

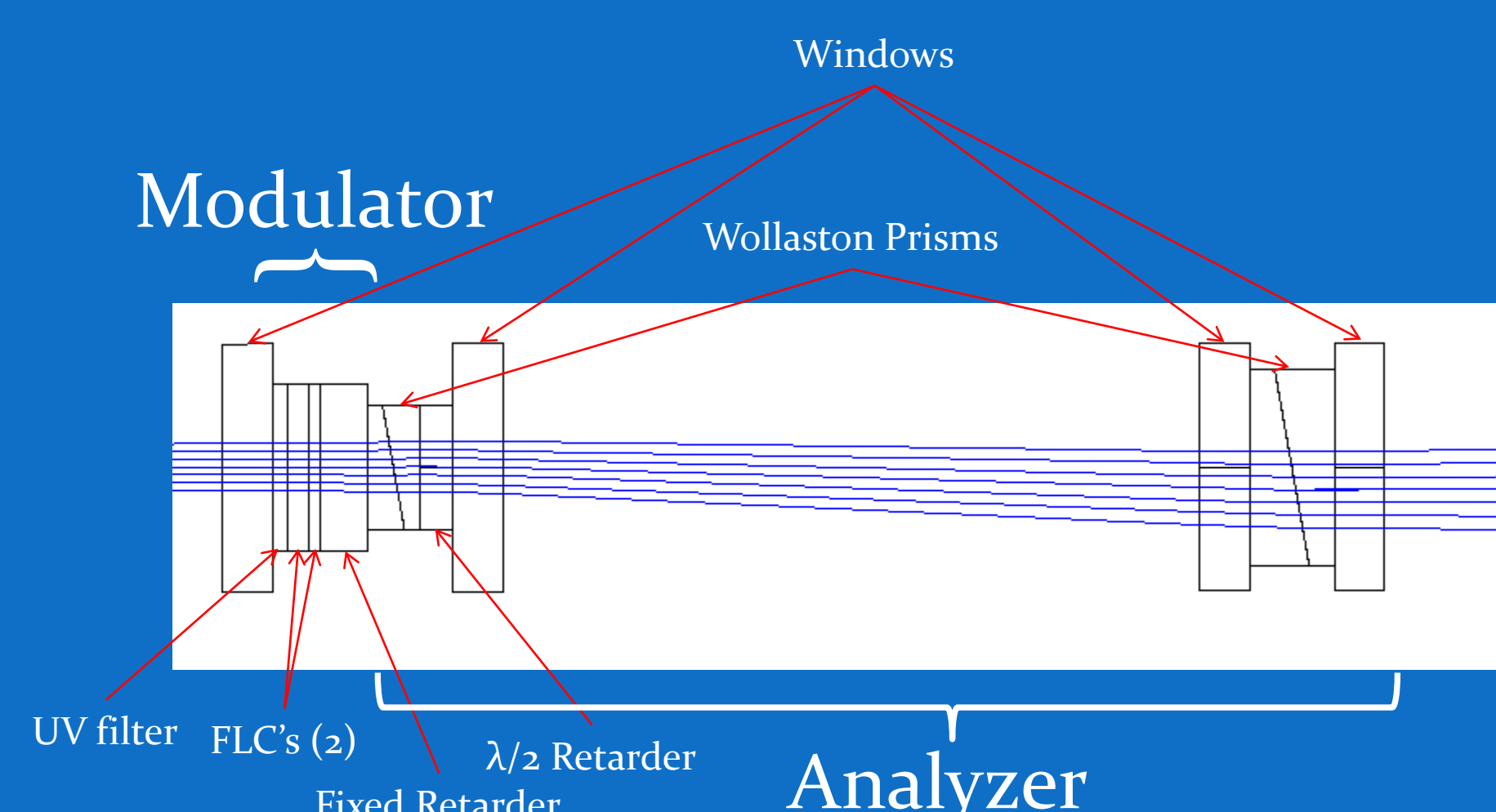


Evans Solar Facility, National Solar Observatory, Sacramento Peak

The Prominence Magnetometer (ProMag) is a dual-channel, dual-beam, slit-scanning, full Stokes spectro-polarimeter designed by the High Altitude Observatory at the National Center for Atmospheric Research (HAO/NCAR) for the study of the magnetism of solar prominences and filaments. It was deployed in August 2009 at the 40 cm coronagraph of the Evans Solar Facility (ESF) of the National Solar Observatory on Sacramento Peak (NSO/SP). In its standard mode of operation it acquires spectro-polarimetric maps of solar targets simultaneously in the two chromospheric lines of He I at 587.6 nm and 1083.0 nm. Since August 2011 ProMag has operated in “patrol mode” with a dedicated observer. We aim to routinely measure the vector magnetic field in prominences. The electro-optic modulator and polarization analyzer are integrated into a single mechanical unit located at the coude feed of the telescope. This location was necessary for proper co-alignment of the dual beams, but complicates the precise polarimeter calibration necessary to achieve the sensitivity required for prominence measurements ($< 10^{-3}$). At this sensitivity, small variations in optical alignment can become significant. We present a calibration method for ProMag, using a polarizer and retarder at coronagraph prime focus. Calibrations are recorded before and after observations. We discuss the success of this method and its limitations.

