Two-Color Ranging Upgrade for the MLRO System

Presented at the Eleventh International Workshop on Laser Ranging

Deggendorf, Germany 21-25 September 1998

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Abstract:

The MLRO system, having recently completed its collocation tests, is undergoing a two-color upgrade. This paper describes the objectives of the upgrade and the two-color approaches that are planned for the system.

Two-color ranging has long been a technique that has held the promise for improving the precision of laser ranging by directly measuring the thickness of the atmosphere with an accuracy great-enough to support sub-centimeter geometrical range measurement. Atmosphere and satellite effects remain strong SLR error sources. Since the inception of the system, it has been the ASI's intention to keep use the MLRO system as a research tool as well as an operational system providing data on a day-to-day basis. In accordance with this philosophy, the system originally designed to accommodate an eventual two-color upgrade. The telescope optics were coated for dual frequency ranging and T/R system design was made open-ended with a laser table and T/R Optics table large enough to accommodate the necessary additional components. The MLRO two-color upgrade will add a powerful multi-purpose tool-set to enable the ASI to work towards improving the SLR ranging accuracy.

When used with enhanced meteorological measurements:

- RF techniques for measuring the atmosphere's water vapor content,

- A regional array of instruments measuring surface pressure and temperature (to determine the local pressure gradient), and

- Cooperative experiments with the regional weather service (employing weather balloons) ,

two-color ranging should allow an improvement to our understanding of the atmospheric model for use with single-color ranging.

In addition to the ability to perform two-color ranging atmospheric studies, the high-bandwidth receiver will allow the ASI to accommodate in-orbit satellite array measurements to perform in-orbit characterization of satellite range correction models.

To measure the geometrical range to a satellite with an uncertainty of one centimeter requires that the differential range measurement be performed at the few picosecond level, as illustrated in the following {[1]& [2]} equation.

$$\sigma^2_{Rg} = \sigma^2_{(\lambda 1)} + ((c/2) * (f(\lambda_1)/(f(\lambda_2)-f(\lambda_1))))^2 * \sigma^2_{\delta T(\lambda 1,\lambda 2)}$$

or, expressed another way:

$$\sigma_{\delta T(\lambda_1,\lambda_2)} = SQRT\{ \ (\sigma^2_{Rg} - \sigma^2_{(\lambda 1)}) \ / \ ((c/2) * (f(\lambda_1)/(f(\lambda_2)-f(\lambda_1))))^{2}\}$$

Where:

σ_{Rg} = Standard deviation of the geometrical range (independent of atmosphere)

$\sigma_{(\lambda 1)}$ = Standard deviation of the 1-color range measurement (including atmosphere)

c = Speed of light

$(f(\lambda_1)/(f(\lambda_2)-f(\lambda_1))$ = The dispersive factor (for 355 nm & 532 nm ≅ 12)

$\sigma^2_{\delta T(\lambda 1,\lambda 2)}$ = The standard deviation of the differential range measurement between the two pulses of differing wavelengths.

The ability to measure the differential range between the two pulses $\sigma^2_{\delta T(\lambda 1,\lambda 2)}$ is dependent on a root-sum-square of the components that contribute to error. These include terms for:

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[1] "Atmospheric Refractivity Corrections in Satellite Laser Ranging", Abshire and Gardner; IEEE Transactions on Geoscience and Remote Sensing Vol. GE-23. No 4 July 1985

[2] "Streak Camera Based SLR Receiver for Two Color Atmospheric Measurements", Varghese, Clarke, Oldham, Selden; Proceedings Eighth International Workshop on Laser Ranging Instrumentation, May 18-22, 1992

- The pulse width (as spread or deformed by the target). This pulsewidth uncertainty can improved with increased signal strength as described by the following relationship:

Pulsewidth contribution

$$\sigma^2_{pulsewidth} = ((pulsewidth)^{2} * \text{Shape distortion or spreading}) / (\text{\# of photoelectrons measured})$$

- The uncertainty in the measurement device for the differential time measurement. For the streak camera this includes the sweep speed uncertainty, MCP beam distortion, and imaging system errors.

