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Light Curve Measurements with Single Photon Counters at Graz SLR

M. A. Steindorfer (1), G. Kirchner (1), F. Koidl (1), P. Wang (1)
(1) Space Research Institute, Austrian Academy of Sciences.
michael.steindorfer@oeaw.ac.at

Abstract. *Sun photons reflected diffusely from satellite structures are detected, counted and recorded with single-photon counting modules. The resulting 100-Hz-resolution light curves allow to derive various spin parameters of cooperative and uncooperative targets. Targets are ranging from sunlit low earth orbiting satellites, up to geostationary satellites, including any space debris. The system is of low cost and works in parallel and simultaneously with our SLR activities. The data is analyzed by means of Fourier transformation, autocorrelation function and phase dispersion minimization.*

Introduction

By means of satellite laser ranging (SLR), especially with kHz repetition rate, it is possible to analyze data for repeating patterns resulting from the spin of the satellite [Kirchner 2014]. Intrinsically, this is only possible for cooperative targets (equipped with retroreflectors which are visible to the observer). We introduce a method using single photon avalanche diodes (SPAD), a field programmable gate array (FPGA) and a brick PC to measure light curves from sunlit satellites or space debris simultaneously to SLR operation. The acquired high resolution data is then analyzed with three different methods: Fourier analysis, autocorrelation (AC) and phase dispersion minimization (PDM). The advantages of AC and PDM are that the spin can be determined independently if higher harmonics of the true spin period are included in the signal Furthermore, with PDM a mean light curve can be found corresponding to the amount of sunlight reflected by the satellite's surfaces.

Materials and methods

Collecting light curves with single photon counting modules

The reflected light of a satellite is gathered with a receiving telescope and separated into two parts. A mirror passes wavelengths of $\lambda = 532\,nm$ to the SLR detection package for standard SLR operation. The rest of the spectrum is redirected to the light curve measurement setup (Fig. 1). Four single-photon counting modules detect light depending on its incoming polarization state, which is a requirement for future quantum cryptography experiments. All four detectors operate in a free running mode - independent from and simultaneously with SLR operation. The setup is prepared for a fifth detector sensitive in the infrared spectral range. Depending on the brightness of the satellite different neutral density filters can be used to adapt the amount of photons received by the SPAD. The single events are collected by an FPGA board using bin widths with lengths of $\Delta t_{bin} = 10\,ms$ giving the measurements a timestamp. Alternatively, all individual epoch times can be stored without binning, leading to high resolution data. Finally, the data is transferred to a brick-PC and stored on disk.

