High-definition Photometry
- a new tool for space debris characterization

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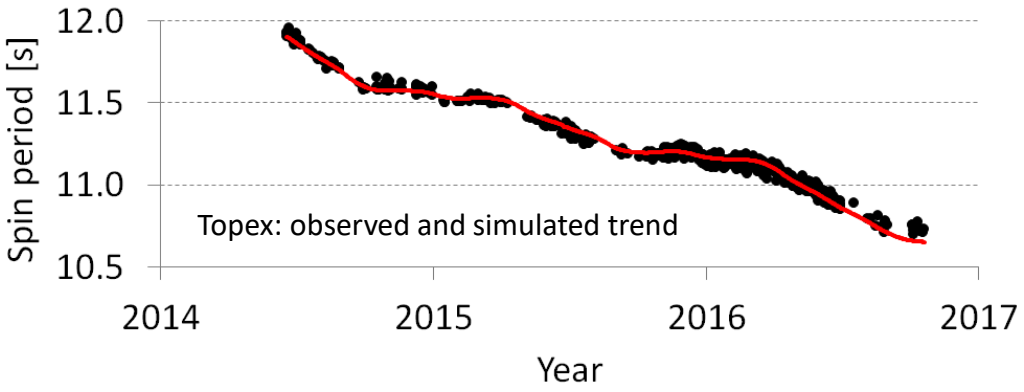
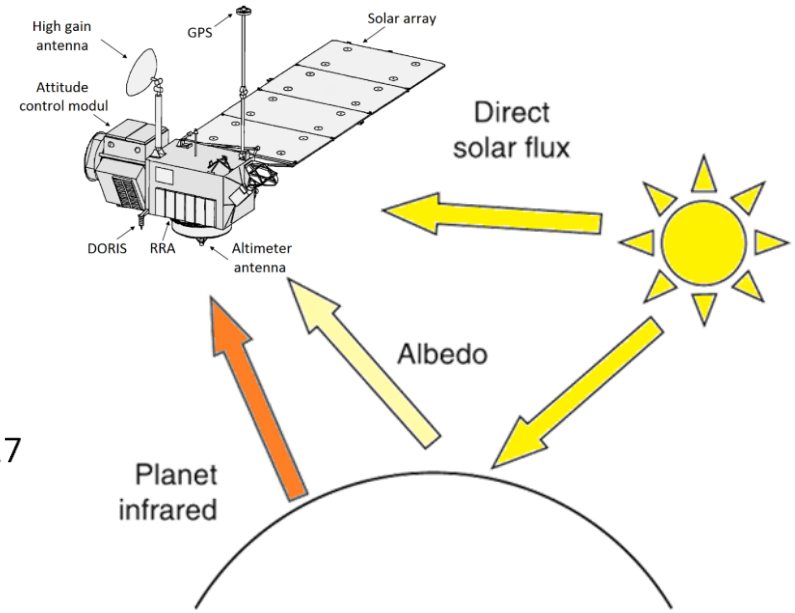
Satellite spin dynamics

Defunct satellites can gain rotational energy due to the forces and torques caused by the environmental effects.

The spin parameters change over time mainly due to:
- solar radiation pressure
- magnetic field interaction
- gravitational torque





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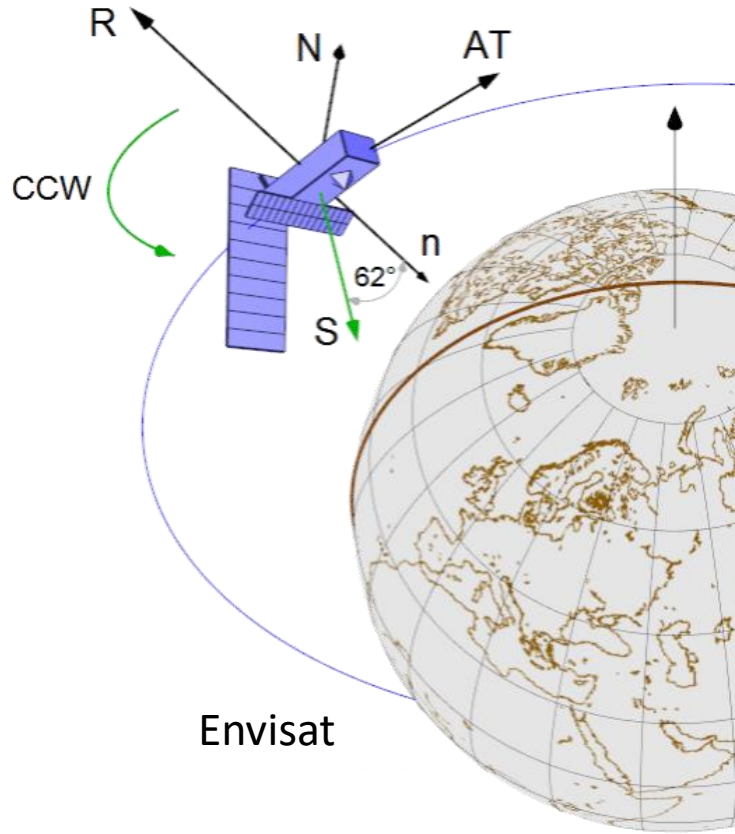
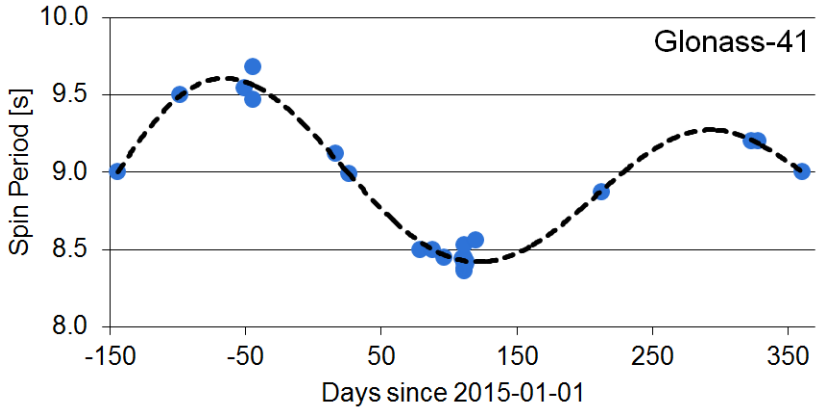
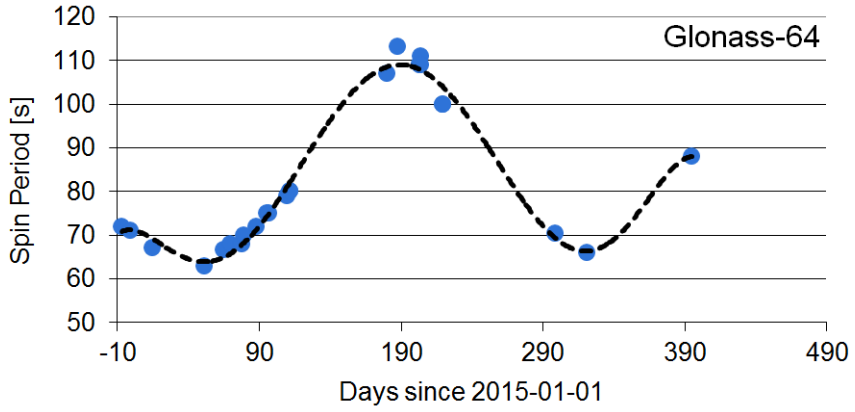


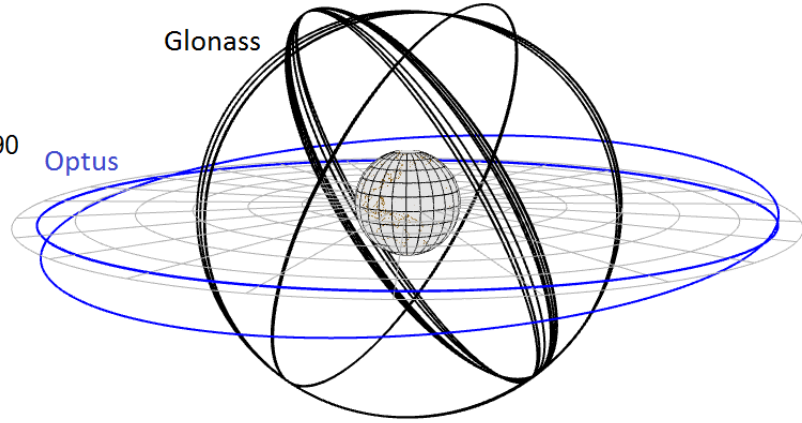
Envisat

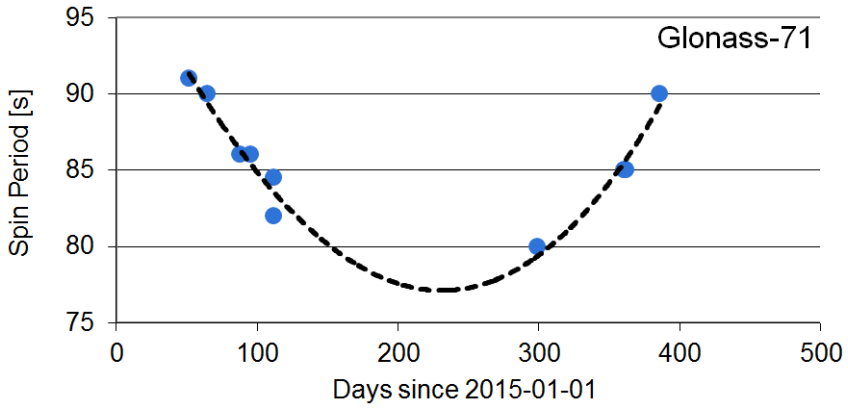
Satellite spin dynamics

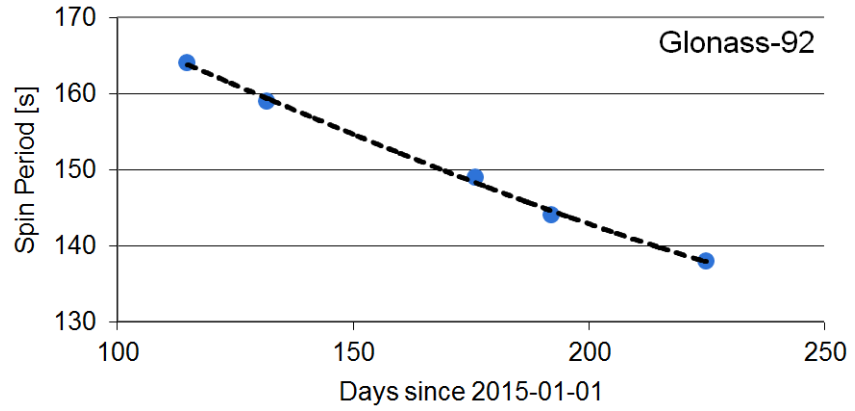
Example of spinning, defunct GLONASS satellites, altitude of 19130 km









