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Key Points:

- Audification can provide new insight in the analysis of time series data
- Wave activity and noise artifacts were detected through auditory analysis
- The scientist continued using auditory analysis after the study was completed

Supporting Information:

- Readme
- Audio S1
- Audio S2
- Audio S3
- Audio S4
- Audio S5

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The bird's ear view of space physics: Audification as a tool for the spectral analysis of time series data

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Abstract The effective navigation, mining, and analysis of large time series data sets presents a recurring challenge throughout heliophysics. Audification, a specific form of auditory analysis commonly used in other fields of research (such as geoseismology), provides a promising technique for the evaluation of spectral features in long heliospheric time series data sets. Following a standard research methodology for the development of new analysis techniques, this paper presents a detailed case study in which audification was introduced into the working process of an experienced heliophysics research scientist and used for the identification and classification of features in high-resolution magnetometer data during a structured analysis task. Auditory evaluation successfully led to the detection of artificial, instrument-induced noise that was not previously observed by the scientist and also the identification of wave activity embedded within turbulent solar wind data. A follow-up interview indicated that the scientist continued using these auditory analysis methods in the assessment of every large data set during the 2 months after the study was completed. These findings indicate that audification can be valuable and enabling for researchers in forming a deeper understanding of both microstructures and macrostructures within large time series. Additionally, as both a standalone methodology and a supplement to visual analysis methods, audification can expedite certain stages of the data survey, analysis, and mining process and provide new qualitative insight into the spectral content of time-varying signals.

1. Introduction

The task of quickly and effectively surveying, mining, and analyzing large time series data sets presents a challenge within space science, and particularly heliophysics. A growing number of NASA satellites produce large and sophisticated data sets that must be analyzed to reveal specific events or visually rendered in plots that depict a subset of the available data dimensions [e.g., *Luhmann et al*., 2008; *Stone et al*., 1998]. For example, the fluxgate magnetometer on the Wind spacecraft has sampled the solar magnetosphere and interplanetary space at a rate of 11 Hz for the past 19 years—spanning a nearly complete magnetic solar cycle of approximately 22 years—while generating more than 6.6 billion individual magnetic field measurements [*Lepping et al*., 1995]. Data from plasma instruments and energetic particle sensors were also gathered, providing a rather complete record of the near-Earth space environment during this time period. These data have led to the acquisition of new knowledge about the Sun and heliospheric plasma, as well as its interaction with the Earth. However, only a very small fraction of available heliophysics data are actually exploited, limited in part by the availability and effectiveness of toolsets for surveying, mining, and analyzing data [*Board*, 2013]. For this reason, novel data mining techniques have become a crucial enabler for new science and large-scale analysis. The most commonly utilized of these techniques rely on basic visualizations with software platforms such as MATLAB or Interactive Data Language (IDL) (i.e., programs that enable data surveys and allow direct computational access). Yet this process has known limitations in several areas [*Brown et al*., 1989], and the detailed analysis of events and waves in plasma data is typically conducted by specialists who apply highly sophisticated methodologies [e.g., *Boardsen et al*., 2009]. However, there are different classes of techniques for the analysis of time series data that are powerful and complementary to the standard methods. Among them are those that use the power of the human ear in conjunction with visual surveying, mining, and quantitative analysis [*Hermann et al*., 2011].

For example, using auditory analysis on data from the Solar Wind Ion Composition Spectrometer (SWICS) on board the Advanced Composition Explorer spacecraft [*Gloeckler et al.*, 1998], new insights were gained regarding the source regions and ionic charge states of heavy ions in the solar wind, providing a very sensitive diagnostic of the electron temperature in the solar wind source region [*Alexander et al.*, 2011; *Landi et al.*, 2012; *Zurbuchen*, 2007]. While this diagnostic was performed by a highly trained listener, early investigation into the effectiveness of auditory displays demonstrated that a multimodal display of information has the potential to increase the rate of information transfer to an initially untrained human operator [*Fidell*, 1970; *Loveless et al.*, 1970; *Pollack and Ficks*, 1954]. Currently, several initiatives at NASA Goddard Space Flight Center are exploring the application of auditory analysis in the heliophysics environment [*Candey et al.*, 2006; *Diaz-Merced*, 2013].

This paper has two primary objectives: (1) to demonstrate the utility and a practical application of this relatively uncommon analysis technique and (2) to equip scientists with the necessary toolset to independently apply audification in the analysis of data gathered from a wide variety of sources (refer to Appendix A1 for a step-by-step guide). To achieve these two objectives, the paper will briefly review the foundations of auditory analysis in the space sciences before presenting a case study in which a research scientist (henceforth referred to as “the participant”) was introduced to audification as a tool for the spectral analysis of one-dimensional time series data. In order to assess the impact of the auditory display, it was crucial to first understand the participant’s traditional working practices. Toward this end, a preliminary workflow assessment uncovered a set of questions that the participant defined as guiding his approach during the early stages of time series data analysis. These questions are generally focused on the integrity and scientific meaning of the data in question:

1. *Are the data well formed and free of errors and gaps*?
2. *What large-scale structures are observable in the time series*?
3. *Can specific time regions that warrant in-depth investigation be identified based on a specific scientific rationale*? (*e.g.*, *the presence of unique wavelet signatures*, *recurring structures*, *or outlying values*.)

The previous success of audification in the investigation of SWICS data suggested that it might support early diagnostic evaluations motivated by questions such as these. In order to evaluate the use of audification for the purposes of exploratory analysis, we used a methodology that is commonly applied in the fields of interface design and usability testing, known as the “Think-Aloud protocol.” This protocol requires a participant to vocalize their thoughts while engaging in a problem solving task, with the hypothesis that these verbalizations can reveal a subset of underlying cognitive processes [*Ericsson and Simon*, 1985]. Our goal was to assess to what extent the participant could use information gleaned from auditory observations to systematically drive the investigation of potential features of interest embedded within the time series. Toward this end the Think-Aloud protocol provided immediate insight as the participant’s attention shifted from one auditory observation to the next. The nature and depth of these observations is the primary focus of this study, and two additional use cases are also presented. The findings support the hypothesis that auditory analysis can be useful in the identification of spectral features embedded in large time series data sets that may have been otherwise overlooked.

