GRAZ KHZ SLR SYSTEM: DESIGN, EXPERIENCES AND RESULTS

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Abstract

Within the last years, we have prepared our Graz SLR system for kHz operation; since October 2003, this 2 kHz SLR system is operational.

Our previous 10 Hz laser (35 mJ @ 532 nm, 35 ps pulse width) has been replaced by a 2 kHz, DPSS Nd:Van laser system, using a SESAM seed laser with a Regenerative amplifier and a post amplifier; this laser delivers 400 µJ @ 532 nm per shot, with a pulse width of 10 ps FWHM; due to the low energy per shot, we receive mainly single photons from higher orbiting satellites, like LAGEOS or higher; from Low Earth Orbiters (LEOs) we still get multi – photon returns, resulting in close to 100% return rates.

As single photon detector we use a standard C-SPAD (Single Photon Avalanche Diode, Peltier cooled) with Time Walk Compensation; the Range Gate Generator with 500 ps resolution was implemented with an FPGA chip in Graz. Time of flight is measured with our Graz E.T. (based on Dassault Event Timer modules) with 1.2 ps resolution; the system is capable of handling up to 500 shots in flight simultaneously.

The system single shot RMS now is 2.5 mm for satellites with low signature; due to high data density of Normal Points – up to 100.000 returns per NP – this system offers in principal accuracies far below the 1 mm level.

Due to the high data density and the high single shot accuracy, the Graz kHz SLR system now can detect single retro-reflector tracks from many satellites; this allows to select only echoes from the nearest retro-reflectors, resulting in a much better defined mean point of reflection, improving again the accuracy. In addition, it is also possible to derive the rotation of passive sphere satellites.

The Laser

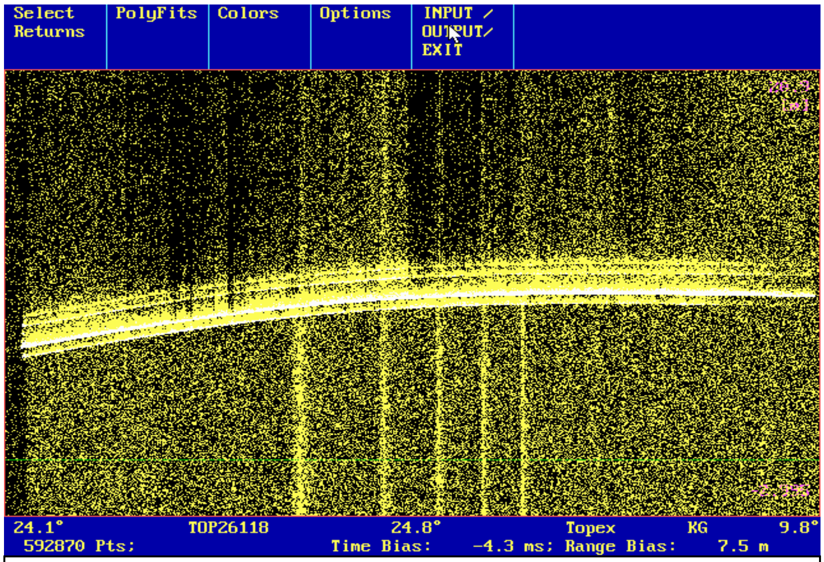
The laser starts with a SESAM oscillator (**SE**miconductor **S**aturable **A**bsorber **M**irror), which is very stable, more or less maintenance free, and produces short pulses with excellent stability. This is followed by a Regenerative Amplifier, which is controlled by an external Pockels Cell to switch in/out the pulses; the amplified pulse is fed into a post amplifier, followed by an Second Harmonic Crystal to convert > 50% of the IR energy into green (532 nm). This last amplifier is pumped by pulsed diodes (with about 90 A in 60 µs), while the first two modules are pumped with CW diodes. The pump diode modules are user replaceable, without having to realign the system; lifetime of the pump diodes is specified with > 5000 h; by minimizing the current, and by fully automatic software control (e.g. automatic switching off at longer periods of inactivity) we expect about 3 years of operation before exchanging the pump diodes.

