Altimetry and Transponder Ground Simulation Experiment

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Abstract

We have designed and built a compact demonstrator unit for the investigation of altimetry and transponder applications. A small light-weight breadboard carries a compact frequency doubled Nd:YAG pulse laser, afocal beam expansion optics, a small receiver telescope with spectral and spatial filter arrangements and a photosensitive detection device (SPCM, PMT or SPAD). The output laser energy can be as high as 45 mJ with a pulse-width of 3 ns and the telescope aperture is 12 cm. Simulations [1] suggested that the link margin for low Earth orbiting satellites (LEO) is comfortable and that it may be possible to obtain echoes from a dual-station experiment in several different configurations. This paper outlines details of the experiment and presents the obtained results.

Key words: Satellite Laser Ranging, Optical Transponder, Laser Altimetry, Interplanetary Ranging
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1. Introduction

Laser ranging at interplanetary distances has become a viable option in recent times. The advances made in optical communications as a result of the need of higher transmission bandwidth for the recent generation of imaging satellites provides the necessary infrastructure namely pointing and spaceborne telescope design.

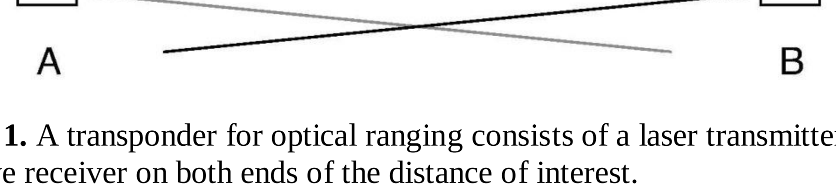

Figure 1. A transponder for optical ranging consists of a laser transmitter and a photo-sensitive receiver on both ends of the distance of interest.

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This suggests to include inter-satellite ranging and Earth to interplanetary satellite ranging as newly available means of precise orbit determination (POD). In other cases of dedicated space missions for fundamental physics, such as the proposed "Einstein Gravity Explorer" [2] laser ranging may provide the tools for high-precision clock comparisons. Therefore it is time to study the potential of interplanetary ranging in more detail. Since dedicated experiments in space are far to expensive and time consuming to be realized, there are only two other possibilities left. Either an existing pulse laser equipped mission can be "misused" to evaluate an interplanetary optical ranging link or a ground based experiment has to be set up such that all relevant parameters of an interplanetary optical link can be examined in great detail. Figure 1 shows the basic concept of an optical transponder. There are two transmitters and receivers located at the ranging terminals A and B. They are firing short laser pulses at each other asynchronously and from a large distance. While the epochs of the detected signals are timed on each local computer, the epochs of laser fire are exchanged via telemetry between both stations. From this one can compute the range and the rate of change (on the radial component) between both stations as well as the respective clock offset. In this way the dependence of the receive signal on the covered distance follows a $1/r^2$ relationship rather than $1/r^4$ like in the case of a two-way optical link from backreflections off corner cubes on artificial satellites and on the moon [3]. While the moon is at about the largest distance that can be practically tracked by using passive retro-reflectors, transponder have the potential to work within the entire solar system on a reasonable link margin. Until today there have been two feasibility studies, which were performed as experiments of opportunity making use of NASA spaceprobes in orbit around Mars and in transfer to Mercury [4], namely:

- One-way ranging to Mars Global Surveyor at a distance of 80 million km
- Two-way ranging during a MESSENGER fly-by at a distance of 24 million km

The Mars Orbiter Laser Altimeter (MOLA) was orientated pointing toward Earth in order to detect laser pulses transmitted from the 1.2 m telescope of the Goddard Space Flight Center in Greenbelt. Since the transmitter of MOLA is no longer working only one-way ranging could be demonstrated successfully based on a very small number of unambiguously identified datations. In a similar way an equipment test of the Mercury Laser Altimeter (MLA) during a fly-by of the MESSENGER spacecraft was used to determine the range and clock offset between the spacecraft and the ground station in Greenbelt by a complete ranging link in both directions. Consistent results were obtained despite the fact that the number of data points were sparse and the laser pulse width of the altimeter was not ideal for such a ranging application.

