Magnetospheric Undulations Sonified Incorporating Citizen Scientists (MUSICS) Teacher Guide

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Abstract

The magnetosphere is the dynamic space environment due to the interplay of the solar wind with Earth's magnetic field. One of the resulting phenomena in this interaction are plasma waves in the ultra-low frequency (ULF) range, < 1 Hz. Many questions concerning ULF waves still remain, such as how often and at what frequencies do various resonances of the magnetosphere occur. Through the sonification of magnetic field data from spacecraft orbiting Earth, your research will involve listening to magnetospheric ULF waves. By using perhaps the best pattern recognition system that we know of, the human auditory system, you will identify wave events and classify them in order to eventually build up a better understanding of magnetospheric ULF wave occurrence and frequencies.

1 Introduction

Earth's **magnetosphere** is the space environment around the Earth formed by the interaction of the solar wind (plasma continually streaming away from the Sun at supersonic speeds) with the Earth's intrinsic magnetic field. The solar wind compresses the magnetic field on the dayside, confining it to typically within 10 times the Earth's radius (R_E), whereas it sweeps back the magnetic field lines on the nightside to some unknown length, possibly up to 1000 R_E. In turn the solar wind is itself slowed and deflected around the magnetic barrier (by a bow shock due to its supersonic speed). Figure 1 illustrates some of the basic structure of the magnetosphere.

The magnetosphere is far from static, for example the solar wind pressure and magnetic field continually change causing the size and shape of the magnetosphere to adjust accordingly. One of the dynamic aspects of the magnetosphere are the number of different **plasma wave** phenomena that can be supported. In the **ultra-low frequency** (ULF) range, defined as waves/oscillations of frequency <1 Hz, there are two fundamental plasma waves of interest:

- Alfvén waves: these are analogous to waves on a string since magnetic field lines in a plasma exhibit a form of tension. Their wave perturbations (both displacement and magnetic field perturbations) are perpendicular to the background magnetic field i.e. transverse, so they do not increase the magnetic field strength, and they transport energy along the direction of magnetic field lines.
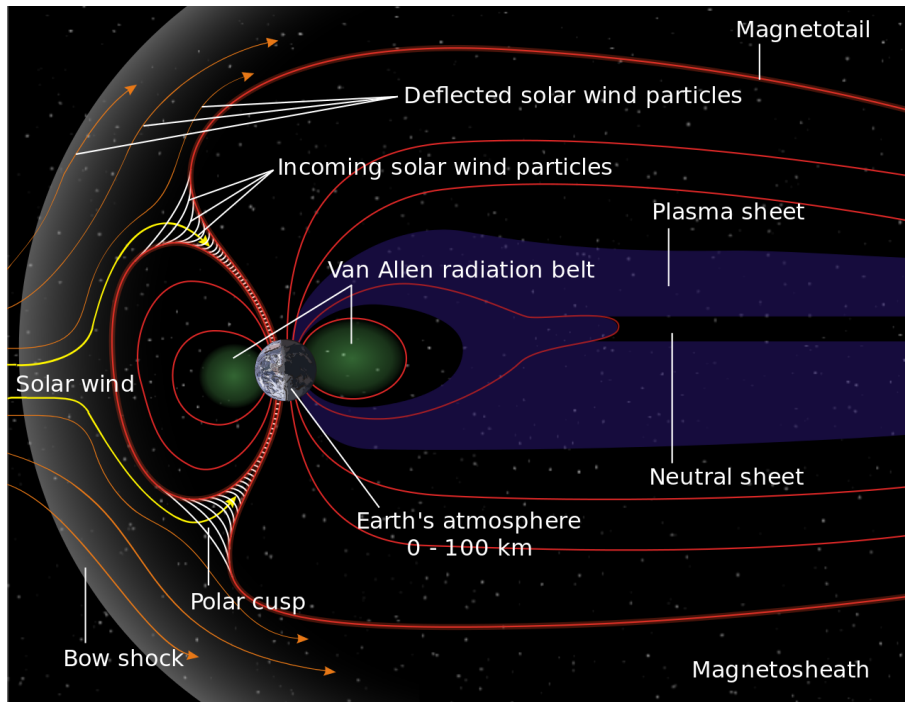
Figure 1: Structure of Earth's magnetosphere.

