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Thomas A Underwood, David Voelz, François-Xavier X Schmider, Jason Jackiewicz, Julien Dejonghe, et al.. Adaptation of Dunn Solar Telescope for Jovian Doppler spectro imaging. SPIE Optical Engineering + Applications, Aug 2017, San Diego, United States. pp.32, 10.1117/12.2275909 . hal-03397369

HAL Id: hal-03397369
https://hal.science/hal-03397369

Adaptation of Dunn Solar Telescope for Jovian Doppler Spectro Imaging

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ABSTRACT

This paper describes instrumentation used to adapt the Dunn Solar Telescope (DST) located on Sacramento Peak in Sunspot, NM for observations using the Doppler Spectro Imager (DSI). The DSI is based on a Mach-Zehnder interferometer and measures the Doppler shift of solar lines to allow the study of atmospheric dynamics of giant planets and the detection of their acoustic oscillations. The instrumentation is being designed and built through a collaborative effort between a French team from the Observatoire de la Cote d'Azur (OCA) that designed the DSI and a US team at New Mexico State University. There are four major components that couple the DSI to the DST: a guider/tracker, fast steering mirror (FSM), pupil stabilizer and transfer optics. The guider/tracker processes digital video to centroid-track the planet and outputs voltages to the DST's heliostat controls. The FSM removes wavefront tip/tilt components primarily due to turbulence and the pupil stabilizer removes any slow pupil "wander" introduced by the telescope's heliostat/turret arrangement. The light received at a science port of the DST is sent through the correction and stabilization components and into the DSI. The FSM and transfer optics designs are being provided by the OCA team and serve much the same functions as they do for other telescopes at which DSI observations have been conducted. The pupil stabilization and guider are new and are required to address characteristics of the DST.

Keywords: Doppler Spectro Imager, Dunn Solar Telescope, Mach Zehnder, Sunspot, Giant Planets, Acoustic Oscillations, Centroid Track, Fast Steering Mirror

1. INTRODUCTION

The internal structure of the Sun has been investigated through helioseismology for more than 4 decades. However, similar seismic concepts can also be applied to study the internal structure of the gas giant planets. For example, Jovian seismology could be used to unambiguously determine the size and mass of Jupiter's core. One sensing approach for planetary seismology is to observe a Doppler velocity image with an accompanying visible image at regular intervals [1-3]. Temporal changes in the velocity field are monitored and oscillations are interpreted in terms of the planet's sound speed profile, which leads to understanding of its internal properties.

The Doppler Spectro Imager (DSI) is a velocity imaging instrument developed for giant planet seismology by the Laboratoire Lagrange at the Observatoire de la Cote d'Azur (OCA) in collaboration with the Institut d'Astrophysique Spatiale at the Universite Paris XI [4]. Originally developed as a space mission prototype, the instrument has recently been deployed at ground-based telescopes at Calern, France for the study of Jupiter and Saturn. The constraints for studying the planets with this type of device are considerable. For example, a mode amplitude detection limit of ~ 1cm/s in the frequency range [0.5 - 4 mHz] is desired [4]. This specification implies a velocity accuracy of on the order of 10 m/s per resolution element on the planet per hour and a relatively high measurement duty cycle over a period of perhaps tens of days. For ground-based observations, several sites distributed around the globe are needed to provide adequate measurement duty cycle.

To this end, the Dunn Solar Telescope (DST) in Sunspot, New Mexico, USA has been identified as the second of three planned installations for giant planet Doppler velocity imaging. The two other sites are in France and Japan. The three installations are spaced approximately evenly around the earth, providing for continuous observing capability from the northern hemisphere. The DST development is supported through the Jovian Interiors Velocimetry Experiment (JIVE) in New Mexico project. Several potential telescopes were considered for the New Mexico site, but the most important reasons for selecting the DST are: 1) availability – since most (but not all) projects reserve the DST for solar observing,

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night-time observing time is available. In addition, daytime observations are possible which allows valuable setup, testing and calibration opportunities, and 2) work space and facilities – the DST provides several science ports and optical tables in an enclosed, temperature-controlled space with access to electronics fabrication and machining capabilities. The temperature control is important as the interferometric subsystem within the DSI instrument is extremely sensitive to temperature variations.