This work is conducted in collaboration with the Solar and Heliospheric Research Group at the University of Michigan and with a group of scientists at NASA Goddard Spaceflight Center, currently the world’s largest Heliophysics-focused research entity. The ultimate goal of this extensive research is to design both a methodology and a specific analysis tool through which space researchers can effectively apply audification techniques in the exploratory analysis of heliophysics-focused time series data.

Upon completing the initial study, the participant continued to use audification in the analysis of high-resolution magnetometer data from the Wind satellite on a weekly basis, and at present a collaborative investigation of features uncovered through auditory analysis is being prepared for publication. This research therefore provides a detailed description of the initial steps toward a larger analysis framework through which data audification methods may be transferred successfully across scientific domains. A step-by-step guide for any scientist who is interested in applying this toolset can be found in Appendix A1, and a set of routines for audification in MATLAB and IDL can be found online [*Alexander*, 2014a].

2. Background

2.1. Audification: A Brief Review

Audification is a specific type of auditory data analysis in which data samples are isomorphically mapped to the amplitude of consecutive audio samples. The general term used to describe the process of transferring

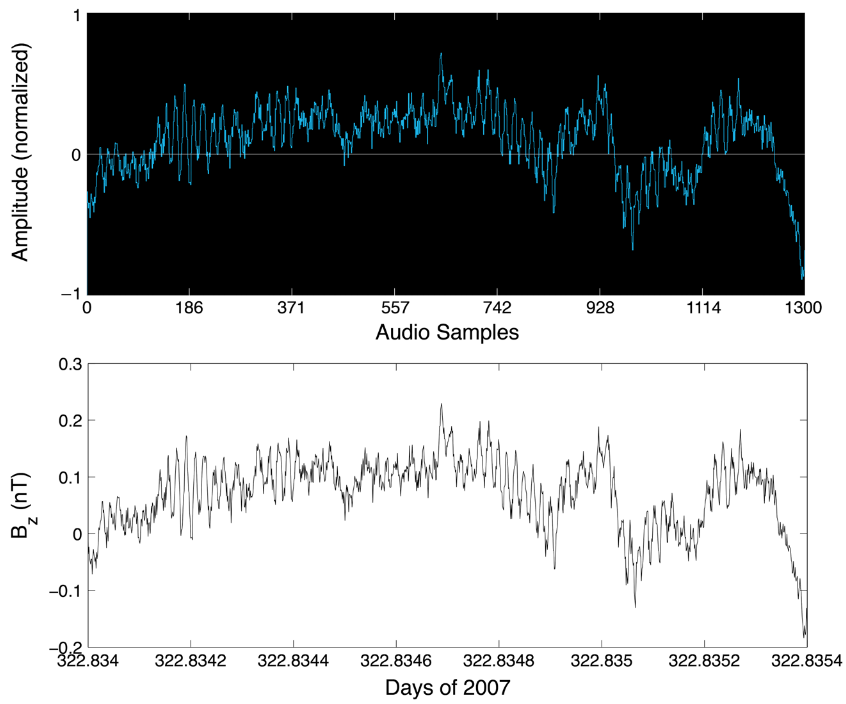

Figure 1. Thirteen hundred samples of high-resolution magnetometer data from the Wind satellite (*Z* component). The audio waveform rendered in (top) iZotope RX and the time series rendered in (bottom) MATLAB are identical, as no data samples are lost in the conversion process.

information through (nonspeech) audio is "sonification" [*Kramer et al*., 1999]. Audification is the most direct form of sonification, as all data samples are preserved and spectral features within the original data will be present as timbral components in the resulting sound file. A time series derived from Wind magnetometer data is directly compared to the resulting audified waveform in Figure 1.

This type of auditory data representation is ideal for large time series data sets, and analytical listening can potentially reveal features that may be overlooked by other sensory modalities [*Alexander et al*., 2014]. In the field of geoseismology, researchers have successfully applied this technique in the analysis of earthquake activity and the detection of instrument-induced error within geoseismic data sets [*Hayward*, 1994]. Recently, concerted efforts have been made toward the systematization of knowledge and methods for data audification [*Dombois and Eckel*, 2011], although an extensive catalog of successful use cases does not currently exist in the published literature.

2.2. Audification in Solar and Space Physics (Heliophysics)

A great deal of terminology used in heliophysics has roots in early auditory observations. Long before researchers had access to satellites for in situ observation, very low frequency radio enthusiasts uncovered a variety of geomagnetospheric phenomena. For example, descending "whistler" modes, the most widely recognized of these features, are generated when radio emissions from lightning disperse along Earth's magnetic field, propagating between hemispheres [*Barkhausen*, 1919, 1930; *Helliwell*, 1965]. It was later observed that some instances of narrowband electromagnetic wave activity resembled the low roar of a lion when played back over a loudspeaker. The term "lion roar" is now the common name for this type of phenomenon [*Smith et al*., 1967; *Smith and Tsurutani*, 1976]. This nomenclature also includes such terms as *tweaks*, *chorus*, *hiss*, and *static*, all of which are derived from the description of acoustic phenomena. Audio examples can be found online [*Gurnett*, 2014].

One example of information revealed through auditory means when it was not immediately apparent through visual analysis can be found in the work of *Scarf et al*. [1982] who reported a number of impulse-like noise bursts through visual analysis of plasma wave data from the Voyager 2 spacecraft. The auditory reproduction of this data set provided a convincing method for identifying the source of the turbulence as bits of material from Saturn's Rings impacting the spacecraft (which resembled the sound of a "hailstorm").

