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SUMMARY REPORT

Metsähovi satellite laser system in characterizing near space objects

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1. Introduction

The space around the Earth is contaminated by many orbiting man-made objects, as well as a few natural ones. Most of these objects and their orbits are well known, but when a satellite dies, its control is lost, and it may disappear. Due to collisions and malfunctions, some parts may also be separated and go in unknown directions. Among this debris, there are also unknown, secret satellite missions by several operators.

The best available catalogues currently list approximately 17000 space objects. Of these, a couple of thousand are active satellites, a few thousand are decommissioned satellites, old rocket stages and other large debris. The rest are small debris, down to the 10 cm scale. The total number of space debris larger than 1 mm is estimated to be in the tens of millions.

Knowing the space situation over Finland is of interest to multiple parties, such as military (other nations' surveillance satellites), civilian safety (the threat of large space debris falling) and, increasingly, commercial satellite operators (communication with their own satellites). There are only a few options to follow this situation. One can trust international sources, or one can try to observe oneself. Typical observation systems include radars, passive optical telescopes, and satellite laser rangers (SLR).

SLR is a space geodetic technique where the flight time of short laser pulses to, e.g., Earth orbiting satellites is used to range the objects with an accuracy that is a couple of mm for low Earth orbit targets. The ground segment includes a telescope (Figure 1) for transmitting and receiving the laser pulse; a detector; a pulsed kHz laser and a time-of-flight timing unit. Traditionally, the observed satellites have an array of retroreflectors pointing to the nadir, which reflect the laser pulses directly back to the laser transmitting station. These are referred here as *cooperative* targets. Currently, there are approximately 150 satellites in orbit equipped with retroreflectors, of which <100 are operational. In this project we also study observing objects without retroreflectors, i.e. *non-cooperative* targets.

SLR stations form a global network of ~40 stations which provide observations through the International Laser Ranging Service (ILRS). Once operational, Metsähovi will be the only SLR station in the Nordic countries as well as one of the most modern SLR systems in Europe.

The Metsähovi research station is a fundamental part of all national and international geodetic infrastructures. It hosts gravity instruments, GNSS receivers, DORIS station, radar retroreflector, and basic point for national heigh system. A new large radiotelescope for geodetic VLBI is under construction. We are also building a state-of-the art SLR station. The new SLR telescope was planned to be operational already 2016, but has been delayed due to various reasons.

2. Research objectives and accomplishment plan

The project goal is to study the capabilities of the Metsähovi satellite laser ranging sys-tem in studying the properties of various space objects. Specifically, how active SLR and passive optical observations can be used to determine properties of space objects, especially the rotation period and axis. The rotation state gives a strong indication of whether the satellite is under active control or not. The 2017 goal was prism-equipped cooperative targets, and in 2018 prismless non-cooperative targets.

3. Materials and methods

SLR data

Two main kinds of data files are used in processing SLR observations. The first are so called *prediction files*, in the Consolidated Prediction Format (CPF), which are produced for SLR targets by computing centres. These contain precomputed ephemerides for a given satellite at some time interval (typically 15 seconds), from which accurate ephemerides can be computed by interpolation. The second type of file are the actual SLR observations, in the Consolidated Ranging Data (CRD) format. These contain the observed times of flight between the station and the satellite, as well as metadata about the station, the instrumentation, calibrations, weather observations etc.

Both the full rate SLR data and prediction files were obtained from FTP servers maintained by the NASA Crustal Dynamics Data Information System (CDDIS, ftp://cddis.gsfc.nasa.gov/pub/slr/) and the EUROLAS Data Center (EDC, ftp://edc.dgfi.tum.de/pub/slr/) as well as the Space Debris server of the Graz Observatory (ftp://sddis.iwf.oeaw.ac.at/pub/fr_crd/).

All of the processing software is written in Python. A Python module written during the 2017 Matine project was used for the parsing of both CPF and CRD files (https://github.com/dronir/SLRdata).

