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SUMMARY REPORT

Characterization of objects in near-Earth space using Metsähovi satellite laser ranging system

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Abstract: The goal of the project is to study the capabilities of active satellite laser ranging (SLR) and passive optical (photometric) observations for the characterization of objects orbiting near the Earth, as well as the possible synergies obtained by combining these two methods. In particular, we explore the possibility to determine spin (rotational) states of the targets using both active and passive optical data. The new project will utilize the Finnish Geospatial Research Institute's satellite laser ranging system in Metsähovi. The first year of the project requires applying the methods of SLR and photometric data processing, leading to the capability to estimate the rotational state of a "cooperative" target, i.e. one which has reflecting prisms for SLR observations. In the second year these methods will be extended to non-cooperative targets (without SLR prisms), and to using the two observational methods with simultaneous observations.

1. Introduction

The goal of the project is to study the capabilities of active satellite laser ranging (SLR) and passive optical (photometric) observations for the characterization of objects orbiting near the Earth, as well as the possible synergies obtained by combining these two methods. In particular, we explore the possibility to determine spin (rotational) states of the targets using both active and passive optical data. Based on the results of a MATINE project completed in 2015, we will utilize the Finnish Geospatial Research Institute's SLR system in Metsähovi in observations of both active satellites as well as space debris.

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 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 nadir which reflect the laser pulses directly back to the laser transmitting station, 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. There is an increasing interest in using SLR systems to observe such targets in low orbits. Those are e.g. space debris or satellites without retroreflectors. This is a demanding application, primarily because the return signals are very weak, but also the

orbits of these objects are often poorly known. The accuracy of the range is worse, because there is no information on the location on the object where the return pulse is reflected. Simultaneous optical positioning can be done to improve the orbit information.
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.

2. Research objectives and accomplishment plan

In order to study how the data from Metsähovi SLR station could be used to determine the spin states (period and direction of spin axis) of Earth-orbiting targets, we broke the work down into following tasks:

1. Processing of SLR range data
2. Determining spin state from SLR data (active)
3. Optimizing passive optical observations with the Metsähovi SLR system
4. Processing of photometric data (passive)
5. Determining spin state from photometric data

While during the first year of the project, it was not yet possible to acquire suitable test data with the Metsähovi system, we implemented the necessary tools for data processing of both active and passive optical data (tasks 1 and 4) and used data openly available from optical systems similar to the Metsähovi system in the analysis (tasks 2 and 5). After concluding literature studies of the available methods for tasks 2 and 5 (Sect. 3.4), we implemented methods for determining the spin state. We demonstrated that it is possible to extract reliably the spin period of targets with the type of data that will become available from the Metsähovi station (Sect. 4.2 and 4.3).

In addition, we showed that in case of a target with changing spin state (e.g. due to various forces acting on an uncontrolled satellite, or due to active maneuvers of controlled satellite), we are able to detect the evolution of spin period over time, given that enough data is available for the analysis. As for the spin axis, our study and experiments revealed that the inversion problem is extremely complicated and either considerably more sophisticated methods than currently available or comprehensive set (possibly including a priori information) are needed to obtain a solution.

In preparation for the second year of the project, we also performed detailed simulations of the system performance (Sect. 4.1) and showed that it is possible to obtain SLR data also for a considerable number of non-cooperative targets, which is the ultimate goal of the project.

3. Materials and methods

3.1 SLR DATA

As the satellite moves along its orbit as well as rotates, the measured distance from the SLR station to the reflecting surface changes. However, to detect the small oscillation due to rotation (from mm's to meters), the raw SLR observations, i.e., distances, are fitted with the predicted orbit to calculate the range residual as the difference between the measured and predicted range. In Figure 2 range residuals from SLR observations from Riga showing a one meter oscillation in the distance to the retroreflectors of TOPEX/Poseidon.

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 was written for the parsing of both CPF and CRD files (https://github.com/dronir/SLRdata).

3.2 OPTICAL PHOTOMETRY

The preparation of the Metsähovi SLR system for passive observations was continued in the project. The system was complemented with a coaxial 152 mm refractor telescope equipped with a high QE CCD for optical tracking of targets. However, because of unexpected delays in the finalization of the SLR system we were not able to acquire usable optical observations during the study period.