2.3. The Think-Aloud Protocol

To date, audification has been applied in the heliospheric sciences on an ad hoc basis. This study is a formal investigation into how this technique may be regularly used by a researcher in the evaluation of large time series data. Accordingly, it was necessary to conduct a pilot study to observe the process of auditory analysis in action in order to gain an understanding of how it might guide a larger investigation. To accomplish this goal, a single case study employing the Think-Aloud protocol was undertaken to gain access to the reasoning process of the participant in real time [*Fonteyn et al*., 1993]. Originally introduced by Lewis Clayton at IBM in 1982 [*Lewis*, 1982], this verbal protocol has remained a cornerstone of software engineering research, and successful use cases can be found across all stages of the design process [*Hughes and Parkes*, 2003]. Notably, the Think-Aloud protocol has been used to assess the effectiveness of various forms of knowledge representation and visualization [*Hahn and Kim*, 1999] and to evaluate the usability of new software tools during early prototyping stages [*Seaman et al*., 2003].

3. Origins of the Case Study

Sonification techniques have proven particularly useful for the exploratory analysis of various types of scientific data [*Hermann*, 2002]. Exploratory data analysis is an open-ended process that involves making large data sets more easily navigable to the human analysts, with the goal of gaining knowledge and uncovering new insight. As opposed to confirmatory data analysis, which seeks to assess how well our assumptions align with available data, exploratory analysis focuses on the acquisition of knowledge that lies outside our realm of expectations [*Tukey*, 1977]. The current study is a portion of a more extensive project to evaluate the application of audification for exploratory data analysis of time series. Previous research indicated that audification has the potential to reveal features that may elude the eye [*Hayward*, 1994], this paper documents multiple cases that support this hypothesis in order to provide a better understanding of the unique spectral characteristics of features that are predisposed to auditory identification in these instances.

3.1. Data Selection

The team worked with the participant to determine a suitable heliospheric data set for exploration through auditory analysis. Generally speaking, data sets appropriate for audification include large one-dimensional time series with samples gathered at regular temporal intervals. Magnetometer data from the Wind spacecraft presented itself as an ideal candidate based on its high (92 ms) time resolution, the variety of spectral features, and the length of continuous data, which extend longer than one solar cycle. This data set enables scientific investigations focused on the microphysics of the solar wind, e.g., the interactions between waves and particles in the turbulent solar wind—fundamental processes that indicate how energy in plasmas is transported and dissipated [*Gurnett*, 1985; *Marsch et al*., 1993]. Certain spectral features in the data can indicate the presence of specific types of waves, such as cyclotron waves, which are a proxy for strong wave-particle interactions [*Jian et al*., 2009]. Such wave bursts are often short-lived and difficult to find through traditional analysis methods, particularly considering the large volume of available high-resolution data. Audification provides a promising alternative, under the hypothesis that these spectral features may be located by listening to a large quantity of data in audio file format.

3.2. Data Cleaning

The first diagnostic evaluation presented in the introduction related to the assessment of errors and gaps in the time series. Listening through several examples of audified magnetometer data quickly revealed that these values can often produce audible “clicks” and “pops.” An initial step in the audification process was to determine the best way to manage these “bad” and missing data values. It was found that in instances where a small percentage of data are missing, linear interpolation across these values may create minimal auditory artifacts while preserving the time scale of the original data set. An alternative approach would be to assign these entries a predetermined value (such as zero) or simply remove them from the audified data altogether [*Edmondson et al*., 2013].

3.3. Preliminary Analysis

The team began with a data survey of Wind high-resolution magnetometer data from 2007 to 2008. These years were prime candidates for the presence of wave activity due to the relative period of inactivity during solar minimum. During the early stages of the study, we used auditory analysis to identify potential wave activity, and a set of specific time regions were provided to the participant for evaluation through traditional analysis methods. Upon repeated exposure to many audified data examples, the participant developed the ability to consistently identify wave activity through the application of analytical listening techniques. The following section explores the nature of this ability in a structured analysis task.

4. Structured Think-Aloud Study

A Structured Think-Aloud is employed to gain access to the evolving reasoning processes of the participant during a multimodal analysis task. This protocol includes the use of predetermined verbal prompts that are provided during an extended period of inactivity (e.g., 5 s) [*Olmsted-Hawala et al*., 2010]. The central hypothesis of this study is that through analytical listening, a research scientist will be able to successfully identify wave activity within audified magnetometer data sets. The participant is a 30 year old male with a physics PhD and extensive experience working with spectrogram displays. He has no self-reported hearing or vision impairment. Consent was given to record audio during the Think-Aloud task, and the University of Michigan deemed the study to be exempt from the oversight of the Institutional Review Board.

High-resolution Wind magnetometer (MAG) data gathered during November 2007 were downloaded from the Coordinated Data Web data repository (CDAWeb, Goddard Space Flight Center; http://cdaweb.gsfc.nasa.gov/cdaweb/sp_phys/). These files were combined in MATLAB and audified as a single 16 bit file in *.wav* format, and two time regions were selected for analysis. All audio examples discussed in this paper can be found online [*Alexander*, 2014b].

All listening tasks were completed with Audio Technica ATH-M50 professional studio monitor headphones. The auditory analysis task was completed on a Macbook Pro using the iZotope RX 2 software platform. All instructions were verbally provided to the participant.

