

The New 100-Hz Laser System in Zimmerwald: Concept, Installation, and First Experiences

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Abstract

In spring 2008 we replaced the Titanium-Sapphire laser by a new 100 Hz Nd:YAG system. One of the requirements for the new laser was a high flexibility in the actual firing rate and epochs to allow for synchronous operation in one-way laser ranging experiments. Firing order and range gate generation are controlled by a Graz-provided PC card with field-programmable gate array. The protection of the receiver from backscatter through our monostatic telescope was realized with a synchronized rotating shutter. First experiences show a very stable operation of the laser without any re-adjustment needs for many months, a much better efficiency regarding return rates to high satellites, and a single shot rms to well-defined targets of about 5 mm in single-photon mode.

Introduction

From 1996 till 1997 the Satellite Laser Ranging facility at the Zimmerwald Observatory was completely renovated: The 50-cm bistatic telescope was replaced by a 1-meter monostatic dual-purpose (SLR and astrometry) telescope and a new two-color Titanium-Sapphire laser was installed. The following years proved the new system to be very productive and efficient. Supported by an increased automation of the system Zimmerwald gradually moved to the top group of SLR stations with respect to the collected data volume. One of the major reasons to go for a dual-color system was the expectation to use the observations in the two wavelengths (423 nm and 846 nm) for the more precise determination of the atmospheric refraction correction (tropospheric delay). However, it turned out that small system-dependent systematic errors (or rather their differences between the two colors) were too large to allow the direct determination of the tropospheric delay with the necessary precision. Nevertheless the second color (infrared) helped to detect and to identify the order of magnitude of such remaining systematic errors and it extended the operation capabilities of SLR e.g., with respect to unfavorable atmospheric conditions because of the better transparency for infrared light.

After ten years of operation the laser system became more and more difficult and expensive to maintain, fatal failures were to be expected. Thanks to the combined support of different institutions (University of Bern, Federal Office of Topography, Swiss National Science Foundation) we could evaluate, order, and finally install a new laser system, ready for operation in April 2008.

Evaluation of the New Laser System

The major requirements for the new system were

- minimum intervention by our staff (e.g., no daily realignments etc)
- fully automatic and remotely controllable
- continuous, uninterrupted operation for weeks in a row
- high single-shot precision (few millimeters)

- suited to support future transponder missions, if possible
- ready for two-color ranging
- about 1 Watt average output power per color

Reliable operation and minimum intervention asked for a solid state diode-pumped laser of a rather high repetition rate, i.e. between about 100 Hz and a few kHz, which seems to be the range within which diode-pumped lasers may deliver the requested average power at the requested pulse length.

The single-shot precision under single-photon conditions mainly depends on the precision of the time of flight measurement (counter, event timer) and the pulse length of the laser pulses. We opted for a pulse length of about 40 ps FWHM, equivalent to a RMS of about 2.5 mm in range.

Future transponder missions will most certainly be designed around the second harmonic of the wavelength of the Neodymium:YAG lasers, i.e. 532 nm. Titanium:Sapphire lasers will therefore not be suited.

Routine two-color ranging however is currently only feasible with Titanium-Sapphire lasers in the two wavelengths 423 nm and 846 nm, where suitable detectors are available. We are not aware of detectors for the primary wavelength of Nd:YAG (1064 nm) that fulfill the requirements for high-precision SLR at this date.

One Watt average output power corresponds to 500 μ J @ 2 kHz or 10 mJ @ 100 Hz.. The Graz two-Kilohertz-system outputs about 400 μ J with a pulse length of < 10 ps.

Before we issued a call for participation we already decided upon the wavelengths: Regarding the rather moderate advantages of a two-color system (experience we had with our own system) and the possible impact of the use of transponders on lunar and interplanetary missions we limited our evaluation to a system capable of generating a wavelength of 532 nm.

As the 1-m ZIMLAT telescope used for both SLR and astrometric observations is monostatic w/r to SLR (identical transmit and receive paths between the transmit/receive switch situated in the basement of the telescope dome and the telescope primary mirror) we have to protect the detectors from the backscatter of the transmit beam by a fast enough electro-optical or mechanical shutter or a polarization-based optical device. Low-loss electro-optical shutters seem difficult to obtain, polarization-based devices need enough space on the optical table and mechanical shutters at one or two kilohertz with the necessary duty factor (<1/10, i.e. < 1 part closed, 10 parts open) might be impossible to build. Our call for tender (issued December 2006) specified either 100 Hz or 1-2 kHz but stated that we would select among 100-Hz bids only, if present.

