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Zimmerwald Dual-Wavelength Observations: First Experiences

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Abstract

On August 14, 2002 Zimmerwald started to submit dual-wavelength SLR data collected on 423 and 846 nm using two Hamamatsu photomultipliers. The paper discusses the special hard- and software installations needed for the dual-wavelength operation and presents first results of acquired passes.

1. Introduction

The new Zimmerwald Satellite Laser Ranging System was introduced in 1997, having replaced the first system which was in use from 1984 until May 1st, 1995. The design of the new system took into account the possibility of dual-wavelength operation right from the beginning. The Titanium-Sapphire laser was selected because of its primary wavelength at 846 nm, which let us hope that suitable detectors, sensitive and fast enough for satellite laser ranging, eventually became available. Together with the second harmonic wavelength at 423 nm, where excellent detectors do exist, we would have the possibility of ranging in these two wavelengths.

With one other exception all satellite laser stations of the International Laser Ranging Service (ILRS) use the secondary wavelength at 512 nm of Neodyne-YAG lasers, only. The big advantage of the Nd:YAG laser is its relatively simple construction and easy maintenance with a good performance (energy, pulse length) for laser ranging. However, there are no off-the-shelf detectors (photomultipliers, avalanche diodes) readily available for the primary wavelength of 1024 nm or other derivative like the Raman-shifted wavelength of 1054 nm.

Measuring simultaneously the same range in two well-separated wavelengths should allow the determination of the total time delay in the time of flight of the laser pulses sent to and reflected by the satellites: The time delay introduced by the refractive property of the atmosphere. The dispersive nature of the refraction generates wavelength-dependent time delays. Provided the dependence is known, the measured difference of the time delays leads to the total delays for the two wavelengths.

The range correction ΔR for the wavelength λ_i at elevation ε can be computed e.g., using the Marini-Murray model (see e.g., [Riepl, 2000]).

$$\Delta R(\lambda_i,\varepsilon) = f(\lambda_i)\,[g_1/\sin(\varepsilon)+g_2/\sin^3(\varepsilon)] + g_3/\sin(\varepsilon)$$

$$= f(\lambda_i)\,g(\varepsilon) + g_3/\sin(\varepsilon)$$

where g_1 depends (among other quantities) on the surface atmospheric pressure P and the water vapor pressure P_w, g_2 depends on P and the surface temperature T, g_3 depends on P_w.

$$R = R_i - \Delta R(\lambda_i,\varepsilon)$$

with R = geometric range, R_i = observation at wavelength λ_i (disregarding other effects like wavelength-dependent target signatures, etc).

The dependency of the factor f on the wavelength λ_i is given e.g., by Barrel&Sears:

$$f(\lambda_i) = 0.9650 + 0.0164/\lambda_i^2 + 0.000228/\lambda_i^4 \quad (\lambda_i \text{ in } \mu m)$$

or others.

From the difference R_2-R_1 between two simultaneously observed ranges in the two wavelengths λ_1 and λ_2 we can immediately compute the factor $g(\varepsilon)$:

$$R_2-R_1 = R+\Delta R(\lambda_2,\varepsilon) - [R + \Delta R(\lambda_1,\varepsilon)]$$

$$= [f(\lambda_2)- f(\lambda_1)]\,g(\varepsilon)$$

i.e.,

$$g(\varepsilon) = (R_2-R_1) / [f(\lambda_2)- f(\lambda_1)]$$

The geometric range can then be reconstructed by

$$R = R_1 - f(\lambda_1)\,g(\varepsilon) - g_3/\sin(\varepsilon)$$

or

$$R = R_2 - f(\lambda_2)\,g(\varepsilon) - g_3/\sin(\varepsilon)$$

The water vapor pressure P_w for the computation of g_3 has to be derived from on-site measurements of the humidity, water vapor radiometer or permanent GPS observations [Neubert, 1996].