Satellite catalogues

The known parameters of space objects are retrieved from two sources: 1) The Space-Track website (http://www.space-track.org) is the main source of satellite orbits in TLE format from the United States Joint Space Operations Center. The website provides an API for downloading data in batches. 2) The SATCAT catalog (e.g. https://celestrak.com/satcat) is a list of over 42000 space objects, giving rough orbital parameters and basic status information, as well as (for some objects) an estimated radar cross section. The SATCAT catalogue also contains past objects which have since re-entered the atmosphere. The total number of objects which are still in orbit and which have an estimated radar cross section is around 14000.

Ray-tracing simulations

A ray-tracing software has been written at the FGI for simulating the interaction between light and space objects. It can take a shape model composed of geometric primitives such as cylinders, spheres and triangulated meshes, apply different reflection models and spectra to these components. Light rays from different types of light sources can then be directed at the object, and various results computed. The outputs include a camera model, which creates a pixel image of the object in the given illumination, a "photometer" which simply computes the total flux from the object in a given direction, and a measurement of radiation pressure forces and torques caused by the illumination.

The output option relevant in this project is the simulation of SLR data from non-cooperative targets. In this mode, the software simulates the reflection of a short laser pulse from a target object, producing the reflected intensity in the backscattering direction as a function of distance, i.e. the shape of the reflected laser pulse. This computed pulse shape can then be combined with information about the telescope system to produce simulated SLR observations of the target.

4. Results and discussion

Estimation of observable targets with passive methods

Some estimates were made of the population of space objects visible with passive optical means (a CCD camera or photometer). For this, a heuristic score was chosen to assess an object's visibility: the negative of the logarithm of the ratio of the radar cross section of the object to the square of the minimum distance. This produces an easily readable scale. The minimum distance is defined as the shortest distance between the observer and any point in the object's orbit. Radar cross sections were used because they are readily available for over 10000 objects, and are assumed to correlate with visual cross sections.

The heuristic is analogous to the magnitude scale used in astronomy, which is based on the logarithm of a ratio between a target's brightness and some reference value. In fact, the heuristic scores could be converted to absolute magnitudes, if the true size and reflectivity of the of the satellite were known, but in practice these parameters are unknown.

Figure 2 shows the histogram of the heuristic score for all the objects for which it could be calculated, as well as the cumulative number of objects. The latter plot can be used to estimate the number of objects theoretically visible with a given telescope, by observing a number of objects with varying heuristic scores until a limiting value is found. An interesting detail is that with this heuristic, a Cubesat (0.01 square meters) on a typical 500 km low-Earth orbit is approximately equally difficult to observe as a GNSS satellite (15 square meters) which orbits 20 000 kilometers away. Observations of GNSS satellites are not uncommon, so in theory cubesats should be observable too. The main difference is the time spent in the Earth's shadow, which is much greater for the low-altitude Cubesat. The Cubesat also moves much faster across the sky, but our telescope system will be able to track such a fast-moving low target.

