Development of a Compact Doppler Magnetograph

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***Abstract*—Solar observations using the 770nm potassium absorption line allow us to detect and measure surface activity such as sunspots and magnetic storms. Helioseismology is the study of propagation of pressure waves within the Sun. Measurement of the Doppler shift of the 770nm line allows us to study these pressure waves and thus better predict solar flares and coronal mass ejections, phenomena which produce severe radiation hazards to astronauts, satellites, and power grids on Earth. We will describe the Compact Doppler Magnetograph (CDM), a remote sensing instrument observing line-of-sight velocities and magnetic field strengths within the photosphere of the Sun. We will also describe the development of the instrument and efforts to improve its sensitivity.**

I. Introduction

The study of the Sun, being the star nearest and most important to Earth, provides key insights into several areas of scientific interest, including astronomy, space weather, and nuclear fusion. In our case, data collected by our instrument through the measurement of the Doppler shift of the Sun's 770nm absorption line would be valuable for use in helioseismology as well as to understand the structure and dynamics of the corona and photosphere of the sun. This would allow us to better predict hazardous phenomena such as solar flares and coronal mass ejections, which, because of their highly energetic radiation content, have the potential to harm astronauts in orbit and disrupt satellites and power grids on Earth. The Compact Doppler Magnetograph is a remote sensing instrument which employs potassium magneto-optical filters (MOF) to image the Sun and measure the surface Doppler shift and magnetic field strength.

II. Project Goal

The Compact Doppler Magnetograph has existed in several forms prior to our development of this version. The goal of the project was to assemble, test, and optimize the instrument in its current form. We intended to achieve a Doppler sensitivity range equivalent to the true range of solar surface velocity, which ranges from ±1.9 km/s at the equator of the sun.

III. Instrument Operation

A schematic of the instrument is shown in Fig. 1. The CDM is a remote sensing instrument which produces Dopplergrams and magnetograms (Fig. 2) by means of narrow pass bands created by the instrument's magneto-optical filters, the unique component of the instrument. Dopplergrams display line-of-sight velocities of the surface of the sun, while magnetograms show areas of magnetic field strength. Sunlight is fed into the instrument by means of a PID-controlled heliostat mirror mounted on the roof of the lab, which tracks the Sun throughout the day. Sunlight is guided through the magneto-optical filters by a series of lenses. A ¼ wave plate and polarization rotator make up the polarization analyzer at the front of the instrument, i.e. just following the instrument aperture. The filter section consists of two crossed polarizers with one of the potassium vapor cells in between. Using a rare-earth magnet, a longitudinal magnetic field is imposed on the cell and the sunlight passing through has its potassium absorption lines split via the Zeeman effect. In the wings of these absorption lines, the light has its plane of polarization rotated by magneto-optical effects, which allows light to pass through the second polarizer. Two transmission bands are produced.

The wing selector consists of a second potassium vapor cell, a quarter-wave plate, and a Wollaston prism. This cell is also placed in a longitudinal magnetic field. The interaction of the magnetic field and K vapor produces partial absorption via the inverse Zeeman effect, causing the two transmission bands to become oppositely circularly polarized (through circular dichroism) The 1/4 wave plate then returns these to orthogonal linearly polarized bands. These are then separated by the Wollaston prism and imaged by the CCD.

IV. Magneto-optical Filter

The magneto-optical filter (MOF, Fig. 5) is a glass cell containing potassium in a reservoir. Heaters allow the amount of potassium vapor in the optical path to be controlled in order to adjust the pass bands that are transmitted. The vapor cell consists of a body, through which the light passes and containing the vapor, and the reservoir, which stores an excess of potassium. The reservoir is kept cool so as to prevent condensation of potassium on the body windows, which would block and otherwise disrupt the optical path. In