The purpose of this paper is to provide a description of the adaptations and interfacing of the Dunn telescope required to support the DSI. A brief description of the DSI instrument and the DST are included to motivate the discussion of the technical criteria for the host telescope and the interface systems.

2. DOPPER SPECTRO IMAGER

The DSI generates images of the object planet with interference fringes whose perturbations can be analyzed to produce a radial (along the line of sight) velocity “map” of the atmosphere’s motion. A schematic of the instrument is shown in Fig. 1. At the entrance to the instrument is a narrowband filter that sufficiently reduces the optical spectrum so that detectable interference fringes can be formed on the focal plane of a CCD camera. An image of the telescope pupil (exit pupil) is presented at the entrance to a Mach-Zehnder (MZ) interferometer arrangement. The interferometer splits the narrowband input light into two paths where one path includes an optical path delay (OPD) and the second path introduces a quarter wave retardance for one transverse axis. The sensitivity of the velocity measurement is proportional to the OPD and the quarter wave shift in the second leg is part of the four-measurement technique to determine the phase of the fringes in the image. A slight angle is introduced between the two paths to ultimately produce spatial fringes and the light is recombined by a beam splitter (BS). The BS output enters two polarizing beam splitters (PBS) that separate the polarization components and also introduce a half-wave retardance to one of the split components in each cube. The resulting four outputs from the PBSs consist of interferometric beams that ideally incorporate zero, quarter, half and three-quarter wave shifts in phase between the beam components. These beams are relayed to individual lenses where four images are formed on the camera focal plane. A four-bin phase recovery algorithm is applied to the fringes in the images where the perturbations of the fringes are interpreted in terms of Doppler velocity and the results map the velocity components to position on the planet.

The instrument design effectively balances the signal level and the contrast of the image fringes in order to achieve adequate signal-to-noise ratio for the velocity measurement. In particular, the filter bandwidth must be narrow enough to produce measurable fringes but wide enough for signal requirement; whereas, the OPD must be long enough for the required velocity accuracy but not so long that the fringes disappear. The filter selected for DSI has a center wavelength of 519 nm and a FWHM of 1 nm. The OPD is approximately 5 mm, although this value is adjustable with a piezo actuator. The entrance pupil of the instrument is approximately 5 mm in diameter and the interferometer section is placed in a vacuum chamber to minimize differential temperature effects on the two lights paths. Each of the four images at the focal plane cover an effect diameter of about 440 pixels. Further details of the design trades, implementation, and calibration issues of the DSI can be found in reference [4].

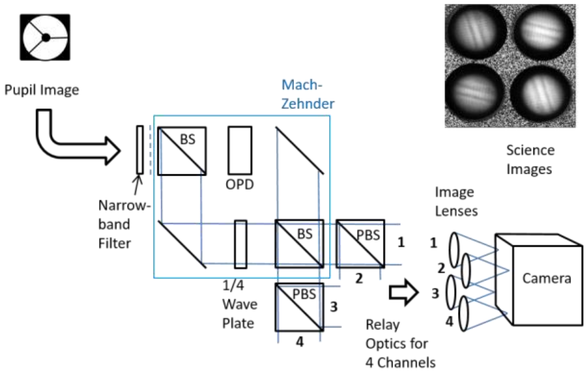

Figure 1. Doppler Spectro Imager

3. DUNN SOLAR TELESCOPE

The DST (Fig. 2) was built in the 1960s and has been for many years one of the foremost instruments in the U.S. for studying the sun. Most of the optical path and primary mirror is in a vacuum to eliminate air disturbances that could be created at the mirror surfaces due to the high solar flux. A cross section of the telescope and facility is presented in Fig. 3. It utilizes an alt-azimuth, heliostat design with two planar mirrors housed in a turret at the top of a 136-foot tower. Light enters the turret through a 76-cm diameter vacuum window and the turret mirrors direct light down the main tube to the 88-cm diameter primary mirror located over 170 feet below ground. The primary mirror can be angled slightly to send light back up to one of several science ports in the working area located at ground level. The science ports, project instrumentation area (where the DSI will be installed) and some of the personnel work spaces are on a science “table” that is suspended along with the structure that supports the optics train. The whole structure including the turret, main tube, primary mirror and science table weighs 250 tons and is suspended from a mercury float-bearing near the top of the tower. The structure can be rotated during observations to remove the rotation of images at the instruments on the science table.

