LIGHT CURVE MEASUREMENTS WITH SINGLE PHOTON COUNTERS

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• Graz measures spin routinely with SLR
• Defunct Glonass satellites using SLR
• >40 satellite with spin periods $T_{\text{SLR}} = 9 - 450$ s
• $T_{\text{SLR}} = 11.8$ s
• Disadvantage: needs retros AND visibility of retros
• Defunct satellites are sometimes flying 'upside down'
Installed into receive telescope / planned for later cryptography experiment

- 4 single-photon detectors (SAP 500, in „τ-SPAD Fast“ packages)
- 780 - 1000 nm spectral detection range (filter)
- 4 different polarization planes

Basic 4-SPAD setup (quantum cryptography)  
SAP 500: Spectral detection efficiency
532 & 1064 nm: SLR detection package
Rest: quantum cryptography package
4 SPAD detectors count single photon events (reflected sun light)
Count numbers of 10 ms bins stored (=> 100 Hz measurement rate)
Ch #1: Additionally, all epoch times stored: High resolution light curves
Spin of uncooperative targets can be determined
DETECTION PACKAGE

IQOQI, 2015-06-10
LIGHT CURVE RAW DATA

- Compass G2, NORAD ID: 34779, perigee: 35397 km\(^1\)
- Box-wing satellite (4-sided box + solar panels)
- No laser echoes (retros never visible), defunct since 2011
- x-axis: elapsed time since start of measurement
- y-axis: number of photons detected at SPAD within \(\Delta t = 10\) ms

\(^1\)http://www.n2yo.com/
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• Zooming in: $\Delta t = 100$ s
• Remove trends + moving average
• All four sides visible, ambiguities for spin period detection
Spin period detection methods

1. Fourier analysis

2. Autocorrelation

3. Phase dispersion minimization
Fourier analysis: time domain $\rightarrow$ frequency domain

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

- Suggests $f = 0.56$ Hz, $T_{\text{FFT}} = 1.79$ s
Autocorrelation: correlation of function with itself at earlier time

\[ x \ast x(\tau) = \int_{-\infty}^{\infty} x^*(t)x(t + \tau) \, dt = x^*(-\tau) \ast x(\tau) \]

Alternative: via inverse Fourier of \(|\hat{x}(f)|^2\)

Maximum: \(T_{AC} = 7.14 \, s = 4 \, T_{FFT} \ldots \) fundamental frequency

Potential ambiguities if amplitude of satellite surfaces similar
PHASE DISPERSION MINIMIZATION

• Signal: $y_l = f(t_l)$
• Define test period $T_{\text{test}}$
• Calculate phases of epoch times related to test period
  \[
  \text{phase} = \frac{t_l}{T_{\text{test}}} - \left\lfloor \frac{t_l}{T_{\text{test}}} \right\rfloor
  \]
• \(\lfloor \cdot \rfloor \) ... round to nearest integer toward negative ∞
• Separate measurements into bins with similar phase
• Calculate variance of $y_l$ values of each bin
• Calculate mean of variances
• Find test period $T \rightarrow$ mean of variances minimized

**Example:** sin-curve with noise

- All points within green intervals (e.g. Δt = 2s) correspond to one bin
- Wrong test period $T_{PDM} = 80$ s (large variance)

- Correct test period $T_{PDM} = 100$ s (small variance)
- Compass G2, NORAD ID: 34779, perigee: 35397 km
- y-axis: theta ... mean bin variance, normalized to [0,1]
- Minimum at $T_{PDM} = 7.14 \, s = T_{AC}$
- Similar values at integer multiplies of $T_{PDM}$
- Ambiguities if light curve changes rapidly

true period
COMPASS G2 - LIGHT CURVE

- Compass G2, NORAD ID: 34779, perigee: 35397 km
- Spin period: $T_{\text{spin}} = 7.14$ s
- Average of all points in one bin -> light curve
- Four sides of satellite clearly visible
- Light curve depends on: sunlight incidence angle, surface normal vector, station vector, surface reflectivity, shape of satellite…
• 8 adjacent LC for one pass, each LC interval 100 s, total 800 s
• Two reflection peaks intensify, two peaks stay constant
• Assumption: solar panel reflection turns to observer
LIGHT CURVES - TOPEX, SL-6 R/B(2)

- TOPEX/POSEIDON, NORAD ID: 22076, Perigee: 1338 km
- SL-6 R/B(2), NORAD ID: 23587, Perigee: 2370 km, Apogee: 37530 km
  rocket body: launched 1995-05-24; highly eccentric orbit (GTO)

\[ T = 11.35 \text{ s} \]

\[ T = 36.19 \text{ s} \]
LIGHT CURVES - GLONASS 044, ENVISAT

- GLONASS 044 (COSMOS 2079), NORAD ID: 20619, Perigee: 19034 km
- ENVISAT, NORAD ID: 27386, Perigee: 772 km

**GLONASS 044 (2015/179)**

\[ T = 38.96 \text{ s} \]

**ENVISAT (2015/202)**

\[ T = 171.77 \text{ s} \]
115 spin periods from 16 passes, $\Delta t = 50$ s

- **Left plot:** spin period vs. day of year 2015
- Spin period decrease $\approx 0.7$ s / year
- **Right plot:** spin period for one pass
- Change of spin period due to apparent spin
ONGOING RESEARCH - BLITS

- BLITS (ball lens in the space), NORAD ID: 35871, Perigee: 823.3 km
- No SLR echos since January 2013 (collision with space debris)
- Spin period now: $T_{\text{spin}} = 2.2$ s, reduced from $T = 5.6$ s due to collision
Light curves:
• Advantage: no need for retros
• Disadvantage: only during night; sunlight needed on target

Laser measurements:
• Advantage: day + night observations
• Disadvantage: needs „visible“ retros

SLR Graz: BOTH methods operating in parallel / independent
• Additional equipment needed: Brick PC, FPGA card, SP detection unit
• Light curves automatically recorded
Summary of Graz Light Curve Measuring system:

- Determines spin of cooperative & uncooperative targets, high accuracy
- Automatically and parallel to / simultaneously with SLR
- Additional SLR data from cooperative targets help to resolve ambiguities (e.g. with box-wing type targets like most GNSS satellites)
- Works for LEO, HEO, and up to / including GEO targets
- At present 4 SPAD channels; 5th IR channel will be added
- Standard resolution is 10 ms (100 Hz) for all channels
- Channel #1: All Single-Photon event times stored => High resolution light curves

- Simple, low cost, easy evaluation -> SLR stations can easily upgrade!
Thank you!
Bisquare-Fit
- Minimizes weighted sum of squares
- Weight given to each data point depends on how far point from fitted line
- Points near the line get full weight
- Farther from line reduced weight
- Points farther from line than expected get zero weight
- Outliers minimized

PDM
- \( d_0 s_0^2 = \sum_{ij} (x_{ij} - \bar{x})^2 \)
- \( d_2 s_2^2 = \sum_{ij} (x_{ij} - \bar{x}_i)^2 \)
- \( d0 = n - 1 \)
- \( d2 = n - r \)