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SUMMARY REPORT

Tracking of space debris with active and passive optical techniques (Avaruuskappaleiden seuranta aktiivisin ja passiivisin optisin menetelmin)

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Abstract.
In this project we study possibilities to track near-space objects with active and passive optical techniques and the possible synergy when combining techniques. This is a pilot project where the goal is to study possibilities to establish in FGI a monitoring and warning system for near-space objects. These objects include both natural and man-made objects, like meteoroids, decaying satellites, space debris and non-cooperative targets (e.g. reconnaissance satellites). FGI is the expert institute following e.g. decaying satellites or space debris and to inform rescue authorities and general public if a major event is possible to occur in Finland. The main research topics are orbit determination methods to improve satellite decay forecasts and usability of the new Satellite Laser Ranging (SLR) system at Metsähovi Fundamental Station in space debris observations.

1. Introduction

The near-Earth space is full of man-made objects due to increased space activities during the past five decades. The use of satellites has increased rapidly in communication and navigation and is now vital for our every-day life. In addition to active satellites, there are a lot of other Earth-orbiting bodies or fragments called space debris. This includes ceased satellites, remnants of launch vehicles and, especially, an ever increasing number of remnants created by mutual collisions of satellites or larger remnant objects (Fig. 1). This increasing population of remnants makes surveillance of space objects more important because the risk to collisions with active satellites is more significant, but also because the risk of a re-entering satellite to fall in populated areas is increasing.

Different observing techniques and advanced orbit determination algorithms are needed for reliable monitoring and re-entry predictions of low-Earth-orbit (LEO) objects. LEO objects are typically observed with radar. Due to the limited range of a radar, one needs optical observations for high and medium orbits (GEO = Geosynchronous Orbit, MEO = Medium Earth Orbit). Additionally, the accuracy of radar observations is quite limited. Optical observations are needed for more accurate orbit determination.

Passive optical observations are made with traditional astronomical telescopes, and those are suitable especially for discovering and monitoring GEO and MEO objects. During recent years, there has been an increased interest also for detecting LEO objects and re-entry bodies. Digital image processing enables automated observations and near-real time analysis. We have developed algorithms within an ESA funded project for the analysis of optical observations of space objects.