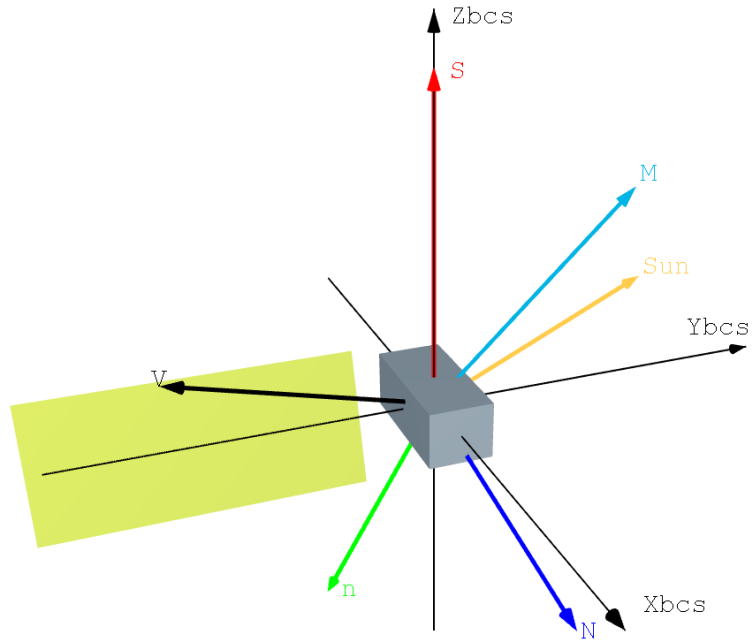


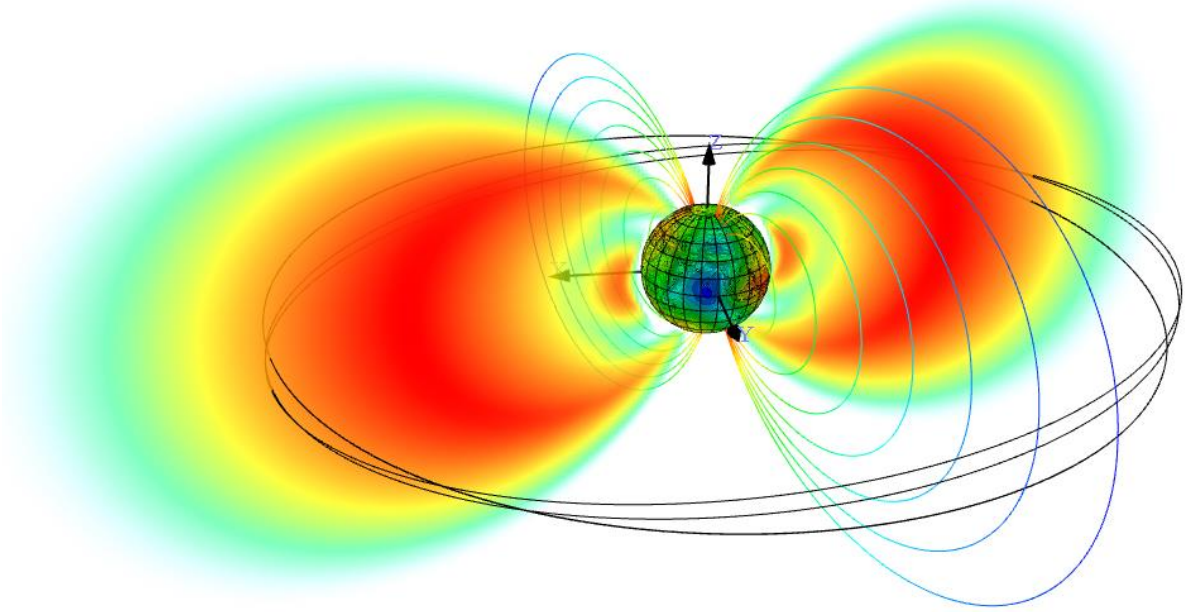
Spin observation from Graz SLR station.

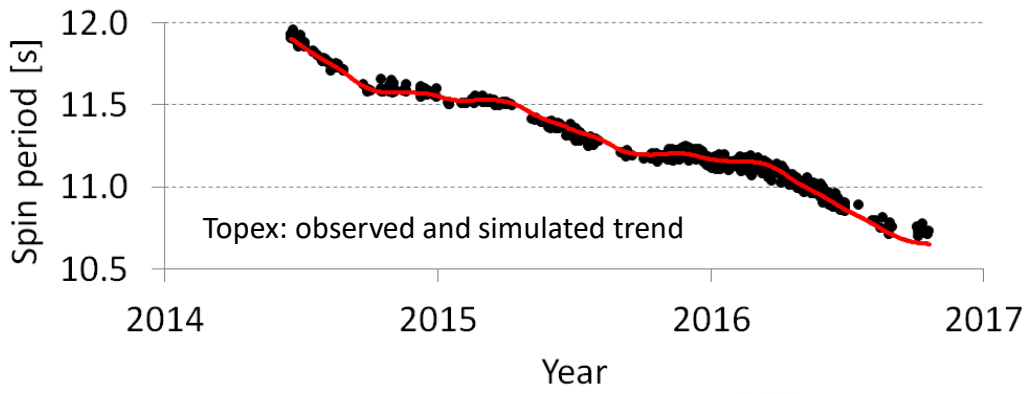
Satellite spin dynamics

The spin dynamics of the passive objects can be modeled with the use of:

- Earth's gravity field (EGM96, geopotential model)
- Earth's magnetic field (IGRF11/TS05, int. and ext. magnetic field models)
- Solar radiation pressure (TSI and shadow function)
- Earth's reflectivity (albedo) and IR emissivity (CERES)
- Residual atmosphere (JB2008, atm. density model)
- Satellite surface thermal effects (sat. macromodel)
- Electrostatic effects (AE-8, AP-8 trapped particle models)







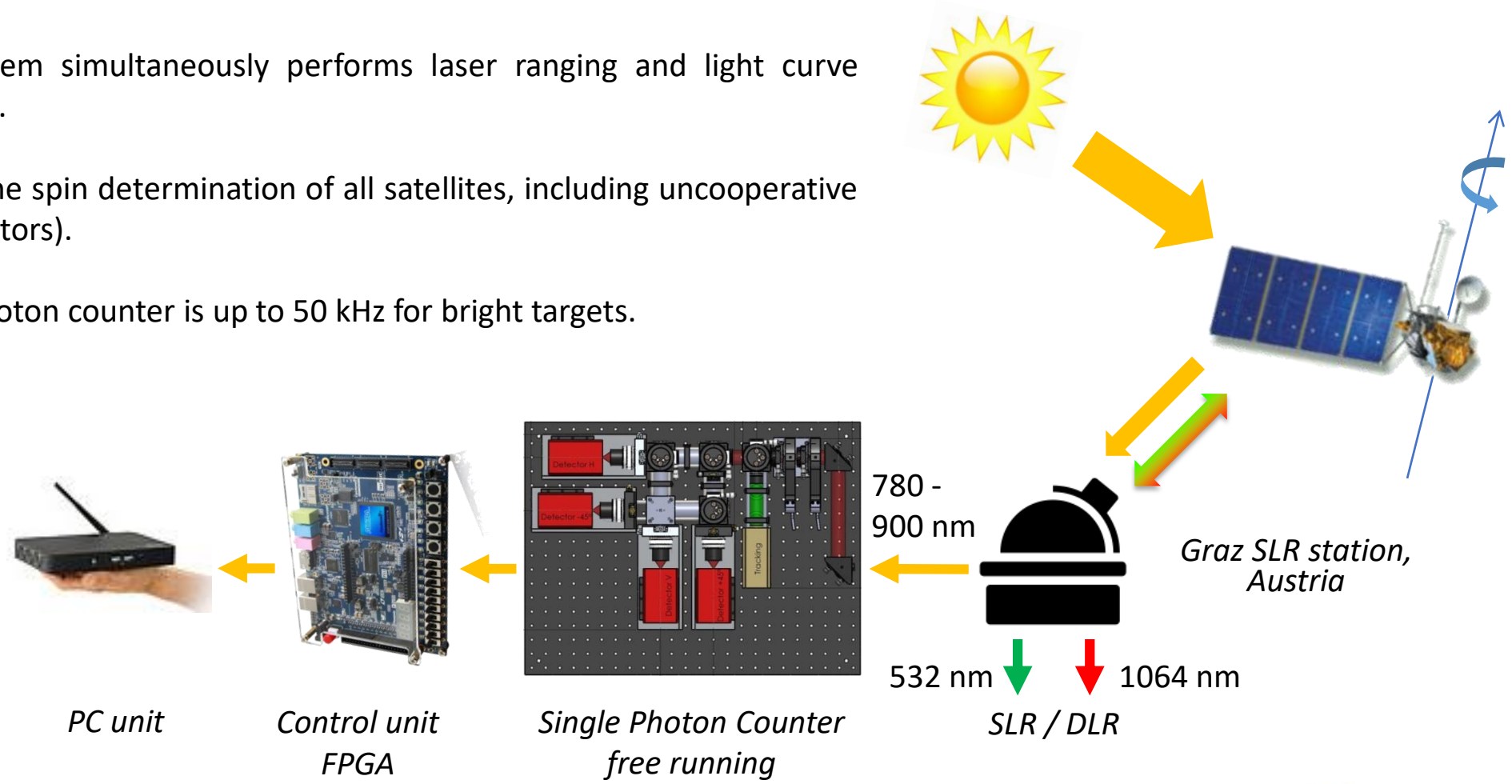
Satellite spin measurement

High rate photometric detectors allow for the accurate spin measurement of the passive satellites

Graz satellite tracking system simultaneously performs laser ranging and light curve measurements (since 2015).

