# Sound for the Exploration of Space Physics Data

PhD Thesis

**Wanda L. Diaz Merced**

**School of Computing Science**

**Supervisor: Dr. Stephen Brewster**

**Dr. Chris Johnson**

# Abstract

Current analysis techniques for space physics 2D numerical data are based on scrutinising the data with the eyes. Space physics data sets acquired from the natural lab of the interstellar medium may contain events that may be masked by noise making it difficult to identify. This thesis presents research on the use of sound as an adjunct to current data visualisation techniques to explore, analyse and augment signatures in space physics data. This research presents a new sonification technique to decompose a space physics data set into different components (frequency, oscillatory modes, etc…) of interest, and its use as an adjunct to data visualisation to explore and analyse space science data sets which are characterised by non-linearity (a system which does not satisfy the superposition principle, or whose output is not proportional to its input). Integrating aspects of multisensory perceptualization, human at tention mechanisms, the question addressed by this dissertation is:

> Does sound used as an adjunct to current data visualisation, augment the perception of signatures in space physics data masked by noise?

To answer this question, the following additional questions had to be answered:

a) Is sound used as an adjunct to visualisation effective in increasing sensitivity to signals occurring at attended, unattended, unexpected locations, extended in space, when the occurrence of the signal is in presence of a dynamically changing competing cognitive load (noise), that makes the signal visually ambiguous?

b) How can multimodal perceptualization (sound as an adjunct to visualisation) and attention control mechanisms, be combined to help allocate attention to identify visually ambiguous signals?

One aim of these questions is to investigate the effectiveness of the use of sound together with visual display to increase sensitivity to signal detection in presence of visual noise in the data as compared to visual display only. Radio, particle, wave and high energy data is explored using a sonification technique developed as part of this research.

The sonification technique developed as part of this research, its application and results are numerically validated and presented. This thesis presents the results of three experiments and results of a training experiment. In all the 4 experiments, the volunteers were using sound as an adjunct to data visualisation to identify changes in graphical visual and audio representations and these results are compared with those of using audio rendering only and visual rendering only. In the first experiment audio rendering did not result in significant benefits when used alone or with a visual display.

With the second and third experiments, the audio as an adjunct to visual rendering became significant when a fourth cue was added to the spectra. The fourth cue consisted of a red line sweeping across the visual display at the rate the sound was played, to synchronise the audio and visual present. The results prove that a third congruent multimodal stimulus in synchrony with the sound helps space scientists identify events masked by noise in 2D data. Results of training experiments are reported.

## Thesis Statement

Current analysis techniques for space physics 2D numerical data are based on scrutinising the data with the eyes. Space physics data sets acquired from the natural lab of the interstellar medium may contain events that may be masked by noise making them difficult to identify. This research explores the use of a novel perceptualization technique as an adjunct to existing, space physics visualisation techniques to improve the analysis/exploration of space physics data. The novel technique proposed was shown to be effective for the analysis of space physics data sets.

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# 1 Introduction

Human hearing may provide a good supplement to the visual way of receiving information for visual exploration and understanding of complex scientific data. This is especially true for scientific data, composed (in the case of space plasmas, space physics data, etc.), of a summation of different oscillation modes resulting in the final complex data set. This thesis focuses on the human ability to adapt to the data and interaction with sound in order to analyse data sets. This thesis explores the possibility of using sonification as an adjunct to data visualisation to explore large data sets to help in finding correlations and patterns for augmenting visually presented data, so that the graphical signatures (signals[1]) can be heard, and not just seen with the eyes.

The new generation of spacecraft has advanced experimental techniques for capturing plasma, particle, radio, magnetic field, and x ray data (to mention just a few) with improved accuracy and time resolution. The ever increasing development of computer power, both in speed and in storage space, has made it possible to perform numerical simulations with increasingly larger number of particles and more grid cells for a longer running time, and with higher phase space dimensions. Some limitations

[1] Signal in Space Science is the interesting part of the data. Signals are regularly surrounded by pervasive noise that has to be filtered to leave just the signal.

space scientists face for detailed analysis of space data are:

I. The absence of efficient techniques with adaptive basis to detail and analyse nonlinear and non-stationary data: The base of expansion for non-stationary and nonlinear data has to be adaptive. That means that the definition of the basis has to be data dependent, meaning *a posteriori* defined basis, which implies an approach very different from the regular mathematical data analysis which has the basis established at the beginning (Bendat, J. S. 1993). Using sonification as proposed in this exploration and human perception the basis may be *a posteriori*-defined.