Important to note is the error propagation for the computation of the range correction:

$$m_{\Delta R} = f(\lambda_i)\,m_{g(\varepsilon)}$$

$$= \quad f(\lambda_i) / [f(\lambda_2) - f(\lambda_1)] \; m_{R2-R1}$$

Any errors in the observations of the difference between R_2 and R_1 are amplified with the factor of

$$f(\lambda_i) / [f(\lambda_2) - f(\lambda_1)]$$

for the computation of the total refraction correction. Depending on the two wavelengths used, the factor lies between about 10 and 20. For our two wavelengths (423nm and 846 nm) it is 14. This means that the differences have to be observed with an accuracy of better than 1 mm, if the refraction correction should be determined to, let us say, 1 cm.

Until now several dual-wavelength ranging tests on satellites have been performed, mostly by using expensive and rather bulky streak cameras to directly record the time difference between the reception of the two simultaneously generated and emitted laser pulses of the primary (1064 nm) and secondary (532 nm) harmonics of a Nd:YAG laser (see e.g., [Riepl et al, 1996]) or by independently measuring the time of flight at 532 nm with Silicon based avalanche diodes and with a Raman-shifted wavelength at 1540 nm using custom-made, Germanium based, cooled avalanche diodes (see e.g., [Greene et al. 1996]).

No dual-wavelength observations have been submitted to ILRS on a routine basis, so far.

2. The Zimmerwald SLR System

As stated in the introduction, the Zimmerwald Titanium-Sapphire Laser generates a primary wavelength of 846 nm in the near-infrared part of the spectrum. About 40 percent of the output energy is transformed into the second harmonic wavelength of 423 nm by means of a non-linear doubling crystal. The resulting (blue) pulses have a width of about 100 ps FWHM.

The two transmitted laser beams are separated for individual alignment and attenuation and reassembled by selective mirrors as show in Figure 1. The two beams have to be parallel to within one to two arc seconds.

The differential refraction in the elevation angle runs from zero (zenith) to about 4 arc seconds at 20 degrees. Depending on the beam divergence used for tracking it might be difficult to simultaneously track the satellite with the two colors at low elevation without steering of the two beams to account for the differential refraction.

All the mirrors and lenses on the transmitting and receiving optical tables and in the Coudé path of the telescope are optimized for the two wavelengths. The smaller mirrors in the telescope (M2 and M3) are broadband-coated with dielectric multi-layers, also optimized for the two laser wavelengths. The primary mirror M1 (diameter 100 cm) has an aluminum coating with protecting dielectric coatings, also slightly maximizing the reflectivity at the two laser wavelengths.

