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Polarization calibration techniques and scheduling for the Daniel K. Inouye Solar Telescope

David F. Elmore

National Solar Observatory,
3665 Discovery Drive, Boulder, Colorado, USA
email: `elmore@nso.edu`

Abstract. The Daniel K. Inouye Solar Telescope (DKIST), formerly Advanced Technology Solar Telescope when it begins operation in 2019 will be by a significant margin Earth's largest solar research telescope. Science priorities dictate an initial suite of instruments that includes four spectro-polarimeters. Accurate polarization calibration of the individual instruments and of the telescope optics shared by those instruments is of critical importance. The telescope and instruments have been examined end-to-end for sources of polarization calibration error, allowable contributions from each of the sources quantified, and techniques identified for calibrating each of the contributors. Efficient use of telescope observing time leads to a requirement of sharing polarization calibrations of common path telescope components among the spectro-polarimeters and for those calibrations to be repeated only as often as dictated by degradation of optical coatings and instrument reconfigurations. As a consequence the polarization calibration of the DKIST is a facility function that requires facility wide techniques.

Keywords. Polarimetry, Telescope Calibration, Solar Polarimetry

1. Overview

The Daniel K. Inouye Solar Telescope (Rimmele 2012) will have five first-light instruments. Four of the instruments are spectro-polarimeters, the Visible Spectro-Polarimeter (ViSP) (Nelson 2010), Visible Tunable Filter (VTF) (Schmidt *et al.* 2014), the Diffraction-Limited Near-Infrared Spectro-Polarimeter (DL-NIRSP) (Lin 2012), and the Cryogenic Near Infrared Spectro-Polarimeter (Cryo-NIRSP). Polarization calibration of these instruments and of the common telescope optics that precede them must achieve a facility-defined accuracy requirement. The telescope and instruments have been examined end-to-end for sources of polarization calibration error, allowable contributions from each of the sources quantified, and techniques identified for calibrating each of the contributors. Efficient use of telescope observing time leads to a requirement of sharing polarization calibrations of common path telescope components among the spectro-polarimeters and for those calibrations to be repeated only as often as dictated by degradation of optical coatings and instrument reconfigurations.

2. Calibration Plan

A baseline polarization calibration plan for the DKIST has been defined (Elmore 2014). Though there are differences in details, calibration of solar telescopes and polarimetric instruments follow similar procedures of introducing optical calibration state generators in front of some or all of the telescope optics and simultaneously inferring parameters of the following polarization matrices that describe telescope and instruments. Examples

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Table 1. Table of polarization measurement error allocations. The total error is the root sum square of each of the contributions.

Component	**RSS Allocation**
M1 & M2	0.70
M3 & M4	0.26
M5 & M6	0.26
M7 through Instrument	0.26
Calibration polarizer orientation	0.20
Calibration polarizer extinction	0.20
Calibration retarder orientation	0.20
Calibration retarder thermal stability	0.25
Modulator thermal stability	0.25
Modulator rotation stability	0.10
Detector exposure stability	0.10
Detector non-linearity	0.20
RSS	1.00

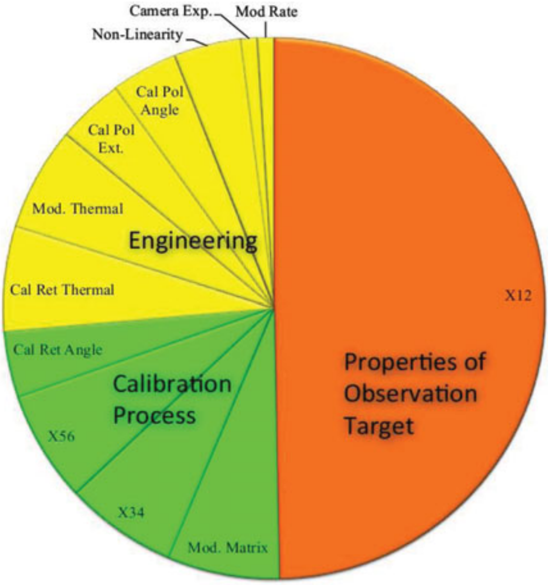

Figure 1. Allocation of calibration error contributions. Each of the RSS contributors is squared in this chart.

