Polarisation at the SGF, Herstmonceux

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ABSTRACT

A property of a light wave is the orientation of the electric field vector, or its polarisation. Laser light, used in Satellite Laser Ranging (SLR), is highly polarised in comparison to other light sources which emit light randomly at all polarisations and are termed to be unpolarised. The performance of optical elements used in SLR, such as mirrors, can depend on the incident polarisation and this is particularly the case if the element is old and has degraded. To understand fully the impact of polarisation on the SLR system at the Space Geodesy Facility (SGF), Herstmonceux, a series of experiments were devised and carried out to first explain some observed phenomena, then to identify and specify an upgrade to a poorly performing optic and finally to consider the control and application of polarisation to the advantage of SLR.

1. Assessment of the impact of polarisation on SLR

It was the suspicion at the SGF that two unexplained observations were caused by a variation of the laser polarisation. The first of these was during calibrations of the two lasers in operation, the original Nd:YAG 12Hz laser and the newly installed Nd:VAN 2kHz laser. The primary SLR calibration target is due west on a nearby water tower and there is also a secondary target due south at a greater distance. Strong return rates from calibrations with the 12Hz laser on the primary target were not replicated when it calibrated on the southern target. However, on calibrating the kHz laser it was quickly apparent that the southern target gave by far the stronger return signal, in opposition to the experience with the 12Hz system. An experiment was devised, fitting an 'analyser' polarising sheet in the emitter telescope, see figure 1. This analyser was rotated 360°, in steps of 10°, during calibrations at each target for each laser and the return rates were recorded.

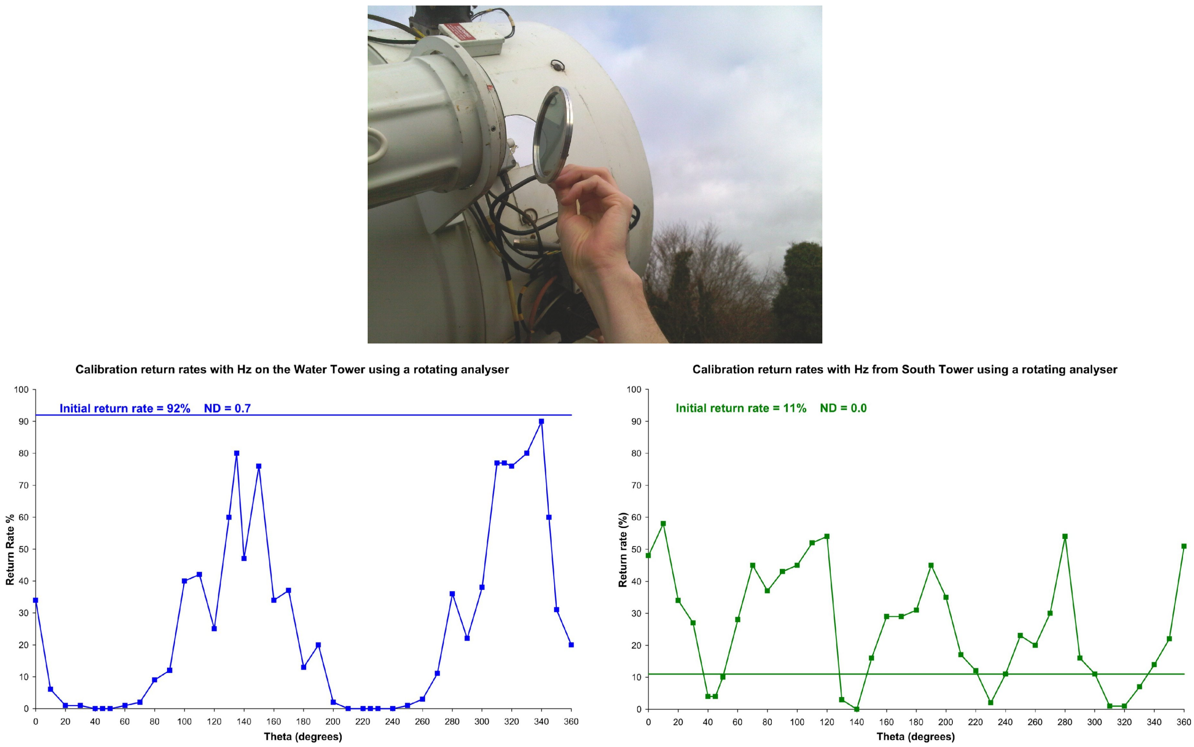

Figure 1. A photograph of the analyser being placed into the emitter and plots of the recorded return rates for calibrations using the 12Hz laser at the western target, left, and the southern target, right.