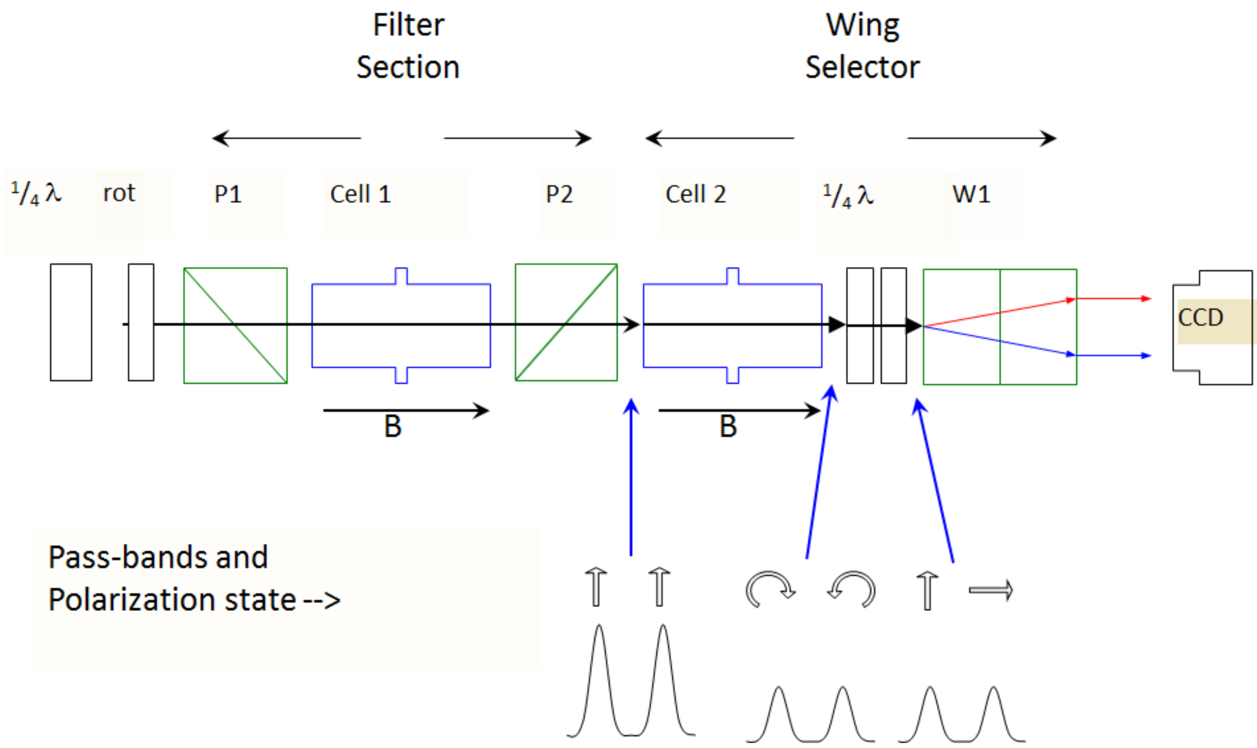

Figure 1: CDM Schematic

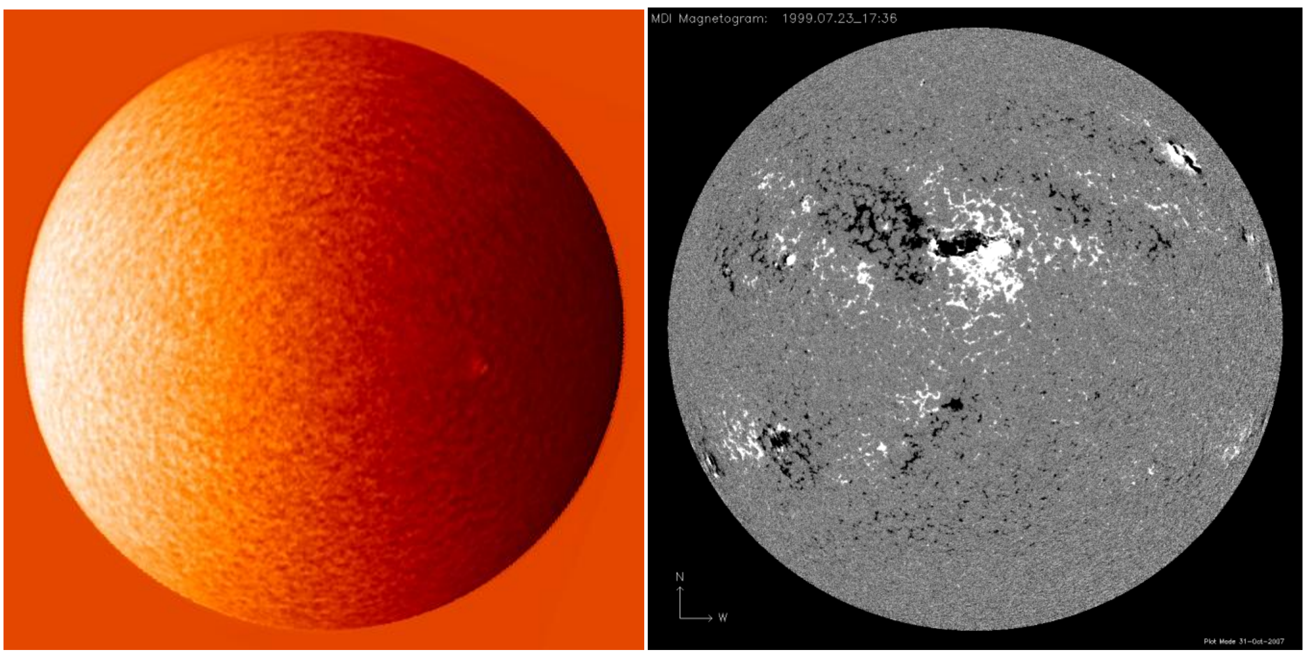

Figure 2: Dopplergram and Magnetogram

our instrument, the MOF's are kept under vacuum to reduce the stress on the windows, which would also distort our image. The MOF is also enclosed in a rare-earth magnet assembly to provide the necessary magnetic field.

V. Development

The instrument has existed in various forms prior to beginning our project (Agnelli et al. 1975). We began assembling the instrument already containing the rare-earth magnet assembly, potassium cells, and 3D printed a structure in order to mount these components within a vacuum chamber (Fig. 3). Development time was allotted for mounting the lens system which focuses the beam of sunlight at the CCD's image plane, the refinement of this lens