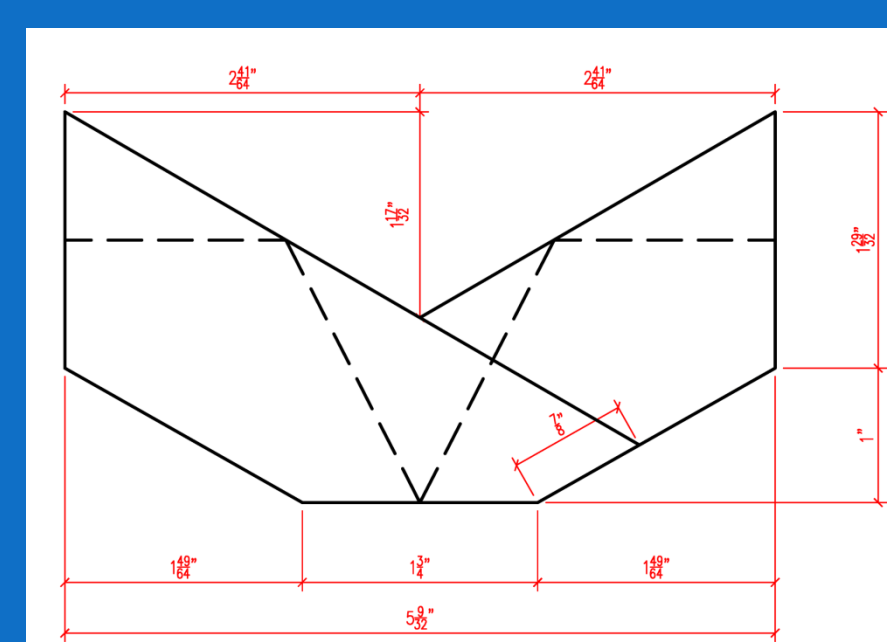
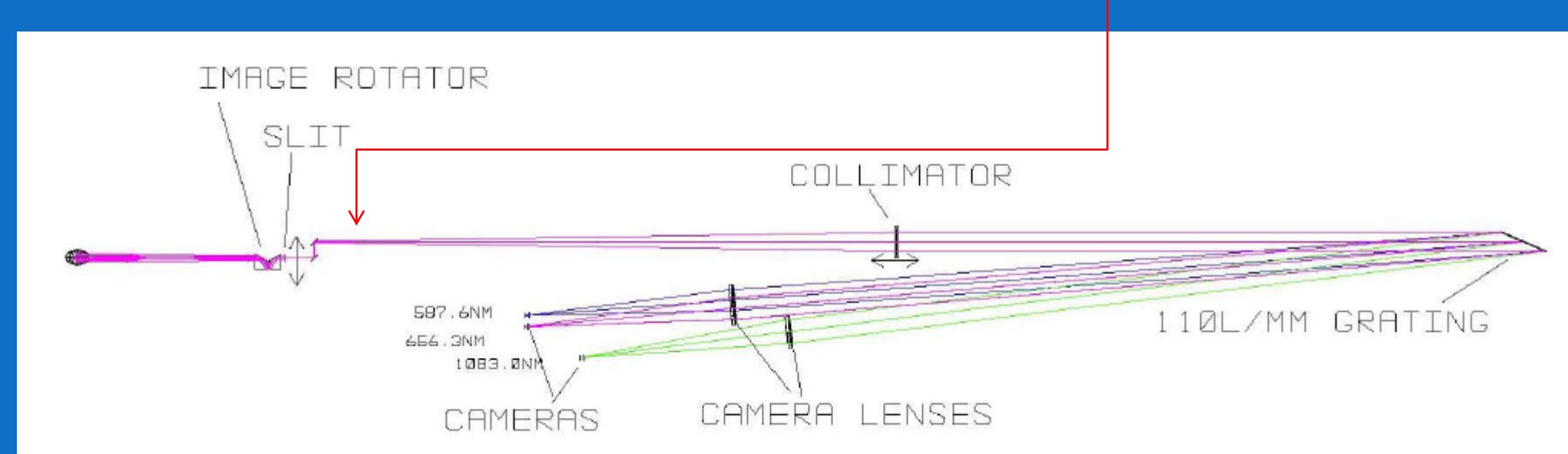
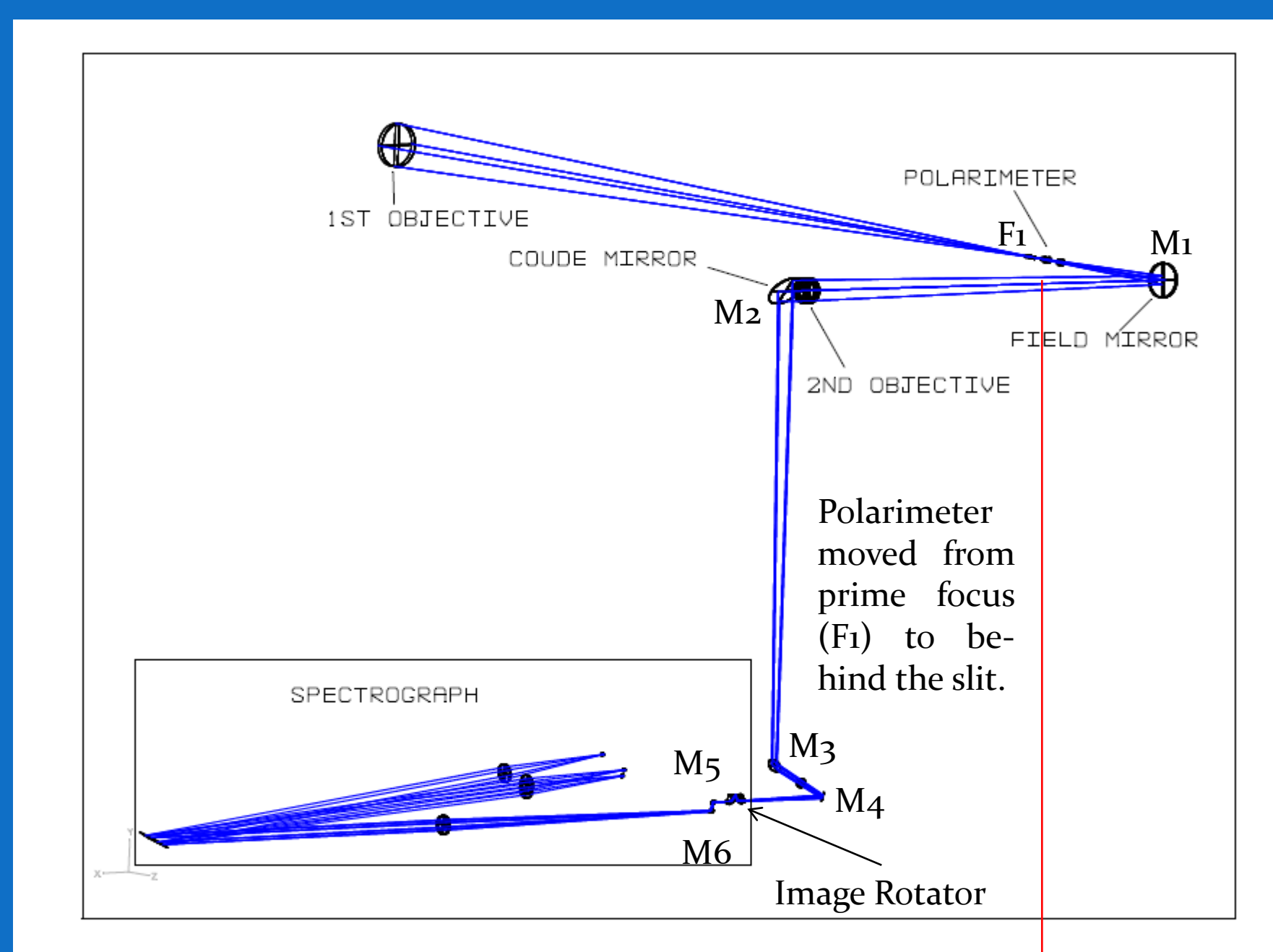
ProMag Polarimeter