The light curves allow for the spin determination of all satellites, including uncooperative targets (with no retro-reflectors).

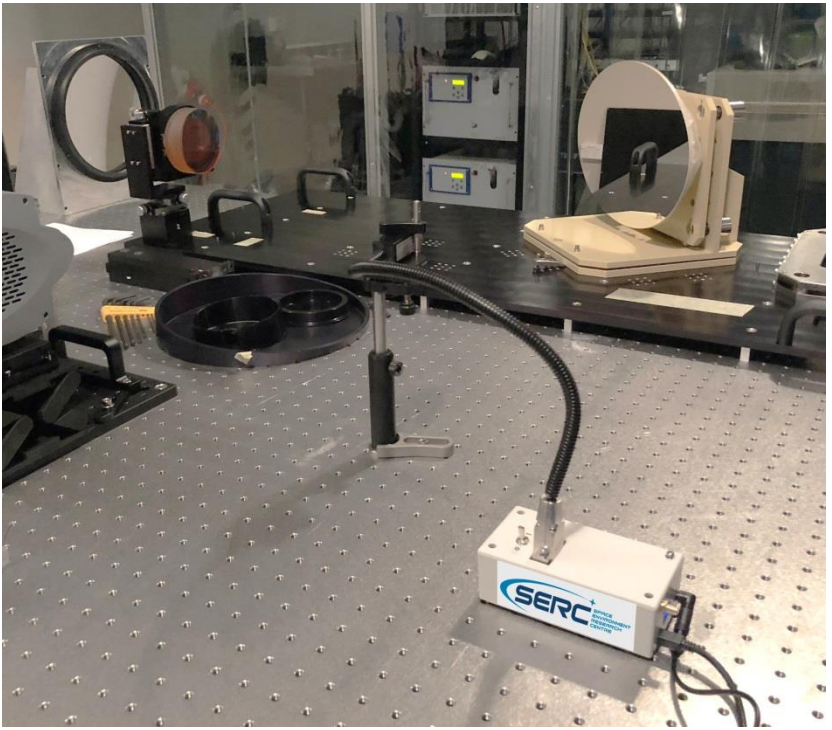
The sampling rate of the photon counter is up to 50 kHz for bright targets.



Kirchner G. et al., Light curve measurements with Single Photon Counters at Graz SLR. ILRS Technical Workshop Matera, October 2015.

Satellite spin measurement

High rate photometric detector development at SERC



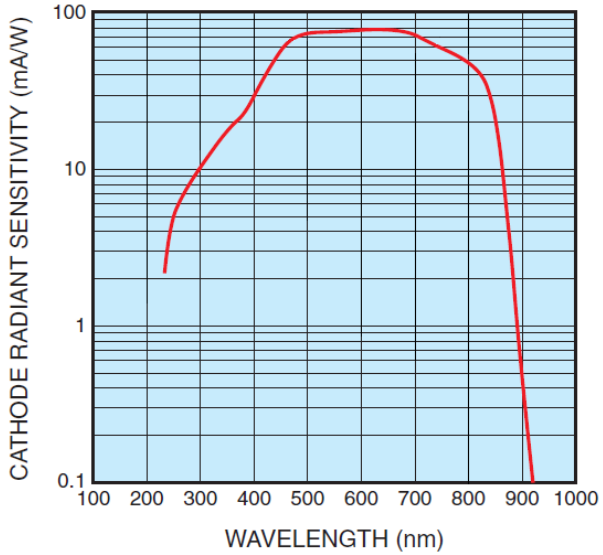
EOS Space Research Centre, Mt Stromlo, Australia

PMT
- Hamamatsu H11901-20
- sensitive over the entire vis. spectrum

PC board
- Beaglebone Black: high-performance (1 GHz CPU), low-power board
- The real time processor (PRU, 200 MHz) samples the input analog signal at 100 kHz rate

GPS
- GPS mouse synchronizes system time

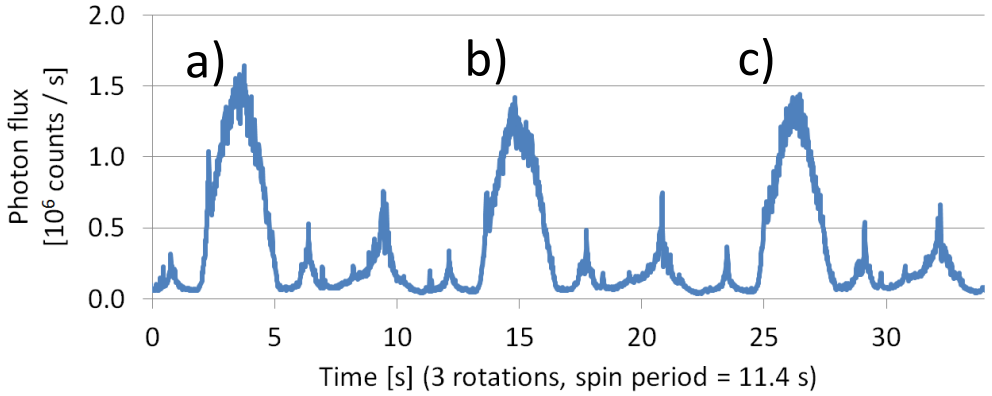
Electronics board:
- allows for an automated signal acquisition



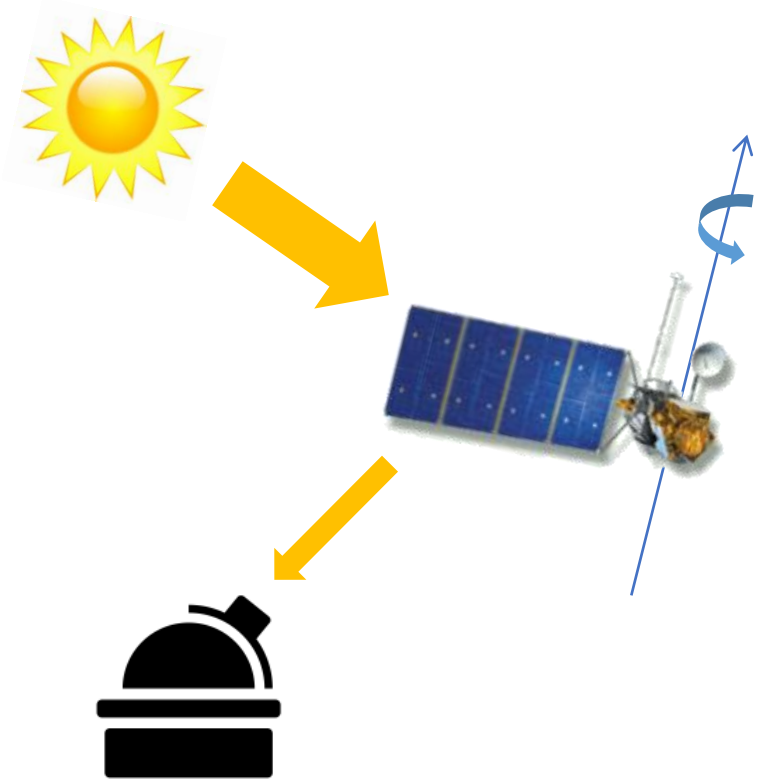
The software:
- All the 100 kHz data points are stored in the binary files. The data is used for the high accuracy spin analysis at the post-processing stage.
- The satellite brightness measurements are processed on-the-fly by the Fast Fourier Transform algorithm in order to measure the frequency of the atmospheric flicker (seeing) in the light path.

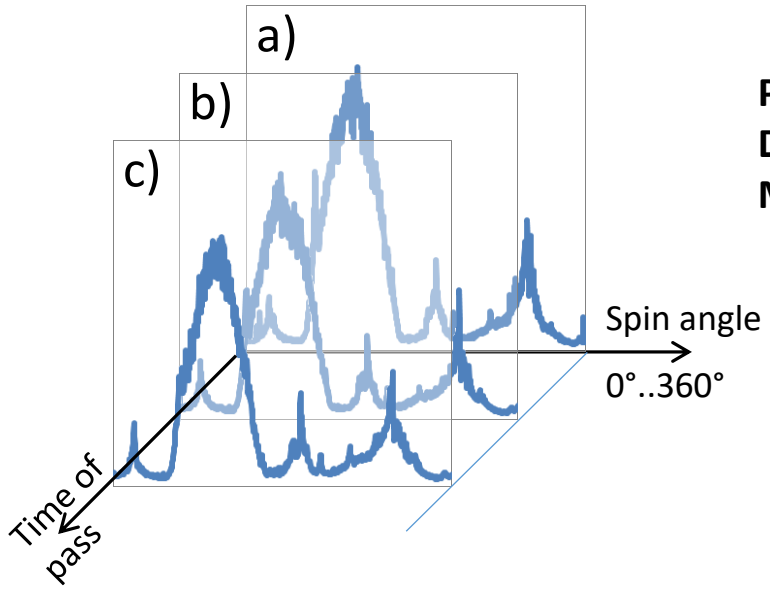
Satellite spin measurement

High rate photometric detectors allow for an accurate spin measurement of the passive, sunlit satellites



