AURALIZATION OF MAGNETIC MULTISCALE SATELLITE DATA: TOWARD INTEGRATED AUDIFICATION IN SPACE SCIENCE

Kristina Collins
Space Science Institute
4765 Walnut St, Suite B
Boulder, CO 80301, USA
`kvcollins@spacescience.org`

Robert L. Alexander
Auralab Technologies Inc.
2174 Overlook Ct
Ann Arbor, MI, 48103, USA
`robert@auralab.io`

Jaye Verniero
NASA Goddard Space Flight Center, Code 672
Greenbelt, MD 20771, USA
`jaye.l.verniero@nasa.gov`

Robert M. Candey
NASA Goddard Space Flight Center, Code 672
Greenbelt, MD 20771, USA
`robert.m.candey@nasa.gov`

ABSTRACT

Audification has an established history in the field of space science, with events such as “lion roars” and “whistlers” drawing their names from auditory observations. As of 2019, NASA’s CDAWeb repository provides audified versions of observations from spacecraft and ground-based instruments as a standard data product. This approach can be extended further through spatialized audio (auralization) of data from multiple sensors. However, there are not currently standardized tools available for spatially rendering audified multispacecraft observations. Here, we demonstrate an auralization of magnetometer data from NASA’s Magnetospheric Multiscale (MMS) Mission, produced using open-source tools in python. Each spacecraft’s audified data is played by a virtual sound source with a location matching the physical arrangement of that spacecraft. This is used to generate a binaural rendering optimized for playback over headphones. This approach eliminates the need for specialized tools, improving access for citizen scientists. It lays a foundation for standardized auralizations of distributed instrumentation systems, both for use in space science research and for systematically evaluating the effectiveness of auralization methods, and supports ongoing work with ground-based magnetometers in polar regions.

1. INTRODUCTION

The geospace environment is replete with diverse, complex and interrelated wave features, for which audification can be a valuable analysis approach. The scale and geometry of the Sun/Earth system motivate an extension of audification techniques to auralization (spatial sonification) for data presentation and exploration. In this work, we present an example of auralized spacecraft data using Python-based tools. Section 2 introduces audification and auralization in the context of space science. Section 3 discusses NASA CDAWeb, and the history of its data audification features. Section 4 describes the Python workflow used to generate the auralization of satellite data presented in this work, and Section 5 describes our example data from the MMS mission. Finally, Section 6 articulates next steps for incorporating auralization into existing workflows for analyzing space science data from CDAWeb.

Audification transforms data points directly into audio samples, maintaining the original dataset’s integrity via a one-to-one mapping. Through this process, 44,100 data samples can be translated into a single second of audio at a standard sampling rate of 44.1kHz, allowing a million data samples to be auditorily assessed in approximately 23 seconds. Adjusting the sampling rate by either lowering it, which slows down the audio file, or increasing it, which accelerates playback, alters the frequency spectrum and duration of the audio. This type of adjustment can help to highlight macro- and micro-scale features and trends in the data, and additional tools commonly employed in the realm of digital audio can also help in the analysis process (e.g. filters and noise reduction).

Audification draws upon the innate spectral analysis capabilities of the human ear, offering a highly sensitive diagnostic tool for the evaluation of continuous signals. It serves as a complementary or alternative approach to traditional visualization methods such as wavelet analysis and Fast Fourier Transforms (FFT). Combined with the ability to distinguish subtle signals within complex and noisy environments—known as the cocktail party effect [1]—the human ear offers itself as an invaluable analytical tool. Research further indicates that a multimodal approach (integrating both auditory and visual analysis) enhances feature identification sensitivity beyond that of conventional visual analysis alone, particularly in the context of evaluating heliospheric time-series datasets [2].

2. AUDIFICATION IN SPACE SCIENCE

Before the advent of modern data visualization technology, auditory analysis played a pivotal role in space science, particularly through the examination of VLF (Very Low Frequency) radio signals. This approach uncovered phenomena like the "whistler" mode waves through sounds generated by lightning in Earth’s magnetosphere [3]. Auditory analysis also led to the first observation of "Lion Roar" emissions in the magnetosheath [4], a discovery which has been pivotal in understanding the dynamics of plasma turbulence and energy transfer in Earth's magnetosphere.

More recently, audification was utilized in the analysis of more than 20 ionic ratios from the ACE/SWICS instrument, revealing C^{6+}/C^{4+} to be a more sensitive diagnostic of the solar wind source region than the more commonly utilized O^{7+}/O^{6+} [5]. In another study, audification of magnetometer data from the WIND satellite led to the discovery of a notable proton cyclotron wave storm, leading to a new understanding of such events as commonly occurring and locally generated within the solar wind [6]. The effectiveness of audification has also been demonstrated in the identification of equipment induced noise in satellite data [7]. Currently, the Heliophysics Audified: Resonances in Plasma (HARP) project, a NASA funded citizen science project with more than a thousand participants is yielding new insights into the nature of ULF waves in the Earth's magnetosphere. [8]

3. AUDIFICATION OF CDAWEB DATA

Coordinated Data Analysis Web (CDAWeb[1]) is a web-based data browsing tool provided by the NASA Space Physics Data Facility (SPDF[2] [9]) heliophysics archive. It facilitates access to a variety of heliophysics data, including current and past missions, related to the study of the physical processes in the space environment from the Sun to Earth and throughout the solar system.

