SPACE OBJECTS OPTICAL TRACKING 3D SOLUTION

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ABSTRACT

We are presenting a technique based on simultaneous angular and range measurements. Optical tracking is a standard technique to determine the orbit of small space objects, space debris in particular. The sequence of angular CCD measurements of an object position relative to catalogued stars is used to calculate the orbit. The time interval between the observations and the angular position resolution and accuracy are the key limiting factors in the resulting orbit determination. The recent laser ranging technology available provides simultaneously: the object illumination, time-stamping of the CCD position readings and a high precision ranging of space objects. Our new technique has been tested at the facilities of the Space Research Institute Graz, Austria. The first results of the test targets tracking are presented.

1. INTRODUCTION

There exists a strong interest to determine the accurate trajectories of the objects orbiting the Earth. The small planets, asteroids, space debris and possible ballistic or orbiting missiles are the targets of interest.

Optical tracking is a pretty standard technique to determine the orbit of space objects, space debris in particular. The sequence of angular measurements of an object position relative to catalogued stars is used to calculate the orbit [1]. Although the registration methods have changed from original visual, over photographic to the presently used a CCD sensor, the basic principle remains unchanged. The ultimate precision of the recorded angular positions is limited mainly by the atmospheric properties. The observation time slot is limited by the requirements that the object has to be illuminated by the Sun and the observation has to be carried out under local nighttime. The typical precision of the angular position reading is of the order of units of arc seconds. To calculate the orbit at least four positions have to be observed. Considering the apparent angular speed of the objects on low Earth orbits, the exact epoch of position reading (exposure) has to be determined with (sub) millisecond accuracy, what is a non-trivial task. Calculating the final orbit, the time interval between the observations and the angular position resolution and accuracy are the key limiting factors in the resulting orbit determination. To generate orbit parameters of the space object on a Low Earth Orbit (LEO), the four observations spanned over one to several days are needed [2-3]. To maintain the orbit solution stability, the angular observations from two different locations are usually needed.

We are presenting the measurement technique based on simultaneous angular and range measurements and providing additional features: object active laser illumination and laser time-stamping of the CCD exposure. The recent laser ranging technology provides a high precision and accuracy, high average power lasers and low transmitted beam divergences. These upgrades open new perspectives in active optical tracking and combined measurement techniques with the main objective of space debris optical tracking and precise orbit determination. The numerical simulations show, that the combined angular / range solution will enable to estimate the orbit determination precision, increase the final solution precision and stability and will enable to identity possible error sources in this process, as well.

2. PROJECT GOALS

The goal of the presented project is the development of a new optical tracing technique of space objects, namely the space debris, based on simultaneous angular and range measurements.

- To develop and numerically model the 3D combined technique,
- to test this technique in a field observation conditions,
- to identify the individual error sources,
- to achieve the time–stamping precision / accuracy of 10 / 100 ns.

3. EXPERIMENT DESIGN AND CONCEPT

The technique is based on a combination of well established optical tracking using CCD sensor, imaging the object on the background of identified stars. The object illumination is combined using solar flux and a laser illumination from the ground station. This is enabling both tracking of space objects in Earth

Proceedings of the Fourth European Conference on Space Debris, Darmstadt, Germany, 18-20 April 2005
(ESA SP-587, August 2005)

shadow and extremely accurate time–stamping of exposures. Additionally, laser illumination allows tracking the entire pass over the observing location, while Sun illumination is usually limited to a small portion of a pass. This effect is pronounced especially for low orbiting space objects.
The existing hardware of the satellite laser ranging (SLR) stations is employed, namely the station in Graz, Austria. Our group has been heavily involved in upgrades of this station within the last 15 years. The combined optical tracking at the satellite laser station does not impair the routine operation of the laser ranging system.

4. 3D TRACKING EXPERIMENTAL SETUP

The initial experiment – the test of optical tracking of laser illuminated space objects has been carried out and the feasibility of the method has been demonstrated in the tracking mission at the laser station in Graz, March, 15.-18. 2005. The station provides both facilities: the Satellite Laser Ranging (SLR) and a CCD tracking systems. See Figure 1.