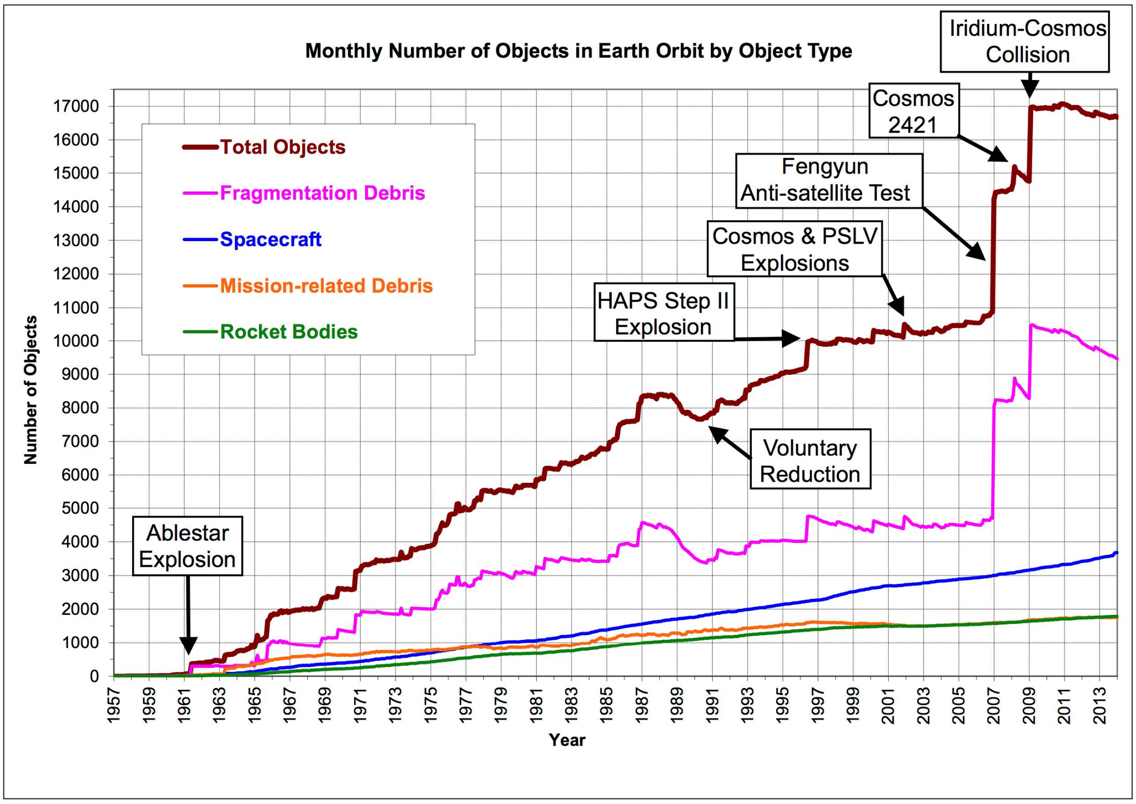


Figure 1. Number of objects in Earth orbit. NASA

Active observations have been made with the Satellite Laser Ranging (SLR) technique. The Finnish Geospatial Research Institute (FGI, until 2015 Finnish Geodetic Institute) has conducted SLR observations since 1978 at Metsähovi Fundamental Station. In SLR observations short laser pulses, the length of which are only some tens of picoseconds, are transmitted towards a satellite. The pulses are reflected back from reflector prisms installed on the satellite. The return pulses are detected with a telescope-attached detector. Observing the pulse flight time, one obtains the distance of a satellite within a few millimetres. Observing the satellite distance along its orbit, enables us to improve the accuracy of orbit predictions or improve studies e.g. on the gravity field of the Earth.

The use of SLR for “non-cooperative targets”, like space debris, reconnaissance satellites or ceased satellites without a prism reflector has been studied for years. However, it is only recently that the observing technology (lasers and detectors) has enabled such observations. Laser pulses reflecting back from such non-cooperative objects are much weaker than from satellites with prisms. To mitigate the loss of return signal one has to use more powerful lasers for such objects. Decaying bodies prior to their re-entry and typical reconnaissance satellites have low orbits which are poorly known and which are changing rapidly. Due to poor orbit predictions, it is more difficult to point the laser beam accurately enough towards the body which also makes observations more challenging. Therefore one must use larger laser beam divergence than normally which weakens return pulses even more.

The research group consists of researchers at the FGI who are specialized in space-object observations and orbit computation. We have a background, e.g., in planetary science and orbit mechanics, and there is a close co-operation with the planetary science research group at the University of Helsinki, led by Prof. Karri Muinonen. Especially developments in asteroid orbit computation, Bayesian orbit inversion method and Monte-Carlo analysis for statistical orbit estimation have been breakthroughs within the group. Statistical analysis has been very successful especially in cases where there are very few observations and the use of traditional orbit determination methods is impossible, a typical situation with the space debris observations.

Related to the passive observing technique, our group coordinated an ESA funded project StreakDet (Streak Detection and Astrometric Reduction) to improve algorithms and analysis of optical observations of satellites and space debris. In the consortium with Finnish space industry companies (Aboa Space Research, Kovilta Oy) we developed an automated processing chain for astronomic pictures containing streaks of unknown objects. The output of this process is a preliminary estimation of the orbit of each unknown object. This is one of the cornerstones of our research in the current project.