The Range Gate Generator

The C-SPAD has to be gated about 65 ns before expected arrival of the return photon(s); on detection of a start pulse, the epoch time of this start pulse is determined, the epoch of the expected return photon calculated and stored in the Range Gate Generator (RGG). Because in our 2 kHz system up to 300 pulses are travelling at the same time to or from a satellite, the RGG uses FIFO registers to store and handle the individual gate epochs. The next expected RG epoch is compared to an actual time scale; if this time arrives, the RGG issues the Range Gate pulse.

This system is implemented within an FPGA (Field Programmable Gate Array) device, but would achieve only resolutions of 100 ns (10 MHz); to improve the resolution, a programmable, analogue delay generator covers an additional resolution of 0 – 100 ns, thus increasing the resolution to < 0.5 ns.

Receive – Transmit Pulse Overlaps



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24.1°          TOP26118          24.8°          Topex     KG     9.8°
 592870 Pts;              Time Bias:    -4.3 ms; Range Bias:    7.5 m
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Fig. 1: Receive-Transmit Pulse Overlaps can increase the noise

When ranging with kHz to satellites, there are repeatedly periods of overlaps between returning photons, and just fired laser shots; the backscatter of these shots – from the first few km travelling through the troposphere – would cause significant noise on the single-photon-diode, reducing the detection probability for the return photon.

To avoid these situations completely, we use the same RGG FPGA chip to produce all laser firing and laser control commands; if return photons are expected within 30 µs after laser firings, an extra delay of 50 µs is inserted before the following laser shot; because all necessary information – next expected Range Gates, AND time of next fire pulse – are already known within the FPGA chip, this processes can run fully automatically within the FPGA hardware, and without any further intervention from the control PC.

In Fig. 1 – an early test pass of TOPEX/POSEIDON satellite – this overlap avoiding feature has been switched OFF intentionally during the central part of the pass, but was switched ON during the first and during the last part, resulting in clearly visible, short periods with increasing noise points due to backscatter during the overlaps.

The Software

The Real-Time Control of the SLR Station Graz is based on a 2.4 GHz PC, with 3 ISA Slots (96 Bit DIO, a Universal IO-Card, and a IEEE-488 Card); to get maximum speed and deterministic real-time response, the PC is running on MS-DOS; all RT programs are written in Fortran. The ranging programs are designed to allow untrained observers to range successfully to satellites after a minimum training period of a few hours only; many automatic routines make even relatively tricky things – like daylight ranging with weak laser pulses and Single Photon Detection as close as 15° to the bright sun – even with only minimum experience simple and straightforward.

The software tries to identify possible returns within the 2 kHz stream of pulses; these identification routines have to be fast, and should deliver stable and informative results. The identification is based on a very simple scheme: For each detected stop event, we calculate the residual (observed minus calculated range), and compare it with the last 1000 residuals; if some minimum number of residuals (e.g. 3) are within a certain band (e.g. 100 ps), the new residual is flagged as "identified", plotted on the screen, and stored on disk. This minimum number can be set by observers to adjust sensitivity versus amount of false alarms; the acceptance band width is adjusted by other routines automatically, according to satellite, range gate width and other parameters. This simple procedure is fast, effective, and gives a very nice user interface for a variety of satellites: Low Earth Orbiters with close to 100% return rate result also in easy interpretable graphics as high orbiting satellites – like GPS -, which can have return rates far below 1%.

Other routines are filling all identified returns into histogram bins; the bin with maximum identified returns is plotted on the screen – another useful and indicative feature for observers – and serves as a guide number for automatic control of range gate width, range gate shift etc.

Thus, most noise points are eliminated, and usually neither displayed nor stored, which not only has advantages for the user interface, but also minimizes storage sizes, amount of data to be handled etc.;

To keep the system at the highest possible accuracy, it is calibrated at least once per hour; during the calibration, the laser pulses are attenuated by de-phasing the pump diodes of the last amplifier (the laser diodes are still pumped with the same pulses to keep the thermal equilibrium, but about 300 µs too late, so that the last amplifier does not contribute anymore); these attenuated pulses are directed into our near calibration target, about 1 m in front of the telescope [4]; in each calibration run, 10000 returns are measured – which takes only about 10 seconds at 2 kHz and 50% return quote – and averaged to give the calibration value plus statistical information (skew, kurtosis, peak minus mean etc.). The main emphasis is on closely watching any changes of the calibration values (usually stable within a few ps), and symmetric distribution of the returns, i.e. peak minus mean should be about ZERO; in 2004, the average was –0.4 ps (Fig. 2).

