High Sampling Rate Photometry of Spinning Satellites for Nano-Perturbation Detection

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ABSTRACT

The attitude dynamics of the passive satellites and space debris objects can be perturbed by the effects arising from the interaction with the Earth's magnetic and gravity fields, solar irradiation and residual atmosphere pressure. We have developed high-definition photometry (HDP) methods that allow for the detailed satellite reflectivity profiling by correlating high rate brightness observations with the surface reflection point given by the object attitude model. The highly detailed reflectivity profiles combined with the physical models improve spin determination and support the force and torque modeling for the accurate spin prediction [1].

1. INTRODUCTION

The high rate photometric data is routinely collected by the Graz Satellite Laser Ranging (SLR) station which operates multiple techniques for the satellite observations. The high repetition rate 532-nm laser system allows for the mm-accuracy range measurements to the satellites and space debris equipped with corner cube reflectors (CCR), while the high power laser is used for the ranging to the non-cooperative objects. The photon counting system is used to detect and count solar photons at wavelengths from 780 nm to 900 nm reflected from the satellites towards the receiver telescope of the station [2]. During the operation, the solar photons collected by the receiver telescope are detected by the Single-Photon Avalanche Diode (τ-SPAD FAST) and converted into an electronic signal which is then processed and time stamped in UTC by the field programmable gate array (FPGA). The acquired data is converted into a light curve at a 10 kHz sampling rate for further analysis. Fig. 1 presents the reference solar irradiance profile (ASTM G173-03) and the photosensor efficiency over the detection spectral range.

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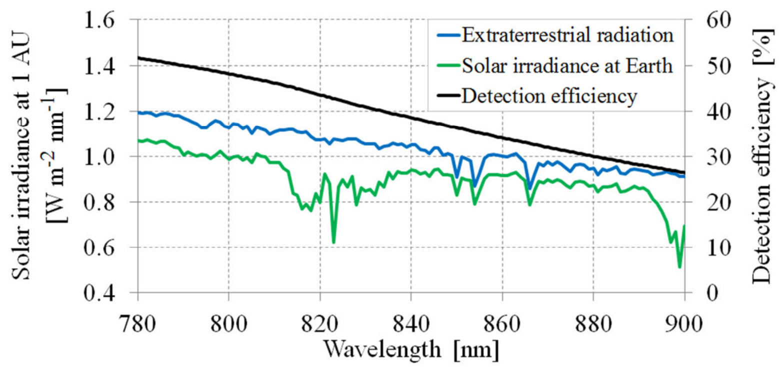

Fig. 1. Solar irradiance and the photosensor detection efficiency at wavelengths of 780-900 nm.

2. HIGH-DEFINITION PHOTOMETRY

High-definition photometry (HDP) is a method of object characterization that allows for detailed surface profiling by correlation of the high-rate brightness measurements with the surface reflection points determined by the satellite attitude model. The HDP method has been tested on the photometric data of the fast spinning satellite Ajisai (altitude of 1490 km, NORAD 16908) - a highly specular object with well modeled spin parameters [3]. Fig. 2a presents a solar flash produced by an Ajisai mirror panel and measured by the Graz detection system. The high temporal resolution and the single-photon sensitivity allow for an accurate geometry analysis of the flash.