FGI has participated SLR observations since mid-1970's using the SLR of Metsähovi observatory. Our group is also responsible for upgrading the Metsähovi SLR which is to be accomplished in 2016. Metsähovi Geodetic Fundamental Station is a part of the global network of geodetic core stations within the Global Geodetic Observing System (GGOS). The network collects data from major space geodetic instruments (Global Navigation Satellite Systems, GNSS; SLR and Very Long Baseline Interferometry, VLBI) to maintain the global reference frame, compute orbits of navigation satellites, determines the orientation of the Earth in space, and participates in various projects to understand geophysical processes on the Earth.

2. Research objectives and accomplishment plan

We have three main objectives:

1. Better orbit and re-entry predictions for space objects
2. Improved space situational awareness of space objects flying over the territory of Finland, and possible threats they pose
3. Better understanding of space debris threats on active satellites

This is a pilot project where the goal is to study possibilities to establish at FGI a monitoring and warning system for near-space objects. As a result, such a warning system could be connected to the existing LUOVA natural disaster warning system and it can offer, e.g., predictions of where re-entering space objects will hit the ground and risk analyses of such events to rescue and safety organizations. At the same time we prepare for observations of for non-cooperative objects with the new FGI SLR system.

The research described here is the first year task of a two-year plan to reach the goal stated above. The work packages are modular, so that first year goals form their own entity. During this plan we apply our orbit determination methods for NEO objects and re-entry satellites. Our approach using the probabilistic interpretation of the inverse problem allows us to, e.g., identify newly discovered space objects or improve estimations of collision or re-entry.

Because the Metsähovi SLR system is being built during the project, we first study requirements and needed modification to the system for space debris observations. Part of these will be accomplished on the telescope which is being built during the year. Simulations with realistic system parameters and target types will provide an estimate of the capabilities of Metsähovi SLR in space debris and non-cooperative target observations and indications on needed improvements and changes for the purpose.

3. Materials and methods

Most of the results of this report are based on computer simulations. A part is related to the development of the SLR system (design changes towards future non-cooperative target ranging). Because the installation of the new telescope is expected in the beginning of

2016, no real observations are yet possible but they will start in 2016. The work is divided in two work packages. The first one is concentrated on satellite orbits and passive observations. Work package two is related to the development of the SLR system and a simulation of space debris observation with it.

WP1: Orbits

We estimate the orbital uncertainties for satellite and space debris using the Bayesian formulation of the statistical inverse problem (see e.g. Muinonen and Bowell, 1993). There the complete solution to the inverse problem is given in terms of the a posteriori probability density function (p.d.f.) for the unknown orbital parameters. We build on our experience in asteroid orbital inversion, where we have developed a variety of numerical methods in particular for objects with only a handfull of observations (see e.g. Muinonen et al. 2012). Using Monte Carlo (MC) or Markov-chain Monte Carlo (MCMC) sampling, we can map the orbital-element phase space and describe the typically large uncertainties with the orbital-element p.d.f. In particular, we have studied the applicability of the so-called statistical ranging technique (Virtanen et al. 2001, Muinonen et al. 2001) to geocentric orbits. In Ranging, the sampling is not carried out directly in the 6D orbital-element space, but instead in the 6D observation space defined by only two topocentric positions. This enables us to attack the orbit computation problem from the discovery moment onwards, when orbital-element p.d.f.s are typically complicated (wide and often multimodal) and the widths of the p.d.f.s, i.e., the orbital uncertainties, can usually not be estimated using linear approximations. The p.d.f.s for the topocentric positions, however, are typically well-constrained and easier to sample numerically even at discovery.

Our probabilistic interpretation of the inverse problem allows us e.g. to identify newly discovered space objects (dynamical classification) or estimate the possibility of collision or re-entry (collision probability).

WP2: SLR

The aim of WP2 is two-fold; first to optimize and simulate the use of Metsähovi SLR system for measuring space debris and other non-cooperative targets without retroreflectors and secondly to simulate optical data for use in WP1. The research will be carried out by using literature sources, international contacts, and by analytical calculations based on the so-called satellite laser ranging link equation.