2. Transponder Simulation

In a very general way one can consider satellite laser ranging (SLR) as a special laser transponder application. Provided that there are two ranging stations located sufficiently close together (within the divergence angle of the reflected laser beam), it is possible to test parts or all functions of a transponder link in an entirely ground based experiment. According to [1] the equivalent transponder distance r_t relative to an SLR laser link of the same station is a function of the actual slant range r_s. For a satellite in near circular orbit at the height h above sea level r_s can be expressed as

$$r_s(h,\Theta) = -r_E cos\Theta + \sqrt{(r_E cos\Theta)^2 + h(h+2r_E)} \quad , \tag{1}$$

where Θ is the zenith distance and r_E = 6378 km the mean radius of the Earth. The equivalent transponder distance then becomes

$$r_t(h,\Theta,\sigma_s) = r_s^2(h,\Theta)\sqrt{\frac{4\pi}{\sigma_s}\frac{1}{T_A^{sec\Theta}}} \quad . \tag{2}$$

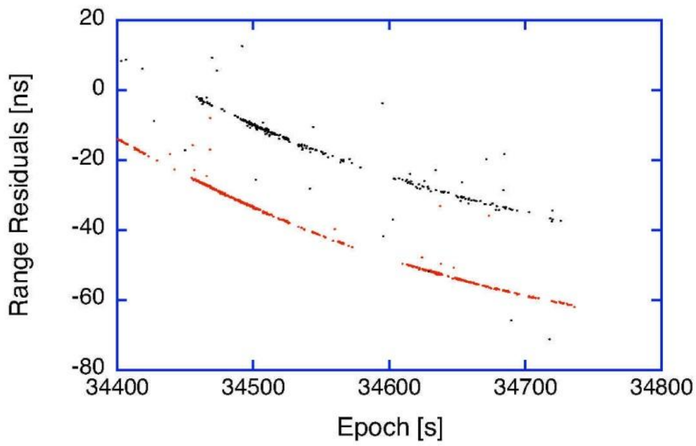

Figure 2. Example of a Topex pass observed by the WLRS on June 20, 2001 under cloudy conditions. The returns on the standard ranging configuration are shown on the lower trace, while the echoes on the small extra receive aperture are displayed on the upper trace.

One can see that it strongly depends on the slant range and on σ_s the laser cross-section of the target in square meters. In the following we are assuming an atmospheric transmission T_A of around 0.7**,** which is the maximum value for the given operational wavelength of the ranging systems of λ = 532 nm. It is difficult to establish a reliable value during the measurements. As pointed out in [1] "real world" tests of transponder functions for distances as far out as the outer planets of the solar system are possible. In a first test we have mounted a small telescope with an aperture of 12 cm to the Wettzell Laser Ranging System (WLRS), pointing along the optical axis of the main telescope in order to detect laser echos independently from the routine ranging hardware. Over a period of several month echoes from a number of satellites including Lageos and Etalon were recorded in parallel on the additional telescope. One example of a satellite pass from Topex on June, 20 in 2001 is shown in fig. 2. This was an intermediate step towards a transponder testbed installation, since it demonstrated a sufficient link margin for such a small receive signal aperture. At the same time this basic setup already resembles a simplified version of the basic layout of an asynchronous transponder concept as outlined in [1]. Figure 3 illustrates the entire operation principle. There are essentially two timescales involved, one for each terminal of the two stations separated by a large distance. Under typical conditions it can be assumed that there is an offset between the two timescales as well as there is a relative drift between them. In the case of an interplanetary transponder the range r between the two stations would be

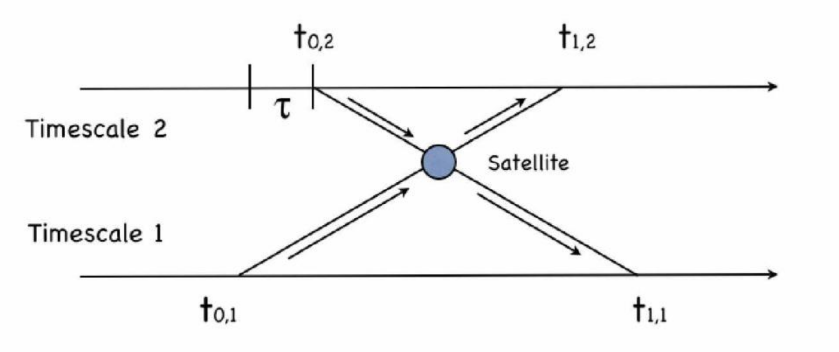

Figure 3. Functional diagram of the transponder simulation application. Time is progressing along the x-axis, while the distance is corresponds to the y-axis. For an interplanetary link laser pulses are transmitted directly between the two ranging terminals. In a ground based simulation experiment, geodetic satellites are used to backreflect the laser pulses, so that they can be detected by an independent ranging system on the ground near the transmitting station.