Instead, photometric light curves of satellites were acquired from a database of the Kazan Federal University Observatory, Russia (http://astroguard.ru/satellites). The data have been observed on the Multichannel Monitoring Telescope, a fast survey telescope designed for observing quickly changing events in the sky.

3.3 SATELLITE CATALOGUES

The known parameters of space objects are retrieved from two sources: 1) The Space-Track website (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.

3.4 REVIEW ON EARLIER STUDIES FOR SPIN STATE DETERMINATION FROM SLR

Earlier studies have shown that SLR observations especially made with a kHz repetition rate laser as in Metsähovi, providing a sufficient data yield and accuracy can be used to determine the spin period of cooperative targets (e.g. Kucharski et al 2008, 2013) and for defunct satellites with reflectors, now space debris, like ENVISAT, TOPEX/Poseidon and defunct Glonass satellites (Kirchner et al. 2013, Kucharski et al. 2014 and 2017). The recent advances in laser and detector techniques has also made observations of non-cooperative targets with SLR feasible (Kirchner et al. 2013).

However, the spin axis has been identified mainly for the so called “geodetic” targets: ETALON, LAGEOS-1 & 2, LARES, STELLA, Larets, BLITS and AJISAI, which all are spherical with a well-known retroreflector setup, as well as a known initial spin state. The only debris targets for which the spin axis is identified from SLR are Envisat (Kucharski 2014) and TOPEX (Kucharski 2017). In the latter, a solar radiation pressure model was used to calculate the apparent decay of the spin period as well as the spin axis orientation. There are no published results of spin axis determinations for non-cooperative targets made from SLR observations.

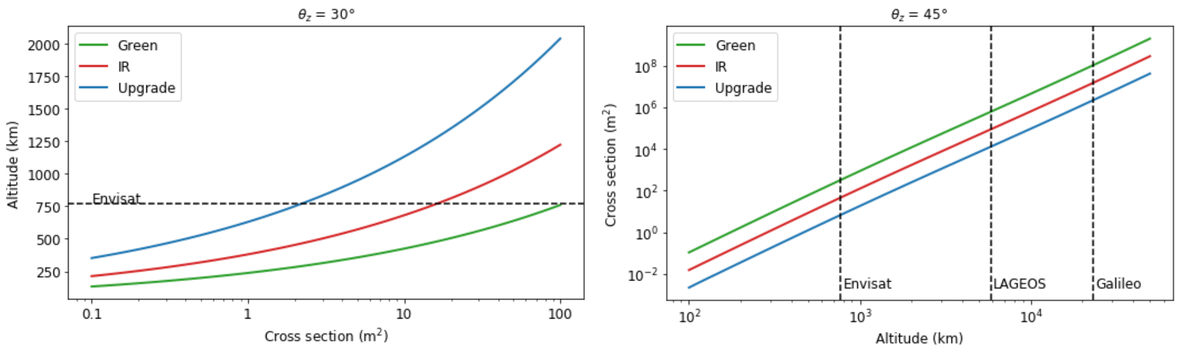
4. Results and discussion

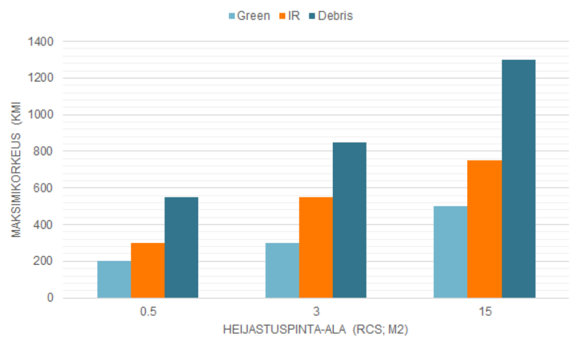
4.1 LASER PERFORMANCE STUDY

The capabilities of an SLR system can be assessed theoretically by using the radar link equation (Degnan 1993), which relates the properties of the laser and optical system, as well as the target, to the number of photons (statistically) received. An SLR observation model was implemented in the Python language (https://github.com/dronir/RadarlinkSLR).