The new facility at Metsähovi has been designed to be upgradeable beyond the standard operation mode, and our main goal is to determine the specifications and operational mode of an SLR system capable of tracking debris. Because the system is not yet in place, we will implement a computational simulation in order to predict the capabilities of our system. The simulation is based fundamentally on the radar-link equation,

$$n = (\textit{transmit and receive efficiencies}) * (\textit{amplification}) * (\textit{outgoing power}) * (\textit{telescope aperture}) * (1/\textit{distance})^4 * (\textit{target cross-section}) * (\textit{atmospheric transmission})^2.$$

This mathematical expression gives a quantitative connection between the outgoing and the incoming signal. It predicts how many photoelectrons n will be triggered by a return signal at the telescope's detector as a function of the properties of the SLR system, the properties and altitude of the target, and the intervening atmospheric medium. From the estimated number of photoelectrons to be received per pulse, the probability of observation can be calculated, taking into account that there are 2000 pulses emitted per second in the new Metsähovi SLR system, and that the receipt of only 5 or 6 of them per second would suffice to detect the target, a reasonable assumption based on the system design parameters.

While some properties of the system, such as most of the optical parameters, are fixed, other parameters – the laser power, the detector quantum efficiency, and the wavelength used for ranging – are variable. By adjusting them within technical possibilities we can modify the basic setup of our system, – originally meant to track satellites equipped with retroreflectors, – and optimize it for the observation of dark space debris. One interesting possibility is to remove the non-linear optics module which in normal use transforms the native infrared (1064 nm) laser beam into a green one (532 nm), obtaining thus an output signal about three times more energetic. Moreover, there is also an improvement in atmospheric transmission, since the atmosphere is naturally more transparent to infrared than to visible light. Detectors capable of detecting infrared light are not today mainstream, but have recently become available with ranging accuracies suitable for non-cooperative targets.

4. Results and discussion

Orbits

One of the goals of the project is to develop efficient numerical methods for space objects in geocentric orbits. We have started the quest by studying in detail the capabilities of our methods previously developed for asteroid orbits. In particular, we have compared three variants of the ranging method: the original ranging, MCMC ranging and most recently developed random-walk ranging.

Results have been submitted to be published in Celestial Mechanics and Dynamical Astronomy. To summarize our findings, first, we have automated all the methods in a consistent way for performance analysis. All ranging methods show comparable capabilities in covering the phase-space region of plausible orbit solutions, while random-walk ranging appears most promising for real- or near-real time analysis in terms of computational speed.

The first application of random-walk ranging for geocentric orbits was discussed in Virtanen et al. (2015), where we show that preliminary dynamical classification of an object on high-Earth orbit is possible based on a streak-like detection in a single discovery image. We have also studied the recent re-entry of space debris, the case of WT1190F.

WT1190F was discovered in October 2015. When its orbit was calculated, it was found to be orbiting the Earth on a very elliptical orbit. Several observations of the object had been obtained during earlier years but it was only with these 2015 observations that an orbit was computed allowing linkages to be made to the earlier observations – a typical case for a space debris. The origin of this 2-m sized body remains uncertain, but it is possible that it was a remnant from the time of Apollo missions to the Moon in 1970's. WT1190F impacted the Earth on 13 November 2015 over Sri Lanka. We successfully tested our algorithms to WT1190F using data from just one night. The computed orbital uncertainties are shown in Fig. 2.

As a preparation for detailed re-entry analysis, we have also evaluated the numerical accuracy of our algorithms. The OpenOrb software has been tested in collaboration with NASA's Jet Propulsion Laboratory using their orbit-computation software. The agreement is on the 1 milliarcsec level after 12 years of numerical integration, which corresponds to 100 times the observational accuracy of present-day optical data.