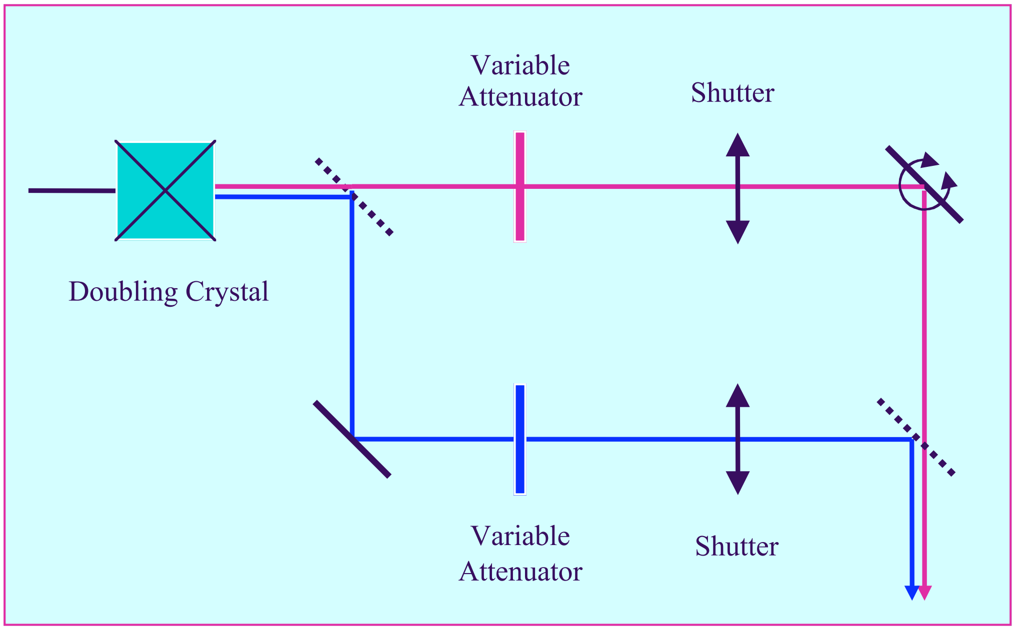

Figure 1: Transmitting Beam

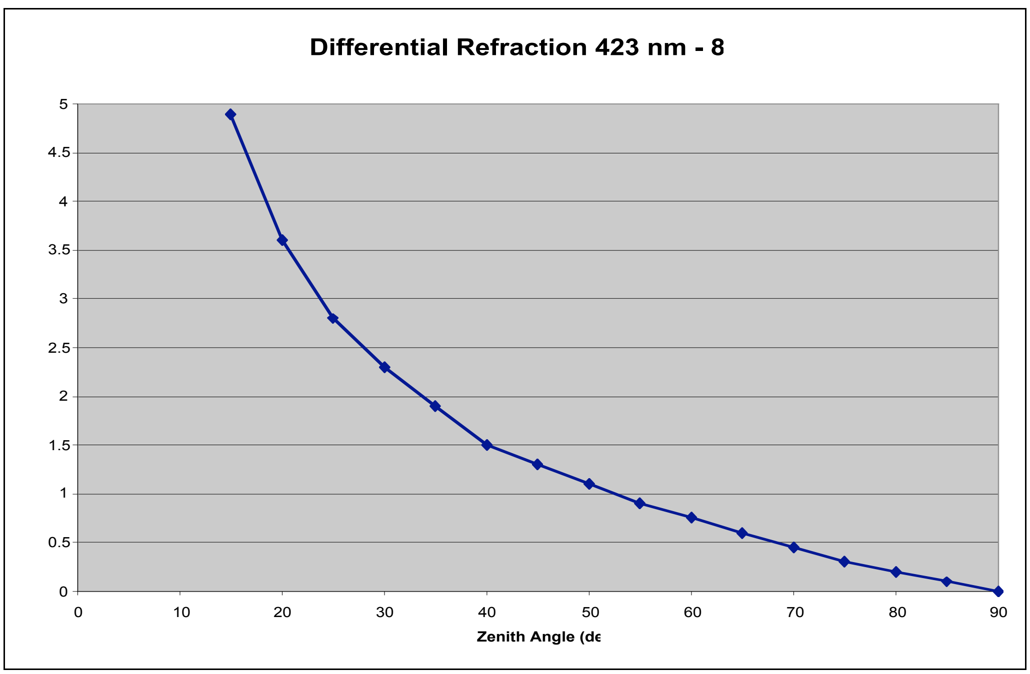

Figure 2: Differential Refraction in Elevaton

The receiving beams are separated into the two colors by a selectively coated mirror and individually filtered by narrow-band filters (Fabry-Perot), see Figure 3.

