
MULTIPLE WAVELENGTH AND REFRACTION SESSION SUMMARY

Chair: Erricos Pavlis

Gurtner presented recent changes at Zimmerwald. The system used internal, near realtime calibration until June 2006. The change was necessitated after routine operations with a second wavelength (infrared) revealed differences between the calibrated ranges of the two colors that could not be explained as errors in the applied refraction models. It turned out that the internal calibration values of the infrared chain showed variations that had not much to do with system calibration. The source of these variations could not be identified. In June 2006 the station switched to external calibration and the differential biases were by and large eliminated. One of the concluding remarks was the need of a 100-fold improvement in the dual wavelength data if they are to be used for refraction modeling.

Müller reported that Lageos-1/2 multi-wavelength normal point data from Zimmerwald and Concepcion were reduced with DGFI's s/w, to estimate station coordinates and color dependent biases. The statistics and the history of bias differences for the Marini-Murray and Mendes-Pavlis refraction models were shown. Full-rate tracking data were also analysed to determine if they lead to results different from the use of onsite normal points. The switch from internal to external calibration at Zimmerwald resulted in a significant improvement of the relative biases, mainly for the infrared side. The tests indicated the superior performance of the new refraction model of Mendes-Pavlis.

Pavlis (for Hulley) presented the validation of the new, sub-millimeter accuracy, zenith delay model of Mendes and Pavlis, [2004] and the sub-centimeter accuracy mapping function of Mendes et al., [2002], using global data from the Atmospheric Infrared Sounder (AIRS), the European Center for Medium Weather Forecasting (ECMWF) and the National Center for Environmental Prediction (NCEP). The models however are still far from the required sub-millimeter accuracy goal for future SLR analysis standards and the requirements place on SLR by the Global Geodetic Surveying System (GGOS) [Pearlman et al., 2005]. They thus developed a new technique, using 3D ray tracing that includes the effects of horizontal refractivity gradients. Global statistics for two years indicated delays can reach even 5 cm at an elevation angle of 10° at certain times of the year and at some locations. Application of the method to a two-year set of global SLR data resulted in variance reduction of the residuals by up to 45%, and 3 mm in RMS.

Hamal reported on a joint activity with Chinese groups using multiple wavelength SLR. He described a novel use of a Single Photon Avalanche Detector (SPAD) for sub-centimeter ranging precision in infrared and sub-millimeter precision ranging in the visible region. This optimum configuration was implemented at the Shanghai station. Ranging was done successfully to satellites distances of 30000 km with one-centimeter precision. The results of direct measurements of atmosphere dispersion were compared to existing refraction models.

Sierk gave a lengthy, entertaining and very animated report of the upgrading activities at Wettzell and Concepcion in an impromptu, unscheduled entry in the session. The brief, 2-slide presentation turned out to be several dozens of slides rolling recollection of every gory detail, of the elaborate steps in upgrading the two systems. At the behest of the anxiously awaiting next presenter, the late Karel Hamal, the chairman had to almost resort to force to put an end to the captivating performance.

Analysis of Multi-Wavelength SLR Tracking Data Using Precise Orbits

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Abstract

Using precise Lageos-1/2 orbit generated by the DOGS (DGFI Orbit and Geodetic Parameter estimation Software) Package (<http://ilrsac.dgfi.badw.de/dogs>), multi-wavelength tracking data from Zimmerwald and Concepcion were analysed. We solved for station coordinates and color dependent biases. Some statistics and the history of bias differences for various tropospheric refraction models are shown. Additionally the available full-rate tracking data were analysed to see if there are differences to the biases obtained from the onsite normal points. The results show that the switch from internal to external calibration at Zimmerwald give a significant improvement of the relative biases, mainly from the infrared part. Finally we tried to rate the refraction models from the resulting bias differences.

Introduction

After an email request from Werner Gurtner to investigate if the new calibration scheme for Zimmerwald, Switzerland, since June 21 2006, has improved the quality of the two frequency data, we decided to reprocess all Zimmerwald data for 2005 and 2006 with the new DOGS programme, version 4.07, (Angermann et al. 2004) and strategy.

For the period 2005/06 we solved weekly Lageos-1/2 arcs using the same models as in the weekly position and EOP series. The parameters solved in this weekly arcs are:

- internal arc parameters
- earth orientation parameters
- station coordinates
- weekly biases for selected stations
- for Zimmerwald additionally a colour dependent bias per pass

Analysis

In a first step we looked into the range residual for the two colours, not solving for biases to see if the discrepancy between red and blue range residuals decrease after the calibration change. It is evident, that the range residuals reduced after the change in the Zimmerwald calibration from internal to external. In figure 1 the residuals prior and after the event are plotted. As next test we compared the relative biases between red and blue to see whether we could see an improvement of the data quality, too. In figure 2 the relative biases red-blue are summarized.

Using these results we tried to look for systematic characteristics in the relative biases. Unfortunately we did not see any correlation between bias and elevation resp. atmospheric data. The relative bias between is small after the change in calibration, see figure 3, but the precision is still not good enough to make full use of information contained in the two colors.