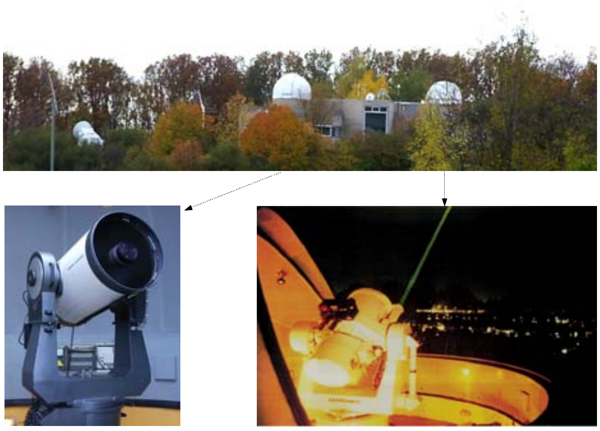

Figure 1. Satellite laser station in Graz, CCD Telescope (left cupola), SLR Telescope (right cupola)

The SLR system is capable to range objects with the millimeter range precision. It is equipped with the Nd-Vanadate laser, providing 10 ps long pulses, pulse energy is 0.4 mJ, the repetition rate is 2 kHz at the 532 nm wavelength. The laser average power is up to 1W, the beam divergence 10-20 arc seconds. The epoch of the laser emission is referred to the local time base with the nanosecond resolution. Returned photons are detected by C-SPAD detector.

The CCD tracking system consists of the Meade LX2000 16'' telescope, focal reducer, green bandpass filter and the CCD camera SBIG ST-10ME, providing filed of view of 40 x 26 arc minutes. The SLR and CCD telescopes have mutual distance 15 meters. The atmospherically back scattered photons of the laser beam are recorded on the CCD camera.

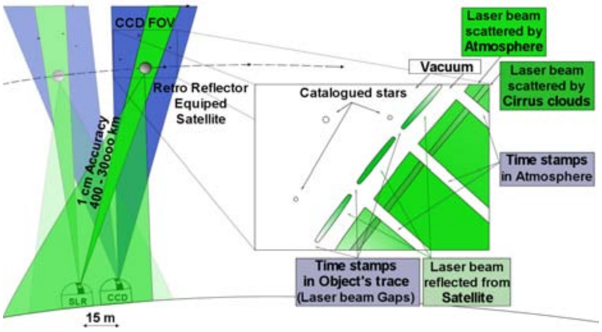

Figure 2. The block scheme of the simultaneous optical and 3D tracking (left) and the observed CCD image description (right)

The experiment block scheme and the explanation of the CCD image are on Figure 2.

The laser station has been modified to provide laser power output modulation to serve as a time marker for the laser illuminated exposures. The laser is switched off for the fixed time interval 50 or 100 milliseconds each one second. This negative laser power modulation provides the accurate time-stamping of the CCD exposures in the trace of the tracked object and also in the atmosphere.

5. 3D TRACKING RESULTS

The laser illuminated retro-reflector equipped satellites have been optically tracked, along with millimeter precision laser ranging, both in shadow and illuminated by the Sun.
The results are summarized on the Figures 3, 4, and 5. On Figure 3 is an example of the CCD exposure of the laser illuminated satellite.

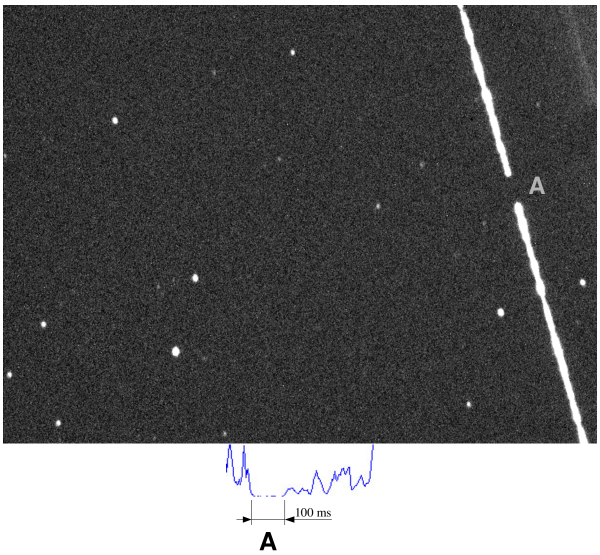

Figure 3. Topex satellite in Earth shadow. Laser illumination. Time-stamp 100 ms (top). Optical trace densitogram (below).