The participant was asked to think aloud while engaging in a directed multimodal data analysis task. Presentation of the data began with playback of the audio file, and the participant was prompted with questions such as "*Can you describe what you're hearing in words?*" and "*Would you like me to replay any certain section?*". This analysis was largely exploratory in nature, as the participant was not specifically asked to identify certain types of features. This provided important information as to the type of event that the participant would auditorily identify as a feature of interest. Once the initial auditory analysis was complete, the participant was provided with the waveform of the audified data for visual reference. At this time, additional prompts were provided such as "*Is there anything interesting about what you're observing?*" and "*Would you like me to zoom-in*, *zoom-out*, *or move to a different region?*". Finally, the spectrogram display was made available, and the participant was asked to continue verbalizing his thoughts as he used the visual and auditory displays simultaneously. The study was conducted in a quiet room over the course of a single session.

5. Results

An audio recording of the Think-Aloud session was transcribed to produce verbal data. During the session, all instances in which the participant directly referred to the audified data set were documented, and the corresponding data sample numbers were logged in the transcript. This allowed vocalizations to be paired with specific features in the data. Any instance in which the participant verbally reproduced the spectrum of the audified data was highlighted, along with any terminology used to describe the auditory phenomena. It was determined that segmentation of the entire verbal protocol was not necessary, as an initial search revealed two specific cases in which the participant anticipated the presence of wave activity based on auditory observations, and subsequently confirmed this activity through visual analysis. These portions of the experimental session have been selected for presentation in this section.

The data used in both instances were taken from the Z component (in the GSE coordinate system) of Wind-MAG observations, as the X and Y components contained an audible tone induced by the spinning of the spacecraft (while the Z component did not). Both examples were measured in close proximity to the passing of a large magnetic cloud. The first example spanned 123,116 data samples from solar wind magnetic field measurements gathered on 18 November 2007. The resulting audio file was approximately 2.8 s in length at playback rate of 44,100 samples per second and represented approximately 3.1 h of real-time recording.

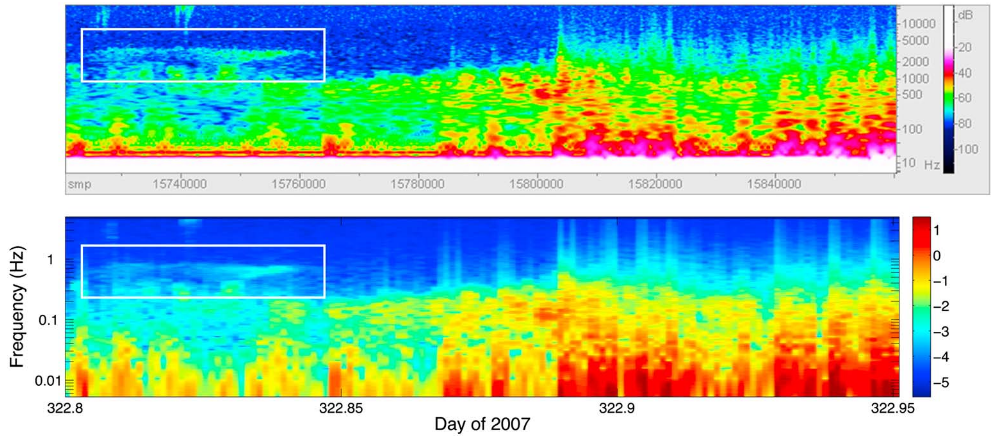

Figure 2. The spectrogram of the first data example rendered in (top) iZotope RX and (bottom) MATLAB. This interval spans 123,116 data samples from solar wind magnetic field measurements gathered by the Wind spacecraft on 18 November 2007 (day of year (DOY) 322). Here the participant described a chirp event corresponding with the band of 1 Hz activity near the left-hand side (see white box).

When listening to the audified data, the participant was able to identify several instances of wave activity, and he expected that the spectrogram display would contain "…a low power, some kind of gradient with a peak at some specific range of frequencies for the chirp at the beginning." He then speculated that the middle portion of this example would contain one or more "peaks" at a lower frequency, and that they would "drift or there will be some change." Additionally, he indicated that the middle portion contained an event that was potentially "percussive" in nature, and marked by a sudden rise in amplitude. He anticipated that the latter half of the event would have a steep slope and the spectrogram should "lift up." In the previous description, a peak refers to a region with increased spectral power, and the "chirp" corresponds to the 1 Hz enhancement that can be seen near the left side of Figure 2. Here a spectrogram of the audified data in iZotope RX (Figure 2, top) is provided for direct comparison with a spectrogram of the original time series rendered in MATLAB (Figure 2, bottom). Note that while the audio file has been transposed into the frequency range of human hearing, the two plots are nearly identical. In both representations, the "rise in amplitude" described by the participant can be seen as an increase in spectral power occurring in the latter half of the time interval.

The participant indicated that his previous experience working with audified magnetometer data informed his assessment of features in this example. Before conducting a visual inspection, he hypothesized that the chirp event would be associated with a region of coherent wave activity. The original hypothesis was confirmed upon the observation of moments of coherent wave activity in the audified data waveform. The time series for this region is provided in Figure 3.

The second example spanned 148,837 data samples from magnetic field measurements gathered on 20 November 2007. The resulting audio file was approximately 3.4 s in length at the same 44.1 kHz sampling rate,

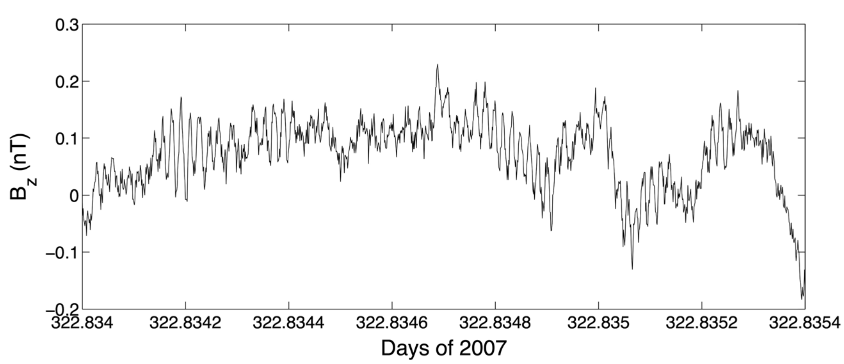

Figure 3. A subregion of the event occurring in Wind magnetometer data that was identified as a chirp through auditory analysis. Instances of coherent wave activity can be seen in the time series as nearly sinusoidal oscillations.

