

# Using Pulse Position Modulation in SLR stations to transmit data to satellites

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## Abstract

The laser repetition rates of SLR stations vary from 10 Hz to 2 kHz. At the Graz 2 kHz SLR station, we upgraded the software to modulate the – usually constant – interval between laser pulses; using such a Pulse Position Modulation (PPM) scheme, we successfully transmitted text files via a 4288 m distant CCR back to a Multi-Pixel Photon Counting (MPPC) module in our receiver telescope. With such a setup at any SLR station, and a suitable detector plus simple time tagging electronics at Low Earth Orbiting (LEO; < 1000 km) satellites, it is possible for any kHz SLR station to transmit data to satellites with a rate of up to 2 kBytes/s - even during standard SLR tracking.

As this technique is easy to implement and does not affect routine kHz SLR tracking, it can be applied to upload data to satellites, using the more than 30 available SLR stations around the world, and with higher data rates than some of the conventional microwave uplinks.

## 1 Introduction

The laser repetition rates used at different SLR stations may vary from 10 Hz to 2 kHz (*M.R. Pearlman et al, 2002*). At the Graz 2 kHz SLR station, we upgraded the software to modulate the – usually constant – interval between laser pulses; using such a Pulse Position Modulation (PPM) scheme, we successfully transmitted text files via a 4288 m distant CCR back to a Multi-Pixel Photon Counting (MPPC) module in our receiver telescope. With such a setup at any SLR station, and a suitable detector plus simple time tagging electronics at Low Earth Orbiting (LEO; < 1000 km) satellites, it is possible for any kHz SLR station to transmit data to satellites with a rate of up to 2 kBytes/s - even during standard SLR tracking.

As this technique is easy to implement and does not affect routine kHz SLR tracking, it can be applied to upload data to satellites, using the more than 30 available SLR stations around the world, and with higher data rates than some of the conventional microwave uplinks.

Using laser repetition rates of e.g. 10 kHz – as planned at Graz SLR – it is possible to transmit standard GSM coded speech to a LEO satellite.

## 2 PPM Scheme for Graz 2 kHz SLR Station

### 2.1 Basic principle

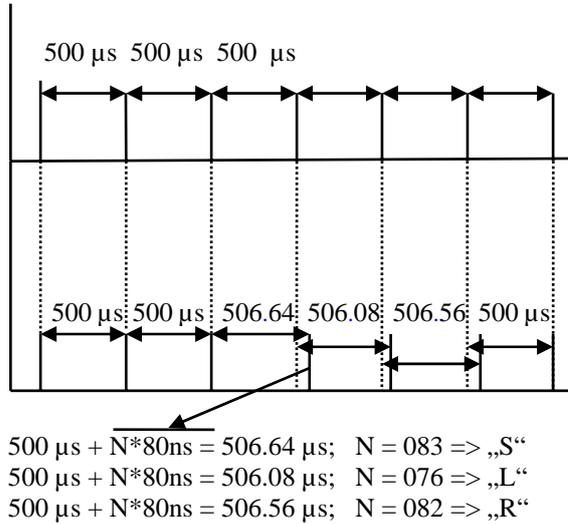
The PPM scheme we used for first tests encodes one single byte into each laser firing interval. The routine SLR procedure – without any PPM - uses constant intervals of 500  $\mu$ s; detecting a minimum of 100 consecutive pulses with such a 500  $\mu$ s interval (but allowing for the intrinsic  $\pm 7$  ns variations of the laser itself) establishes the basic grid for the PPM application (fig. 1, top). To apply PPM, we insert for each laser firing command small additional delays against this basic grid (fig. 1, bottom); the amount of this delay determines the byte value.

### 2.2. Suitable detector for SLR PPM

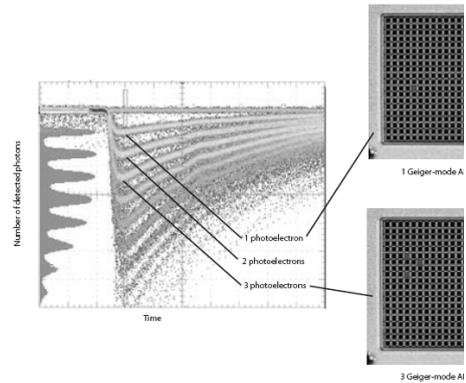
Our standard detector for SLR is a C-SPAD: A Single-Photon-Avalanche-Diode with time-walk compensation; while this is an excellent device for SLR, it is not suitable as a PPM detector: It is single-photon sensitive, thus reacting on any arriving background photon; in addition, at 2 kHz gating rate it produces a dark noise of about 400 kHz – when gated, a break occurs after about 2.5  $\mu$ s average, without any photons involved; all that ends up in a lot of noise points, prohibiting its use as a PPM detector.