Spinning TOPEX/Poseidon light curve



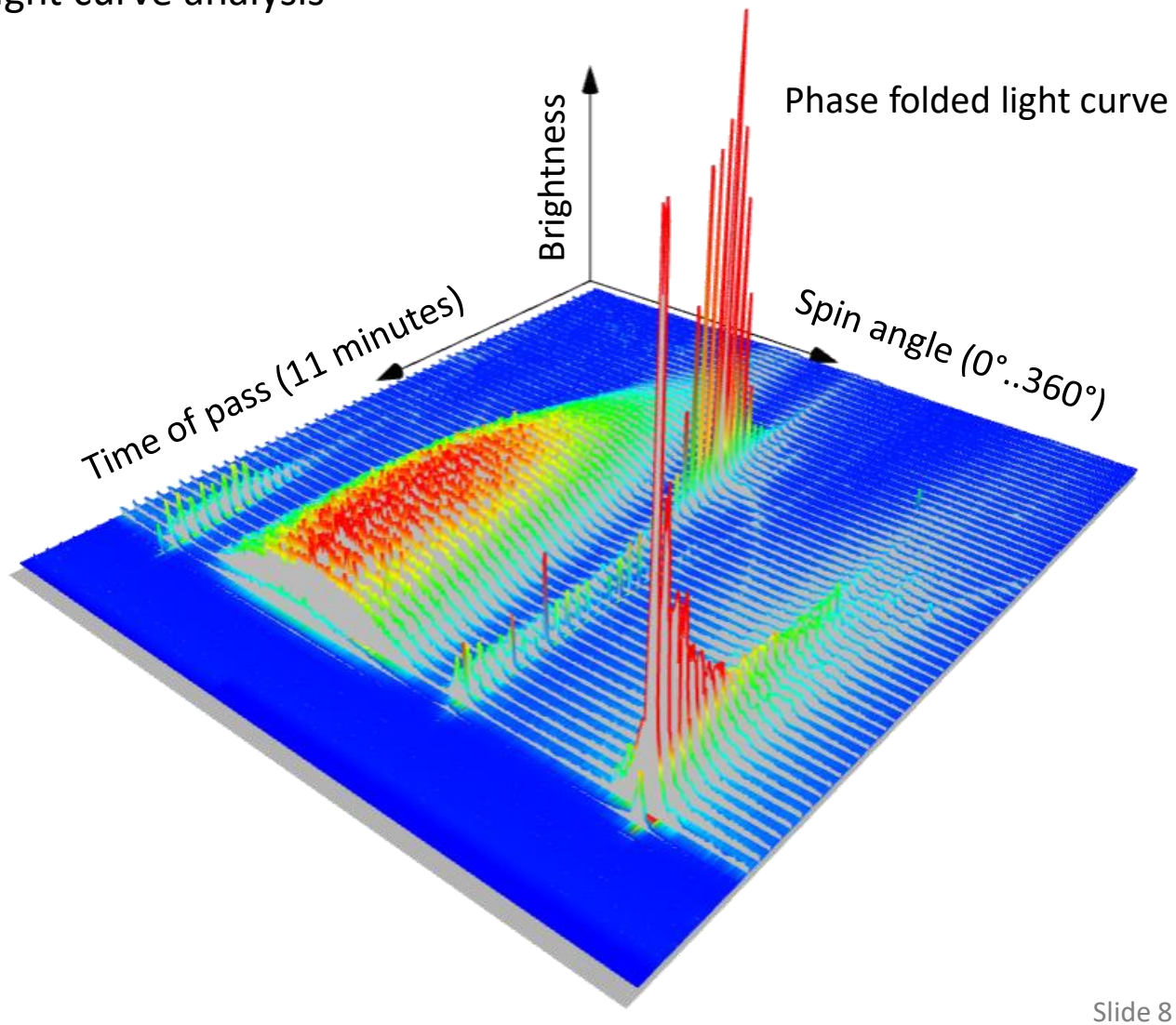


Phase
Dispersion
Minimization

Satellite spin measurement

High rate light curve analysis

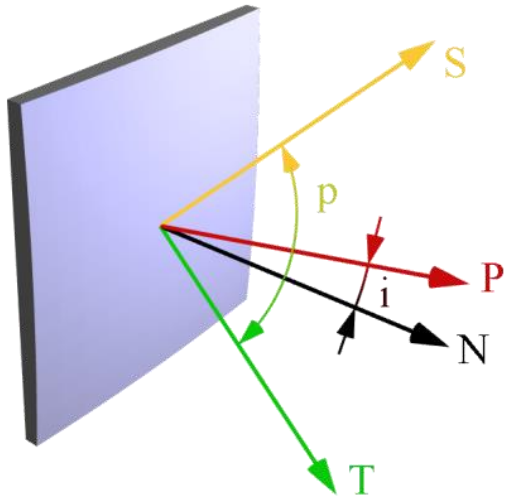
TOPEX/Poseidon light curve
- Phase folded pass, 57 rotations (11 minutes)
- mix of specular and diffuse reflections from different sides / surface elements of the spinning body



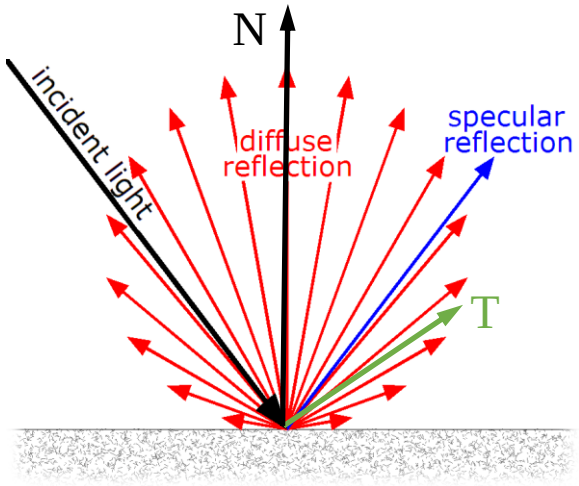
Satellite spin measurement

Specular and diffuse reflections form geometrical patterns

Specular reflection



Diffuse reflection

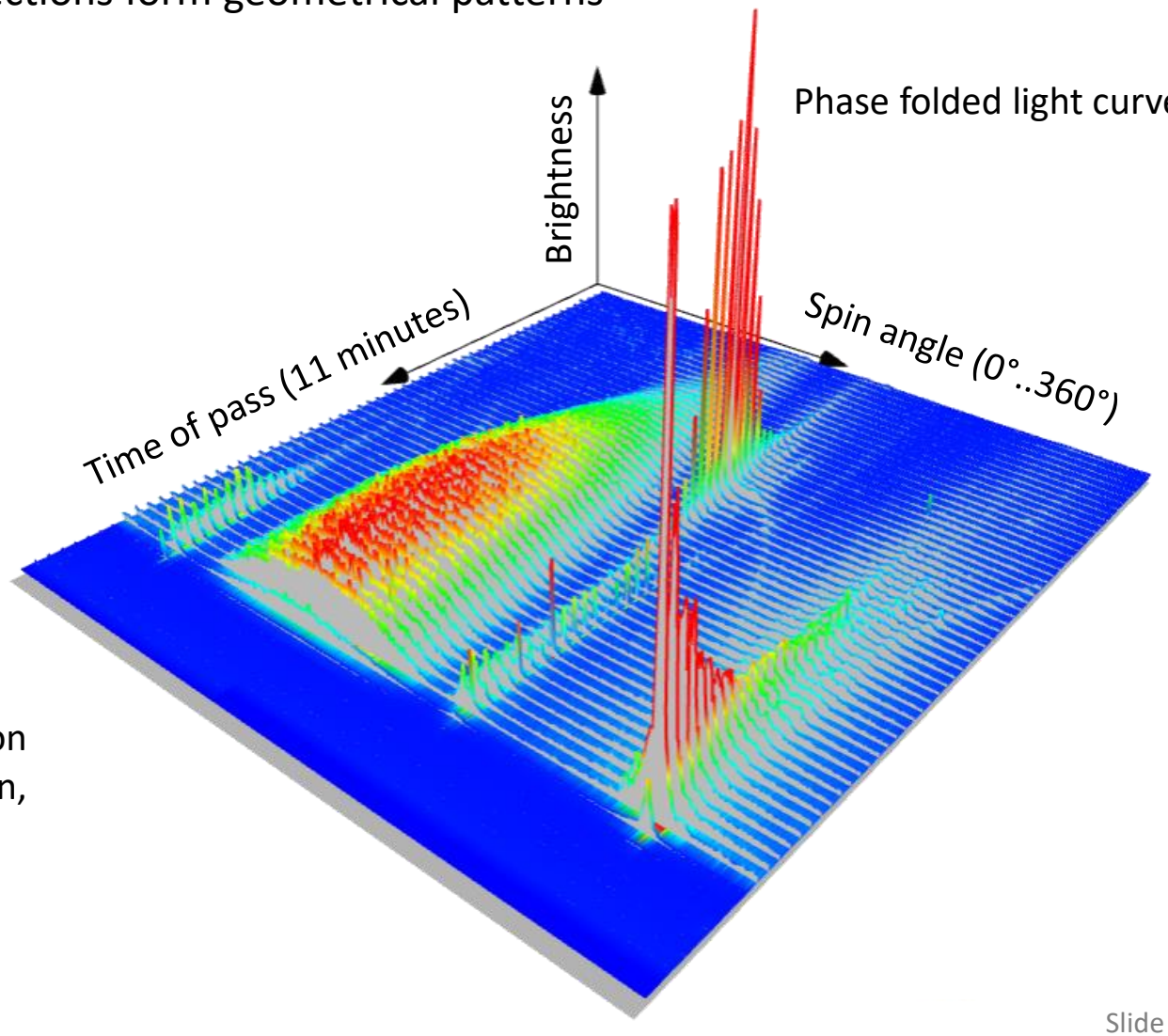


BRDF Lambertian model

S: sun
T: telescope
P: phase vector = S + T
p: phase angle
i: inclination angle (<0.25°)

The intensity of diffuse reflection depends on the angles between Sun, Telescope and the Normal vectors.

Phase folded light curve

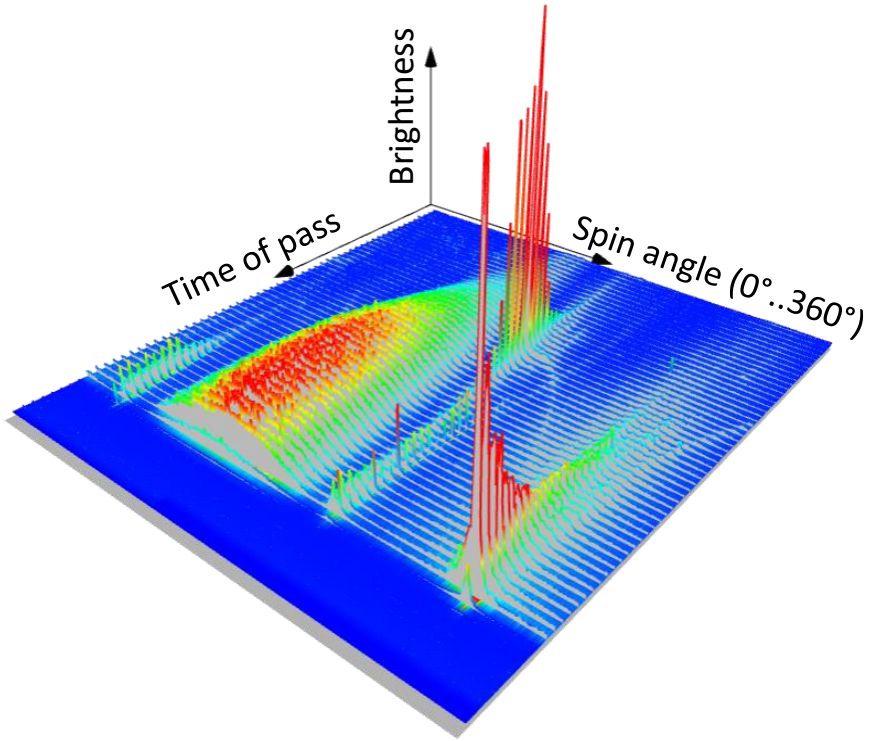


BRDF: bidirectional reflectance distribution function; Lambertian model is the most common one.