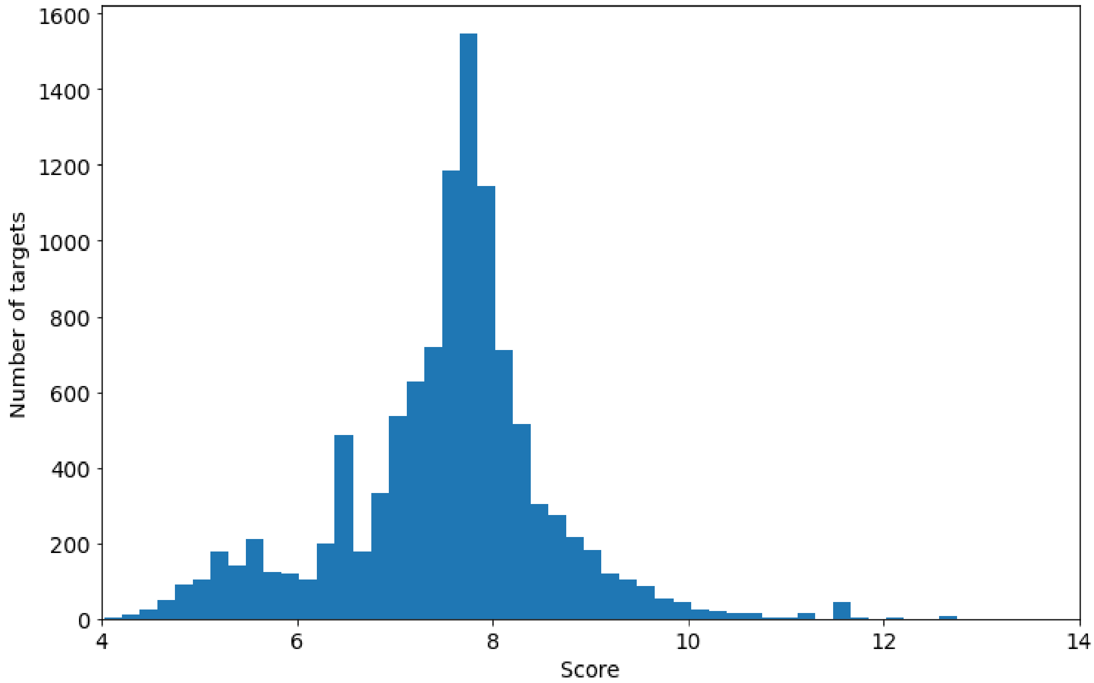

Figure 2: Histogram showing the number of space objects by their observability score, as defined in the text.

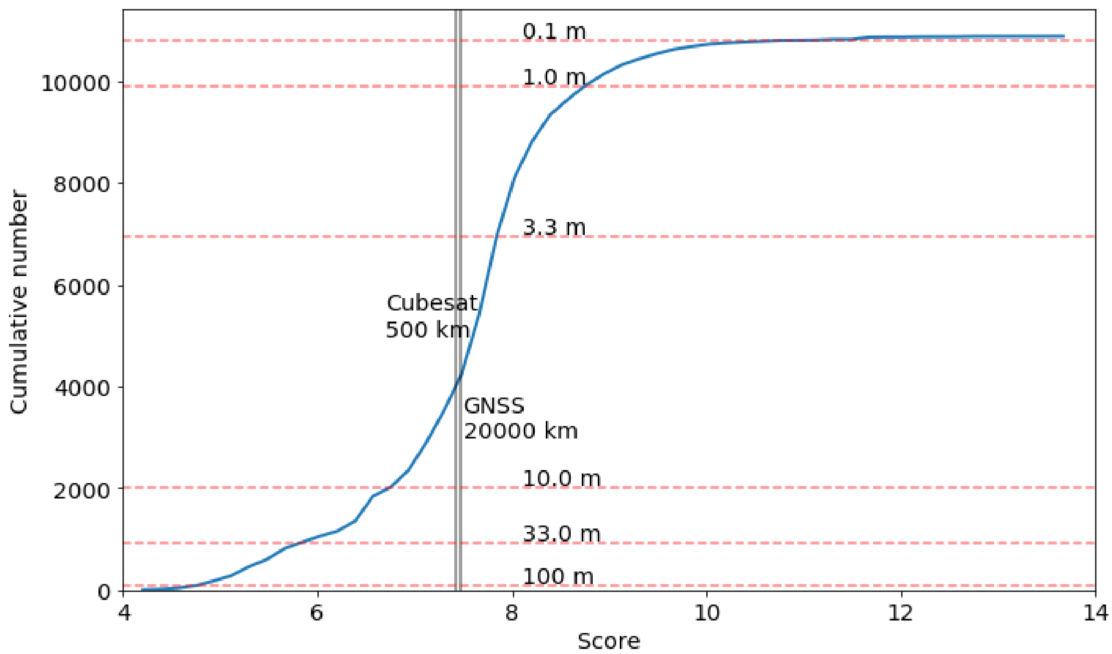

Figure 3: Cumulative number of space object up to a certain score. The horizontal lines show how many objects can theoretically be observed if a given sized object is observable at 1000 km. I.e. if a system can observe a 10 meter sized object at 1000 km, it should be able to observe ~2000 objects of the whole space object catalogue.