$$r = \frac{c}{2}[(t_{1,1} - t_{0,1})(t_{1,2} - t_{0,2})], \tag{3}$$

where c is the velocity of light and $t_{n,m}$ are the corresponding epoch registrations on each ranging terminals. During a typical transponder application many such pulses are transmitted from both sides and a priori range estimates have to be applied to work out the respective corresponding pairs of epoch registration used in eq. 3. However for a transponder simulation setup with a geodetic satellite reflector target employed there are essentially three scenarios available for studies. Case 1 is the usual satellite ranging operation for the station associated with timescale 1 alone. Case 2 is the additional laser ranging operation associated only with timescale 2. Transponder operations (case 3) can be realized by transmitting laser pulses asynchronously from one station, receiving it by the other station and vice versa. In the most simplified case both stations share the same telescope drive for pointing, while all other hardware components like timers, control system and lasers etc. are independent. More generally the two ranging terminals could be realized by two individual SLR stations in close proximity as proposed in a NASA concept [5].

3.Transponder Demonstrator Experiment

A balanced transponder link is characterized by a comparable number of recorded photo-electrons on both ends of the transmission path. For an optical satellite to satellite link this usually would mean the application of similar laser transmitters and telescope apertures on both terminals. However for a ground to satellite link it is desirable to have a large telescope and a powerful laser on the ground where it is readily accessible and only a low-power laser and small telescope in space. This reduces the demands on payload requirements substantially. Therefore we have followed a similar approach for our testbed experiment. The WLRS was used as Station A [6]. It operates a 0.75 m diameter telescope and a 180 mJ frequency doubled Nd:YAG laser. The pulse width is 80 ps. A Quantel Brio laser with 35 mJ (3 ns pulse width) with a transmit aperture of 3 cm was used for Station B. The corresponding transmitter divergence has a minimum of 24 arc seconds. The receive telescope is a 12 cm Maksutov type aperture with additional spatial and spectral filters in order to allow daylight operation. Several different photo-detectors may be attached.

Experiments were carried out with a PMT (12% quantum efficiency), the SPCM module of EG&G and a SPAD for single photo-electron detection.

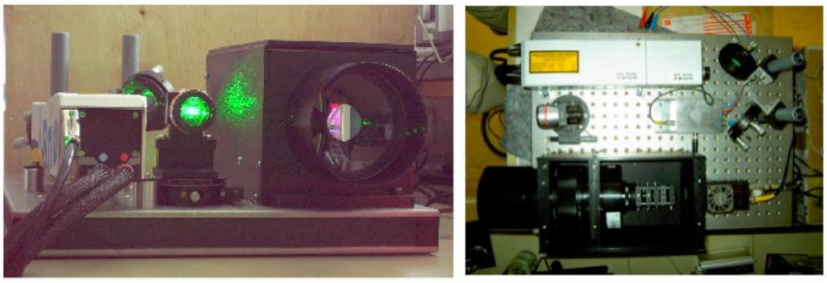

Figure 4. Hardware layout of the transponder simulation module. On the left hand side one can see the laser (from the backside), the transmit and receive aperture. The top view on the right hand side also shows the filter arrangement behind the receive aperture and the photo detection device

Figure 4 shows the compact design of the transponder simulation module. A diaphragm in the receive path allows the adjustment of the receiver field of view in the range of 20 to 90 seconds of arc. Basic test operations of the transponder simulator were carried out by ranging to a local ground target, namely a diffuse reflecting concrete pillar 180 m away.