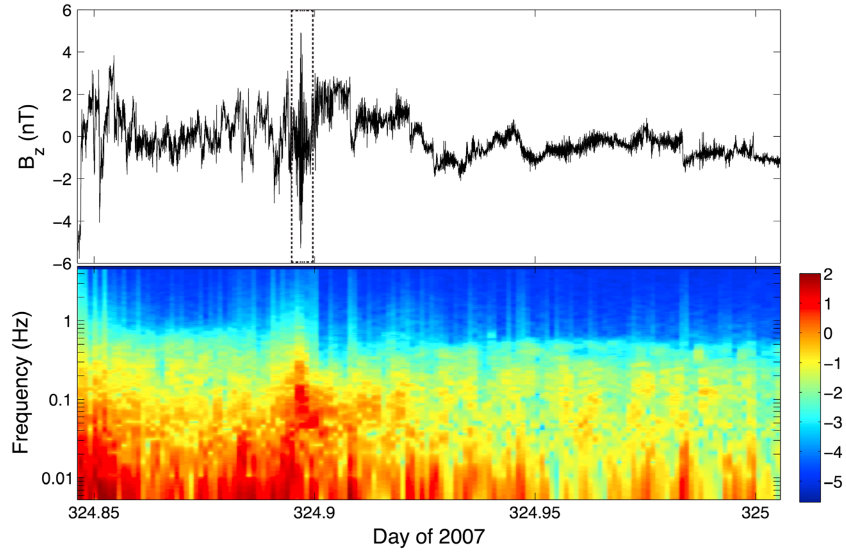

Figure 4. The (top) time series and (bottom) spectrogram display for the second audified data example. This interval spans 148,837 data samples from solar wind magnetic field measurements gathered by the Wind spacecraft on 20 November 2007 (DOY 324). The participant divided this example into three sections he described as a warble noise, a knock, and finally a hissing. A dotted line has been placed around the knock event in the time series, and this region is expanded in Figure 5.

representing approximately 3.8 h of real-time recording. Upon listening to the audified data (without access to the spectrogram display), the participant observed three distinct sections: A *warble* noise leading up to a short *knock* at a slightly higher frequency, and finally a quieter segment containing broadband noise that was both rising and "*hissing*." He hypothesized that wave activity would present itself in small packets across a range of frequencies. The time series and spectrogram representation for the second audified data example are provided in Figure 4.

The event described as a "knock" can be seen in both the time series and spectral display as a short increase in power occurring roughly at day 324.9. When subsequently provided access to the audio waveform, the participant inspected this region using a combination of auditory and visual analysis methods to isolate the knock feature. Visual inspection revealed the presence of six relatively clear oscillations within a larger amplitude envelope. The time series for this region is provided in Figure 5.

Additional investigation of these two time intervals through traditional analysis methods confirmed the presence of wave activity. The first example likely contained waves caused by a stream interaction region and the second example contained the reverse magnetosonic shock of an interplanetary coronal mass ejection [*Gosling and Szabo*, 2008].

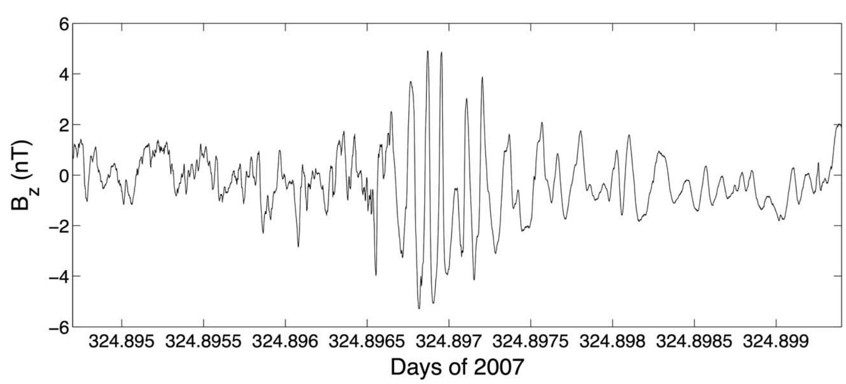

Figure 5. A subregion of the event occurring in WIND magnetometer data (*Z* component) that was auditorily identified by the participant as a knock. Close inspection of the time series reveals six periodic oscillations within a larger amplitude envelope.

6. Discussion

In this case study, the research scientist was able to extract important spectral cues through the application of auditory and multimodal analysis methods. While a correlation between assessments made through audition and was established by *Pauletto and Hunt* [2005], this case study further demonstrates how auditory analysis may be useful when applied in an open-ended feature identification task.

6.1. Cross-Modal Cues

Across the two data examples, the participant related instances in which features were easier to detect through either visual or auditory analysis. In the first data example, some portions of the frequency spectrum only became audible upon viewing the spectral representation. Specifically, the participant stated that once he could see the spectrum he was able to hear a lower frequency feature that had eluded identification during initial auditory analysis. He indicated that he had been distracted by a simultaneous "cheep" event that occurred at a higher frequency. Here the audified low-frequency content remained peripheral until it was pulled into focal awareness by visual observation. This underscores one of the potential strengths of multimodal analysis: one sense may cue the other into the presence of important information that may otherwise be lost.

In the analysis of the second example, auditory observations prompted the participant to conduct additional visual exploration of the spectrogram display. In this instance, the participant indicated that he could hear a feature that was imperceptible in the spectrogram, and through a subsequent rescaling of the data he was able to visually confirm the presence of a subtle narrowband spectral enhancement.