High-definition photometry

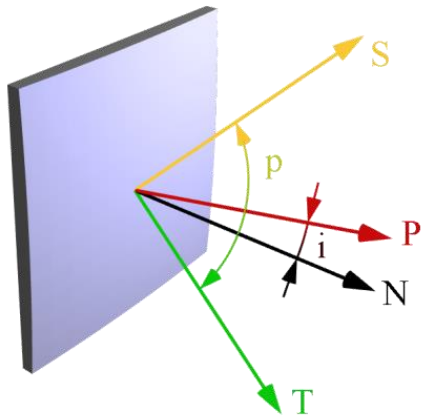
HDP generates detailed reflectivity maps by projecting satellite brightness measurements onto a phase vector expressed in the body fixed coordinate system.

Time dependent pattern
(depends on the view angle)

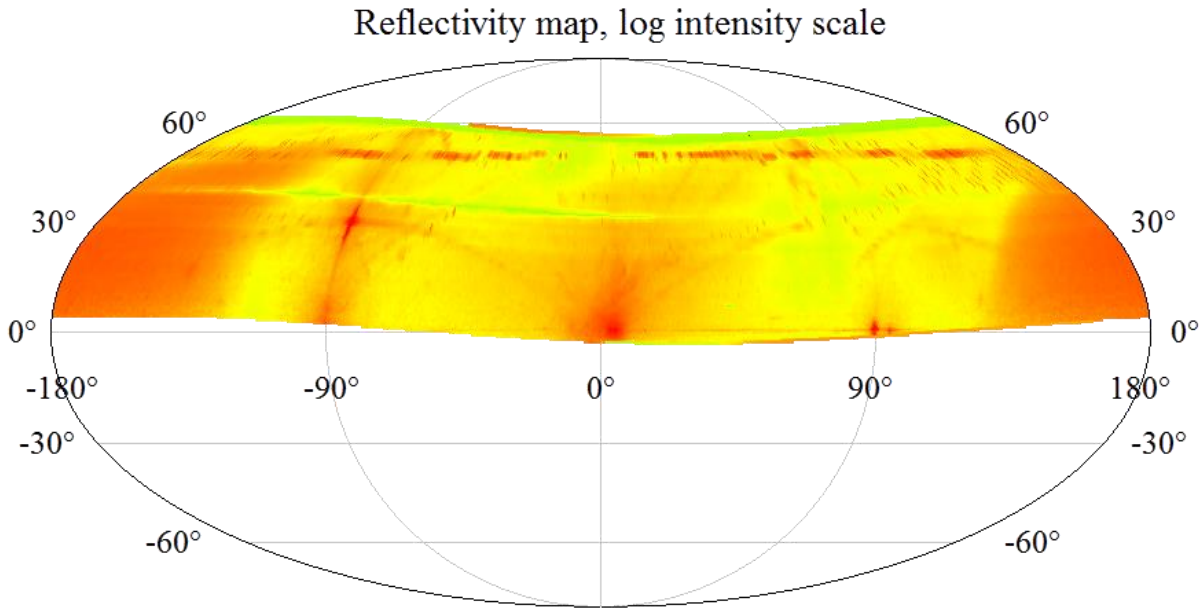


$$\boldsymbol{P}_{BCS} = \boldsymbol{S}\,\boldsymbol{P}_{ICS}$$

P: phase vector
S: transformation m.



Time independent pattern
(fixed with the satellite body)



The specular reflection occurs when the phase vector and surface normal coincide, thus the location of the specular reflections in BCS is fixed (assuming rigid body).

Kucharski et al., Photon pressure force on space debris TOPEX/Poseidon measured by Satellite Laser Ranging, AGU Earth and Space Science, 2017

High-definition photometry

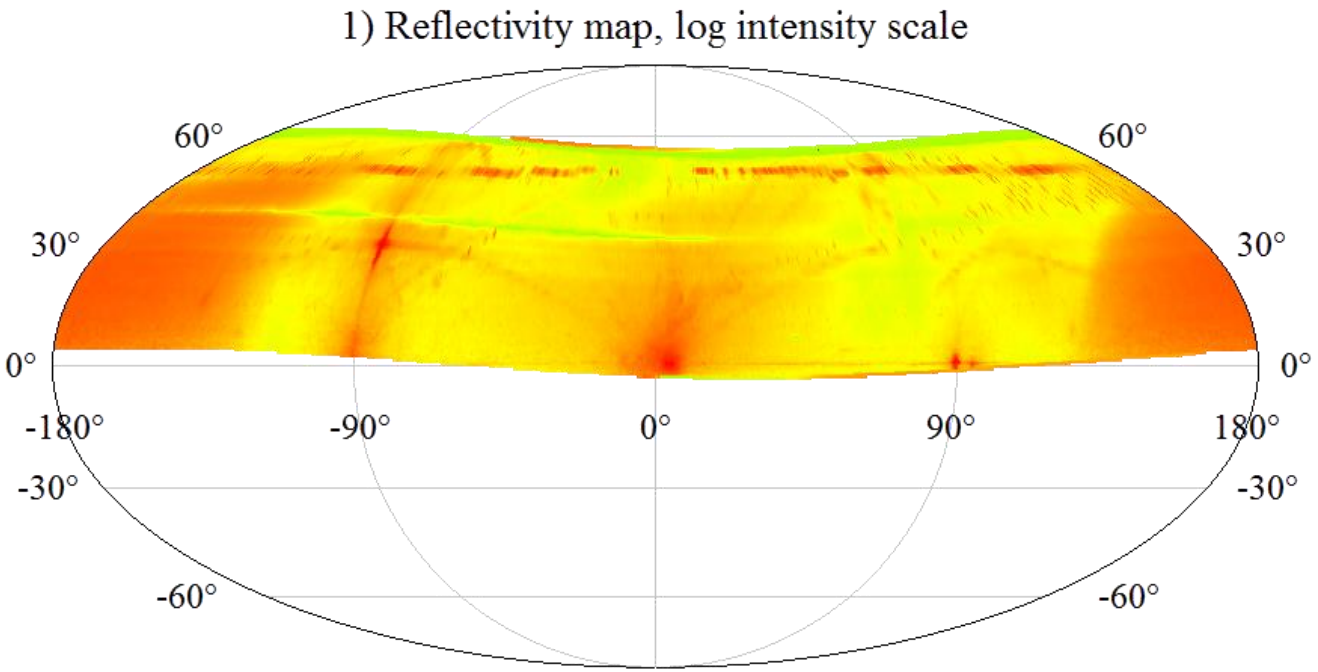
The transformation of the phase vector from the inertial to the satellite body fixed frame can be realized by the matrix S, under the assumption that the satellite spin parameters remain constant during a single pass.

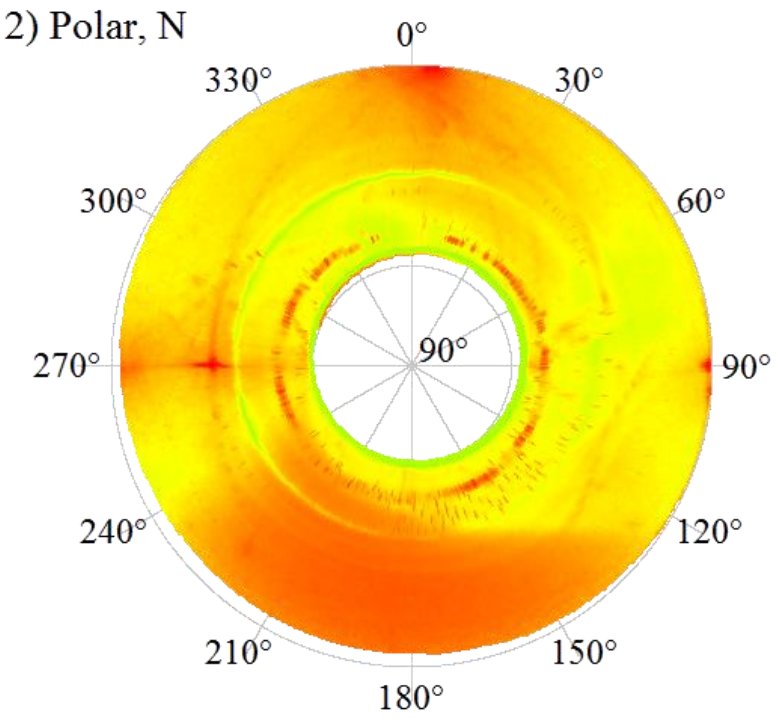
$$\boldsymbol{P}_{BCS} = \boldsymbol{S}\,\boldsymbol{P}_{ICS}$$

$$\boldsymbol{S} = \boldsymbol{R_2}(-x_p)\boldsymbol{R_1}(-y_p)\boldsymbol{R_3}(\gamma)\boldsymbol{R_1}\left(\frac{\pi}{2}-\delta\right)\boldsymbol{R_3}\left(\frac{\pi}{2}+\alpha\right)$$