Finally we selected a 100 Hz Nd:YAG system offered by Thales Laser , France.

The New Laser System

The new Thales System was installed in March/April 2008. Together with a fatal failure of the old system end of January 2008 we suffered from interruption of SLR operation of about three months.

Table 1. Major characteristics

Manufacturer	Thales Laser, France
Technology	Diode pumped solid state Nd:YAG laser
Pulse generation	SESAM technology oscillator (SEmiconductor Saturable Absorber Mirror)
Wavelengths	1064 + 532 nm
Pulse rate	90-110 Hz, adjustable with external trigger Additional decimation with pockels cell
Configuration	Oscillator (TimeBandwidth), regenerative amplifier, doublepass amplifier
Pulse energy	21 mJ @ 1064 nm before doubling 9 mJ @ 532 nm
Pulse width	58 ps (FWHM)
Pulse contrast	< 1/200
Beam diameter	8 mm
Stability of energy	< 1%
Pointing stability	< 5 arc sec

Two specifications could not be met:

1. The pulse width had to be increased to nearly 60 ps because of non-linearity problems in the amplifier
2. Originally we intended to have the possibility to use the remaining infrared after the second harmonic generation (about 50 % of the original beam) for two-color ranging, provided a suitable detector were available. However, the beam quality of the infrared component of the beam after the SHG was insufficient. It was decided to modify the setup in order to bypass the SHG with a selectable fraction of the infrared in case of two-color or infrared-only operation.

Figure 1 shows the major components and the paths of the beams before, after and around the second harmonic generator.

The pump diodes can be triggered with a variable rate between approximately 9 and 11 ms in steps of 10 microseconds, the variability of which is limited by thermal stability conditions. By means of the pockels cell selecting the pulses to be attenuated the actual firing rate can be decimated by any additional integer factor⁵.

All major laser commands (e.g., power on, status request, power off) can be issued over a TCP/IP connection between the station computer and the manufacturer-provided laser control

⁵ For the upcoming LRO one-way ranging experiment the laser will be fired at approximately 14 Hertz, i.e. with a basic pump rate of 10.200 ms \approx 98 Hertz and a decimation factor of 7.

PC. This LabView–based control program also allows interactive manual control of all laser parameters.

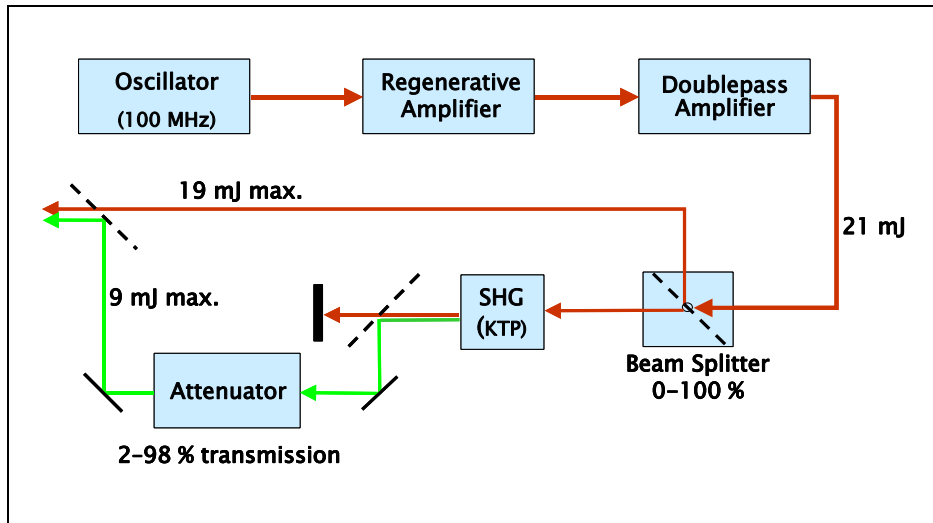


Figure 1. Laser Main Components

Laser trigger signals for pump diodes and enabling/disabling signals for the pockels cell as well as the signals for range gate generation and rotating shutter control (see below) are generated by the FPGA card prepared and programmed by the Technical University of Graz.

Other Components

Transmit/receive switch

Originally we used a perforated mirror as transmit/receive switch: The laser transmit beam entered the Coudé path through an eccentric hole of a coated glass plate. The received pulse, filling the full aperture (with the exception of the center part shadowed by the secondary mirror of the telescope) was reflected by the front face of the 45-degree mirror into the receiving path.