Of particular interest to our project is the approach the DST uses to guide on the sun. An elliptical pickoff mirror suspended near the center of the main tube sends a 3-inch beam of light into the guider tube (“periscope”) that is adjacent to the primary tube (see Fig. 3 (a)). Optics in the guider tube produce a 3-inch diameter image of the sun at a large quad cell mounted to a small table on the science platform (Fig. 4). Analog offset signals from the quad-cell are used to drive the turret mirrors in a tracking loop. Computer guiding is also available for driving the telescope based on ephemeris calculations; however, there is typically a slow drift in the computer guide point relative to the sun position, so the quad-cell guiding is much more accurate. Our approach to the development of a night guider was to use the periscope and replace the quad-cell with a camera.

Figure 2. Dunn Solar Telescope, Sacramento Peak, Sunspot, NM [photo credit: Dr. Patrick Gualme]

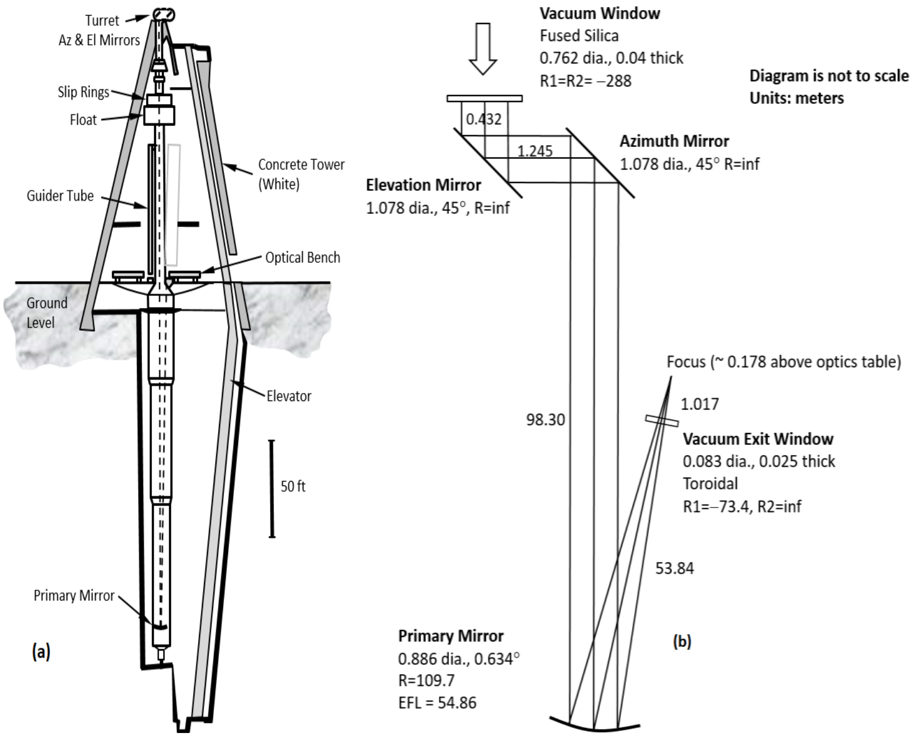

Figure 3. Dunn Solar Telescope (DST)

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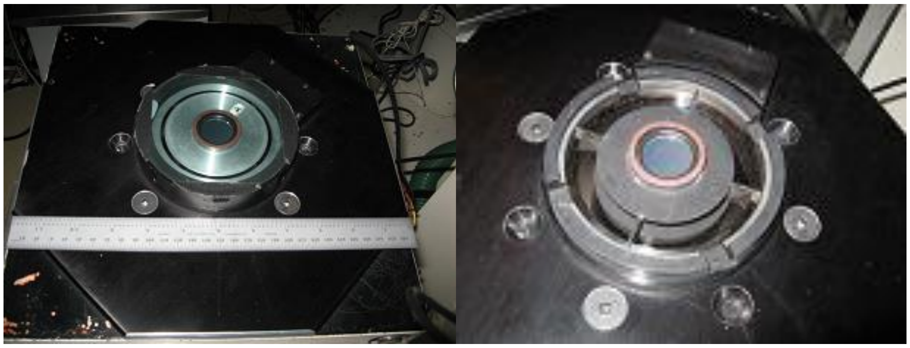