Other possible error contributions include uncertainty introduced by smoothing and fitting algorithms.

The satellite will have a different far-field diffraction pattern for each wavelength, and varying cube corner contributions for each wavelength. This makes it important that the data acquired be analyzed to overlay the satellite model with the apparent return pulse structure and will be the analytical challenge as the ASI conducts the two-color experiments.

The goal of the two-color ranging system upgrade contract will be to provide the support for acquisition of the data that will support this research. The relationship between single-color precision, geometrical precision, and differential (two-color) precision, defined analytically above, will have numerical consequences as illustrated in Figure 1.

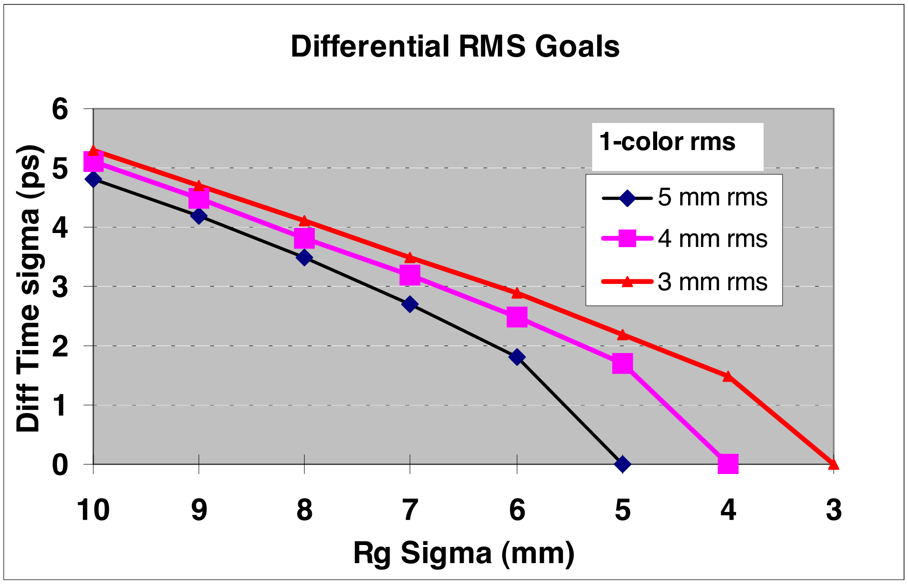

Figure 1: Relationship between differential time of flight measurement and geometrical range precision

The three curves represent the relationship between geometrical (no atmosphere) ranging precision and two-color differential range measurements. Curves for three different assumed single color ranging-precision are plotted. As shown, to achieve a one centimeter geometrical ranging precision for a particular satellite that the system tracks with a 5mm RMS (single shot) precision, will require a 4.8 picosecond RMS differential time of flight measurement. The MLRO can track Starlette with a 3 mm single shot RMS (including satellite spin effects) so a 5 ps RMS differential time of flight measurement should support 1 cm geometrical ranging precision. The MLRO system streak camera should support a differential time of flight measurement of 3.5 picoseconds RMS assuming a photoelectron level of between 50 and 100 photoelectrons for each pulse-cube. This precision has been determined experimentally in the laboratory using a 40-picosecond pulse. If the two-color signal levels are greater than this, the precision will improve somewhat.

In addition to the precision goals, the upgrade is also designed to allow for an easy transition between the single-color ranging mode and the dual-color ranging mode. The anticipated switching time should be on the order of a few minutes to minimize the impact on the system's overall schedule and to make the best use of the system's time for the experiment. Many of the functions on the MLRO are already automated, or computer-assisted. This philosophy is being carried on to the two-color ranging configuration.

The MLRO system will be able to perform two types of two-color ranging. These are: dual MCP-PMT ranging and streak camera ranging.