Observability of non-cooperative targets

Simulation studies were conducted on the observability of non-cooperative targets using the ray-tracing simulation software described in Section 3. Various shape and reflection models were tested. The reflected pulse shapes were computed in various orientations of the object. The statistics of the reflected pulse can be used to estimate the size of the object. Different shape models produce different pulse distributions, but identifying or classifying shapes based on the pulse distribution is a difficult problem.

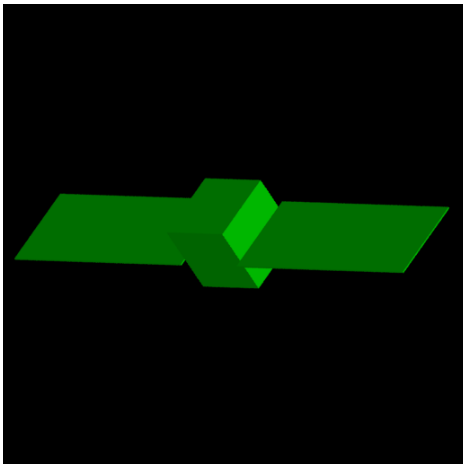

Figure 5 shows simulated SLR data for a simple rotating box-wing type shape model. The model has an Ashkhmin-Shirley surface reflection model, which is assumed to be the same for both the solar panel "wings" and the body. Using a different reflection model for the solar panels would produce more realistic results, but is noticeable mainly as a relative dimming of the signal from the panels compared to the body. In this case, we examined the differences caused by varying the parameters of the reflection model, which are total reflectivity, the balance between diffuse and specular reflection, and the width of the specular peak.

This simulated data is considerably better quality than real observed data would be.

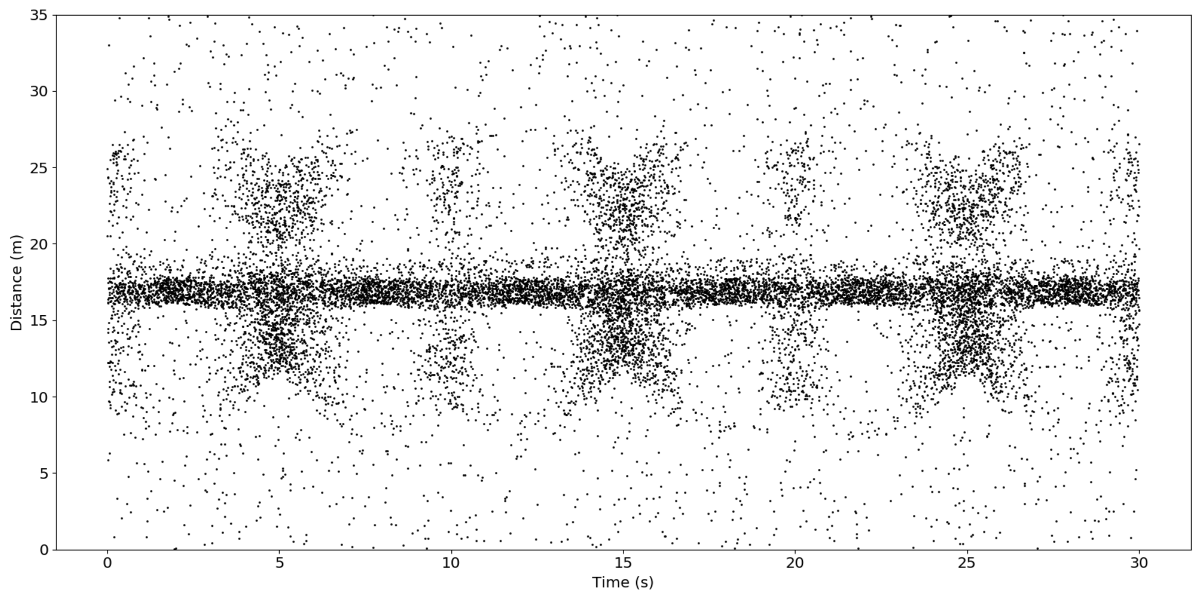

Figure 5. Simulated SLR data for a rotating box-wing shape model. The rotational period is 20 seconds, though the apparent period is 10 seconds due to the mirror symmetry of the object.

