Relating Spectroscopic Measurements of the Solar Corona to Alfvén Waves and Turbulence

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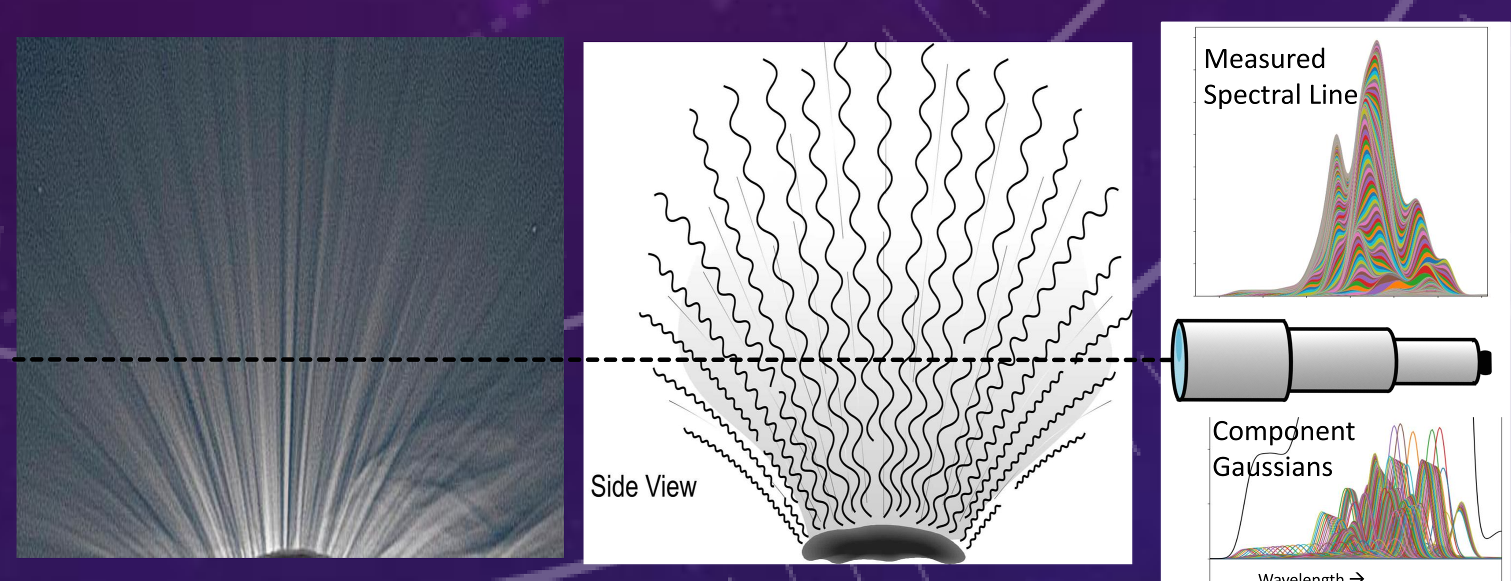
Abstract

There is debate in the solar community regarding the mechanism by which the corona is heated to millions of Kelvin. Alfvén waves, driven by fluid motion in the photosphere and propagating upwards to dissipate in the corona, are one of several popular hypotheses for the source of the thermal energy. Observations of off-limb spectral lines are able to constrain some properties of these waves (e.g., amplitudes and phase speeds) as a function of heliocentric altitude. In this work, a forward model is used to simulate plasma properties along many optically thin sightlines over the limb, which are then used to generate spectral lines. These lines are then studied to determine how their properties are related to the known wave and turbulence properties along each line of sight. This poster will focus on the effects of time-integration on spectral measurements.

What are we looking at?

Above the poles of the Sun, open magnetic field lines define magnetic plumes which are being shaken by **photospheric convection**. Because these oscillations are transverse, they cause a slight **Doppler shift** in the spectral lines they produce. But because there are many such flux tubes along a line of sight, measurements are the sum of many individually Doppler-shifted spectral lines.