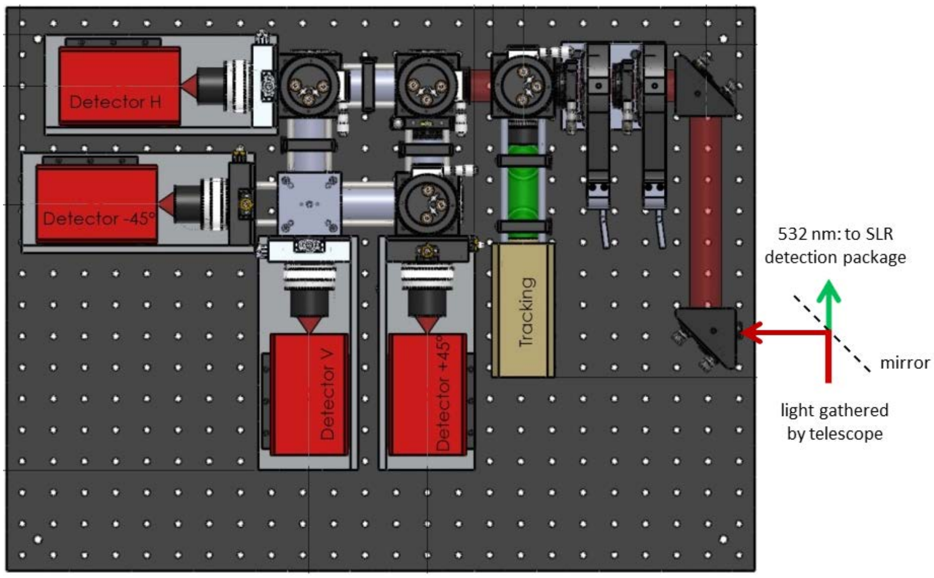

Figure 1. Setup of the light curve measurement detection package. Light is collected by a telescope, $\lambda = 532\ nm$ is passed to the SLR detection package, the rest of the spectrum is used to simultaneously record light curves with four single-photon counting modules used for different polarization states.

Data analysis

The recorded data is analyzed by three different methods giving information on the spin period of the satellite: Fourier analysis, autocorrelation and phase dispersion minimization. Each of the methods will be summarized briefly.

1) Fourier data analysis transforms a signal $x(t)$ from the time domain into the frequency domain $\hat{x}(f)$ and vice-versa according to

$$\hat{x}(f) = F\big(x(t)\big) = \int_{-\infty}^{\infty} x(t)e^{-i2\pi ft}\,dt \ ; \ x(t) = F^{-1}\big(\hat{x}(f)\big) = \int_{-\infty}^{\infty} \hat{x}(f)e^{i2\pi ft}\,df$$

t ... time, f ... frequency, $x(t)$ ... signal strength, $\hat{x}(f)$ ... signal strength Fourier transformation

2) Autocorrelation ($\star$) is the correlation of a function $x(t)$ with itself at an earlier point of time $x(\tau)$. It can be expressed by the convolution ($*$) of the complex-conjugate $x^*(-\tau)$ with $x(\tau)$.

$$AC\ (\tau) = x \star x\ (\tau) = \int_{-\infty}^{\infty} x^*(t)x(t+\tau)\,dt = x^*(-\tau) * x(\tau)$$

or alternatively by using the Wiener-Khinchin theorem [Wiener 1930] by performing the inverse Fourier transformation of the power spectral density of the Fourier transformation $\hat{x}(f)$

$$AC = F^{-1}\big(\,|\big(\hat{x}(f)\big)|^2\,\big)$$

The true spin period then corresponds to the time τ where the autocorrelation function reaches a maximum.

3) A third approach refers to a method called phase dispersion minimization (PDM) first introduced in 1978 [Stellingwerf 1978]. For a time-dependent signal $y_i = f(t_i)$ a test period T_{test} is defined. For each of the times t_i the phase φ related to the test period is given according to

$$\varphi_i = \frac{t_i}{T_{test}} - \left\lfloor \frac{t_i}{T_{test}} \right\rfloor$$

The symbol $\lfloor x \rfloor$ is equivalent to rounding x to the nearest integer towards $-\infty$. According to these phases, the data points y_i are divided into bins corresponding to similar phases. It is important to state, that the bin sizes do not have to be equally spaced in time and that single data points can be included in multiple bins. The variance of all of the function values in each bin is then calculated and the mean of all bin variances determined. The true period of the signal corresponds to the test period where the mean of the bin variances (the θ function) is minimized. The complete PDM algorithm used can be found in [Schwarzenberg-Czerny 1997].

In the following, light curve data for several satellites from low to high earth orbits and space debris will be analyzed with the three described methods.

Results and discussion

Analysis of light curve data of Compass G2

To demonstrate spin determination with Fourier analysis, autocorrelation and phase dispersion minimization data taken from the pass of the Compass G2 satellite (NORAD ID: 34779) on day 157 of the year 2015 is presented. Within a bin size ($\Delta t_{bin} = 10\ ms$) on the average 100 single-photon events are counted by the SPAD (Fig. 2a). The observation was done simultaneously to the SLR measurements within a total time span of 936 s. Cutting the signal to an interval of $\Delta t = 50\ s$ between 200 and 250 s reveals the additional information light curve measurements contain (Fig. 2b). It can be clearly seen that 4 peaks repeat periodically with a period below 10 s. Compass G2 is a box-wing satellite and the four peaks correspond to sunlight reflected either by the surfaces of the central box or the solar panel wings. The closer the direction of the reflectance maximum is to the direction of the observer the more intense a single reflectance peak gets. Furthermore the signal is intensified by the size of the surface area and albedo of the surface.