The dual MCP mode will rely upon normal point precision for the differential measurements by forming two independent time-of-flight measurements to the satellite each shot where both wavelength's signal returns. This is a less-precise technique that relies on a slow-changing experimental condition to minimize the variable conditions through the normal point. Since the two measurements are independent their errors will add in a random fashion and one should expect that if a system produces a 1 mm normal point RMS, then it should produce a 1.41 mm differential normal point RMS. The MLRO is capable of acquiring single-color normal points with almost 1200 points with a single-shot jitter of ≅ 4.0 mm RMS for LAGEOS. This may allow us to obtain some level of results using this approach, but we should expect a reduction in the number of points for dual frequency ranging. This is because the overall signal level for each wavelength is reduced and the probability of receiving both wavelengths for each shot is also significantly less than that of a single color. The dual MCP technique is primarily intended for use with slower-moving satellites like LAGEOS where the atmosphere of interest is not changing quickly, however, satellite orientation variation coupled with variable satellite response to the different wavelengths will probably affect the results.

The streak camera measurement uses a high-bandwidth receiver to measure the differential time-of-flight and a single MCP-PMT for the single-color range measurement. This technique relies on single-shot accuracy to measure the atmosphere's thickness. Since each measurement is precise enough to support the application, the reliance on statistical methods with a large data volume less. The streak camera results may also be binned into normal point results and this should provide some interesting comparisons with the other technique. Another advantage of the streak camera technique is its ability to isolate the satellite effects through analysis of the return waveform. This may be critical since, as discussed earlier, the satellite's response to each frequency is likely to vary considerably. Also the contribution of the satellite's rotation is removed from the measurement. Analysis by the ASI and Telespazio of MLRO collocation data showed that the satellite's rotation is a significant contributor to the overall single-shot RMS.

The design of the two-color upgrade is based on the experience obtained while working with NASA scientists (including John Degnan, Jan McGarry, and Tom Zagwodzki) at the Goddard 1.2-meter facility. A number of enhancements have occurred to the basic approach that should provide a significant improvement to the two-color ranging performance.

As before, the design uses 532nm and 355nm light. A differential delay is imposed between the outgoing two pulses. This delay will be adjusted in real-time to allow the return signals to arrive within a usable window of the streak camera that is set to the 1 nanosecond sweep speed.

Since the MLRO is designed as a synchronous system (to support two-color and time transfer experiments) its laser transmit time is also synchronous and predictable with an RMS jitter of about 3 picoseconds. Streak cameras normally require a pre-trigger pulse 20 to 30 nanoseconds before the anticipated arrival of the signals to be measured. This is usually provided by a second detector, which senses a small part of the return signal and triggers the camera while most of the return signal is delayed using a series of mirrors to allow the streak camera enough time. Since the MLRO fire time is very predictable, it will allow us to trigger the sweep of the streak camera based on a predicted time of arrival for the return pulses. This prediction needs to be better than the normal satellite predictions because the entire streak camera window is only 1 ns. Since the system is also ranging to the satellite using the event timer, the streak camera trigger time will be extrapolated from the observed-calculated (O-C) calculations of the single-color ranging measurements. The use of a predicted trigger will provide a significant enhancement of the signal over our previous experiments (in 1992) since we will not be required to use the long optical delay path and its associated losses to pre-trigger the streak camera.

The new Hamamatsu streak camera has eliminated the internal grid used to accelerate the electrons freed from the photocathode by the incident light. This will provide a 2-times improvement of the photoelectron throughput over our previous experiments. The new design moves the input slit inside of the streak tube and uses the slit structure to induce the electric field. Another enhancement to our previous tests will be a simpler input coupling optics system that will provide us with an additional factor of 2 throughput.

Another added measure will be the use of real-time beam divergence controls (already used by MLRO) and real-time steering of the 532 nm beam to compensate for the differential refractive angle between the green and uv (355nm) beams as a function of telescope elevation angle.