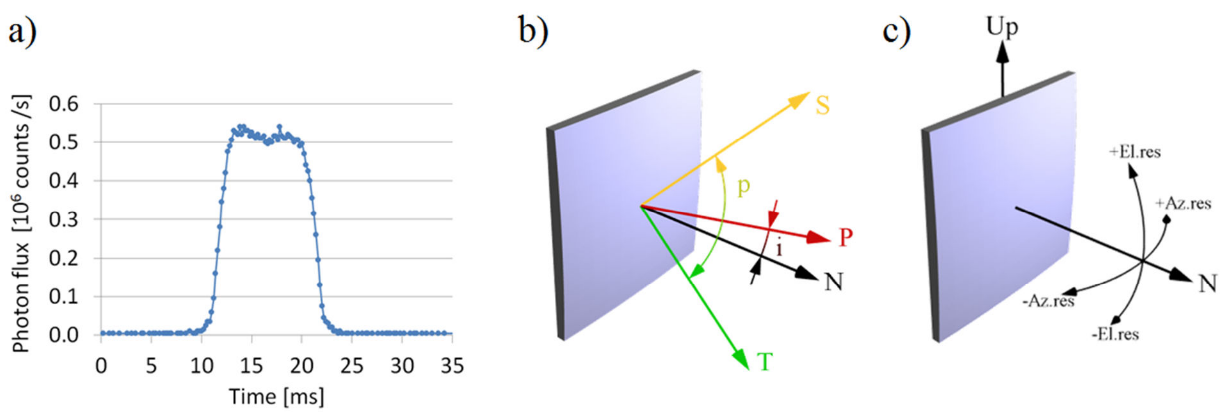

Fig. 2. A) solar flash from a single Ajisai mirror measured by Graz photometric system. B) the vector/angle system used in the analysis of the specular reflections: Sun $\boldsymbol{S}$, telescope $\boldsymbol{T}$, surface normal $\boldsymbol{N}$, phase vector $\boldsymbol{P}$, phase angle $\boldsymbol{p}$, inclination angle $\boldsymbol{i}$. C) Deviation of the phase vector $\boldsymbol{P}$ from the normal N can be defined by azimuth and elevation residual angles; the Up direction points towards the top of the satellite body.

In order to model and analyze the specular reflections of sunlight it is necessary to express the direction vectors to the Sun $\boldsymbol{S}$ and to the ground observing telescope $\boldsymbol{T}$ in the satellite body-centered and -fixed coordinate system (BCS). The phase angle p between $\boldsymbol{S}$ and $\boldsymbol{T}$ vectors is bisected by the phase vector $\boldsymbol{P} = \frac{\boldsymbol{S}+\boldsymbol{T}}{|\boldsymbol{S}+\boldsymbol{T}|}$ (Fig. 2b).
An example of the solar flash intensity measurements from a single mirror panel of Ajisai is presented on Fig. 3a - the angular coordinates indicate deviation of the phase vector $\boldsymbol{P}$ from the surface normal $\boldsymbol{N}$. The averaging method is used in the process of panel's reflectivity profile computation - Fig. 3b.

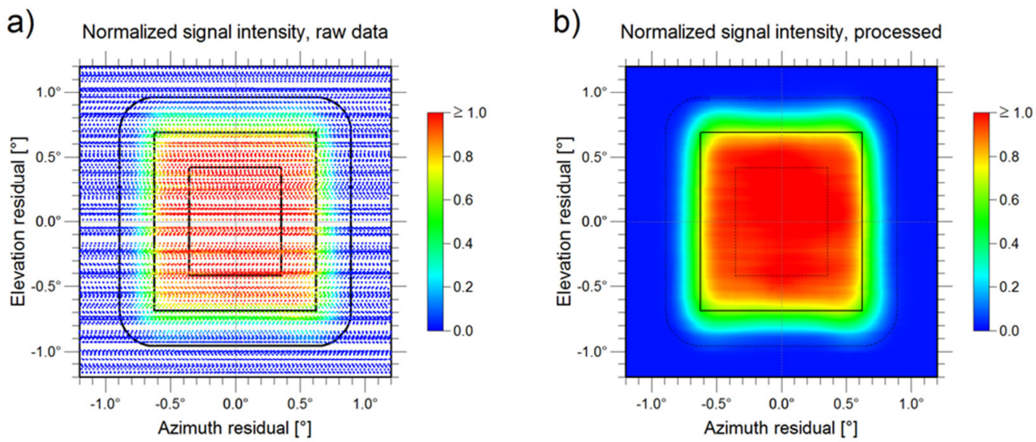

Fig. 3. An example reflectivity profile of a single mirror panel (approx. size of 20 x 20 cm) of Ajisai determined by HDP. A) normalized photometric observation at the angular coordinates of the corresponding phase vector. B) the post-processed reflectivity map of the panel. The inner rectangular frame represents the maximum reflectivity area defined by a slight convex curvature of the panel; the middle frame is the angular size of the mirror and the outer frame limits the reflectivity area of the mirror.

3. REFLECIRVITY MAP OF TOPEX/POSEIDON

The spin parameters of defunct TOPEX/Poseidon (altitude of 1340 km, NORAD 22076) can be modeled with a high accuracy [1] and allow for the photometric data to be converted into the satellite body frame BCS. Fig. 4 presents a phase-folded high-rate light curve of TOPEX (spin period of 11.4 s). The collected 11 minutes of data reveal a combination of the high intensity specular flashes with the smoother structures of the diffuse reflections from the spinning body.