A slightly larger interval of $\Delta t = 100\ s$ was chosen for the following calculations. The Fourier analysis (Fig. 3a) clearly shows an issue which exists for signals containing higher harmonics of the true period. It is most sensitive to the largest existing frequency which is in this case $f = 0.56\ s$ or $T_F = 1.786\ s$. This problem is resolved when looking at the autocorrelation function (Fig. 3b). The maximum can be found at $T_{AC} = 7.14\ s$ which is four times T_F . The same spin period follows from the phase dispersion minimization algorithm (Fig. 4). The θ function is also minimized at $T_{PDM} = 7.14\ s$. It is now possible to compare the results from two independent spin period determination algorithms to SLR data and hence further expand the number of monitored satellites.

From the PDM calculations the mean values of all measurements within each bin can be determined for the true spin period T_{PDM}. This “light curve” is plotted representing the normalized reflected amplitude in dependence of the phase of the satellite spin (Fig. 5). Four surfaces according to the box-wing satellite shape are clearly visible as well as some additional information in between these peaks potentially coming from minor surfaces of the satellite.

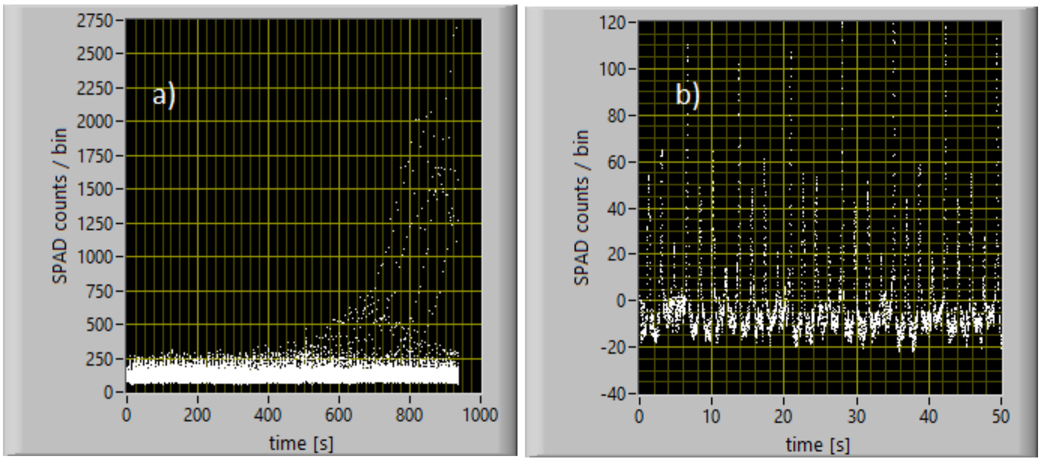

Figure 2: Light curve raw data (a) and cut data for an interval of $\Delta t = 50\ s$ between 200 and 250 s (b) for the Compass G2 satellite

