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SP-DART: Single-Photon Detection, Alignment and Reference Tool

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Abstract. *The Single-Photon Detection, Alignment and Reference Tool is a Mini-SLR-Station, without mount and without receive optics. The system includes an optical laser transmit module and an electronic control unit to handle e.g. laser control, event timer and time synchronization. It can be mounted on telescopes of different SLR stations as a reference tool to evaluate their operational status in terms of return rates. A further application is to verify the detector alignment of host-telescopes for bi- or multi-static space debris ranging.*

Introduction

The SP-DART (Single-Photon Detection, Alignment and Reference Tool) consists of a transmitting module, a control unit with a laptop and a field programmable gate array (FPGA), a Riga Event Timer, a GNSS Time & Frequency receiver and meteorological instruments. The SP-DART thus is a complete, transportable Mini-SLR-System, but without mount and without any receive telescope. The laser transmit module is a low-cost and low-weight (<10kg) device. When mounted on a suitable host tracking & receiving telescope it is able to range to retro-reflector equipped satellites up to cooperative HEO (High Earth Orbit) targets (e.g. GNSS satellites). In this setup it is possible to use the SP-DART as a reference tool to compare the return rates of different stations. A further application is to set up astronomy telescopes as passive SLR receiving stations to build up a network of stations for bi-static / multi-static measurements. Due to the pulse length of about 1ns, the single-shot accuracy is currently limited to 15cm. However, equipping the system with a picosecond laser would allow up-to-date millimeter accuracy.

Materials and methods

The SP-DART transmitting module

The transmit unit contains two low-power pulse lasers, including all transmission optics (Fig. 1) mounted on a small optical bench with low weight (Fig. 2), to be mounted on host telescopes. Any bulky cooling systems, large cable bundles etc. are avoided. The centerpiece of the SP DART transmit unit consists of two lasers, one in the visible spectral range at a wavelength of λ = 532 nm, the other in the near infrared at λ = 1064 nm. They operate with a pulse repetition rate of up to 2 kHz, with pulse energy of up to 30 µJ@532 nm and 68 µJ@1064 nm and output diameters below 1 mm. The pulse width is approximately 1 ns. The transmit unit was designed to operate at both wavelengths simultaneously, without any mechanical switching element, while minimizing the space requirement of the system to keep it transportable. With the optical ray tracing software tool OpticStudio™ the transmitting telescope was simulated, using commercial off-the-shelf (COTS) lenses from Edmund Optics GmbH. The telescope setup consists of the three telescopes with in total 8 lenses:

a) A pre-magnifying vario-telescope for the green laser ($L1_{532}$, $L2_{532}$, $L3_{532}$).
b) A pre-magnifying vario-telescope for the infrared laser ($L1_{1064}$, $L2_{1064}$, $L3_{1064}$).

c) A two-lens telescope expanding the green and infrared beam simultaneously (L4, L5).

The pre-magnifying telescopes increase the diameter of both laser beams to a diameter of approx. 0.5 - 1 cm and also correct chromatic aberration errors resulting from the fixed distance of the main telescope. The main telescope further magnifies the laser beams of both wavelengths by a factor 5 to an output diameter up to 45mm. Due to the three-lens setup it is possible to vary the output diameter by adjusting the distances between the lenses.