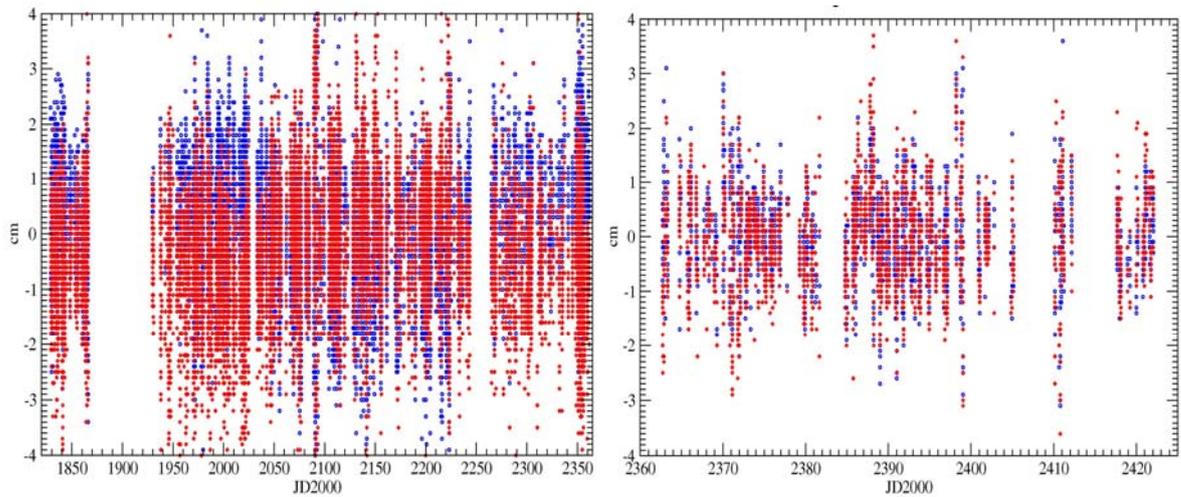


Figure 1. Lageos-1 range residuals (red and blue Laser) for Zimmerwald

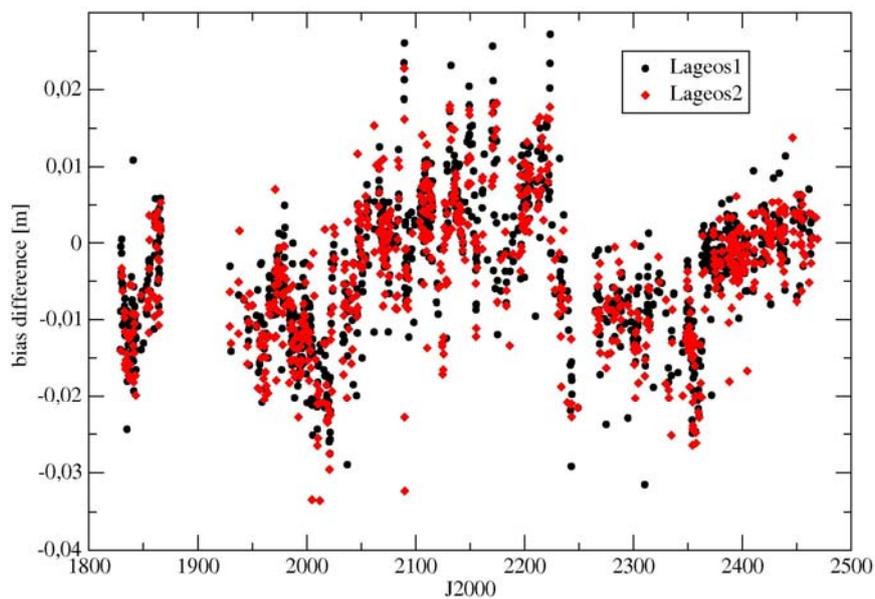


Figure 2. Relative bias between red and blue Laser (cal. change at 2362.5 JD2000)

A test to use the full rate tracking data provided for some of the Zimmerwald passes, did also fail because the epochs of the returned pulses are not identical and an interpolation to simultaneous results did not reach the required accuracy.

There is another station, Concepcion in Chile, operated by the TIGO system, which has the capability of two frequency ranging. We also tried to analyse these tracking data, but there is also no evidence of any systematic in the relative residuals. Mainly due to the fact the most of the time TIGO only delivers red wavelength tracking data, see figure 4, for all two-frequency passes available in 2005/06. The only result is that the biases are bigger than the Zimmerwald biases which could indicate that the calibration of the TIGO system is not stable enough because the tropospheric conditions in Chile are not so different to Europe. But there could also be other reasons for that higher noise in the relative biases.

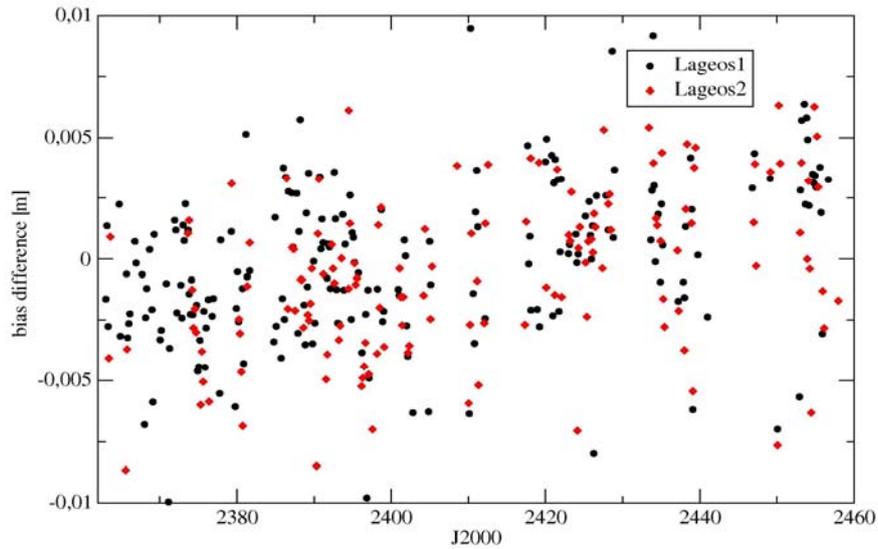


Figure 3. Relative bias after calibration change for Lageos-1/2

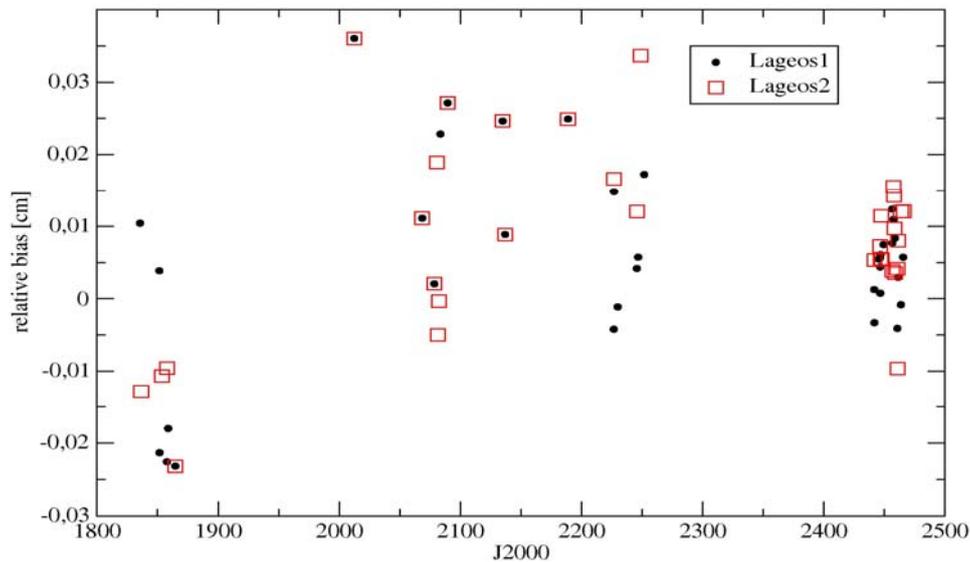


Figure 4. Relative biases for Concepcion in Chile (TIGO system)

Analysis of Troposphere Models.

To get at least some results from our computations we tried to see if there is a difference in the relative biases for the presently used Model Marini-Murray and the new Mendes-Pavlis model. There is no direct improvement if we look into the relative biases only, see figure 5. But if we look into the orbital fit, a clear indication that the new Mendes-Pavlis model gives an improvement is the mean weekly r.m.s. fit for the Zimmerwald SLR station which decrease significantly. In figure 6 we see the weekly r.m.s for Lageos-2 for Zimmerwald with solved station coordinates and relative range biases.

Conclusion

The new calibration at Zimmerwald, Switzerland, improved the quality of the two frequency SLR tracking data but there is still not enough precision in the relative biases to make full use of the data. The other two wavelength tracking system TIGO

at Concepcion in Chile has higher relative biases which could be the cause of calibration problems, like the Zimmerwald system.

The new Mendes-Pavlis tropospheric delay model gives, at least for the two frequency systems, an improvement compared to the old Marini-Murray model.