II. A major problem limitation for the utility of visual displays is that the data typically contain much more information than can be effectively displayed using currently available technologies. For example, large data sets have a large amount of information spanning dozens of orders of magnitude in space and time. It is also important to consider the limitations imposed by nature on the human eye. In addition, even the best computer screens available are limited to a range of spatial resolution. This limitation affects the useful dynamic range of the display, reducing the amount of data scientists can study at any one time.

III. The human ability to interpret space-extended data is limited by the display and perceptualization of the data. Scientists currently work around this limitation by filtering (prioritising) the data, so as to display only the information they believe is important to the problem at hand. But since this involves making some assumptions about the result they are searching for, many discoveries may be missed.

IV. The high costs of data mining algorithms (Lupton Robert, 2011) (Solutions inc, 2012) has lead Astronomers to employ sophisticated data mining algorithms often at prohibitively high computational costs (GNUplot, 2012). The tools for visualisation and exploration are used to rapidly and intuitively inspect very large data sets to identify regions of interest within which to apply time-consuming algorithms. The data exploration tools are limited to the processing and displaying of 2D images or to the generation of meaningful 2D and 3D plots.

The space physics community is in need of new methods to facilitate a more dynamic and detailed inspection of large data sets. All efforts have been directed to the further development of high performance architectures (i.e. multicore CPUs, and powerful graphic boards), interoperability (different applications can operate simultaneously on shared data sets) and collaborative workflows permitting several users to work simultaneously, exchanging information and visualisation experiences. The approach of integrating multimodal perceptualization (sight and hearing) to data exploration is new for space physics data analysis.

Attention is a term used to describe a neurological network that acts to filter out distracting and irrelevant information bombarding the senses, and amplify content (Posner, 1994). Attention drives both the acquisition of automaticity and the expression of automaticity in “skilled performance” (Logan and Compton 1998), selected information directly influence the instances that drive performance. The information that is disregarded or unoticed does not. Moreover, if attention is not paid to the right cues, associations dependent on those cues will not be retrieved (Johnson & Proctor 2004, Logan & Etherton 1994).

Logan and Compton describe attention as an interface between memory and events in the world. Then according to these authors “knowing (or learning) what to attend to is a critical component for skill developmement”. Other authors have emphasised that learning not to attend to irrelevant information is also a component of skill acquisition, (Johnson A. 2003) (Weiner 2012).

Ordinarily, when something causes a load in the central visual field, say during the process of reading, sensitivity to distracting stimuli in the periphery is reduced (Schwartz, *et al.*, 2005). It is known from audiovisual experiments that a stimulus in one modality can change perception in the other (Sekuler R 1997); (Shimojo and Shams 2001); (Alais and Burr, 2004), (Witten and Knudsen 2005) (Ichikawa and Masakura 2006)

It has also been shown that the auditory cortex can be profoundly engaged in processing non-auditory signals, particularly when those signals are being attended to (Shinn-Cunningham 2008). Van Ee *et al.*, (2009) demonstrated that “ability to select, and attentively hold, one of the competing alternatives in either sensory modality is greatly enhanced when there is a matching cross-modal stimulus”.

They evidenced that a congruent sound aids attention control over visual ambiguity. They went further and tested that auditory or tactile information, and combined auditory–tactile information, enhances attention control over competing visual stimuli and *vice versa*. Moreover, the multimodal enhancement of attention selection seems to require a conscious act of attention, as passively experiencing the multisensory stimuli does not enhance control over the stimulus (Ericson, 2001) and (Van Ee, 2009).

(Frassinetti, Bolognini and Ladavas 2002),(McDonald, et al. 2002) (Mc Donald, Teder-Salejarvi and Hillyard 2000)and (Shimojo and Shams 2001), provide experimental evidence that involuntary orienting of attention to sound enhances early perceptual processing of visual stimuli. Mozolic,(Mozolic, et al. 2007), points out that stimuli occurring in multiple sensory modalities that are temporally synchronous can be integrated together to enhance perception. These ideas serve as a framework to explore if sonification as an adjunct to data visualisation may help astrophysicists identifying signal in their data analysis. Based on these results, this dissertation studies if the use of sonification as an adjunct to data visualisation enriches\enhances sensitivity to the detection of signal for improving the analysis of scientific (in this case space-physics) data. Of particular interest is the identification of events in visually ambiguous data, e.g. low signal-to-noise ratio.

The purpose of this dissertation is to provide experimental evidence that sound used as an adjunct to visualisation augments or improves sensitivity to the perception and identification of signals masked by noise in astronomy data. The framework of attention control mechanisms and sound used to disambiguate visual perception, presented in the introduction and the increasing need in the astronomy community to filter noise to leave signal and to scan the always-larger data sets leads to this research.