It is not immediately obvious exactly how to extract the properties of the waves from such a profile. One method often used, but little verified, is to simply fit the line with a Gaussian and then **relate the line width to the RMS amplitude**. Care must be taken to subtract out the thermal width to get the true nonthermal (wave/turbulence) width of the line. [3,7,5,10] Another way to get this information is to **track the centroid of the line over time** and measure the standard deviation of the centroid. This method runs into difficulty because the many swaying plumes work to cancel out each other's motion. [6,8,9]

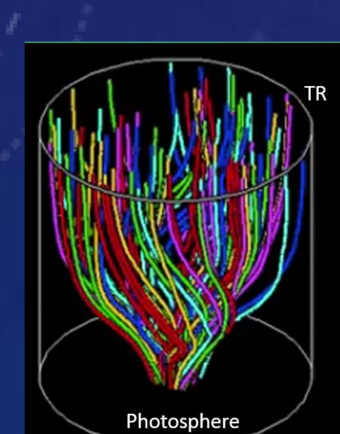
Neither of these methods are well verified. The purpose of this work is to try to better understand how the shape of the spectral lines is related to the Alfvén waves in the corona.

The BRAID and the ZEPHYR Codes

In order to simulate the spectral lines, three kinds of input are needed:

The **ZEPHYR** code is a 1 dimensional code that simulates the plasma properties of the corona as a function of altitude. [2] It produces tabulated output of the following variables, which are read into the CoronaSight model: **Density, Wind Speed, Alfvén Speed, Temperature.** These values are used as the average background values, which are modified by the magnetic field strength.

The **BRAID** code is a simulation of a bundle of flux tubes expanding in the chromospheric network. [1] From that simulation, we are able to draw an average x and y velocity as a function of time. This gives us a **wave profile** that we can draw from in the CoronaSight model. For future work, a distribution of wave speeds will be drawn from BRAID, instead of a single profile.

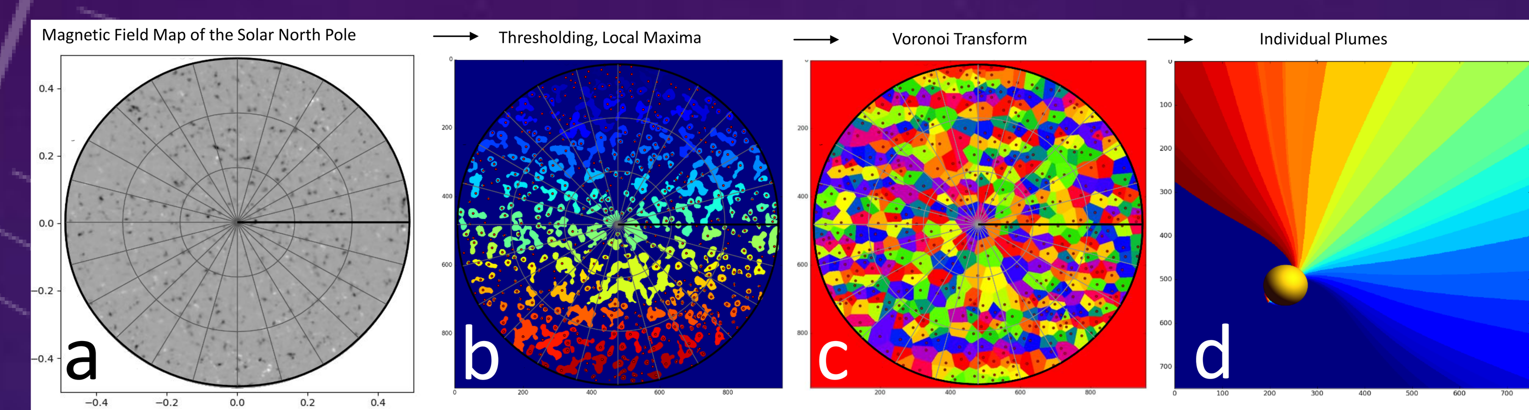


A **Magnetic Field map** must also be provided to the code. Because we don't have a line of sight to the solar poles, these maps must be partially synthesized. The magnetic field maps from **SOLIS/VSM** [4] magnetograms taken of large coronal holes between 2010 and 2013 were stitched together to yield maps subtending about 30 degrees of latitude from the pole.