During the Think-Aloud session, the participant noted several examples of wave activity that were visible in the audio waveform (the presence of waves was later confirmed through traditional analysis methods). This speaks to the isomorphic nature of the audification process—as all data samples were preserved, the participant readily regarded the audio waveform as a one-dimensional line plot of the original data (see Figure 1). In several instances, upon detecting a feature in the waveform, the participant immediately associated the region with a specific sound that was observed during audio playback.

6.2. Descriptive Language and Vocalization

Another way to understand how the participant categorized features he heard within the data is to observe the language he used to describe these features and, in some cases, how he attempted to imitate the sounds he heard. Throughout the experimental session, the participant used a variety of descriptive techniques in communicating the form and structure of features within the audified data. Wave activity was described in terms including *warbles*, *whooshing*, *swirling*, *chirping*, and *whirling*. In several instances the audified data were related to familiar acoustic phenomena such as a knock, a spinning hollow tube, or sounds derived from a metallic cable. On more than one occasion, nearby objects were used to convey acoustic information: in the instance of the knock event, the participant slapped the top of the desk to indicate the percussive nature of the sound.

Another strategy involved using the mouth as a complex filter to vocalize the nature of the evolving spectrum. In these instances hard consonant sounds such as "ck" and "ch" relayed the presence of transient broadband noise. The presence of narrowband noise was conveyed with exhalation while opening and closing the mouth, indicating the presence of low- and high-frequency content, respectively.

6.3. General Discussion

In the month prior to the Think-Aloud study, the participant was exposed to several examples of audified Wind-MAG data. He noted that he had developed the ability to auditorily detect spectral components that occurred close to the cyclotron frequency and that these specific sounds would lead him to suspect that wave activity would be present in the data. This preexposure was important in developing the ability to auditorily distinguish "normal" solar wind turbulence from abnormal behavior (in many instances a new vocabulary was necessary to describe abnormal activity that had yet to be defined in scientific terms). This study demonstrates that the participant's listening abilities were sufficiently developed to associate specific auditory observations with certain types of wave-particle interactions, supporting the earlier suggestion that audification can assist in the identification of time regions that contain features of interest. Though the participant had never been exposed to the auditory examples provided in the Think-Aloud, the spectral content was sufficiently familiar to classify wave activity based on the participant's acquired "auditory vocabulary." The ability to reliably connect auditory observations with precise regions of the original data set

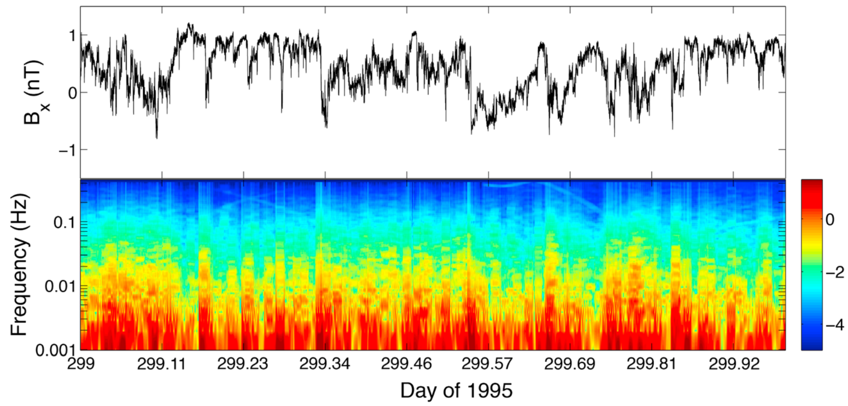

Figure 6. The (top) time series and (bottom) spectrogram display of data from the ULYSSES magnetometer instrument. This interval spans 86,401 data samples from solar wind magnetic field measurements gathered on 26 October 1995 (DOY 299). The spectrogram contains aliased artifacts at high frequencies. These artifacts were first identified by the participant through auditory analysis and later confirmed through visual analysis.

relies on the fact that certain features in the solar wind (e.g., ion cyclotron waves) will consistently give rise to similar spectral features in audified data, and the resulting auditory streams, which *Bregman* [1990] refers to as auditory objects, are closely tied to the evolving physical phenomena.

Another key question posed in the introduction was whether audification could support the observation of large-scale structures in the time series. The level of detail provided by the participant when asked what he expected to see in the spectrogram display indicates that he was able to both auditorily extract specific features and also observe the wider frequency spectrum as it evolved. This type of auditory scanning may be particularly well suited for the purposes of exploratory analysis, as potential features of interest may be present across a wide-frequency range. Furthermore, as the initial assessment of the frequency spectrum was conducted without any visual reference, it is feasible that the eyes could be engaged in a secondary task, though additional research is necessary in order to quantitatively assess the impact of multimodal displays when applied toward an exploratory analysis task.

7. Two Additional Examples

7.1. Detection of Equipment-Induced Noise

The participant independently audified 200 days of solar magnetic field observations gathered by the magnetometer on the ULYSSES spacecraft, the resulting audio file has been uploaded to a web-based repository [*Alexander*, 2014b]. Through auditory analysis, he was able to detect equipment-induced noise that he had not observed previously. Specifically, he observed aliasing in the high-frequency range of the audified data, which was most likely introduced by the tape recorder on the spacecraft. As the two spools run at different rates, aliased “drifting tones” can appear in the data (T. Horbury, personal communication, 2014).

The participant stated that this noise was “something that stood out by ear more than it stood out by eye.” This supports the suggestion posited by *Hayward* [1994] that one of the most promising applications for audification may lie in the identification of noise and equipment-induced error. The aliasing effects in the audified ULYSSES data are observable as thin green lines sweeping across the high-frequency ranges in Figure 6.