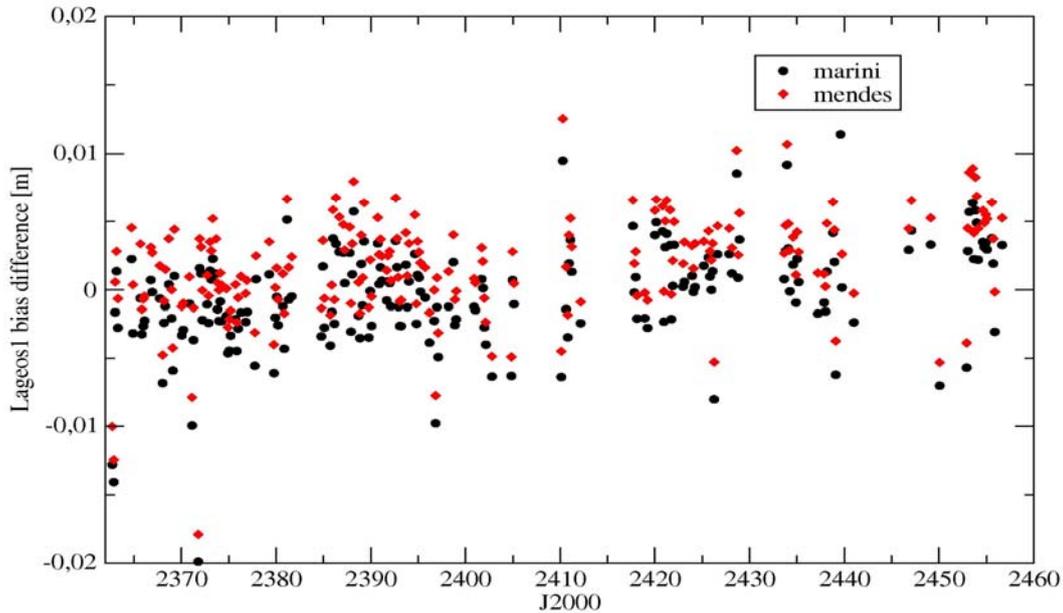


Figure 5. Relative biases for Lageos-1 using Marini and Mendes refraction model

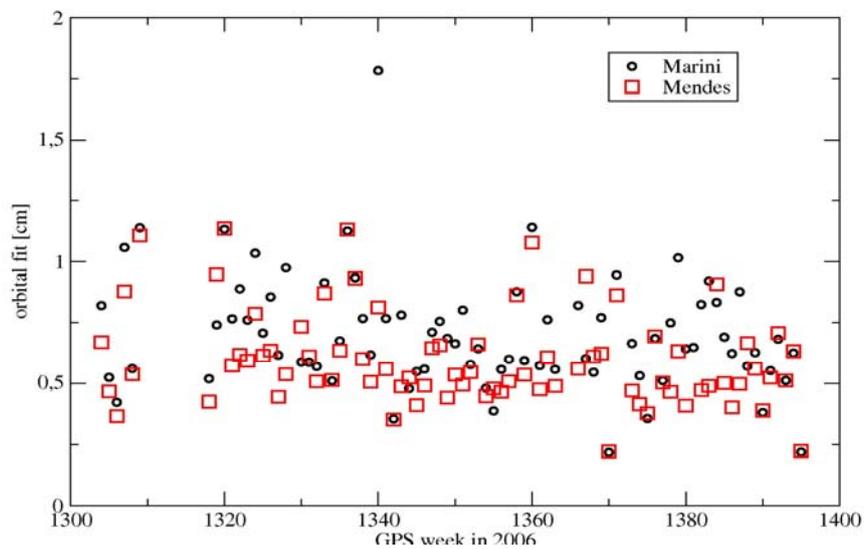


Figure 6. Mean weekly residuals of Lageos-2 arcs for Zimmerwald

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Improvement of Current Refraction Modeling in Satellite Laser Ranging (SLR) by Ray Tracing through Meteorological Data

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Abstract

The accuracy of current modern space-based geodetic systems such as Satellite Laser Ranging (SLR), Very Long Baseline Interferometry (VLBI), the Global Positioning System (GPS), and satellite altimetry all suffer from limitations in the modeling of atmospheric refraction corrections. The current modeling of atmospheric refraction in the analysis of SLR data comprises the determination of the atmospheric delay in the zenith direction and subsequent projection to a given elevation angle, using a mapping function (MF). Recently a new zenith delay (ZD) model of sub-millimeter accuracy [Mendes and Pavlis, 2004] and a new MF of sub-centimeter accuracy [Mendes et al., 2002] were developed, applicable to the wavelengths used in modern SLR instrumentation.

We have already assessed and validated the new ZD model and MF's using 2-d ray tracing and globally distributed data from the Atmospheric Infrared Sounder (AIRS), the European Center for Medium Weather Forecasting (ECMWF) and the National Center for Environmental Prediction (NCEP). However, the models still remain far from the required sub-millimeter accuracy goal for future SLR analysis standards as set forth by the International Laser Ranging Service (ILRS) based on the requirements place on SLR by the Global Geodetic Surveying System (GGOS) [Pearlman et al., 2005].

To further improve atmospheric delay modeling, we need to look at the application of ray tracing and horizontal refractivity gradients on SLR data collected at the core SLR sites around the globe. We have found horizontal gradient delays of up to 5 cm at an elevation angle of 10° at certain times of year and SLR site locations. The effects of applying ray tracing results, including horizontal gradients to a set of global SLR geodetic data resulted in reduction of the observation residuals by up to 45% in variance, and 3 mm in RMS. This is a highly significant contribution for the SLR technique's effort to reach an accuracy at the 1-mm level this decade.

Introduction

All current models of atmospheric delay for SLR observations assume a spherically symmetric atmosphere, ignoring horizontal gradients in the refractive index of the atmosphere. In order to improve models of atmospheric delay, horizontal gradients in the atmospheric refractive index need to be understood and modeled on a global scale. Currently, ignoring horizontal gradients is the largest source of error in atmospheric delay models for SLR at low elevation angles. We have demonstrated that the contribution of horizontal gradients to the total atmospheric delay is primarily at the few-centimeter level at 10° elevation, and can be as large as 5 cm at certain locations (where SLR stations operate) and times of year. Although centimeter delay corrections seem small, horizontal gradients need to be taken into account because they can lead to significant errors in estimated vertical and to a lesser extent, horizontal station coordinates, which in turn affect the accuracy of the scale and origin of the International Terrestrial Reference Frame (ITRF) [Altamimi et al., 2002].

Presently, we are attempting to develop the infrastructure and enabling science that will allow us to develop future ITRF's with an origin accurate to 1 mm at its epoch of definition and a stability of 0.1 mm/year or better, a tenfold improvement over our current capabilities that are no better than 0.4 parts per billion (~3 mm) in origin stability. Part of this effort requires the improvement of our atmospheric delay corrections to the SLR data with an accuracy of 1 mm or better. In the past, VLBI groups used NCEP fields to calculate refractivity gradients in order to make comparisons with results obtained from their VLBI geodetic data. However, we are entering a new era where global snapshots are available from satellite-borne instruments on a daily basis and at much higher spatial resolution than weather models. We will primarily be using atmospheric profiles from the AIRS instrument on NASA's AQUA Earth Observing System (EOS) platform in order to compute the atmospheric delay by ray tracing and including horizontal refractivity gradient contributions. We also use global data sets from ECMWF and NCEP to supplement, compare, and validate the AIRS results.

