PREPARING THE NEW 2 KHZ SATELLITE LASER RANGING SYSTEM FOR SPACE DEBRIS OBSERVATIONS IN FINLAND

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ABSTRACT

We discuss the capabilities for space debris observations of the forthcoming 2 kHz satellite laser ranging (SLR) system in The Metsähovi Geodetic Research Station of the Finnish Geospatial Research Institute (FGI). We simulate the capability of the Metsähovi SLR station for space debris tracking and also discuss foreseeable developments towards dedicated subsystem for debris observing. We investigate the system performance using the laser link equation to estimate how small and distant objects can be successfully ranged with a geodetic SLR system. Based on the simulations, we show that the Metsähovi SLR system should be capable of tracking meter-sized objects at least up to altitudes of 500 km. We discuss the possibility of adding a second transmit and receive system, e.g., a powerful NIR laser with corresponding receiver. This allows efficient usage of the system where geodetic and space debris targets can be observed in an interleaved way. In the future, we also anticipate simultaneous photometric imaging and ranging to selected targets.

Key words: Satellite laser ranging; observing technique; near infrared; space debris.

1. INTRODUCTION

There is an increasing interest in using SLR systems to observe non-cooperative targets (e.g. space debris with or without retroreflectors) in low orbits. For example, the rotational state and evolution of space debris targets can be determined from kHz ranging (e.g., [4]).

The Metsähovi Geodetic Research Station of the Finnish Geospatial Research Institute (FGI) of National Land Survey of Finland (former Finnish Geodetic Institute) is one of the core stations in the global geodetic network. All major space geodetic instruments are installed at the station and all of them are either recently upgraded or currently under renovation. When completed, it is one of the most versatile geodetic station in the world. The instrumentation include several GNSS receivers (starting with GPS in the global geodetic network since 1992), capable of observing all navigation satellites; a new SLR system, currently in final installation phase; a new radio telescope for geodetic VLBI, to be completed in 2018, and a French DORIS beacon. The Metsähovi station is also the Finnish contribution to the global sustainable geodetic network, a request of the resolution of the United Nations General Assembly in 2015 to the member states.

FGI started SLR observations in 1978. The current system, to be completed in 2017, is the third one. It has a modern telescope, capable of tracking all Earth-orbiting satellites with orbits above 200 km, and a fast 2 kHz pulse laser. Expected observing accuracy is a few millimetres in range to low-orbit satellites, and one centimetre up to the distance of the navigation satellites.

SLR is one of the major instruments in space geodetic observations and essential in maintenance of global geodetic network. The origin of the global reference frame is realized with SLR observations, as well as the orbits of GNSS satellites and geodetic satellites in low orbits.

All traditional SLR targets have retro-reflectors which enable a well-defined return signal and even a mm-range accuracy in range. In recent years, objects without reflectors have been experimentally observed. These include space debris and dead satellites, but also active satellites without reflectors. 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.

2. METSÄHOVI SLR STATION

The SLR system is located in a modern observatory building with a fast-moving slit-type dome and two rooms for instrumentation and the operator and control system. The main components of the system are: a telescope for transmitting and receiving laser pulses; a laser with a stable repetition rate, energy level and pulse lengths; an event timer for measuring the flight time; and a detector for receiving the laser pulse.

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A bistatic telescope system with a 0.5 m receive telescope and a 0.1 m transmit telescope has been supplied by Cybioms Corp. (USA). The returning laser pulse will be detected with a single photon avalanche diode (SPAD), installed into an environmentally sealed detector box in the Cassegrain focus of the telescope. The detector box will have space also for additional detectors, such as an IR sensor (see Sect.4), and a CCD camera.

The SLR electronics as well as the HighQ 2 kHz 532 nm laser are located in the instrument room with an almost clean-room environment and temperature stability within one degree Celsius.

SLR operations will be carried out using the SCOPE (SLR Control and Operation Software) software stack for SLR stations by SpaceTech GmbH (STI). It consists of a daemon which commands and controls all station hardware components in real-time, an operator interface which allows the operator to monitor and perform all SLR operations, and the SCOPE station simulator for software verification, troubleshooting and training.

In addition, the system will be complemented with a coaxial 152 mm refractor telescope equipped with a high QE CCD for optical tracking of targets.

The next step is to extend the capability of the range gate electronics controlling the laser fire rate and detector, and the SCOPE software to allow advanced SLR applications like synchronized space debris tracking together with other stations, i.e., multistatic mode. In this mode one station is sending the pulse and several other stations are observing the returning pulse ([6]).

The system is expected to be ready for geodetic operations during 2017.

