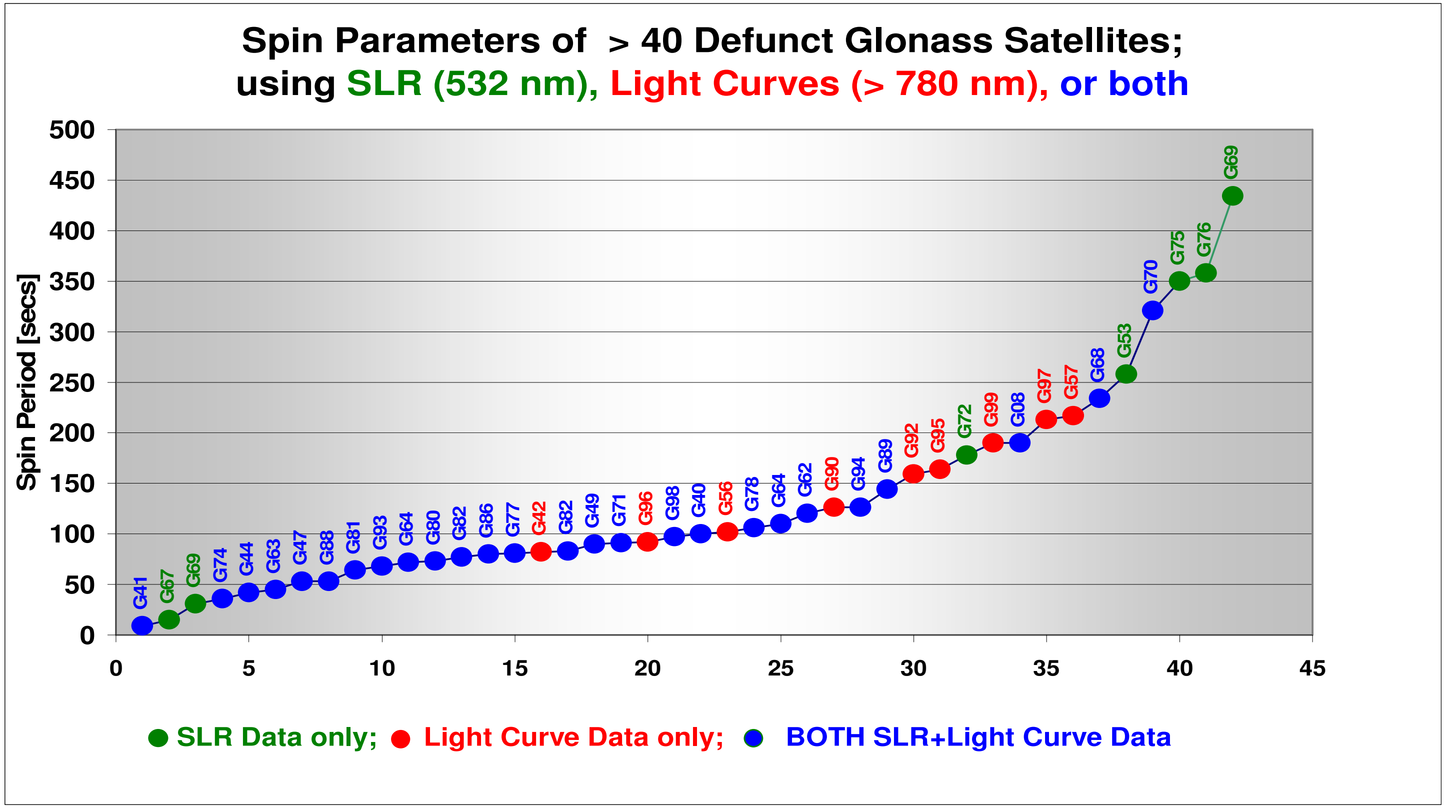
LIGHT CURVE MEASUREMENTS WITH SINGLE PHOTON COUNTERS

Georg Kirchner, Franz Koidl, Peiyuan Wang, Michael Steindorfer, Daniel Kucharski
Space Research Institute, Austrian Academy of Sciences

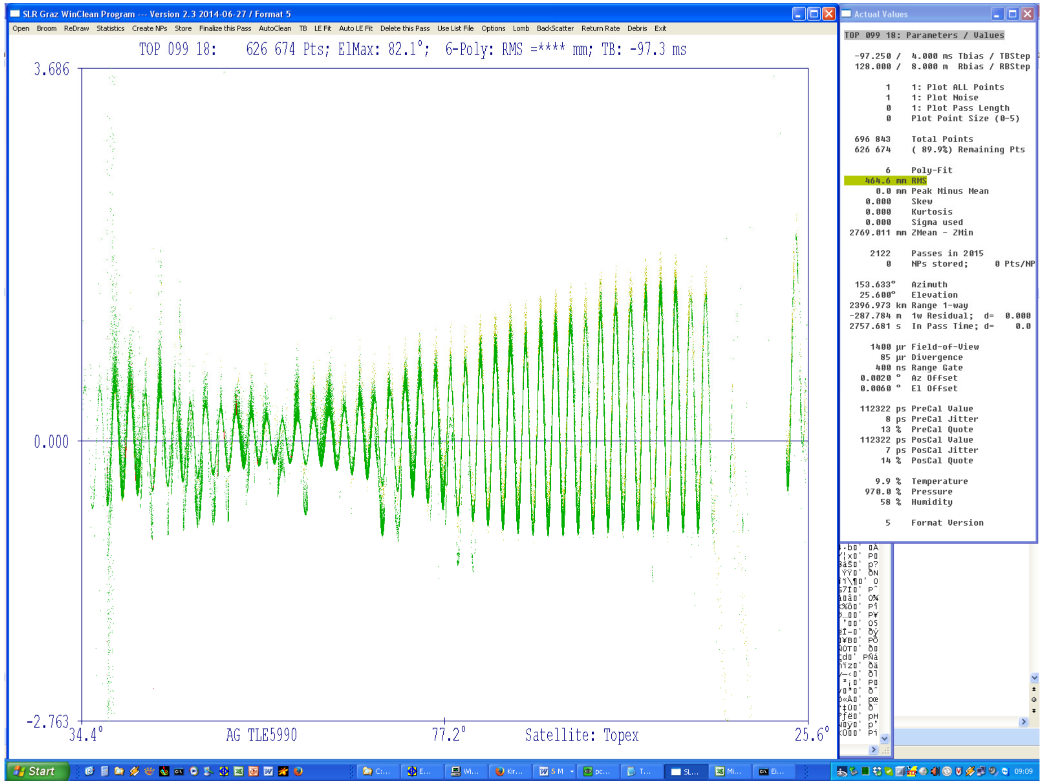
TUMBLING GLONASS SATELLITES

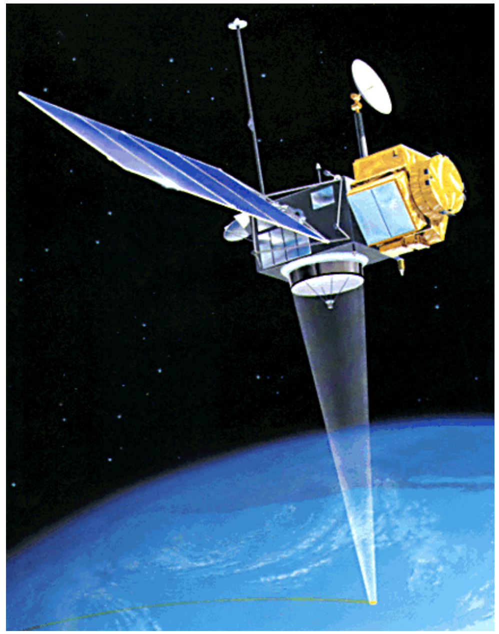
- Graz measures spin routinely with SLR
- Defunct Glonass satellites using SLR
- >40 satellite with spin periods T_{SLR} = 9 - 450 s