We compared three laser configuration options (see Table for parameters): the *green laser* currently installed in Metsähovi, the *IR laser* (same laser operated at the infrared 1064 nm wavelength), and a potential more powerful *debris laser* (based on a laser used at the Graz observatory).

The IR laser option is approximately twice as powerful, and the debris upgrade option approximately four times as powerful as the current green laser in terms of the maximum altitude and minimum cross section of observable non-cooperative targets, as well as the number of observable objects out of the SATCAT catalogue (cf. Table).





	Green	IR	Debris
Aallon-pituus	532 nm	1064 nm	532 nm
Energia	0.4 mJ	0.8 mJ	80 mJ
Taajuus	2 kHz	2 kHz	200 Hz
Kohteita	**270**	**563**	**1218**

Figure 1: Simulation of laser performance at Metsähovi. Cross section of targets versus altitude with three different lasers. Characteristics of the lasers are shown in table.

4.2 SIMULTANEOUS SLR AND PHOTOMETRIC OBSERVATIONS

We have estimated the numbers of non-cooperative space objects that can potentially be observed with SLR and an optical telescope at Metsähovi. Software was written to compute the numbers of visible satellites with both techniques at a given time. The same observation model as above was used for estimating the SLR visibility, using SATCAT radar cross sections. We found 13515 space objects currently in orbit for which both a radar cross section (from SATCAT) and TLE orbital elements (from Space-Track) are available.

A satellite was deemed visible in the optical when it is at least 15° from the horizon and not in the Earth's shadow, while the Sun is lower than 5° below the horizon. The chosen magnitude limit of 13 represents the expected performance of the Metsähovi telescope-camera system, though the exact limit depends on the final system properties, as well as weather conditions and the time of day and year. To estimate the brightnesses of satellites visible with the passive optical telescope, a rough estimate of optical brightness based on the radar cross section is made (McCue et al. 1970).

The number of objects which appear brighter than magnitude 13 ranges 250–400 on a typical night in October (Fig. 2). The number peaks near sunrise and sunset, when the Earth's shadow is low in the sky. It must be noted that the estimate is based on broad assumptions about the optical properties of the objects, and serves only to give a rough sense of the number of visible objects.