The ProMag modulator is a two element ferroelectric liquid crystal (FLC) retarder followed by a fixed wave-plate, providing four modulation states. The integrated polarization analyzer consists of two Wollaston prisms with an interposed $\frac{1}{2}$ wave super-achromatic retarder oriented at 45° with respect to the Wollaston optical axis.



The polarimeter was moved in Dec 2011. The new location is subject to the effects of instrumental polarization from 6 mirrors and the image rotator. The instrumental polarization varies according to time-of-day, time-of-year, and Position Angle (PA) of targets on the Sun (due to the image rotator).

The image rotator polarization is analogous to a rotating assembly of 3 mirrors, 2 total internal reflections with a silvered surface between them.



Calibration Procedure

The 4-vector of camera signals I^\pm (for dual beams, + and -) is related to the incoming solar Stokes vector I by the equation

$$I^\pm(t) = \mathbf{S}\mathbf{P}^\pm\mathbf{M}(t)\mathbf{T}(PA, t)\mathbf{I}$$

where \mathbf{T} is the Mueller matrix of the telescope, composed of a train of Mueller matrix components, \mathbf{M} is the modulation matrix of the polarimeter, \mathbf{P}^\pm is a polarization matrix extracting either the horizontal (+) or vertical (-) beams, and \mathbf{S} represents the effect of the spectrograph. \mathbf{T} is a slow function of time, varying on daily and seasonal time-scales, and is also a function of target PA. \mathbf{M} is a fast, periodic function of time, varying with the modulation cycle (6.25 Hz).

The calibration optics consist of a polarizer and fixed retarder (of retardance r) in rotation stages located at F1. The polarizer angle, α , is varied in 12 steps of 15° , and then reset to the initial position, for each of 3 60° steps of the retarder angle, β . Clear images (without the calibration optics) and darks are also taken. The equation for the camera signals becomes

$$I^\pm(t) = \mathbf{S}\mathbf{P}^\pm\mathbf{M}(t)\mathbf{T}(PA, t)\mathbf{R}(r, \beta)\mathbf{P}(\alpha)\mathbf{I}$$