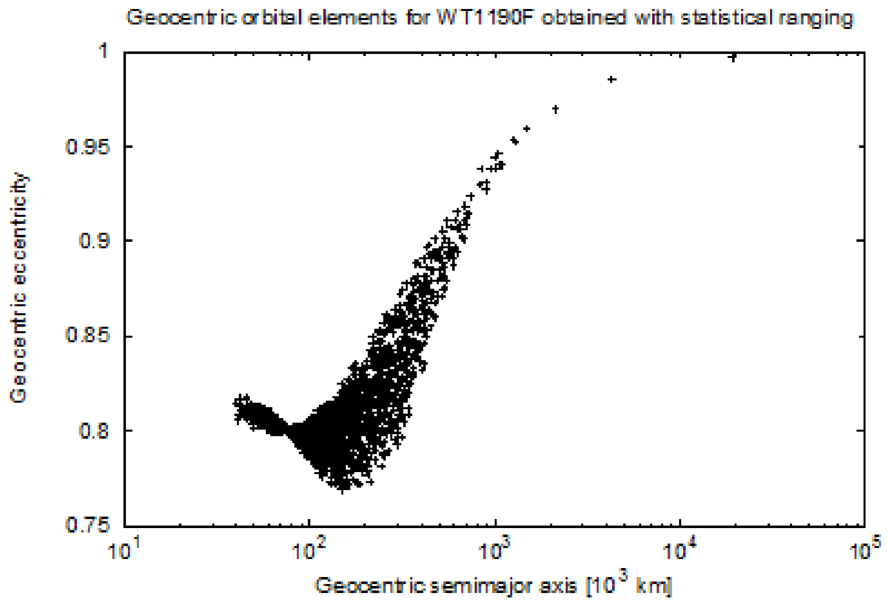


Fig. 2. Orbital uncertainties of WT1190F based on one-night data.

SLR system improvements

Based on international collaboration, literature state-of-art study, and the satellite laser link equation calculations, we modified the optical design of the new Metsähovi SLR telescope (being manufactured in the USA, installation beginning of 2016) to allow measurements in near-infrared wavelengths. The Nd:VAN laser used in Metsähovi has the native wavelength at 1064nm and there are several benefits for using this wavelength for measurements of non-cooperative targets. For example, the laser transmission at the native wavelength is more powerful and sky contrast is better. The main reason for not using 1064nm for standard SLR measurements lie in the detector technologies that are as of yet not as mature as in visible wavelengths. For targets lacking well-defined reflection points (i.e., retroreflectors), these disadvantages are not so important.

In addition, we ordered an auxiliary telescope with a high-quantum-efficiency camera that will help in finding dim and fast moving sun-illuminated targets.

We have also begun, after discussions with Potsdam and Riga SLR stations, the planning on how to upgrade the SLR operating system in Metsähovi to allow observations of non-cooperative targets. The implementation would be through the company that built the SLR operating system both in Metsähovi and in Potsdam. In the first instance Metsähovi would operate as the receiving station for laser pulses sent from another European SLR station (so-called multistatic space debris measurement) as the power output of the current laser in Metsähovi is not optimized for non-cooperative target measurements. Should we be able to obtain a second, more powerful, laser together with suitable detector, having this capability already built-in in the operating system would allow for fast development of Metsähovi SLR into a single-station (i.e., monostatic) non-cooperative target measuring station.

We contacted the satellite laser ranging station in Graz, Austria, and discussed extensively their ground-breaking research into observing non-cooperative targets with satellite laser ranging. The discussions were especially in the context of how the new Metsähovi SLR system (procements finished in 2015, integration, testing and operation in 2016) could be improved for observing non-cooperative targets and also to allow flexibility in the future to upgrade the system as new techniques become available.

We found out that there is no actual need to simulate SLR data, as real data is freely available from both SLR data repositories and also from international partners, such as SLR stations in Graz (AUT), Herstmonceux (UK), and Potsdam (DE). Raw, that is unprocessed, SLR data is not the main product in the International Laser Ranging Service (ILRS), but it has been collected and stored on certain dedicated projects.