Period analysis techniques were applied to the simulated data, and prove to be applicable. A Lomb-Scargle periodogram computed for the simulated box-wing satellite (Fig. 6) shows peaks at the true frequency and its overtones, though slightly shifted. Due to the symmetry of the body, the first overtone is stronger than the fundamental frequency. The analysis works also with noisier data, or less bright signal, but the accuracy of the period determination suffers somewhat. Filtering of the data before the period analysis may improve the results further, but must be explored more thoroughly in the future.

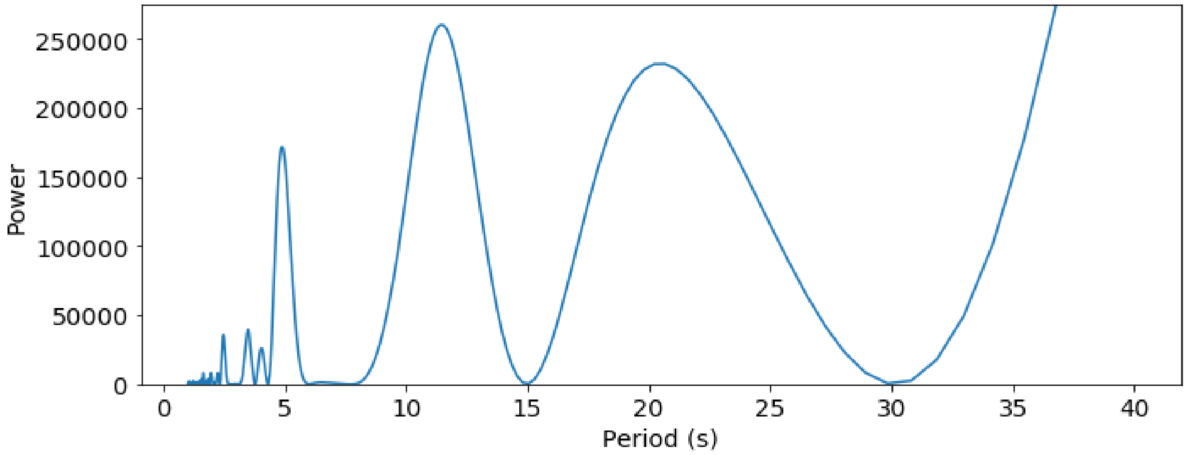

Figure 6. A Lomb-Scargle periodogram of the data shown in Figure 5. The true period of the model which generated the observations is 20 seconds, though the apparent period is 10 seconds due to the mirror symmetry of the body.

A peer-reviewed publication is being prepared from the results of these simulation studies, which were also presented at the AMOS 2018 conference. Another conference paper is being prepared applying the same technique to simulate observations of flybys of small near-Earth asteroids.

Multi-static observations

Multi-static SLR observations involve more than one station observing the same object simultaneously. One station, usually the one with the most powerful laser, will illuminate the object with its laser, while all the stations observe the reflected pulses. This way, in theory, stations with weaker laser transmissions can participate in observations of non-cooperative targets.

Multi-static observations have two main limitations: Firstly, the target must be visible from multiple stations simultaneously, which limits the distance between the stations. Secondly, the weather conditions must allow observations at all the stations.

The Metsähovi station is theoretically capable of multi-static observations with at least two stations: Riga (Latvia) and Borowiec (Poland). Discussions have been started with the Riga station operators regarding multi-static experiments once the Metsähovi station is operational.

Collaboration with nano-satellite builders

We have obtained some samples of satellite solar panel material from the Aalto university satellite team. These samples will be measured in laboratories at the FGI and also by colleagues at the University of Helsinki in order to characterize their bidirectional reflectance properties. These properties can be used e.g. to improve the ray-tracing reflection model described above.