- Magnetosonic waves: the equivalent of sound waves in plasmas, since plasmas consist of both thermal and magnetic pressures. Unlike pure sound waves, however, they exhibit both longitudinal and transverse components. Magnetosonic waves, unlike Alfvén waves, can transport energy across magnetic field lines.

Inside the magnetosphere, where the magnetic effects dominate the plasma's motion compared to thermal ones, both these waves have the same speed: the Alfvén speed $v_A = B/\sqrt{\mu_0 \rho}$ where B is the magnetic field strength, ρ is the plasma mass density and $\mu_0 = 1.2566 \times 10^{-6}$ m kg s^{-2} A^{-2} is the permeability of free space/magnetic constant. Therefore the wave speed (and thus the frequency of any resonances) depends on both the magnetic field and the plasma properties, both of which change with location and time throughout the magnetosphere.

Exercise: Near the dayside magnetopause, magnetic field strengths of ∼50 nT and proton densities of ∼1 cm^{-3} are typical. What is the wave speed under these conditions?

First don't forget to convert the units into SI i.e. $50\,\mathrm{nT} = 50 \times 10^{-9}\,\mathrm{T}$ and $1\,\mathrm{cm}^{-3} = 1 \times 10^6\,\mathrm{m}^{-3}$. Also don't forget to include the mass of the proton when calculating the mass density

$$
\begin{aligned}
v_A &= B/\sqrt{\mu_0 \rho} \\
&= 50 \times 10^{-9}/\sqrt{1.2566 \times 10^{-6} \times 1 \times 10^6 \times 1.67 \times 10^{-27}} \\
&= 1090\,\mathrm{km\,s^{-1}}
\end{aligned}
$$

Note we tend to use km rather than m for distance due to the generally large scales involved.

It is worth mentioning that the majority of the dynamic solar wind - magnetosphere interaction is invisible, bar phenomena such as the aurora, thus much of our understanding of magnetospheric processes come from **spacecraft/satellites** in orbit around the Earth which can directly measure the particles and fields. Despite having built up a global picture of ULF waves in Earth's magnetosphere, shown in Figure 2, there are still many aspects about these waves we do not know. For example, the variability in the frequency of different types of magnetospheric resonances (such as field line resonances and cavity modes) are not well understood since we often do not have enough spacecraft observations to properly characterise observed waves/oscillations. You will therefore be investigating various aspects of ULF waves in the magnetosphere through the use of spacecraft observations at geostationary orbit.

Exercise: Field lines near the dayside magnetopause are typically about $70\,R_E$ long, where $1\,R_E = 6378.1\,\mathrm{km}$ is the radius of the Earth. Using your Alfvén speed from earlier and assuming a constant wave speed over the entire field line, estimate the fundamental frequency of standing Alfvén waves on these field lines.

Fundamental wave will have wavelength

$$\lambda = 2 \times 70 \times 6378.1$$
$$= 893000\,\mathrm{km}$$

Using the relation between speed, wavelength and frequency we have

$$f = v_A/\lambda$$
$$= 1090/893000$$
$$= 0.0008\,\mathrm{Hz}$$
$$= 0.8\,\mathrm{mHz}$$

The assumption of a constant wave speed is, however, not really valid in the magnetosphere since of course the magnetic field strength gets much larger at the poles meaning much larger wave speeds, as shown below.
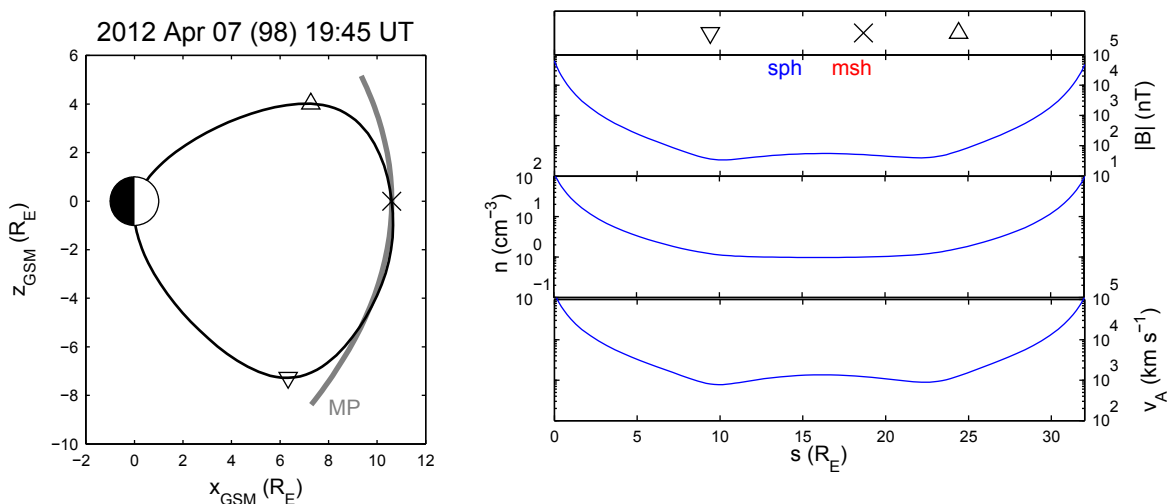
A way around this is to use the time-of-flight technique whereby the frequency of the wave is found by integrating the amount of time it takes a wave to travel infinitesimally small segments of the field-line i.e. the period of the standing wave is