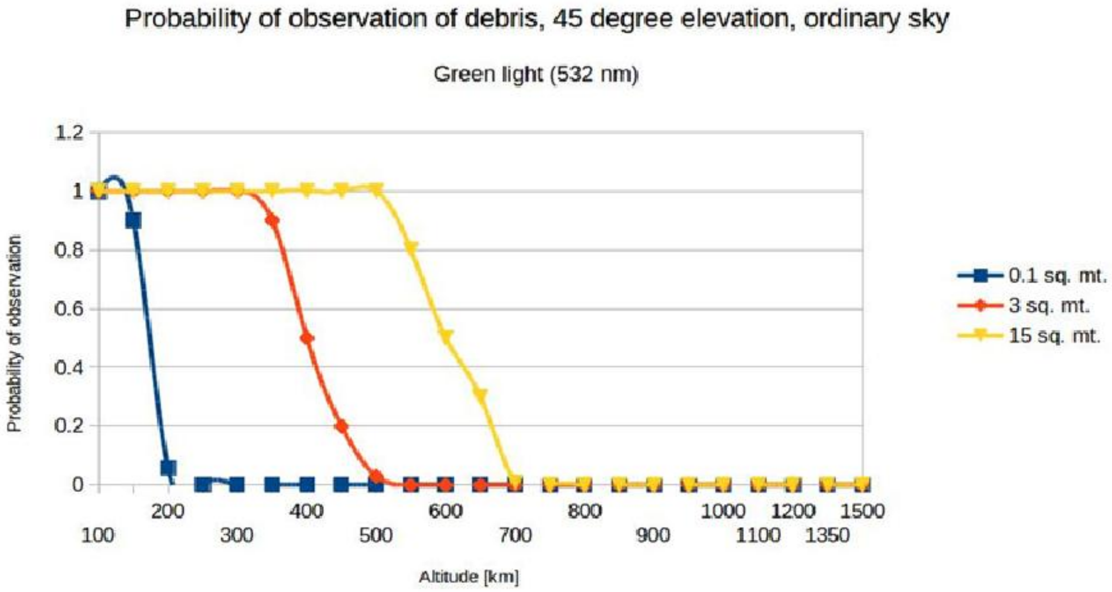
SLR performance simulations

We simulated the system performance, using as realistic parameters as possible for the new Metsähovi system. 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 promising preliminary results.

We found that, observing at an intermediate 45 degree elevation angle, a dark object with an optical cross-section of the order of 3 square meters could be detected on orbits up to 500 km under normal sky conditions, and up to 600 km under best sky conditions. In order to increase this range, which is somewhat limited, we considered next using the system with its native, more powerful infrared wavelength (1064 nm) instead of the regular green one (532 nm). In that case, we found that a dark object with an optical cross-section of the order of 3 meters could be detected on orbits up to about 700 km under normal sky conditions, and up to 1000 km under best sky conditions. A larger object with an optical cross section of 15 square meters (approx. 4 m x 4 m) could be observed further out yet: with green light, up to 600 km under ordinary sky conditions and up to 900 km under best sky conditions; and with infrared light, up to 1100 km under ordinary sky conditions and up to 1500 km under best sky conditions. In all cases, raising the elevation angle that is towards the zenith would further increase the altitude at which the objects could be observed. Examples are shown if Fig. 3.

The results obtained in these simulations seem to us reasonable enough, and to be in good accord with simulation results obtained by researchers in other countries, where studies similar to these have been made with their own systems in mind. Thus, the results obtained so far provide us with valuable information about possible observing concepts for our upcoming system. On the basis of this information, we can next develop an optimal observing procedure for debris, and we can better estimate the expected strengths and limitations of our system and in which ways to upgrade.

We note that, 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.