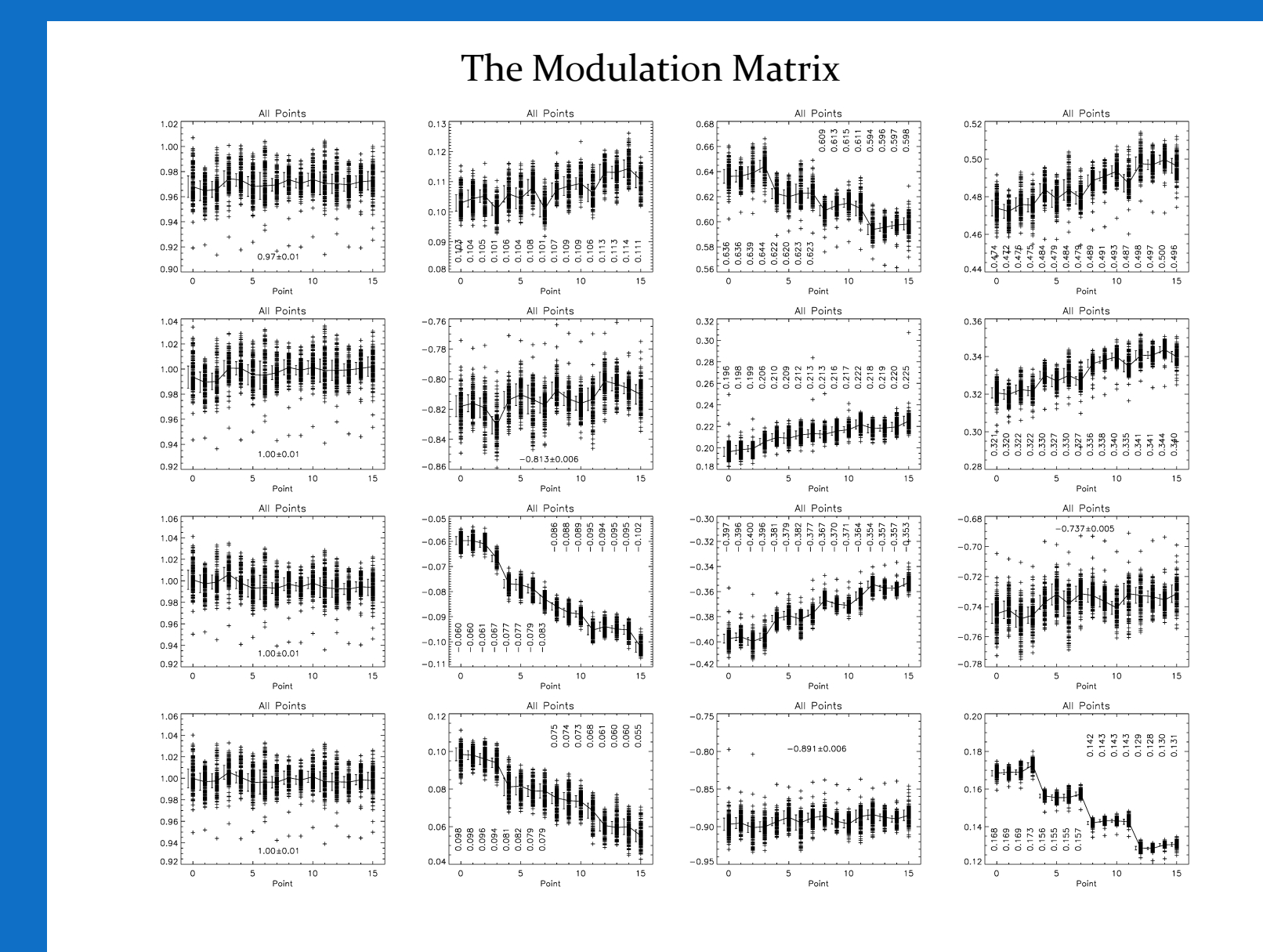
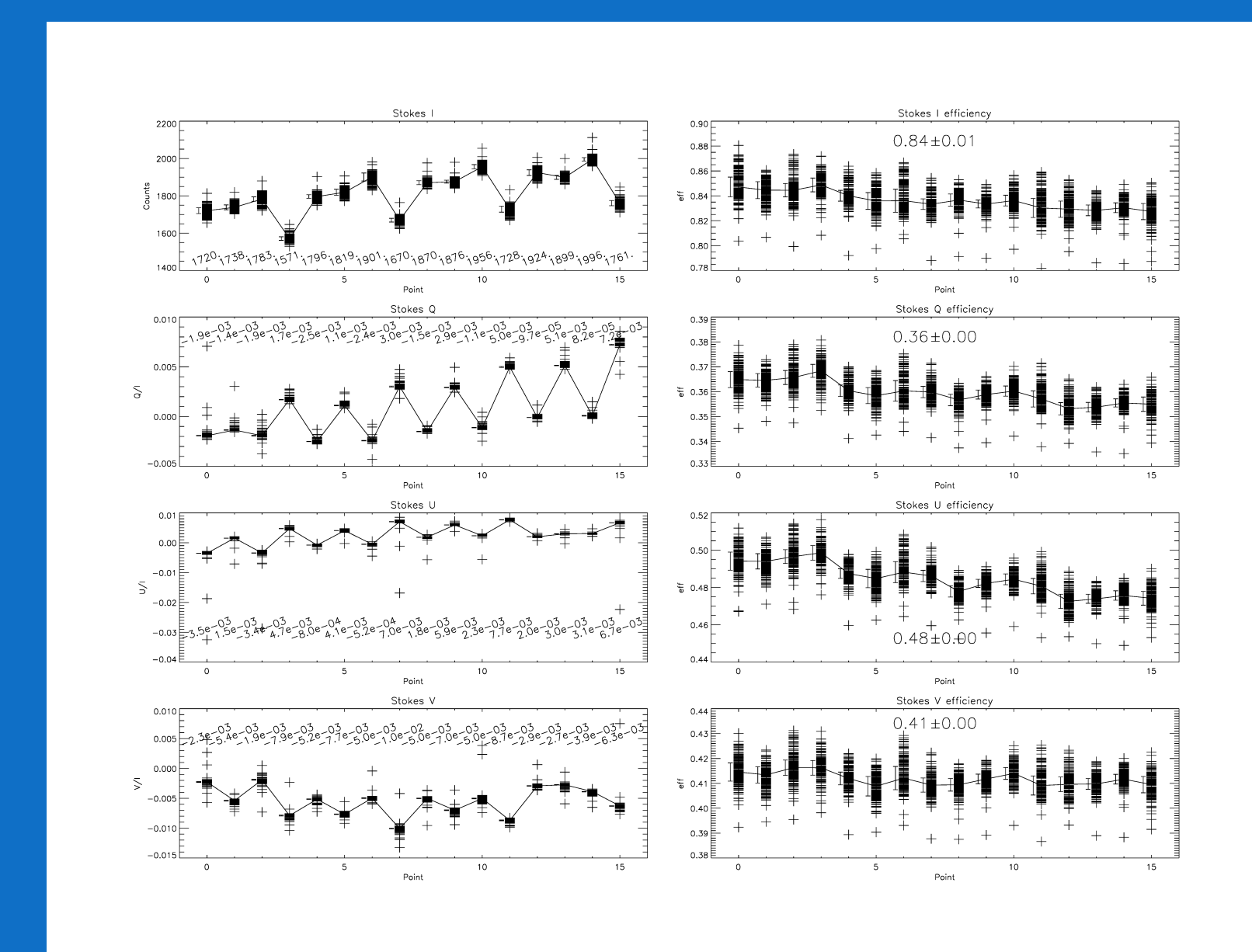
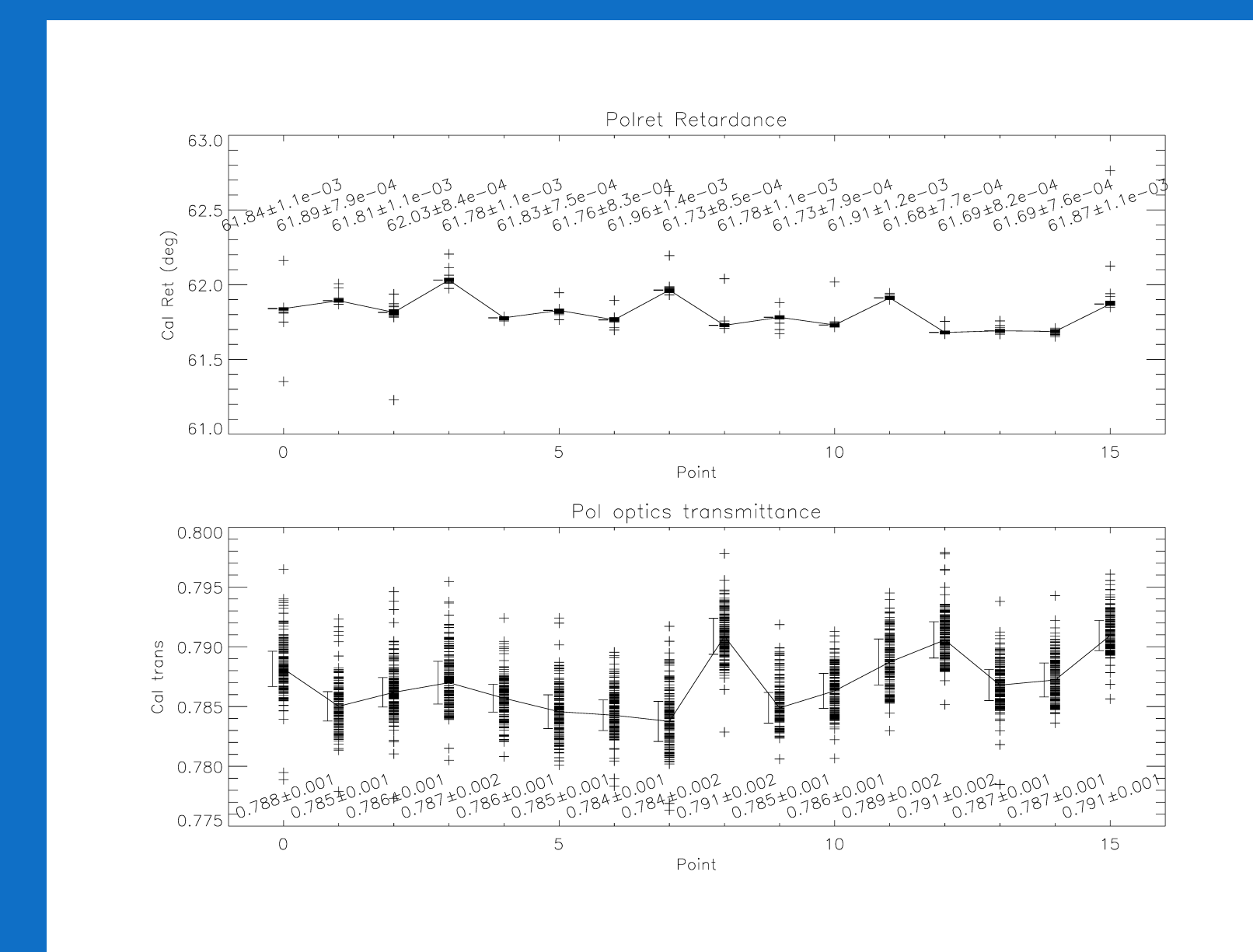
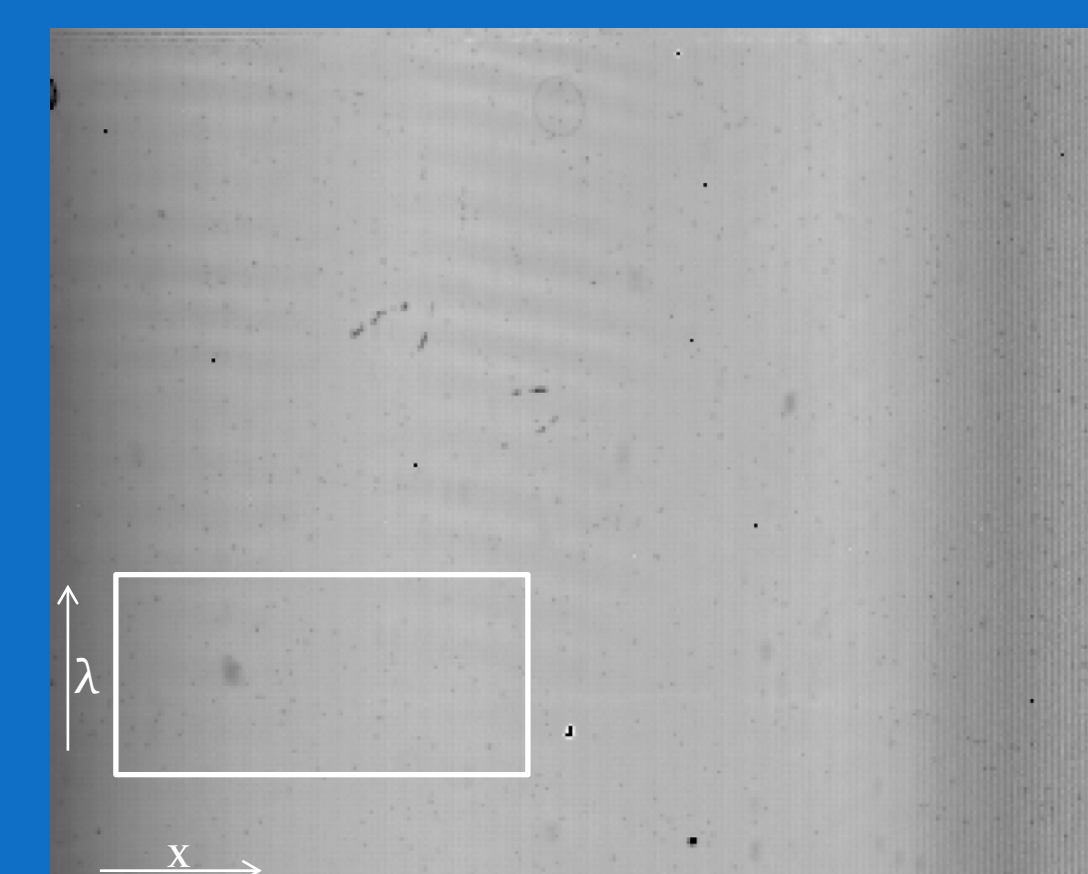
The calibration procedure determines the product $\mathbf{M}(t)\mathbf{T}(PA, t)$. In effect, the telescope has become part of the modulator. We perform this calibration procedure immediately before and immediately after a prominence map (at the same PA) and interpolate the resulting modulation matrices to arrive at the modulation matrix for the prominence map.

