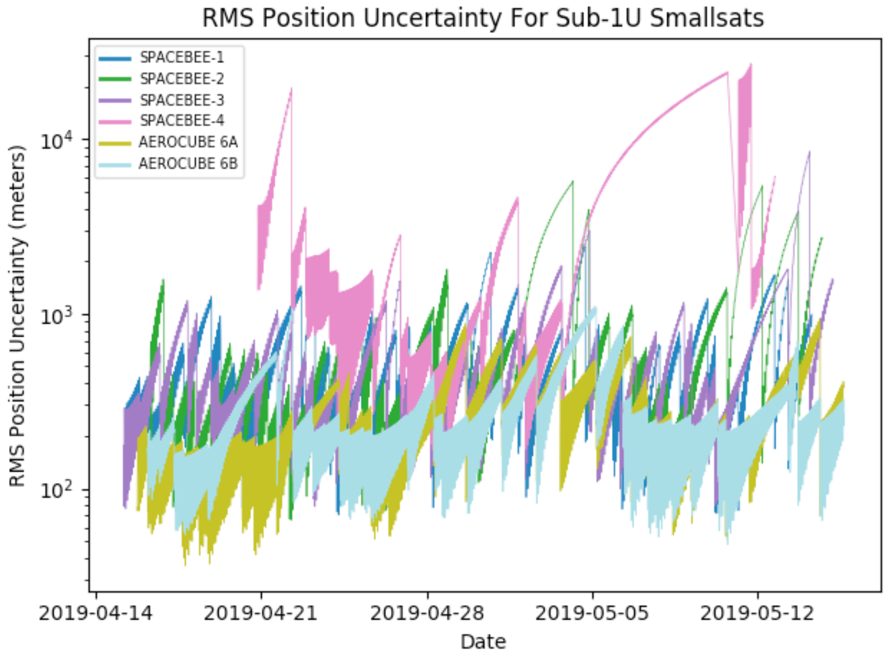

Figure 7: Propagated position uncertainties for six 0.25U and 0.5U smallsats

CONCLUSION

LeoLabs provides a data platform built on top of a global network of phased array radars (including one currently under construction in New Zealand that will enable the creation of a catalog that includes debris down to 2 centimeters in size). This data platform can provide measurements, orbital state estimations, propagations, conjunction information, and detailed visualizations of objects in the LEO environment.

Information from LeoLabs provides increased transparency to operators over existing sources of information, and is provided via both programmatic (API) and graphics-based (web GUI) interfaces. Performance of LeoLabs systems versus a set of 68 small CubeSats (≤1U) is seen to be favorable, with greater than 50% of epoch RMS position uncertainties falling below 200 meters. Propagated uncertainties of several sub-1U satellites over one month are also largely contained with the same (100 meter) order of magnitude.

Major improvements to both accuracy and precision are expected in the near future, as LeoLabs continues to deploy new radars and refine orbit its algorithms.

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