system, and optimization of the instrument sensitivity. The lens system was modeled in Winlens 3D, an optical modeling program. Fig. 4 below displays one of the solar disks imaged at the CCD being modeled in the program, as well as what it looks like in reality. Winlens allowed us to model lens distances and decenters in order to work around certain physical constraints present in the real system, such as ensuring lens pairs fit entirely within the vacuum chamber. During this process, it was found that the camera mounting hardware was insufficient for our needs. Therefore, we designed and 3D printed a custom camera mount (visible in Fig. 6) to be able to place it on a translation stage, allowing for fine focus of the image.

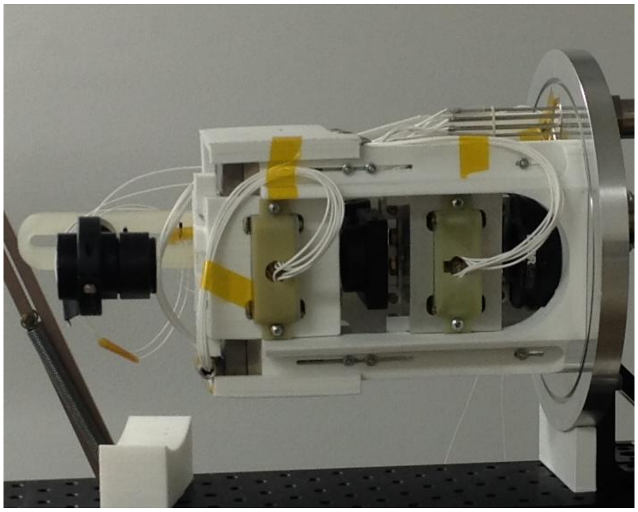

Figure 3: 3D printed MOF mount within vacuum chamber.