5. Conclusions

The upcoming SLR system at Metsähovi is theoretically capable of SST work to a certain extent. Based on the studies in the 2017 MATINE project, the system can track and range all co-operative targets (objects with retro-reflectors) up to geostationary orbit. Being optimized for geodetic work, it lacks the laser power to observe non-cooperative targets beyond low orbits, up to 500–750 km for the largest objects.

The system's capability is enough to begin experimental space debris observations once the system is operational, while future upgrades can provide the boost in capability to include a larger population of targets.

Retrieving information about the spin state of the target is possible for co-operative targets as long as the target's spin period is short enough. For non-cooperative targets, simulations indicate that at least the spin period is possible to measure, given good enough data.

Bi-static observations with the stations in Latvia and Poland are technically possible. Discussions about co-operation between stations have been started. Mutual scheduling and weather requirements will limit the practical operational time.

The co-axial optical telescope with a CCD camera allows a different population of targets to be observed. The number of possible targets could be several thousands, mostly in high orbits (10000 km and above). Because the objects can not be resolved at the camera's resolution, the observations are taken photometrically, which can enable spin period determination for many targets. However, the same targets are rarely observable with both the CCD and the SLR due to their different limitations. A photometric detector based on a photon-counting avalanche diode will be investigated for improved photometric spin state determination.

Another major limitation of Metsähovi SLR system for SST is that it is dedicated primarily for geodetic work, which ideally requires all useable observation time, and thus only small part of time can be used for SST. Despite that, we recommend continuing SST activities in Metsähovi, when it is ready. The Metsähovi SLR will be updated with a more powerful and up-to-date laser in next 5 years.

During the process, we have identified several more near or far future options to improve debris tracking beyond current Metsähovi plans:

If the geodetic accuracy of 1 mm is not needed, much more powerful lasers and wider beams can be used with faster scanning and full time operation, to find at least 100 times more debris than using sporadic-time geodetic SLR. Several systems are coming into the market, with a price range probably only in hundreds of thousands of euros.

In addition to SLR bound passive optical telescope, one can setup several robot telescopes to scan the sky around the country. Moderately priced off-the-shelf components can do the job well (~tens of thousands of euros). With novel polarimetric techniques shiny artificial satellites stand out from the polarization-neutral star background and make automatic detection more precise.

To overcome the cloud barrier, the observatory could be flown over the clouds, using drones or electric-propelled rigid airships, providing long endurance, high stability, vibration isolation, and reasonable costs. This could give up to 90% operation time. We are partnering with www.hipersfera.hr for new applications. There are still risks and several years time span for readiness, but if working, it would open new era in aerial geodetic, scientific, and military measurements.

Active and passive radars can complement the picture in many ways. Future cooperation possibilities have been discussed with the Sodankylä radio observatory, who will have a redundant radio telescope after the new EISCAT-3D system begins operations.

We further recommend strongly, that every piece launched in space, should have prisms to detect them in any part of life cycle.

While performing this work, we have contributed to Finnish SST strategy, which will be a major cornerstone in all future actions.

6. Scientific publishing and other reports produced by the research project

“Ray-tracer for Modeling Interactions of Light with Space Objects”, technical paper at the Advanced Maui Optical and Space Surveillance Technologies Conference, Wailea, Hawaii, 11.–15.9.2018. Peer-reviewed publication in preparation.

SSA Strategy for Finland, under preparation by SSA strategy working group chaired by J. Virtanen.

Conference presentations:

Space geodesy, satellites and debris, presented at the Finnish Satellite Workshop, 17.–18.1.2018, Espoo, Finland.

The new Metsähovi satellite laser ranging system, presented at Nordic Geodetic Commission General Assembly, 3.–6.9.2018, Helsinki, Finland

Ray-tracer for Modeling Interactions of Light with Space Objects, presented at the Advanced Maui Optical and Space Surveillance Technologies Conference, Wailea, Hawaii, 11.–15.9.2018.

Metsähovi Geodetic Research Station – a future GGOS core station, presented at 21st International Workshop on Laser Ranging, 5.–9.11.2018, Canberra, Australia

Metsähovin satelliittilaser lähiavaruuden kohteiden karakterisoinnissa, presented at the MATINE seminar, 22.11.2018.