The measures described above should provide between a 10 and 20 times improvement in signal level. These improvements, combined with the MLRO's larger telescope and its ability to transmit a very narrow beam, should provide the signal levels required.

The physical changes to the system will involve the addition of a separate T/R optical path and two additional full-time MCP-PMT detectors dedicated to the two-color channel. The streak camera will be interfaced to the T/R system and sets of moveable mirrors will allow automated transition between the three ranging modes: single color, dual MCP-PMT two-color ranging, streak camera two-color ranging. This is illustrated in Figure 2. Additionally, a number of software modules and processes will be added to acquire data, calibrate and diagnose the new system elements, and analyze the two-color data.

The Streak camera will be coupled with a 1024 X 1024 pixel CCD camera and will employ real-time binning and windowing of the data to handle the potential volume of data produced by the 10 Hz frame rate. The MLRO system will receive a fourth real-time VME computer and second frame grabber dedicated to acquiring and processing the streak camera images. A number additional of X-Windows GUI applications will be developed to allow the system users to acquire and analyze the data and to calibrate the system. These GUI applications will run on the existing MLRO main workstation and will be integrated with the existing software.

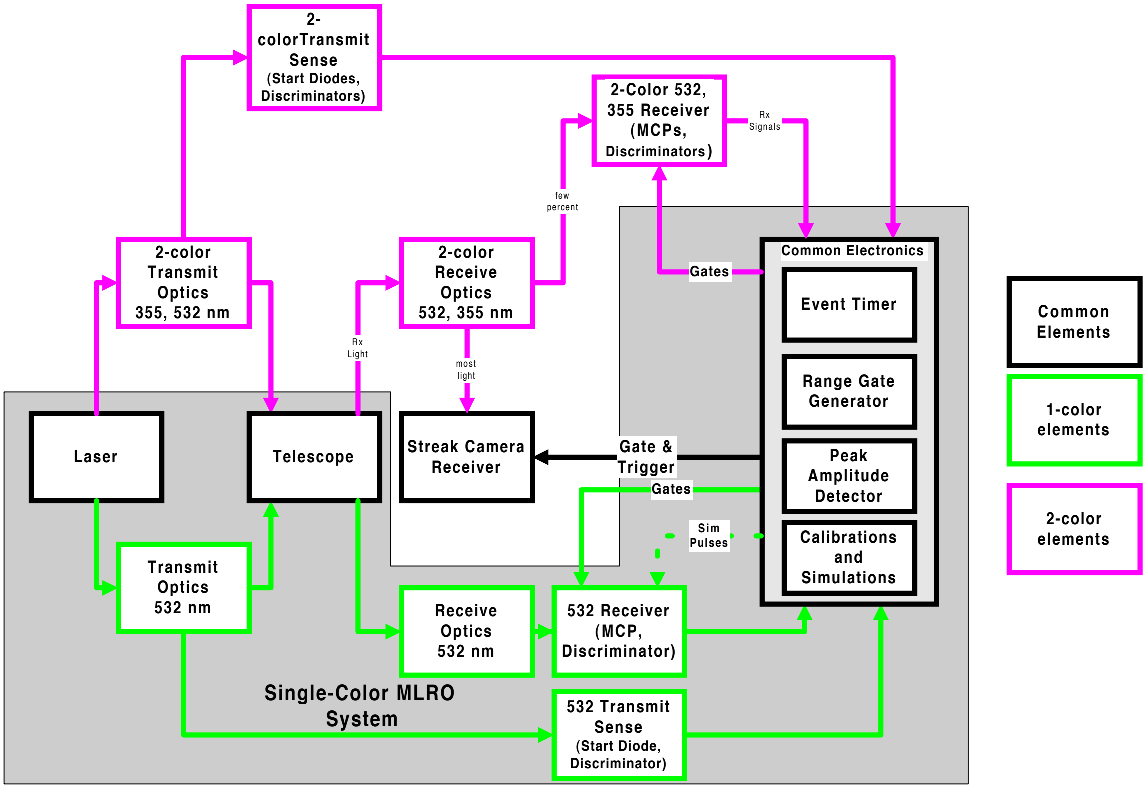

Figure 2: Two-Color Additions Block Diagram

A streak camera calibration assembly will be added to the system to calibrate and perform diagnostics on the streak camera receiver. The principle behind this mechanism is illustrated in Figure 3. A diode laser produces pulses used to map-out the sweep speed of the streak camera and to perform an independent measurement of the system's ability to measure a predetermined pulse separation.

