A Hands-On Tutorial with Local Helioseismology Data[1]

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These exercises are designed to allow you to visualize and understand some of the basic data used in helioseismology. The velocity data are obtained from the Global Oscillation Network Group (GONG) instruments (Harvey et al., 1996), and the Michelson Doppler Imager (MDI) onboard the *SOHO* spacecraft (Scherrer et al., 1995). Please consult these references to learn more about the data[3]. Please also look over the "User Manual" for instructions on the Python interface.

[3] To obtain data yourself, one convenient tool is the Virtual Solar Observatory: `https://sdac.virtualsolar.org/cgi/search`

1 *Full-Disk Data*

Before we study the time-series data, let's first have a look at some snapshots of the full disk of the Sun in different observables.

Plot[4] the Dopplergram[5], magnetogram, and continuum-intensity images in 3 separate windows. These data are from the MDI instrument. Note that one side of the Dopplergram is red and the other side is blue.

[4] Any tasks you need to carry out with the graphical interface will be printed in this type of font

[5] The Dopplergram shows the line-of-sight velocity of the photosphere at each pixel; a positive velocity indicates motion away from the observer

> **QUESTION 1.1:** [5 pts]: From the Dopplergram image, determine the solar rotation period (in days) at the equator. The radius of the Sun is 696 Mm. What happens as you go toward the poles?

Notice the large patterns in the Dopplergram increase in contrast towards the limb of the Sun. These features are called *supergranules*[6].

[6] Supergranulation is motion of the plasma that can be thought of like a fountain structure. It flows up to the surface from below and diverges horizontally. See Rieutord and Rincon (2010)

> **QUESTION 1.2:** [3 pts]: Do you see any evidence of supergranulation in the continuum image? What about in the magnetogram image? Try to explain physically why you do or do not see these features in these other observables. It may be necesssary to change the contrast of the colorscale and/or "zoom" into the images by adjusting the "range" values in the plotting tools.

> **QUESTION 1.3:** [5 pts]: Pick the observable with the best supergranulation signal. Given the number of pixels that cover the solar disk in the image, approximately how large (in Mm) is a typical supergranule? You should first estimate roughly the physical size of each pixel in Mm. You may again need to "zoom" into the figure or alter the contrast to get an accurate estimate.

2 *Local Seismology Data*

The two datasets (data1 and data2) are three-dimensional arrays (2 spatial and 1 temporal) of the Doppler velocity. One of the datasets is from the space-based MDI instrument, and the other is from the ground-based GONG network. The data were obtained simultaneously.

PLOT AN IMAGE OF THE FIRST TIME SLICE OF EACH DATA SET IN SEPARATE WINDOWS. Study the plots.[7]

[7] In the slice plot menu D1, D2, D3 denote the three dimensions of the dataset. By default, if all three boxes are empty, clicking "view" will plot all of D1 and D2 at the first value of D3

> **QUESTION 2.1:** [3 pts]: Can you determine which dataset is from GONG and which is from MDI? What is your reasoning?

MAKE A SCATTERPLOT OF THE POINTS IN THE FIRST TIME SLICE OF DATA1 VS. THOSE OF DATA2. Note that both datasets are in units of $\mathrm{m\,s^{-1}}$. Even though the data were obtained at exactly the same time and cover the same portion of the Sun, the slope of the scatterplot is not unity.[8]

[8] You may need to adjust the x and y axes of the plot to make the ranges equal

> **QUESTION 2.2:** [5 pts]: Can you describe why the scatterplot looks the way it does? Describe any important features you notice. Does this plot help you answer (or does it confirm your answer) from Problem 2.1? Explain your reasoning.

The spatial area covered by the datacubes represents only a a small 128 by 128 pixel subarray of the full disk images you saw earlier. The pixels are each 0.002 solar radii, or 1.39 Mm in size. The area is centered on a sunspot, and the datacube is tracked at a constant solar rotation rate. The flows in the sunspot region are called Evershed flows.[9]

[9] The Evershed flow is an outflow from the sunspont umbra

> **QUESTION 2.3:** [3 pts]: Study one of the 2D slices again from data1 or data2. Why does the Evershed outflow look the way it does in the image?

3 *Acoustic Signals*

The solar oscillations in which we are interested have periods of around 5 minutes. The images in the datacubes are obtained every minute. Let's see if we can study the oscillations a bit.

FIRST, COMPUTE 2 NEW QUANTITIES FROM DATA1 AND DATA2, THE 2-MINUTE DIFFERENCE AND THE 2-MINUTE AVERAGE. PLOT EACH OF THESE 2 IMAGES IN SEPARATE WINDOWS.[10]

[10] The difference operation here is the subtraction of 2 images taken 2 minutes apart. The average operation is the average of those 2 same images.