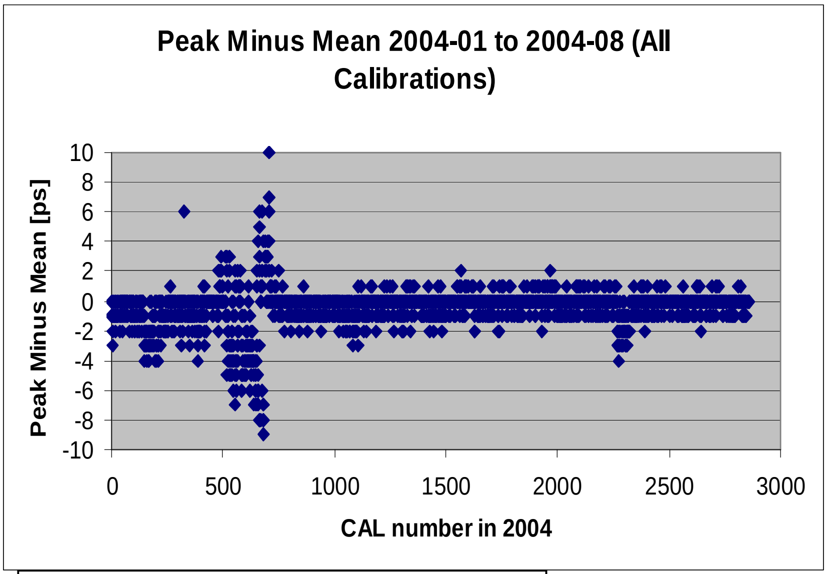


Fig. 2: CAL: Peak Minus Mean; 0.4 ps

Results

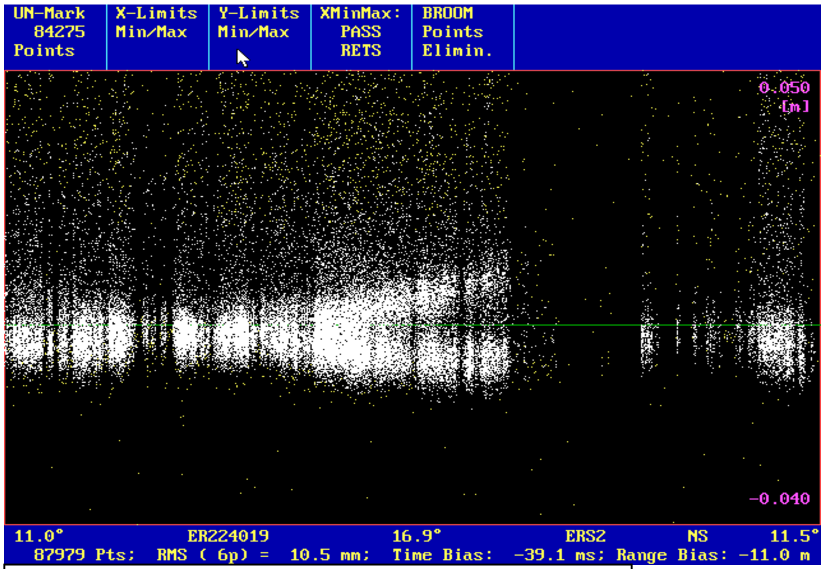
The 2 kHz repetition rate, combined with return quotes not far from 100% for LEO satellites, results in corresponding huge return numbers (Table 1), as compared to conventional SLR stations with 5 or 10 Hz repetition rates; for example, we have measured passes of LAGEOS-1 and AJISAI with more than 1 million returns, and for many LEO satellites with more than half a million returns; when compressing these returns into Normal Points, these NPs contain up to > 100 k points / NP, with corresponding better definition, higher accuracy etc., than the previous NPs of our old 10 Hz system with few 100 points / NP maximum (Table 1).