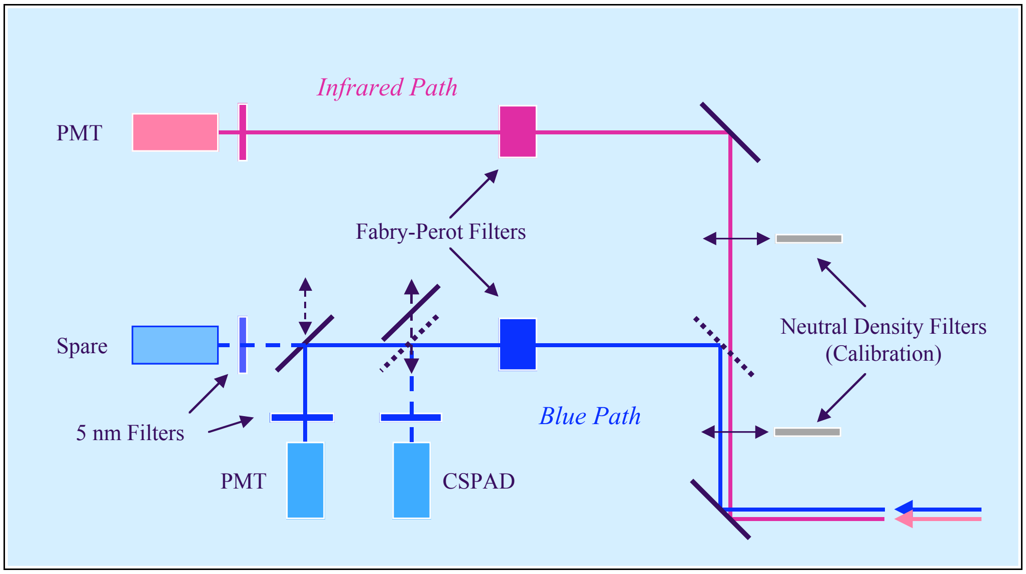

Figure 3: Receiving Path

By means of the polarizers in the transmitting beam the return rate on the two colors can be adjusted individually and kept on the same level (single to a few photons). An individual variable attenuation on the receiving table is in preparation.

The tracking system automatically identifies the true returns among the noise pulses by comparing (majority voting) the 50 latest returns, i.e., the differences between the measured times of flight and their respective predicted values as well as these differences interpreted as time biases in the predictions (along track errors). This detection scheme has been modified to accept both, blue and infrared measurements.

Until mid 2002 all the routine observations of Zimmerwald submitted to the International Laser Ranging Service were performed on the 423 nm wavelength only, using the Hamamatsu H 6533 photomultiplier. The single shot precision turned out to be of the order of 0.12 – 0.18ns = 1.8 – 2.6 cm (on Lageos 1,2).

In spring 2002 the ILRS Formats and Procedure Working Group finalized the dual-wavelength data submission procedures, and the ILRS Data and Analysis Centers were asked to get prepared to accept two-wavelength normalpoint data.

After getting the OK from ILRS in August and initial tests in July and August, Zimmerwald started to submit two-wavelength ranging data on August 14, 2002, the infrared returns being detected by a Hamamatsu photomultiplier H7422P-50.

3. First Experiences

From August 14 to August 31, 2002 168 out of 345 passes were observed in two wavelengths and submitted to the ILRS Data Center at DGFI in Munich.

Let's have a look at one of the Lageos-1 passes:

Wavelength	Single shot observations	Single shot RMS	Calibration RMS	Number of Normalpoints	Average difference
Blue 423 nm	1323	0.16 ns	0.12 ns	18	0.05 ns
IR 846 nm	1337	0.18 ns	0.23 ns	21	

Table 1: Lageos-1 Pass: 25 August 2002, 19:40-20:30 UT

Table 1 shows the total number of observations (i.e. observations having passed the onsite data screening) in the two wavelengths, the single shot RMS determined by the data screening, the RMS of the calibration values collected during the pass and the number of normal points formed with the observations. The average residual difference between the two colors (having applied the Marini-Murray refraction model corrections to all observed ranges) showed to be in this pass 0.05 ns = 7.5 mm, the infrared observations being shorter on the average.

Most passes systematically showed slightly shorter averages for the infrared observations, between about 0.0 and 0.05 ns. No significant dependence on pass elevation or satellite could be identified, so far.