The question addressed by this dissertation is:

> Does sound used as an adjunct to data visualisation, augment sensitivity to the perception of signatures in data masked by noise?

To answer this question, the following additional questions had to be answered:

a) Is sound used as an adjunct to visualisation effective in increasing sensitivity to signals occurring at attended, unattended, or unexpected locations, extended in space, when the occurrence of the signal is in presence of a dynamically changing competing cognitive load (noise) that makes the signal visually ambiguous?

b) How can multimodal perceptualization (sound as an adjunct to visualisation) and attention control mechanisms, be combined to help allocate attention to identify visually ambiguous signal?

These two questions are answered through:

- Development of a user centred sonification prototype for the sonification and visualisation of space-physics data. This was refined by:
    - Focus group evaluation
    - Usability evaluation
- Carefully designed perception experiments measuring performance of different perceptualization techniques.
- Carefully designed training experiments testing the acquisition of the skill when using sound as an adjunct to visualisation.
- Use of perceptualization techniques using sound as an adjunct to visualisation to analyse space science data sets.

Given the literature review on skill acquisition, this dissertation hypothesizes over different aspects of training to acquire the skill of using multimodal perceptualization (visual and audio) to augment signatures in 2D data.

Following the introduction the reader will find:

- A review of data analysis methods used in space science and a review of sonification in space physics;
- A description of the xSonify sonification prototype created for this thesis along with its usability evaluation;
- An evaluation of different sonification prototypes available for space physics;
- Development of sonification prototype supported by focus group and usability evaluation.

- An analysis of different samples of space science data using sound as an adjunct to data visualisation;
- Perception experiments and training experiments forming the core work in the thesis;
- Conclusions discussing the work done and its place in the literature.

As a footnote, the use of sound may be especially valuable to open the field of science to an underserved (in terms of participation in science) community. This is because it could widen the human Computer interaction bandwidth and make this field of science fully accessible to visually impaired people and those more aurally oriented by developing an alternative way to analyse data, discover and make contributions to space science.

Even though this is not the aim of this dissertation, it is hoped that the completion of the sonification prototype and the research presented in this thesis may contribute to the opening up of space physics data to a new community of researchers and students now excluded from space physics research.

Mass media coverage of the work done supports the interest of space scientists to integrate sonification into their current data analysis techniques:

http://www.physicstoday.org/resource/1/phtoad/v65/i5/p20_s1?bypassSSO=1

http://www.nasa.gov/centers/goddard/about/people/Wanda_Diaz-Merced.html

http://www.studio360.org/2011/may/06/blind-astrophysicist/

The Sounds of Science PWJun11careers-merced.pdf (Physics World June 2011)

http://asc.harvard.edu/newsletters/news_19/index.html

Listening to X-ray Data

http://www.cfa.harvard.edu/sed/projects/star_songs/pages/xraytosound.html

(Star Sound)

## 1.1 Peer Reviewed Papers Published during the 3 years of the PhD

1. Wanda L. Diaz-Merced, Robert M. Candey, John C. Mannone, Fields David, Emilio Rodriguez. SONIFICATION FOR THE ANALYSIS OF PLASMA BUBBLES AT 21 MHz. Sun and Geosphere. vol.3, no.1, p.42-45

   See details in Chapter 7 pg. 117

2. Diaz-Merced, Wanda Liz, Schneps,M.; Brickhouse,N.; Pomplun,M.; Brewster,S.; Mannone,J. Exploring Sound to Convey Information. American Astronomical Society, AAS Meeting #218, #131.03; Bulletin of the American Astronomical Society, Vol. 43, 2011

   See Details in Chapter 7 pg. 91

3. Wanda L. Diaz-Merced, Robert M. Candey, Nancy Brickhouse, Matthew Schneps, John C. Mannone, Stephen Brewster, and Katrien Kolenberg. Sonification of Astronomical Data. New Horizons in Time-Domain Astronomy Proceedings IAU Symposium No. 285, 2011

   See Details in Chapter 7 pg. 106

4. Wanda L. Diaz-Merced. Can You Create the Sound of Astronomical Data?. The Classroom Astronomer. No.17, Fall 2013.

# 2 Literature Review

## 2.1 Introduction

This chapter provides background to the main topics covered in the thesis. It begins with a review of the use of sonification in space science, continues with an overview of the most common visualisation techniques currently used by space physicists and then discusses the types of data and analysis techniques used. It concludes with a review of sonification in general.

