CORRELATING IMAGERY WITH SONIFED HELIOSEISMIC DATA FOR IMMERSIVE MEDIA FORMATS

Elaine diFalco
University of North Texas
Media Arts
Elaine.diFalco@unt.edu

Timothy Larson
Moberly Area Community College
Physical Science
tplarson@sun.stanford.edu

Seth Shafer
University of Nebraska Omaha
Communication, Fine Arts and Media
SethShafer@unomaha.edu

This abstract extends research by the authors into the sonfication of solar harmonics that was presented at the International Conference on Auditory Display (2019), the International Computer Music Conference (2019), and the 234th American Astronomical Society Conference (2019). This abstract is concerned with the ongoing effort to create imagery that corresponds with the same data used to generate solar harmonics sonifications with the tool discussed below. The goal is to use these visualizations in immersive media formats.

ABSTRACT.

The Sun is a resonant cavity for very low frequency acoustic waves, and like a musical instrument, it supports a number of oscillation modes, also commonly known as harmonics. By observing how the Sun's surface oscillates in response to these harmonics, we can determine its dynamic internal structure. Though this data has been studied scientifically for decades, it has rarely been sonified. The Sonification of Solar Harmonics (SoSH) Project seeks to sonify data related to the field of helioseismology and distribute tools for others to do the same. Creative applications of this research by the authors include musical compositions and installation artwork. Moving forward, the SoSH team is currently seeking ways to combine sonifications with corresponding scientific visualizations of model data to create documentaries and other productions for traditional flat screens as well as immersive new media formats such as full-dome projection and virtual reality.

1. INTRODUCTION.

It is a poignant coincidence that acoustical physics is such an intrinsic part of our most prominent celestial object when so much of Western philosophical history connects the cosmos to sound, an idea referred to as Music of the Spheres. Our home star appears as a mass of boiling plasma and it rings like a bell reverberant with the churning energy from deep within it [1]. By applying the mathematics of spherical harmonics and fluid dynamics we are able to determine various properties of the Sun's internal structure. Although the data used is acoustic in nature, scientists have only very rarely listened to it, despite the fact that sonification of other types of solar data has yielded new scientific insights [2].

After a short introduction to the subject of helioseismology, we describe a collaborative research initiative called the Sonification of Solar Harmonics (SoSH) Project. This project seeks to transform helioseismology into a listening experience for scientists and non-scientists alike. Additionally, it seeks to find creative ways to accompany the sonified data to visually representative imagery for applications such as documentary productions and art installations for traditional flat screens as well as immersive formats such as virtual reality and planetarium dome projection. One of the initial outcomes from the SoSH project is a software tool for rendering helioseismic data as audible sound. This tool is the most advanced contribution to helioseismic sonification and provides the first access to audio generated from the most recent data available.

2. A BRIEF PRIMER ON HELIOSEISMOLOGY.

The study of oscillating acoustic waves inside the Sun is called helioseismology. Turbulent convection near the solar surface excites sound waves, and the waves with frequencies that resonate form the harmonics. Just as the frequency of a plucked guitar string becomes higher with greater tension and lower with greater thickness, the frequencies of the Sun's harmonics enable us to infer properties of the solar interior such as its pressure and density. And just as any acoustic instrument produces a set of harmonics above a fundamental frequency that combine to create a characteristic timbre, so too does the Sun.

2.1 Spherical harmonics.

The input data for helioseismology are typically velocity images of the Sun, where each pixel gives the speed of that plasma element toward or away from the observer. It is a mathematical theorem that any such image of the Sun's surface can be expressed as a sum over spherical harmonics, which are simply a special set of functions of latitude and longitude. Each of these functions are labelled by two integers: the spherical harmonic degree l and the azimuthal order m. The degree l is ≥ 0, and for each l, there are $2l+1$ values of m, ranging from $-l$ to l.

One way to understand spherical harmonics is in terms of their node lines, which are the places on the sphere where the spherical harmonics have an amplitude of zero. The degree l tells how many of these node lines there are in total, and the absolute value of the order $|m|$ gives the number in longitude, so the number of node lines in latitude is $l-|m|$. Therefore, a spherical harmonic with $m=0$ has only latitudinal bands, while one with $m=l$ has only sections like an orange. A third integer, the radial order n, tells how many nodes the oscillation has along the Sun's radius. Since only the surface of the Sun is visible to us, all the values of n are present in each spherical harmonic labelled by l and m, although only some of them will be excited to any appreciable amplitude. The total mode, then, is represented as a product of a spherical harmonic and another function of radius, known as radial eigenfunction. The radial eigenfunction depends on both n and l.