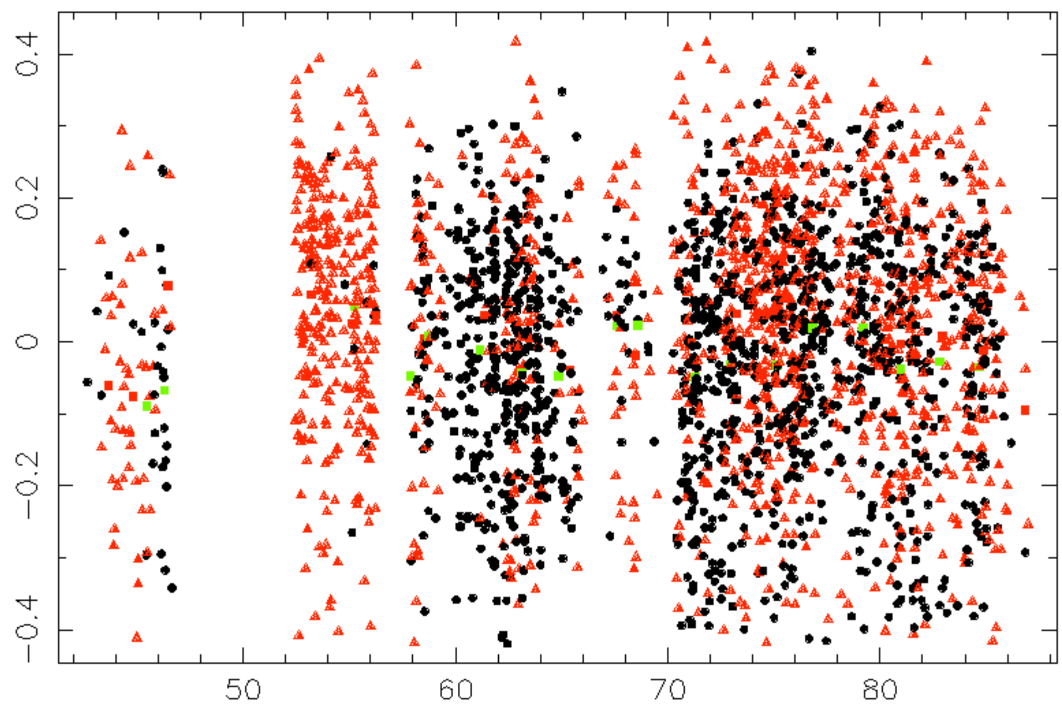

Figure 4: Single Shot Residuals in ns. Black Dots: 423 nm, Red Triangles: 846 nm

Figure 4 shows the single shot residuals, Figure 5 the normalpoint residuals in nanoseconds for the Lageos-1 pass in function of the epoch (minutes of the hour). The black dots show the values at 423 nm, the red ones the infrared values at 846 ns. (Definition of the residuals: „computed minus observed"!)