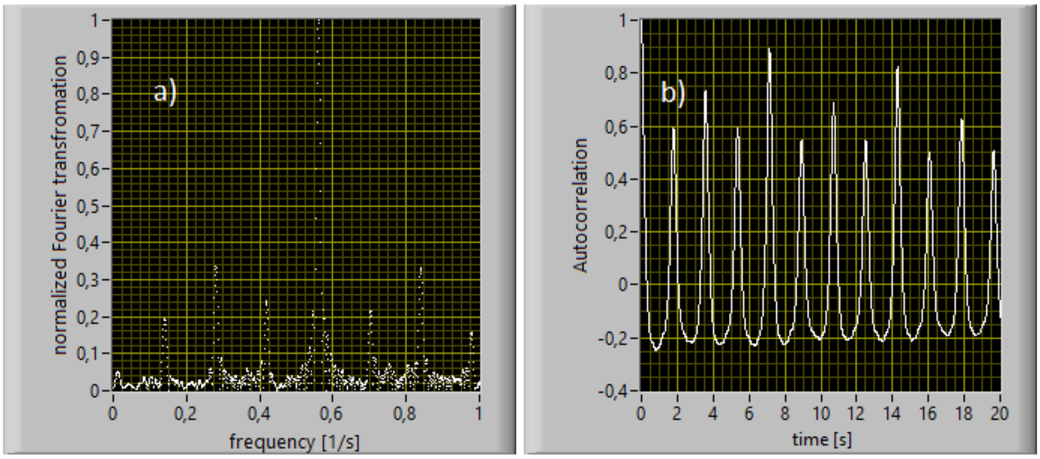

Figure 3: Fourier transformation (a) and autocorrelation function (b) for the Compass G2 satellite.

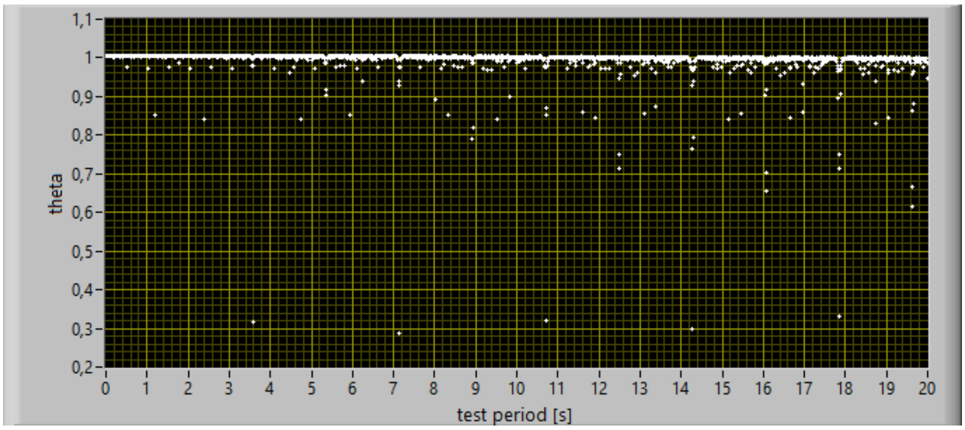

Figure 4: Phase dispersion minimization θ function in dependence of the test period T_{test} for the Compass G2 satellite.

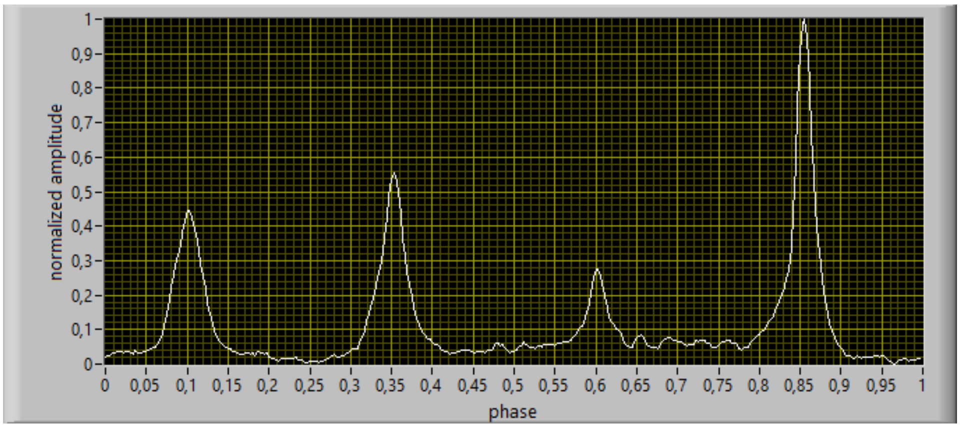

Figure 5: Mean light curve of the Compass G2 satellite for the interval between 200 and 300 s. The phase on the x-axis ranging from 0 to 1 corresponds to the spin period of $T_{PDM} = 7.14\ s$ which was determined by using the autocorrelation function and phase dispersion minimization algorithm.