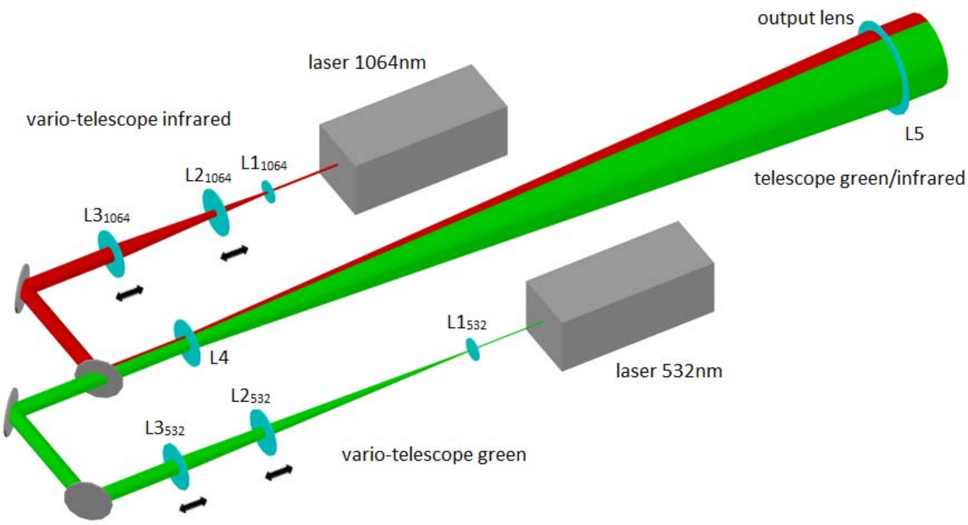

Figure 1. Optical setup of the SP-DART transmit unit. A green and an infrared laser beam are expanded to an output diameter of up to 45mm.

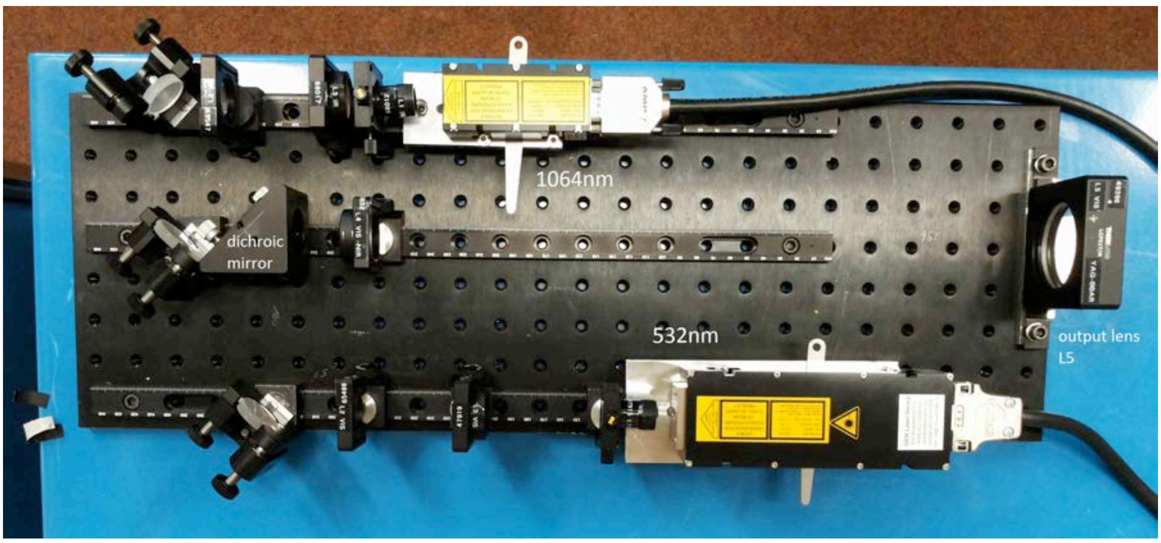

Figure 2. The transmit unit including a green and an infrared laser is mounted on an optical bench which can be set up on different receive telescopes. The direction of the dichroic mirror is rotated by 90° relative to the arrangement in Fig. 1.

The lenses were chosen to minimize optical aberrations. When increasing the output diameter, especially the output lens (L5) gets more and more overfilled. To reduce the spherical aberrations, an achromatic lens was selected. The orientation of the achromatic lens relative to the optical axis is crucial to the performance of the system. The crown glass has to point outwards to successfully reduce optical aberrations.

