Developing a Compact Doppler/Magnetograph for Solar Diagnostics

Ivan Bernal [1], Dr. Neil Murphy [2]

Victor Valley College [1], Jet Propulsion Laboratory [2]

Abstract:

Line-of-sight velocity and magnetic field measurements on the Sun's surface are used frequently in the field of Helioseismology. Instruments capable of making these measurements are called Doppler/Magnetographs. Future NASA and ESA missions call for a Doppler/magnetograph as part of their instrument package. To meet the payload mass constraints of these missions a compact and low mass version of such an instrument is being researched at JPL that is a fraction of the mass of similar space borne Doppler/Magnetographs. The design verification model (DVM) of this instrument has been built and tested at JPL. The lessons learned from the DVM have inspired a new detailed flight design.

Introduction:

To further our understanding of the Sun scientists cannot directly measure seismic activity as they do here on Earth. To get around this problem they take advantage of the luminous plasma. Light emitted from the Sun is Doppler shifted by the motion of granules (giant convection currents) in the various layers in the Sun. In the field of Helioseismology scientists observe pressure waves in these granules as they travel through the Sun's interior in order to understand the forces at work there. In addition to making Doppler measurements, magnetic field measurements are also made to help understand how magnetic forces influence the electrically charged gases. The SOHO spacecraft, currently in operation, has a Doppler/Magnetograph on board known as the Michelson Doppler Imager (MDI) as part of its instrument package. Researchers at JPL are investigating the possibility of building an instrument of similar performance capability to the SOHO MDI, but only one tenth of the mass.

Project goal:

The primary goal of this project is to develop an instrument capable of measuring line of sight velocity and magnetic fields near the photosphere. This instrument, known as a Compact Doppler Magnetograph (CDM), operates near the 770nm absorption line, and will be a factor of ten lighter than current flight instruments. Since an instrument of this type has never been made this small before, a prototype must be built on an optical breadboard to test performance and verify the design.

Methods used:

The first task was to build a relatively economical breadboard version of the instrument that will be used to perfect the design of the flight version. The first of the optical components to be installed on the breadboard were the lenses and mirrors. Since these are the only components that need to be aligned with precision, it was important to align them before other components were put in the way. To allow for reasonable image quality, the prototype needed each component to be mounted in its own individual mount that could be adjusted on several axes. This compounded the difficulty of the alignment process, which lasted several weeks. The breadboard was then mounted in front of a solar telescope in the magnetometer building at JPL. The beam from the solar telescope was used to center the optical axis of the instrument with the image of the sun.

To reduce the footprint of the instrument, the CDM uses two mirrors to bend the light path at right angles in two places. This reduces the length of the instrument by 17 inches, while keeping its width under 9 inches. In between these mirrors is where the main components of the instrument lie. To mount several of these components centered on the optical path an aluminum instrument box was modified and used to house the magnet assembly, the two potassium cells, a linear polarizer, and a quarter wave plate. These components form the heart of the instrument and occupy less than 10 cm of optical path length. The box housing these components is then placed carefully between a lens, a Wollaston prism, and the two mirror mounts. The confined space in and around the box called for careful planning before mounts were permanently modified to fit in place.

Once the breadboard was complete, the initial tests with the instrument showed low light intensity was reaching the CCD. This was attributed to a failure in the filter section and wing selector of the instrument. The CDM relies on a magneto-optical filter to select two very narrow, 100mA wide, pass-bands of light near the 770nm absorption line. Narrow pass-bands are needed to accurately image specific layers of the Sun. This is combined with a wing selector that absorbs one of the Doppler shifted pass-bands. Both of these components consist of heated glass cells containing potassium. The cells were designed to function in vacuum where they vaporize potassium into a gas. If the cells are operated under atmospheric pressure they will lose too much heat to the surrounding air and fail to vaporize the potassium inside. Therefore, in order for the CDM to function properly the entire instrument box containing the filter section and wing selector had to be under vacuum.

The design and construction of a vacuum sealed environment for the instrument box would later prove to be well worth the effort. Tests performed on the sealed instrument box showed that it was capable of holding a steady 250miliTorr vacuum. This allowed the instrument to produce its first set of Magnetogram and Dopplergram images.