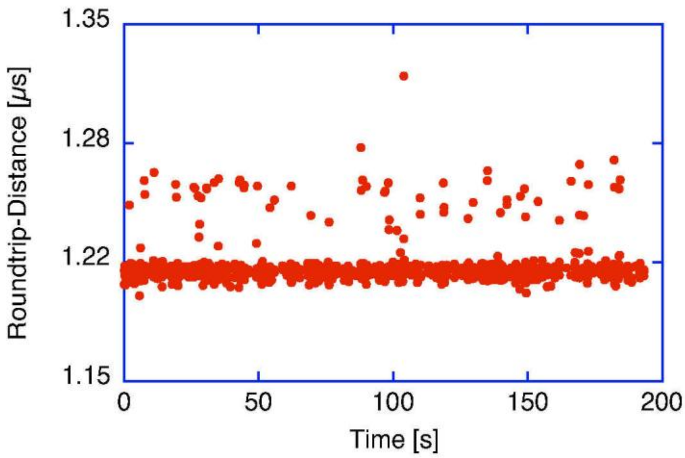

Figure 5. Example of a ground target range measurement sequence. The low energy laser pulse was reflected from a concrete pier at a distance of about 180 m.

Figure 5 shows a typical result of these ground tracks, detected with the photomultiplier as a receiver. In order to operate the full transponder experiment we have set up a completely independent ranging environment, including the event timer and control system software as outlined by the block diagram in fig. 6. For simplicity it is assumed that the computer control and data logging is part of the timer module. Each system needs a start and stop pulse to perform the range measurement function and in addition a gate signal to arm the detector for the reception of the return signal. Since both systems operate entirely asynchronous with a repetition rate of 10 Hz in the case of the WLRS and 20 Hz for the transponder module, it is necessary to cross over both the detector signal cable and the rangegate generator signal between the two systems. Apart from this change both stations are treated like independent ranging environments. Following [1] link budget calculations show the expected return signal strength for a number of configurations summarized in table 1. For this calculation a zenith distance of 30° and an atmospheric transmission of 0.7 was used. This corresponds to reasonably good but not ideal conditions and assumes a collimated laser beam for both transmitters. In order to operate the simulation module on top of the laser telescope of the WLRS one has first to align the optical axis of the transmitter of the simulation module to be collinear with the corresponding optical axis of the receiver. This was done by imaging the ground target 180 m away from the simulator test location on the receive telescope of the simulation module. Once the laser beam was in the center of the field of view of the receiver telescope the alignment screws were tightened up. Then the entire base plate was lifted and mounted on a adjustable frame over the elevation axis of the WLRS telescope. Figure 7 shows the simulation module sitting on the much larger telescope of the WLRS. The alignment of the simulation module relative to the optical axis of the WLRS was achieved by pointing the two systems to a reference target approximately 5 km away from the ranging site. The entire simulator was adjusted with the mounting frame to also image the remote reference target in the eyepiece of the receiver telescope.

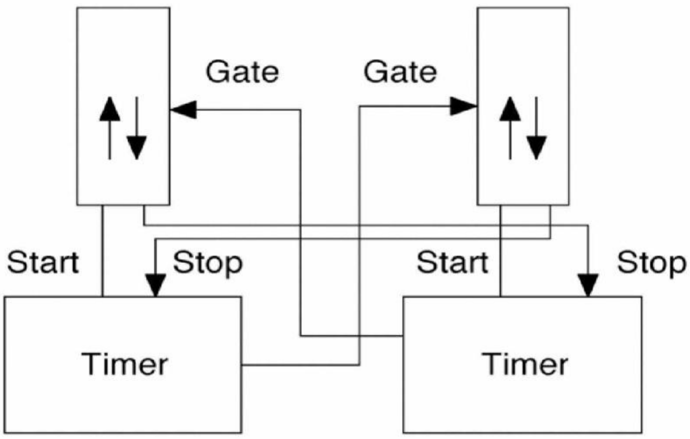

Figure 6. Block diagram illustrating the cable crossover required for the transponder simulation experiment.

Table 1. Expected link budget for ground based transponder simulation. The figures for the WLRS are computed for the Micro-Channel-Plate photomultiplier.

Configuration	n_{ph} Ajisai	n_{ph} Envisat	n_{ph} LAGEOS
WLRS - Transp.	4.5k	1.5k	10
Transp. - WLRS	10k	3.5k	24
WLRS - WLRS	240k	79k	547
Transp. - Transp.	817	272	1.8

Figure 7. Simulation module mounted on top of the WLRS telescope.