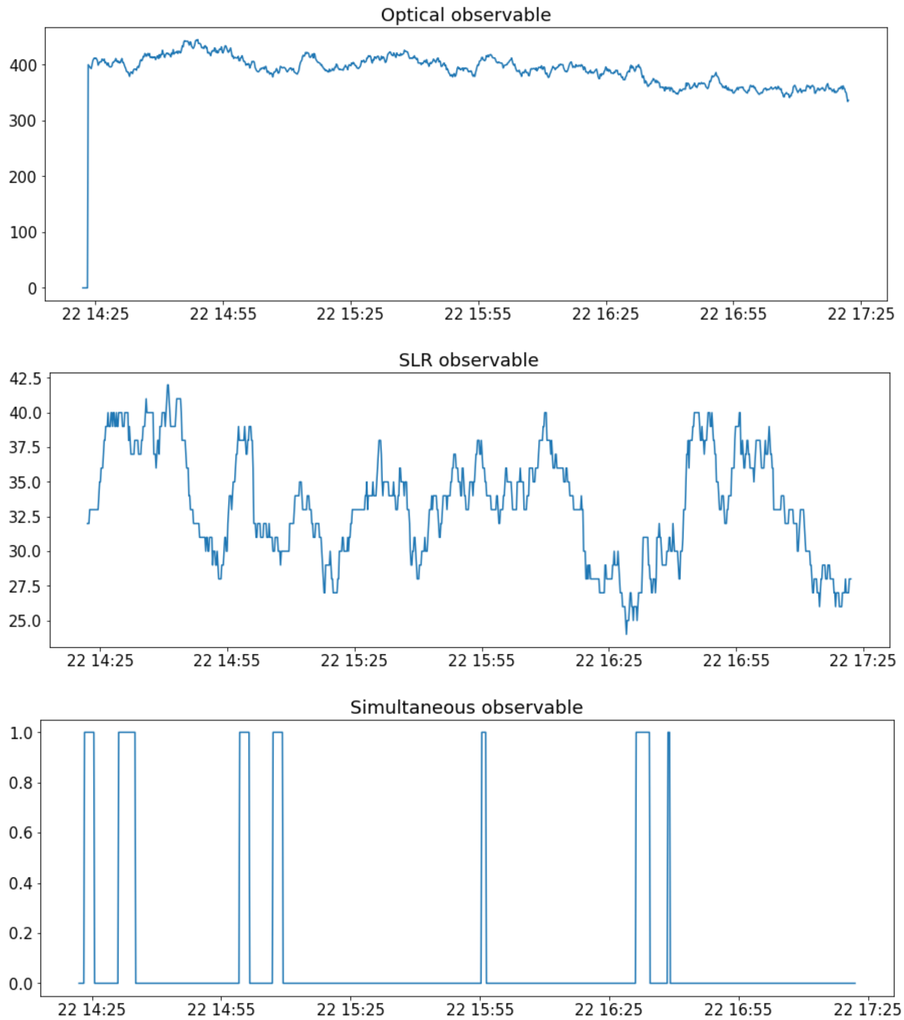


Figure 2: Number of known space objects observable from Metsähovi with different methods. The x-axis shows three hours of time from 14:25 to 17:25 on October 22, 2017. Top: number of optically visible (brighter than 13 mag) objects. Middle: number of non-cooperative objects observable with SLR. Bottom: number of non-cooperative ob-

jects observable simultaneously optically and with SLR.

Simultaneously approximately 30–35 non-cooperative objects are theoretically observable through SLR. The overlap between these two sets is very small, however. This is because the SLR observable objects are on low orbits, which usually place them into the Earth's shadow. There is overlap between the two sets only near sunrise/sunset, when the Earth's shadow is still low in the sky. Even then only individual objects are observable in both optical and SLR at any given time, for short parts of their sky traces. The main constraint on this number is the capability of the SLR system, which restricts SLR observations to low orbits.

4.3 PERIOD FROM SLR OBSERVATIONS

Many well-known algorithms exist for finding periodicity in time series data, and are directly applicable to the problem of determining the spin period from SLR residuals. We implemented the Lomb-Scargle periodogram (VanderPlas 2017) and the Phase Dispersion Minimization (PDM; Stellingwerfer 1978) methods. It turns out that it is straightforward to determine the apparent spin period from the available data, as long as the data set is long enough to cover at least one or two full periods. Figure 3 shows a single pass of the TOPEX/Poseidon satellite, observed at the Riga SLR station, as well as the Lomb-Scargle periodogram, and the data re-plotted at the best-fit period of 10.818 seconds.

Lomb-Scargle works ideally for data sets with a sinusoidal variation, while PDM theoretically works for any kind of periodicity. In practice, both methods produce the same results for typical "good" data. We find that PDM works better when parts of the rotation period are systematically missing, such as SLR observations where the retroreflector is only visible during some part of the rotation. However, the Lomb-Scargle periodogram is somewhat faster to compute, and works well when the data has no such gaps. On the other hand, PDM sometimes identifies the wrong harmonic of the fundamental rotation period.