TOPEX LASER MEASUREMENTS

- T_{SLR} = 11.8 s
- Disadvantage: needs retros AND visibility of retros
- Defunct satellites are sometimes flying ‚upside down‘





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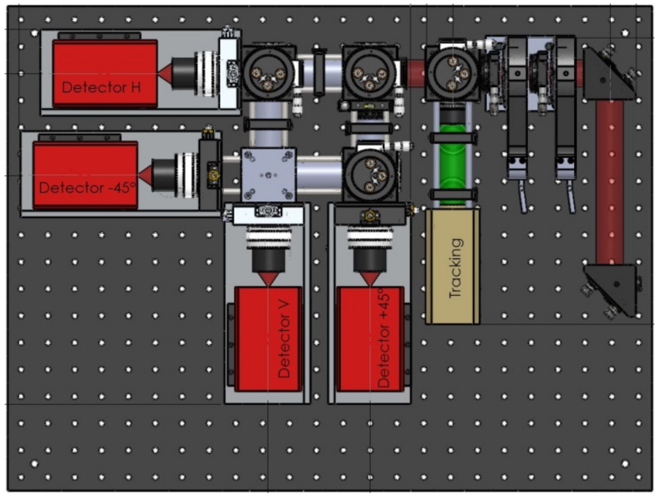
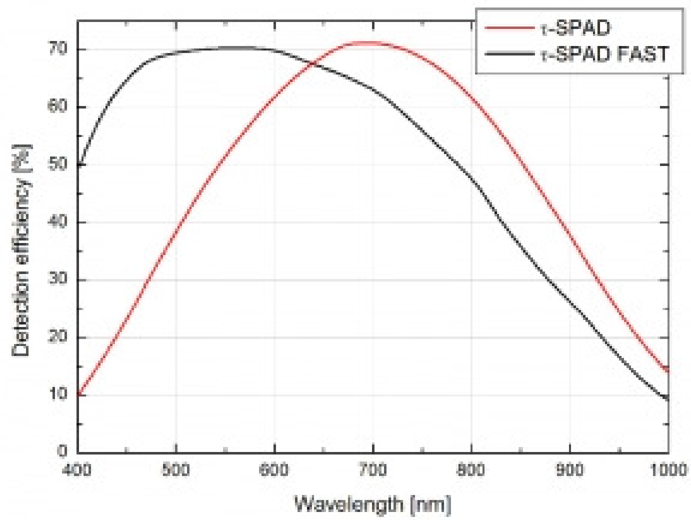
LIGHT CURVE SETUP

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



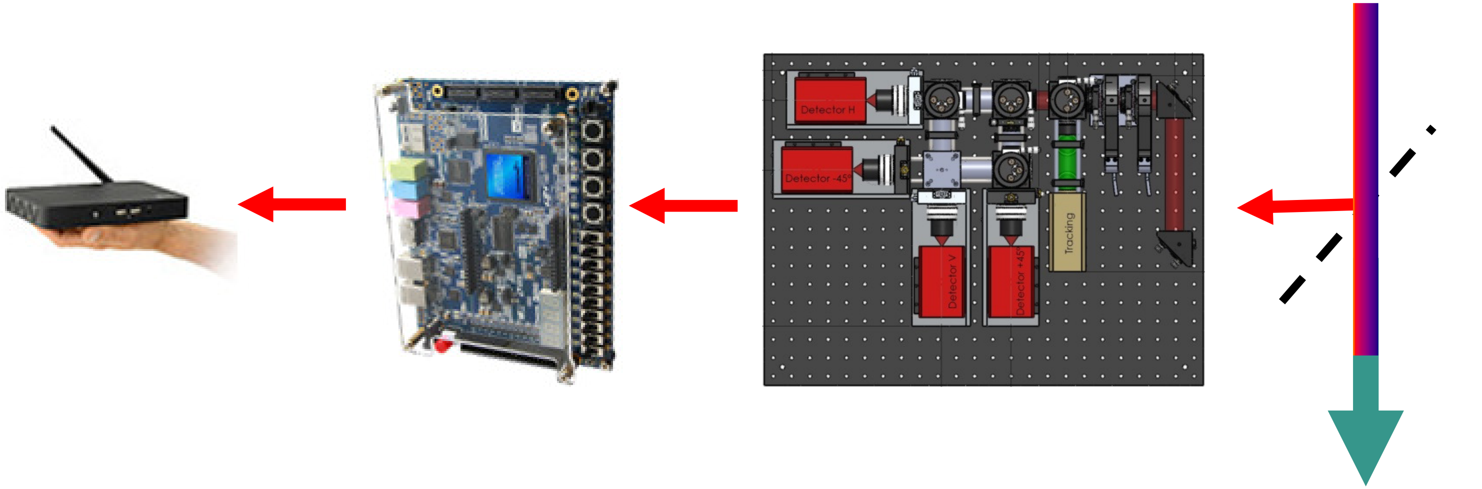
Basic 4-SPAD setup (quantum cryptography)