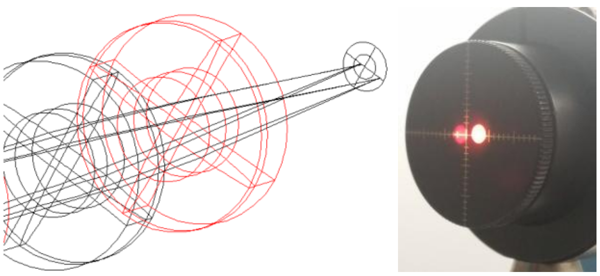

Figure 4: Image of sun modeled in Winlens 3D (left); real image (right)

The entire optical system was aligned via a laser aimed parallel to the optical bench. This beam defined the optical axis. Each part of the system (lenses, polarizers, the MOFs and the CCD) was placed so that this beam passed through the exact center of each component, resulting in less optical distortion at the image plane.

We encountered several issues during the course of development. The first was not an issue with the instrument, but rather the heliostat. The quad-diode light sensor controlled heliostat malfunctioned just as the lens system placement and alignment was completed. We were able to return the heliostat to a quasi-automatic mode which functions for reasons which are not as of yet known. This is one area of the system in which future improvements will take place. Another issue we encountered was an aberration visible as a bright spot on our final image. This was determined to be because of potassium cell window deposition, which will also be addressed in future improvements.

Optimization was the final stage of development carried out. As mentioned, we aimed to achieve a maximum sensitivity of ±1.9km/s in our measured Doppler shift, matching the true range of radial velocity at the Sun's equator. 1/4 wave plate orientation was adjusted to allow minimum light leak through. The magnetic field inside each of the magnet assemblies was also measured using a Gaussmeter. These data will be used by Dr. Neil Murphy to model the field's effects on the transmission pass bands, and in the future will be optimized to allow the absorption bands produced by the wing selector to align exactly with the transmission bands produced by the filter section.

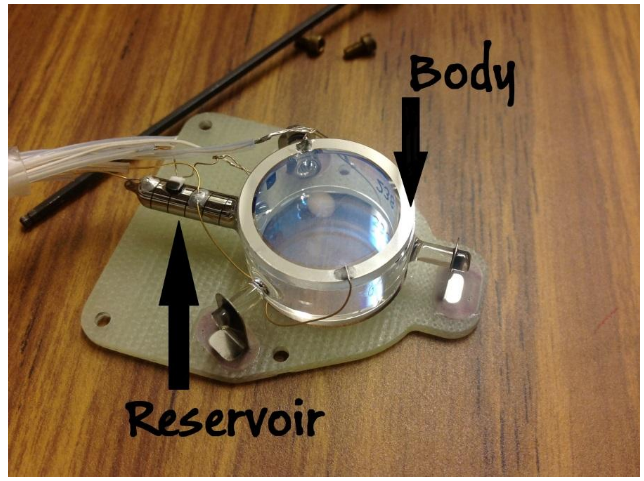

Figure 5: Magneto-optical filter with body and reservoir denoted.

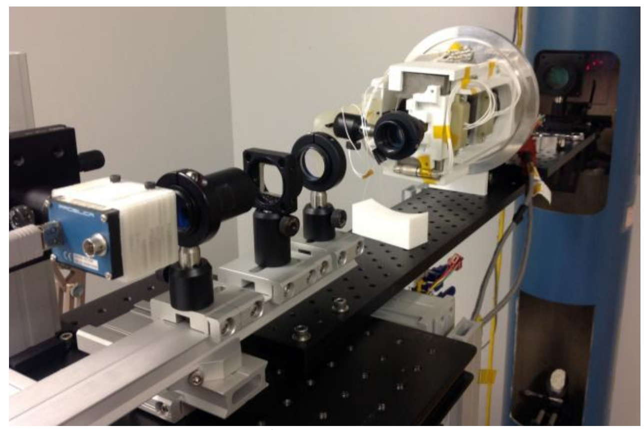

Figure 6: Full optical layout of instrument; aperture in background, CCD with 3D printed holder in foreground