Figure 1 contains two plots of return rates as the analyser was rotated 360°. The left plot contains results using the 12Hz laser on the primary target in the west and shows two peaks where the emitted laser pulse polarisation is aligned with the transmission axis of the polarising sheet and two extinctions where the light is blocked by the analyser. The right plot is for the 12Hz laser during calibration on the southern tower. In contrast to the previous plot there are now 4 peaks and more surprisingly the low return rate increases with the insertion of the analyser from its initial rate of 11% up to nearly 50%. The analyser rotates the emitted polarisation to a more favourable orientation for the receive optical path. The kHz laser plots were similar but in reverse for the targets. The two lasers were later found to emit orthogonally opposite linear polarisations.

The second observation was made using the daytime camera by viewing the laser beam in the telescope iris, which would disappear in certain parts of the sky. To record this, two photomultipliers were used simultaneously to measure the backscattered laser light at the primary port where the SPAD detector is installed and at the secondary port, which receives light reflected by a dichroic mirror. Backscattered light largely retains its polarisation if scattered by small particles such as air molecules or water vapour, but this is not necessarily the case for larger scatterers such as pollutants, aerosols or ice crystals. Figure 2 shows the results recorded by these two devices as the telescope was pointed to the zenith and rotated steadily in azimuth, which causes the emitted polarisation to rotate. Both plots show variability with azimuth, but the peaks are in opposite phase. This suggests that the dichroic mirror, internal to the telescope, reflects more at certain polarisations and so transmits less and for other polarisations reflects less and transmits more.

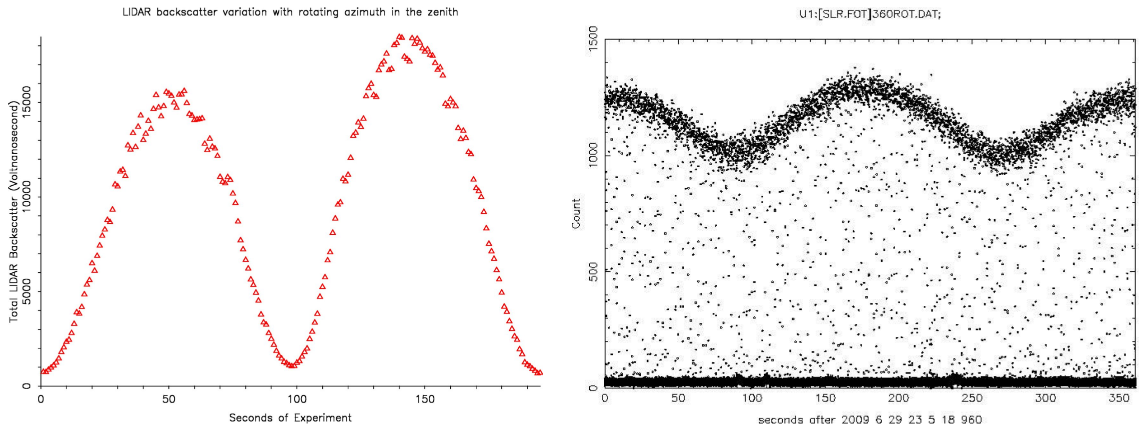

Figure 2. The light detected at the primary port, transmitted through the dichroic, on the left and reflected by the dichroic to the secondary port on the right.