Methodology

The optical path length between the tracking station and satellite is defined as the integral of the group refractive index along the path of the ray. We define the atmospheric delay as the difference between the optical path length and the geometric path length:

$$d_{atm} = \int_{ray} n ds - \int_{vac} ds \quad (1)$$

where n is the group refractive index, and $ds = dr/\sin\theta$ is a differential element of length along the path of the ray. The subscripts *ray* and *vac* in the integral indicate the actual ray path and vacuum path of the signal. If we express the group refractive index in terms of the group refractivity, N

$$n = 1 + 10^{-6} N \quad (2)$$

then the atmospheric delay can be expressed as:

$$d_{atm} = 10^{-6} \int_{ray} N ds + \left[\int_{ray} ds - \int_{vac} ds \right] \quad (3)$$

where the first term represents the excess path delay or velocity error, and the bracketed term is the delay due to the bending of the ray, called the geometric delay (d_{geo}).

By expanding the refractivity, N , in a Taylor's series expansion around the laser site [*Gardner, 1977*], the total atmospheric delay including gradients, can be written as:

$$d_{atm} = 10^{-6} \int_{r_s}^{r_a} \frac{N(r)}{\sin\theta} dr + d_{geo} + \left[\int_{r_s}^{r_a} \frac{N_{ns}(r)\rho}{\sin\theta} dr \right] \cos\alpha + \left[\int_{r_s}^{r_a} \frac{N_{ew}(r)\rho}{\sin\theta} dr \right] \sin\alpha \quad (4)$$

where θ is the elevation angle at altitude calculated using Snell's law, $\rho = r\phi$ represents horizontal arc distance from the station, r_s is the geocentric radius of the station, and r_a is the geocentric radius at the top of the atmosphere. The third and fourth terms are the contribution to the total delay from horizontal gradients, where N_{ns} and N_{ew} are the North-South (NS) and East-West (EW) components of the horizontal refractivity gradient. The $\cos\alpha$ and $\sin\alpha$ terms project the NS and EW gradient components onto the azimuth of the observation.

Ray Tracing

The most accurate and comprehensive way of calculating the atmospheric delay is by using a technique known as ray tracing. The computation process is based on geometric optics theory applied over a series of thin spherical shells, concentric with the earth, within which a constant refractivity is assumed. Using Snell's law to calculate elevation changes and horizontal refractivity gradients to calculate azimuth changes along the ray's path, one can trace the ray accurately through the atmosphere in two or three dimensions and calculate the total delay by integrating the incremental delay at each atmospheric layer until the top of the atmosphere using equation (4).

Atmospheric delay modeling has been neglected for decades, with the official model for SLR being that of Marini and Murray [1973], developed in the early 70's. Only in recent years, has an improved ZD model [Mendes and Pavlis, 2004] and MF [Mendes *et al.*, 2002] been developed, applicable to the wavelengths used in present day SLR. The new ZD model and MF, called the Mendes-Pavlis (M-P) model, was adopted for the reanalysis of all SLR data from 1976 till present, and in the production of the weekly operational products, beginning January 1, 2007. However, these are still models and the assumption of uniform, spherically symmetric refractive index layers made in their development is unreasonable as it makes the delay only dependent on elevation and not on azimuth. We now have the capability to use atmospheric fields from AIRS that are available at near-real time, twice-daily (day and night), and on a global scale. This enables us to compute the total delay, including gradients, by ray tracing at any elevation and azimuth using real-time atmospheric conditions at any chosen SLR site on the globe. Although ray tracing can be computationally expensive and involves many steps, the results are more physically meaningful than those calculated from delay models, and with the computing facilities available today, the benefits far outweigh the costs. Furthermore, the process can be highly automated at a single, "clearinghouse" type location, with the results disseminated to the users via Internet services and the World Wide Web.

Horizontal Refractivity Gradients

Until now, the contribution from horizontal refractivity gradients to the total atmospheric delay has essentially been ignored in the analysis of SLR data. Previous studies of horizontal gradients (see, for example, Gardner *et al.*, 1978; MacMillan, 1995; Chen and Herring, 1997) were all based on developing models to account for the gradient delay. We have found these models to be unreasonable in estimating the delay for several reasons: The mapping function used by Chen and Herring [1997] ignores higher order terms in the expansion of the continued fraction used in calculating the mapping function, and the development is based on the fact that the gradients have the same direction at all levels in the atmosphere. The model developed by MacMillan [1995] includes an extra term, $cot(e)$, that accounts for larger gradient changes at low elevation angles, but the delay becomes infinite at small elevation angles as a result. The Gardner [1978] gradient model is dependent on surface gradient values of temperature and pressure, thereby ignoring gradient values at higher altitudes that could introduce significant errors in the magnitude and sign of the gradient delay.

We calculate the gradients in a more direct and accurate way by ray tracing using the third and fourth terms in equation (6) combined with atmospheric profiles from AIRS, ECMWF, and NCEP. Our initial results show that the largest gradient variations occur as a result of seasonal and diurnal changes. Stations situated in mountainous regions,

such as McDonald, TX and Monument Peak, CA had larger horizontal pressure gradients, while stations in close proximity to large bodies of water such as Yarragadee, Australia, had larger horizontal temperature gradients. No significant non-hydrostatic (wet) gradients were found, with maximum wet delays only reaching a few tenths of a millimeter during the summer at Greenbelt, MD. Maximum NS gradient delays of up to 5 cm were found at Yarragadee and Herstmonceux, UK, at an elevation angle of 10°, while standard deviations ranged from 6-12 mm depending on location and time of year. The EW gradients were smaller in magnitude and variability than the NS gradients.

Results

We now look at the impact of using ray tracing with AIRS, ECMWF and NCEP data on the analysis of a set of real SLR data for the geodetic satellite LAGEOS 1 during 2004 and 2005 and for 10 of the globally distributed core SLR stations. We analyze our results by looking at the RMS and variance percent difference between the ‘corrected’ SLR residuals with the atmospheric delay estimated by ray tracing and including horizontal gradients, and the ‘original’ residuals, that use the M-P model for calculating the atmospheric delay. The total number of observations used in the statistics for all stations is 47664. Positive values of RMS and variance indicate improvement in the results.