The Topex satellite at the distance of ~ 1340 km has been illuminated by the SLR laser, the time-stamp in negative laser modulation is 100 ms. The track intensity profile sample is enclosed below.

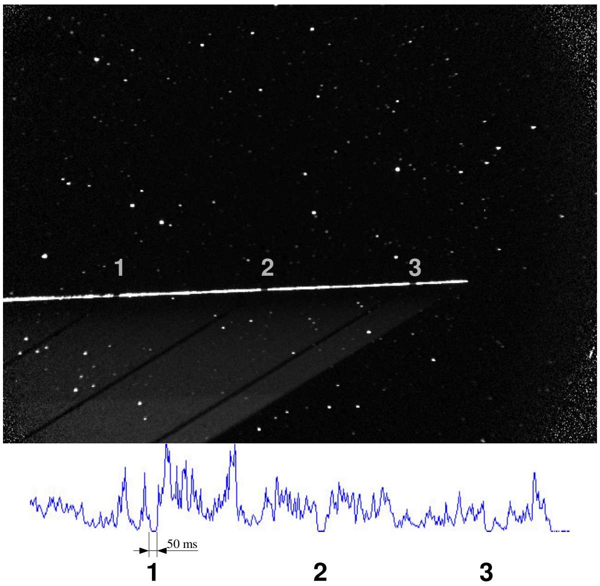

Figure 4. Topex satellite. Laser and Sun illumination. Time-stamp 50 ms each 1 second (top). Optical trace densitogram (below).

The CCD exposure of the Topex satellite illuminated both by the Sun and the laser is on Figure 4. Despite of the Sun illumination, the intensity modulation of the trace is noticeable. The time-stamps are 50 ms long, each one second.

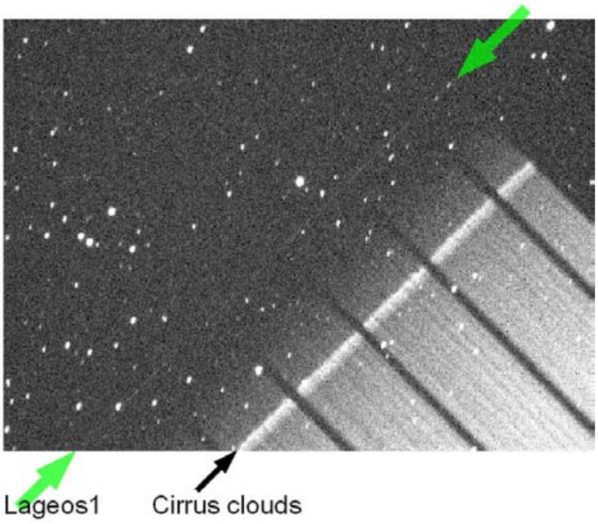

Figure 5. Lageos1 satellite. Laser and Sun illumination. Time-stamps 100 ms each 1 second.

The limiting signal to noise ratio situation is demonstrated on Figure 5. The Lageos satellite at the distance of approximately 6000 km has been tracked, when it was illuminated by the Sun and the laser, as well. The trace of the satellite can be identified on the CCD exposure, the trace intensity is too weak to enable time-stamping of the exposure. However, the laser photons back-scattered by the atmosphere provide the information necessary to reconstruct the timing and its connection to the position within the exposition frame.

For the exposures on Figures 4 and 5, the range determined by the laser has been compared to the satellite orbit computation based on the single exposure. These values coincided within 10 km just indicating the capability of the technique.

This method was successfully tested on other satellites with retro-reflectors e.g. Champ (~ 400 km), ERS2 (~ 800km), GPS-35 (~ 20ooo km)

The availability of high average power lasers of the order of 1 kW and the adaptive optics assisted telescopes providing low beam divergence [4] and large aperture telescopes will enable to track and range optically non-cooperative targets.