Figure 4. Solar Guider Quad-cell

4. TELESCOPE GUIDING AND INTERFACING

4.1 Overview

The SNR of the interference fringes produced by the DSI is important for calculation of the object planet radial velocity map. This section describes how the major operational elements of the DST-DSI integration work together to maximize SNR over the measurement period. The instrumentation overview diagram of Fig. 5 shows the major hardware components, data connections and control messaging of the integrated system. There are aspects of the interface optics design and installation critical to DSI operation (e.g. input beam size, the specific light spectrum, precise optical alignment of all elements, etc.) that are not discussed, or only mentioned in passing, in this paper. All but the Guider/Tracker elements of this section were designed and built by the OCA team who also provided valuable input and feedback to the NMSU team during development of the Guider/Tracker.

This section focuses on the dynamic corrections and adjustments required to maintain stationary pupil and planet images at the DSI input port and science-camera focal plane, respectively.

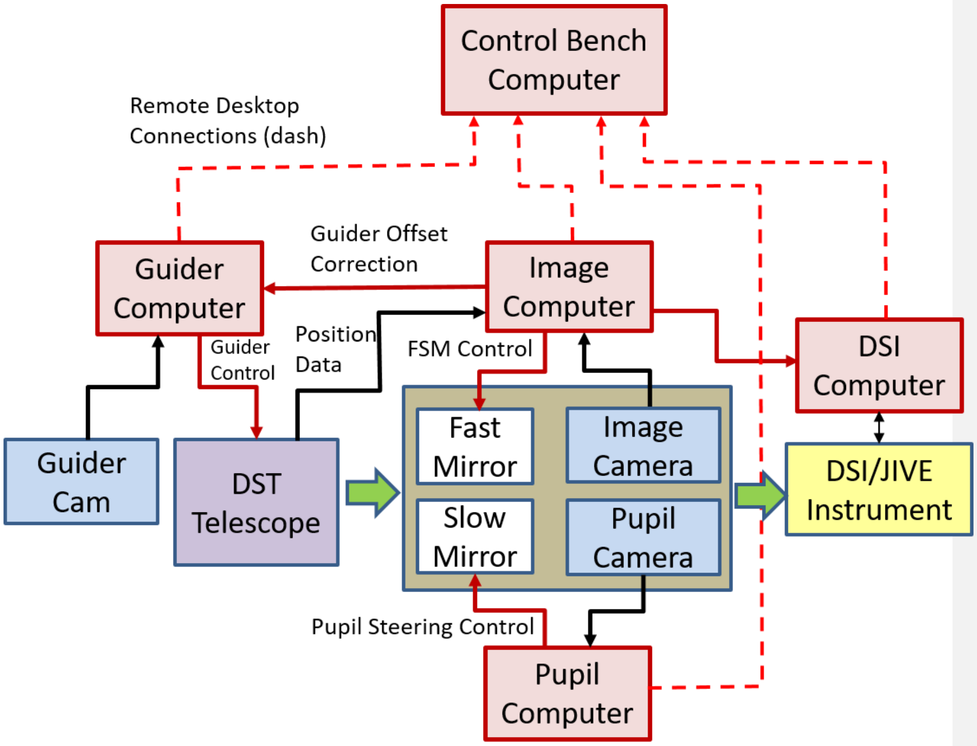

Figure 5. Instrumentation Overview Diagram

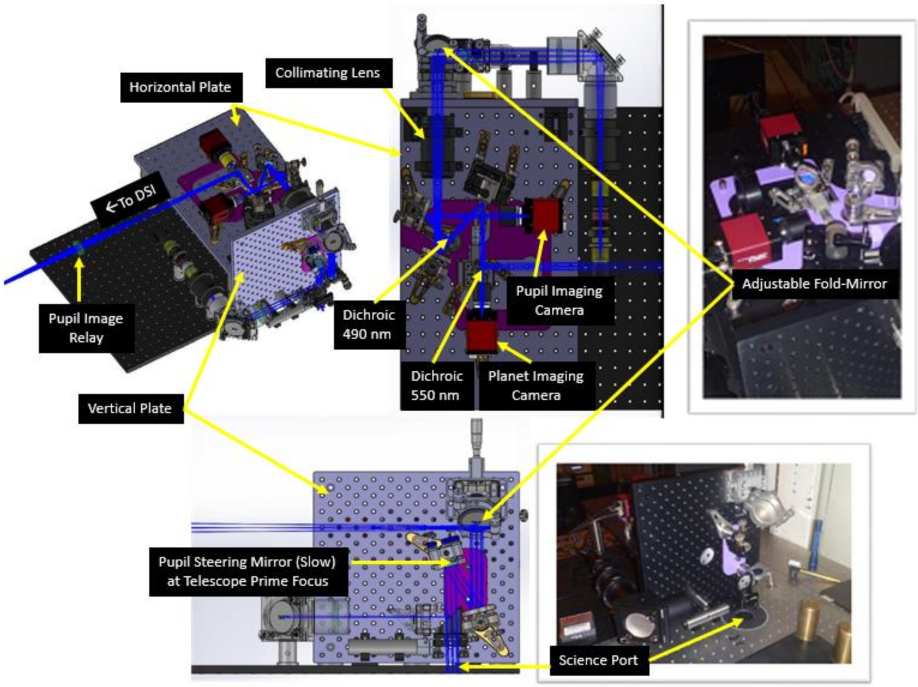

Figure 6. Telescope Interface Optics

4.2 Interface Optics

Please refer to Fig. 6 to follow this description of the light path from the DST science port, through the interface optics. The first element of the interface optics is a “slow” steering mirror (SSM) that is part of the Pupil Stabilization stage. It is mounted on a vertical plate at the telescope’s prime focal plane. Light reflects up to an adjustable fold-mirror that sends light onto a horizontal plate. A collimating lens compresses the light producing a pupil image (Ø 4.2 mm) at a fast steering mirror (FSM) that is part of the Image Stabilization stage. Two dichroic beam splitters (before and after the FSM) shunt light to two cameras. One camera images the pupil using the shortest wavelengths (below 490 nm) and the other images the planet using the longest wavelengths (above 550 nm). The 490-550 nm band is passed on to a relay-lens that transfers the pupil image to the DSI input port. Just before entering the DSI a narrowband filter (center wavelength at 519 nm and FWHM of 1 nm) limits the spectrum for generation of the interference fringes.