2. Specifying a replacement dichroic mirror

The dichroic was removed from the telescope and an experimental set-up was designed to test the polarisation variability of the mirror. This consisted of an adjustable half-wave plate in the laser path, a 45° mount for the mirror and an energy monitor. The energy monitor was first placed to record the transmitted laser light and then the reflected laser light as the half-wave plate rotated the polarisation incident on the dichroic mirror. A large variation was seen in both measurements as shown in the left plot in figure 3.

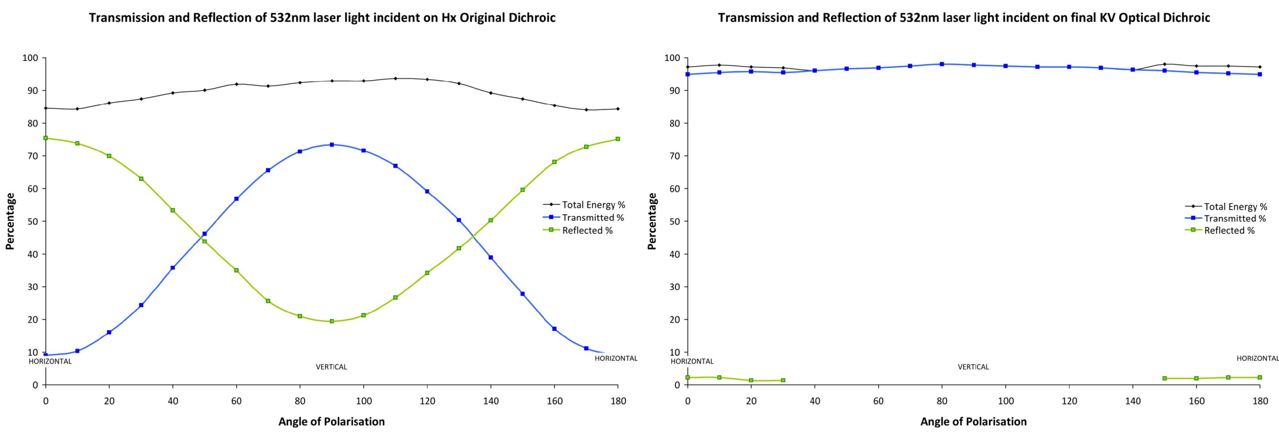

Figure 3. The transmission and reflection recorded from the old dichroic (left) and new dichroic (right)

A replacement for the dichroic was specified and manufactured after testing a number of samples using this standardised laser bed test. On receiving the new dichroic it was tested for transmission and reflection at 532nm and gave the results present in the right hand plot in figure 3. This dichroic replacement improved SLR return rates from satellites by more than 100%. A duplicate dichroic was later sourced by the Graz SLR station and similar improvement was seen.

Further tests were made using the standard laser bed setup on mirrors in the coudé chain and a range of behaviour was discovered. The newer mirrors performed well with near 100% reflectance for all states of incident polarisation. The older mirrors showed reduced reflections for polarisations parallel to the plane of reflection. For most this was to approximately 95% but for an old mirror, previously at the end of the coudé chain which experienced prolonged exposure to sunlight, this reduced to around 65% reflection. In addition to this, the second mirror in the coudé was found to convert linear polarised light to circularly polarised light at certain positions; this mirror was replaced with an old spare.