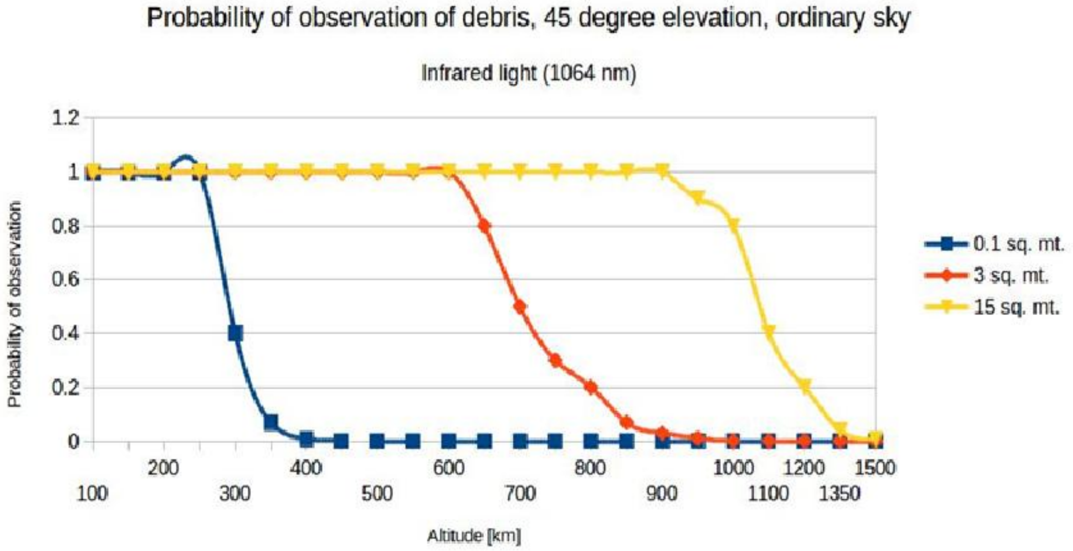


Figure 3. Simulation of the SLR performance. Upper picture shows the situation when the normal green wavelength (532 nm) is used. Lower picture is with the infrared 1064 nm. Three curves show three different-sized objects, 0.1 m^2, 3 m^2 and 15 m^2. If we take the probability 0.6 as the detection limit, one can estimate the distance where each object is detectable with current Metsähovi system under normal observing conditions.

5. Conclusions

First tests for the Earth-orbiting satellites were made in 2014 in a project funded by the European Space Agency applying our methods developed for asteroids. We have continued the development of our ranging technique, especially new random-walk ranging which has shown very promising results. First paper on the new method has been submitted to a peer-reviewed scientific journal. One of the recent tests was to apply it to the WT1190F. We have demonstrated that our method is suitable also for Earth-orbiting bodies. Next task is to develop the technique further for LEO and MEO objects. This implies a more complicated environment due to air drag and other effects affecting bodies at low-elevation orbits. Also we will modify software to apply both optical (passive) and SLR (active) data. Active data will drastically improve the accuracy of orbit determination.

Work with the SLR has been advanced as planned. Collaboration with other SLR observatories allowed us to introduce several improvements in our SLR system during the construction phase. With these changes we enhanced our readiness for space debris observations. Simulation of the system performance showed us that observations of non-cooperative objects are possible with our current system. Actual tests and further development are started when the system is operational in 2016. At the same time it is possible to start to build the space situational awareness infrastructure.

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

Jyri Näränen, Arttu Raja-Halli, Markku Poutanen, and Jenni Virtanen. New 2 kHz satellite laser ranging system at Metsähovi Geodetic Research Station. FinCOSPAR, Sodankylä, Poster, 2015.

Jyri Näränen, Arttu Raja-Halli, Jenni Virtanen, Markku Poutanen, and Diego Meschini. New 2 kHz satellite laser ranging system at Metsähovi Geodetic Fundamental Station. Finnish Remote Sensing Day, Espoo. Poster, 2015.

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