The results when including the gradients in Figure 1 (i.e. delay = model + gradients) show that the residual variances when using AIRS data are reduced by up to 10-15% in variance when only gradient corrections are applied. ECMWF and NCEP results also show improvement with residual reductions ranging from 5-10%. AIRS ray tracing results had a greater improvement in RMS and variance when compared to

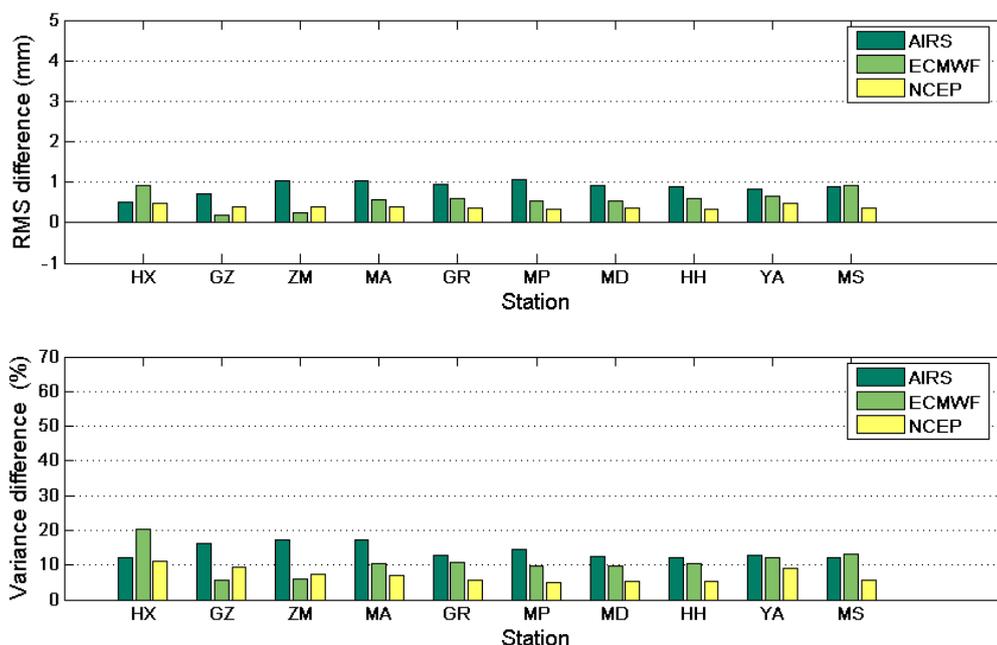


Figure 1. RMS (top) and variance (bottom) differences between the original residuals (model) and the gradient-corrected residuals (model + gradients) for stations: HX (Herstmonceux, UK), GZ (Graz, Austria), ZM (Zimmerwald, Switzerland), MA (Matera, Italy), GR (Greenbelt, MD), MP (Monument Peak, CA), MD (McDonald, TX), HH (Hartebeesthoek, South Africa), YA (Yarragadee, Australia), and MS (Mt. Stromlo, Australia).

NCEP and ECMWF results for all stations. This can probably be attributed to the higher resolution of the AIRS data, providing the ability to calculate the gradients on a much finer scale.

When the total correction is applied (i.e. delay = ray tracing + gradients) with no dependence on the model, the NCEP results actually show larger improvements than AIRS and ECMWF (Figure 2). However, it is interesting to note that there are instances where we see negative RMS differences for NCEP at Herstmonceux, Graz and Greenbelt, even though the corresponding variances show improvement. This is most likely due to either a large positive or negative bias in the mean of the corrected residuals. There is an overall greater improvement in the results when the total correction is applied, and this can be seen as an increase in variance percent difference from Figure 1 to Figure 2. However, at Yarragadee and Mt Stromlo, AIRS total correction actually does slightly worse than the gradient correction. AIRS variances decrease from 12.8% for the gradient correction, to 12.4% for the total correction at Yarragadee and from 12.3% to 9.8% at Mt Stromlo. High AIRS variabilities in boundary layer pressure and temperatures on the interface between land and ocean at these stations could be a factor in this case.

Summary and future plans

Our current and near-term plans are to improve and generalize our 3-d ray tracing process and to include as many sources as presently available. In a second step, we plan to establish an automated daily service for all SLR-tracked targets with high-accuracy requirements (i.e. those used for the ITRF, sea-level monitoring, etc.), and provide the community with value-added data sets including these improved atmospheric delay corrections.

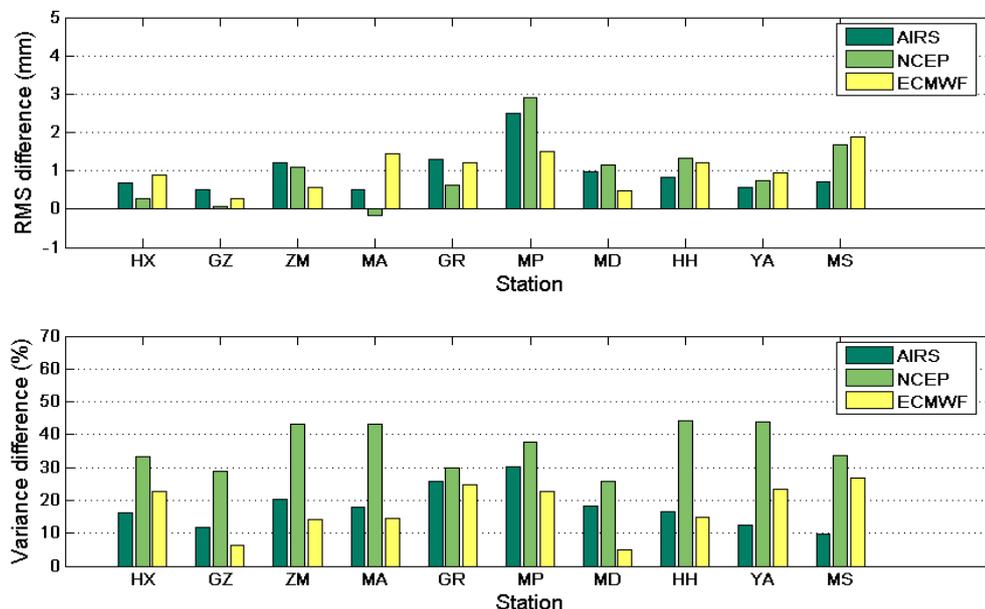


Figure 2. Differences between the original residuals (model) and the total-corrected residuals (ray-tracing + gradients).

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Two-Color Calibration of The Zimmerwald SLR System

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Abstract

The current and the preceding Zimmerwald SLR systems have used internal, near-realtime calibration with apparently good success. The addition of the second wavelength (infrared) to our system revealed, after some time of routine operation, differences between the calibrated ranges of the two colors that could not be explained with errors in the applied refraction models. It turned out that the internal calibration values of the infrared chain showed variations that had not much to do with system calibration. The source of these variations could not be identified. In June 2006 we switched to external calibration by necessity.

Introduction

The 1-meter Zimmerwald satellite laser ranging system, installed in 1997, has been designed for two-color ranging right from the beginning. In order to have two wavelengths with suitable sensors and reasonable reception signal power at our disposal we chose a Titanium-Sapphire laser with the primary wavelength at 846 nm (near infrared) and the second harmonic at 423 nm (blue).

As receivers we are currently using a compensated SPAD at 423 nm and a Hamamatsu H7422P-50 photomultiplier at 846 nm. The time walk of the latter is compensated using an empirical correction table in function of the measured return pulse energy.