> **QUESTION 3.1:** [5 pts]: Explain the differences between the average and difference images for one particular data set, and why you think they look that way. What are the structures appearing in the difference image? How do the average and difference images compare between dataset 1 and dataset 2?

4 *Time Slices*

Let's explore how the data vary with time, which is the third dimension of the datacubes. The 512 images are obtained at a rate of 1 per minute, and thus span a range of 8.53 hours.

PLOT A SLICE THROUGH DATA 1 ALONG THE SECOND SPATIAL DIMENSION (D2), SO THAT YOU HAVE A RESULTING 2D IMAGE OF SPACE AND TIME. TRY TO AVOID THE AREA IN AND AROUND THE SUNSPOT FOR NOW.[11]

[11] To answer some of the questions you may need to zoom into the figure by using the "range" capability on the x and y axes. Or, you can also use the magnifying button in the plot window to zoom.

> **QUESTION 4.1:** [5 pts]: Can you see evidence of five-minute oscillations? Describe how you can or cannot. Can you also hypothesize what the "vertical" patterns of alternating dark and light are? If can't yet identify what they are, can you at least describe what might be happening?

If you look closely at such plots for data1 and data2, you may see gray horizontal lines or bands in each image. These represent missing data, which in these datacubes have been replaced with zeros. If you have trouble spotting these gaps, try plotting the data through the sunspot (vs. time), which will enhance the contrast.

> **QUESTION 4.2:** [3 pts]: Based on what you now know about the MDI and GONG instruments, can you guess why there are more gaps in one of the datasets? The frequency of gaps are typical of both instruments.

5 *Time Averages*

Let's get a sense of how the surface evolves with time.

RUN A FEW ANIMATIONS OF DATA1 AND DATA2. First, animate each dataset along the time dimension so you see a "movie" of the surface (20 frames/second might be a good choice). Then, animate each dataset along one of the spatial dimensions. Make sure you understand how the data are being stepped through.

COMPUTE THE TEMPORAL MEAN OF DATA1 AND DATA2.[12] PLOT THE RESULTING DATA AS WELL AS A SINGLE TIME SLICE FROM BOTH DATASETS FOR COMPARISON.

[12] The "mean" calculation will average over all times

QUESTION 5.1: [5 pts]: From comparing everything you've done, can you now identify the vertical dark features in the time slices as you showed in Q. 4.1? What might be a lower limit on their lifetimes? Can you estimate the typical velocities of these features?

6 *Residuals*

Here we will study what the data look like when we remove time averages.

COMPUTE THE RESIDUALS DATA1 AND DATA2[13]. PLOT A TIME SLICE FROM THE RAW DATA, AND THE SAME TIME SLICE OF THE RESIDUAL DATA IN A NEW WINDOW.
Now we need to look at the variance of the residual signal across the region of the Sun.

[13] This operation subtracts the temporal average from each time slice.

LOAD IN ONE OF YOUR RESIDUAL DATA CUBES, AND COMPUTE THE VARIANCE OF IT[14], AND PLOT IT ALONGSIDE THE OTHER 2 PLOTS YOU HAVE OPEN. The variance image is kind of an acoustic power map, although it does contain contributions from things besides p modes.

[14] This operation is the sum of the square of all of the residual data cubes

QUESTION 6.1: [xx pts]: Does the residual image still show the Evershed flow? Are the fluctuations of the remaining signal in the residual image random over the entire frame? Where is the variance smaller (darker) than usual?

It is well known that acoustic waves have suppressed amplitudes in magnetic-field regions(Braun et al., 1992).

QUESTION 6.2: [3 pts]: Can you guess the cause of the enhanced white regions around the sunspot in the variance images?

The computation of helioseismic signals from datacubes spanning several hours is routine and often necessary for collecting sufficient statistics. During this time, solar features may evolve and change position. Dealing with this is a challenge for some research goals in helioseismology, since not all unwanted effects can be reduced.

7 *Power Spectra*

We will now look at the analysis which reveals some of the important properties of solar oscillations by computing power spectra. The formula for the computation of a power spectrum from a time series is given in the appendix.

COMPUTE THE POWER SPECTRUM OF THE TWO RAW DATACUBES (ACTUALLY, A "CLEANER" POWER SPECTRUM WILL RESULT BY COMPUTING IT FROM THE RESIDUAL DATASETS, WHY?).[15] It is up to you to explore and view these power spectra so that you can answer the questions below. A useful task may be to animate the 3D spectrum by stepping through the 3rd dimension. There are many features in these data that are important to understand.