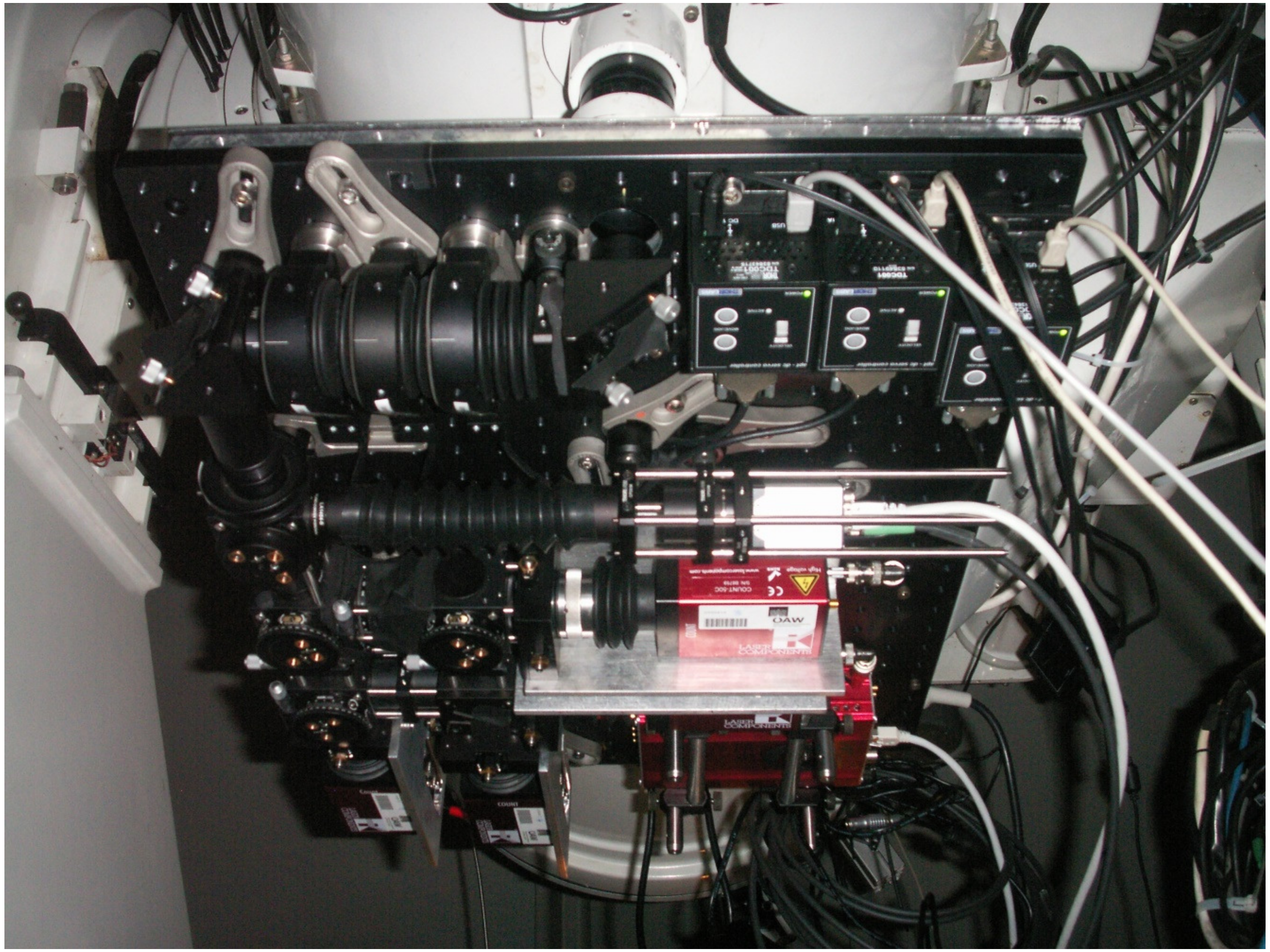
SAP 500: Spectral detection efficiency

LIGHT CURVE SETUP

- 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



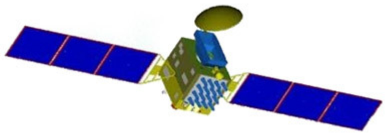
DETECTION PACKAGE

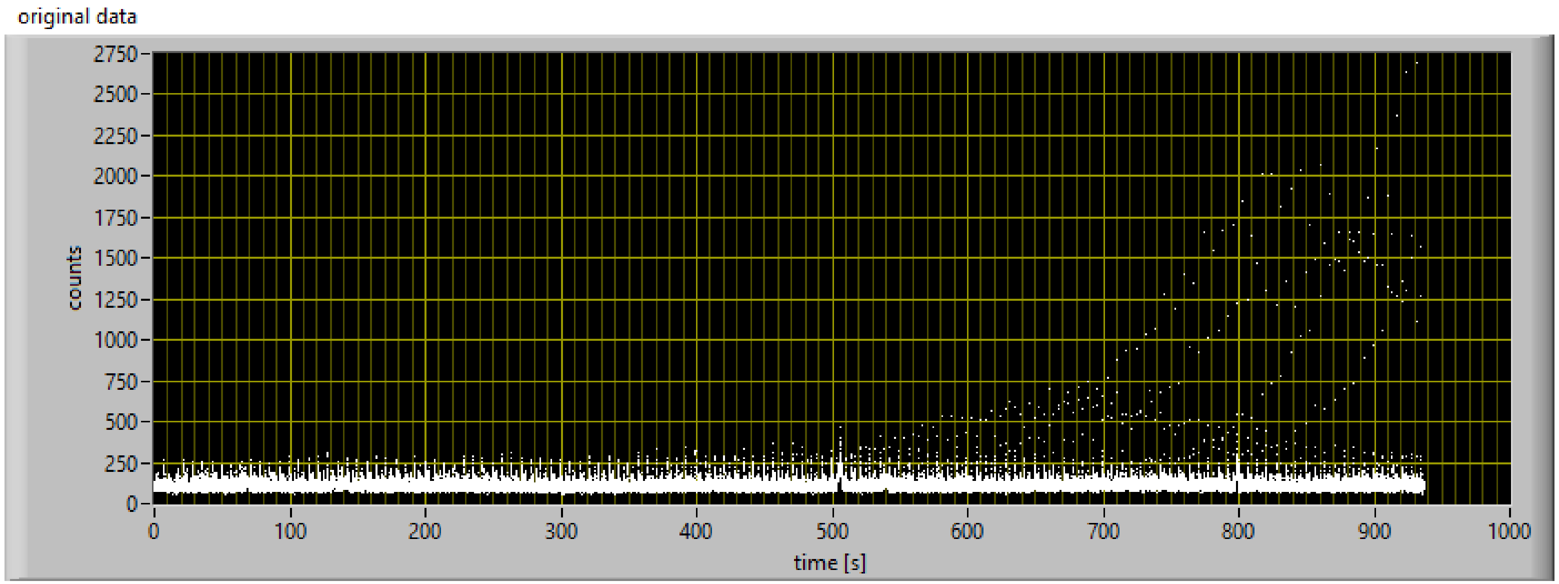


IQOQI, 2015-06-10

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 Δt = 10 ms





[1] http://www.n2yo.com/

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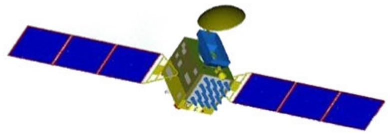
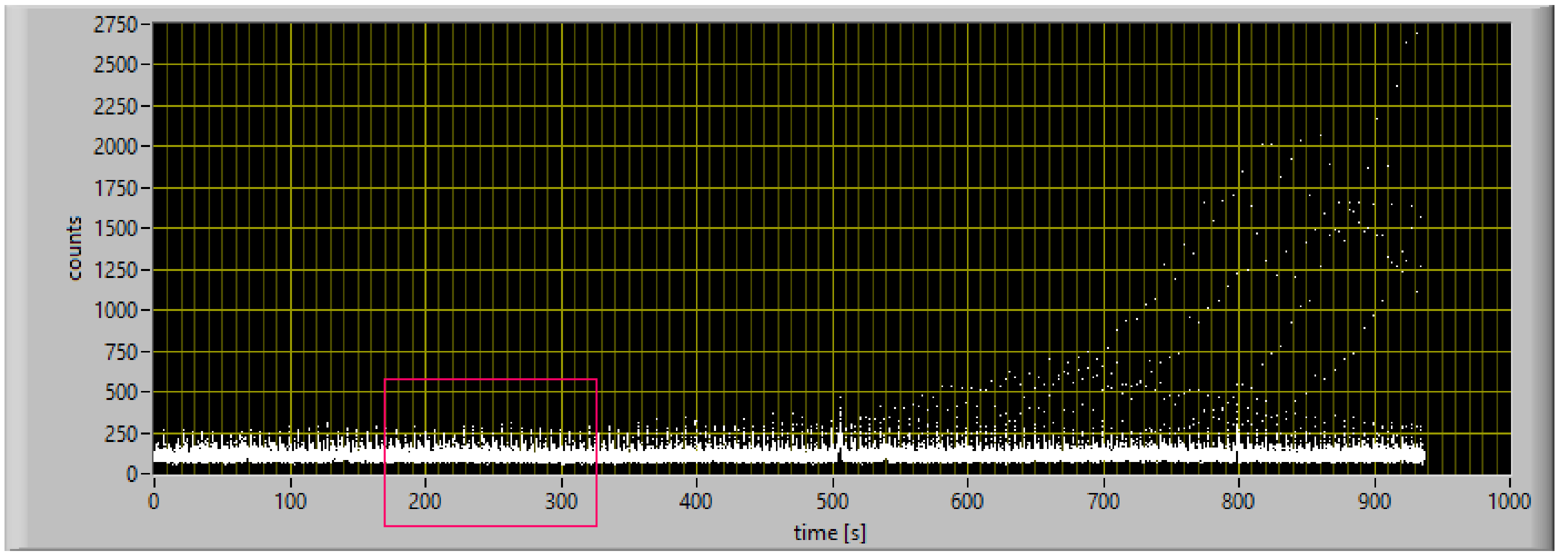