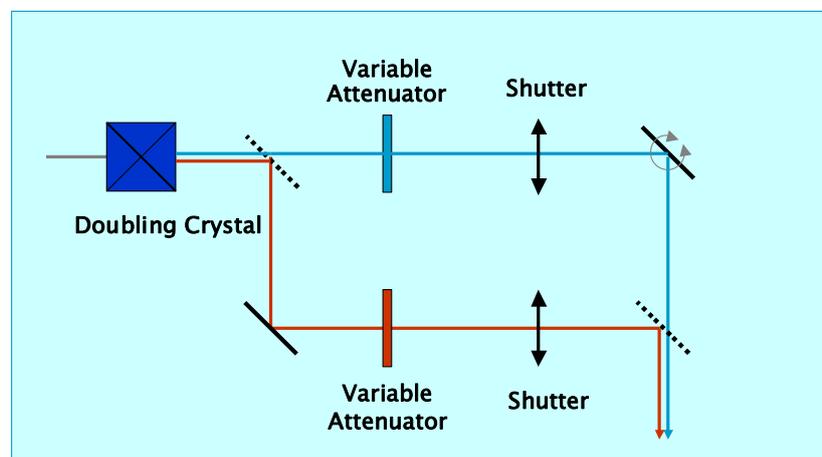


Figure 1: Transmit path: Individual attenuation

Single-shot precision is of the order of 60 ps in blue and 150 ps in infrared.

The optical paths to and from the telescope have been optimized for transmission for the two wavelengths. The two beams can be individually attenuated, both in the transmit as well as in the receiving path.

At the International Laser Ranging Workshop 2002 in Washington we reported (Gurtner, 2002) first results of dual-wavelength operation. We concluded;

- The average difference between infrared and blue residuals per pulse is between 0 and 0.05 ns after a Marini-Murray refraction correction using onsite surface met values.
- Apart from the above mentioned tendency we could not yet detect any systematic behavior of the differences so far.
- The differential Marini-Murray refraction corrections between 423 and 846 nm seem to be better than < 10 mm.
- However, there could still be range biases between the two reception channels of the same order of magnitude.

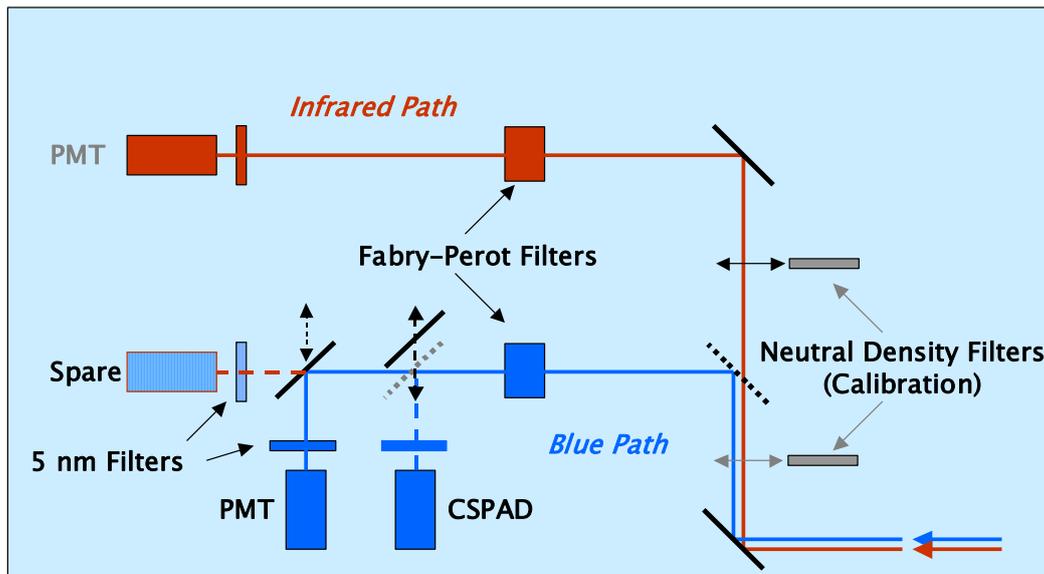


Figure 2: Receiving path: Separation of the two colors

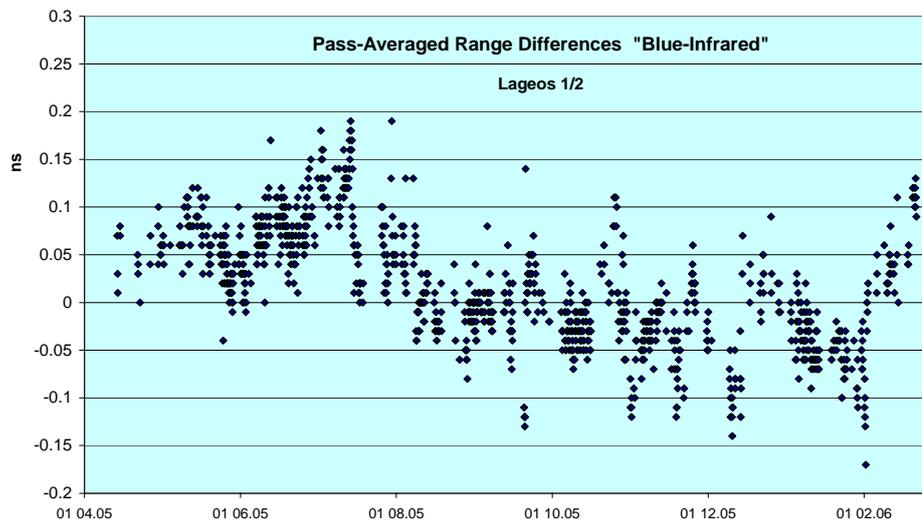


Figure 3: On-site-determined differences blue-infrared

Slowly Varying Systematic Differences

In the meantime, however, the refraction-corrected pass-average differences between the two colors showed slowly varying systematic effects that have nothing to do with remaining errors in the applied refraction corrections. These variations could be seen

in on-site generated differences (Figure 3) as well as in the pass-averaged residuals of global analyses performed by ILRS analysis centers (Figure 4). These variations were as large as plus and minus 2 cm!

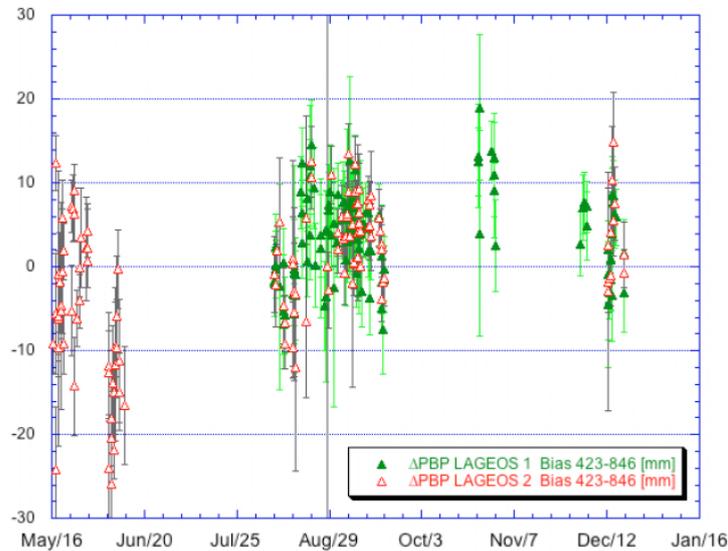


Figure 4: Pass-averaged biases between blue and infrared (JCET analysis center, 2004)

A closer investigation showed that these inter-color bias variations highly correlated with the calibration values used to correct the infrared ranges to the satellites (Fig. 5).