7.2. Manipulating the Audified Data

In a subsequent analysis session, the participant hypothesized that the second example from the Think-Aloud study contained an instance of a reverse shock. A reverse shock occurs when a fast plasma stream is followed by a slower one, resulting in a shock wave that travels toward the Sun within the reference frame of the plasma (while still traveling away from the Sun in the reference frame of the spacecraft). If this event were indeed a reverse shock, the physical structures would be nearly identical to a forward shock but would evolve in reverse temporal order. Here the participant suggested that the audio for this reverse shock event should be played backward, sped up, and compared with a forward shock to assess for similarity.

The audified data were subsequently processed in Audacity, a free software platform for editing and manipulating audio waveforms. After reversing the file, the team used auditory analysis in tandem with calculations of the anticipated Doppler shift to match the spectral contour with that of a known forward shock. The resulting audio was a convincing match, and the original hypothesis was confirmed. This audio example can be found online [*Alexander*, 2014b].

Many Digital Signal Processing (DSP) techniques used in the processing of heliospheric time series data have correlates in the digital audio domain. When carefully applied, DSP algorithms for noise reduction and filtering may potentially reveal new features within an audified data set. For example, it has been found that artificially induced frequencies from spacecraft spin tone can often be auditorily attenuated through the application of a notch filter; and adjusting the sampling rate or playback speed of the audio will shift the entire frequency spectrum, revealing new micro and macro features inherent within the data.

8. Conclusion

In the case study reported in this paper, auditory analysis techniques were successfully applied by a research scientist in the detection of wave activity embedded in 11 Hz Wind-MAG data. Though the participant had some familiarity with data of this type, the fact that he was able to auditorily recognize wave activity in regions of the data to which he had no previous exposure suggests that he had acquired a sort of auditory vocabulary for specific types of wave-particle interaction. Additionally, the participant was able to use audification to identify equipment-induced noise that had been previously unobserved. This research, therefore, suggests that audification can reveal spectral features in solar wind time series that can inform early diagnostic evaluations. More specifically, this study indicates that audification can be useful in the initial stages of overview and feature identification, providing a new “big picture awareness” that was not present before. This global perspective could be described as a *bird's ear view*, a macrounderstanding of large time series brought about through auditory scanning, a process that preserves the small time scale features that may be difficult to see when performing a large-scale visual scan.

A follow-up interview with the participant indicated that he has continued to use audification in the assessment of every large high-resolution data set he has worked with in the 2 months since the study was completed and that in many instances auditory scanning has been preferable to visual scanning methods. Further analysis of cases like those found here has led to the discovery of intervals of wave activity that have clear correlations with other phenomena such as particle beams; these observations represent scientific advances that will be discussed in a future publication.

It should be noted that the observations in this paper reflect an interaction with one research scientist and were motivated by a number of previous scientific studies in which audification led to important results when applied by a trained specialist [e.g., *Landi et al*., 2012]. A generalized study that focuses on the broad applicability of audification as a data analysis tool is currently in progress, and this ongoing investigation includes a significantly larger participant pool. We will analyze research scientists' visual and auditory observations in depth to better understand the specific strengths and weaknesses of each modality (as well as their interplay). This follow-up experiment has been designed to produce quantitative results that should be more readily transferrable to other scientific domains. Additional qualitative research will continue to assess the evolving workflow of research scientists as they begin to integrate auditory analysis tools and methods. Ultimately this work will inform the design of a tool for the multimodal analysis of large one-dimensional time series and the creation of an interactive web-based tutorial series.

While visualization has long been the standard technique for representing scientific data sets, this research indicates that audification can be a valuable diagnostic tool in the analysis of large time series data sets. This investigation is an initial step toward a larger framework through which data audification as a method for spectral analysis may be transferred across scientific domains.

Appendix A1: Audification: Step-by-Step Guide

An overview of the steps that can be taken to audify data from a wide range of sources across a variety of scientific domains is provided in Figure A1. This guide focuses on the use of audification for the purposes of exploratory data analysis and provides basic instruction for data preparation, auditory analysis, and knowledge extraction. Example code is available online [*Alexander*, 2014a].