## 2.2 Review of Sonification Prototypes in Space Science

Since the first sonification prototype for space physics was launched, space scientists have made efforts to use the human ability to hear and see as a multimodal perceptualization tool to improve the exploration of data sets. Scientists at the Harvard Smithsonian Center for Astrophysics reported during the focus group done for this research, attempts to use sound as an adjunct to visualisation to identify if a signal[2] is real or not. Any sound, whether produced by a musical instrument or not, can be defined as a variation of air pressure travelling to the ear. The duration of each vibration period determines the pitch of the sound, whereas waveform characteristics determine its timbre.

[2] Signal is the interesting part of the data. Regularly signal is surrounded by pervasive noise that has to be filtered to remain with the signal.

The ear is able to process sounds in such a way that both pitch and timbre of each individual sound are identified. This may imply that the ear can discriminate these sounds in terms of their period duration as well as their waveform. Moreover, von Helmholtz states that the human ear is able to analyse a sound wave into its sinusoidal components.

Even though it has not been widely used due to the lack of a strong theoretical foundation, the use of sound to analyse space science data is not a new idea. For about forty years Dr. Donald Gurnet has used sonification of Space Data and produced the first documented attempts (Gurnett 2012) to use sonification to analyse/unravel/convey information contained in space physics data from different missions (e.g. Cassini, Voyager).

Other examples of documented sonifications of space physics data are:

- Cassini's Radio and Plasma Wave Science (RPWS) crossing the bow shock of Saturn (Gurnet, 2004).
- Playing data as sound for detecting micrometeoroids impacting Voyager 2 when traversing Saturn's rings (Scarf 1982);
- Using an early Beatnik/JavaScript-based tool, tested several sonification techniques on Hawkeye magnetic field and plasma measurements for magnetopause, bow shock and cusp crossings (R. M. Candey, Sonification 2009) (R. M. Candey, 98)
- xSonify, Java-based tool, presents time series data from text files and from all of CDAWeb's space physics holdings via web services. (R. M. Candey, Sonification, 2009).

The following section reviews the sonification prototypes created for the analysis of space physics data. Interest in sonification across the space physics community has been increasing since the first prototype for the sonification of space physics data was launched in September 2005 (Candey *et al*. 2005). The prototype was launched by the heliophysics division at NASA Goddard Space Flight Center (GSFC), with an interest of using sound parameters to perform more detailed exploration of plasma and particle data corresponding to the solar wind.

Between the months of December 2009 and March 2010 improvements were performed on the sonification prototype, given the usability evaluation performed at NASA GSFC and the Harvard-Smithsonian Centre for Astrophysics. The original prototype was authored by Anton Schertenleib, Robert Candey and Wanda Diaz and launched at the NASA Goddard Space Flight Center Space Physics Data Facility.

It was proposed by space scientists that sonification techniques might augment the detection of signatures in the search for extra-solar planets acquired by the Kepler Telescope. In 2009, Greg Laughlin, an astronomer at Santa Cruz, California developed a data reduction tool for this purposes (http://oklo.org) (Laughlin, 2012). The tool includes sonification (as well as other tools, such as periodograms, etc). With this tool when the orbits are Keplerian, it can be heard from the harmonics .

The tool includes links to a lot of exoplanet data that may be visualised and sonified. On February 2011, Batalha, from San Jose State University in California, and a key member of the Kepler Science Team, played sonified data during the Harvard Smithsonian Center for Astrophysics colloquium (Batalha 2011). Batalha played sonified data for Kepler 10b which is the smallest (1.4 Earth radius) exoplanet found so far. In order to establish the planet's properties, they had to perform asteroseismology on the star,, so in the sonified data it is possible to hear different frequencies that may indicate the presence of an exoplanet.

The tool does not allow the user to map over parameters such as timbre, volume, or pitch or allow the user to scroll the data as it is being sonified. The researchers working with Kepler exoplanet data proposed to use the sonification prototype, created as part of this thesis research, xSonify (R. M. Candey, xSonify, 2006), to treat each photometric point like a note with the brightness determining the pitch and duration for each note that is the probable length of a typical transit. This is really promising, as it will improve the time-efficiency when new interactions with sound will enable the researcher to explore the data. Dr. Alicia Sodeberg from the Harvard Smithsonian Center for Astrophysics is equally using sonification of Radio Supernova data for research and outreach purposes (Drout M.R 2013) (Sodeberg 2012).