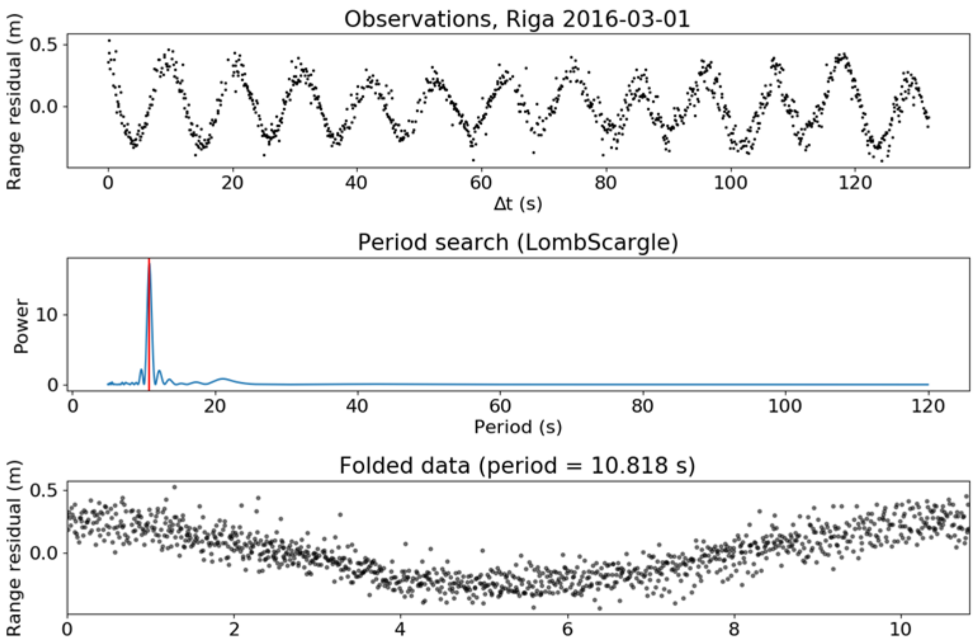


Figure 3: Spin period computation from SLR residuals. Top: observed SLR residuals. Mid-

dle: Lomb-Scargle periodogram showing a clear single solution. Bottom: the same observed data folded with the best period.

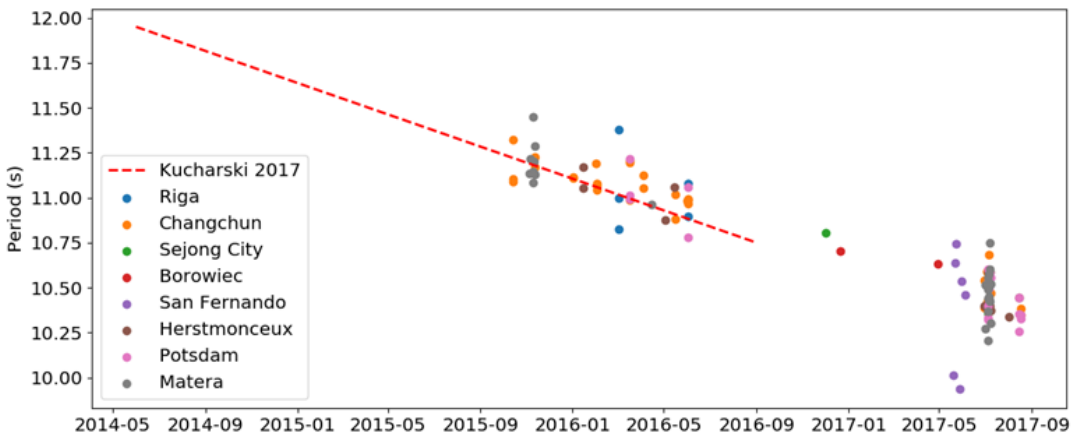


Figure 4: The apparent spin period of TOPEX/Poseidon computed from observations between late 2015 and summer 2017. The trend reported in an earlier study published by Kucharski, 2017, is shown with a red line.

The periods computed for TOPEX/Poseidon agree with those reported in previous studies. By analysing data from different dates, we can observe the spin period changing over time (Figure 4). The trend we see in our period analysis agrees well with previous studies.

4.4 PERIOD FROM OPTICAL OBSERVATIONS

The same period estimation methods were applied to high-frequency photometry from the MMT telescope. The MMT surveys the sky using very short exposure times, which allows various sharp features to be seen in the data (see figure 5). The period analysis tools were found to work well for the photometric data, with some caveats. Firstly, if the exposure time is not short enough compared to the spin period, the signal from the spin will be smoothed out. This depends on the size and properties of the object, as smaller and darker objects require longer exposure times. Secondly, if the object is too symmetric, its brightness will not change much as it spins, and no information of the spin state is conveyed.