original data



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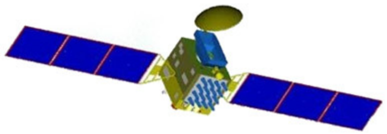
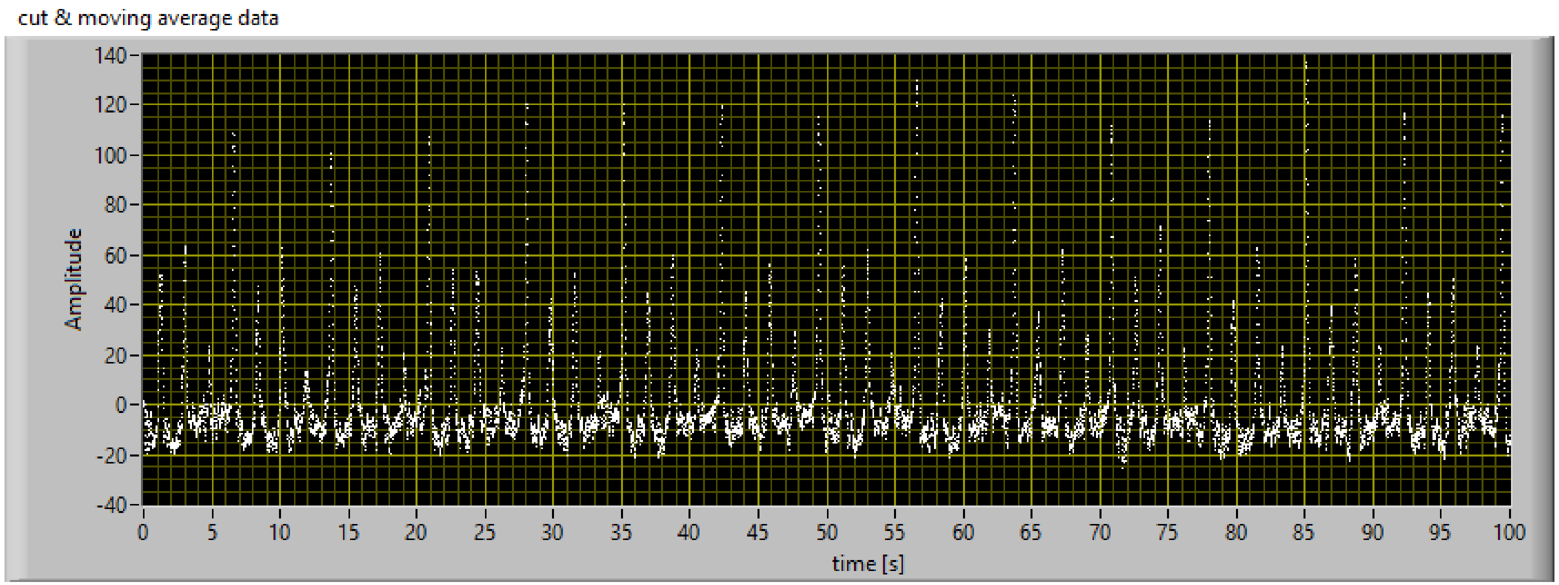
COMPASS G2



- Zooming in: Δt = 100 s
- Remove trends + moving average
- All four sides visible, ambiguities for spin period detection



THREE APPROACHES

Spin period detection methods

1. Fourier analysis

2. Autocorrelation

3. Phase dispersion minimization

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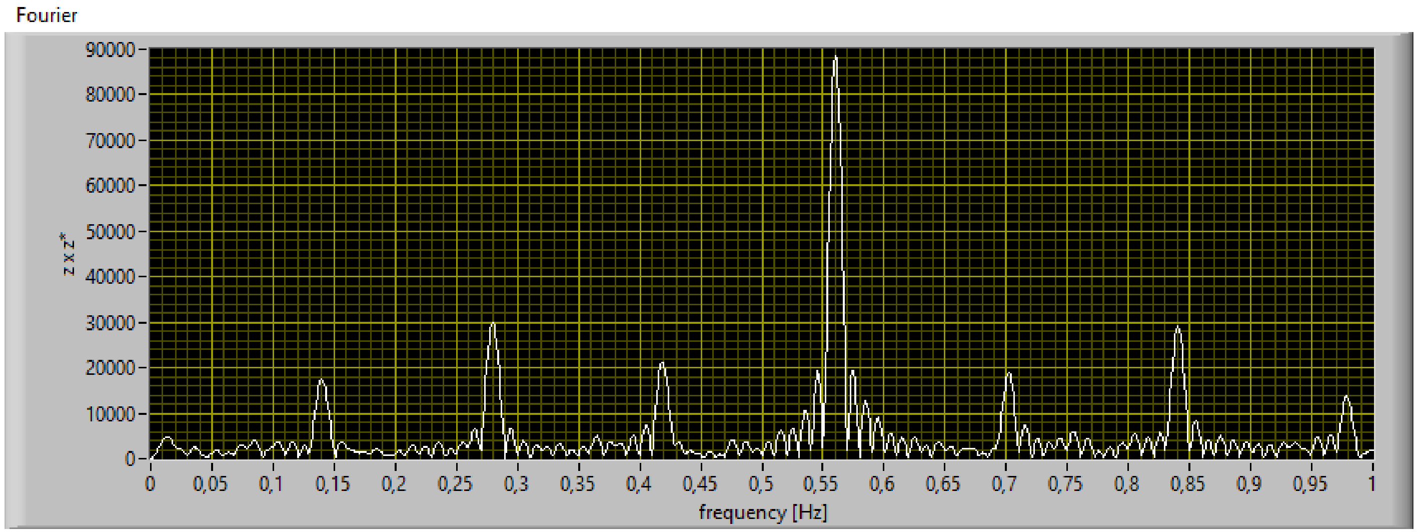
FOURIER ANALYSIS