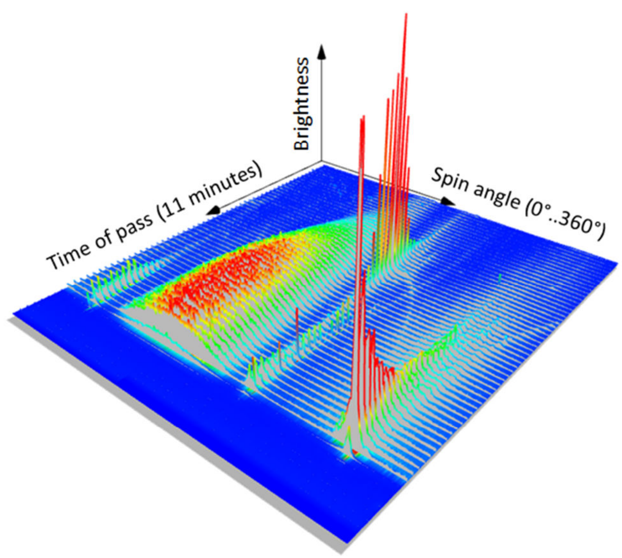

Fig. 4. The phase-folded high-rate light curve of TOPEX/Poseidon measured by Graz system.

In order to determine the reflectivity profile of the satellite the photometric observations are expressed in the satellite body coordinate system. Fig. 5 presents an example profile of TOPEX obtained with a single pass data as observed by Graz station:

a) the Mollweide and polar (only northern hemisphere) projections of the satellite reflectivity map with the linear intensity scale - the location of the strong, specular flashes is visible.
b) the photometric data plotted in the logarithmic scale - the low intensity patterns are visible.
c) demonstration of the method sensitivity to the satellite spin period: the increase of the initial spin period value (11.310 s) by 100 ms significantly affects the geometry of the pattern.

The high sensitivity of the pattern geometry to the spin parameters allows for the detection of the small-scale spin perturbations that occur during a single orbital revolution. We estimate that the reflectivity pattern analysis allows achieving a millisecond accuracy level of the spin period determination which corresponds to the sub-μNm torque detection in the case of TOPEX [1].