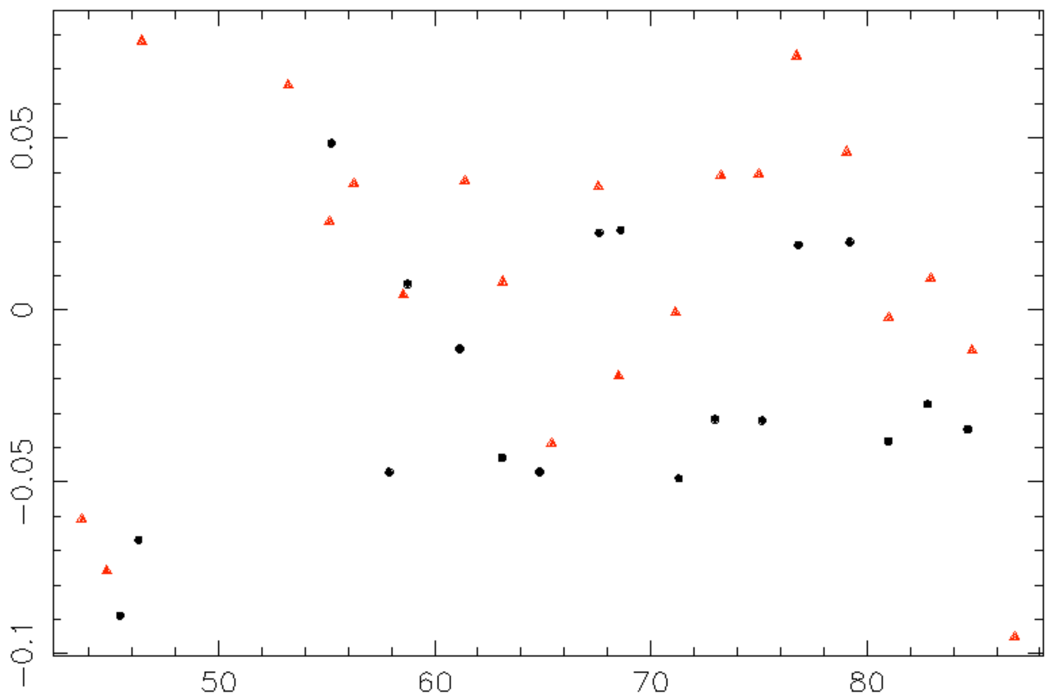

Figure 5: Normalpoint Residuals in ns. Black Dots: 423 nm, Red Triangles: 846 nm

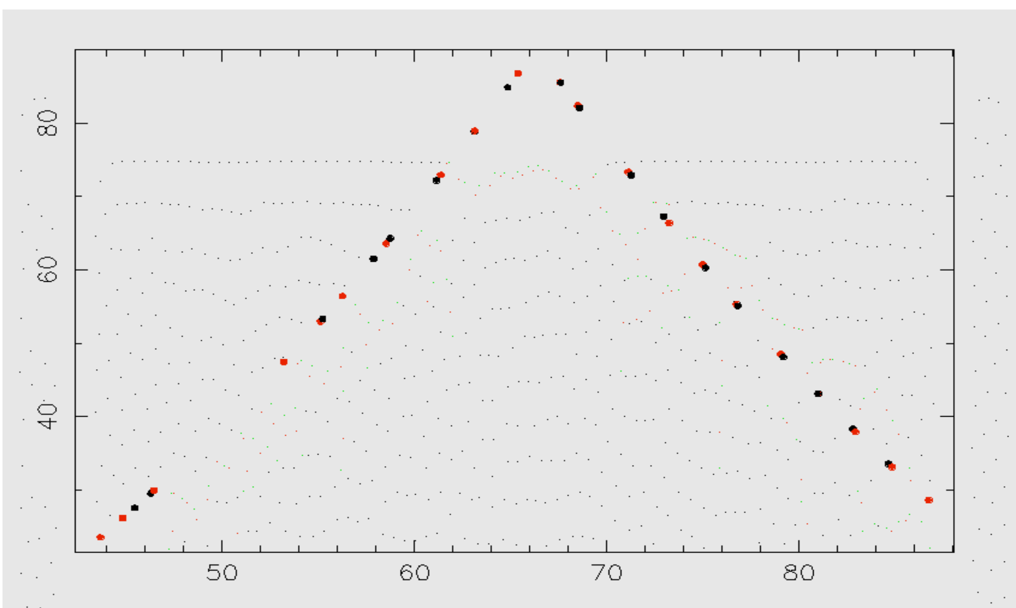

Figure 6: Elevations at the Normalpoint Epochs

For reference we show in Figure 6 the elevations of the satellite at the epochs of the normal points. The satellite covered the range between about 25 and 87 degrees. No systematic differences of the normalpoint or single shot residuals with respect to the elevation can be seen.