Even slight variations over time in the path that light travels through the MZ could degrade the fringes generated because the MZ optics that produce the interference fringes are not spatially uniform. An important step (not discussed in detail in this paper) prior to collecting data with the DSI is the positioning of the pupil and planet images at the DSI input port and science-camera focal plane, respectively, which establishes this path. The pupil and image stabilization stages of the interface optics hold this path constant by keeping the pupil and planet image positions fixed in their respective conjugate planes throughout the DSI data collection. In addition, since the primary data product of the DSI is the sequence of planet images and fringes collected, the relatively low fringe contrast and limited light available for imaging require exposures of more than 20 seconds so the planet image position must be fixed to prevent motion blur.

4.3 Pupil Stabilization

A small misalignment of the DST turret and primary mirrors results in a slow (a few arcseconds per hour) "wander" of the pupil image at the science port as the turret follows a planet or star. The pupil stabilization stage is designed to monitor the image of the telescope's pupil and command SSM deflections to keep its position fixed. After passing through the collimating lens the shortest wavelengths (< 490 nm) of light are shunted to a Prosilica GE680 CCD camera by a dichroic BS. The centroid of the pupil image captured by the camera is used to measure movement. Any centroid displacement is converted into the angular tip/tilt of the SSM that will counter the movement. Software developed by the OCA team captures the pupil image frames, calculates the centroid and commands the SSM. Updates to the SSM are expected to be << 1 Hz.