4.Experimental Results

4.1. Transponder Link

The transponder module remained on the WLRS telescope for one week and a total of 21 successful satellite passes were observed in different arrangements, covering all the different options of table 1. In this paper we only report results from the two most demanding configurations, namely the actual transponder setup and the case where a high Earth orbiting satellite (LAGEOS 1) has been observed with the transponder module in SLR configuration. Figure 8 shows the result for a daylight Beacon C path, asynchronously running in the transponder configuration (fig. 6). This satellite is in a near circular orbit approximately 1000 km above the ground. According to tab. 1 one would expect a stronger echo detection rate on the WLRS system, because of a link margin, which is by a factor of two higher and because of the much higher laser pulse rate. However the data recorded by the transponder hardware turned out to be much denser in the end. Although the reason for this behavior was not unambiguously identified, circumstances suggest that this happened because of a residual misalignment of the emitting laser beams between the two ranging systems. While the colinearity of the optical axis of both receivers has been verified repeatedly by observing a landmark several kilometers away, similar checks for the transmitting branches of the two system have not been possible. Therefore it is very likely that a small misalignment is responsible for the reduced link budget, because the divergence of the laser beam of the transponder had to be increased. In subsequent observations there were two regimes identified around 30 seconds of arc apart, where the return rate for each of the two systems is at a maximum [7]. After the noise and the trend was removed from the residuals of both data-sets by fitting a polynomial to the transponder data and applying the same parameters to the WLRS measurements, the plot of fig. 9 is obtained. The observed scatter of the WLRS data is much higher than for the simulation unit. This is caused by the much broader pulse width (3 ns) of the Brio laser. In comparison the WLRS laser provides a pulse width of 80 ps. There is more noise in the WLRS ranging window (fig. 8 bottom part) because of a repetition rate twice as high as for the WLRS laser. The effect appears to be smaller than it is in reality, since the WLRS operates under a much smaller field of view (50 μrad rather than 200 μrad) and also uses a cooled detector. The transponder system has not been calibrated to the reference point of the WLRS hence the observed offset of 10 ns between both systems.

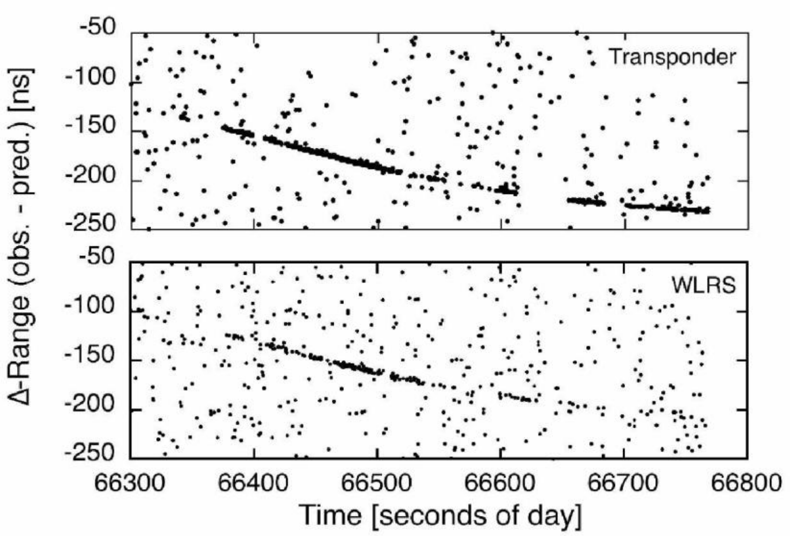

Figure 8. A simultaneous observation of a Beacon C satellite pass with both ranging systems in asynchronous transponder configuration. The pass was observed on August 16, 2008 in daylight.

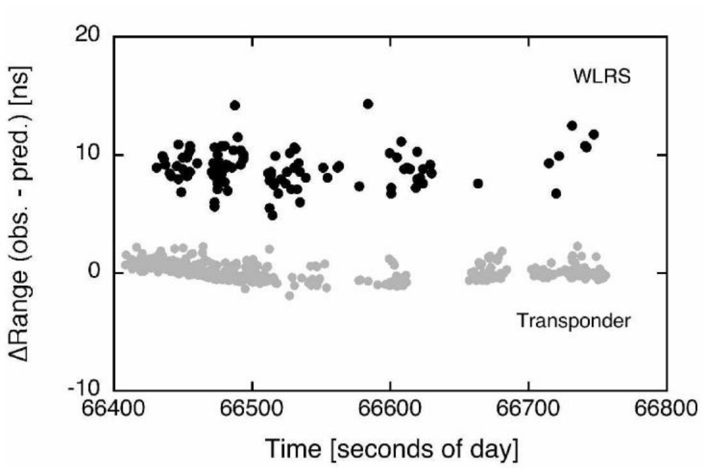

Figure 9. The filtered transponder echos from fig. 8. The data recorded on the WLRS exhibits a larger scatter caused by the 3 ns pulse width of the transponder transmitter. The offset between the two tracks is introduced for better visibility.