Figure 1 below illustrates modes with degree $l=5$ and all nonnegative values of m. Modes with $m < 0$ are not included because on a still image they are indistinguishable from modes with $m > 0$. As spherical harmonics evolve in time, one would see the two signs of *m* rotate in opposite directions; this is discussed further below. One can see that different spherical harmonics sample different latitudes, according to the value of $|m|$ relative to the degree *l*. Modes with high absolute values of *m* have their maximum amplitude at low latitudes, whereas lower values extend to higher latitudes.

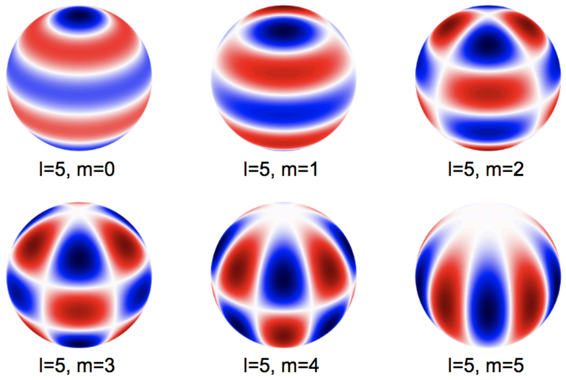

Figure 1. Surface views of the Sun showing all harmonic modes with degree *l*=5.

2.2. Modelling the Sun's interior.

The harmonics we are able to measure have frequencies ranging from 1000 to 5000 microhertz. For any given value of the degree *l*, we will find a certain range of values of the radial order *n*, with frequency increasing as *n* increases. The next two figures show interior views of the Sun for two different radial orders and degree *l*=5. For clarity, in Figure 2 we show radial order *n*=3, although this mode is expected to have a frequency too low to measure. Figure 3 shows radial order *n*=20, which is easily measured, but at this frequency the nodes along the radius become so closely spaced near the surface that they are difficult to discern at this scale. It is important to realize that we are seeing modes of many different *n* in each spherical harmonic. For instance, for degree 5 we might measure modes with *n* ranging from 7 to 28, each oscillating at its own frequency, roughly 140 microhertz apart from each other.

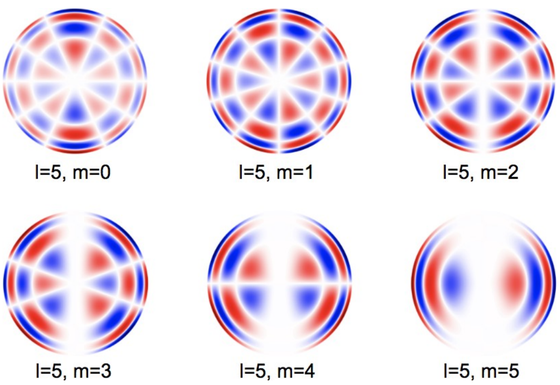

Figure 2. Interior views of the Sun showing the harmonic modes with degree *l*=5 and radial order *n*=3. A model predicts these modes to have a frequency of 800 microhertz.

Each mode oscillates with its characteristic frequency, and each samples different depths inside the Sun. At a given degree, high frequencies will penetrate more deeply, while lower frequencies are trapped closer to the surface. Likewise, at a given frequency, high values of the degree *l* will be trapped near the surface, while low values will penetrate almost all the way to the core, with *l*=0 even reaching the center.

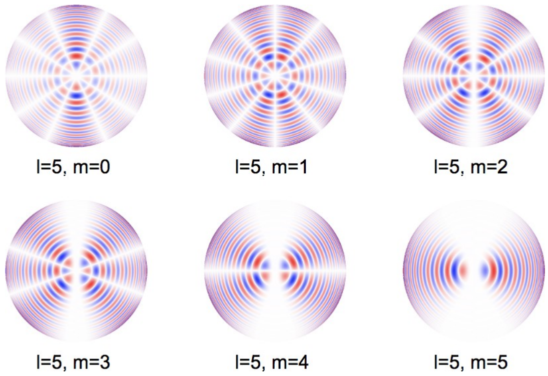

Figure 3. Interior views of the Sun showing harmonic modes with degree *l*=5 and radial order *n*=20. A model predicts to have a frequency of 3190 microhertz.

