AUDIFICATION AS A DIAGNOSTIC TOOL FOR EXPLORATORY HELIOSPHERIC DATA ANALYSIS

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ABSTRACT

To date, scientific data analysis is almost exclusively conducted through the visual modality, though the perceptual benefits of multi-modal stimulation are well known [1]. Visualization tools utilize parameters such as color, size, and shape to render data sets of moderate complexity. However, a growing number of NASA instruments produce extremely large and complex data sets that must be visually rendered in groups of sub-dimensions [2]. One such instrument, the Solar Wind Ion Composition Spectrometer (SWICS) on the Advanced Composition Explorer (ACE) satellite, has measured a large number of solar wind parameters for the last 13 years. The effective navigation and analysis of these massive data sets is a persistent challenge. New data mining tools are necessary in order to fully engage the large number of variables involved with these extremely complex systems. New multi-modal interfaces will have far reaching applications for exploratory heliophysics research. This work will demonstrate that audification is a powerful diagnostic tool for mining and analyzing solar wind data.

Through audification, this research has revealed new insight into data parameters used for differentiating solar wind types. For example, an ion charge state ratio previously considered to be unimportant is proving to be a leading indicator of the boundaries between coronal hole and non-coronal hole wind, as discussed below. A deep understanding of space weather, to which the solar wind is a decisive component, will be increasingly important as we continue to explore the space environment [3].

1. INTRODUCTION

The ability to forecast space weather has extensive benefits, as accurate predictions of solar storms can protect astronauts from health hazards due to extreme space environment conditions. Accurate forecasting also allows preventative measures to be taken towards minimizing damage to delicate instruments, as solar storms can disrupt satellites and interfere with ground communication.

The occurrence of solar storms directly correlates with solar activity, which oscillates in an 11-year cycle. We can glean insight into this cycle by closely studying the solar wind. With tools such as SWICS, we are able to analyze the composition and determine the source of solar wind plasma. Coronal hole wind, also known as "fast" wind, has an average bulk speed of 750 (km s^{-1}). This wind originates from coronal hole regions, which are areas of low temperature (~0.8MK) and open magnetic flux located primarily at the poles during solar minimum. Non-coronal hole wind, also known as "slow" wind, has an average bulk speed closer to 400 (km s^{-1}) and comes from hotter regions (~1.3MK) in the solar corona.

These two types of wind are more accurately identified by their charge state composition than their speed [4]. In fact, temperatures derived from observed charge states are unique for different elements [5] and indicate the temperature of the wind at the height where charge states "freeze in." (**Figure 1**) They provide invaluable information as to the solar wind type, source region, and acceleration mechanism. Currently, the O^{7+}/O^{6+} ionic charge state ratio is utilized as a tool to distinguish between differing types of solar wind plasma based on their freeze-in temperature [6]. However, the team was able to utilize audification to reveal C^{6+}/C^{4+} as a better indicator.

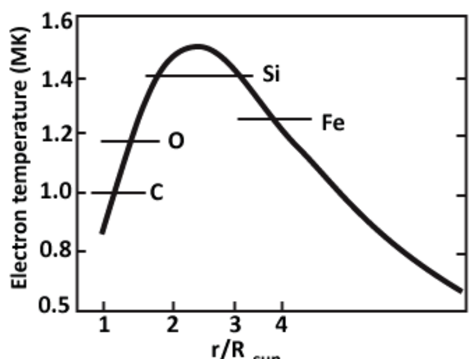

Figure 1: Electron temperature, measured from charge states, as a function of distance from the sun. Figure adapted from Geiss et al. (1995).

2. AUDITORY DATA ANALYSIS METHODS

Audification (direct one-to-one mapping of data to audio-samples) and sonification (data are mapped to parameters for the generation of sound) have proven successful in the exploration of high-dimensional and complex data sets [7, 8]. Tools such as XSonify [2] have enabled researchers and science enthusiasts to conduct independent sonification research. However, a similar tool for enabling high-level exploratory data analysis through audification has not been developed.

Early research in the field of Auditory Seismology has proven that the ear is able to challenge the epistemological power of the eye [9, 10]. Geoseismologists have employed audification for over 40 years, and this technique has proven successful in identifying key seismic events and detecting equipment induced error within geoseismic data sets. Furthermore, geoseismic audification research indicates that combined graphical and auditory representations can enable individuals to quickly learn to identify significant events, thus expediting the education process and resulting in a significant reduction in cost [9]. Initial auditory analysis of SWICS data builds upon the successful application of audification in geoseismic data analysis. While heliospheric and geoseismic data sets are substantially different, the benefits obtained through auditory analysis are very similar.

Though visual analysis techniques have long been the standard, the auditory modality is better suited for many data analysis tasks [11], and the ability to carefully analyze auditory data is a skill that can be trained and refined. A course at the University of Michigan (U-M) entitled "Timbral Ear Training" teaches students to notice subtle changes in the spectral composition of white and pink noise fields [12]. Upon repeated listening, pattern-recognition processes within the brain rapidly begin to enhance deeply embedded structural details of extremely noisy signals [13]. This type of rigorous training will also prove effective in training researchers to recognize subtle differences between audified data sets. Research in the field of neuralplasticity indicates that repetitive training over long periods of time enacts changes within the physical structure of the brain [14].