Furthermore 8 adjacent light curves of Compass G2 within this pass were evaluated (Fig. 6). Each interval length is $\Delta t = 100\ s$ and the total observation length 800 s. To be able to compare the intensities with each other in this case the light curves are not normalized. It can be clearly seen that within the 800 s the second and fourth peak intensify while the remaining peaks remain constant. Our assumption is that this behavior results from the reflection maximum of the solar panels turns into to direction of the observer.

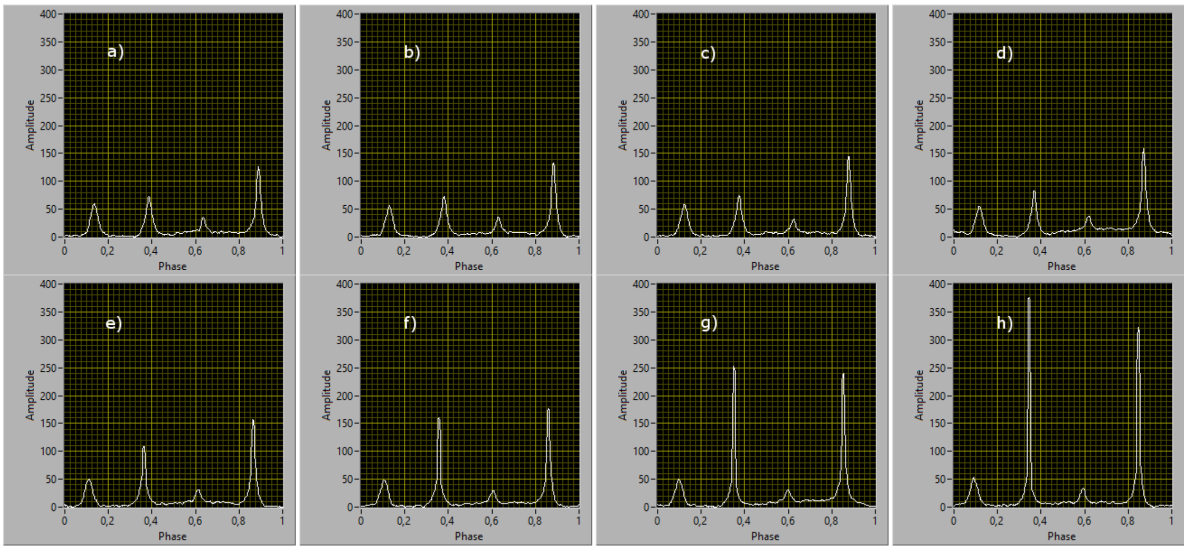

Figure 6: Time series of 8 adjacent Compass G2 light curves with interval lengths of $\Delta t = 100\ s$. The light cure series covers a total time span of 800 s from a) to h).

Light curves and statistics of Topex and SL-6 R/B 2

As further examples for the wide range of observable satellites light curves from Topex/Poseidon (Fig. 7a) and SL-6 R/B 2 (Fig. 7b) are presented. Topex (NORAD ID: 22076) is a former oceanographic satellite in a low earth orbit around Earth with a perigee of approximately 1340 km. According to our PDM measurements on day 158 of the year 2015 it spinned with a period of $T_{PDM} = 11.36\ s$. The light curve also clearly shows the 4 distinguishable reflection peaks. SL-6 R/B 2 (NORAD ID: 23587) is a rocket body with a highly eccentric orbit ranging approximately from 2500 km perigee to 37500 km apogee; it has no retroreflectors and is hence not observable with SLR. The light curve shows 3 separate reflection peaks resulting from the cylindrical shape of the rocket body. The spin period was determined with $T_{PDM} = 36.19\ s$ on day 220 of the year 2015.