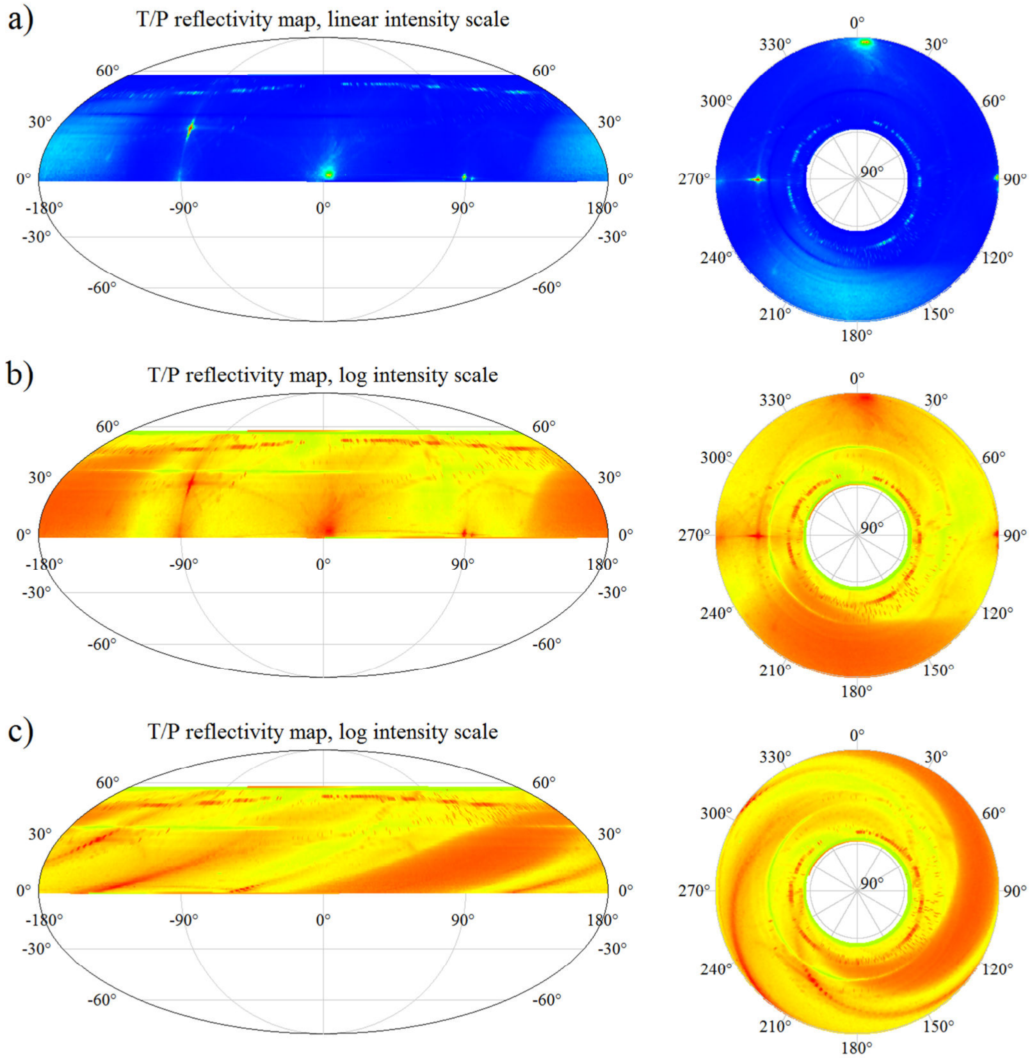

Fig. 5. TOPEX reflectivity map presented in the Mollweide (the prime meridian indicates front of the satellite body) and polar (only northern hemisphere) projections. A) reflection intensity in the linear scale, b) logarithmic scale, c) the pattern distortion caused by 100 ms increase in the spin period.

4. HIGH RATE PHOTOMETRIC DETECTOR AT SERC

Further improvement in the accuracy of the satellite spin determination and torque analysis is possible if the satellites are observed from multiple geographical locations and the high-rate photometric data is collected from different view angles. Space Environment Research Centre (SERC, Australia) has developed a light curve detector (Fig. 6) that measures brightness of the satellites at the sampling rate of up to 100 kHz. The detector unit is designed as a plug-and-play device and is based on the photomultiplier module (PMT) Hamamatsu H11901-20 which has a high sensitivity over the entire visible spectrum. The PMT output signal is sampled by the real time processor (PRU) of the Beaglebone PC board and stored in the binary output files. The high rate detector is installed at the SERC geotracker telescope (Mount Stromlo, Canberra) and is currently tested with various satellites and space debris objects. The high sampling rate allows for the accurate timing analysis of the short solar reflections from the satellites (Fig. 7) that will further improve the accuracy of the spin analysis and torque detection.

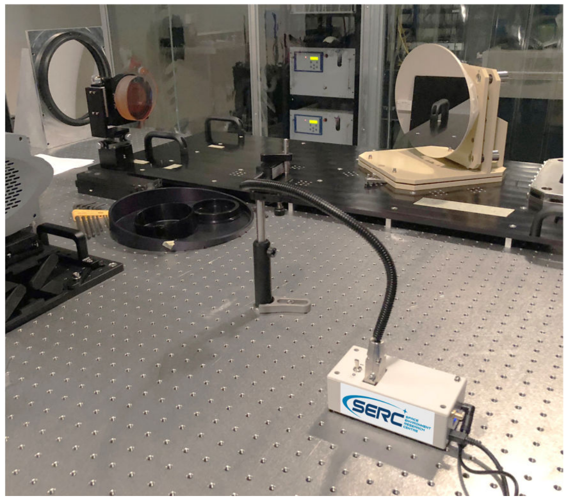

Fig. 6. The high-rate photometric detector during the laboratory tests (Mount Stromlo).

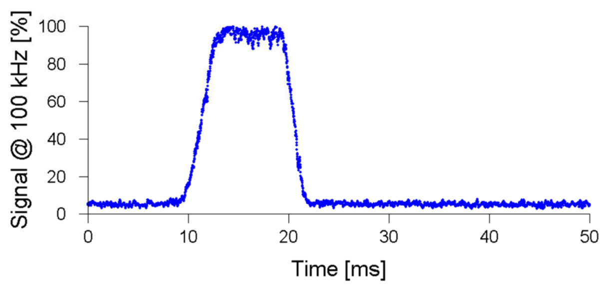

Fig. 7. Ajisai solar flash measured by the SERC high-rate detector at 100 kHz sampling rate.

5. CONCLUSIONS

High-definition photometry correlates the brightness observations with the satellite surface reflection point via spin models and delivers detailed reflectivity profiles which can be further analyzed for the small-scale spin perturbation detection and modeling. The unique patterns present in the high-resolution reflectivity maps can support the development of the innovative object characterization methods - such as the satellite biometrics identification proposed by Dr. Moriba Jah.

6. ACKNOWLEDGEMENT

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7. REFERENCES

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