SECTION 6

EMERGING TECHNOLOGIES

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Introduction

This report is largely, but not exclusively, based on the technical papers presented at the 16th International Workshop on Laser Ranging, held in Poznan, Poland in October, 2008. The report also draws on material from external sources. It is not intended as a review of all that was presented, since the online abstracts and papers do that adequately. Instead, it is a subjective attempt to organize, summarize and comment on the key technology trends and highlights (hardware only) and to tie key engineering activities into an overall perspective. .

Kilohertz Photon-Counting Systems

Eyesafe Systems

NASA researchers reported on the operational status of the Next Generation Satellite Laser Ranging (NGSLR) system, formerly known as SLR2000 [McGarry et al, 2008]. Using a transmitted eyesafe energy of only 60 µJ, the system has routinely tracked LEOs down to 10º elevation and LAGEOS to 30º elevation. The system has also successfully ranged to GLONASS at high elevations. Starcals are now totally automated, and a new short pulse laser is being developed at GSFC, which will provide a capability to change repetition rate and pulse energy over a wide range to access the highest satellites in non-eyesafe mode. Routine daylight tracking was initiated following successful implementation of a dual Risley prism device to point the transmitter ahead of the receiver [Degnan et al, 2008]. The automated fine pointing of the receiver using the quadrant detector has proven more difficult than anticipated due to an inability to date to acquire the necessary stability in the relative response of the four quadrants (see Section 5.2 for other modifications.).

Non-Eyesafe Systems

Graz reported on results from a new “skin-tracking” approach for determining the satellite orbit using kHz data. They were able to reduce the scatter of their normal points from several cm to less than 1 mm by only accepting returns from the leading edge (LE) to LE+20 mm [Kirchner et al, 2008b].

Because the Graz ET requires 400 µsec to fix an event time, they have recently developed a medium resolution (~250 psec) ET with a much faster 20 nsec response to set their new 500 psec resolution Range Gate Generator (RGG) [Iqbal et al, 2008].

Transitional or New Sub-kHz Systems

UK researchers at Herstmonceux continue to operate in a dual mode, i.e. the older 10 Hz system and the newer 2 kHz system. [Gibbs et al, 2008]. They generally report higher precision results with 2 kHz but still have some difficulty dealing with solar count rates that are significantly higher than the satellite return rates, especially high altitude satellites with broad impulse responses such as Etalon. However, the dual mode operation, like NGSLR, allows them to participate in transponder experiments to the LRO spacecraft.

The Chinese stations in Shanghai [Zhang et al, 2008] and Changchun [Fan et al, 2008] have both demonstrated an ability to operate in the kHz regime using long pulse (40 – 50 nsec) test lasers and are planning to install subnanosecond kHz lasers in the near future. Within the next two years, it is expected that all of the Chinese SLR stations, with the exception of Kunming, will go to 2 kHz operations. [Yang et al, 2008a].

The Swiss Zimmerwald station reported on their experiences with a 100 Hz, 40 psec pulse, 8 mJ transmitter at 532 nm [Gurtner et al, 2008]. They were able to achieve a 13% return rate on high altitude GNSS satellites using a rotating mechanical transmit/receive (T/R) switch for backscatter protection at the lower rate.

The Russian delegation reported on the new 300 Hz system at their Altay site which started providing data to the ILRS in October, 2008 [Burmistrov et al, 2008]. The laser outputs 2.5 mJ of energy in a 150 psec pulse.

Other Applications of kHz Data

Graz is presently using the atmospheric backscatter from their SL transmitter to run a parallel cloud detection lidar with a 15 m range resolution. To date, it has measured cloud heights up to 10 km [Kirchner et al, 2008a].

Some preliminary experiments were reported where the photon-counting kHz system at Herstmonceaux was used to measure the impulse response of satellites already in space [Otsubo et al, 2008]. The method takes advantage of the bias-free nature of photon-counting systems. However, the measured profile must be deconvolved with the instrument impulse response to obtain the satellite response.