are (Beck *et al.* 2005) for the German Vacuum Tower Telescope at the Izaña Observatory on Tenerife, Canary Islands, Spain, the polarimeters on the Hinode spacecraft (Ichimoto *et al.* 2008), and the Dunn Solar Telescope, National Solar Observatory, Sacramento Peak Observatory, Sunspot, NM, USA (Socas-Navarro *et al.* 2011). The calibration plan for the DKIST builds upon the calibration procedure described by Skumanich *et al.* (1997), with the addition of solving for certain properties of the calibration optics themselves. Challenges include a telescope optical train that introduces significant polarization with a net polarization that varies with solar elevation and azimuth and an extremely broad

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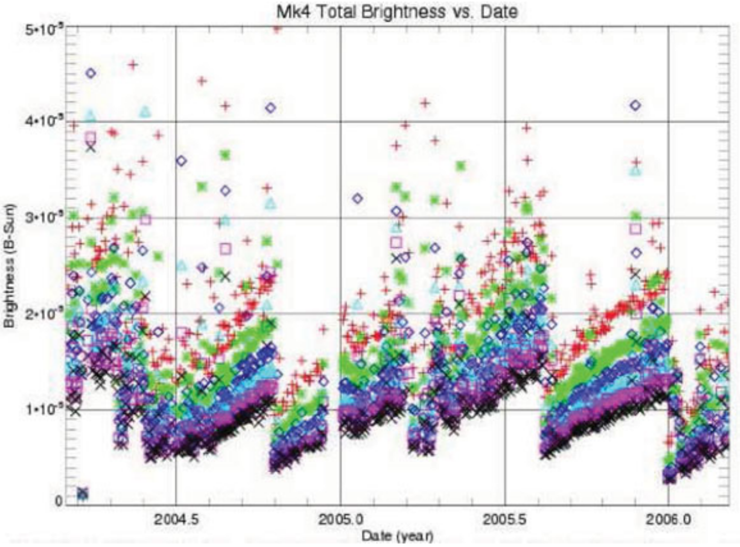

Figure 2. Example of optic surface degradation over time. Families of symbols represent the amount of scattered light seen at various nights in the solar corona (color version of this figure is available on the on-line edition). Of significance is the ramped degradation with steps occurring at times of washing of the lens.

wavelength range spanning 380nm–5000nm. Individual instruments must be calibrated in addition to the optical path shared by each of the instruments. Calibrations are performed over a range of telescope elevations and azimuths and over a range of wavelengths, utilizing the multi-instrument and multi-wavelength capabilities of instruments to infer contributions from each of the groups of optics in the telescope, of each instrument, and as a function of wavelength.

3. Error Allocation

Polarization calibrations must be performed that achieve the overall polarization measurement accuracy requirement for the DKIST of 5×10^{-4} P/I_c, where P is the total polarization, $\sqrt{Q^2 + U^2 + V^2}$, and I_c is the intensity of nearby unpolarized solar continuum radiation. Contributions to that error have been identified and each given an allocation (Table 1 and Figure 1). The root sum square of all the contributions totals to the allowable error. Contributors to the error budget include a number of items that are clearly independent of each other and that can be characterized in the lab or on test bench. Entries such as the extinction ratio the calibration retarder or the rotational rate stability of a polarization modulator rotation mechanism fall into this engineering category. Since these can be measured independently and accurately, allocations are relatively small. A number of contributors depend upon the polarization calibration process that simultaneously infers contributions from a number of optical components. The calibration process utilizes polarization state generation optics at the Gregorian focus of the telescope to infer parameters that describe optical groups including instruments themselves. The process simultaneously infers properties of several components. Note that error allocation assumes, even though this is a single fitting process, each of the contributions from parameters from the Gregorian focus through the instruments are uncorrelated. The final contributor to calibration error is from the Mueller matrix product of the secondary mirror acting upon light from the primary mirror $X_{12} = M_2\#\#M_1$

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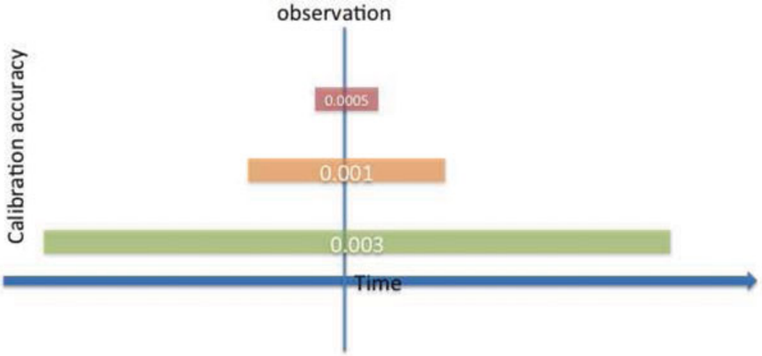