The CoronaSight Model

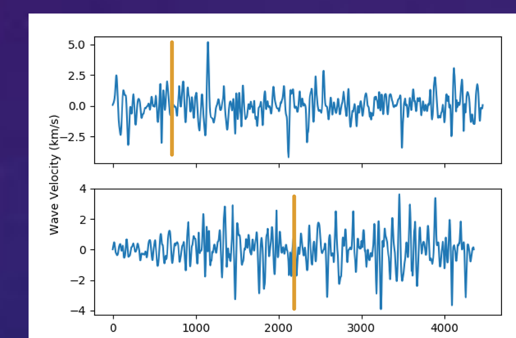
Creating the Plumes

The goal of this code is to simulate spectral lines created by the environment above the pole of the sun. The first step is to define the environment (see the figure below). (a) A magnetogram is read in to the software where (b) it is thresholded to find individual magnetic plumes. (c) The maxima of each of these magnetic spots are then labeled, and used as seeds for a Voronoi transform, such that every point in the volume above the sun can be mapped to a point in the field. (d) This creates a fully tessellated field, such that every point in the volume above the sun can be mapped to a point in the field.



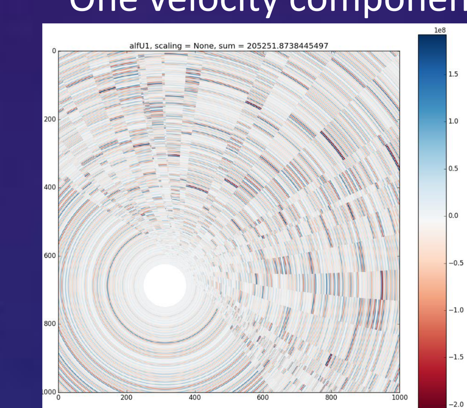
Each of these plumes can now be considered a separate instance. Each plume is assigned two random starting times and a random angle. The wave travel time from the surface is calculated to determine the orthogonal velocities along the whole plume. The actual wave profile is drawn from the BRAID code.

Wave Profiles from BRAIDS



Cross-section of a single plume

One velocity component



Generating the Light

The main portion of the code is radiative transfer. A sightline is established, and the light produced by each point along the sightline is determined. (See the figure by the telescope to the left) There are several factors that go into this determination. The model includes:

- **Solar Wind Velocity**
- **Line of Sight Wave Velocities**
- **Thermal Line Width**
- **Ionization Fractions as a Function of Temperature (CHIANTI)**
- **Density (Intensity) as a Function of B-Field Strength**

CoronaSight can generate sightlines anywhere in the space. There are three general modes in current use: ImpactSim, ImageSim, and EvolveLine.

ImpactSim allows us to generate **many spectral lines at a single impact parameter** to get statistics on their properties. Several different magnetic field maps are used, and sightlines are generated at many angles over the Sun's pole. We can then do this at many altitudes to see how the statistics change. These are the yellow to red plots in the right column.

ImageSim is a synthetic imaging spectrometer, giving us a **spectrum at each pixel**. We can then look at images of the centroids and widths of the spectral lines. This is what created the Centroid and Line Width plots in the right column.

EvolveLine allows us to study the **a single spectral line as it evolves in time**. This is how we generated the wave profile seen in the right column.