Data processing will be performed automatically, but will provide a user interface to adjust the processing parameters based on sampled images. The raw and pre-processed data will be available for analysis by the ASI scientists. Data results and other important parameters will be stored in the MLRO Long Term Trend Analysis Diagnostic System.

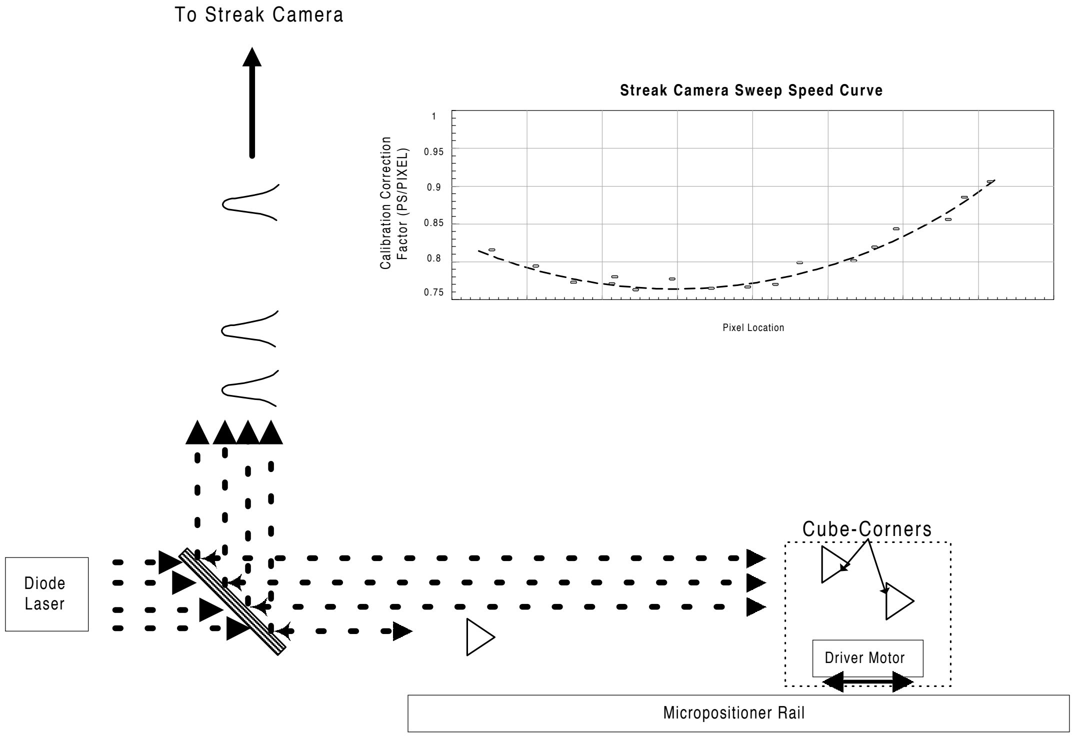

Figure 3: Streak Camera Calibration and Diagnostics Mechanism

Summary

The MLRO system was developed to serve as both a highly-automated operational system and a research tool. The MLRO two-color upgrade is a project to add an additional powerful research tool-set to the MLRO system. It will allow the system to perform two-color ranging using two different and complementary techniques and provide a high (almost Tera-Hz) bandwidth receiver that can be used for two-color ranging and for single-color ranging to characterize satellite arrays in-orbit. The upgrade will closely follow the high-quality philosophy used thus for the MLRO system.