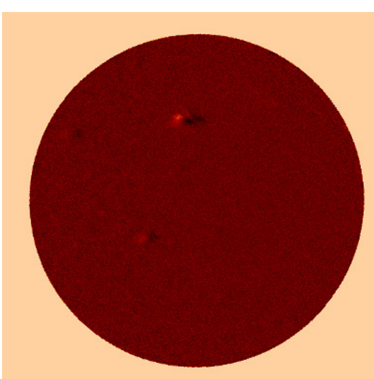


Figure 1

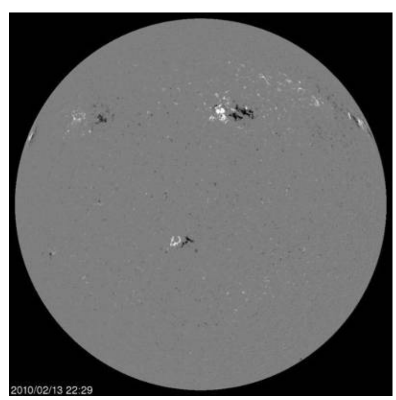


Figure 2

The Magnetogram produced by the CDM in Figure 1 shows a fuzzy image of the Suns disk with dark and bright contrasts representing different magnetic field intensity and polarity. The Magnetogram in Figure 2 is an image taken on the same day from the SOHO spacecraft. The SOHO image clearly reveals many magnetic regions on the Sun that are not visible with the CDM.

For the first two weeks of spring, the CDM was seeing a steady increase in performance with each test. Then suddenly each day of testing resulted in a mysterious decrease in signal strength and sensitivity to velocity and magnetic fields.

The poor performance of the CDM could partially be attributed to low amounts of potassium vapor in the cells, but this was puzzling since the tests were performed using the same temperature and procedures each day. There was also no leak in the cells that could allow gas to escape. The culprit for this strange behavior has not been precisely determined. However, progress had been made that had appeared to temporarily solve the problem.

After dismantling the instrument box containing the filter section and wing selector it became apparent that the close proximity of one of the cell windows with the magnet assembly was creating a cold spot. This is obvious because the potassium vapor created during operation will condense on the coldest part of the cell after it is shut down. Since the cell window on the wing selector was covered in potassium, it was clear that the window on the wing selector was the coldest part of the cell. This helps explain the poor sensitivity to magnetic fields and velocity on the Sun. Condensation of potassium crystals on the end windows of the filter section may also be responsible for the strange behavior of the filter section.

The vacuum in the instrument box has been improved from 250 milliTorr to less than 50 milliTorr. This factor of five performance increase helped reduce the condensation problem.

The two potassium cells have a heat sink built in to them that is intentionally kept colder than the rest of the cell. This is known as the reservoir, and was created so that any condensing vapor will do so away from the windows. After modifying the experimental procedure to allow these regions to cool long before the heaters are shut off, the potassium no longer condenses onto the cell windows.

During testing of the breadboard, the goal is to achieve maximum sensitivity in terms of velocity and magnetic field. To do this the absorption band of the wing selector must match one of the pass bands of the filter section. If a pass band is not properly absorbed then it will affect the data reduction process negatively. The light from the red or blue pass band cannot be separated in the software; therefore it must be done by the wing selector. The polarization rotator at the front of the instrument allows the other pass band to be transmitted to the CCD and saved as a different image.

Long periods of testing revealed a few weaknesses in the design of the cell. During a test run, the temperature sensor on the filter section had detached from the cell and was left hanging in vacuum. As the temperature sensor slowly cooled the temperature control unit attempted to maintain the temperature of the cell by heating it further. When the increase in power to the heater element failed to raise the temperature of the sensor, the control unit further increased the heater element power. This caused the cell temp to rise far above what it was designed for. The wires connecting to the heater element failed (figure 3) and the cell was returned to the manufacturer for repairs.

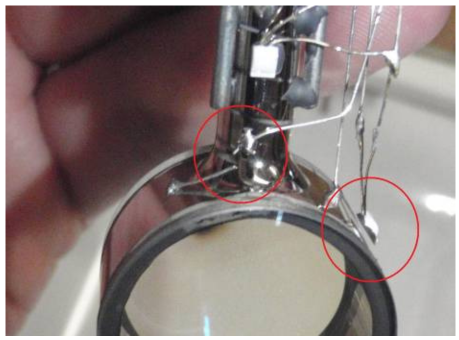


Figure 3

After being repaired, the filter section cell was placed in the instrument for testing, where it continued to perform poorly. It was obvious that there was still a problem which had not yet been diagnosed. It turns out the epoxy used to bond the end windows on started to outgas into the cell and contaminated the potassium, which permanently damaged the cell. To prevent this from happening again the next generation of cells will use a silicate bonding technique which uses a catalyst to grow glass between the end windows and the cell body. This forms a perfect seal and eliminates the possibility of epoxy contaminating the potassium again.

Results:

Before hardware malfunctions halted progress with the prototype, the compact instrument was performing at nearly one half of its predicted resolution in terms of velocity and magnetic field.

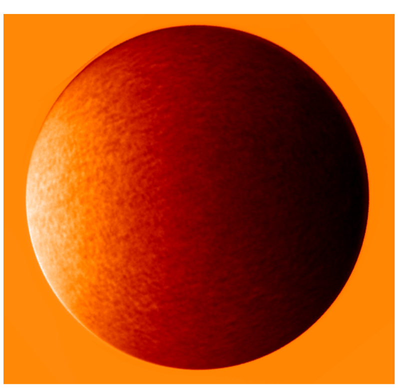


Figure 4

Figure 5

The Dopplergram produced by the CDM in Figure 4 is an image from one of the most recent tests. The image in Figure 5 was taken at JPL by a similar instrument that operates on the same spectral line as the compact version. The difference in contrast on the images of the Sun correlates to different line-of-sight velocities of regions at that point. The images darken from left to right, which shows the rotation of the Sun.