The repository is regularly updated to provide the latest and most accurate data to both researchers and the public. The interface offers access to datasets selectable by mission (e.g. Parker Solar Probe, Voyager), and/or instrument type (e.g. electric and magnetic fields, energetic particle detectors, and radio and plasma waves). Users then select data variables to visualize or download for a given time range (in various formats and with other options).

Audification functionality was added to CDAWeb in 2019, enabling users to generate .wav files from individual vectors at a sampling rate of 22kHz. This sampling rate was chosen over the more traditional 44.1kHz to ensure that important information within the audio file falls within a frequency range audible to a wide range of individuals. This sampling rate also requires fewer data samples to produce a single second of audio. Missing data samples are smoothed via linear interpolation in order to avoid artifacts that can be produced by alternative methods such as value assignment.

Numerous datasets on CDAWeb are well-suited for audification, notably those involving high-cadence measurements (e.g. magnetic fields, electric fields and radio waves). In some instances, "burst mode" data may be available, offering a significantly higher sampling rate over limited intervals of time. Several examples of audified solar wind data can be found in the Audification README file on CDAWeb[3].

4. SPATIAL AUDIO IN PYTHON

Python libraries, such as `spacepy` [10], `ai.cdas`, and `pyspedas` [11], which use CDAWeb's REST API to automatically pull data, are already widely adopted in the space science community. [12] Often, these tools are used in Jupyter notebooks, which are designed to enable reproducible computational workflows in a web-based format [13]. These workflows can then be iterated upon with relative ease. An audification approach which can be integrated into a Jupyter notebook, therefore, has advantages for the research community over a workflow which requires separate or proprietary tools.

Auralization, defined by Kleiner et al. [14] as a technique for rendering virtual sound fields, is a natural extension of audification where multiple sound sources are concerned. This approach utilizes a Head-Related Transfer Function (HRTF) to generate a binaural sound field, enabling a listener to reliably identify the perceived direction in which a sound originates. To date, this method is not widely used in the space science community.

5. EXEMPLAR: SPATIALIZED MMS DATA

The Magnetic Multiscale (MMS, [15]) satellite mission, launched by NASA in 2015, comprises four spacecraft flown in a tetrahedral formation. To auralize this data, we created a set of four loudspeakers in `spaudiopy` [16], as shown in Figure 2. The audified signal for each spacecraft was then assigned to its respective virtual speaker, and used to produce a binauralized recording. From the listener's perspective, MMS2 is to the left, MMS4 is to the right, MMS3 is directly ahead and MMS1 is below as the satellites fly through the magnetosheath.

We chose as an example event a period between 9:00 and 9:05 UT on 9 December 2016. As reported by Phan [17], this period includes an observation of a novel electron driven magnetic reconnection event at 9:03:54 UT, during which two plasma outflow jets in opposite directions were observed.

MMS Level 2 Search Coil Magnetometer AC Magnetic Field Burst data (8192S/s) were audified in a spatial field as described in 4. The Bz component was used for each spacecraft as it was found to have less instrumentally induced noise than the Bx and By. Five minutes of data for a single satellite corresponds to 2.46 million data samples, or 1 minute and 52 seconds of audio at a sampling rate of 22kHz. In the audification, high-amplitude low-frequency waves associated with reconnection events resemble the sound of a strong wind hitting a microphone. Close listening reveals a set of higher frequency "chirps" which suggest there may be some wave particle interactions associated with these reconnection events. Many events present with a subtle but notable variance in their stereo field location, and the low-frequency waves present with a stereo width suggesting phase variance. This type of spatial information may be helpful in the exploratory analysis of structural properties of the solar wind.

This audification was time-aligned with videos generated by NASA's Scientific Visualization Studio, shown in Figure 3, and rendered as a presentation video [18]. For this rendering, the audification was mastered in order to balance the low frequencies that otherwise dominate the mix, and dynamic compression was added to prevent strong transient events from overpowering the mix. Instrumental noise was also reduced through a combination of filtering and de-noising algorithms applied in iZotope RX.

6. FUTURE WORK

The key accomplishment of this work is the direct auralization of space weather data using open-source tools in Python. Extending this proof of concept to a general-purpose workflow for auralizing CDAWeb data may entail:

1. **Further experimentation.** The example here is a first pass; there is much room to explore with regard to speaker position (and potentially changing it over time to track satellite

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[1] `https://cdaweb.gsfc.nasa.gov/`

[2] `https://spdf.gsfc.nasa.gov/`

[3] `cdaweb.gsfc.nasa.gov/audification_readme.html`

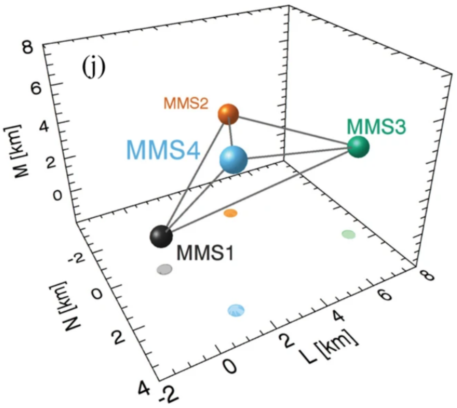

Figure 1: Fig. 3b from [17], showing configuration of MMS satellites in LMN coordinates.