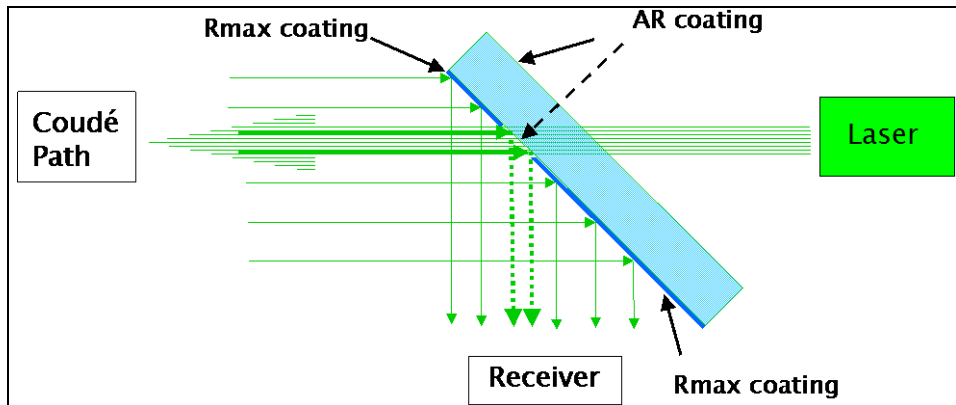


Figure 2. Transmit/receive switch

The hole in the mirror had two distinct disadvantages: It was rather difficult to manufacture and it did not reflect the received beam from a calibration corner cube outside of the dome.

We found a manufacturer that agreed to specially coat the glass plate with

- an anti-reflective coating on the back side (towards the laser)
- a reflective coating on the front face with the exception of the portion where the transmit beam passes the glass plate
- an anti-reflective coating on the front face where the transmit beam passes the glass plate. This portion is also used to separate a small percentage of the received calibration pulse into the receiving path.

Rotating shutter

The rotating shutter has to protect the receiver from the backscatter of the transmitted laser beam during satellite ranging. It opens the receiving path for the time of reception only. The duration of the opening has to include the uncertainty of the opening and closing instants, but it should be short enough to allow the processing of return pulses as close to start pulses as possible.

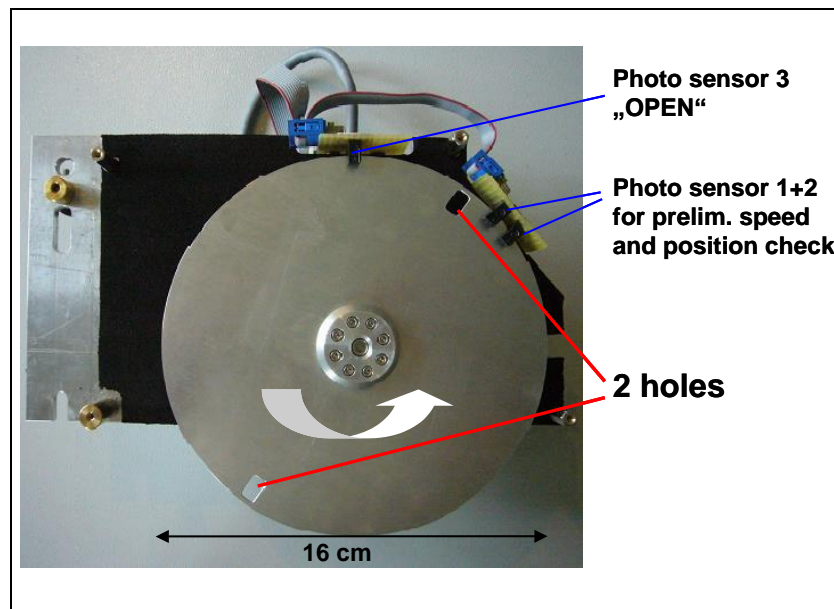


Figure 3. Rotating Shutter

The shutter is realized by a thin aluminum disk with two diametrically opposed holes of 6 mm diameter each at a radius of 70 mm. It is driven by a DC servo motor with integrated controller operated in stepper mode at a frequency of approximately 50 Hz (=3000 rpm), precisely synchronized with the actual firing rate of the laser (see above). The shutter is placed very close to an intermediate focus of the received beam used for the limitation of the field of view with a pin hole.