Our optical ray tracing software is - in its standard version - limited to non-diffractive simulations. To make a prediction about the divergence θ one has to keep in mind that the minimal achievable divergence is limited by the Rayleigh criterion.

$$\theta = 1.22 \frac{\lambda}{D}$$

At a constant wavelength λ the divergence θ is inversely proportional to the diameter D of the output beam. With a system operating at λ = 532 nm and λ = 1064 nm with e.g. an output diameter of 40mm the Rayleigh divergence cannot be lower than θ_{532} = 16 µrad and θ_{1064} = 32 µrad. The simulated divergences yield θ_{532} = 1.7 µrad and θ_{1064} = 2.7 µrad. Hence, for the described simulation setup the simulated divergences are well below the Rayleigh criterion and suggest that the transmission unit is diffraction limited for both wavelengths.

Alignment of the transmit unit to the optical axis of the receive telescope

To simplify the alignment of the transmit unit to the optical axis of the receive telescope, additional optical elements are introduced to the transmit unit. A small retro-reflector in front of the last output lens can be switched in. It will reflect laser light back into the SP-DART transmitter. To avoid excessive backscatter into the laser, a suitable ND-filter will be inserted. The retroreflector can be switched into the laser path only if these ND filters are activated. Optical elements focus the reflected laser light on a CCD. The mount of the tested telescope tracks an arbitrary star and the image of the star is displayed on the CCD as well. By adjusting the deflection mirrors of the transmit unit the image of the star and the reflection of the laser are aligned. This procedure allows to achieve an exact pointing of the SP-DART transmit module parallel to the host optical receiver.

Single-Photon detector Units

For the application of SP-DART in non-SLR telescopes (e.g. astronomy telescopes), suitable single-photon detectors have been designed, built, installed and aligned. Three different options are possible.

The C-SPAD offers a 200 µm chip, is Peltier-cooled to -60°C and has fully time-walk compensated electronics [Kirchner 1996] and offers single shot accuracy of 2-3mm and a resolution down to 0.2mm. The quantum efficiency is larger than 20%. However, the small chip size limits the accepted field of view of the sensor.

With a diameter of 500 µm, the handling of the SAP-500 is significantly relaxed, and offers more flexibility when installed in other telescopes; the quantum efficiency is > 60% [Stipcevic 2010]. The reduced accuracy does not affect its application in a reference unit like SP-DART at all; thus it is the preferred choice here.

The detector chips used for 532 nm are usually based on Silicon. For 1064 nm the quantum efficiency of Silicon-based chips drops to 1% or lower, which is not acceptable. Thus we have to switch to InGaAs type detectors. Due to inherent higher noise in these materials, the maximal available effective diameter presently is 80 µm. The lower size of the sensor decreases the field of view if the same focusing optics is used. Hence a redesign is done, using a lens combination with lower focal length. Simultaneously the spot size was minimized to be significantly below the 80 µm detector size.

SP-DART Control Unit

The control unit is the center of the SP-DART, performing all functions in interaction of a PC-based software plus specialized FPGA-based hardware with external devices, e.g. two lasers, two detectors, event timer, GNSS time & clock reference, meteorological instruments, and so on. The PC-based software provides a GUI and access to above devices via USB, LAN, WLAN or RS232 according to different requirements.