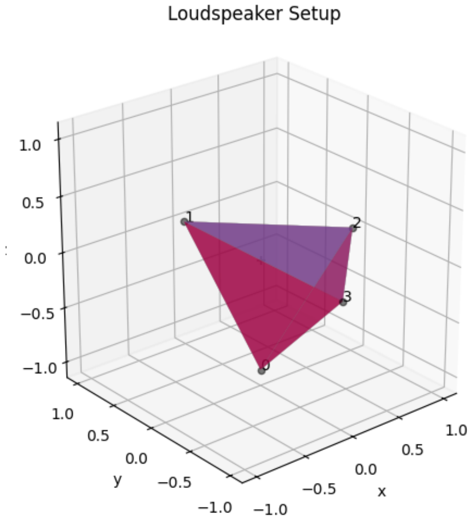

Figure 2: Speaker layout for MMS satellites, generated by `spaudiopy`. The listener is located at the origin point and faces the positive direction of the X-axis. MMS1 is labeled as 0, MMS2 as 1, and so on.

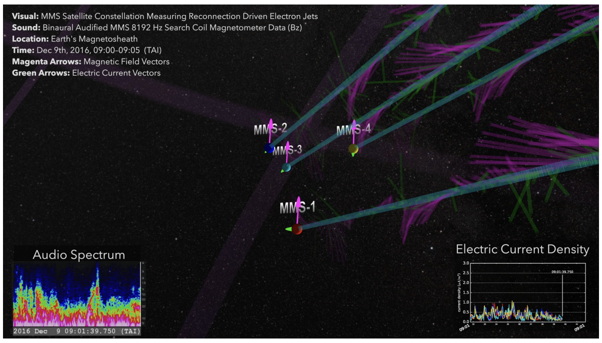

Figure 3: Synchronized visuals NASA's Scientific Visualization Studio, presented with the auralization. The visualizations are documented at `https://svs.gsfc.nasa.gov/4639`.

paths); ways to spatialize B_x, B_y, B_z components; appropriate sampling rates, and other aspects.

2. **Integration into a python package.**
3. **Extension to other spacecraft and distributed sensor systems.** CDAWeb offers data from ground-based stations as well as satellites. Interhemispheric conjugate magnetometer chains (i.e., on opposite ends of Earth's magnetic field lines [19]) are of particular interest for spatial sonification. In some cases, combined sonifications from multiple instrument systems may be of interest.
4. **Documentation of common and uncommon phenomena.** Developing audio guides to a "day in the life" of a sensor system, perhaps using synthetic data, will help new users develop an intuition for what a given dataset sounds like. This approach was used to great effect in the HARP project [4], and is particularly valuable for citizen scientists processing new data.
5. **Direct integration of auralization modes with CDAWeb.** Once prior steps are validated, spatial auralizations could be included as a CDAWeb product.

This represents an audio-first approach, but is conducive to integration with immersive visual modes of data presentation, particularly virtual reality and planetarium shows. Immersive audio-only displays, such as head-tracking headphones, may also be valuable platforms for expressing these data.

The auralization in Section 5 also suggests new avenues of investigation specific to MMS. This particular event is an example of "electron-only" reconnection, whereby the reconnecting magnetic fields are coupled only to the electrons, and not the ions, differing from traditional pictures where both particle populations are involved. Although this means background ion movement is not detectable, hidden features heard in the magnetic field might hold clues. Several open questions regarding reconnection—such as its onset, rate, and overall role in energy conversion—may be elucidated by examining the behavior of the generated waves. Ultimately, both the electrostatic and electromagnetic waves driven by reconnection (such as whistlers and solitary waves [20]) will interact with the overall turbulence dynamics. An overarching question in space plasma physics is how turbulent energy dissipates across disparate scales. Electron-only reconnection reveals how turbulent energy from the reconnection may bypass ion-scales and only heat electrons [21]. Future work will thus also include the electric field to hear the electrostatic waves responsible for the observed electron acceleration and distinguish the electron-scale dissipation of the energy cascade. Finally, auralization of multi-spacecraft data will maximize scientific return of other upcoming missions, such as HelioSwarm, a swarm of 9 spacecraft capable of unique tetrahedral configurations to capture dissipation of turbulence from large to sub-ion scales. [22]

7. OPEN RESEARCH

This work uses data from the Magnetospheric Multiscale (MMS) mission, available from the NASA SPDF archive [9] via CDAWeb. Visualizations from NASA's Scientific Visualization Studio are available at `https://svs.gsfc.nasa.gov/4639`. The code used to compose the sonification is available at [23]. At the

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[4] HARP resources are available at `listen.spacescience.org`.

time of writing, the sonification discussed herein [18] is available at `https://youtu.be/cTauKjcRCPY`.

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