VI. Results and Future Work

Fig. 7 shows a filtergram (top) and a dopplergram (bottom). The filtergram is the raw image captured by the CCD. The Dopplergram is the result of processing carried out in LabView; each of its pixels is the difference of the intensity values of the corresponding pixels in the left and right image, divided by their sum:

$$V = \frac{I_A - I_B}{I_A + I_B}$$

A brightness scale defines the magnitude of the velocity of the Doppler shift at each pixel. The bright areas represents radial velocity towards the observer (our instrument), and dark areas radial velocity away. It is known that the Sun is a nearly perfect sphere; thus we would expect a smooth gradient of velocity differences when looking from left to right across the image. By looking at the Dopplergram, however, we can see that the surface is granulated, representing turbulence caused by hot air currents on the surface. These data, combined with magnetograms (we were unable to produce these over the summer due to a required part which we will acquire in the near future) as well as observing the movement of visible sunspots in the filtergram, will allow us to collect valuable solar data for analysis and bettering of our knowledge of solar and space weather. These capabilities are currently provided by the Solar and Heliospheric Observatory's 56.5kg instrument named the Michelson Doppler Imager (MDI). The Compact Doppler Magnetograph has a goal to achieve a mass of 2.5kg and a volume of less than $(10\text{cm})^3$ to be able to fit within a CubeSat, providing data collection for a fraction of the launch cost and development time of the MDI. Future improvements to be made to the CDM include finding the ideal potassium vapor cell heater operation temperature, adding a plexiglass heliostat window cover to prevent contaminants from entering the system, a polarizer rotator for capturing magnetograms, and miniaturizing the current design further.

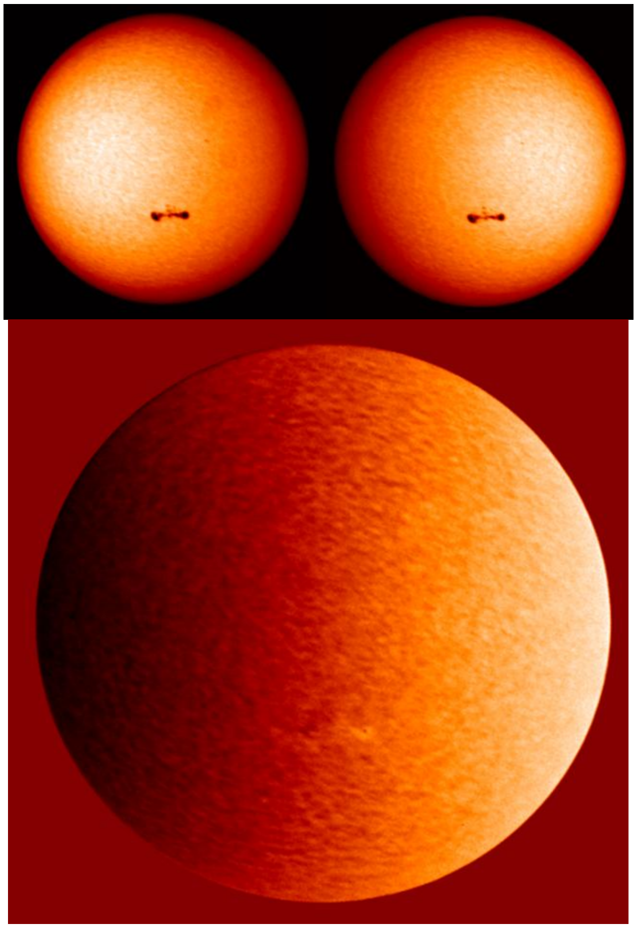

Figure 7: Filtergram (top) and Dopplergram (bottom), taken Sunday, August 23, 2015.

VII. Acknowledgements

I would like to acknowledge firstly my mentor Neil Murphy for taking the time out of his very busy schedule to help carry out the assembly of this instrument and for his guidance and mentoring. I would also like to acknowledge my cointern, Gerardo Hernandez, who designed and printed all of the 3D components mentioned and visible in this report. I had a great time building the instrument with him this summer. My acknowledgements also go to Paul McCudden of LACC, CURE program director, David Falk of LAVC, and the National Science Foundation, without whom this internship could not have happened. I would also like to thank Marshall Fong, laboratory technician at JPL for his assistance and guidance in building the instrument. Finally, I would like to acknowledge my parents for their support of all kinds during my internship.

VIII. References

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