$$\tau = 2 \int \frac{ds}{v_A}$$

Note, at geostationary orbit the fundamental frequencies of field-line resonances are often higher in the ∼3–10 mHz range.

Exercise: The distance between the dayside magnetopause and the plasmapause (the boundary of the cold plasma torus near Earth) is usually around $6\,R_E$. Assuming the magnetopause acts like an open boundary (anti-node) whereas the plasmapause is fixed (node), estimate the fundamental frequency of a cavity mode between these two boundaries again assuming constant wave speeds.

Fundamental wave will have wavelength

$$\lambda = 4 \times 6 \times 6378.1$$
$$= 153000 \, \text{km}$$

Using the relation between speed, wavelength and frequency again

$$f = v_A/\lambda$$
$$= 1090/153000$$
$$= 0.0071 \, \text{Hz}$$
$$= 7.1 \, \text{mHz}$$

This isn't actually too bad an estimation.

2 Data

The Geostationary Operational Environmental Satellites (GOES) are a series of spacecraft in geostationary orbit above North America. They are equipped with Space Environment Monitoring Subsystems (SEMS), which include a **magnetometer** for measuring changes to the magnetospheric magnetic field, useful for both research purposes and in monitoring/forecasting space weather.

A summary of the GOES spacecraft available is given in Table 1, listing their location in longitude as well as how to calculate their local time (LT). Local time essentially measures position relative to the Sun (think about why we have time zones for instance). Therefore, a local time of 12h/noon means the spacecraft is directly between the Sun and the Earth; whereas a local time of 00h/midnight means the spacecraft is behind the Earth compared to the Sun. See Figure 3 for an illustration. In geostationary orbit this is a very easy quantity to calculate as the spacecraft orbit at the same rate as the Earth's rotation, so there is a direct link between Universal Time (the standard time used in science, a modern continuation of Greenwich Mean Time) and the spacecraft's Local Time.
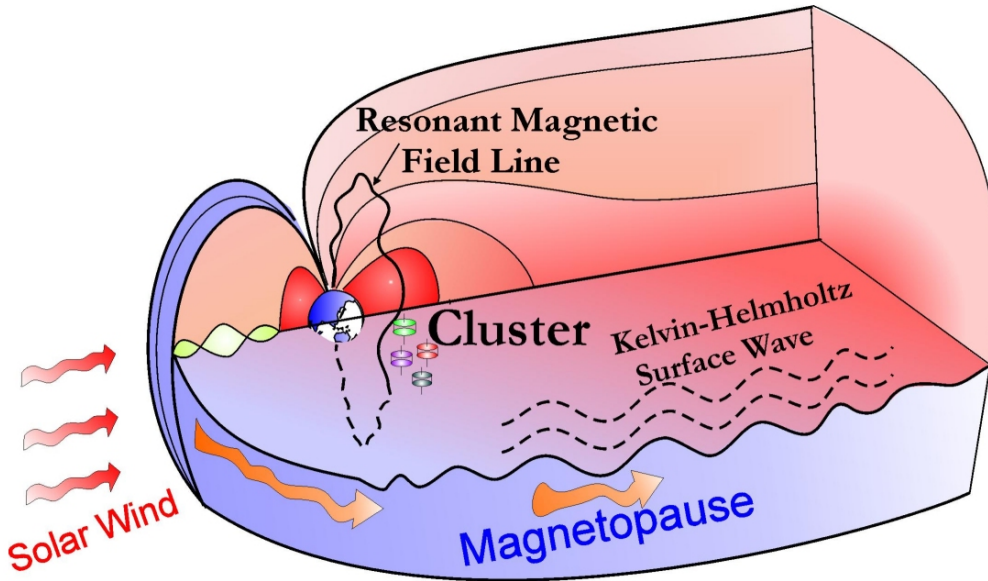
Figure 2: Illustration of some of the ULF wave modes supported by Earth's magnetosphere including waves directly driven by the solar wind (red), waves generated by the Kelvin-Helmholtz instability (dashed), resonant cavity modes (green), and field line resonances (black).