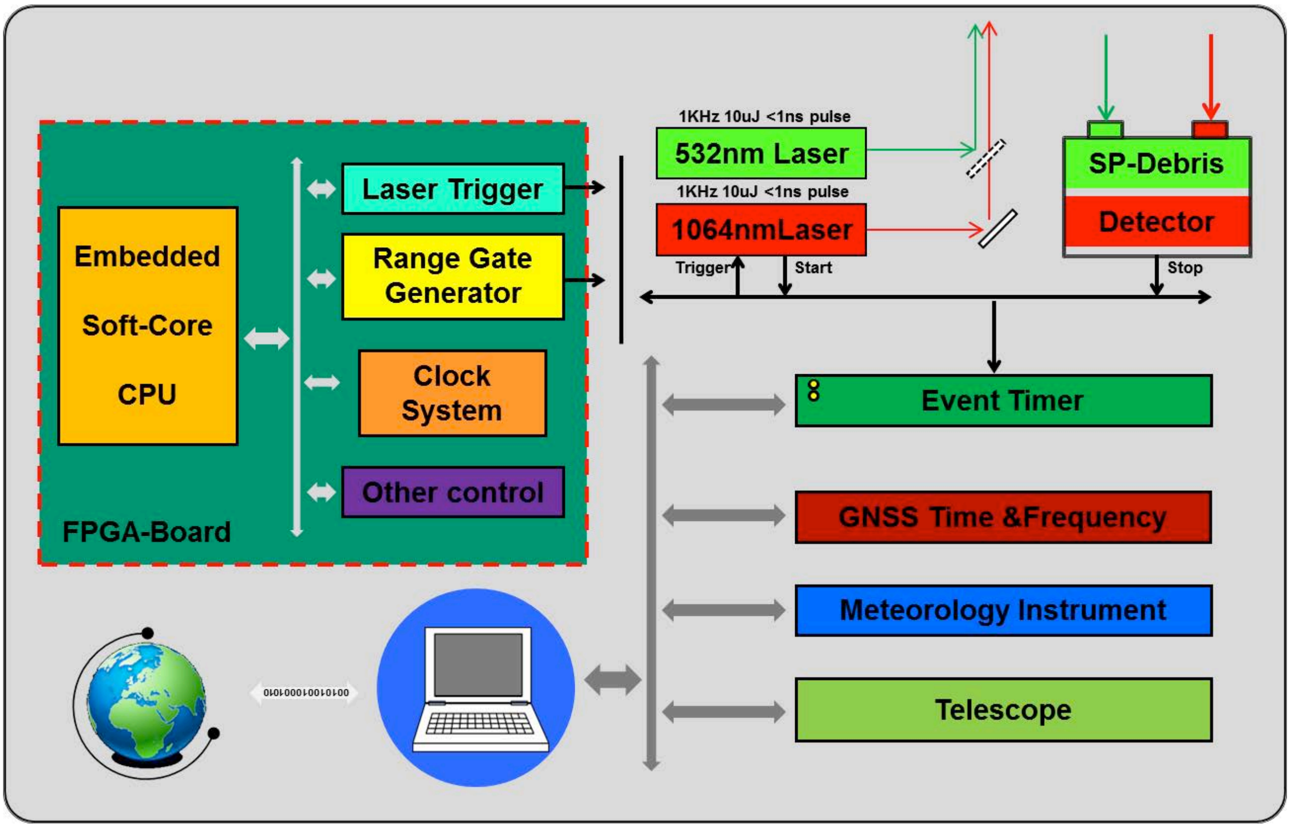

Figure 3. Overview of the setup of the SP-DART control unit operating e.g. the laser, the range gate generator or the event timer.

Design of SP-DART FPGA Board

A COTS board from Terasic Ltd. with Cyclone V FPGA chip has been selected as SP DART FPGA board, to perform tasks like laser trigger, calculating ranges and range gate data, object prediction, command processing etc.

The laser control features three working modes: two individual 532 nm or 1064 nm wavelength modes, and concurrent mode. Two parallel laser triggering circuits are designed to generate trigger pulses in which repetition rate can be adjusted from 1 Hz up to 10 kHz (up to 5 kHz in concurrent mode). For the purpose of bi-static laser ranging, the triggering pulses can be synchronized to 1 pps UTC, with an optional offset of up to ±0.5 s. At kHz repetition rate, there are always several pulses in flight simultaneously. If a return is expected at the same time when a new laser pulse is transmitted, the atmospheric backscatter of the transmitted pulse significantly reduces the chance to detect a single photon returning from the target. To avoid such overlaps, a circuit has been designed within the FPGA to shift the laser firing accordingly. This shift value can be disabled, or set from 20 µs to 80 µs.