Components

Detectors

The vastly different recovery times, following a photon event, of Single Photon Avalanche Diodes (SPAD) and MicroChannel Plate PhotoMultiplierTubes (MCP/PMTs) can have important consequences for photon-counting systems operating in daylight [Degnan, 2008b]. Recovery times range from about 1.6 microseconds for a passively quenched SPAD (PQ-SPAD), to about 50 nsec for an Actively-Quenched SPAD (AQ-SPAD), to less than 2 nsec for an MCP/PMT. The fast recovery time (or short deadtime) of the MCP/PMT results from the fact that an incoming photon depletes only a small subset of microchannels in the vicinity of the strike. Hence, there are thousands of remaining high gain microchannels available for recording subsequent photons. With high solar backgrounds, long deadtimes can significantly reduce the signal count rate from the satellite. Thus, every effort must be made to reduce the solar count rate through the use of spectral and spatial filtering. Temporal filtering or gating can reduce the number of solar counts observed but does not increase the signal count rate. In NASA's NGSLR system, use of a Dual Risley Prism system to compensate for transmitter point-ahead allows a substantial reduction in the receiver FOV [Degnan et al, 2008].

If the combined recovery time of the detector and range receiver is slow compared to the solar background rate, most or all of the satellite returns will not be observed. As a case in point, NASA's NGSLR system incorporates a low deadtime (<2 nsec) Quadrant MCP/PMT but, since all four quadrant channels outputs are combined into a single input channel of the HTSI Event Timer with a deadtime of 60 nsec, the overall system response is no better than that of an AQ-SPAD. For the purposes of SLR, the PQ-SPAD is a single stop device, and thus a single solar photon appearing within a typical range gate can prevent the system from seeing the satellite return.

The Compensated SPAD (C-SPAD) is the photon-counting detector used at the kHz Graz and Herstmonceux stations. The Herstmonceux group [Wilkinson et al, 2008] estimates that the loss for LAGEOS and HEO satellites during daylight C-SPAD operations ranges from 20% to 50% of the total shots fired. Furthermore, since the C-SPAD must be armed 50 to 100 nsec before an observation to avoid any range bias, Herstmonceux researchers experimented with a high speed Pockels Cell shutter designed to shield the C-SPAD from noise counts within the spectral filter passband until about 10 nsec before the expected satellite return. Unfortunately, the polarization losses are high (50%) and alternative polarization-insensitive switching schemes are either too slow or have other technical issues [Wilkinson, 2008]. In a similar vein, Czech researchers [Prochazka and Blazej, 2008] reported on several SPAD detectors developed for Laser Time Transfer and one-way ranging experiments (see Section 5 of this report). Their ability to operate under high solar background conditions appears to be largely due to a fast gating capability ability (<30 nsec before the expected event), but this assumes extremely accurate prior knowledge of when the event will occur, which will not always be the case in future interplanetary transponder or altimetry missions. In simple terms, the uncertainty of the signal photon arrival time must be very small compared to the mean interval between background photons for the Herstmonceux Pockels Cell approach or new Czech detector to be viable. On the other hand, it has already been demonstrated that range receivers using MCP/PMTs can record multiple photon events within a wide temporal gate with a deadtime of only 1.6 nsec [Degnan,2008b]. MCP/PMTs also have lower dark count rates than SPADs and Herstmonceux is preparing to conduct experiments with them.

Other recent detector developments not reported at the Workshop include a new infrared MCP/PMT available from Hamamatsu (Japan) and a segmented anode SPAD array sold by SENSL (Ireland). Hamamatsu guarantees 10% QE and has achieved as high as 18% QE at wavelengths 1064 nm and beyond. The new tube is somewhat bulkier, requires more cooling, has a higher dark count rate, and is less technologically mature than its visible counterpart, but the significant efficiency improvement over prior NIR photon-counting devices (18% vs 3%) certainly improves the competitiveness of NIR systems. The SENSL device, operating in the visible, attempts to confer some of the advantages of MCP/PMT devices to SPAD arrays. The fast recovery of MCP/PMTs is due to the fact that a photon incident on the photocathode only depletes a small number of microchannels in the vicinity of the strike, leaving thousands of other microchannels available for subsequent photon “hits”. The common anode was then able to sum the output of the various microchannels for an effective “zero” deadtime [Degnan, 2008b]. Similarly, a common anode in the new SENSL device sums the outputs of individual SPADs and significantly reduces the number of timing channels required to record the various photon events. Further mimicking MCP/PMTs, the company also provides multi-anode versions of the SPAD arrays. A preliminary look at these devices, however, suggests that output pulse rise times are too long for precise ranging but the technology may merit further consideration since SPADs, unlike MCP/PMTs, do not have life-limiting mechanisms related to total charge transfer.