[15] The computation produces a full 3D power cube, as well as one that averages about the spatial frequency vector according to Eq. (9) in the Appendix, and the name has Avg. attached to it

QUESTION 7.1: [2 pts each]

a. Why is the azimuthally-averaged power spectrum less noisy than a slice along the $k_y = 0$ plane of the full 3D power?
b. Can you see "rings" and/or "trumpets" in the power spectra when plotted along different dimensions? See Hill (1988).
c. How high in wavenumber and frequency can you see oscillations?
d. What would be the temporal and spatial Nyquist frequencies for these data?
e. Where is most of the power located in frequency? What period does this corresond to?
f. Over what wavenumber range is most of the power located? What wavelength of waves does this correspond to?
g. Do you see any evidence of granulation in the power spectra?
h. In one of the datasets there is a feature at about 1.3 mHz at high spatial wavenumbers. Is it present in both? What does this tell you about whether the feature is solar?
i. From the frequency of this feature, estimate its temporal period.

References

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Appendix: Power Spectra

Over the sphere of the Sun, global p-mode oscillations are traditionally decomposed into functions proportional to the spherical harmonics. For local helioseismology, however, we consider local regions of the Sun that are sufficiently small that we can employ Cartesian coordinates. This provides a benefit such that Fast Fourier Transforms (FFT) may be used, which are efficient algorithms.

Local helioseismic analysis usually begins with line-of-sight Dopplergrams as functions of postion and time. Imagine the velocity is sampled at discrete locations: $x_{n_x} = n_x \mathrm{d}x$, $y_{n_y} = n_y \mathrm{d}y$ and time: $t_{n_x} = n_t \mathrm{d}t$. The sampling intervals are $\mathrm{d}x$, $\mathrm{d}y$, and $\mathrm{d}t$, such that the velocity is $v(x_{n_x}, y_{n_y}, t_{n_t})$. The discrete Fourier transform of such a data cube can be expressed as

$$V(k_x, k_y, \omega) = \sum_{n_x=0}^{N_x-1} \sum_{n_y=0}^{N_y-1} \sum_{n_t=0}^{N_t-1} v(n_x \mathrm{d}x, n_y \mathrm{d}y, n_t \mathrm{d}t) e^{-i(k_x n_x \mathrm{d}x)} e^{-i(k_y n_y \mathrm{d}y)} e^{-i(w n_t \mathrm{d}t)}. \tag{1}$$

The spatial wavenumbers k_x and k_y are sampled at discrete values

$$k_{x,q} = \frac{2\pi q}{N_x \mathrm{d}x}; q = -\frac{N_x}{2}, \ldots \frac{N_x}{2}, \tag{2}$$

$$k_{y,r} = \frac{2\pi r}{N_y \mathrm{d}y}; r = -\frac{N_y}{2}, \ldots \frac{N_y}{2}, \tag{3}$$

and the temporal (angular) frequency is sampled at

$$w_s = \frac{2\pi s}{N_t \mathrm{d}t}; s = -\frac{N_t}{2}, \ldots \frac{N_t}{2}. \tag{4}$$

The power spectrum of the oscillations is simply

$$P(k_x, k_y, \omega) = |V(k_x, k_y, \omega)|^2. \tag{5}$$

The extreme values of indices q and r above correspond to the lower and upper limits of the Nyquist critical sampling range, and the highest spatial wavenumber is given by the Nyquist wavenumber

$$k_{\mathrm{nyq}} = \frac{\pi}{\mathrm{d}x}. \tag{6}$$

Similarly, the frequency domain also has a maximal value due to finite time sampling given by

$$\omega_{\mathrm{nyq}} = \frac{\pi}{\mathrm{d}t}. \tag{7}$$

Note that it is typical in helioseismology (as in this tutorial) to use the cyclic frequency ν rather than the angular frequency, and they are related by

$$\omega = 2\pi\nu. \tag{8}$$

From the earlier exercises you see that solar oscillation spectra exhibit particular spatial and temporal symmetry in the spatial wavenumber and temporal frequency domains. One thing to not is *azimuthal* symmetry. While there are solar properties that can break the azimuthal symmetry, helioseismologists typically can ignore this in certain cases and construct two-dimensional power spectra. This is done by summing the power in "rings" in the (k_x,k_y) plane and only consider a total *horizontal wavenumber*

$$k_{\mathrm{h}} = \sqrt{k_x^2 + k_y^2}. \tag{9}$$

This operation is carried out in the interface software when power spectra are computed. Helioseismologists often call the resulting plot of the power a $k - \nu$ diagram.