To establish the range gate, an event timer with 2 ns resolution is designed in FPGA to record laser start epochs. According to the prediction of object and start epochs, the soft-core CPU Nios II will calculate the time-of-flight of that pulse, and store its estimated return epoch into a first in - first out buffer (FIFO). The 47 bits real time comparator checks the UTC time and the first value of the FIFO continuously. On coincidence, a range gate pulse will be issued.

A new version of Event Timer (ET) A033-ET with USB2.0 interface – instead of the previous LPT port – is used. This ET offers two inputs to measure events on these inputs alternately with 50 ns dead time. The result of every single measurement (epoch time-tag) is represented in digital form with 1 ps resolution (least significant bit). Time-tags appear at the timer's output in the order of events measured. Each time-tag is marked to indicate the input of the measured event.

The transmit module has been mounted on the Graz SLR receive telescope, and the whole SP-DART system, including the tiny µJ-lasers, has been tested to various satellites, including several GNSS targets. The return rates for these HEO satellites were between 1.5% and 3%, depending on elevation, weather conditions etc.

Results and discussion

Setup at Wettzell Geodetic Observatory

Between Sep 28th and Oct 1st, 2015, a first out-lab SP-DART test was carried out at Wettzell laser ranging observatory (WLRS, ILRS Code 8834) in Germany. Most parts of WLRS are at the most optimized status for laser ranging, so the goal is to test and demonstrate mainly the portability and ranging capabilities of SP-DART. All optical and mechanical components of SP-DART transmit unit are mounted on a 60 cm x 25 cm standard optical breadboard with two working wavelengths (λ = 532 nm and λ = 1064 nm, see Fig. 4a) simultaneously, while minimizing the space requirement to enhance its transportability. All lenses and mirrors had been already well aligned in Graz, except the last four mirrors (two for 532 nm, two for 1064 nm) which determine the direction of the outgoing laser. Additionally, an adapter board with 3 screws was involved between WLRS telescope and SP-DART breadboard to allow for a coarse initial alignment. To achieve parallelism, a first, rough alignment was done by observing and pointing to a reference point on the radio telescope at Wettzell observatory. Then, a bright star was tracked, and used as a reference target, to adjust the DART laser to point to this star.

The electronic parts of the SP-DART - including a GPS time/frequency unit, FPGA board, event timer etc. - are mounted in a 19'' rack (Fig.4b). The SP-DART can start to work, as soon as GPS antenna, laser trig/start, single photon detector range gate and USB cables for laptop communication are connected to the corresponding terminals.

Figure 4. The SP-DART transmit unit is mounted on the Wettzell laser ranging observatory receive telescope (a). Image of the 19'' rack including the part of the SP-DART control unit (b).

Active / Passive Ranging Experiments

Due to the high quality performance of the WLRS, it is possible to test the SP-DART FPGA and its software in passive mode during daylight. In this mode, WLRS operated as usual: It fired its 20 Hz laser, generated range gates for its detector, and collected data, while SP-DART only collected start pulses from the 20 Hz WLRS laser and stop pulses from the WLRS detector, calculates and displays O-C residuals, and stores raw data. This experiment was done for a Galileo102 pass while the SP-DART worked in passive ranging mode.

An active ranging test was scheduled during night; it used the real laser ranging mode, using only the WLRS telescope and WLRS detector. The SP-DART generated the prediction file, triggered the tiny µJ-laser with 2 kHz, generated range gates to the WLRS detector according to the start signals of the DART laser and satellite predictions, displayed O-C residuals and stored the raw file. From LEO to HEO, the return rates from three different altitude satellites ranging are listed in Table 1. A screenshot of our software, visualizing the O-C residuals of Glonass128, is presented in Fig. 5.