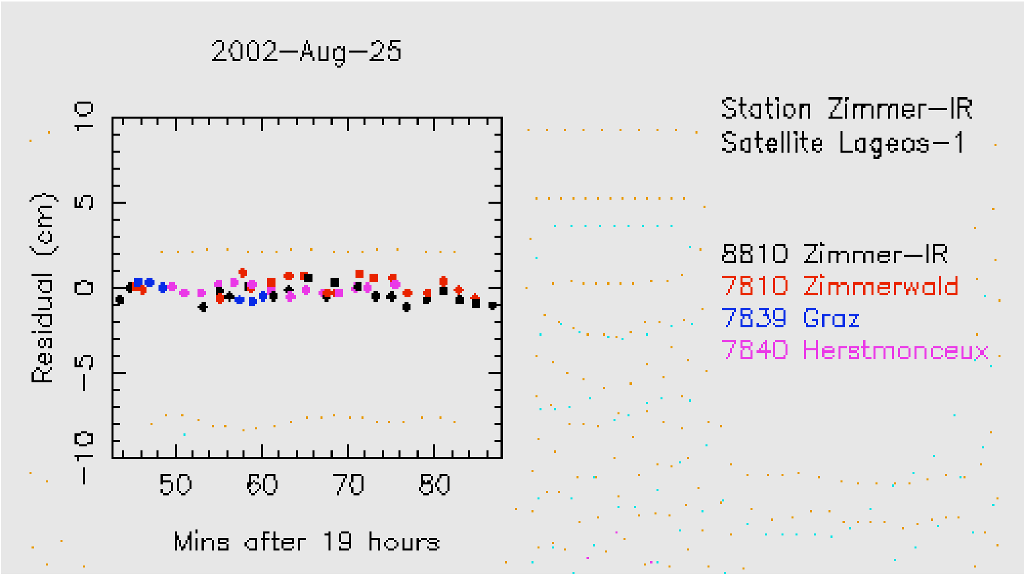

Figure 7: Short-Arc Residuals

Ranging data of all satellite passes simultaneously observed by more than one station in and around Europe are processed in a short-arc mode by the ILRS Associate Analysis Center at the Natural Environment Research Council (NERC) Space Geodesy Facility, United Kingdom (see e.g. http://nercslr.nmt.ac.uk/slrweb/auto_analysis.html). Figure 7 shows the normalpoint residuals of the LAGEOS-1 pass discussed above simultaneously observed by Graz (Austria), Herstmonceux (UK), and Zimmerwald, “Zimmer-IR” being the Zimmerwald infrared residuals. No obvious systematic differences can be detected, at least not on the level of one centimeter.

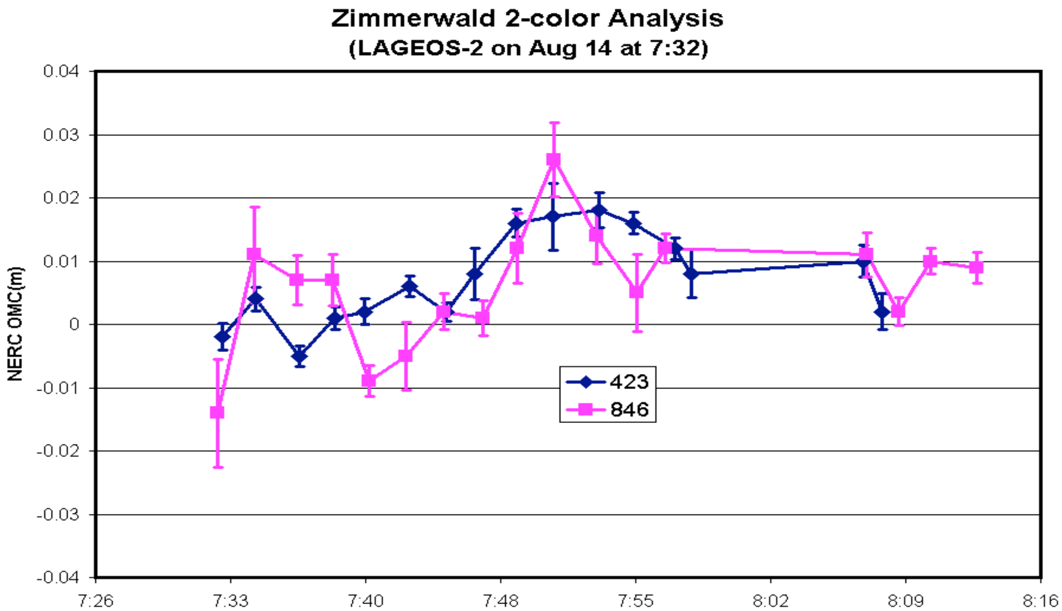

Figure 8: LAGEOS-2 Long-Arc Residuals (NERC)

Another example, a LAGEOS-2 pass on August 14, 2002, analyzed by both the NERC group and the Communications Research Laboratory (CRL), Japan, is shown in the Figures 8 and 9. The general trend of the residuals along the pass depends on the reference orbit of the analyses. The scattering of the normalpoint residuals and the differences between the two colors agree very well between the two solutions. Again, no obvious systematics between the two colors can be seen.