Smooth elongated objects, such as discarded rocket bodies, generally have clear and smooth light curves with the spin period easily visible if it is long enough. Objects with many sharp surfaces, such as most satellites, have complex light curves, which depend strongly on the attitude of the satellite w.r.t. the Sun, because of specular reflections.

The optical telescope and CCD camera in the Metsähovi telescope system will be capable of high-frequency photometry only for particularly bright objects. However, the exposure times should remain short enough to perform period analysis for many debris objects with rotation periods longer than a minute.

High-frequency photometry of space objects is also possible using a separate single-photon counting detector. This technology has been implemented at the Graz Observatory (Austria) and proven to be very promising (Kucharski *et al.* 2017). Such observations can be performed alongside SLR operations of the same target and do not require large investments in hardware. Therefore we are considering it as a future upgrade to the

Metsähovi system for improving our space object characterization capabilities.

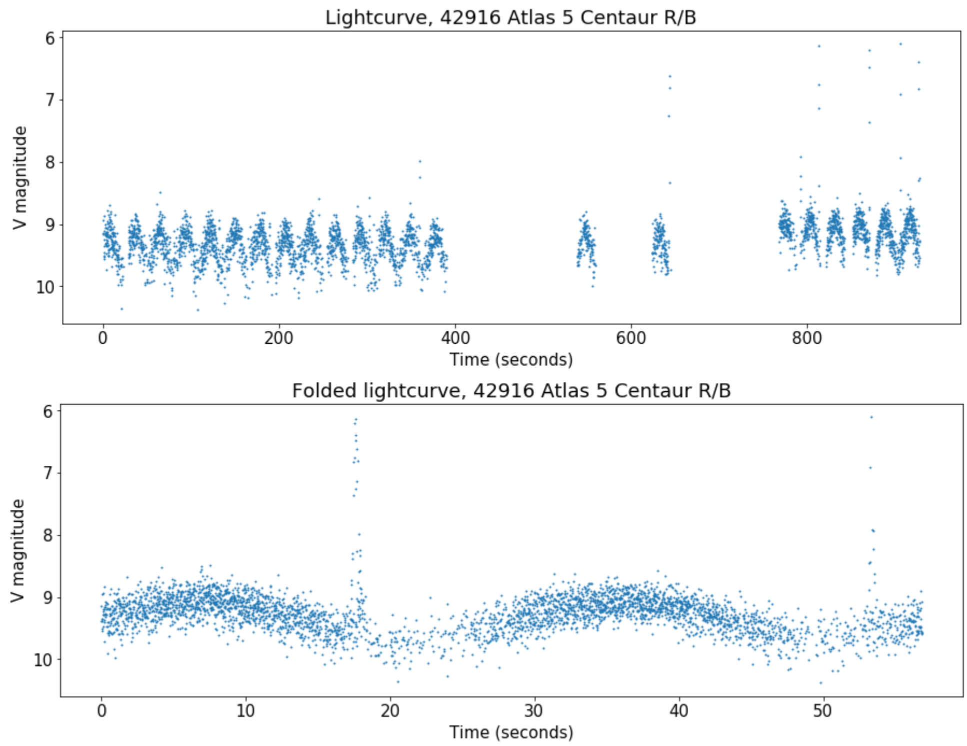


Figure 5: Period analysis of an optical light curve from a discarded Atlas 5 Centaur rocket body. Top: High frequency optical light curve of a rocket body, observed with the MMT survey telescope. Bottom: The same light curve, folded with the best period estimate. Two sharp brightness peaks are visible, possibly specular reflections from flat surfaces, or brighter materials. The best period was found to be approximately 58 seconds.

4.5 SPIN AXIS FROM SLR OBSERVATIONS

The published methods for estimating the spin axis direction of cooperative targets from observed SLR residuals are all relatively simple and problem-specific. Thus, we aimed at developing a more general method, and approached the problem through Bayesian model fitting using a Markov-Chain Monte Carlo algorithm. The method is based on equi-energy sampler (Kou et al. 2006) and enables us to study also complex, multimodal parameter distributions, which have been indicated to result for the spin parameters (e.g. Lagaune 2016). Our method is promising, but its current version was found to have limitations in practical use, due to problems in defining the model for a particular satellite. Results for the spin axis determination (Figure 6) are therefore still preliminary, and it seems that problem-specific adjustments may always be necessary.