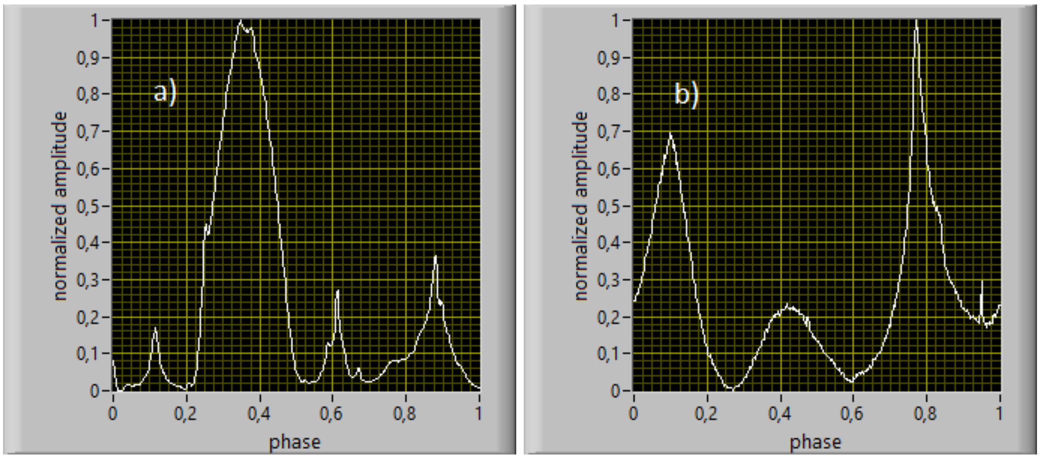

Figure 7: Mean light curves of Topex/Poseidon (a) and the SL-6 R/B 2 rocket body.

From 16 passes of Topex within 45 days a trend was derived from 115 PDM spin measurements with intervals with $\Delta t = 100\ s$. Fitting a straight line through the data clearly shows that the spin rate is decreasing. The data suggests a decrease rate of approximately 0.7s/year during the observation period (Fig. 8a).

All light curves refer to the apparent spin of the satellite. Fig. 8b shows the spin period change within a single pass, reaching a maximum around closest approach. The sign of this change is a simple indication of the spin direction.

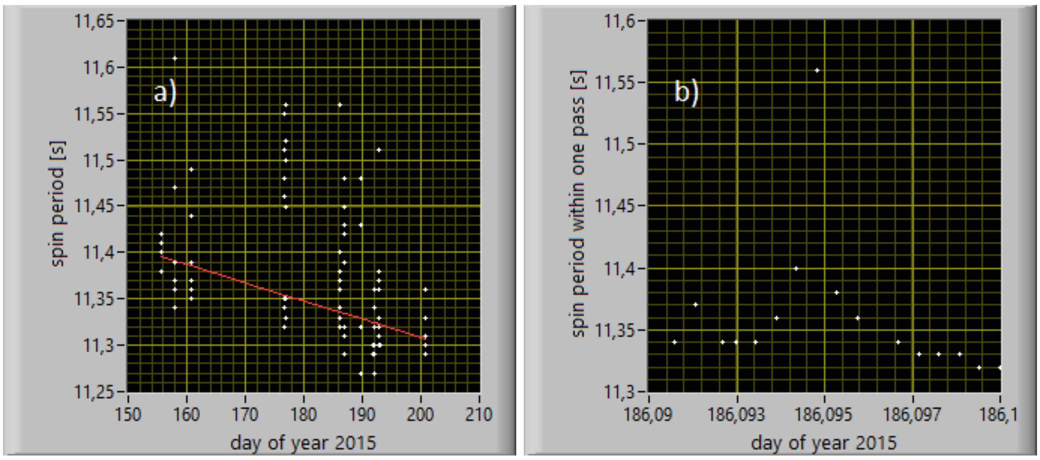

Figure 8: Decrease of the spin period of Topex/Poseidon for a total 115 spin periods calculated from 16 passes with time intervals lengths of $\Delta t = 100\ s$ (a), change of Topex/Poseidon spin period due to the apparent spin within a single pass (b).