Instead, we used a Hamamatsu Multi-Pixel Photon Counter Module (MPPC; C10507-11-050U, ); this device consists of 400 SPAD elements of 50 x 50  $\mu$ m each, arranged in a square of 20 x 20 SPADs on a single chip (fig. 2); all 400 outputs are

summarized on a single pin. Although it produces even more dark noise (up to 800 kHz) than our SLR SPAD, the resulting dark noise pulse amplitudes are according to single photons only; however, if a 10 ps laser pulse from our SLR laser arrives, it triggers many or all of the 400 SPAD elements simultaneously; the combined outputs are superimposed in a much higher – analogue - output pulse; thus, although such a MPPC remains basically single-photon sensitive, it can easily discriminate our laser pulses against very high dark noise and against significant background noise.



**Fig 1: Top: Basic Grid: Constant 500  $\mu$ s intervals; Bottom: Deviations from grid in 80 ns multiples define the ASCII value of the byte**



**Fig. 2: Hamamatsu C10507-11-050U MPPC (Multi-Pixel Photon Counter) with 400 pixels, arranged in a 20x20 pixel (each pixel 50x50  $\mu$ m) matrix, with a**

The leading edge of the MPPC analogue output is discriminated by a fast comparator with adjustable trigger level; the TTL output of this comparator is connected to the ISA FPGA PC card. A simple 5 ns counter in this FPGA time tags the events; the 5 ns resolution of this counter is sufficient to resolve the number of 80 ns multiples. The PC reads these event times, and decodes the corresponding ASCII values.

## 2.3 Test Setup

The Laser Control PC read one of several ASCII text files, and pointed the telescope to a retro-reflector in a distance of 4288 m. The attenuated laser fired to this target, and on request of the observer it applied PPM to the laser firing epochs to encode the characters of the selected ASCII text file.

The photons reflected from the retro-reflector were detected by the MPPC, which was mounted in the main SLR receiving telescope; with proper attenuation of the incoming photon stream, the MPPC produced the required output pulses, their epoch times were decoded, and the complete ASCII text file recovered and compared with the original file.

## 2.4 Detecting the SLR photons at the satellite

A typical kHz SLR station – example: Graz SLR – tracks LEO (Low Earth Orbiting) satellites with a divergence of the laser beam of about 20 arc seconds; the advantages of such a relatively high divergence are less demanding tracking requirements, and insensitivity against atmospheric seeing effects, beam wander etc.

With a single shot energy of 400  $\mu$ J @ 532 nm, the Graz SLR station transmits about  $10^{14}$  photons per shot; at a typical LEO distance of 1000 km, the beam diameter will be roughly 100 m; a single 50x50  $\mu$ m pixel of the MPPC thus will see an average of about 32 photons; this amount of photons will trigger most of the 400 MPPC pixels, resulting in a well determined analogue output pulse of the MPPC module.

At low energy kHz SLR stations, tracking HEO satellites requires the minimum laser beam divergence (< 5 arc seconds for Graz kHz SLR), which than still results in about 14 photons per MPPC pixel in about 6000 km; but this small divergence in turn causes much higher sensitivity to atmospheric turbulence, beam wander etc; while this only reduces SLR results, it is more or less prohibitive for the suggested simple PPM uplink channel.

## 3 Applications

There are more than 30 active SLR stations around the world; within the next few years, about one third of them will use kHz lasers – with repetition rates between at least 0.1 and up to 2 kHz; there are also plans for higher repetition rates on some stations. In principle, many of these kHz SLR stations could be easily and with minimal costs upgraded to perform such PPM based data uploads to satellites. The available data rate is given mainly by the laser repetition rate; the 2 kHz at Graz result in a maximum of 2 kbytes/s, which is already significantly more than e.g. the microwave upload rate to the satellite CHAMP (119 bytes/s).

On the satellite side, the only requirement is the installation of a suitable receiver (e.g. MPPC) and some simple electronics (basically a 5-ns time tagging unit); the energy density of the laser beam at least in satellite orbits up to 1000 km is enough to trigger reliably most elements of such an MPPC, without the need for additional optics or telescopes; the only requirement would be a 532 nm filter of at least 1 nm bandwidth (to allow for incidence angle variations). Such a satellite add-on would be of low weight (a few 100 g) and low power consumption.

To verify the successful transmission of data to the satellite, all conventional techniques for error detection and / or correction can be applied (parity bits, checksums, cyclic redundancy checks, error correction codes like the Verhoeff algorithm etc.). In addition, a basic check is possible also at the SLR station: If the satellite is equipped also with a CCR, it can be assumed that if a specific shot produced a valid return at the SLR station, this shot DID hit the detector on the satellite, and should have triggered the MPPC there.

In addition, using a standard simple microwave down-link from satellite to a receiver at the SLR station could provide a real-time feedback, allowing immediate re-transmission of any missing or disturbed data.

A simple first test could be with ACES, flying on the ISS within the next years; for time transfers, there will be already a CCR on board; adding the MPPC and the mentioned simple electronics would complete the test setup there.

## 4 Limitations and improvement possibilities

### 4.1 Data Rate Considerations

The data rate is limited by the repetition rate of the laser used at the SLR system; at present, the maximum repetition rates in use are 2 kHz (e.g. Graz, Herstmonceux); some SLR stations are upgrading to 2 kHz (Potsdam, Metsahövi) or use up to 1 kHz laser systems (Shanghai, Changchun, TIGO). Repetition rates of up to 10 kHz are feasible; above that there are limitations due to overlapping transmit / receive pulses, detector noise problems and event timer speeds.

