Detecting Chlorophyll Fluorescence By Measuring Solar Fraunhofer Lines

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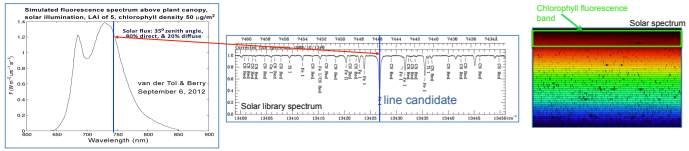
Abstract: Chlorophyll fluoresces in the red and near infrared as a byproduct of energy production in the Photosystem II. By measuring the rate of this fluorescence, we are making a direct measurement of the energy production by vegetation. These measurements will be important for measuring production of crops and the global consumption of CO_2 by the biosphere. The measurement of fluorescence is complicated by the solar light reflected by plants and the Earth surface. The fluorescence can be separated from Solar emission because the fluorescence has no Solar absorption lines in the observed high resolution spectrum. The fluorescence is seen as a "filling in" of the solar lines. This technique of separation works well only where there is a strong spectral variation in the Solar spectrum, that is, near strong Solar absorption lines. Almost all of the discrimination signal is in a few strong lines. Given that the spectral information is contained in a few widely spaced lines, we have developed a field- widened Fabry-Perot Interferometer to optimize the observation. This instrument allows a very wide simultaneous field of view with high spectral resolving, providing a near-optimal signal to noise ratio for each pixel. The multiple lines can be observed using additional Fabry-Perot units. The instrument we have developed has no moving parts, is extremely compact, and is a strong candidate for space applications.

- Most of the signal is in a small number of Fraunhofer lines
- The lines are narrow and require a high resolving power ~ 30,000
- Large field of view to achieve the best performance is required

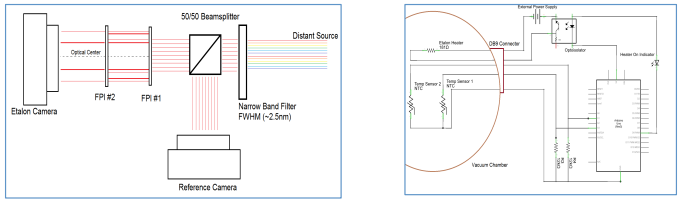
- Measure selected lines within chlorophyll fluorescence band (650nm to 860 nm)
- Sample the spectrum at 2-4 lines within the band
- High signal to noise continuum measurement ~ 100



Left: The theoretical prediction for chlorophyll fluorescence. Middle: The corresponding line in the solar spectrum in which we have observed fluorescence. Right: the full solar spectrum with the region which we have focused on highlighted in green.

Instrument Approach

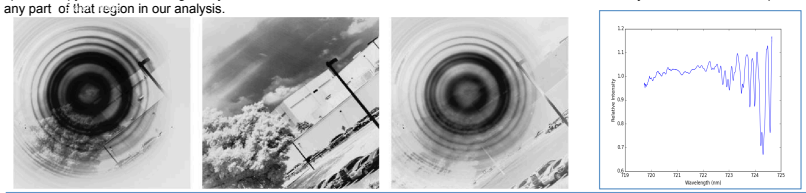
The primary goals of this project are to use high resolution spectroscopy to make measurements of diffuse objects using solid state Fabry-Perot interferometers (etalons). This involved thorough testing in a lab setting to prove the reliability of the instrument as well as its optical performance. The instrument was then able to make spectra of Fraunhofer lines from the solar spectrum in reflection from both the sky and from leaves on a tree. By comparing the line depths in these two cases we were able to observe a decrease in depth corresponding to the filling in of the lines by chlorophyll fluorescence.



Left: A schematic layout of the instrument. The source enters from the right, passes through the filter then the beam splitter. It is then sent to the etalons and the reference camera. The etalons are shown here working in tandem and thus blocking out the extra orders from the first etalon. Right: The circuit diagram of the thermal control system.

Development

Our approach to high resolution spectroscopy is to first use a narrow band filter to select a small part of the spectrum. This eliminates the number of orders appearing in the instrument and thus we are able to focus on a small part of the spectrum at high resolution. That light is then passed through a beam splitter and one side is sent to our reference camera and the other is sent into the etalons. The reference camera will be used in the analysis to determine the changes in intensity of the source which need to be eliminated to leave only the spectrum of the source. The other path moves to the etalons where there is a suppression of light that is not an integer multiple of the plate separation. This creates an optical effect of concentric rings in the resulting image. It then passes through a second etalon which has a different separation of the reflective surfaces. This then suppresses the orders that are not common to both etalons. Running the etalons in tandem allows for true spectroscopy to be done using Fabry-Perot interferometers. We can then scan the instrument across an object and recover the spectrum of any part of that region in our analysis.

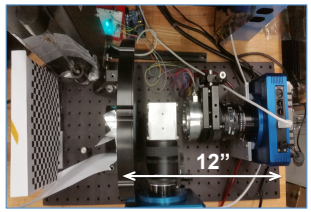


Left: Example images from the etalon and the reference cameras. The rightmost image shows the spectral image which is recovered by taking the division of the etalon image and the reference image after alignment of the images. Right: The recovered spectrum from the spectral image.