α: spin axis RA
δ: spin axis Dec

γ: spin angle
x_p, y_p: pole position





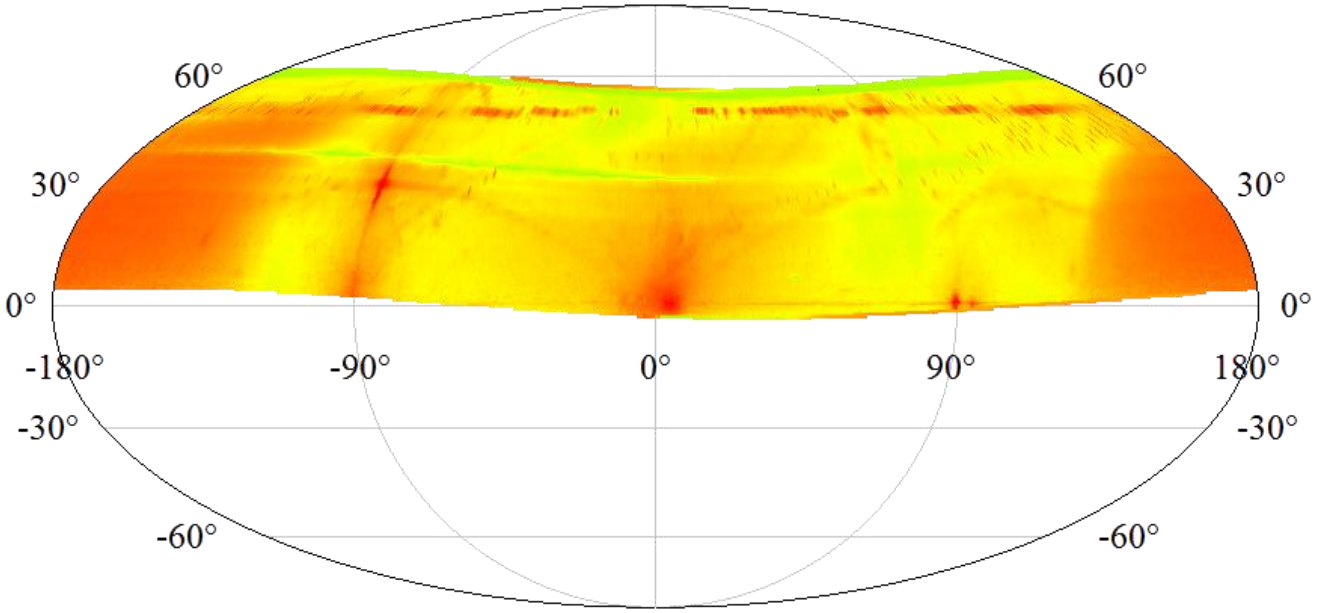
Kucharski et al., Photon pressure force on space debris TOPEX/Poseidon measured by Satellite Laser Ranging, AGU Earth and Space Science, 2017

High-definition photometry

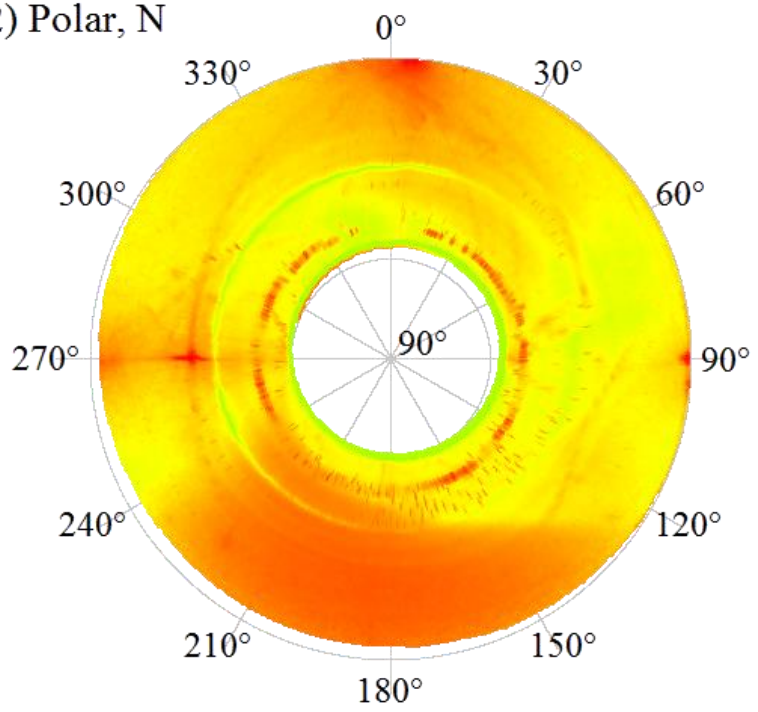
Spin characterization

2015-July-9, ~10 minutes pass
spin axis: RA = 94.3°, Dec = -64.8°
spin period = 11.308 s
pole position: x_p = 3.1°, y_p = -1.6° (offset = 3.5°)

1) Reflectivity map, log intensity scale



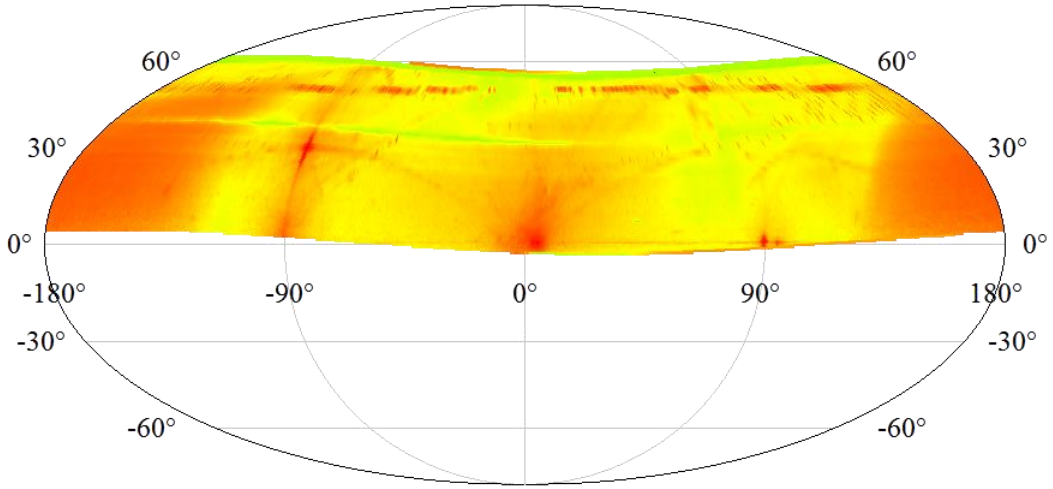
2) Polar, N



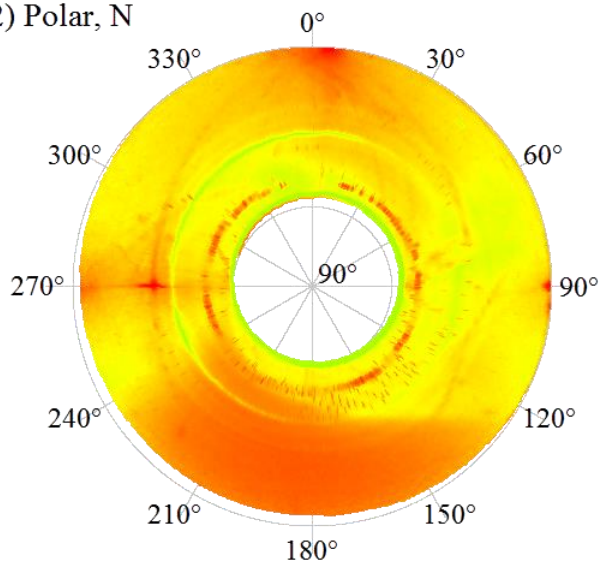
The map is not complete due to the limited view angles from a single station during a single pass.