3. SIMULATING SLR PERFORMANCE

We investigate the system performance using the so-called radar link equation for SLR [1], which gives the number of photoelectrons expected to be received for a single laser pulse,

$$n_e = \eta_q \left(E_T \frac{\lambda}{hc} \right) \eta_t G_t \sigma \left(\frac{1}{4\pi R^2} \right)^2 A_r \eta_r T_a^2 T_c^2, \quad (1)$$

where η_q is the detector quantum efficiency, E_T is the energy of the laser pulse, λ is the laser wavelength, h the Planck constant, c the speed of light, η_t the efficiency of the transmit optics, G_t the transmitter gain, σ the target's optical cross section, R the slant range to the target, A_r the telescope aperture area, η_r the efficiency of the receive optics, T_a the one-way atmospheric transmission and T_c the one-way transmission of cirrus clouds.

The parameters E_T, η_q, η_t, η_r, G_T and A_r are properties of the laser-and-telescope system. The values of σ and R depend on the chosen target, and T_a and T_c depend on local weather conditions.

Assuming that the number of detected photoelectrons is Poisson distributed, the probability of detecting at least k electrons from a single pulse is

$$p(k|n_e) = 1 - e^{-n_e} \sum_{m=0}^{k-1} \frac{n_e^m}{m!}. \quad (2)$$

Knowing this probability $p = p(k|n_e)$, the number d of detections per second follows the binomial distribution,

$$p(d|f) = \binom{f}{d} p^d (1-p)^{f-d}, \quad (3)$$

where f is the laser fire rate (pulses per second). The probability of receiving *at least* n pulses per second is then

$$p(n|f) = 1 - \sum_{d=0}^{n-1} p(d|f). \quad (4)$$

Knowing the parameters of the telescope system that go into Equation 1, and choosing suitable thresholds for the numbers k (electrons per detection) and n (detected pulses per second), we can use Equations 1–4 to estimate the performance of the system for different targets under various atmospheric conditions.

4. RESULTS AND DISCUSSION

System development for debris observations. We have studied the upgrade of the SLR system for observing non-cooperative targets, which do not have retroreflectors. While some properties of the system, such as most of the optical parameters, are fixed, other parameters — the laser power and wavelength and the detector quantum efficiency — can be adjusted in the link budget calculations. We have considered two upgrade options for the Metsähovi system: operating in the native wavelength of the HighQ laser in near infrared (instead of green light) and using a more powerful green laser. In addition, we describe the ongoing upgrade to complement the SLR system with an additional telescope and CCD detector for simultaneous passive observations.

The possibility of observing in near infrared has been considered recently in the SLR community (e.g. [5, 3]) and there are several benefits in using this wavelength for measurements of non-cooperative targets. First, the laser transmission at the native wavelength is more powerful, and second, the sky contrast is better, since the atmosphere is more transparent to infrared than to visible light.

The current laser used in Metsähovi has its native wavelength at 1064 nm, which in normal use is transformed into green (532 nm) by using a non-linear optics module. This reduces the power output approximately 50%. To allow observations with the native wavelength of 1064 nm all the optics in the telescope system were coated with high damage threshold coatings with optimum reflectance or transmittance in both 532 nm and 1064 nm.

The main reason for not using 1064 nm for standard SLR measurements is that the quantum efficiency of the detectors has been low and timing accuracy poor in near infrared. However, recently single photon IR-detectors with better timing characteristics and quantum efficiencies have become available, offering suitable ranging accuracies for space debris observations where range accuracies are in the meter range rather than in mm-range. We have recently acquired a SPAD sensor with a QE of approximately 25% in 1064 nm to be installed into the detector box, adding the possibility of doing interleaving observations with 532 nm and 1064 nm.

In the future, we foresee the possibility for using a dedicated more powerful laser for space debris observations. The instrument room is equipped with two separate optical tables from which two independent lasers can be guided up through to the telescope's Coudé path.

Finally, the Metsähovi SLR system will be equipped with an auxiliary refractor and CCD camera which allows simultaneous photometric imaging and ranging to selected targets. We are investigating the capabilities of the telescope as well as suitable observing strategies for attitude determination of space debris using both types of observations.

Simulations. We simulated the system performance for three scenarios using as realistic system parameters as possible: 1) the upcoming standard geodetic SLR system, 2) same system in NIR, 3) same system with a secondary, more powerful laser. Table 1 shows the key parameters of the three laser configurations.

Some of the parameters for the upcoming system are not currently known exactly. In these cases we used known values for similar systems worldwide. The goal was to estimate how small objects and how far away can be successfully ranged with an SLR system originally engineered for other purposes. We have implemented a simulation method based on the radar-link equation, and have obtained results that indicate that space-debris observations are feasible for Metsähovi SLR even with the current setup, but performance is much enhanced if the 1064 nm wavelength is used.

We compared the performance of the three instrument setups by estimating the probability of detection using Eqs. 1–4. For the target to be detectable, we assumed a threshold of 2 photoelectrons per pulse received needed to trigger the detector. We set the minimum detection rate to six detected pulses per second.

	Green	IR	Upgrade
Wavelength, λ	532 nm	1064 nm	532 nm
Pulse energy, E_T	0.4mJ	0.8 mJ	80mJ
Repetition rate, f	2kHz	2kHz	200Hz
Detector QE, η_q	25%	25%	20%

Table 1. The three different laser configurations used in this study. The names given in the first row are used as labels in figures below.