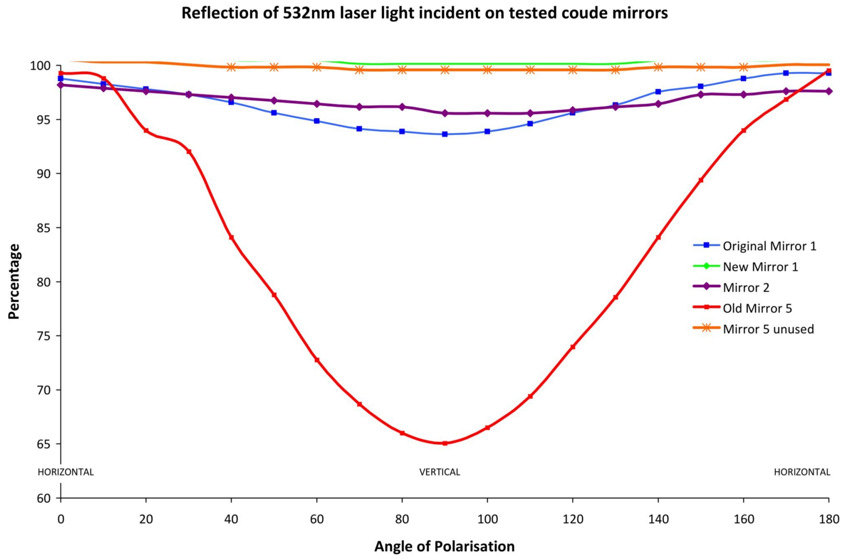

Figure 4. The reflectances of mirrors tested for polarisation variability.

3. Modelling and controlling the emitted polarisation

During SLR the telescope tracks the satellite in azimuth and elevation as it passes overhead. This rotates the optical path of the laser light as it travels to a smaller side telescope attached to the large, 60cm, receiving telescope. This rotation results in a varying emitted polarisation orientation, which depends on both azimuth and elevation.

In order to model this variation the laser beam polarisation was considered as two components, perpendicular to each other and to the direction of the laser light. Polarisation parallel to the plane of reflection, figure 5a), is preserved after a 45° reflection when considered in the frame of the direction of the light. Polarisation perpendicular to the plane of reflection undergoes a 180° phase shift, as shown in figure 5b).

Figure 5. Polarisation parallel a) and perpendicular b) to the plane of reflection

If the polarisation is represented by a two-component vector $\begin{bmatrix} S & P \end{bmatrix}$ where S is the perpendicular component and P is the parallel component then a mirror reflection can be represented by the following matrix $\begin{bmatrix} -1 & 0 \\ 0 & 1 \end{bmatrix}$. At the SGF, and considering the 2kHz laser which emits linearly polarised light, orientated parallel to the laser bed, the first coudé mirror is similar to that in figure 5b) where the polarisation is perpendicular to the plane of reflection and is shifted 180° in phase. The second mirror is not as straight forward as the first. The second mirror moves with the azimuth of the telescope so that the reflection is always 45° but not always so that the polarisation is parallel or perpendicular to the plane of reflection. The method used for mirror 2 was to consider the new plane of reflection at a particular azimuth and calculate the magnitude of the parallel and the perpendicular components. Then the reflection could be treated with the same simple matrix operator as the first mirror. The translation matrix in this case was calculated to be $\begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \sin(\theta) & \cos(\theta) \end{bmatrix}$, where θ is the telescope azimuth. The third and fourth mirrors are in the same reflection plane as the second mirror and so no translation matrix was needed, only the reflection matrix. The fifth mirror moves with telescope elevation and again a translation was used to calculate the polarisation parallel and perpendicular components in the new plane of reflection. This translation was $\begin{bmatrix} \sin(\phi) & \cos(\phi) \\ -\cos(\phi) & \sin(\phi) \end{bmatrix}$, where φ is the telescope elevation.