The ear is able to detect minute changes in pressure, and these changes are broken down into a series of component frequencies in a process akin to a Fast Fourier Transform (FFT). This process has a high resolution in both the time and frequency domains [15]. The standard rate of audio playback is 44,100 samples per second. In the case of data audification, the brain is able to analyze one million data points in less than 23 seconds. It has been demonstrated that the auditory modality will often reveal spectral characteristics that may be overlooked through traditional visual analysis techniques [9].

3. A NEW INTERFACE FOR EXPLORATORY DATA ANALYSIS

Digital Signal Processing (DSP) techniques used to isolate and remove unwanted frequencies (e.g. filtering and noise reduction) have powerful applications in the processing of time-series data [16]. Once the data have been converted into audio, DSP algorithms can be applied to explore the spectral characteristics of the audio.

An interface for auditory data analysis was created with the Max/MSP programming environment (**Figure 2**). This prototype is currently available for Mac platform, and can be downloaded from a web-repository [17]. The user is able to select a folder containing audio files, which automatically populate a drop-down menu. This interface contains a bank of 3 biquad filters that can be toggled between the following modes: low-pass, high-pass, band-pass, band-stop, peak/notch, low-shelf, high-shelf, resonant, and all-pass. These filters can be employed in tandem to isolate interesting features within the frequency spectrum. The user can conduct a comparative analysis by flipping a toggle switch to quickly bypass these filters.

Control over playback speed has also been provided to facilitate the exploration of multiple temporal resolutions. Adjusting the rate of playback shifts the frequency spectrum of the audio, revealing important micro and macro features inherent within the data. Through this process, the data become extremely malleable through direct, real-time interaction. Multiple visualizations of the audio stream provide additional feedback as to the spectral characteristics of the data.

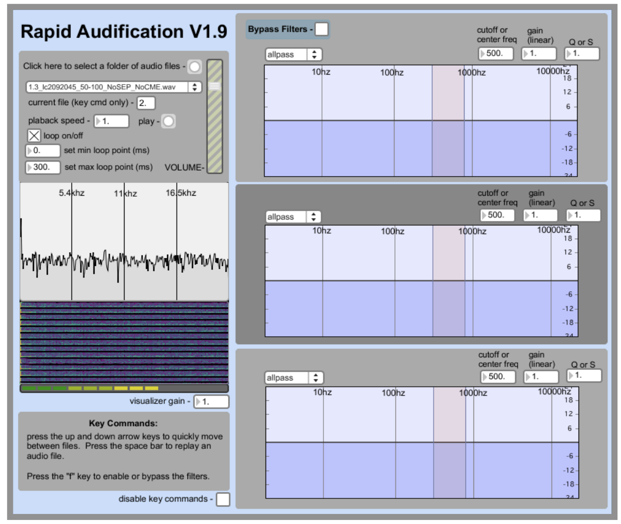

Figure 2: A preliminary software interface was constructed as a diagnostic tool for rapidly exploring SWICS data through audification. Initial research has provided new qualitative insight into the nature of the solar wind.

4. AUDITORY ANAYSIS OF SOLAR WIND DATA

ACE SWICS Level 2 data for the number of C^{4+}, C^{5+}, and C^{6+} ions in the solar wind from the years 1998-2010 were imported into the "text" object of the Max/MSP programming environment. The "line" message was used to read through successive data entries. The minimum and maximum entries were used to scale the data as a series of floating-point values between -1 and 1. These data were then stored within sequential samples of an audio buffer. All examples in this section have been uploaded to a web-repository [18].

The audio file should be trimmed such that the first sample corresponds to the first data entry *0*, and the last sample corresponds to the last data entry *n*. After a periodicity is recognized within the audio file, the frequency can be mapped to the original time-scale of the data using (1).

$$f_d = \frac{f_a t_{a,n}}{(\tau_{d,n} - \tau_{d,0})} \tag{1}$$

Here, f (Hz) represents the periodicity, and t (s) and τ (s) are the elapsed time in the audification, *a*, and the data, *d*, respectively. Event *i* at time $t_{a,i}$ in the audification can be located in the data at time $\tau_{d,i}$ using (2).

$$\tau_{d,i} = \tau_{d,0} + \frac{t_{a,i}}{t_{a,n}}\left(\tau_{d,n} - \tau_{d,0}\right) \tag{2}$$

Though these audio files initially appear to be noisy and chaotic, close listening reveals an underlying "hum" with a frequency of 137.5 Hz, which translates to 26.41 days within the original data and corresponds to the synodic rotation period of the Sun. The presence of this hum implies features on the solar surface that affect the number of ions and persist across multiple solar rotations. While this periodicity is present in both C^{6+} and C^{5+}, these two waveforms have notably different spectral characteristics. The application of a bi-quad band-pass filter confirms that C^{6+} contains a unique amplitude envelope that is absent in C^{5+}. However, the amplitude envelope and spectral characteristics of C^{6+} are extremely similar to those of C^{4+}, both contain a distinct rise in amplitude towards the end of the waveform. As the total number of C^{4+} and C^{6+} ions correlate inversely with temperature, the similarity in underlying frequency indicates a periodic change in temperature and hence of solar wind type. **Figure 3** shows the high temperature sensitivity of carbon charge states as opposed to the more commonly used O^{6+} and O^{7+}.