Spacecraft	G10	G11	G12
Geographic Longitude	60° W	135° W	75° W
$LT[h] = UT[h]+$	-4	-9	-5

Table 1: Summary of the three GOES spacecraft available during 2008. The full spacecraft locations with year are contained within the provided spreadsheet.

GOES magnetometer data can be used to research ULF waves in Earth's magnetosphere. In this project you will be undertaking such a study using the novel approach of actually listening to these waves. This is because, unlike many automated computer algorithms, the human auditory system is perhaps the best pattern recognition system that we know. In order to make the f_{real} =0.5-244 mHz waves audible to human ears though, the data has had to be rescaled in time

$$t_{audio} = t_{real}/(Fs \times dt) \tag{1}$$

and thus also frequency

$$f_{audio} = f_{real} \times Fs \times dt \tag{2}$$

where $Fs = 44,100$ Hz is the sampling frequency of the audio file and $dt = 2.048$ s is the time resolution of the magnetometer data used. This rescaling converts an entire year of magnetic field measurements into an audio file less than 6 min long.

Exercise: Calculate how long an entire day in is in the audio files.

$$\begin{aligned} t_{audio} &= t_{real}/(Fs \times dt) \\ &= (24 \times 60 \times 60)/(44100 \times 2.048) \\ &= 0.9566\,s \end{aligned}$$

Exercise: If the time in the audio are quoted in seconds to either one, two or three decimal places, what level of accuracy does this correspond to in real time?

$$t_{real} = t_{audio} \times Fs \times dt$$

$$= \begin{cases} 0.1 \times 44100 \times 2.048 & \text{One decimal place} \\ 0.01 \times 44100 \times 2.048 & \text{Two decimal places} \\ 0.001 \times 44100 \times 2.048 & \text{Three decimal places} \end{cases}$$

$$= \begin{cases} 9032\,s \text{ or } 2.5\,h & \text{One decimal place} \\ 903\,s \text{ or } 15\,min & \text{Two decimal places} \\ 90\,s \text{ or } 1.5\,min & \text{Three decimal places} \end{cases}$$

i.e. students should quote times as accurately as possible here. Clearly one decimal place is not nearly enough, though two may be sufficient depending on the circumstances e.g. long-lived waves.

Exercise: Calculate the date and local time of G11 in 2008 at 3m24.054 s into the audio.

First calculate the real time from the beginning of the year

$$\begin{aligned} t_{real} &= t_{audio} \times Fs \times dt \\ &= (3 \times 60 + 24.054) \times 44100 \times 2.048 \\ &= 18429504\,s \\ &= 213\,days\,7\,h\,18\,min \end{aligned}$$

Note we only quote the time to the nearest minute because, as shown earlier, the accuracy of our times from the audio are only good to a couple of minutes in real time. Using a day of year calendar e.g. http://disc.gsfc.nasa.gov/julian_calendar.shtml the date is 1 Aug 2008 (remember that 2008 is a leap year and the day of year starts at 1 and not 0). We now calculate the local time at GOES:

$$\begin{aligned} LT &= UT - 9\,h \\ &= 7\,h\,18\,min - 9\,h \\ &= 7.3 - 9 \\ &= -1.7\,h \\ &= 22\,h\,18\,min \end{aligned}$$

Note we must keep the local time within the range 0–24 h, just like with hours during the day. Since Local Time is a measure of spatial position relative to the Sun though, we don't have to worry about altering the date as one would when working out the date and time for a given time zone, compared to GMT (or equivalently UT).