4.2. Biases from Receive Signal Intensity Variations

Apart from demonstrating the basic functions and the feasibility of this transponder link experiment, this setup is also useful to investigate systematic receive signal biases [8]. For this purpose only the WLRS laser fires and both telescopes receive the same return signal from the satellite. According to tab. 1 there is approximately a factor of 50 difference between the generated numbers of photo-electrons on each detector system. Some of this imbalance in receive power will usually be compensated by an adjustable gray wedge in the receiver path of the WLRS system, but there are no simple rules for the settings. However when the range residuals from a weak and a strong signal return level are plotted against each other and intensity dependent detector delays appear, this will reflect as a systematic signature in the residual vs. residual plot.

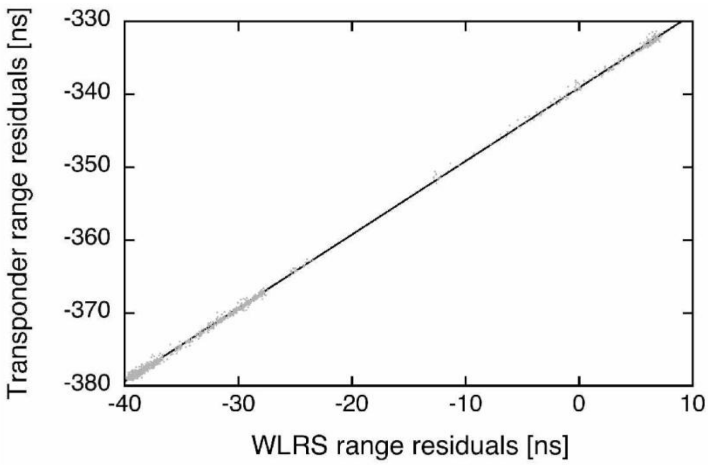

Figure 10. Range residual plot of a Beacon C pass taken on August 13, 2008. Simultaneous detections on both ranging systems are plotted against each other in this chart.

Figure 10 shows such an example for a observed Beacon C pass. A higher density of observations suggest higher intensity on the return signal. The linear regression of this data set yields a slope of 1.008, which is the first indication of a systematic difference between both signals. In the next step we have applied the linear regression to the data and then plotted these residuals versus time. This yields the scatter plot of fig. 11. The solid line superimposed on this data was derived by taking the average of all data points in 1 minute intervals. As expected, areas of high data density have a tendency towards shorter ranges. This is in accordance with both the behavior of avalanche photodiodes operated in the Geiger mode, where a higher return signal level by-passes several stages in the multiplication process, which leads to the breakdown of the bias voltage of the diode. Also photomultipliers employing a constant fraction discriminator for a signal voltage independent timing of the arrival of the laser pulse are expected to measure shorter ranges for higher signal levels, since the discriminator only works in a very limited signal voltage range.

4.3. Simulated Interplanetary Distance

Finally, we have also explored the weakest satellite link listed in tab. 1 and observed a LAGEOS satellite pass on the transponder module alone. The return echo rate was very weak as it is to be expected from a statistically obtained 2 photo-electrons from such a small system.

Figure 12 shows the measured range residuals. There were about 60 returns detected within 560 seconds. This means that 0.5% of all shots (repetition rate: 20 Hz) obtained a valid return signal. This is less than expected from tab. 1. A 2 photoelectron return signal level would usually result in a data rate of about 10%. We believe that this discrepancy can be attributed to both, a slightly larger beam divergence of the outgoing laser beam and an effective atmospheric transmission below the maximum value of T_A= 0.7. During the time, where valid satellite returns have been detected the slant range varied from 7500 km $\leq r_s \leq$ 6700 km with the marginally higher return rate at the longer distances at the beginning of the pass. With s_r = 7500 km, a radar cross section of the satellite LAGEOS of σ_s = 15 million square meter and an assumed value of T_A = 0.6 the equivalent transponder distance for the here described transponder simulation module turns out to be r_t = 0.44 AU.