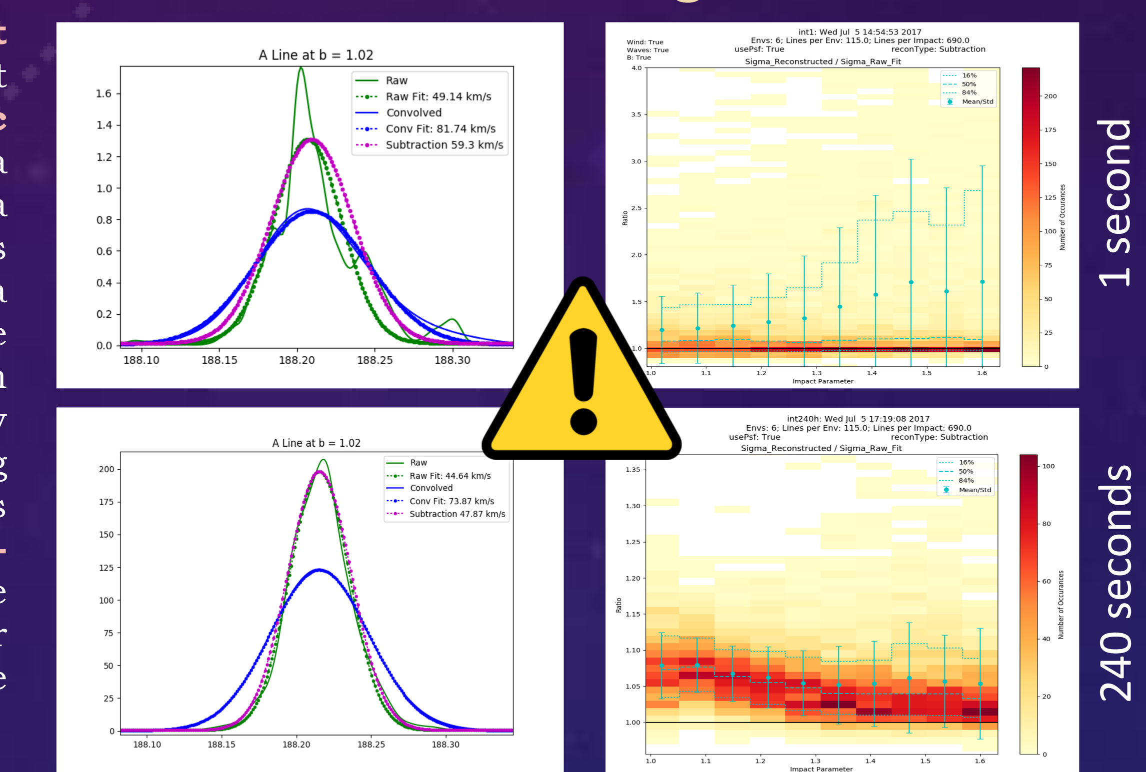
References

[1] van Ballegooijen, et. al. 2011, ApJ, 736, 3
[2] Cranmer, S. R., et al. 2007, ApJS, 171, 520
[3] Esser, R., 1990, JGR, 95, 10261
[4] Henney, C. J., et al. 2009, ASP Conf. 405, 47
[5] Landi, E, Cranmer, S.R., 2009, ApJ, 691, 794
[6] Morton, R. J., 2016, ApJ, 828, 89
[7] Seely, J. F., et al. 1997, ApJ, 484, L87
[8] Threlfall, J., et al. 2013, A&A, 556, A124
[9] Tomczyk, S., et. al. 2009, ApJ, 697, 1384
[10] Tu, C. Y., et. al, 1998, ApJ, 503, 475

Early Results

Gaussian Fits to Non-Gaussian Lines? Dangerous!

Because the spectral lines are **not actually Gaussians**, treating them that way might be adding **systematic errors**. The plots to the right depict a spectral line in green being fit by a Gaussian (dashed green). Then it is convolved with the PSF and fit with a Gaussian again (blue). The width of the Gaussian PSF is then subtracted from the convolved line width to allegedly remove the effect of the smoothing (magenta). For long integrations, this practice adds a **systematic error of 5-7% on average** (difference between pre and post smoothing fit parameters). For shorter integrations, this can be more like 20%. See the Figures on the right.