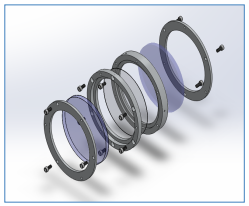
The major developments for this project have come in two broad categories the hardware to take the data and the software to analyze it. The hardware developments have focus on proper mounting, tuning, and control of the etalon. The first step to this was to design and construct a holder for the etalon which would be thermally isolated from the outside environment. We came up with a design for a holder which uses sapphire windows to protect the fragile etalon as well as radiatively couple the heating of the etalons with the heating of the windows. Through testing in Solidworks and later testing in the lab we found that this has good thermal contact and relatively low losses. To isolate this holder we built a chamber which could be place the etalon in vacuum but we discovered that there is very little convective losses so there is not a significant gain to using a vacuum. This chamber can then be mounted on a tip tilt stage which helps in the alignment of the two etalons which need to be perfectly parallel.

The second major development was made in the software used to process this data which is written in Python. This allowed for the use of existing astronomical software packages which significantly improved the speed and reliability of the software. The analysis includes routines to find the optical center, align the images, and conduct analysis of the spectra of any region of the image. This involves some computer vision analysis to find the best alignment between the two images. The software can then use the spatially scanned data to reconstruct a panoramic image which gives information about the spectrum in each region of the individual images.

Instrument



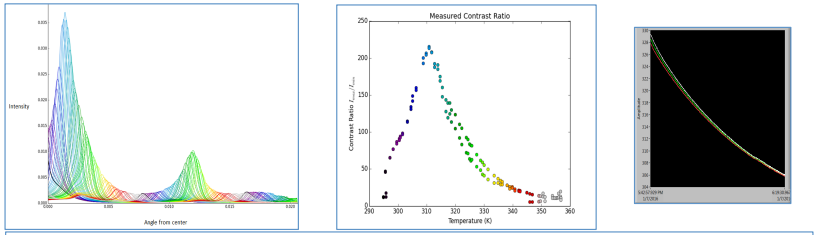
Etalon assembly



Left: An image of the instrument in its current configuration. The etalon camera is on the right. We are using a reference pattern to test the alignment of the images in the processing routine. Right: An exploded rendering of the Solidworks model we have used to test the thermal and mechanical properties of the etalon holder.

Characterization

The characterization of the instrument is crucial in determining its performance and reproducibility in the field. To test the instrument reliably it was tested in the lab using gas discharge tubes. These provided a stable and bright source with which to test both the hardware and the software. The ability to tune the etalons was tested by thermally expanding the etalon until at one particular temperature there was a large increase in contrast as well as a noticeable increase the intensity.

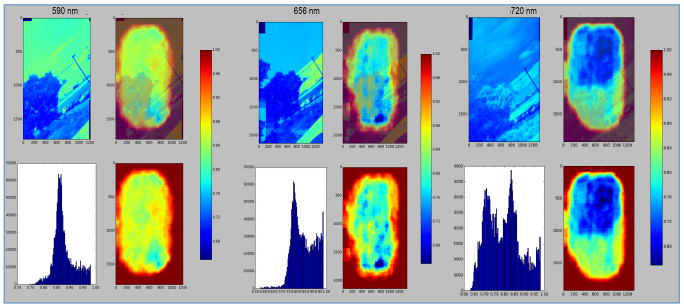


Left: A spectrum showing a spectrum of Hydrogen in the H alpha filter as the etalon is swept in temperature. This shows the increase in intensity at a particular temperature (315 K). Center: The contrast ratio, the maximum intensity over the minimum intensity, for the data shown on the left. This shows a peak at the alignment temperature. The height of this peak matches the theoretical prediction for this characteristic of the etalons. Right: A plot of the temperature versus time.

Results

We can use the spatially scanned data to reconstruct the spectrum at a series of small patches of the area observed. We can then measure the average line depth of that spectrum. In doing this we can look for regions which have a significantly shallower line. This would indicate that there is something filling in that line which we observe to be the result of chlorophyll fluorescence. This signal should be strongest at 720 nm, weak at 656 nm, and nonexistent at 590 nm. We have observed a difference in line depths of 15% at 720 nm, about 5% at 656 nm and no difference at 590 nm.

- We have observed the fluorescence of chlorophyll in reflected spectra
- Our observations of the change in fluorescence signal with wavelength is consistent with theoretical predictions
- Our method of spatial reconstruction of spectra is robust and widely applicable
- The technology of solid Fabry-Perot etalons is simpler and more stable than a mechanically tuned counterpart



All figures show the mean line depth over the field of view. Top Left: The panoramic image of the reference. Bottom Right: The mean line depth map, note that the scale of the line depth map is common to all the figures and shows blue as the deepest lines and red as the shallowest. Top Right: The line depth map overlaid on the panoramic image showing the relationship between the line depth and the reference. Bottom Left: A histogram of the line depth map, this shows that there is a signal of a difference in line depths. The left group shows the results at 590 nm, the center group shows 656 nm, and the right group shows the 720 nm results.