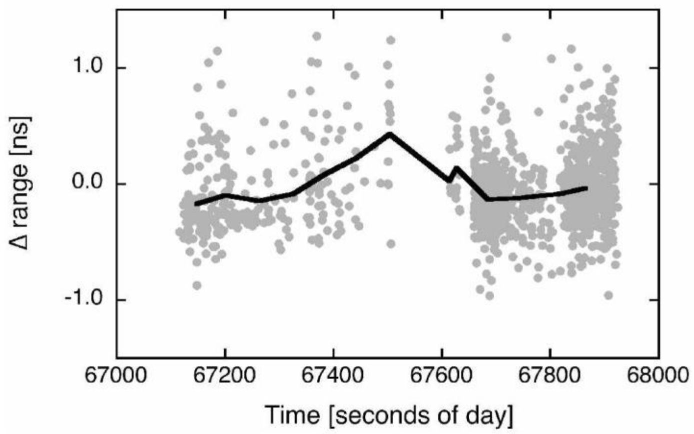

Figure 11. Range residual plot of a Beacon C pass taken on August 13, 2008. The residuals are obtained from a linear regression on simultaneous detections on both ranging systems. The black line was derived from this data set by averaging the data over 1 minute intervals.

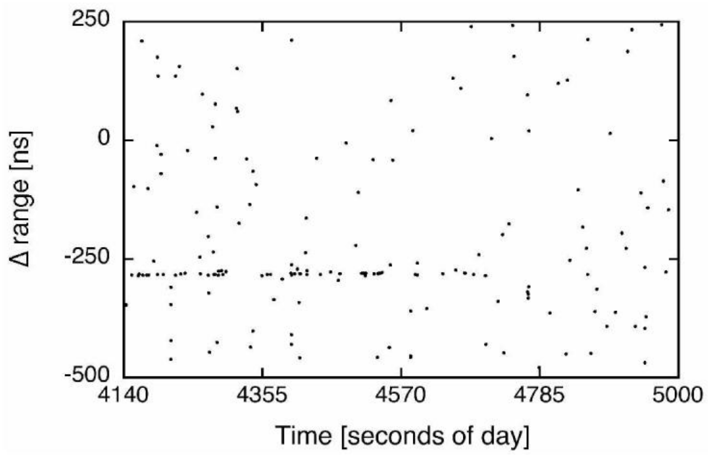

Figure 12. Range residual plot of a LAGEOS 1 pass taken on August 19, 2008 using the transponder module alone. The satellite track is very weak as expected from the low signal level calculated for this case (tab. 1).

If we apply the same calculation for the WLRS system, which routinely tracks GPS satellites and also obtained laser echoes from the Apollo 15 laser reflector, we find a convenient equivalent transponder distance of $r_t \approx 4$ AU and a maximum demonstrated marginal transponder distance of $r_t \approx 110$ AU. However this would require a balanced transponder link, with a space segment about 5 times more efficient than the module investigated in this paper.

5.Conclusion

In this paper we have simulated basic properties of optical interplanetary transponder links experimentally. A small transponder module comprising a pulse laser, a small telescope including provisions for spectral and spatial filtering and an event timer unit was used together with the Wettzell Laser Ranging System for the simulation. During the experiment laser pulses from one system were transmitted to orbiting geodetic satellites. The back-reflections were recorded on the respective other system. The characteristics of the two independent ranging instruments were then used to compute the equivalent transponder deep space distance. While the transponder module showed sufficient sensitivity to cover distances of up to 0.44 AU, the WLRS has a comfortable l-way range margin of about 4 AU. However, since successful lunar echoes have been obtained from the WLRS in the past, it has demonstrated a very marginal equivalent transponder range to about 110 AU, but this cannot be called operational. While the laser link margin is certainly an important parameter, other needs like precise pointing and the alignment of the transmit and receive path are of similar concern for successful interplanetary transponder applications. This is also evident in our experiment, since the measured signal levels always lagged behind the link budget calculations. The great advantage of the transponder simulation is a complete end to end test of a transponder link under real conditions, including all of the involved hardware and the atmosphere, from an easily accessible ground based observatory. The only differences between this experiment and a real deep space transponder link are a double pass of the optical signal through the atmosphere and the alignment of the optical path between the observatory on the ground and an interplanetary spacecraft.

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