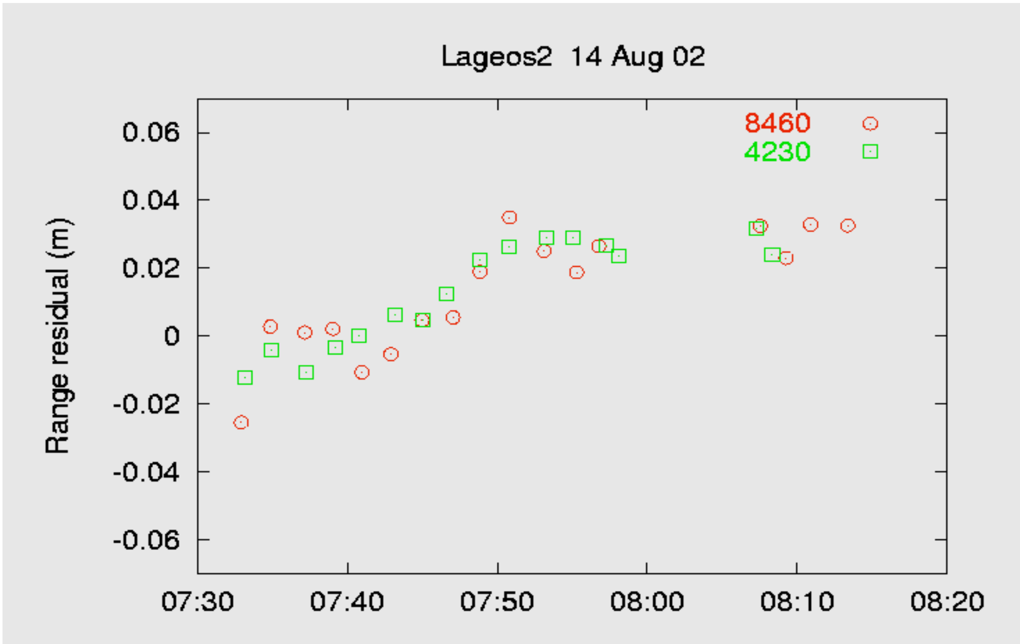

Figure 9: LAGEOS-2 Long-Arc Residuals (CRL)

4. Conclusions

First and very preliminary conclusions can be drawn as follows:

- The beam alignment is rather critical. As we use for the higher satellites a very narrow beam (a few arcseconds only) the blue and infrared beams have to be aligned very carefully
- During the day the infrared channel experiences about half of the background noise of the blue one. This ratio of course is a combination of the differences in the clear sky background noise, the transparency of the optical components and the sensitivity/quantum efficiency of the two receivers in the two wavelengths. In September/October 2002 we had our primary mirror re-coated. It will be interesting to see if this ratio will change significantly (we assume that the old coating deteriorated more importantly in the short wavelengths).
- It is not clear yet under which conditions we get more infrared than blue returns or vice versa. We had passes with a ratio of 2 to 1, others with 1 to 2, or anywhere in between.
- The calibration RMS (ranging to a flat target on the optical bench in single photon mode) is larger on infrared by at least 100 percents (0.2 vs. 0.1 ns). It is not clear yet what contribution comes from the detector and how much comes from a larger pulse length in infrared . (The

conversion of part of the infrared energy to the second harmonic by a non-linear crystal shortens the resulting blue pulse to a certain extent.)

- 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.
- In order to use differences of two-color ranges (single shot, normal point or pass average differences) to improve the tropospheric refraction correction we need an accuracy of these differences to better than one millimeter. Although the averaging process can reduce the precision of these differences to the required level, remaining systematic errors will be scaled with a factor of 10 to 20 into the range corrections. Such differential systematic errors can be generated by the ranging system but also at the satellite's corner cube reflectors as has been shown by [Arnold 2002].
- Although it is doubtful that the current accuracy of the Zimmerwald two-color ranges already allows for an improvement of the tropospheric refraction, we are convinced that the capability and routine performance of ranging with two receiver channels helps to identify and remove or reduce additional systematic errors.

References

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