We fit a model to the calibration data, containing 25 parameters: The combined modulation matrix, \mathbf{MT} (16), the input Stokes vector, \mathbf{I} (4), the retardance, r , and overall transmission of the calibration optics (2), an offset angle for each of polarizer/retarder – in case of misalignment between the calibration optics and the rotation stages (2), and the CCD bias (1). The parameter fit is accomplished by minimizing the χ^2 statistic using a robust non-linear minimization algorithm. For the data shown here we used a Downhill Simplex (Amoeba) method. We took a Monte-Carlo approach to explore more fully the 25 dimensional parameter space. The Amoeba is initialized with a randomized starting point; random offsets are added to the initial guess. The result of this procedure is fed into a 2nd iteration as the initial guess, to which random offsets are added as before. A 3rd iteration is performed using the output of iteration 2 with the size of the random offsets reduced by a factor of 5. This procedure was repeated 153 times for each of 16 “super-pixels” covering the spatial and spectral domain of the He I 10830Å line in a 4×4 grid. All data shown here are for the 10830Å line.

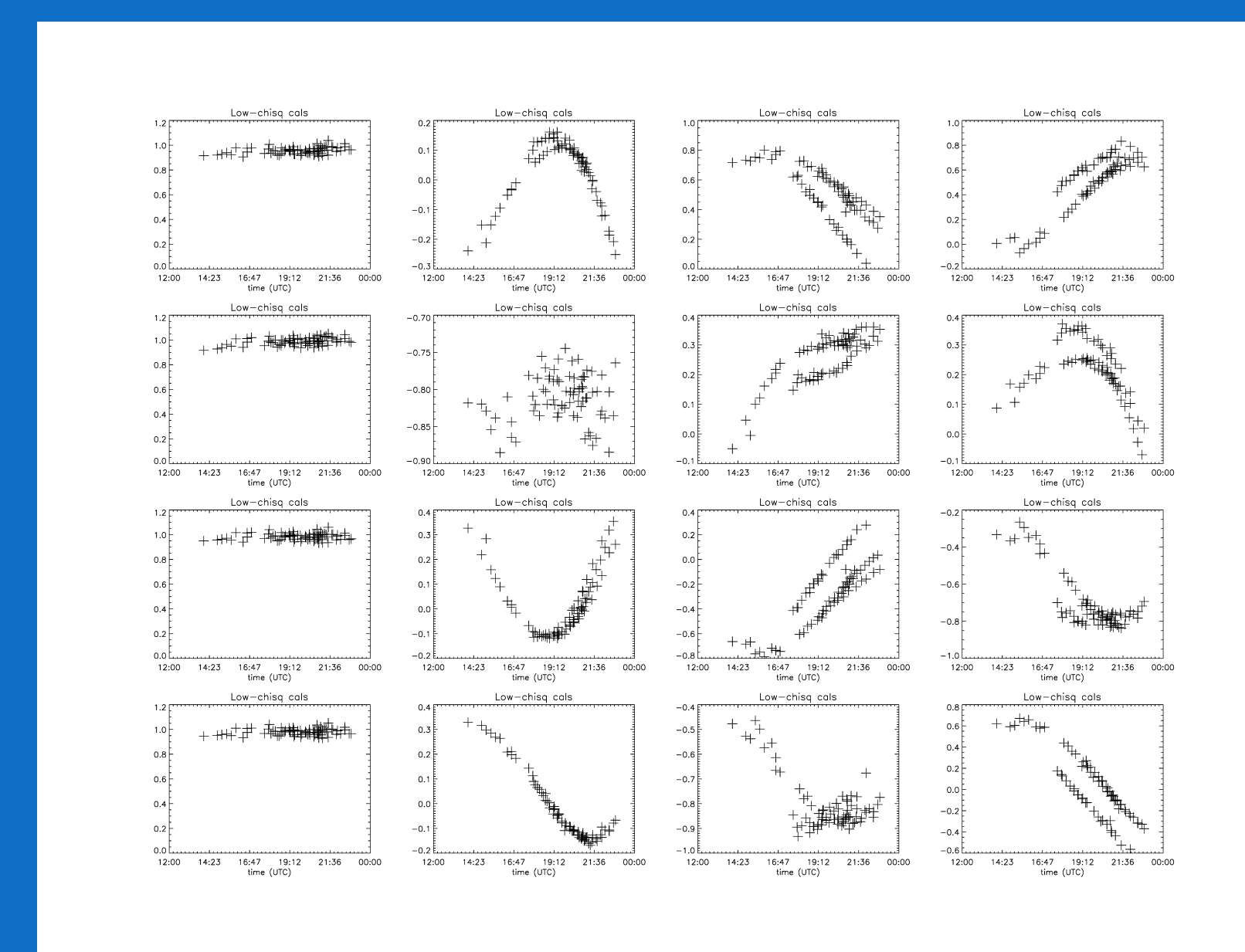
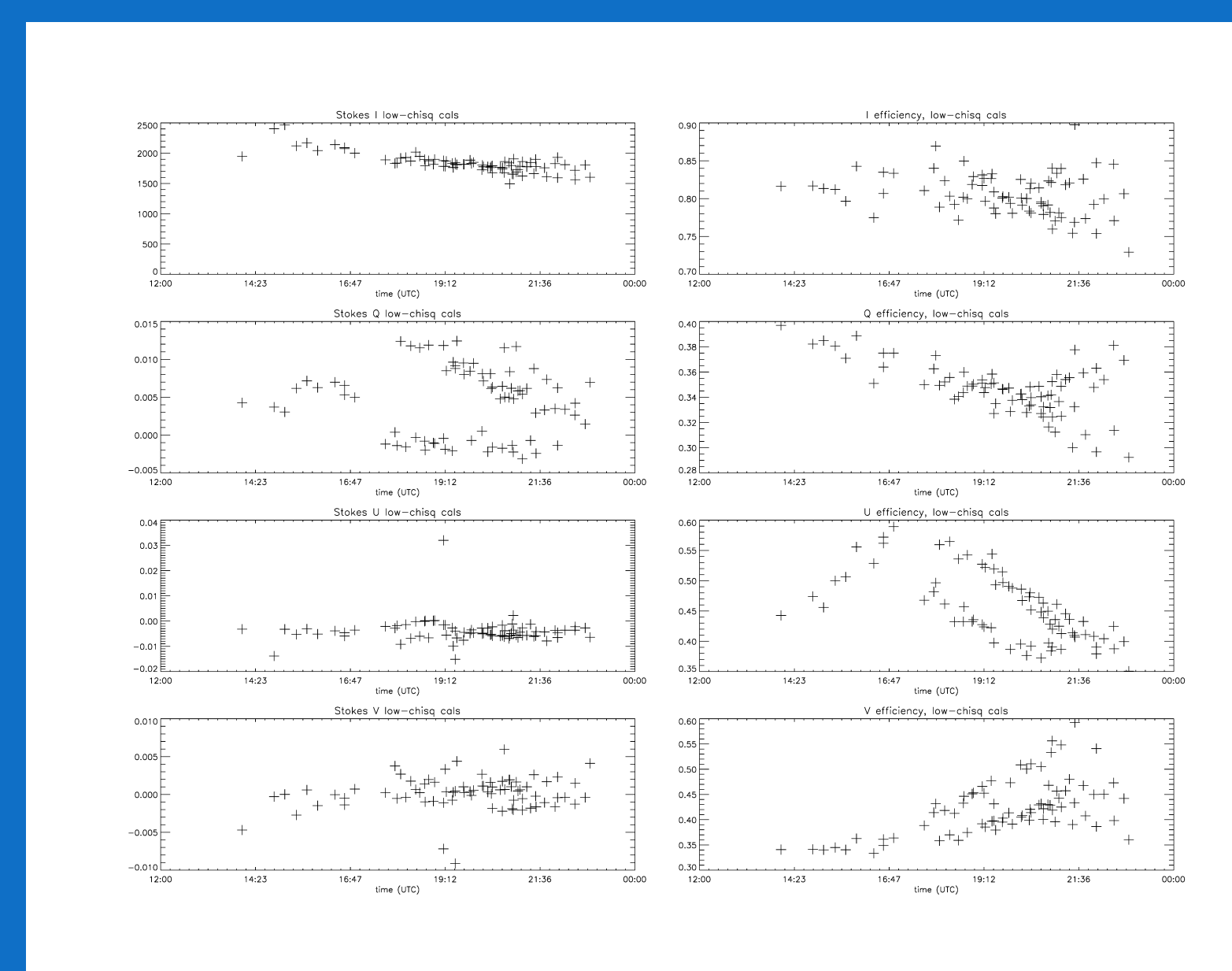
Calibration Results