4.4 Image Stabilization

The primary purpose of the image stabilization stage is to remove the high-frequency image displacements caused by wavefront tip/tilt perturbations at the telescope entrance pupil due to atmospheric turbulence. The guider/tracker discussed in the next section is designed to keep the telescope pointed "well enough" for this stage to perform its function.

As with the pupil stabilization stage, a dichroic BS is used to send part of the light to a Prosilica GE680 CCD camera. In this case, the longest wavelengths (> 550 nm) of the spectrum are shunted to the camera to image the planet. The centroid of the planet image for each video frame is used to measure its displacement (in pixel coordinates) relative to its boresighted location. This lateral image displacement is the "error" input to a PID (Proportional-Integral-Derivative) control-loop that generates the FSM angular tip/tilt commands to keep the image as close to its boresight location as possible. Software developed by the OCA team captures and processes the video frames, and controls the FSM.

The maximum image correction that this stage can affect is determined by the mechanical tip/tilt range of the FSM which is nominally ±5 mrad in both axes. This is equivalent to ±10 mrad in optical deflection.

The telescope pointing error (less the additional margin required to handle turbulence-induced motion about this position) on the sky that the image stabilization stage can tolerate is calculated by multiplying the FSM's maximum, nominal optical deflection by the angular demagnification (M_a) between the telescope pupil and the FSM. M_a is the ratio of the pupil image diameter at the FSM to the diameter of the telescope's pupil which, for the DST, is determined by the dimensions of the fused silica window (Ø 762 mm) of the turret (Fig. 3(b)). The maximum telescope pointing error ($P_{e,sky}$) is:

$$P_{e,sky} = 10 \cdot M_a \text{ mrad} = 10 \cdot (4.2/762) \cdot (1e\text{-}3) \cdot (180/\pi) \cdot 3600 \approx 11.3 \text{ arcseconds.}$$

Although the guider/tracker is designed to keep the planet image well within this constraint, there is relative motion during an observation between the images formed at the guider/tracker periscope and the science port. As the guider/tracker holds the image fixed (i.e. at a "set-point") in its FOV, the science port image moves. This is similar to the "pupil wander" corrected by the pupil stabilization stage and results from a small misalignment between the periscope and primary tube optical paths that is evident as the turret or primary (e.g. for image de-rotation) move relative to each other. Without dynamic adjustment, the science port image will move too far from its boresight location and exceed the physical limits of the image stabilization stage FSM. The image stabilization software sends new set-points to the guider/tracker using Transmission Control Protocol/Internet Protocol (TCP/IP) messages that keep the science port image boresighted.

4.5 Guider/Tracker

After discussions with DST telescope operators, systems engineers and management, a decision was made early on to use the solar-guiding interface for guiding rather than pointing the telescope with the DST's software control interface. Some of the considerations that led to this decision included: 1) a successful "night-guiding" solution adds a useful capability for the DST, 2) the solar-guiding mechanism is the most used and proven telescope guiding method available at the DST for telescope control, and 3) only the turret is "commanded" through the solar-guiding interface while the rest of the optics-train remains under the operator's control. This includes enabling and disabling field de-rotation and direct commands to rotate the science table. The inability of the guider to cause inadvertent optics train rotation and the associated safety concerns was an important consideration in making the decision to adapt the solar guiding periscope for the JIVE project.

Details of the guider periscope are shown in Fig. 7. The pickoff mirror (M1) sends the light to the guider tube where an objective lens (L1), field lens (L2), and an image lens (L6) produce an image of the sun on the quad-cell at the guider table. For the night guider, the quad-cell was replaced with a lens (L7) and a CCD camera.