- Fourier analysis: time domain -> frequency domain

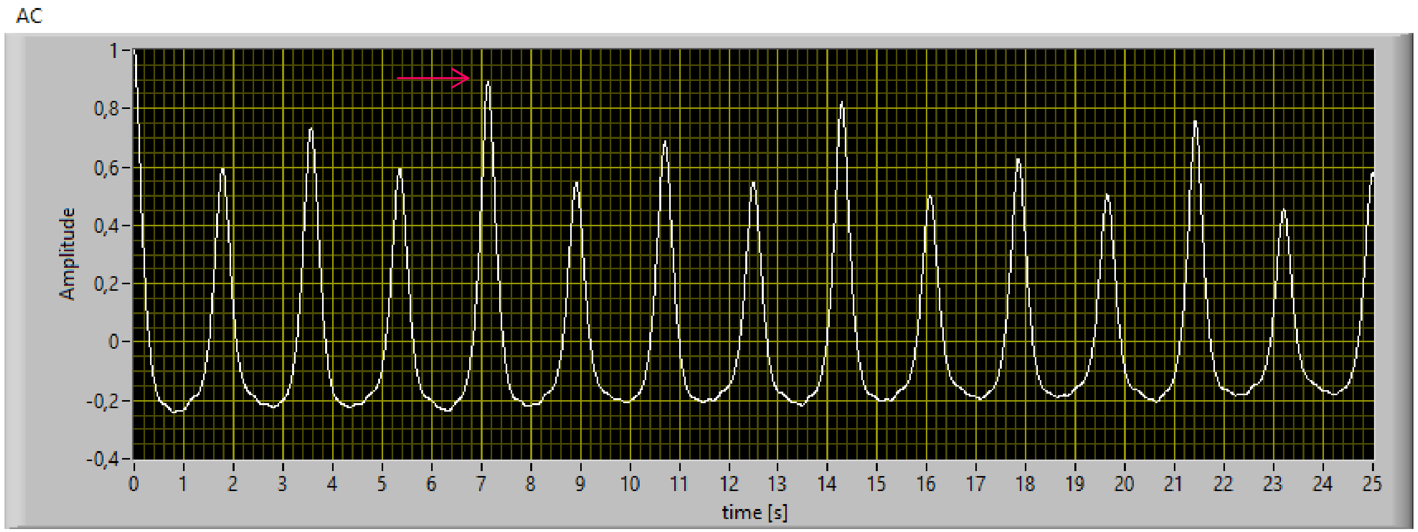
$$\hat{x}(f) = \int_{-\infty}^{\infty} x(t)e^{-i2\pi ft}\,dt \;;\; x(t) = \int_{-\infty}^{\infty} \hat{x}(f)e^{i2\pi ft}\,df$$

- Suggests f = 0.56 Hz, T_{FFT} = 1.79 s



AUTOCORRELATION

- Autocorrelation: correlation of function with itself at earlier time
- $x \star x(\tau) = \int_{-\infty}^{\infty} x^*(t) x(t+\tau)\, dt = x^*(-\tau) * x(\tau)$
- Alternative: via inverse Fourier of $|(\hat{x}(f))|^2$
- Maximum: $T_{AC} = 7.14\, s = 4\, T_{FFT}$ … fundamental frequency
- Potential ambiguities if amplitude of satellite surfaces similar



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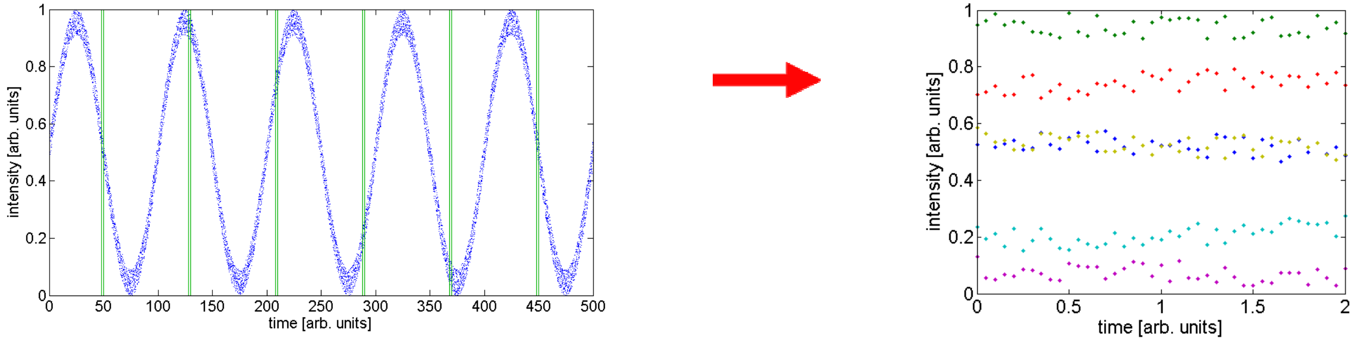
PHASE DISPERSION MINIMIZATION[2]

- *Signal:* $y_i = f(t_i)$
- *Define test period* T_{test}
- *Calculate phases of epoch times related to test period*
- $phase = \frac{t_i}{T_{test}} - \left\lfloor \frac{t_i}{T_{test}} \right\rfloor$
- $\lfloor \rfloor$ *… round to nearest integer toward negative ∞*
- *Separate measurements into bins with similar phase*
- *Calculate variance of* y_i *values of each bin*
- *Calculate mean of variances*
- *Find test period T -> mean of variances minimized*