High-definition photometry

1) Reflectivity map, log intensity scale

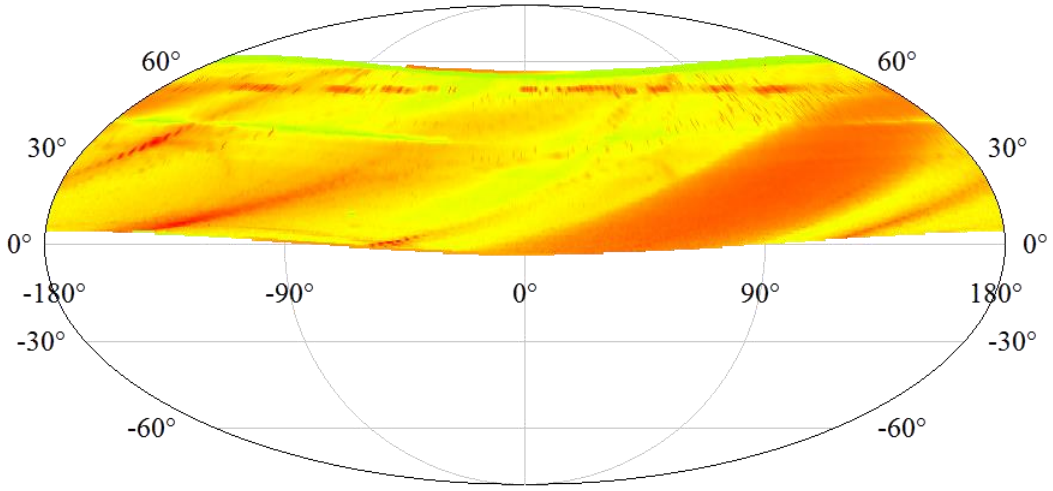


2) Polar, N

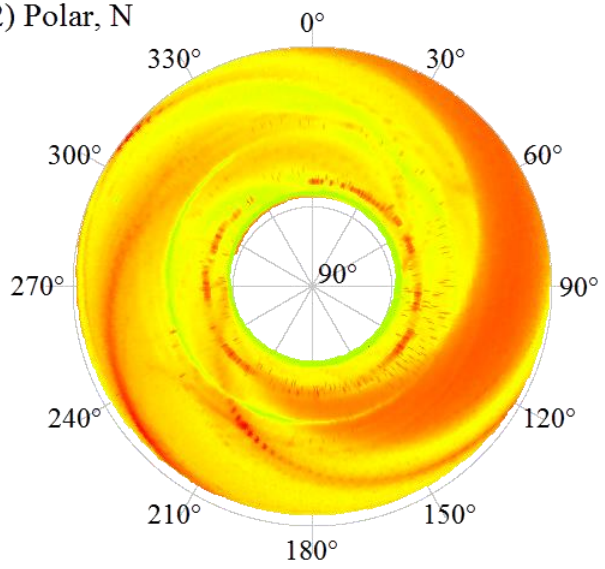


spin period = 11.308 s

1) Reflectivity map, log intensity scale



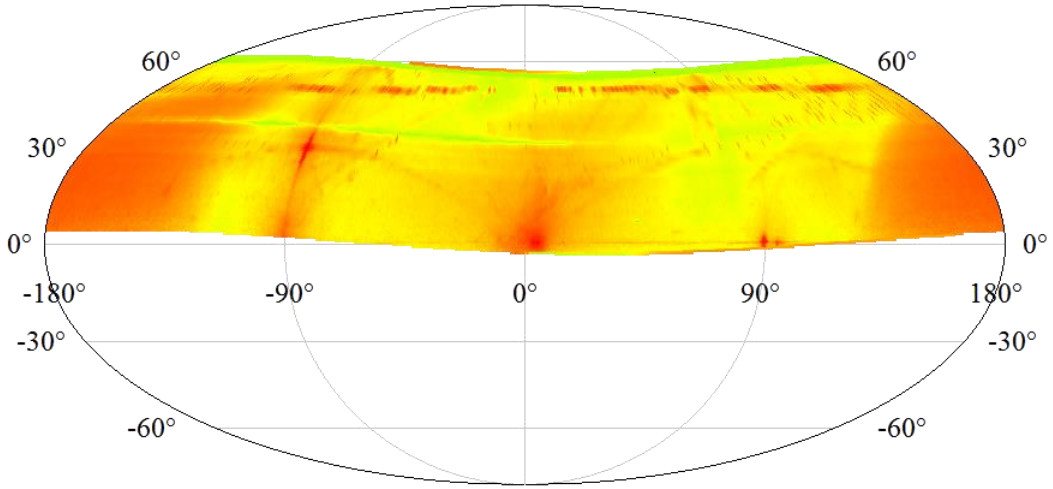
2) Polar, N



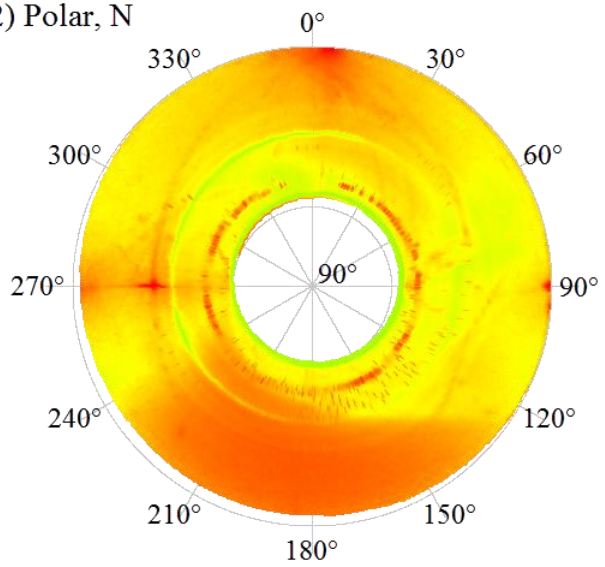
spin period + 100 ms

High-definition photometry

1) Reflectivity map, log intensity scale

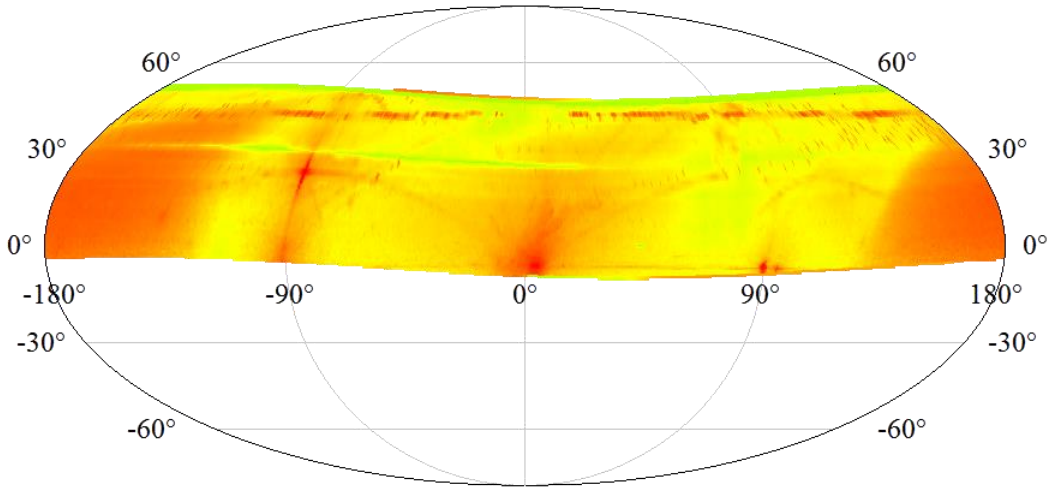


2) Polar, N

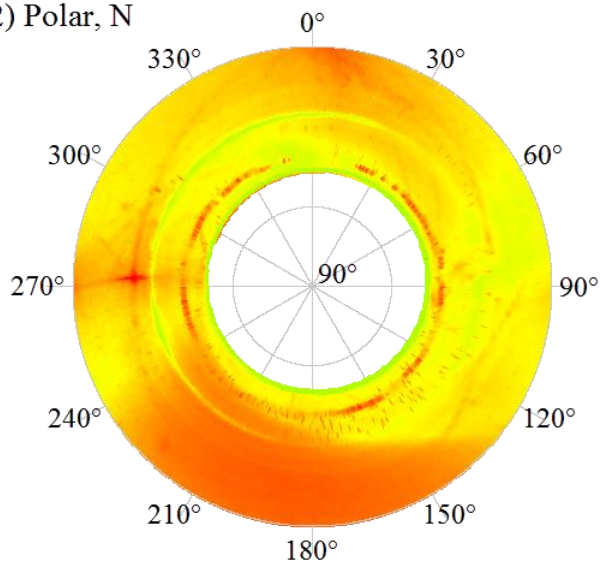


spin axis: RA = 94.3°, Dec = -64.8°

1) Reflectivity map, log intensity scale



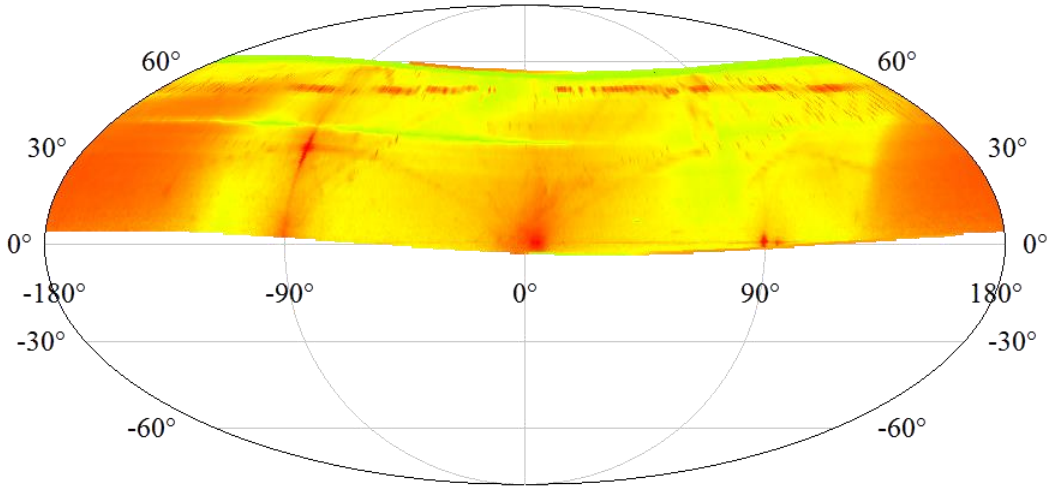
2) Polar, N



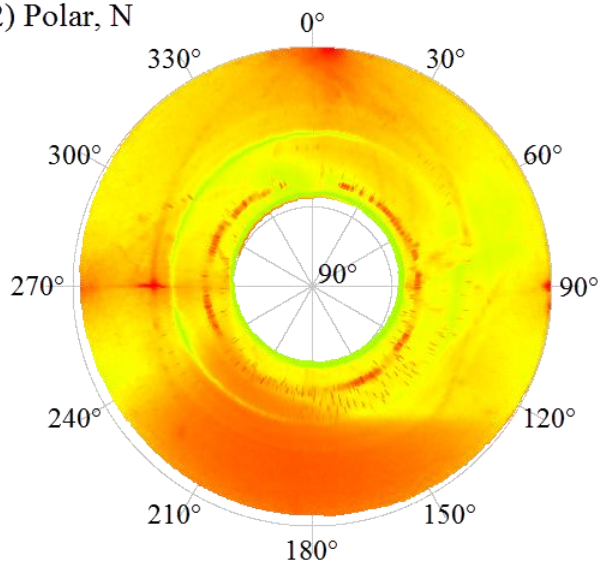
Dec - 10°

High-definition photometry

1) Reflectivity map, log intensity scale

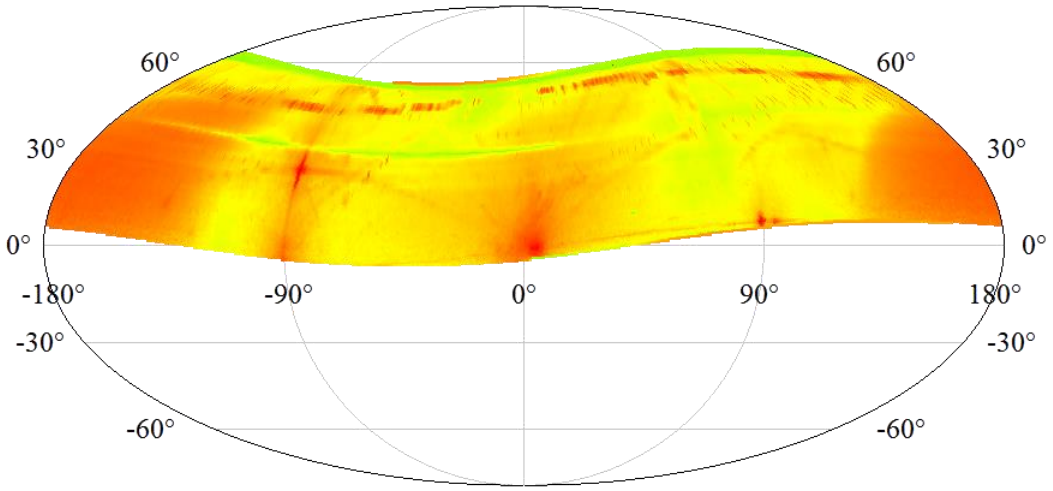


2) Polar, N

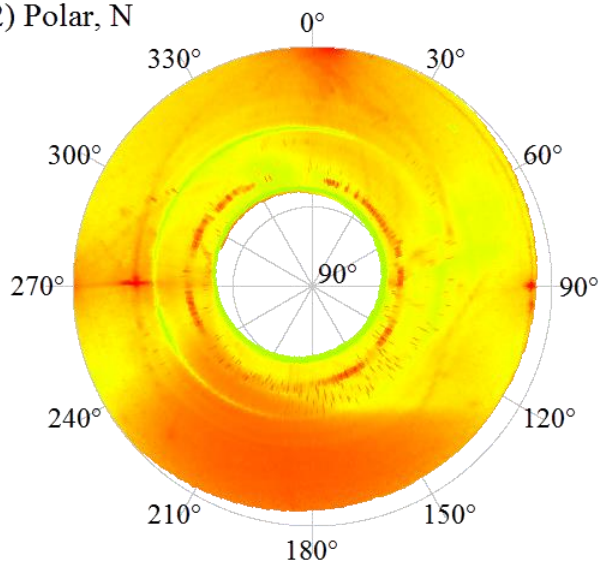


pole position: x_p = 3.1°, y_p = -1.6°

1) Reflectivity map, log intensity scale



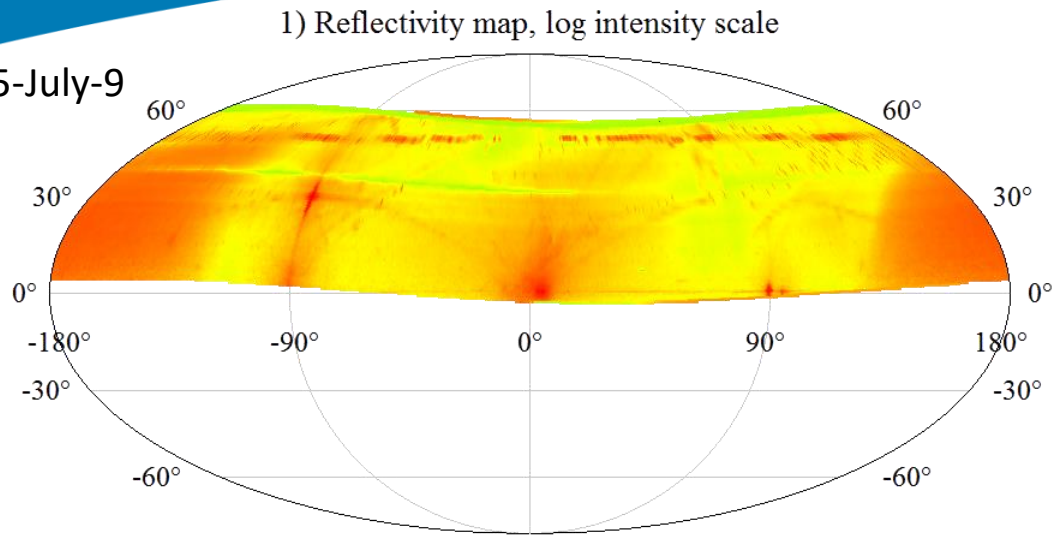
2) Polar, N

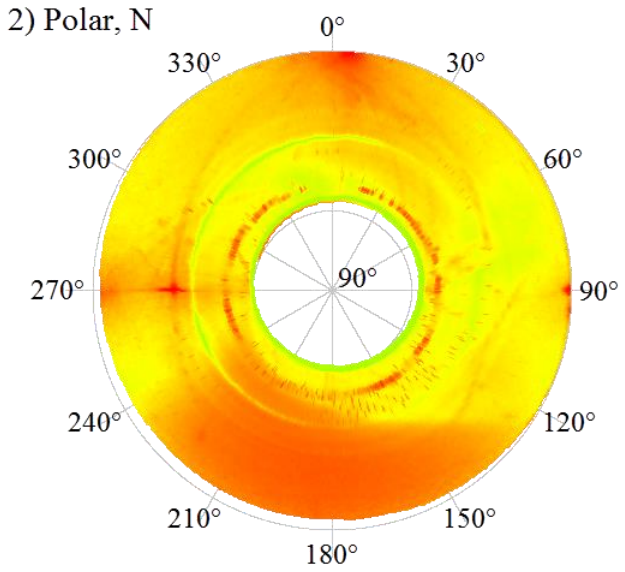


pole position: x_p = 5.0°, y_p = 5.0°

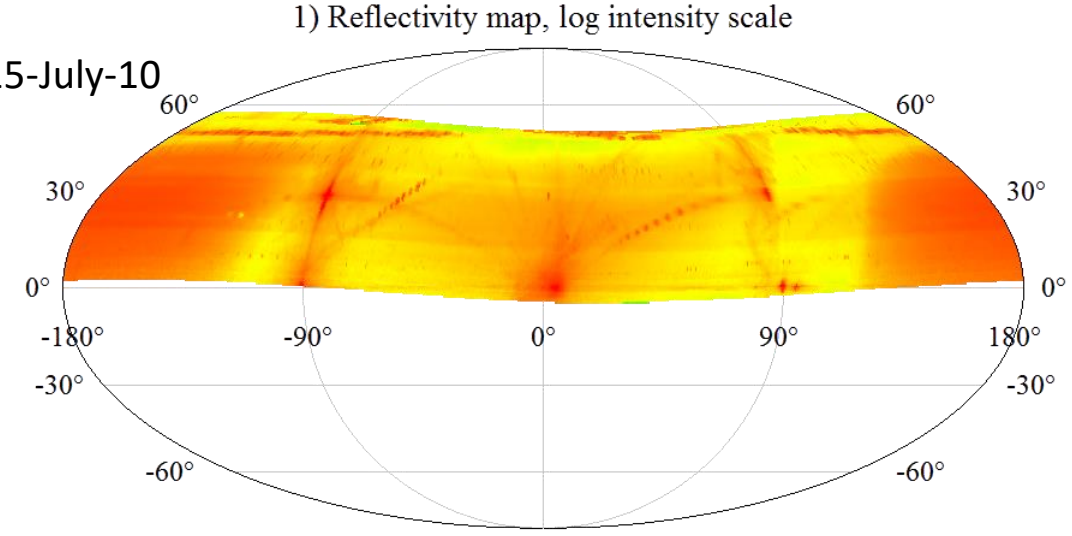
High-definition photometry