We have used reasonable values for the atmospheric transmittance at 532 nm and 1064 nm, corresponding to sea-level visibility of 23 km. The values represent good, but not exceptionally clear, atmospheric conditions. Cirrus cloud transmittance was computed with a cirrus parameter $t = 1.3$, representing thin cirrus clouds (see [1], Eq. 3.5.1).

For the target objects, we assumed a range of optical cross sections from 10^{-1} up to 10^{8} m^2, comparable to a nanosatellite, such as a Cubesat, and GNSS satellite with a retroreflector, respectively. The zenith angle of the target is fixed at 30°.

We found that, a dark object with an optical cross-section of the order of 15 m^2 could be detected on orbits up to 500 km under normal sky conditions, and up to 600 km under best sky conditions (see Fig. 1). In the case of NIR wavelengths, the same object could be detected on orbits up to about 700 km under normal sky conditions, and up to 1000 km under best sky conditions.

Figure 2 shows the minimum cross section required for a 50% detection probability as a function of altitude. The relationship is exponential, showing as a straight line in the logarithmic plot. Changing the properties of the telescope system (in effect, changing the expected number of photoelectrons per pulse) moves the curves up and down, while the slope stays the same. The slope of the lines depends slightly on the zenith angle. The figure shows that the upgrade to NIR would improve the performance of the system by almost an order of magnitude, in terms of the smallest detectable object. The more powerful green laser would improve the system by another order of magnitude still.

Figure 3 shows the maximum altitude at which a 50% detection probability is achieved for a range of debris sizes up to 100 m^2.

In all cases, increasing the elevation angle would further increase the altitude at which the objects could be observed.

The results obtained in these simulations seem realistic, and are in good accord with simulation results obtained

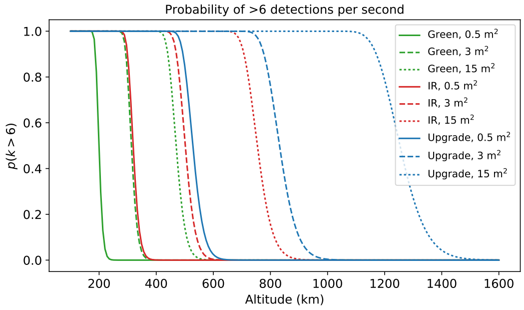

Figure 1. Detection probabilities as a function of target altitude for the three laser configurations and three target cross sections.

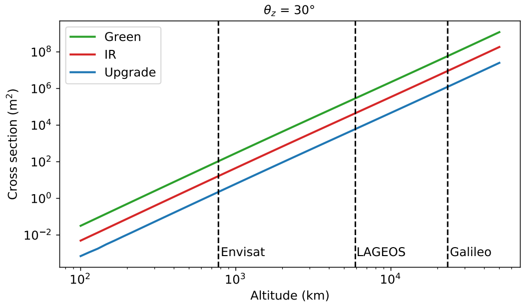

Figure 2. The minimum optical cross section required for a 50% detection probability as a function of altitude, for three different laser configurations.

in similar studies for other SLR systems (see e.g. [2]).

5. CONCLUSIONS

Based on the preliminary performance study presented here, we anticipate that debris observations will be feasible with the upcoming Metsähovi SLR system. The Metsähovi system has been design to be flexible and easily upgraded, and we will have the possibility to observe both geodetic and space debris targets in an interleaved way. Based on simulations, we should be capable of tracking meter-sized objects at least up to altitudes of 500 km. In all the cases studied, the system can detect the objects prior to the final and rapid orbital decay caused by atmospheric drag. The Metsähovi SLR can therefore provide the observational data necessary to constrain re-entry predictions. However, these theoretical estimates need to be confirmed with real observations once the system is operational, first light expected during 2017.

In the future, we foresee the possibility of developing a dedicated subsystem for debris observations. Upgrading the system to be used in NIR (wavelength 532->1064nm) or with a more powerful laser (e.g. 0.4->80mJ) will increase the performance considerably. In addition, we are investigating the capabilities of the auxiliary telescope for target characterization as well as suitable observing strategies for attitude determination using both passive and active observations.

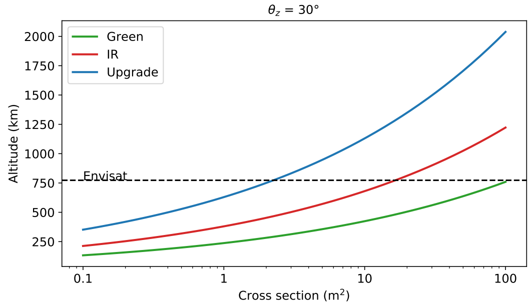

Figure 3. The maximum altitude for a 50% detection probability as a function of debris cross section, for three different laser configurations.

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