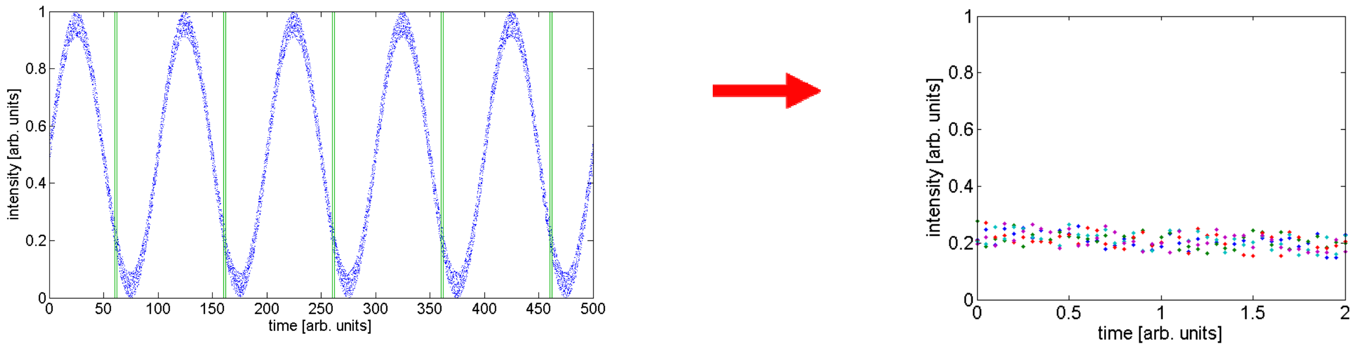
[2] Schwarzenberg-Czerny, A. (1997). The Correct Probability Distribution for the Phase Dispersion Minimization Periodogram. *Astrophysical Journal*, *489*, 941. http://doi.org/10.1086/304832

PHASE DISPERSION MINIMIZATION EXAMPLE

- Expample: 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)

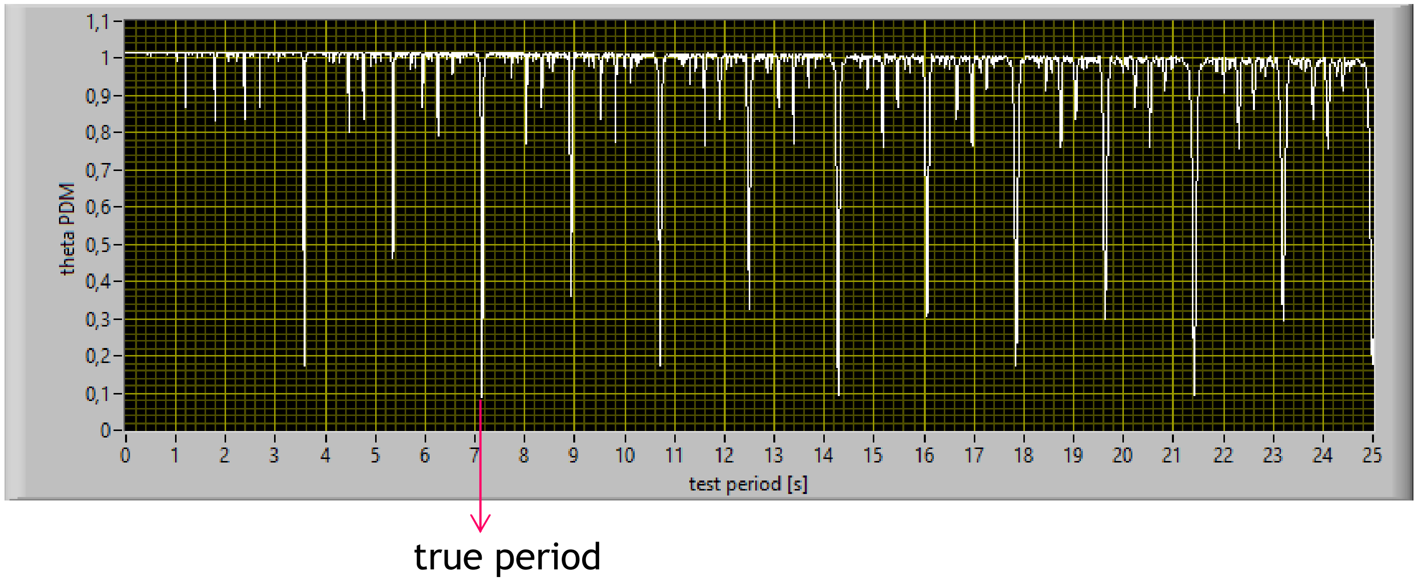


- Correct test period T_{PDM} = 100 s (small variance)

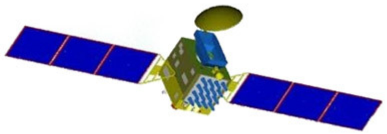


PHASE DISPERSION MINIMIZATION COMPASS G2

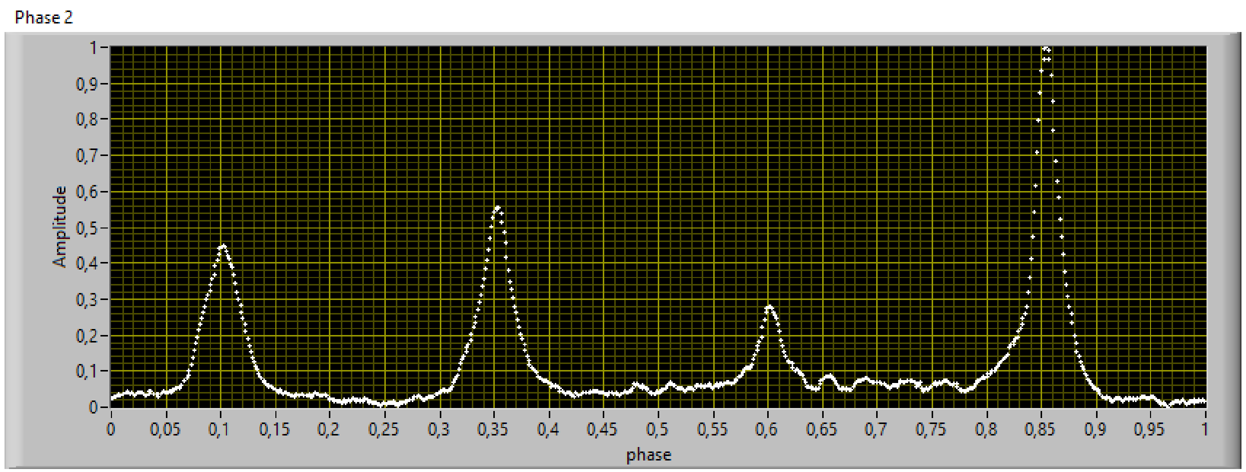
- Compass G2, NORAD ID: 34779, perigee: 35397 km
- y-axis: theta ... mean bin variance, normalized to [0,1]
- Minimum at $T_{PDM} = 7.14\,s = T_{AC}$
- Similar values at integer multiples of T_{PDM}
- Ambiguities if light curve changes rapidly



COMPASS G2 – LIGHT CURVE



- Compass G2, NORAD ID: 34779, perigee: 35397 km
- Spin period: T_{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…