Precision Timing

Latvian researchers reported on the status of their latest event timer, the Model A033-ET. The principal focus is on replacing outdated components on their earlier A032-ET and making it a commercially viable product [Artyukh et al, 2008]. The updated unit consumes less than 6W of power, has a single NIM input, a resolution of less than 4 psec, and a 40 nsec deadtime.

Another Latvian group reported on a High Speed Event Timer based on the commercially available Time-to-Digital Converter (TDC) chips [Boole and Vedin, 2008]. The principal features include 6 independent event measurement channels (4 primary and 2 TAG channels), 90 psec RMS resolution at rates up to 5 MHz, and a 6.5 nsec deadtime.

Czech researchers reported on their New Precision Event Timer (N-PET), which uses a novel and recently patented Surface Acoustic Wave (SAW) filter excitation as a time interpolator [Prochazka and Panek, 2008]. In addition to a 0.9 psec RMS timing precision, the authors claim high timing linearity (+0.2 psec nonlinearity over the interpolator range) and a low temperature drift (<0.3 psec/K). However, like the venerable French Dassault ET, the N-PET has an extremely long dead time (~10 msec) which limits its usefulness in certain applications and operational environments.

Laser Transmitters

Picosecond, Kilohertz Lasers

The Austrian firm, High-Q Lasers, gave an overview of their ultrashort pulse laser products, which span the femtosecond and picoseconds regimes. [Huber et al, 2008]. The kHz stations in Graz and Herstmonceux presently use their pico-REGEN system, which produces nominal 10 psec pulses at 2 kHz with a single pulse output energy of about 0.4 mJ. The company achieves this performance through the use of a modelocked oscillator (to obtain short but very low energy pulses) and a regenerative amplifier which boosts the energy by many orders of magnitude via a large number of passes through the amplifier before the circulating pulse is switched out. Some scientific users are requesting higher energies in the few mJ range, and the company is presently working on two strategies: (1) the use of a post-amplifier in their standard Nd:Vanadate system; and (2) moving to a different laser material, such as Nd:YLF. The Zimmerwald station recently installed a 100 Hz, 40 psec, 8.3 mJ (@ 532 nm) transmitter composed of a SESAM (SEmiconductor Saturable Absorber Mirror) oscillator, a regenerative amplifier, double pass amplifier, and doubling crystal [Gurtner et al, 2008].

The principal drawback of modelocked oscillators and regenerative amplifiers for some ranging applications is their relatively large size (long oscillator and regenerative amplifier optical lengths are typically required) and their relative complexity (e.g. high voltage electro-optic switches operating at kHz rates in the regenerative amplifier). Their principal competition as transmitters for kHz SLR systems is the passively Q-switched microchip laser followed by one or more passive amplifiers in a Master Oscillator Power Amplifier(s) (MOPA) configuration, as is presently used in NASA's eyesafe NGSLR system. While much more compact and energy efficient (and therefore better suited to spaceborne transponder and airborne altimetry applications), microchip oscillators to date have difficulty generating pulses much shorter than about 250 psec at the required energies. Using (SESAMs) as the passive switching media in a quasi-monolithic microchip laser, European researchers [Nodop et al, 2007] recently produced pulsewidths as short as 50 psec at repetition rates up to 40 kHz. The single pulse energy (~1 μJ) was substantially lower than that obtained from conventional Cr^4+:YAG- switched microchips but roughly three orders of magnitude greater than typical CW pumped modelocked oscillators. One would expect future transmitters based on similar oscillators, perhaps coupled into fiber amplifiers for the initial stage of amplification, to provide shorter pulsewidths than conventional microchips and be much smaller, lighter, more power efficient, and less complex than modelocked oscillator/regenerative amplifier combinations.