6. CCD IMAGE PROCESSING

CCD image processing consists of three steps:

1) Image pre-processing:

Flat field correction and Background removing

2) Objects areas and boundaries detection:

On the original image there is applied optimized 2D median filtering with window size two-times larger than the size of the biggest object of our interest [5]. In the resulting image there are almost all the objects of the defined and smaller size removed. The removal quality depends on the window shape and surrounds of the objects). This image, either the raw or amplified or processed (areas of bigger (brighter) objects are recognized), is then fully or partially subtracted from the original image to obtain the image with only the interesting objects for their faster area detection.
Several combinations of subtracting images after 2D median filtering with differently large windows could be applied for enhanced objects filtering by their size.

For images with laser beam scattering by the atmosphere, image is divided to two parts: one with the objects and one with the scattering, both parts being processed independently, and the results are then used together.

To increase the precision of the estimated areas of objects, their areas with narrow surrounds are twice correlated. In the first step, they are correlated with the Gaussian function, which is an approximation of the Point Spread Function (PSF) of the telescope system, and, in the second step, they are correlated with the function based on time-stamps.

In an image with visible time-stamps, i.e. scattering of the laser beam by the atmosphere, the boundaries of time-stamp-areas could be approximated with lines, and these lines are extended to cross the object areas and obtain further time-stamps or use them to increase the precision of the time-stamps positions.

3) Object angular speed estimation

The lengths between the objects (with subpixel precision in the image), which correspond to the known lengths of time-stamps (with picosecond precision) are used in relation to the lengths in pixels and in degrees between the known stars on the image to estimate the angular speeds of the objects for the corresponding times.

7. CONCLUSION

The SLR stations world wide network could be used for time-stamping of CCD images with high precision: SLR station tracks the object by its predicted path; the operator corrects the laser tracking using the real-time optical feedback from the CCD camera.

The laser illumination will enable to track optically the objects in the Earth shadow, what will increase the total amount of angular optical data, especially for LEO. The combination of angular and high accuracy range data along with the precise time-stamp of the angular information will improve the solution stability of the computed orbit. This might be enable to compute orbits on the basis of a single tracing location within a single pass. These facts will result in increase of observation productivity and orbit computation stability in comparison to the techniques used recently. The feasibility of orbit tracking technique has been tested in a series of experiments early 2005 in a series of combined optical and laser tracking of space objects at the Observatory of Graz, Austria.

8. ACKNOWLEDGEMENT

This research has been supported by grant form Czech Science Foundation No. 205/03/0314. The authors would like to express their thanks to Martin Fuchs from the Stefanik observatory in Prague for the technical assistance.

9. REFERENCES

1. L. Aardoom , A. Girnius, and G. Veis, *Geometric methods*, in Geodetic Parameters for a 1966 Smithsonian Institution Standard Earth, vol. 1, edited by C. A. Lundquist and G. Veis, pp. 63-75, Smithsonian Astrophys. Obs. Spec. Rep. No. 200, 1966
2. S. Isobe, T. Tajaina, *CHOPPING TECHNIQUES TO DETECT GEOSYNCHRONOUS SPACE DEBRIS*, Proceedings of the Second European Conference on Space Debris, ES0C, Darmstadt, Germany, 17-19 March 1997, (ESA SP-393, May 1997), pp. 89-92
3. T. Schildknecht, U. Hugentobler, G. Beutler, *TECHNIQUES FOR OPTICAL OBSERVATIONS OF SPACE DEBRIS - PERFORMANCE TESTS WITH THE NEW 1 METER ZIMMERWALD TELESCOPE*, , Proceedings of the Second European Conference on Space Debris, ES0C, Darmstadt, Germany, 17-19 March 1997, (ESA SP-393, May 1997), pp. 93-98
4. B. Greene, C. Smith, Y. Gao, J. Cotter, C. Moore, I. Ritchie, C. Burman, *Advanced Techniques at the EOS Space Research Centre,* 14th International Laswer Ranging Workshop, San Fernando, Spain, June 7-11, 2004, published in Boletin ROA No. 4/2004, Real Instituto Observatorion de la Armada, en San Fernando, ISSN 1131-5040, edited by J.M.Davila, 2004
5. M. Nemec, *Data Acquisition and Image Processing on Windows CE*, Diploma Thesis, FNSPE, CTU in Prague, 2004