Summary and outlook

In this paper we demonstrate the measurement of light curves with single photon counting modules. Three different methods for the evaluation of light curves are presented. Fourier analysis has the disadvantage that it is sensitive to the highest frequency component in the given data. For objects with multiple reflective surfaces this will result in wrong spin periods. Spin determination by autocorrelation or phase dispersion minimization resolves this problem and delivers the correct satellite spin period. With the phase dispersion minimization algorithm, mean light curves can be calculated for the optimized spin period, allowing conclusions on the orientation of the satellite. To resolve ambiguities we simultaneously operate SLR spin determination and light curve measurements. Light curve measurements have the advantage to give also results for uncooperative targets or when the retroreflector is not visible. By using SLR data and light curves the spin period was determined for 42 defunct Glonass satellites (Fig. 9).

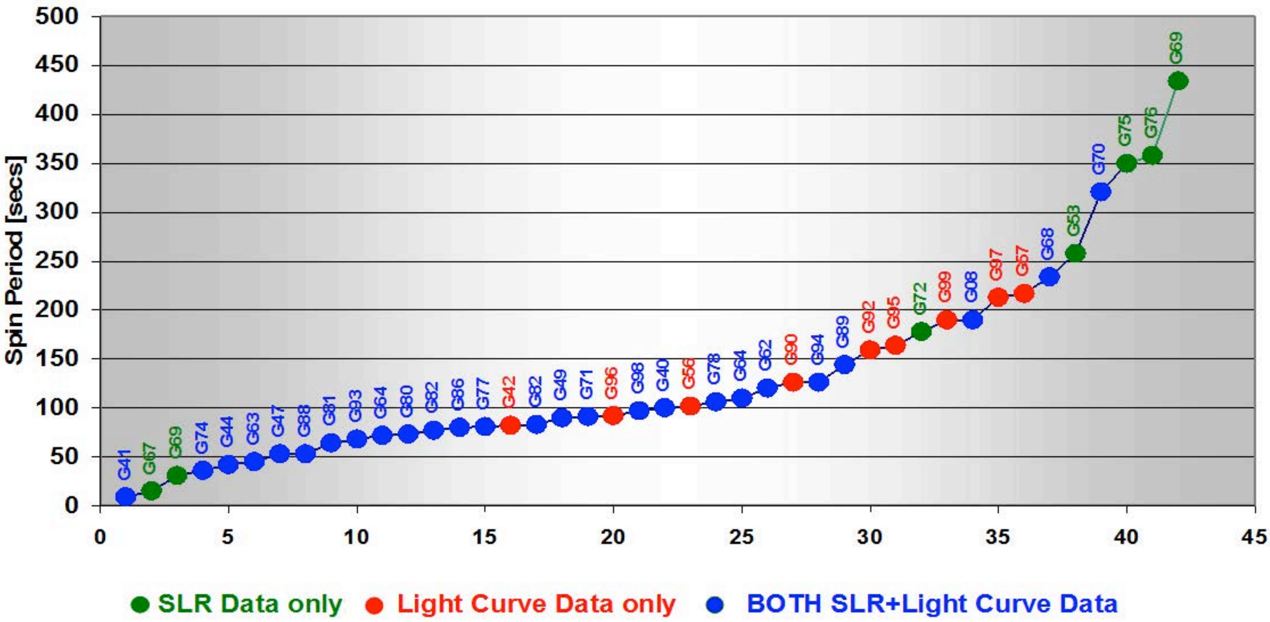

Figure 9: Spin periods for 42 Glonass satellites determined by SLR only (green), light curves only (red) or SLR and light curves simultaneously (blue).

The described setup and analysis has the advantage that it is simple, of low cost and the data evaluation methods are easy to realize. We recommend other SLR stations to upgrade their receiving units to record light curves simultaneously to SLR.

References

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