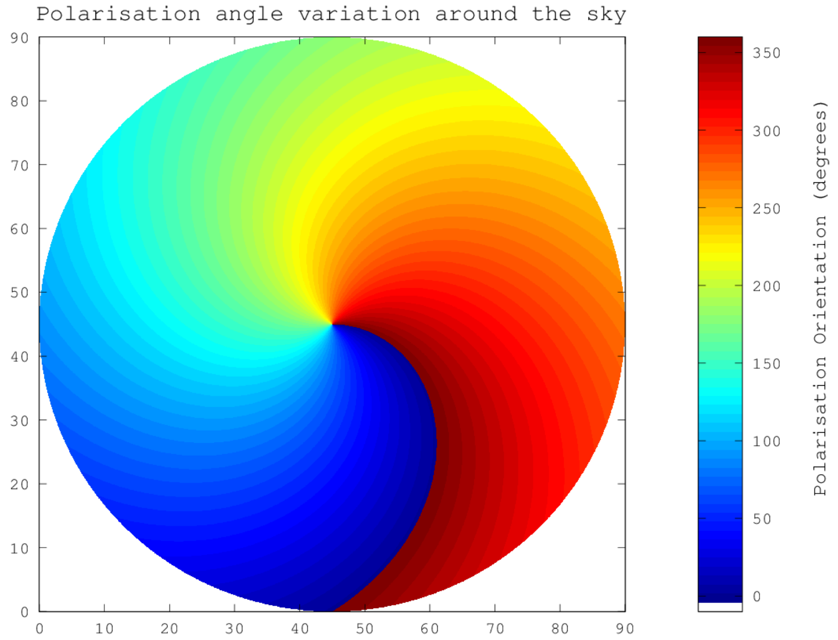

Figure 6. The polarisation of the kHz laser beam leaving the emitter at different telescope azimuth and elevations.

Simulating the change of the laser polarisation as it travels through the coudé and as the telescope moves in azimuth and elevation was straight forward once this model was complete and this is presented in figure 6. The model was tested using the analyser in the telescope emitter and by driving the telescope to an arbitrary position. The model predicted the laser polarisation leaving the emitter and the analyser was positioned to screen the laser. The prediction was then confirmed by firing the laser on low power and with protective eyewear, this was repeated for a series of different telescope positions.

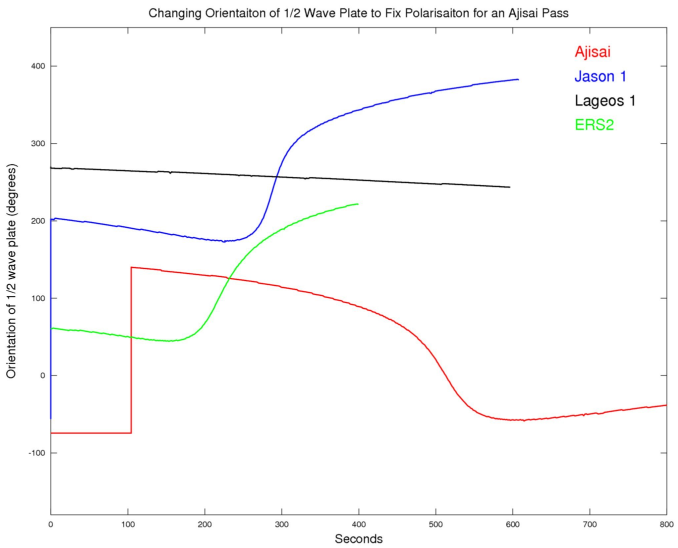

Figure 7. The rotational change of the half-wave plate for satellite passes to fix the emitted polarisation.

The model was then reconstructed to run backwards through the mirrors using a fixed end polarisation, parallel to the telescope elevation axis. This gave the polarisation parallel and perpendicular components required from the laser to produce the fixed polarisation at the emitter. To test this the analyser was reinserted into the emitter in a position to screen the fixed polarisation, the telescope was driven to arbitrary points and the input polarisations were predicted and provided using a half-wave plate. The effective screening of the output laser was observed, projected on the closed dome and through a camera mounted on the telescope and was confirmed with small movements of the half-wave plate.

An application to control the emitted laser polarisation is a future possibility. This could be done either to fix the polarisation at a particular orientation, which could then be used to screen the returning laser light, or, with knowledge of each satellite retro-reflector target, to optimise the outgoing polarisation to give increased return rates. Figure 7 shows the calculated position of the half-wave plate for a number of satellite passes to fix the outgoing polarisation. The movement of the half-wave plate is steady and continuous.

4. Conclusion

The Herstmonceux SLR station now has a far better understanding of the impact of polarisation in the system. This work lead to identifying the dichroic mirror to be not performing as required and replacing this mirror gave an improvement in SLR return signal of more that 100%. The polarisation orientation of the emitted laser beam varies across the sky and this has been modelled. Fixing the polarisation emitted would be possible by controlling a 1/2-wave plate in real-time. This could benefit the SLR of more difficult targets such as GNSS either by noise filtering or by optimising polarisation for return rate.

References

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