The selected basic value for the PPM delay unit (80 ns chosen in our tests) has to cover mainly the  $\pm 7$  ns variations of the laser; and it has to take into account also the motion of the target satellite in orbit between 2 consecutive laser shots; for a 2 kHz SLR station, the minimum value to cover both effects is about 50 ns; the maximum value depends on the chosen encoding system (or number of different values to encode); the maximum resulting delay should not be more than about 10% of the standard laser pulse interval for undisturbed operation of the laser itself (for the Graz 2 kHz laser this would be 50  $\mu$ s maximum); using a 255 character set for the PPM, the maximum delay unit than is 50  $\mu$ s / 255 (about 200 ns); however, since this value does not affect PPM data rate nor the basic SLR operation, the exact value is not critical at all.

A slightly modified PPM scheme – the differential pulse-position modulation, or DPPM – encodes each pulse position relative to the previous pulse, such that the receiver has to measure only the difference in the arrival time of successive pulses. This limits the propagation of errors to adjacent symbols, so that an error in measuring the differential delay of one pulse – or errors due to a single missed pulse - will affect only two data bytes, instead of affecting all successive measurements. However, this modified PPM scheme slightly reduces the SLR repetition rate, and was therefore not implemented and tested in Graz.

### 4.2 Problems due to atmospheric seeing, clouds, beam wander ...

Due to the used optical wavelengths (532 nm in almost all SLR stations), optical visibility in the line of sight to the satellite is required; any clouds, fog etc. will prohibit SLR as well as successful data transmission; therefore, the above mentioned conventional techniques for error detection and / or correction should be applied.

Microwave uplinks to satellites use beam divergences in the order of 0.1° to 1° (depending on band, antenna size (Kumar,2008)), simplifying the required tracking accuracy; however, the optical wavelengths used in SLR allow – and require - much narrower beams, in the order of a few arc seconds (for High Earth Orbiting satellites, HEO) to several tens of arc seconds (for LEO satellites). Because the suggested PPM data uplink is targeting at LEO satellites only, the tracking requirements for any SLR station are rather reduced. And even with the relatively weak pulses of Graz kHz SLR station (400  $\mu$ J per pulse, according to about  $10^{14}$  photons), a divergence of up to 20 arc seconds – as used for LEO satellites – is sufficient for about 32 photons for any 50x50  $\mu$ m pixel of the 400-pixel MPPC.

The relaxed divergence demands for LEO satellites allows neglecting effects of atmospheric seeing (most times between 4 and 10 arc seconds in Graz), which is generally a problem for optical uplink channels to HEO satellites (Morio Toyoshima,

2008). In addition, optical uplinks to satellites are less affected by atmosphere than optical downlinks, mainly due to the relatively smaller beam sizes in relation to the atmospheric inhomogeneity.

### 4.3 Non-constant intervals due to Overlap Avoidance Procedures

In case of kHz SLR, always multiple laser pulses travel simultaneously between station and satellite; if one or few photons from a previous laser shot arrive at the same time when a new laser shot is fired (“overlap situation”), the backscatter of the new laser shot will increase significantly the noise as seen by the detector. To avoid this, most kHz SLR stations use some overlap avoidance procedure; all of these methods are modifying or changing the otherwise constant time intervals between laser pulses.

The overlap periods for LEO satellites are shorter (few seconds), and due to relatively high return signals – up to a few 1000 photons per shot - less severe than for HEO satellites (which are tracked with return quotes of 0.1% average – only 1 out of 1000 shots results in a single detected photon). Therefore, the overlap problem is less perturbing for LEO satellites.

Therefore it can be tolerated for the PPM application to LEO satellites to switch off these overlap avoidance procedures; according to tests at Graz kHz SLR station, the resulting increased noise at the SLR station receiver for several short periods throughout a standard satellite pass can be handled without problem.

### 4.4 Space qualified detectors

If the MPPC is considered as detector for the PPM SLR uplink channel, its space qualification must be proven; according to the manufacturer, this has not been done yet. In case the MPPC is NOT space qualified, any other linear detection device based on a photon detector in linear gain mode may be used; such a space qualified detector is successfully used e.g. for the T2L2 experiment (*E. Samain et al, 2007*) on the LEO satellite Jason-2.

## 5 Conclusion

Applying simple Pulse Position Modulation (PPM) to the firing times of laser pulses at existing and operational kHz SLR stations, offers an opportunity for a new data upload channel to satellites in orbits up to about 1000 km. The only requirement at the satellite side is a simple photon detector without the need of optics – except a simple laser wavelength spectral filter -, a 5 ns resolution time tagging unit, and possibly a CCR; on the kHz SLR station side, the upgrade depends on the specific hardware, but in many cases that would be simply a few more lines of software to control the laser firing times of the SLR station with an accuracy of some nanoseconds.

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