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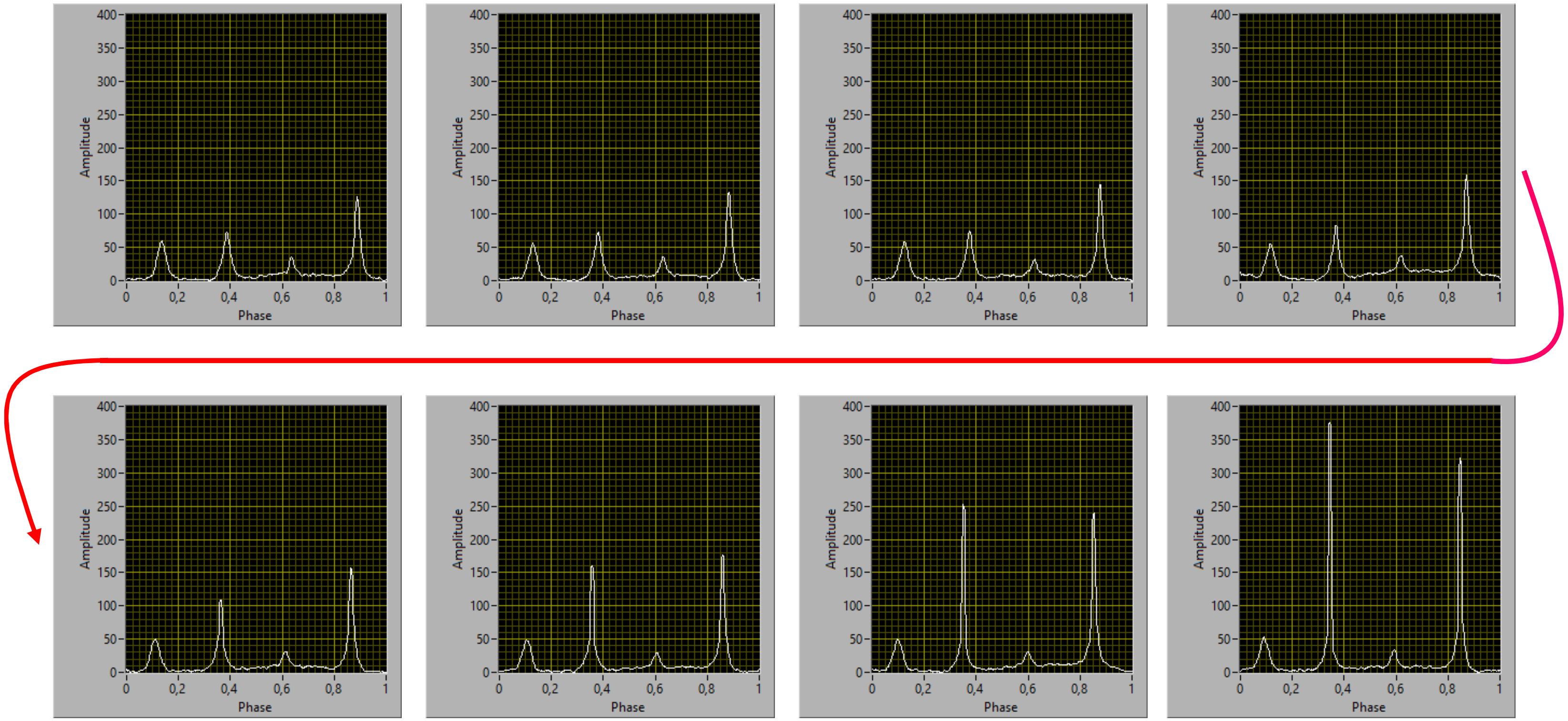
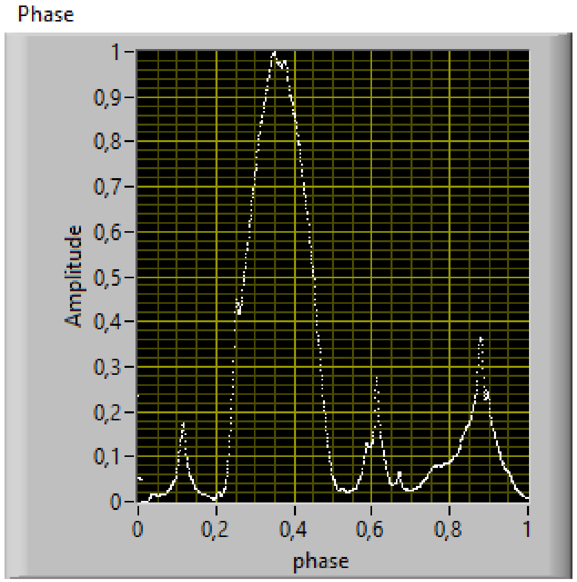
COMPASS G2 – LC SEQUENCE 2015/157

- 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



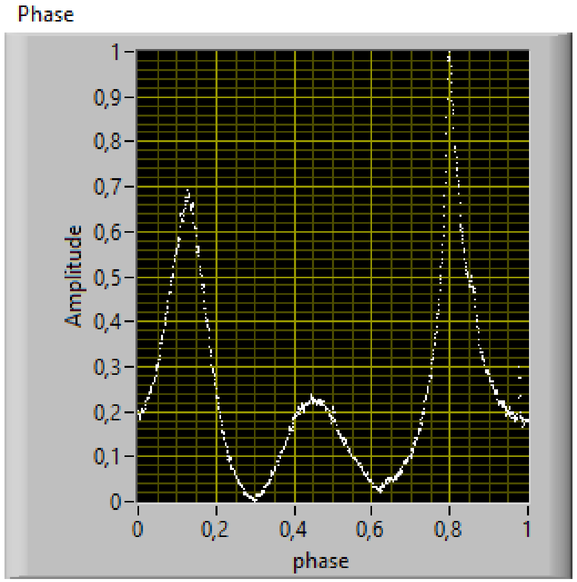
LIGHT CURVES – TOPEX, SL-6 R/B(2)

- 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)



TOPEX (2015/158)

T = 11.35 s

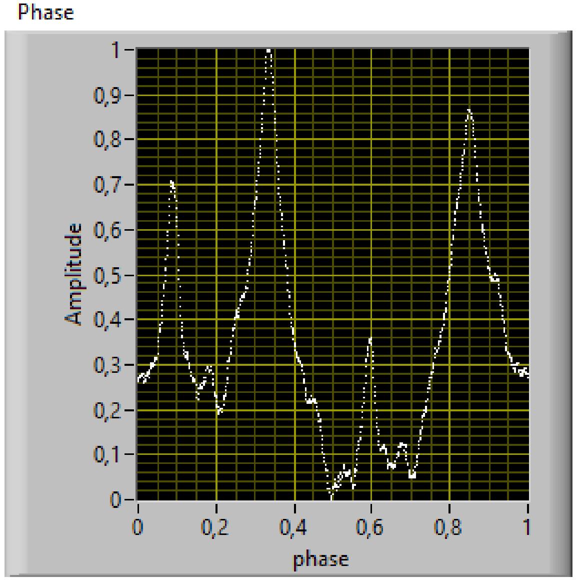


SL-6 RB2 (2015/220)