Other Laser Developments

HTSI reported on modifications to the NASA MOBLAS acousto-optically and passively modelocked Pulse Transmission Mode (PTM) laser oscillator [Oldham et al, 2008]. The original laser used both an Acousto-Optic Modulator (AOM) and a passive modelocking dye to generate the short pulses. An internal electro-optic switch (Pockels cell) switched the pulse out at or near its peak intensity to produce several mJ of output. Since the dye and its solvent presented somewhat of a biohazard and needed to be replaced periodically, the HTSI engineers looked at two alternatives – a Saturable Absorber Mirror (SAM) and a bulk Cr^4+:YAG passive modelocker (PM). With the SAM substituting for the dye, the output energy was low (~nJ) and unstable whereas the PM produced a stable, higher energy pulse (mJ) pulse, especially when it was located close to the active modelocker. An internal etalon was used to select a particular pulsewidth. The modifications are scheduled to be implemented in all of the NASA MOBLAS and TLRS systems as well as MLRS.

Australian researchers reported an increase in productivity at their Mt. Stromlo station following a 3-fold increase in the power of the laser transmitter – from 0.4 W (13 mJ @ 30 Hz) to 1.2W (20 mJ@60 Hz) [Moore, 2008].

Multi-Wavelength Ranging

To the author's knowledge, no new hardware or atmospheric model related activity in this area was reported at the Poznan workshop or elsewhere in the literature during this period.

Lunar and Interplanetary ranging

Lunar Laser Ranging (LLR)

Progress toward 1 mm lunar ranging precision continues to be made at the Apache Point Observatory for Lunar Laser Operations (APOLLO) [Murphy et al, 2008b] . Single pulse returns as high as 10 photoelectrons and high return rates have been obtained with a modestly powered laser transmitter (115 mJ @ 20 Hz) thanks to an exceptionally large 3.5 m telescope aperture and a high QE 4 x4 detector array provided by MIT Lincoln Laboratories. Nevertheless, returns are 100 times weaker than expected at or near Full Moon and approximately 10 times weaker overall. APOLLO researchers do not believe this discrepancy is due to the increased solar background.

French researchers reported on the status of their new MeO system, which will be dedicated to tracking satellites from 400 km to the Moon [Samain et al, 2008a]. First satellite echoes were obtained in July 2008 with the first lunar attempts scheduled for November 2008.

Lunar Reconnaissance Orbiter (LRO)

Several research groups reported on activities related to the first operational laser tracking of a satellite in lunar orbit, Lunar Reconnaissance Orbiter (LRO). Ground SLR stations will fire at the LRO spacecraft and a one inch diameter telescope, mounted on the spacecraft microwave antenna, will collect the photons and relay the photons to one of four ranging channels on the Lunar Orbiter Laser Altimeter (LOLA) instrument. The received energy must be sufficient to trigger the onboard detector. Furthermore, since the channel is shared by laser ranging and altimetry functions, the ground laser fires must be timed precisely so that they enter the LOLA range gate within a narrow8 msec interval at maximum rates of 28 Hz, corresponding to the altimeter laser fire rate. The purpose of the one-way SLR tracking is to improve knowledge of the lunar gravitational field and LRO orbital precision [Smith et al, 2008a].

In order to support the LRO experiment from the new NGSLR station, NASA researchers have added a higher energy (50 mJ) , longer pulse (6 nsec), low repetition rate (28 Hz) transmitter option which shares the NGSLR telescope and tracking mount for uplink only ranging to LRO [McGarry et al, 2008]. The transition between eyesafe 2 kHz and non-eyesafe 28 Hz operation is accomplished with a simple drop-in mirror and toggle switch. A standard NASA aircraft radar was also added to support high energy ranging to LRO. An overview of the comprehensive pre-launch testing program at NGSLR was also provided at the Poznan workshop [Mallama et al, 2008]. Preparations for LRO tracking by the MLRS LLR station in Texas were also described [Wiant et al, 2008].

Czech researchers reported on a pocket-sized device which can be used for precise epoch timing unit (130 psec RMS) and control laser time of fire with a resolution of 100 nsec in one way laser ranging experiments [Kodet and Prochazka, 2008].