Of the space debris objects with retroreflectors, the two with the most observational data are TOPEX/Poseidon and Envisat. Unfortunately both proved difficult test cases. In the case of TOPEX, the configuration of retroreflectors on the satellite body is unusual, and difficult to model. In previous work by others, *a priori* information and assumptions about the satellite's orientation are used. Our model can in principle be tuned to each satellite by adding such assumptions. Envisat, on the other hand, is a slow rotator, which causes problems in determining the SLR residuals. This problem can be solved with more sophisticated ways of computing the residuals, which requires precise orbit computation.

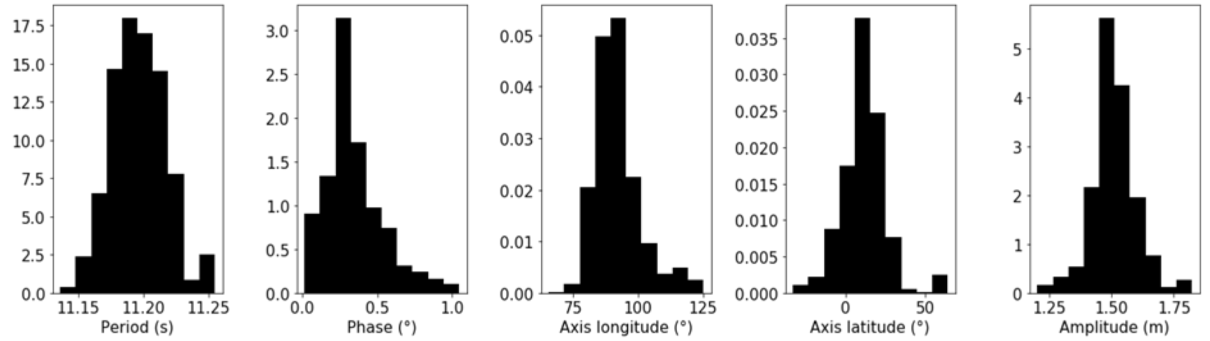


Figure 6: Preliminary examples of statistical distributions of the spin state of TOPEX/Poseidon based on the SLR residuals of one observational pass.

5. Conclusions

The SLR station in Metsähovi, once operational, will be able to track all Earth orbiting satellites which are equipped with retroreflectors. The data rate and quality expected from the system will be sufficient for studies of the rotational state of cooperative (retroreflector equipped) targets. Based on our simulations, the system will be capable of tracking all cooperative targets and at least some dozens (possibly hundreds) of non-cooperative targets on low-Earth orbits (below 1000 km). By upgrading the system, a significantly higher level of performance could be reached.

Simultaneous observations of non-cooperative targets with SLR and the optical telescope will be possible but are constrained by the fact that the targets observable with the current Metsähovi system are in low orbits, and spend much of their time in the Earth's shadow.

Existing period analysis methods work well for SLR distance residuals. Good residuals can be computed for fast-rotating objects, but the process is more complicated for slow rotators. Software has been developed for reading SLR data and prediction files, as well as performing the period and spin axis analysis.

We have also developed a novel method for determining the spin axis from the SLR range residuals and optical light curves by using a Markov Chain Monte-Carlo algorithm based on a Bayesian model fitting method. However, we discovered that determining the axis unambiguously is very challenging without *a priori* knowledge of the object characteristics. To improve the method and its ability to identify the spin axis we need to gather and incorporate more *a priori* information on the objects. Our future aim is also to study whether the combination of active and passive observations can help in the inversion.

The results from this project have been presented in the FinCOSPAR conference (http://www.astro.utu.fi/fincospar2017/index.html) and at the 7th European Conference on Space Debris organized by the European Space Agency (Virtanen et al. 2017). A paper is under preparation to be submitted to Advances in Space Research. A visit to the Graz Observatory (Austria) was made, to investigate a state-of-the-art SLR station with a strong focus on space debris studies.

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