T = 36.19 s

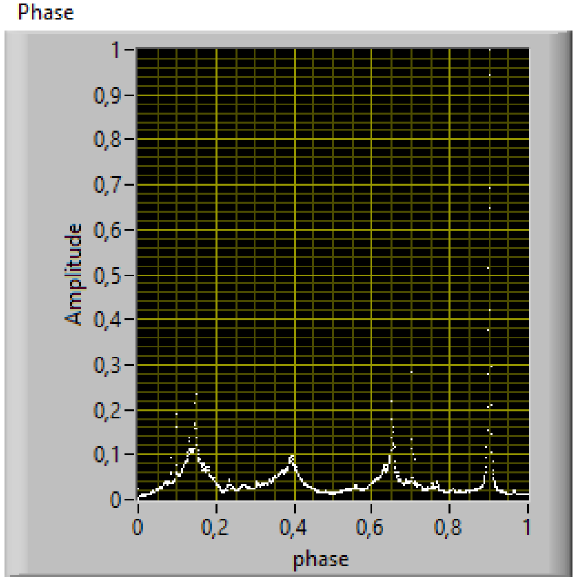
LIGHT CURVES - GLONASS 044, ENVISAT

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



GLONASS 044 (2015/179)

T = 38.96 s

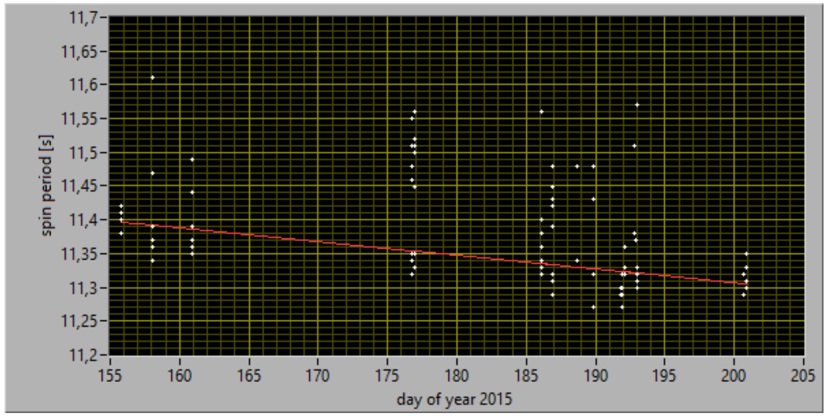


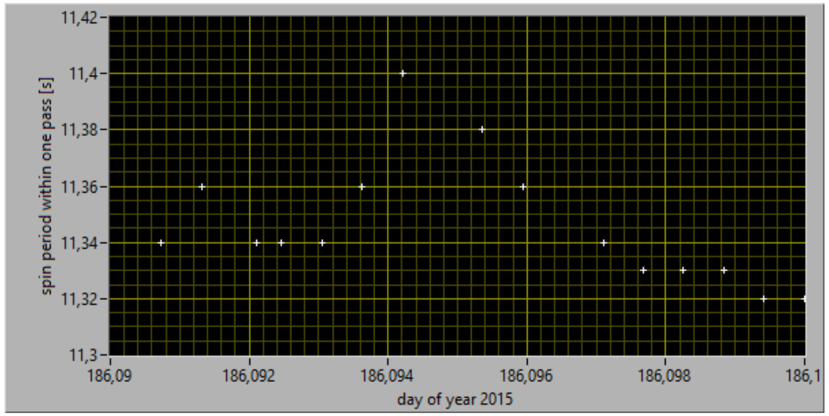
ENVISAT (2015/202)

T = 171.77 s

STATISTICS TOPEX

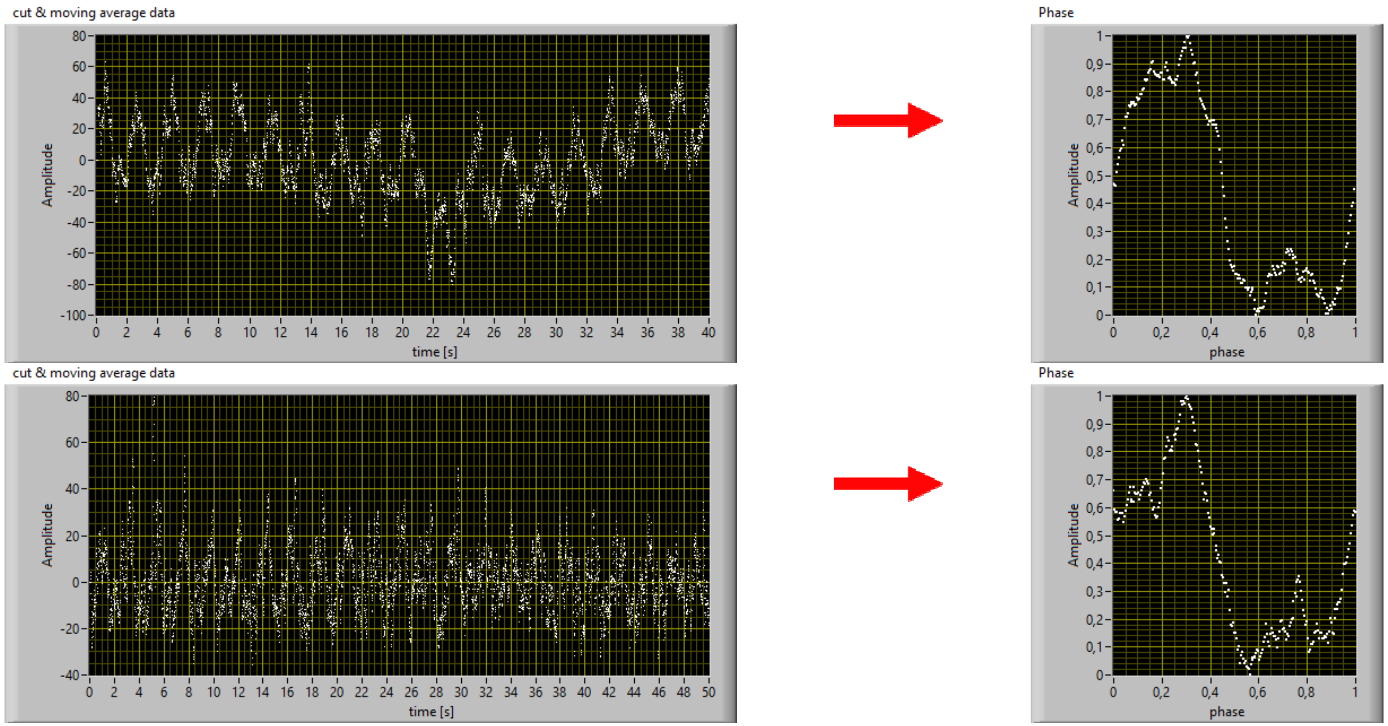
- 115 spin periods from 16 passes, Δt = 50 s
- **Left plot:** spin period vs. day of year 2015
- Spin period decrease ~0.7 s / year
- **Right plot:** spin period for one pass
- Change of spin period due to **apparent spin**





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_{spin} = 2.2 s, reduced from T = 5.6 s due to collision



LIGHT CURVES vs. LASER DATA

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

POSSIBILITIES AND OUTLOOK

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 !

ADDITION

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

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