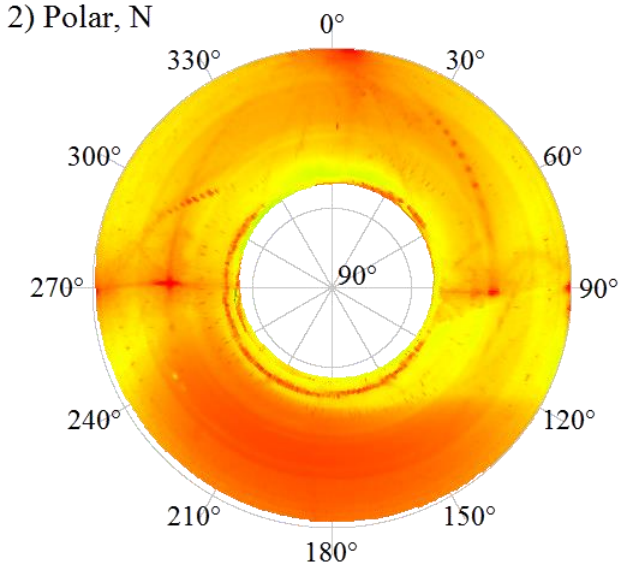
2015-July-9





2015-July-10





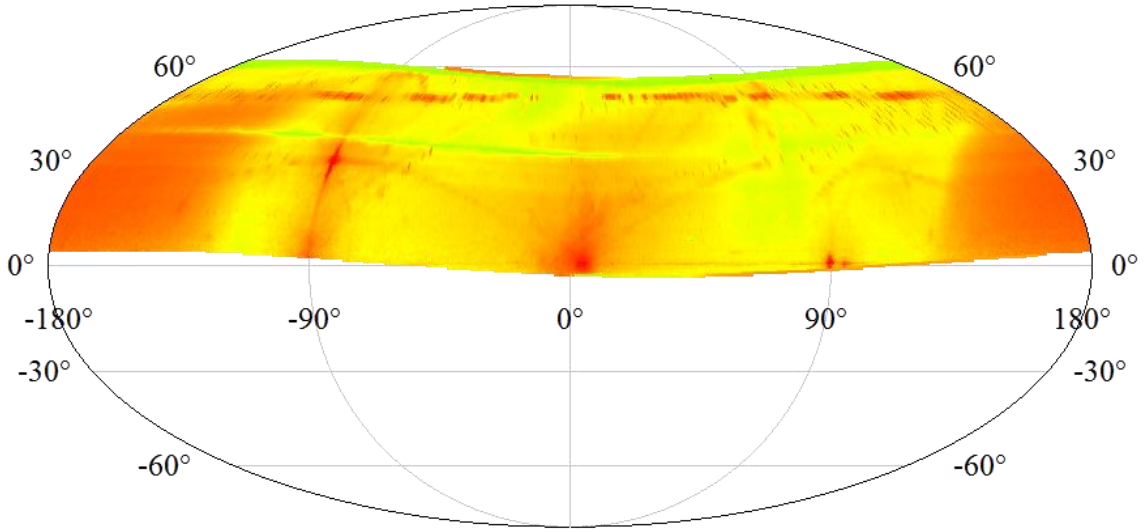
1) The pattern geometry remains constant because sunlight is specularly reflected from the satellite rigid body.

2) superposition of multiple passes will allow for generation of the more accurate reflectivity maps (signal normalization method will have to be applied).

3) Collecting measurements from multiple geographical locations will broaden the view angle and complete the reflectivity maps that later can be used to produce a unique satellite fingerprint ID.

Conclusions

- We have a method for complete and accurate satellite spin characterization (even during a single pass).
- The accurate spin model can be used to predict orientation of the solar panel for the laser time transfer experiments.
- The complete, high-resolution reflectivity patterns can be used for the satellite biometrics identification (fingerprints).
- The geographically distributed high-rate photometric network is needed in order to increase the satellite view angle (and produce complete maps).



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