Interplanetary Laser Transponders

US researchers from a variety of collaborating institutions reported on a recent scientific and technology study of a laser transponder mission to Mars, or alternatively the Martian moon Phobos [Murphy et al, 2008a]. Scientific interest centers on the study of gravity, especially as it pertains to General Relativity. Millimeter accuracy ranging over interplanetary distances can provide orders of magnitude better precision in the measurement of key relativistic parameters. The technology portion of the study, carried out largely at NASA's Jet Propulsion Laboratory (JPL), proposes a 3 year mission. A telescope aperture of 12 cm and a transmitter power of 250 mW are proposed for the spaceborne terminal. The nominal Earth terminal would have a 1 m telescope and transmit 3 mJ, 12 psec pulses at kHz rates.

German researchers [Schreiber et al, 2008] reported on the first experimental attempt to simulate an interplanetary transponder link using the dual station ranging technique [Degnan, 2006]. A small transceiver package (AltiDemon) was operated alongside the Wetzell SLR system, with each system observing the reflected pulses of the other. The experimenters used the ERS, Ajisai, and LAGEOS satellites to simulate a link between Earth and its nearest planetary neighbors, Mars and Venus..

Laser Time Transfer

The long awaited French T2L2 (Time Transfer by Laser Link) experiment was launched onboard the Jason-2 spacecraft in June 2008. Fundamental physics goals include measurement of the anisotropy of the speed of light and validation of the one way laser ranging concept [Samain et al, 2008b]. As of the workshop, 15 SLR stations had met the requirements for participation in the experiment,

Chinese and Czech researchers reported on the results of their joint Laser Time Transfer (LTT) experiment on the Compass-M1 spacecraft, which was launched into a 21,500 km high orbit in April 2007 [Yang et al, 2008b]. The time difference between the ground hydrogen maser and the spaceborne rubidium clocks was made by the Changchun SLR station with a single pulse precision of 300 psec. The measured frequency drift and stability of the spaceborne rubidiums were $1.47\text{x}10^{-10}$ and 10^{-13} respectively. The uncertainty in the relative frequency difference is about $3\text{x}10^{-14}$ averaged over 2000 seconds. Solar noise corrupted the measurements, and the best results were obtained during night operations.

In a somewhat different vein, Spanish researchers have used SLR range measurements to Galileo GIOVE-B to decouple the radial error in the orbit from onboard clock offsets, which are highly correlated [Hidalgo et al, 2008].

Laser Altimetry

US researchers reported on recent results obtained with a 2nd generation photon-counting 3D imaging lidar and discussed its implications for future spaceborne missions [Degnan, 2008a]. The airborne lidar operates with 100 beams from a single 22 kHz laser transmitter resulting in a maximum 2.2 Megapixel per second rate ,which produces high resolution and contiguous images of the underlying terrain. Two space applications were discussed. One was the 16 beam Cross Track Channel (CTC) Lidar system proposed for NASA's ICESat-II mission. The nominal system requires 4 W of 532 nm output power (25 microjoules per pulse per channel x 10 kHz laser repetition rate x 16 channels). At this repetition rate, the terrain is interrogated every 70 cm in the alongtrack direction and every 140 m in the crosstrack direction within a total 2.1 km swath in order to provide ice scientists with much needed slope information in both axes. The second space application studied was NASA's Jupiter Icy Moons Orbiter (JIMO) mission. It was demonstrated analytically that a 100 beam scanning lidar, similar to the current airborne system, could map all three of Jupiter's moons – Ganymede, Callisto, and Europa – within a few months. The relatively low solar background at the outer planets makes them especially attractive targets for photon-counting lidars.

German researchers reported on a Laser Altimeter Simulator, which was developed in support of ESA's BepiColombo mission to Mercury [Heiner et al, 2008]. The history of US spaceborne laser altimetry missions and the science goals for the Mercury Laser Altimeter (MLA) enroute to Mercury and the Lunar Observer Laser Altimeter (LOLA) on LRO were reviewed [Smith and Zuber, 2008b].

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