The shutter is open during about 300 μ s with an uncertainty w/r to the expected time of reception of ± 50 μ s. Frequency and phase are controlled and commanded by a PC via the FPGA card mentioned above.

A hardware-implemented safety monitor assures that the shutter is not unintentionally open at firing time: It checks speed and position two milliseconds before firing time and blocks the laser if a conflict between transmit and receive pulse is to be expected by disabling the Regen pockels cell of the laser and closing a fast mechanical safety shutter within the Regen.

FPGA PC Card

The PC card containing a field-programmable gate array (FPGA) was built and programmed by F. Koidl of the TU Graz.

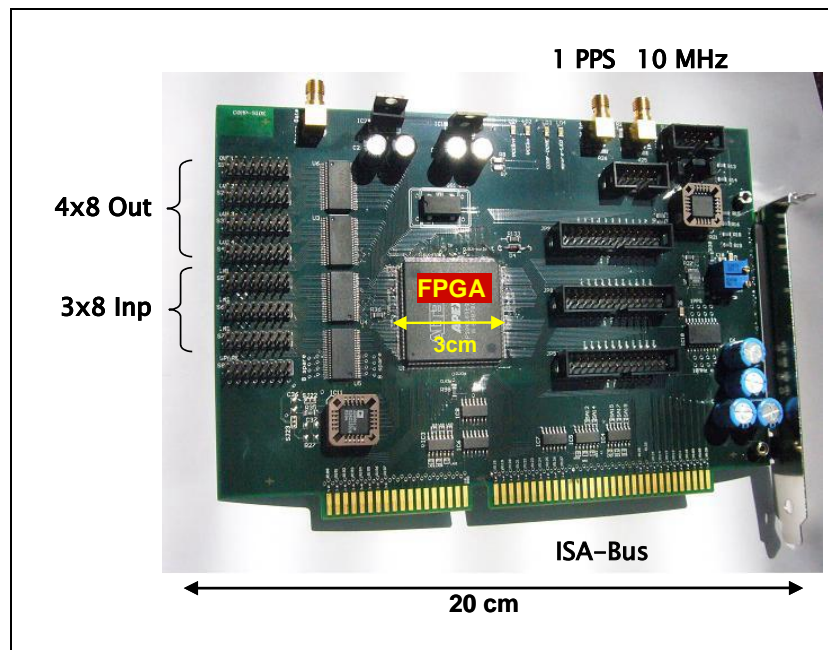


Figure 4. FPGA Card

Its main functions are

- the generation of
 - pulses to control the Laser firing rate (periods of 9 to 11 ms at a resolution: 10 μ s)
 - pulses for the range gate (epoch and duration (resolution: 5 ns)
 - frequency for the rotating shutter control
 - Laser firing pre-pulses (rotating shutter safety monitoring)
- the measurement of
 - the current epoch (resolution: 1 μ s)
 - the epoch of the shutter's open position (resolution: 1 μ s)
- to make available
 - control register to enable Laser pump diodes, the Pockels cell, safety shutter etc
 - several auxiliary I/O channels

It is mounted in the dual-boot (DOS and Windows XP) PC used for control and data collection. The actual control program is written in MS-Fortran, communication with the FPGA is performed through registers on the I/O page of the DOS system.

Overlap Avoidance

Conflicts between transmit and receive pulses have to be avoided to protect the receiver from the backscatter. This can be achieved by

1. cutting all conflict zones from the satellite passes (losing about 5 percent of the pass duration in our configuration)
2. adjusting the firing epochs several times by inserting short delays during the conflict zone (Graz solution)
3. changing the firing rate once to “jump” over a conflict zone. During a short time (approximately the current flight time) after the change laser firing has to be stopped.

We selected option 3 with the possibility to switch to the simplest option one, if desired.

First Experiences

Laser Stability

Only one slight re-adjustment of the regenerative amplifier was necessary after five months of operation.

Ranging to a well-defined target

Ranging to Champ, Grace A/B, Envisat and similar satellites with well-defined corner cube signal structures show a single-shot RMS of 5 to 6 mm.

The system is always tuned to operate in single-photon mode by automatic adjustment of a the return rate to about 5 to 15 percent by a variable neutral density filter in the receiving path.