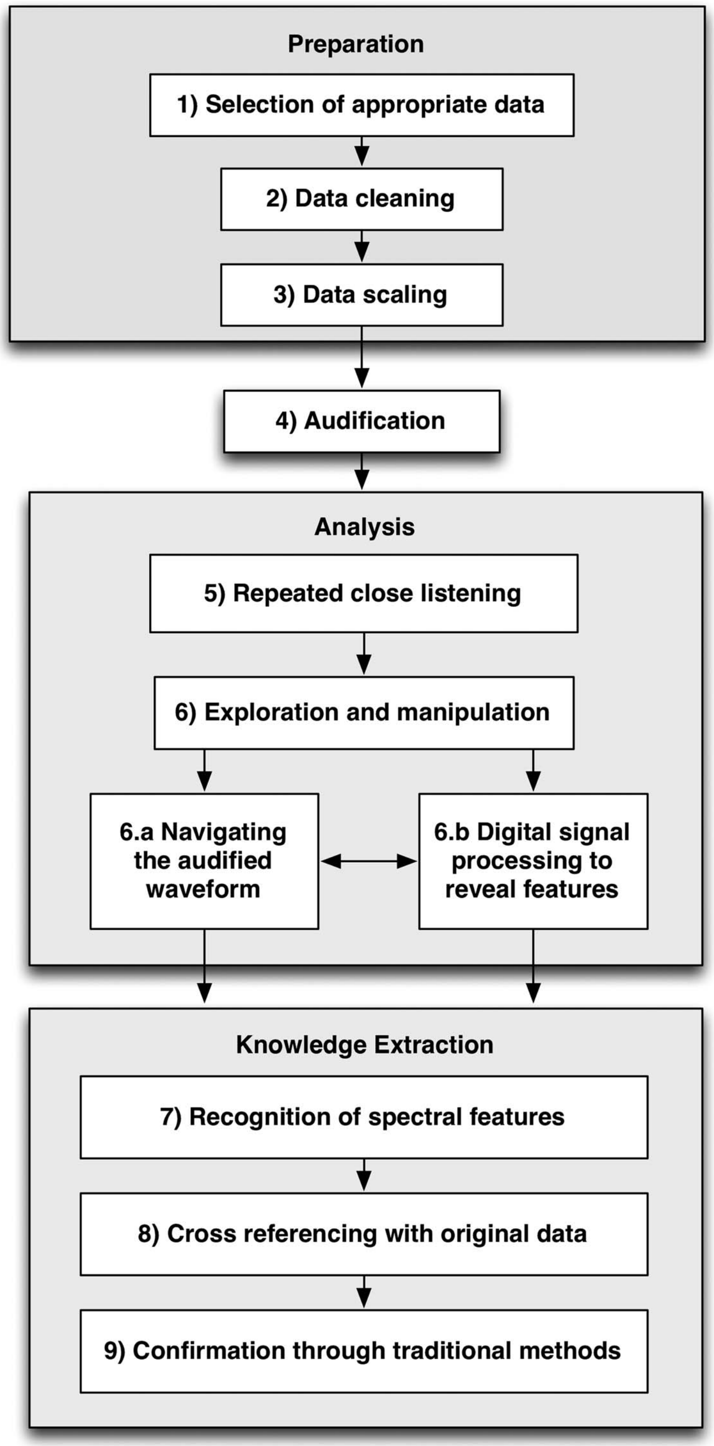

Figure A1. A flowchart of the audification process.

1. *Selection of appropriate data*. The data that lend themselves ideally for spectral analysis through audification match the following criteria: (i) one-dimensional time series, (ii) observations recorded at equal temporal intervals, and (iii) a large source of available data (approximately 44,000 data samples = 1 s of audio at the standard rate of sound file playback).
2. *Data cleaning*. Missing or bad data can produce audible artifacts, and extreme outlying values can greatly reduce the overall dynamic range of the resulting audio file. Three methods for handling these values

Table A1. Various Methods for Handling Bad or Missing Data Values

	Flagged Data Values are ______.	Audible Clicks and Pops?	Preserves Temporal Progression of Audio?
Interpolation	Smoothed	Minimized	Yes
Value assignment	Assigned a constant value	Likely	Yes
Exclusion	Removed from audio	Likely	No

are provided in Table A1 (Nearest-neighbor interpolation may be considered a form of value assignment). It should be noted that some data sets may also require spike elimination.

3. *Data scaling*. Appropriate scaling will maximize the signal-to-noise ratio of the audio signal while simultaneously avoiding clipped values. The range to which the data values should be scaled will vary based on the bit depth of the audio, the file format, and the platform used for audification.
4. *Audification*. Many high-level programming languages such as MATLAB and IDL contain functions for directly audifying variables stored in memory and writing audio files in various formats. These files can then be played and manipulated using various third-party software platforms.
   a. *Bit depth*. The number of bits used to encode the amplitude of each audio sample (i.e., each audified data sample). The industry standard is 16 bits, though 24 or 32 bits are recommended.
   b. *Sampling rate*. The number of amplitude measurements (audified data samples) played back per second, as measured in Hertz. The industry standard sampling rate is 44.1 kHz.
   c. *Audio channels*. In most cases, each data parameter should be written as a single-channel audio file. Distributing two or more data parameters across multiple audio channels will allow for spatialization. Two channels (stereo) is the industry standard for most speakers and headphones.
   d. *File format*. Uncompressed audio formats (e.g., WAVE and AIFF) are preferable, as spectral distortion can occur when encoding to a "lossy" format such as MP3.
5. *Repeated close listening for feature detection*. High-fidelity speakers or headphones are necessary to maximize clarity and spectral bandwidth during audio playback. A poor reproduction of the audio signal (e.g., via laptop speakers) can introduce artificial distortion and resonance. Before playing the audio file, reduce the volume to avoid a potential sudden burst of noise. While the data may initially sound very "noisy," subtle spectral details will begin to emerge after repeated listening. Finally, it is recommended that new practitioners begin by observing features that they know to be present in the data before auditorily scanning for previously unobserved features.
6. *Exploration and manipulation*. Various software platforms enable the navigation and manipulation of digital audio waveforms (*Audacity* is a free cross-platform audio waveform editor). Additionally, several techniques can expedite the process of finding and extracting features of interest:
   a. *Navigating the audified waveform*. Smaller subregions are selected for playback and looping.
   b. *Digital signal processing*. Many mathematical operations that are used in the investigation of scientific data sets have correlates in the realm of digital audio. For example, filters can be useful for accentuating a portion of the audio spectrum or removing unwanted noise. Increasing or decreasing the sampling rate (or playback speed) of the audio will respectively shift spectral content higher or lower and reveal structures at large and small scales.
7. *Recognition of spectral features*: Depending on the type of data under observation, potential features of interest may range from a recurring sinusoidal oscillation to a transient broadband impulse (to name a few examples). These features may be extremely prominent or quite subtle, and a listener should remain open to a broad range of spectral cues, as structures may be present at very large or very small scales.
8. *Cross referencing*. Features in the audio file can be associated with specific time regions in the source data, and frequency content can be mapped from the audio sampling rate to the cadence of the original time series.
9. *Confirmation through traditional methods*. Traditional data analysis techniques can be used to confirm the presence of the feature within the original data set. For example, the time series can be represented as a simple line plot, and the frequency spectrum can also be assessed through wavelet or Fourier transforms. In many instances, it is helpful to then evaluate the time period in question across multiple (potentially correlated) data parameters.

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