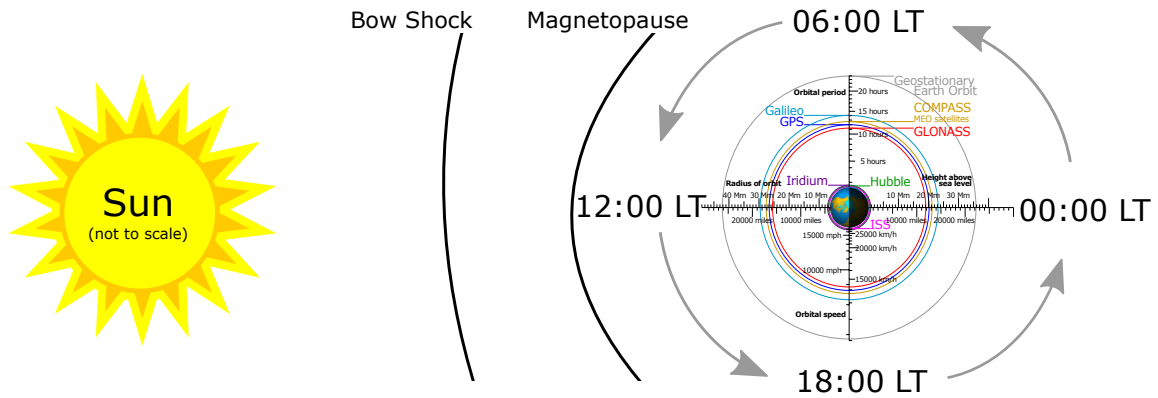The filename of your audio file is in the format:

Figure 3: Diagram looking down on Earth's North Pole, demonstrating local time (LT) as a measure of position relative to the Sun.

<p style="text-align:center"><code>g10_2008_Ball_10nT_diff.ogg</code></p>

- `g10`: which spacecraft the data is from

- `2008`: the year the data is from

- `B___`: magnetic field data in mean-field aligned co-ordinates where the following are used

    - `pol` = radial/poloidal component only
    - `tor` = azimuthal/toroidal component only
    - `com` = field-aligned/compressional component only
    - `all` = a combination of all three with `pol` in the left channel, `tor` in the right and `com` shared between both. This is good for initially listening to the data.

- `10nT`: the data has been divided by this amplitude factor

- `diff`: if present the data has been differenced in time to make spectograms clearer

3   Method

You will be using an audio editing package, **Audacity**, to listen to and analyse the magnetic field data provided. If this software is not installed on your computer, you can download a portable version at http://portableapps.com/apps/music_video/audacity_portable.

Audacity allows you to look at audio either as a waveform or as a spectrogram (a visual representation of the spectrum of frequencies in the audio as they vary with time). For the latter, you should (at least initially) use the log(f) spectrogram view since this is closer to how we interpret sounds ourselves and also allows you to clearly see the full spectral range of frequencies from low to high. You may need to change some of the Preferences (in the Edit menu of Audacity) to show the ULF waves more clearly e.g. Window Size=1024, Maximum Frequency=20000 Hz, Gain=0 dB, Range=60 dB.

Note that the differenced waves (i.e. those with "diff" in the filename) will show the clearest spectrograms, whereas the original ones (i.e. without "diff") will show the clearest waveforms.
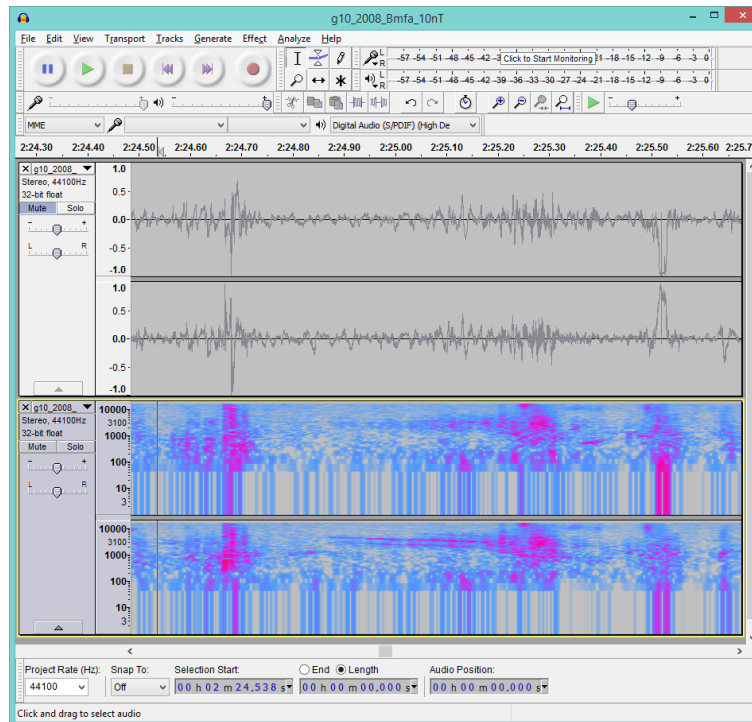
Figure 4: View in Audacity with the original waveforms shown in the top panels and the log(f) spectroview of the differenced waves in the bottom panels.