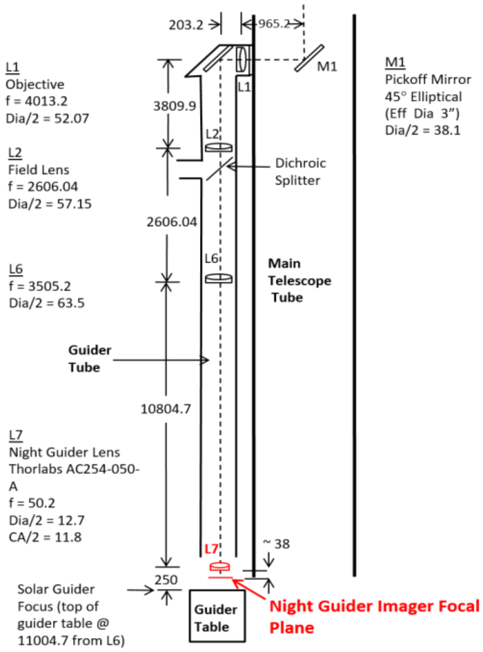

Figure 7. DST "Periscope"

The DST solar-guider quad-cell, that the JIVE guider/tracker replaces, produces three output signals to control the telescope turret. Two (X and Y) drive signals (±10V) are converted by the telescope's analog circuitry into azimuth and elevation controls. The third signal, light-level, is the summation of the four photodiode outputs and is utilized by the telescope to automatically disable turret control if the light striking the quad-cell is below a preset threshold. The threshold is set by the operators such that a light-level below this threshold may indicate that the sun is partially or completely obscured and the drive signals may be invalid or unreliable.

The guider/tracker consists of an Imaging Source DMK 21AU04 CCD camera and a "phidget" 1002_0 four-output DAC (shown in Fig. 8), a computer, and the software to operate the guider. The software performs the following functions: 1) processes the camera's digital (640x480) video frames, 2) determines if a planet or star is in the frame and whether there is enough image contrast for processing, 3) calculates a centroid value for the frame, 4) processes TCP/IP set-point changes from the image stabilization stage, 5) calculates the appropriate drive and light-level signal outputs, 6) handles any GUI control inputs/actions, and 6) sets the DAC voltage output signals to control the turret.

A centroid-tracking algorithm and PID control-loop process the camera video and generate the turret control signals to keep the planet centroid at the current set-point. If there is no "clear" object present in the frame or the contrast of the image frame is not sufficient for the centroid algorithm, the light-level output signal is used to "turn-off" turret control.

The software's GUI allows for manually enabling or disabling the guider/tracker by simply setting the light-level below the operator-prescribed threshold for automatic control. It also allows for manually setting and adjusting the initial guide set-point used to boresight the planet image at the science port. Image "de-rotation" (by rotating the entire optics train), if explicitly enabled by the operator, is "linked" to turret pointing and, therefore, does not require explicit control by the guider. As for solar-guiding, if turret control is disabled by dropping the light-level signal, ephemeris control takes over and can maintain turret pointing well enough to keep the tracked object within the JIVE guider camera's FOV for many minutes so that momentary, often repeated, planet occlusions by clouds results in "hand offs" of turret control between the JIVE guider and the ephemeris guiding.

The current JIVE guider camera has a ¼-inch sensor with 640x480, 6.5 um, square pixels. Each pixel has an instantaneous field of view, IFOV, of approximately 1.2 arcsec so that the 11.34 arcsecond correction capability of the image stabilization stage corresponds to ≈ 9.5 JIVE guider pixels.