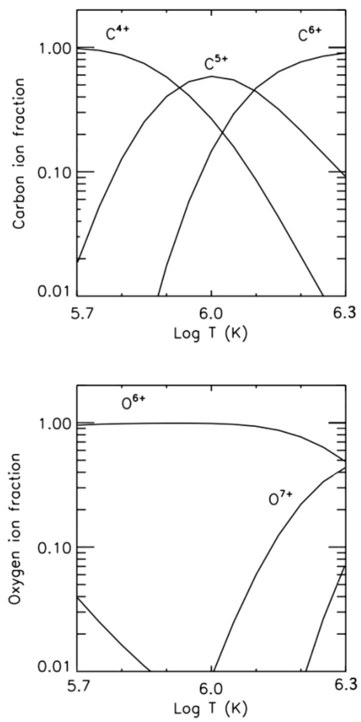

Figure 3: Ionization fraction of carbon (top) and oxygen (bottom) as a function of temperature. The X-axis spans the typical range of solar wind temperatures. The C^{6+}/C^{4+} ratio allows the sampling of a larger temperature range than O^{7+}/O^{6+}.

Close listening to these charge states also reveals that their spectral characteristics share a unique "flavor" that is difficult to discern through visual analysis. Upon close listening, strong partials above the fundamental frequency (137.5 Hz) are heard at 275 Hz and 550 Hz. With a known fundamental periodicity of 26.4 days, the first three harmonics are calculated as occurring with periodicities of roughly 13.2, 8.8, and 6.6 days. These periodicities are noticeably stronger in the audification of C^{6+} and C^{4+}, and less present in C^{5+}. This periodicity was related to a triad of equally spaced coronal holes on the surface of the Sun [19]. The subtle amplitude variation of these harmonics, clearly detectable through audification, allows us to study the temporal evolution of the wind source regions.

The turbulent solar wind has been studied through numerical simulations, which have proven useful in determining the symmetries of solar wind fluctuations [20]. While simulations are valuable, they require a pre-determined set of variables that often simplify the complexity of the underlying system. Audification may allow researchers to find new features within datasets that have been thoroughly analyzed through traditional (visual) analysis methods. Audification of solar wind velocity data has revealed several coronal mass ejection (CME) events that contain unique "resonances," many of which last longer than 60 days. These "resonances", which are invisible through FFT analysis, coincide with large CMEs that produce strong helioseismic activity. Furthermore, they appear to occur as "echoes" of CMEs roughly .45 years earlier. These events are being explored through audification and traditional research methods. An expert trained in the aural analysis of solar wind data can listen to an extremely wide array of variables and determine correlative properties embedded in the subtle spectral characteristics (**Figure 4**). Extensive research needs to be conducted as to how multiple waveforms might be audified in tandem within unique spectral ranges.

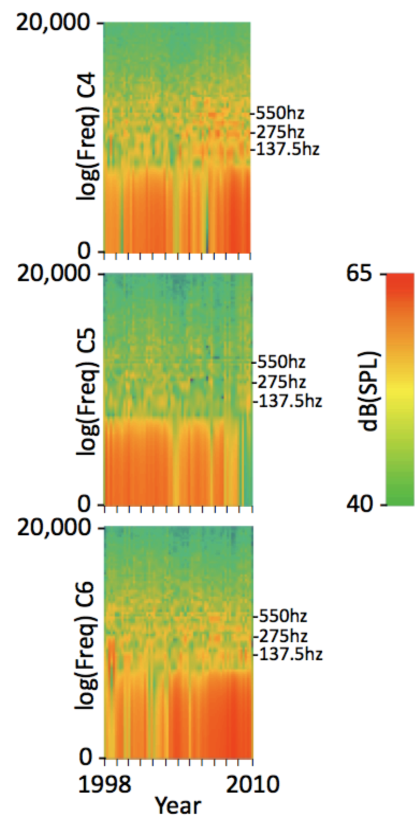

Figure 4. Spectral properties of the audified carbon charge state distributions. Notice that the 137.5 Hz periodicity and overtones are visually overpowered by low-frequency noise. Research indicates that the ear quickly recognizes features of the spectrum that may be overlooked by the eye [9].

5. CONCLUSION

The visual modality has long been the standard for scientific data analysis, but research indicates that the auditory modality is an extremely powerful tool for the analysis of large data sets. Audification as a data-mining tool will rapidly produce new qualitative insights into the nature of the solar wind. Preliminary auditory exploration of SWICS data, in collaboration with traditional analysis methods, has produced several promising research findings such as the utilization of the C^{6+}/C^{4+} ratio as an indicator for coronal hole and non-coronal hole wind.

6. REFERENCES

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