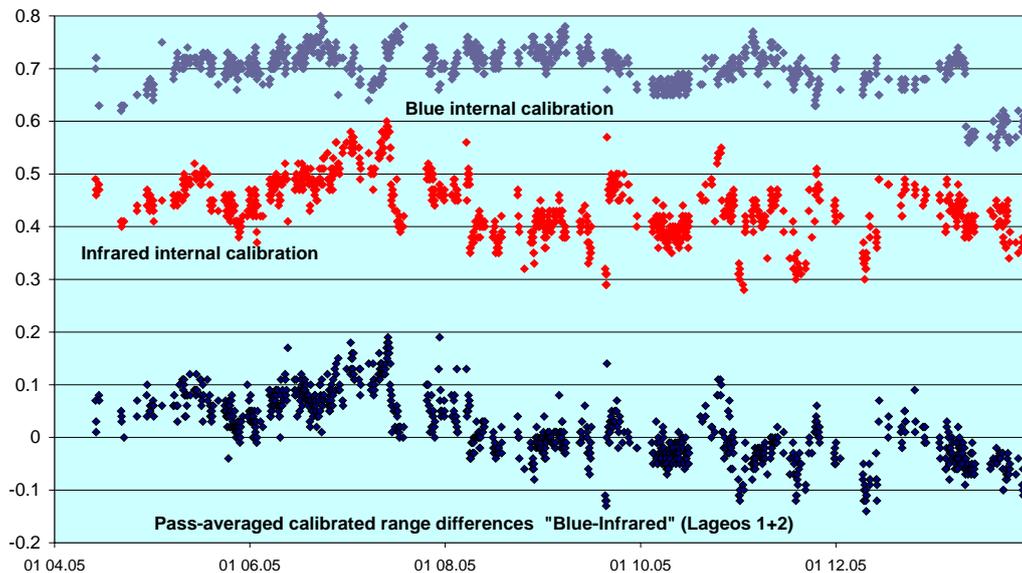


Figure 5 : Time series of internal calibration values and inter-color biases

It can be clearly seen that the time series of the infrared calibration values (middle series, covering about 10 months from April 2005 to February 2006) shows the same features as the pass-averaged calibrated range differences between blue and infrared.

The standard calibration procedure used so-called internal calibrations: During the satellite passes, interleaved with the ranging to the satellites, flight time measurements of a weak calibration beam extracted from the main laser pulse and sent through an internal path of known length are performed to keep track of small changes in the

system behavior (e.g. temperature changes) leading to errors in the measured satellite ranges.

The differences between the calibrated ranges (corrected for tropospheric refraction) to the satellites in the two colors should then only contain biases from residual errors in the tropospheric corrections and the applied calibration values, and various random errors from the measurement procedures. The fact that we see slowly varying inter-color biases correlated with the infrared calibration lets us assume that there is a problem with the respective calibration procedure.

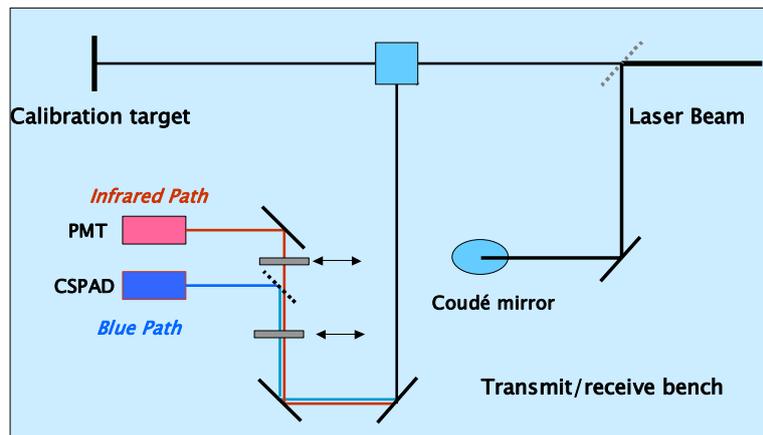


Figure 6: Internal Calibration

Occasionally we also perform calibration observations to an external target at about 600 m distance. Figure 7 shows time series of separate internal and external calibration sessions for infrared over the same 10 months and again the pass-averaged differences of calibrated blue-infrared satellite ranges. It is obvious that the external calibrations do not show the same variations.

A possible reason for the problem with the internal calibration (in infrared) could be the behavior of the respective Stanford counter at the very short time of flight (a few tens of nanoseconds). However, a comparison between the two counters used in the two receiver chains (blue and infrared) and the newly purchased A032ET event timers