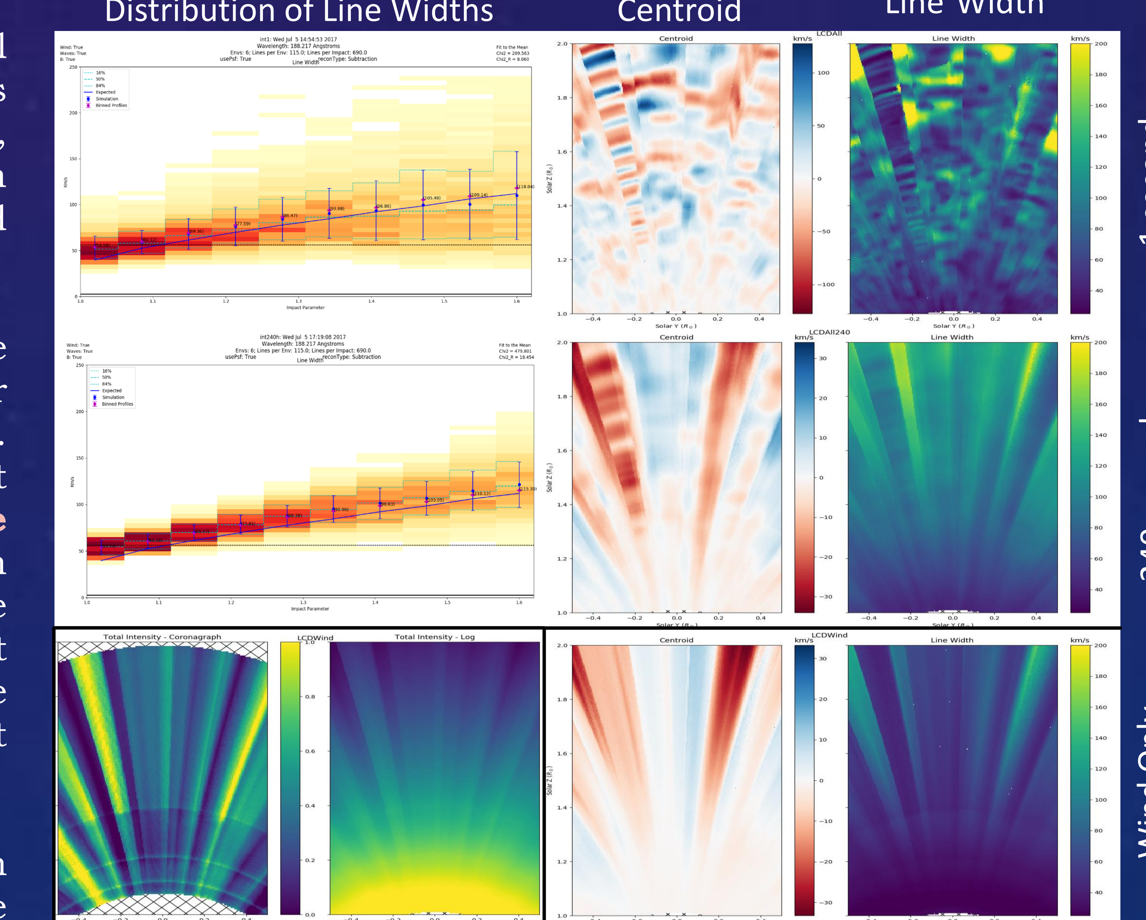


Time Integration Narrows the Measurable Distribution of Line Widths

Here we are generating many spectral lines and fitting them with Gaussians to discover their line width. On the left, a histogram of line widths as a function of height. On the right, centroid and line width images above the solar pole.

When the time integration is short, the range of measurable values is wider than when the time integration is long. This is because it is more likely that you get **strong components in the wings** with short integrations. When integrating for longer times, the individual waves become smeared out and a given height becomes more homogeneous. The mean values don't seem to change at all, which is good.

Notice that the line widths are much **smaller in the wind-only case**. Future work involves using this difference to determine the wave power.



Time Integration Decreases the Std. Dev. of the Line Centroid

On the left is an instantaneous spectral line profile as it evolves in time. On the right is that same profile, but with increasing time integration as you go from top to bottom. At the far right is the standard deviation of the centroid of the line.

If you want to understand the wave motions by looking at the centroid as it changes over time, it is important to understand how the **cadence of the observation will attenuate that motion**. The bulk of the attenuation seems to occur within the first two minutes of exposure.

Future work involves discovering a **numerical relation between centroid swaying and wave amplitudes**.