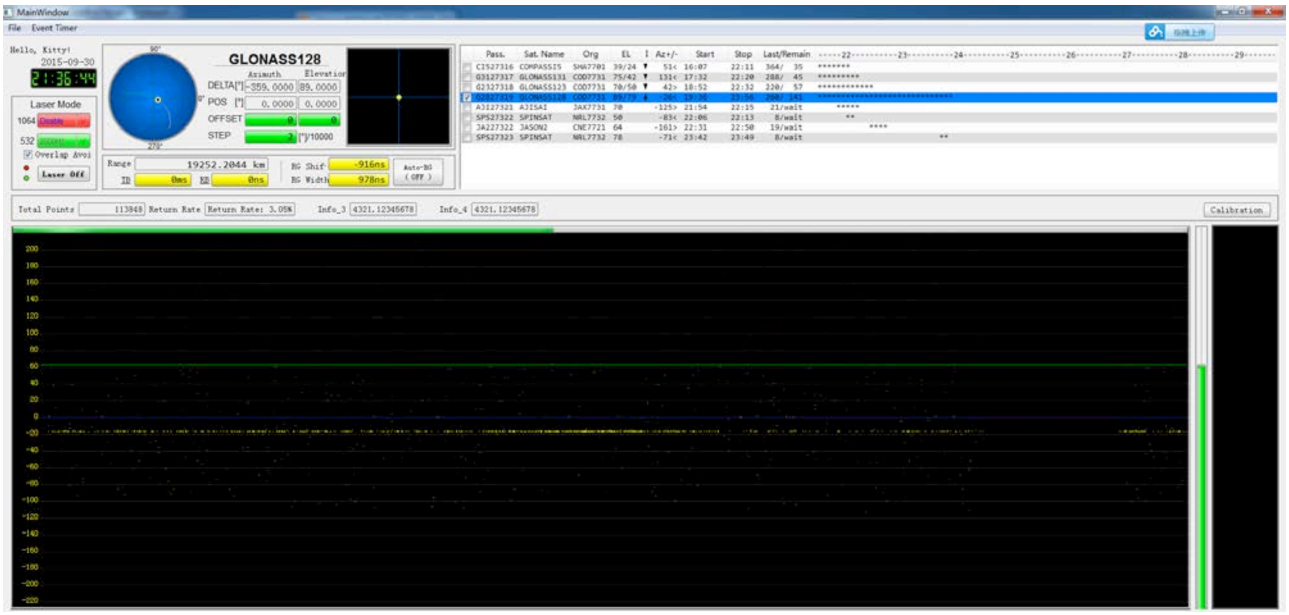

Figure 5. O-C residuals of Glonass 128 as visualized by our SP-DART software package.

Table 1. Summary of the return rates of three different altitude satellites ranging from LEO to HEO orbits. Even Glonass 128 showed a return rate of up to 3.5%.

Data&Time(UTC)	Satellite Name	Average Altitude	Max. Return Rate
2015/09/30 20:01	AJISAI	1485km	35.1%
2015/09/30 20:43	LAGEOS-2	5850km	12.56%
2015/09/30 21:36	Glonass128	19140km	3.5%

Summary and outlook

Our Single-Photon Detection, Alignment and Reference Tool (SP-DART) works as a mini SLR-station, using a host mount and host telescope. It includes an optical transmit unit with two µJ lasers with kHz repetition rate and an electronic control unit. The whole transmit unit is lightweight, and can be mounted on other SLR mounts to test and compare their operational performance. It was successfully tested at Wettzell laser ranging observatory in Germany yielding return rates of up to 3.5% for the Glonass 128 satellites. Besides its application as a reference tool it is possible to adjust and align single-photon detectors e.g. at astronomy telescopes, which then can work as passive SLR detection units. It will hence be possible to setup a network of stations for bi- and multi-static space debris measurements. The ongoing miniaturization of powerful lasers with pulse lengths in the picosecond regime will potentially lead to small, cost efficient SLR stations with lasers mounted directly on the receiving telescope, thereby avoiding any issues resulting from inherent Coudé – path problems.

References

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Stipcevic, M., Skenderovic, H., Gracin, D, *Characterization of A Novel Avalanche Photodiode for Single Photon Detection in VIS-NIR Range*, Opt. Express 18 (16), p. 17448-17459, Zagreb 2010