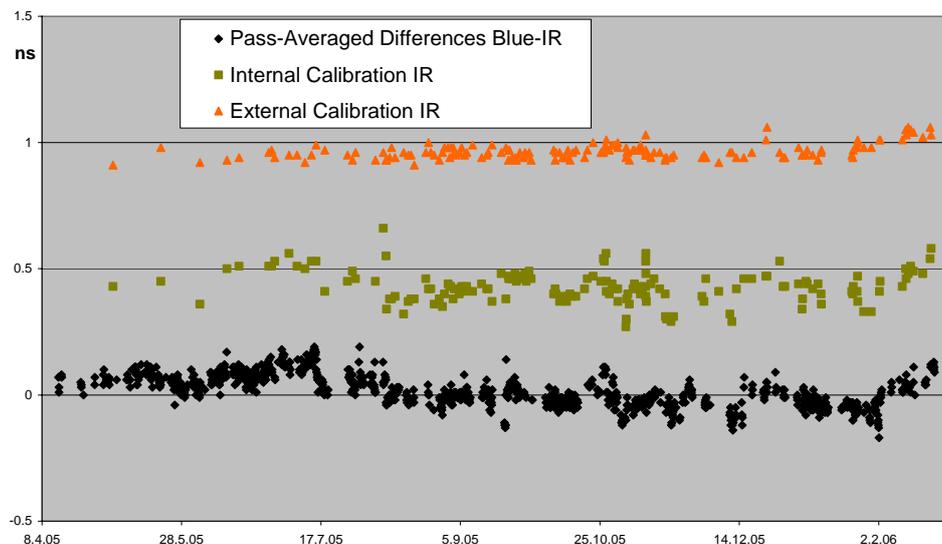


Figure 7: Internal/external calibration, inter-color biases

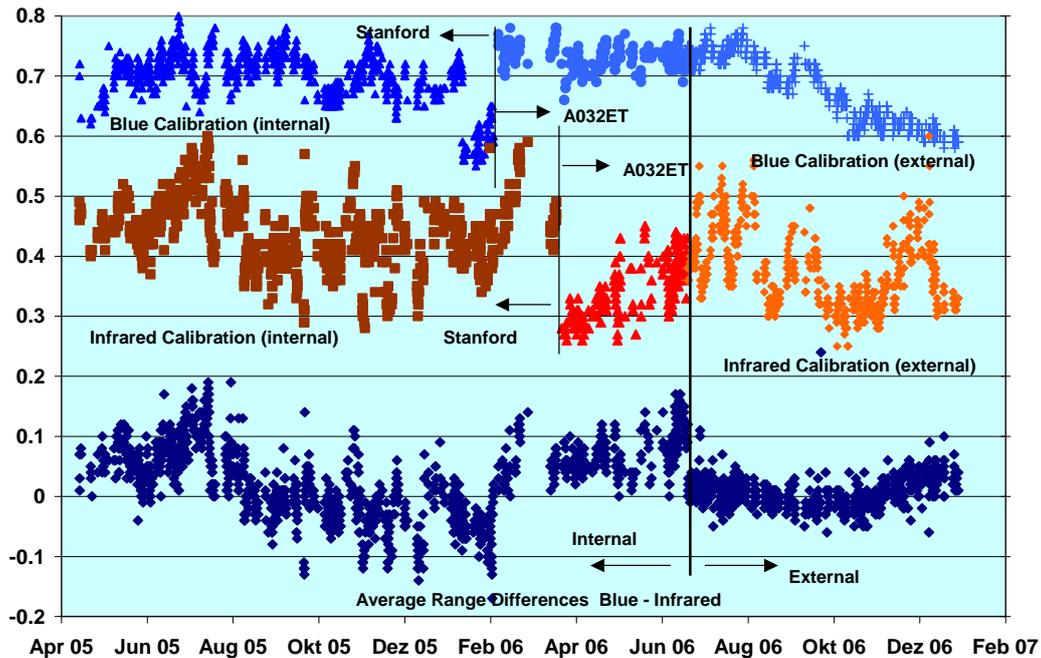


Figure 8: Calibrations, inter-range biases

did not reveal anything suspicious. The later replacement of the Stanford counters by the event timers in spring 2006 did not solve the problem either.

Consequently we decided to replace the internal calibration procedure by calibrations to the external target. We modified the observation procedures accordingly: The scheduler inserts now approximately every half hour a short calibration session into the satellite passes.

Figure 8 shows now the behavior of the inter-color biases before and after the modification of the calibration procedures on June 21, 2006. The variations (bottom time series in the Figure) became significantly smaller. There still seems to be a small signature in the time series. We will have to closely monitor these differences and hopefully be able to later correlate these variations with some system parameters.

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Multi Color Satellite Laser Ranging At Czech Technical University

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Abstract

We are reporting on our activity on Satellite Laser Ranging (SLR) using multiple wavelengths. The reasons for simultaneous multi-frequency laser ranging of artificial Earth satellites are discussed. Atmospheric dispersion study and the eye-safe wavelength region are both considered. To detect the returned signal, the Single Photon Avalanche Detector (SPAD) is operated in so-called Geiger mode. The silicon, germanium, and gallium arsenide phosphide based SPAD are used depending on wavelength to cover nearly the entire optical region having the single photon response, temporal resolution better than 120ps FWHM, and quantum efficiency of about 15%. The active area size and the compact design of the detector packages permitted their application in satellite laser ranging yielding sub-centimeter ranging precision in infrared and sub-millimeter precision ranging in the visible region. The active area of the detector used is from 100 to 200 μm . Detectors for the visible region are cooled thermo-electrically and detectors for infrared, based on germanium, are cooled cryogenically with a custom design liquid nitrogen Dewar. The design and diagnostics of a hydrogen Raman-shifted picosecond Nd:YAG laser operated at 10 Hz repetition rate are presented. Both the far-field beam structure and temporal picosecond pulse profile are monitored for different laser configurations. The optimum laser configuration has been implemented to the SLR station in Shanghai for two color ranging. To operate the SLR station in Graz in visible range, three color ranging is accomplished by Nd:YAG SHG 532 nm, the first Stokes Raman at 682 nm and the first anti Stokes at 432 nm using Hydrogen. To operate the eye safe SLR in Tokyo at the 1540 nm wavelength, the laser was operating at 1064 nm to pump the first Stokes at 1540 nm using methane. To operate the SLR in Bern and Wettzell (move to Chile) Titanium-Sapphire based laser has been operating at 852 nm and SHG 426 nm. The color set has been established at the Shanghai observatory since 2004. The ranging has been successfully accomplished for retro-reflector equipped satellites up to a distance 30000 km with one centimeter precision. The results of direct measurements of atmosphere dispersion are presented and compared existing atmosphere models.

Introduction

We have the experience in field of SLR since the seventies of last century. To range satellites or Moon one has to consider several “contributors” to the overall accuracy of the SLR measurement chain: the station itself, satellite retroreflector array, and the atmosphere as well. Current SLR technology aims toward millimeter accuracy. From the point of view of the SLR station, rms of the laser pulse duration, Start and Stop detectors rms and the Event Timer jitter are involved. Related to the atmospheric dispersion, the existing models are not yet explaining the contribution at millimeter

accuracy level. The SLR at different wavelengths might help to understand the atmospheric mapping function down to millimeter and consequently sub-millimeter level. In fact, multi-color SLR is a unique method for overall optical path dispersion model direct verification.

Experiment arrangement

Assuming the atmospheric dispersion, to find the right laser for multiple wavelength millimeter SLR, one can consider the Nd:YAG / SHG / THG, Nd:YAG / SHG / Raman First Stokes / First antiStokes in hydrogen, Nd:YAG / SHG / Raman First Stokes in methane and the Titanium Sapphire Fundamental / SHG, all of them at different repetition rates. The basic of Raman conversion is described by eq. 1.

$$\frac{1}{\lambda_{shifted}} = \frac{1}{\lambda_{pump}} + k \cdot \nu_R, \text{ where } k \in (-\infty, -1) \cup (1, \infty) \quad (1)$$

Where λ is symbol for the wavelength and ν is material constant describing Raman shift for the selected gas. For hydrogen it is 4155 cm^{-1} , for methane 2914 cm^{-1} , and for deuterium 2987 cm^{-1} .

The selection of the laser transmitter concept is influenced by the required reliability in the routine field operation. Considering that the 6 picoseconds round trip time corresponds to one millimeter range, therefore to reach the millimeter goal, the acceptable laser pulse width within the range of 10 to 50 picoseconds is desirable. The experiment energy budget requires the energy in one pulse in order of several tens of millijoules. The selection of the right wavelength pair is determined by the atmospheric dispersion mentioned above, by atmosphere transparency, and by the availability of high effective frequency shifters. In principle it is difficult to use to independent lasers due to the required picosecond synchronization.

The available detectors have to be considered. Our laboratory has long term experience in the field of picosecond temporal resolution solid state detectors¹. For the visible range we did examine mainly silicon based SPADs, for the eyesafe SLR Germanium based SPADs. The silicon one can be operated at thermoelectrically cooling temperature. The germanium based cooled detector is suitable for eyesafe wavelengths; however it has to be cooled by liquid nitrogen. Using the Quantel YG580 Laser 30 mJ / 1.06 μm , 35 ps, different Raman tubes filled by Hydrogen at different pressure, different focusing lens, we were getting 8 mJ / 0.68 μm , 1 mJ / 0.45 μm . Considering the eyesafe SLR using Raman shift in methane from fundamental we were getting 3 mJ / 1.54 μm .

Conclusion

We are presenting a review of our activities on multiple color SLR and recent results from Shanghai SLR observatory². The selection of the right wavelength pair is discussed and together with our experience with available and effective frequency shifters selection and tuning. The multiple color laser transmitter based on Nd:YAG picosecond laser generating the second harmonic frequency and the Raman Stokes and anti Stokes frequencies is dedicated for the new Shanghai SLR station, the part of Western Pacific Laser Ranging Network.

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