The plots at right contain each of the 153 runs, designated by + symbols. The lines connect median values. Error bars, representing the median \pm the median absolute deviation from the median, are shown offset slightly to the side for clarity (in many cases they are difficult to see because the distributions are so narrow). Numbers printed on the plots provide the median values, or when only one number is present, the median across all 16 points (super-pixels)

Statistically significant variations exist across super-pixels. It is possible these variations are part of the modulation matrix, but it seems unlikely e.g. in the calibration retardance and transmission. The very large variations in input Stokes Q, U, V are also of concern. A possible explanation is the lack of flat-fielding performed on these data. A flat-field for the ProMag does not exist yet, but a preliminary version is shown below. The approximate region of the He line is shown by the box.



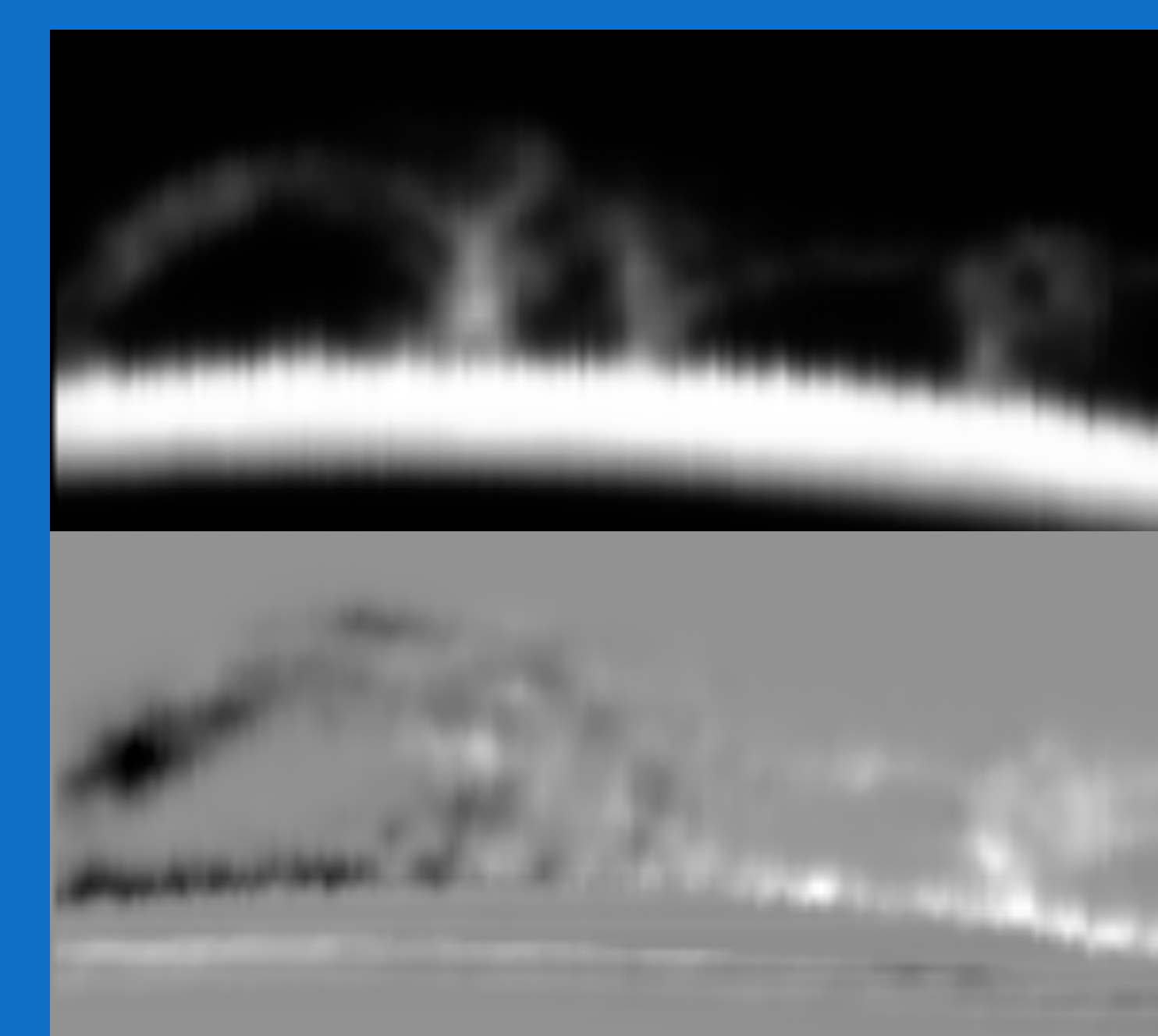
The two plots below show the results of running the calibration procedure at various times of day for the dates: Jan 5, 8, 17, 18, 23; Feb 1, 6; Apr 8, 22, 26; May 17, 22; Jun 6, 21. The model fit was run once rather than 153 times, thus each is a single realization of the calibration analysis. The χ^2 -weighted average of the 16 super-pixels from each run is shown as a single + symbol. The daily variation is apparent. The seasonal variability is less obvious, but 2 or perhaps 3 regimes are visible, corresponding roughly to the data taken on each side of the vernal equinox. We are encouraged that the modulation efficiencies never drop much below 30%. In fact, some are quite good.



What's Next?

The set of steps necessary to arrive at our 1st Stokes map are: 1) Adequate flat-fielding, 2) further refinement of calibration procedures to produce stable, precise calibration matrices, 3) demodulation of prominence data to Stokes vectors, 4) coalignment and dual-beam subtraction to remove seeing-induced crosstalk. After producing our 1st quality Stokes map, inversion to physical quantities via scattering polarization techniques will begin.

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Stokes I map of a 10830Å prominence observed Aug 25, 2012 with Dopplergram below