It may therefore be beneficial in your analysis to import both of these tracks into Audacity and mute one of them, as displayed in Figure 4.

In your analysis you may wish to use a number of Audacity's tools and effects, for example:

- Plot spectrum: Quantifies the amount of signal at each frequency for the selected audio, which can be used to find any clear peaks at specific frequencies.

- Noise Reduction: By providing a sample of noise or unwanted signals, these are reduced thereby making other signals more prominant.

- Spectral edit multitool: By making a selection in frequency and time in spectrogram view, you can filter out unwanted signals. This may be useful if multiple signals at different frequency ranges are present.

You should read the Audacity Manual (see section 5) for more details on all these tools/effects and others. Be careful not to overwrite your audio file with any changes you may make to it in the analysis process.

You may wish to add labels/markers for any events/sounds you find. This can be done by pressing Ctrl+M to add one at the playback position, i.e. when you're listening to the audio, or Ctrl+B to add a marker to the selected audio. Note that you can add text to your markers as a description.

4   Research

You will be conducting independent research into magnetospheric ULF waves and oscillations.

4.1   Initial Activities

As a first step you should simply listen to some of the sonified magnetic field data to get accustomed to what it sounds like and how to use Audacity. So pick a year and spacecraft and listen to one of the `Ball` files to start with. Below are some suggested things to try:

- Pick a distinct sound and characterise it.

  - How would you describe the sound?This is subjective, but it may help distinguish between the different types of waves that are present.

  - How loud is it? What is its amplitude (remember the original waveforms have been divided by an amplitude factor)?Amplitudes should be estimated using the non-diff files. Students may need to convert from decibels to the (dimensionless) waveform units before applying the 10nT amplitude factor.

$$\begin{aligned} A[\text{dB}] &= 10\log_{10} A \\ A &= 10^{A[\text{dB}]/10} \end{aligned}$$

  - Look at the spectrogram or plot a spectrum. Does it have a well defined frequency or set of frequencies/harmonics? Or does the sound occur over a wide range of frequencies?Remember that spectra or spectrograms should be done with the diff files. The reason for this is that, like many other physical systems, the background noise profiles approximately follows a 1/f spectrum meaning that there is more power at low frequencies than at high. Spectrograms with the normal files will therefore be red near the bottom and blue near the top irrespective of what sounds are present as shown in the top panels of the figure below. The diff file essentially flattens out this background by taking the time difference (or derivative in time) so features on top of the 1/f noise are more distinguishable, therefore serving itself better for spectra and spectrograms as demonstrated in the bottom panels below.

If a number of well defined frequencies are present, it is likely a standing wave of some sort within the magnetosphere and you can attempt to estimate the fundamental frequency. Often the fundamental frequency itself will not be excited/detected though by calculating the spacing between the detected harmonics or matching the ratios of these frequencies you can usually get an idea as to which harmonics they are.

– Does the frequency or amplitude change as part of the sound? The spectrogram is key to this first part. The frequency can change because of the changes to the wave speed (magnetic field strength and/or density) or the field-line length. These two factors can change either because the spacecraft is sampling a different region of the magnetosphere or that these quantities have actually changed e.g. in response to a change in the solar wind.
Similarly with the amplitude, this may be due to the wave amplitude actually increasing/decreasing due to driving/damping or because the spacecraft has moved into/out of the region where these waves are occurring.

– Is the wave predominantly poloidal (left channel), toroidal (right channel) or compressional (both channels)? This can inform what type of plasma wave it actually is. If it is solely poloidal or toroidal this points to Alfvén waves as these are the transverse components of the magnetic field. A compressional wave must be magnetosonic in nature.