Figure 3. Time range over which calibrations are valid for an observation vs. calibration accuracy

where ## is a row major matrix multiply. Even though the X_{12} contribution can be simplified to two free parameters, the lack of a controlled and calibrated light source entering the telescope and the necessity of observations being calibrated up to the Gregorian focus meeting requirements, lead to half of the calibration error being ascribed to X_{12}. The baseline technique for X_{12} in the calibration plan (Kuhn *et al.* 1994), extended to the visible wavelength weak field regime (Elmore 2012), relies upon the fact that, when evaluated statistically, symmetric linear Zeeman polarization profiles across a solar spectrum line are not correlated with asymmetric circular polarization profiles, and there is no signature of intensity in polarization profiles. Another technique being considered (Harrington *et al.* 2011) depends upon modeling X_{12} to correctly infer two properties of Rayleigh sky polarization—that it has no circular polarization and that the linear polarization is perpendicular to the direction from the sky location to the sun.

4. Implications for telescope operation

The DKIST will operate predominantly in service mode (Rimmele *et al.* 2012). Traditionally solar telescopes have been operated in access mode where the principal investigator collects science observations and all supporting calibrations as part of a single visit to the telescope. Operational efficiency is required by the Operational Concepts Definition of the DKIST facility. In service mode scheduling, the most appropriate approved experiment in the observation queue is selected to run. Considerations in scheduling to facilitate operational efficiency are sharing of polarization calibrations among multiple experiments and sharing of the calibration of telescope optics preceding a number of instruments. Provided experiments are performed following standard light distributions to the instruments and standard configurations within instruments are utilized, and that these configurations are stable and repeatable, calibrations are then suitable for multiple experiments. New calibrations are required whenever a not previously calibrated configuration is used. Calibrations are required when temporal changes likely due to contamination of optical surfaces are sufficiently great to invalidate previous calibrations. Surface contamination effects properties of optics, both scattered light and polarization performance. An example of surface contamination of the coronagraph lens of an instrument (Fisher *et al.* 1981) on Mauna Loa (Figure 2), Island of Hawai'i shows increase in scattered light over time that is repeatedly corrected through washing the telescope objective. One could expect similarly shaped curves for mueller matrix parameters of mirrors in the DKIST. The less stringent the polarization accuracy requirement of a

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particular experiment, the more contamination can be tolerated, and the longer polarization calibrations remain valid. Figure 3 shows the concept that calibrations are valid for a certain amount of time before and after an experiment is conducted and that the valid time varies as a function of polarization accuracy. Until calibrations are performed during integration test and commissioning (IT&C) &/or early in operations of the DKIST, time scales for each of the optical contributions are unknown. It is expected that depending upon polarization accuracy and the particular contributor being considered the time scales will vary from a day or less for the most sensitive optical components and highest required polarization accuracy to months or more for less sensitive optical elements and lower polarization accuracy. At the highest accuracy, calibrations may have to track the contamination curves for some optical groups whereas for less stringent accuracy a calibration may remain valid from cleaning cycle to cleaning cycle.

5. Summary

A polarization calibration error budget has been defined that encompasses contributions from the DKIST and its instruments. Procedures for inferring the contributions to the calibration to required accuracies have been defined. Drivers for when and how often calibrations must be performed during DKIST operations have been identified and will be quantified during IT&C &/or early in operations.

6. Discussion

This allocation of polarization error technique has been described as a systems engineering approach to the calibration problem (del Toro Iniesta 2014). Certain aspects of the allocation of errors, those attributed to engineering, certainly support that assertion. The inference of the parameters describing Mueller matrices for telescope optical groups simultaneously with the modulation matrix for instruments in one single calibration procedure raises concerns about sound systems engineering, in particular, regarding degeneracy of the solutions for the various matrix contributions (is RSS appropriate), completeness of the solution, optimum efficiency, and error propagation. Work is continuing in an attempt to define optimum polarization calibration and its applicability to the DKIST.

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