2.3. Typical data pipeline.

To determine frequencies of the Sun's harmonics, a typical instrument might take an image once a minute for 72 days. For each image, we decompose it into its various spherical harmonic components. For each of these components, we form a timeseries of its amplitude. From the timeseries we are able to construct the power spectrum (acoustic power as a function of frequency). It is here that we are able to separate the two signs of *m.* Without delving into complex analysis and theory of the Fourier transform, we simply state that the two signs correspond to the positive and negative frequency parts of the power spectrum. Furthermore, the sign of *m* that rotates in the same direction as the Sun will be shifted up in frequency, while the sign that goes against the solar rotation will be shifted down. Because different modes sample different regions of the Sun, we are able to use their frequencies to determine solar properties as a function of both depth and latitude. For example, we are able to use the frequency splitting in *m* to measure internal solar rotation.

Once the power spectrum is calculated, the location of peaks will correspond to the frequencies of the modes. The height of each peak tells us the mode amplitude, and the width of the peak tells us how much the oscillation is damped. Each *n* will have its own peak in the power spectrum.

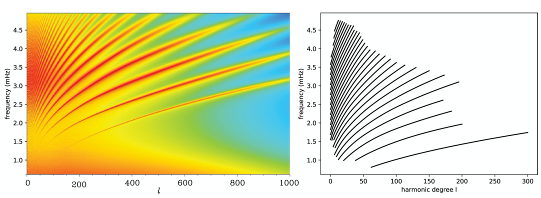

Figure 4. Degree-frequency diagrams. Left panel shows raw power, right panel shows the modes that we are able to fit.

3. OVERVIEW OF THE SoSH PROJECT

3.1 Datasets for Sonification.

The Sonification of Solar Harmonics (SoSH) Project aims to sonify any solar harmonics dataset. Several such datasets are available for sonification. The first of these comes from the Michelson Doppler Imager (MDI) [3] onboard the Solar and Heliospheric Observatory (SoHO). It was in operation from May 1996 to April 2011. In 2010, MDI was superseded by the Helioseismic and Magnetic Imager (HMI) [4] onboard the Solar and Heliospheric Observatory (SDO). HMI observes a different spectral line at a cadence of 45 seconds and remains in operation today. The SoSH Project represents the only sonification of HMI data to date.

3.2. The SoSH Tool

The SoSH Project developed a tool to input complex spherical harmonic timeseries and output sonified audio of that data. The only preprocessing needed is to convert the timeseries from FITS (Flexible Image Transport System) to WAV format. This first step represents a pure audification of the data [5]. The subsequent processing done by the SoSH Tool exactly parallels the steps in the scientific analysis. By using fitted mode parameters to filter and transform the data, we produce a sonification. The strongest of the Sun's harmonics have periods of only about 5 minutes, corresponding to frequencies of only about 0.003 hertz. Unfortunately, this is far below the range of human hearing, which is typically taken to be 20 – 20,000 hertz. In order to experience the sound of the Sun with our ears, these very low frequencies must be scaled to the range of what we can hear.

The SoSH Tool is an open-source system implemented in the visual programming language PureData (PD). Upon launching the demo patch "modefilter_standalone.pd" (see Figure 5), you are required to specify a path to your local data directory. The patch will search this directory for ASCII files containing the fitted mode parameters, as well as the WAV files for whatever spherical harmonics you wish to sonify. With these files in place, the dataset is now accessible by the day number corresponding to the first day of the timeseries, the spherical harmonic degree l, the radial order n, and the azimuthal order m. By default, the tool is set to use MDI data. If it is successfully able to load the necessary audio files, it will automatically trigger FFT analysis of them. Next, the fitted mode parameters corresponding to the inputs are used to generate a gain array in which full output is allowed for a frequency interval centered on the mode frequency and of width five times the mode width. Full attenuation is set for all other bins. This default width of the pass band is the same as that used for the fitting, but it can be increased multiplicatively in the software by specifying the "width factor."

Once the gain array is generated, the FFT data is multiplied by it and resynthesized. If a downshift factor is specified, the FFT will be shifted down by this amount before the inverse transform.

Beyond the basic sonification of single modes, several extensions to the SoSH Tool enable more advanced functions. One extension processes several modes and additively outputs their results into a single array (see Figure 6). Another extension turns the tools into a kind of multitimbral sampler that can trigger different modes assigned to different MIDI pitches. Yet another extension reads a score from a text file to produce a sequence of modes.

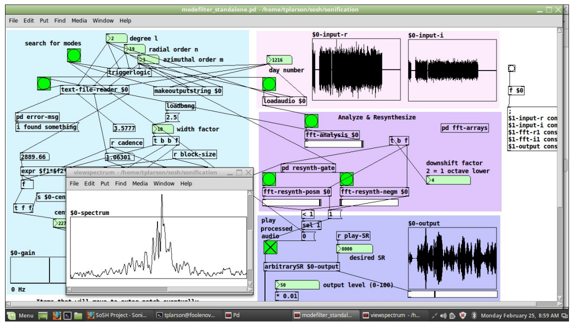

Figure 5. A screen shot of the core processing engine inside the SoSH Tool.