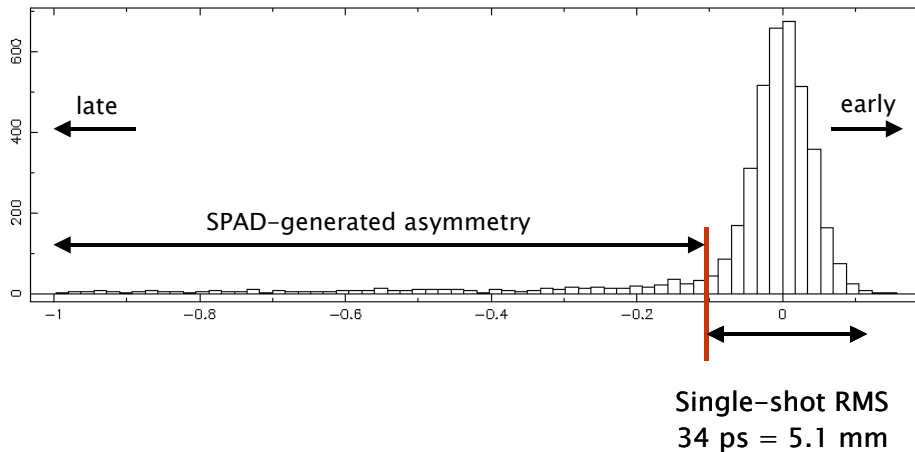


Figure 5: Champ: Distribution of returns

Ranging to Lageos 1 and 2

The target signal structure of the Lageos satellites distorts the observed time of flight distribution and increases the apparent RMS of single-shot observation, as can be seen in Figure 6.

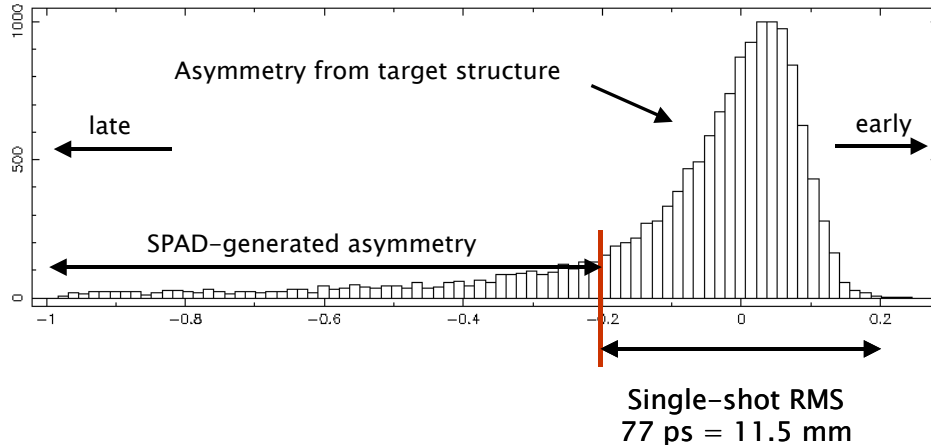


Figure 6. Ranging to Lageos 1 and 2

Performance to GNSS satellites

A sample pass of a Glonass satellite shows up to about 4000 returns per normal point corresponding to a return rate of 13 percent maximum.

Table 2. Normal point statistics of a Glonass pass

Bin Number	Number of Obs per Bin	Residual (ns)	RMS (ns)	Residual (mm)	RMS (mm)
1	575	0.007	0.007	1.0	1.1
2	1348	0.000	0.005	0.0	0.7
3	1320	0.003	0.005	0.5	0.7
4	786	-0.018	0.006	-2.8	0.9
5	1312	-0.001	0.003	-0.2	0.5
6	2434	-0.002	0.002	-0.3	0.4
7	970	-0.003	0.004	-0.5	0.7
8	1918	0.003	0.003	0.5	0.4
9	3884	0.001	0.002	0.2	0.4
10	3577	-0.002	0.002	-0.3	0.4
11	3769	0.002	0.002	0.4	0.3
12	3074	-0.001	0.002	-0.2	0.4
13	2217	0.004	0.003	0.7	0.4
14	3302	0.001	0.002	0.1	0.3
15	2832	-0.002	0.002	-0.4	0.3
16	3040	0.000	0.002	0.0	0.3
17	1703	0.003	0.003	0.4	0.4
18	1589	-0.006	0.003	-0.9	0.4
19	1691	-0.002	0.003	-0.2	0.4
20	3460	0.005	0.002	0.7	0.3
21	2594	-0.009	0.002	-1.3	0.3
22	2699	0.001	0.002	0.1	0.3

Conclusions

The new laser system fulfills nearly all our expectations. We are certain that we will continue to produce as much if not significantly more SLR data of even higher quality as before April 2008.