The magnetic field sensitivity has improved drastically from recent tests. Before, only large active regions with very intense magnetic fields were visible. Now it is possible to see much more detail in the Magnetogram.

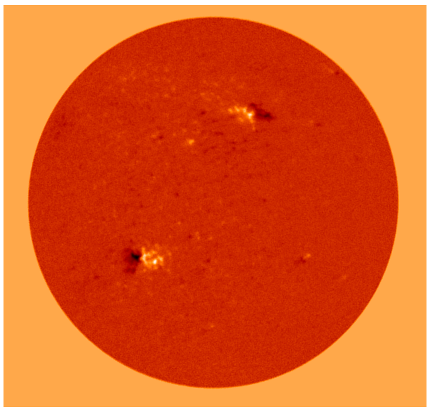


Figure 6

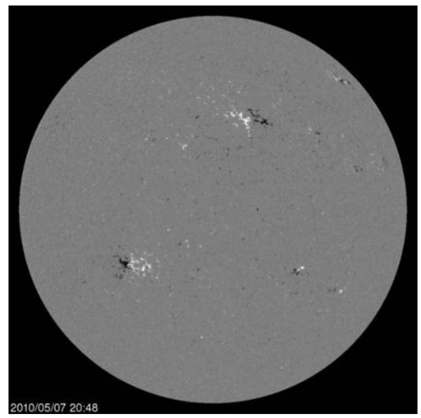


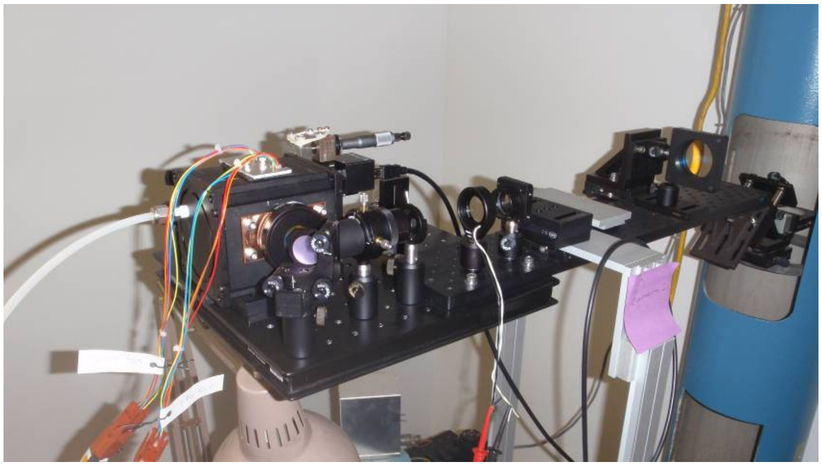
Figure 7

The Magnetogram in Figure 6 is one of the most recent produced by the CDM breadboard. To the right in Figure 7 is a Magnetogram produced by the SOHO MDI on the same day. The images are very similar in detail. It is hard to calculate the exact resolution of the CDM at this point, but it is estimated to be around 20 Gauss in one minute, which is equivalent to the 20 Gauss in one minute of the SOHO MDI (song). It is expected that the CDM could be improved to at least 10 Gauss in one minute.

The data from the CDM has issues with the focus that are caused by a ghost image formed at the windows of the box containing the cells. If these windows were replaced by a pair that is anti reflection coated, then the image quality would improve.

Conclusion:

Although the best images produced by the instrument have a few issues with the image quality and sensitivity, they serve as proof that the instrument is capable of producing data that is competitive with similar flight instruments. Once new cells are placed in the breadboard, the instrument can be fine tuned to determine its maximum performance. The results from all the tests done on the design verification model are being used to help design a more detailed flight version of the instrument. Second generation prototypes of the CDM can benefit greatly from the lessons learned dealing with hardware malfunctions from the first.



Above is an image taken of the instrument mounted on the solar telescope in the magnetometer building at JPL. This is where research on the CDM will continue in the future.

Acknowledgement

The work was supported by the National Science Foundation under grant 0852088 to Cal State LA. Thanks are due to the NASA Jet Propulsion Laboratory, Dr. Stephan Gillam and Dr. Milan Mijic, CURE program directors, Dr. Neil Murphy, research mentor, and Michael Butros, home college advisor.

References

Song, Hui. "The Michelson Doppler Imager (MDI) Instrument." Center for Solar-Terrestrial Research. 24 may 2010. New Jersey Institute of Technology. 24 may 2010 <http://solar.njit.edu/~cdenker/physics681_hui_instrument.pdf>.