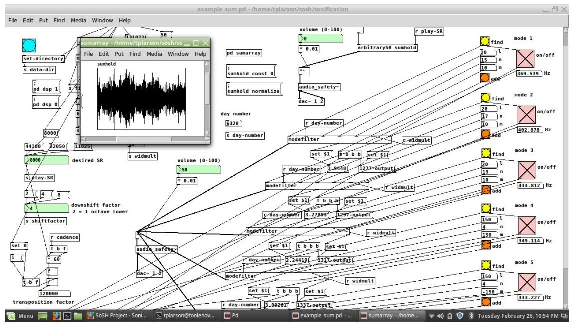

Figure 6. A screen shot of an extension to the SoSH Tool that additively combines modes into a single output array.

4. CREATIVE APPLICATIONS

The idea for the SoSH Project originated from of the precompositional research conducted by diFalco for an orchestral composition entitled *Helios,* out of a set of works collectively called Cosmophonia [6]. The composition applies the acoustic phenomenon of helioseismology by scoring the natural harmonic series as it relates to the position inside or outside of the Sun. In addition, the primary pitch material is derived from a solar flare recorded on November 23rd, 1998 by Peter Messmer et al. at the Institute of Astronomy in Switzerland (see Figure 7) [7].

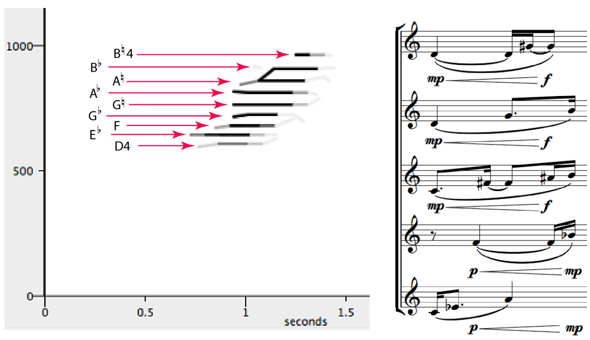

Figure 7. Analysis and orchestration of a solar event used in *Helios* (2018) by Elaine diFalco.

The SoSH Tool's potential for installation-based work is particularly attractive. Shafer's multichannel projector installation *Sol Invictus* (2015) uses the raw visual data from the Atmospheric Imaging Assembly (AIA) onboard SDO to display the complex convection happening in the chromosphere (see Figure 8) [8]. The gigantic scale of the of the solar forces is subverted by the miniscule dimension of the images generated by the five micro projectors.

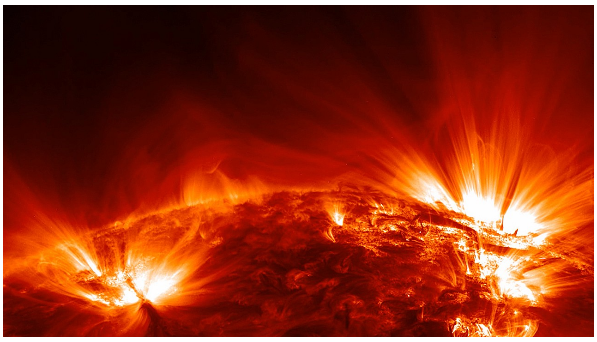

Figure 8. A still from the multichannel projector installation *Sol Invictus* (2015) by Seth Shafer.

Another important outcome from the SoSH Project is the SoshPy Visualization Package. Written in Python, this software package was used to generate Figures 1-3 of this extended abstract. It can also plot all three components of the vector velocity associated with any given mode, as well as its energy density. More interestingly, it is also able to plot sums of modes and create animations.

Plans for large-scale intermedia experience using the SoSH Tool are underway. Creating immersive experiences for virtual reality and planetarium full-dome projection is the critical next step to expand on the SoSH Project. By creating scientific illustrations that utilize the same data sets sonified by the SoSH Tool – especially if designed for spatial audio applications – it is possible to produce viscerally powerful ways to communicate and illustrate the concepts behind helioseismology to a science-seeking public.

Beyond the SoshPy Visualization Package, the team is currently exploring TouchDesigner and Unreal Engine 4 as potential applications to visualize or illustrate helioseismic data for artistic purposes as well as for science communication and education.

5. REFERENCES

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