Table 1: Returns per Pass, Returns per Normal Point

	Old Laser: 35 mJ	**New Laser:400 µJ / Shot**	**New Laser:400 µJ / Shot**
Satellite	Returns per Pass	Returns per Pass	Returns per NP
ENVISAT	5000	Up to 400.000	> 25.000
JASON-1	5000	Up to 530.000	> 20.000
TOPEX	7000	Up to 750.000	> 20.000
AJISAI	8000	> 1.000.000	> 50.000
LAGEOS	14000	> 1.000.000	> 100.000
GPS 35/36	300	≈ 10.000 / hour	> 5.000

Detecting Single Retro Tracks

The huge amount of data, much more stable NPs etc. are not the only results; in addition, it turned out that we are now able to identify the single retro-reflectors of most satellites within the data stream; typical ERS-2 examples of a very low elevation pass (max. elevation



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11.0°          ER224019          16.9°          ERS2        NS       11.5°
  87979 Pts:  RMS ( 6p) =  10.5 mm:  Time Bias:  -39.1 ms: Range Bias: -11.0 m
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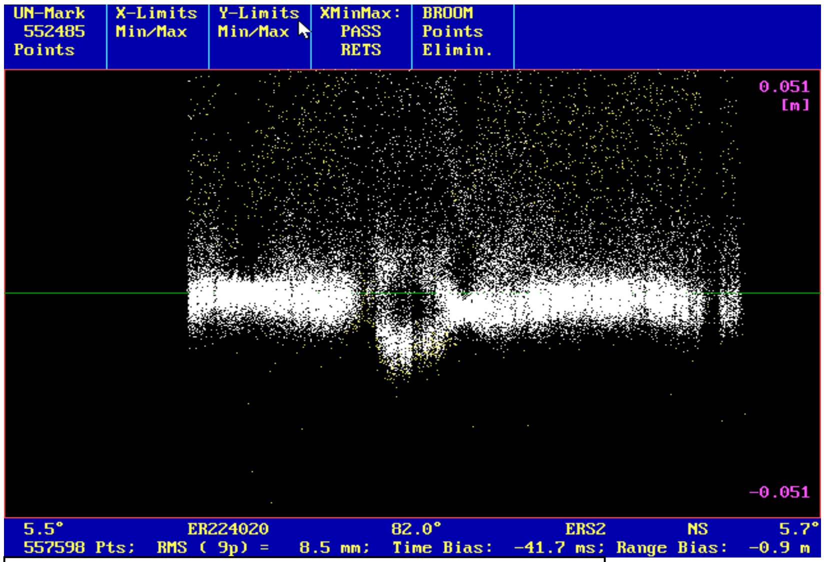
Fig. 3: ERS-2, Elevation 17°: 2nd Retro



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  5.5°          ER224020          82.0°         ERS2        NS       5.7°
557598 Pts;  RMS ( 9p) =   8.5 mm;  Time Bias:  -41.7 ms; Range Bias:  -0.9 m
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Fig. 4: ERS-2, Elevation 82°: 2nd Retro

<17°, Fig 3) and a very high elevation pass (max. elevation 82°, Fig. 4) are given below; the low elevation pass shows a clear track of a second retro-reflector, as it deviates around Closest Approach; both tracks than disappear due to clouds; the high elevation pass shows that around maximum elevation also a second retro-reflector is involved; while these effects are now clearly visible with a kHz system with up to 500.000 returns per pass, they have not been seen in any of the 10 Hz systems (although the effect is there also !)

In general, all stabilized satellites (mostly earth observation satellites) and those satellites which already stopped their original rotation (e.g. LAGEOS-1) allow in many passes identification of different retro-reflectors (or retro-reflector panels, as in case of the various GLONASS satellites); the exceptions are CHAMP and LaretC satellites, for Champ, theoretically such multi-tracks could be visible at elevations above 70°, but these passes are very rare (due to the low altitude of Champ) and difficult to track continuously due to the necessary high telescope azimuth speed.

References:

1. Kirchner, G., Koidl, F., *Graz Event Timing System: E.T.*, Proceedings of 12th Int. Workshop on Laser Ranging, Matera, 11/2000; http://geodaf.mt.asi.it/html/news/iwlr/index.htm

2. Kirchner, G., Koidl, F., *Short Distance Calibration;* Proceedings of 10th Int. Workshop on SLR Instrumentation, Shanghai 11/1996:, pp 431 - 435