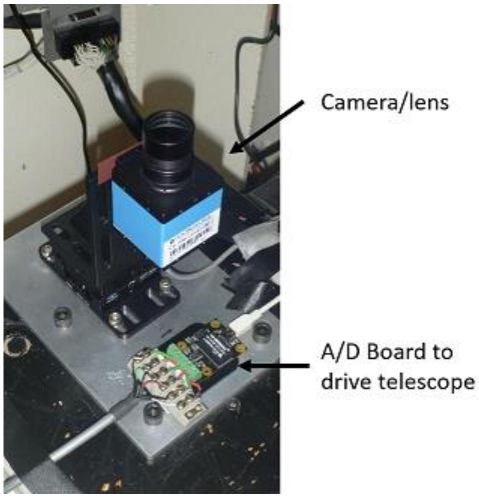

Figure 8. JIVE Guider

A plot of magnitude error between the calculated planet centroid and commanded set-points is shown in Fig. 9. Data was collected for just under 10 minutes. The error "spikes" are due to manual changes to the guide set-point. The turret pointing changed quickly without oscillation or any signs of instability which would have been evident in the centroid errors. The steady-state error (~ 3 pixels) is well below the 9.5 pixels calculated as the upper limit of correction possible with the FSM. Also, the oscillations about this average centroid location vary with the guider/tracker camera frame rate which is ~26 frames per second (fps) which is well within the frequency response of the FSM. If the guider/tracker control loop cannot be tuned to eliminate steady-state error, the image stabilization stage software will adjust for it by commanding set-point changes for the guider/tracker.

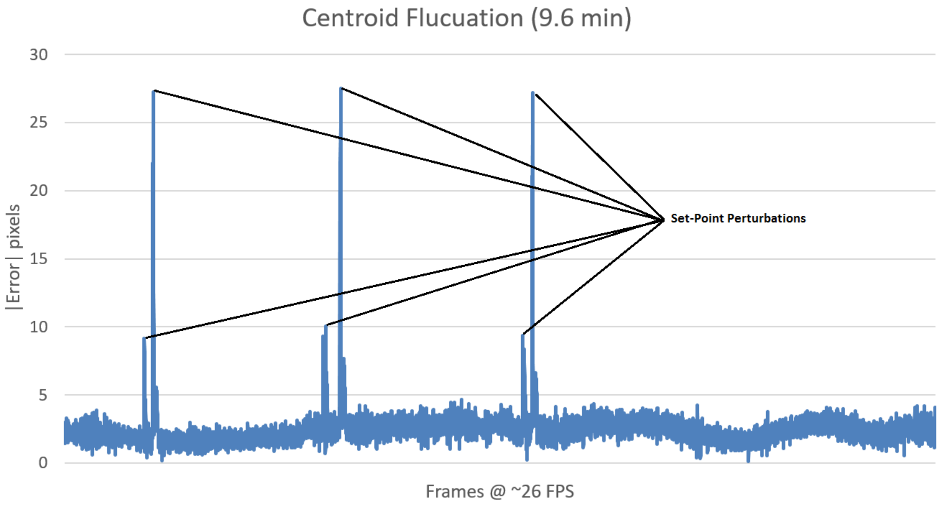

Figure 9. Centroid Errors and Perturbation Response

5. SUMMARY

Teams from Laboratory Lagrange, University Côte d'Azur, Observatoire de la Côte d'Azur, France and New Mexico State University, Las Cruces, NM, USA are collaborating to integrate the Doppler Spectro Imager (DSI) instrument with the Dunn Solar Telescope (DST) on Sacramento Peak in Sunspot, NM, USA.

The DSI uses interferometry based on a Mach-Zehnder (MZ) interferometer to measure perturbations in the doppler shift of light reflected from gas giant planets such as Jupiter. These perturbations are used to calculate the radial velocity of acoustic oscillations that, when entered into models of the planet's sound speed profile, lead to improved understanding of the planet core's size and mass.

The DST was chosen as the second of three planned DSI sites that are spaced approximately equally around the world to provide continuous planet coverage from the northern atmosphere over data runs planned to last for tens of days. The first site is in Calern, France and the third will be in Japan.

Integration with the DST involves some of the same types of instrumentation as with other telescopes, but the primary design of the DST as a solar observatory presents unique opportunities as well as challenges. The interface optics, pupil stabilization and image stabilization instrumentation were designed and implemented by the OCA team and are variations on systems utilized in Calern, France. The night-time telescope pointing approach designed and implemented by the NMSU team is unusual because it is based on the DST's solar-guiding mechanisms rather than a more common technique of making relatively small corrections to the telescope's ephemeris guiding.

A test of the JIVE guider/tracker at the DST in June 2017 provided an opportunity to test the JIVE guider/tracker. The data collected shows that it should be a viable approach for the DSI integration with the DST.

A test of all instrumentation integrated with the DSI is scheduled at the DST in October 2017.

This work was funded by NASA through the New Mexico Established Program to Stimulate Competitive Research (NM EPSCoR).

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