- Try to identify at least three different types of wave events / sounds that are present?

  – How would you describe the sounds?

  – Look at the spectrogram or plot a spectrum. Can you relate how the waves sound to the different types of spectra? Broadband waves (waves with enhanced power across a wide continuous range of frequencies) should have more noisy or thud like sounds compared to waves of distinct frequencies which should have sounds a bit more like musical instruments.

  – Where do these waves occur in local time? e.g. are they around for example dawn (06:00), noon (12:00), dusk (18:00) or midnight (00:00)? This only really applies to sounds less than a day in duration, otherwise it's clear the wave is a global phenomenon and likely of solar wind origin.

  – How long until the next similar event occurs? You could build up a histogram of waiting times to see whether the events occur regularly (peaked distribution at a specific waiting time), at random (exponential distribution whereby you could use a fit to get the characteristic waiting time) or some other distribution.

- Is there an identifiable daily cycle in the ULF activity?

  – Where in local time do they occur?

  – How variable is this cycle from day to day? The frequencies and amplitudes should vary from day to day, the variability of these is a key research question at the moment.

4.2 Independent Research

In your research groups you should now decide what it is you'd like to research using the sonified magnetic field data. You should attempt to identify, analyse and catalogue ULF events which fit within your chosen topic. Here are few ideas or approaches you may wish to take in your research:

Approaches

- **Case studies:** You may wish to focus on just one event or a handful of similar ones. You should then perform thorough analysis on it to fully characterise the wave, looking for the same event at the different spacecraft and trying to identify any likely drivers of this ULF

wave activity. These types of studies are particularly important for rare events. Students may need additional data to look into drivers of their case study events, please get in touch if you need help finding this.

- **Statistical surveys:** Ideal for wave events that occur many times within the data, statistical studies can help us understand how often and where similar events occur and what range of properties they have. You should decide what aspects of the waves you'd like to investigate in this manner and attempt to build up a comprehensive picture of these aspects of the waves over the course of the year-long data file, or indeed across multiple years if you have time.

- **Surveying Specific Conditions:** You may wish to take a converse approach, rather than going through the ULF data to find events you could choose a specific set of solar wind or magnetospheric conditions or previously identified events and then investigate the magnetosphere's ULF activity for these. Students can look up published catalogues of events like Coronal Mass Ejections (CMEs), Corotating Interaction Regions (CIRs) etc. or specific solar wind conditions like southward solar wind magnetic field. There are also magnetospheric activity indices which denote geomagnetic storms which may be of interest. Get in touch if you need help finding this additional data.

Potential Topics

- What were the causes of certain wave events?

- When and where do specific types of wave events occur?

- How variable are the frequencies of certain types of wave events?

- When or how often do large amplitude ULF events occur?

- How effective are different solar wind structures or features at driving ULF waves?

You do not have to follow one of these approaches or topics, though do discuss thoroughly in your group and also with your teacher before getting started with your research. Be sure to collate all your results on ULF wave events into the **provided spreadsheet template**. Enter your data into the white boxes, these will automatically calculate the dates, times and local times for you to save effort. You will likely, however, need to add extra columns depending on your research topic so discuss what information it is you need. You may also wish to use Audacity's editing tools to save clips of specific types of events for cataloguing and/or presenting your findings.

5 Useful links

Audacity manual: http://manual.audacityteam.org/o/index.html
Dr Archer's PhD Thesis (suggest only the first few chapters): https://spiral.imperial.ac.uk:8443/handle/10044/1/24743
GOES magnetometers: http://www.swpc.noaa.gov/products/goes-magnetometer
Geomagnetic pulsations: https://wiki.oulu.fi/display/SpaceWiki/Geomagnetic+pulsations
Magnetic Pulsations (comprehensive): http://www.whoi.edu/science/AOPE/emworkshop/pdf/mcpherron.pdf
Magnetospheric ULF waves: http://www-ssc.igpp.ucla.edu/gem/IAGA_Div3/2011_Menk_ULF.pdf
Sonification of data: http://dx.doi.org/10.1063/PT.3.1550
Standing Alfvén waves at geostationary: http://onlinelibrary.wiley.com/doi/10.1029/2009JA015243/abstract