Asquith (Asquith 2010) developed LHC Sound to sonify data from the Large Hadron Collider, http://lhcsound.hep.ucl.ac.uk/page_library/ SoundsLibrary.html, launched in 2010. It represents real and simulated data using musical instruments. Another example of sonification of data is the effort to detect Gravitational Waves. These waves and/or their sources, like black holes, may not be seen with the eye.

The Laser Interferometer Gravitational Wave Observatory (LIGO) team at Syracuse University expressed the need for tools to turn ultra-small events into something noticeable. For example, Janna Levin, assistant professor of physics and astronomy at

Barnard College, Columbia University, and her group has sonified predictions for the gravitational waves from black hole pairs, rendering the sounds of colliding black holes (Explorations 2011).

The University of California, at Berkeley, (UC Berkley), http://cse.ssl.berkeley.edu/stereo_solarwind/sounds_examples.html, has recently implemented a sonification tool to convey information on characterised parameters in solar wind data. UC Berkeley has developed a software program to sonify solar wind data from a three-dimensional colour plot of the data (Bithell and Morales, http://cse.ssl.berkeley.edu/stereo_solarwind/sounds_programs.html). David Bithell created this software with support and consulting of Laura Peticolas, Nahide Craig, Janet Luhmann, and Stuart Bale. In this program there are five different ways to sonify the data with the ability to change the fundamental frequency used in each. Currently, they have made available four plots of ion composition energy flux data for Helium (He), Carbon (C), Magnesium (Mg), and Iron (Fe) from NASA's Advance Composition Explorer (ACE) satellite. This tool is targeted for outreach and education.

For non-linear processes, the fundamental of the data waveform may change or, as in the case of turbulent plasmas (like in the solar wind), the fundamental may not be the lowest component of the waveform. Then, to establish *a priori* the fundamental of the data waveform impose filtering and linearization in the data. Robert Alexander, doctoral student and composer from University of Michigan, performed the sonified solar wind data for the department of engineering and atmospheric sciences at the University of Michigan  (Alexander 2010) (Alexander 2010). In this case, the researchers' primary goal was to try to hear information that their eyes might have missed in solar wind speed and particle density data gathered by NASA's Advanced Composition Explorer satellite (ACE).  The work was presented at the 2010 ICAD meeting in Washington DC.  The author used a high level of artistic license. The sonification did not lead the researchers to any new discoveries but they acknowledged the power of sonification for the analysis of solar plasmas.

The physics department at the University of Iowa has used sonfication to convey information contained in the data acquired by satellites (http://www-pw.physics.uiowa.edu/space-audio/). This group sonified the Cassini radio and plasma wave science experiment detecting Saturn's Bowshock crossing.

Dr.Kolenberg postdoctoral researcher of the Harvard-Smithsonian Center for Astrophysics (CFA) tried the sonification prototype developed at the University of Glasgow (xSonify) with asteroseismic data. Kolenberg aims to use sound to decide whether a signal is real or just noise when the visual data was confusing.  According to Kolenberg with databases of millions of stars or other objects, it may be a time saver to use sound in addition to visual data to classify objects.

### 2.2.1 Conclusions

The prototypes reviewed are often intuitively developed by space scientists with a need to explore data in a different way.  The prototypes are not user centred but focused on the data to be explored.  For instance the prototypes reviewed only work on data format from the experiment (satellite) it has been created for. The prototypes presented do not allow the space scientist to reduce the uncertainty imposed by system architecture. The latter refers to the need of real time scripting and intuitively handling the prototype functionalities. This raises the need for developing a user-centred sonification prototype that may be used by a wider audience inside the space physics community. Of course, this means that it needs to accept a wide diversity of data formats and allow the user to adjust the sonification parameters towards maximizing sensitivity to signal detection (to maximize human perception).

In Chapter 3 the reader will find the further user-centred iterative development of the xSonify space physics sonification prototype following the focus group and usability evaluation suggestions.

The sonification prototypes reviewed in this section, successfully map and aurally display the data. These sonification prototypes were built around the data set to be sonified and not around the needs of the target user. Undeniably these prototypes underline the need space scientists have for alternate ways to analyse their data by using multimodal perceptualization to augment signatures in the data and even to identify if a signal is real or not. This should be seen as an effort to complement the always-developing technology with human abilities.

## 2.3 Review of Data Visualisation Methods Used in Space Physics

In space science there is an increasing need to assign meaning to numerical data acquired from the natural laboratory of the interstellar medium, and develop new data analysis techniques and tools as new data acquisition techniques arise. The Introduction briefly listed the challenges space scientists face when performing data analysis and proposed the use of sound as an adjunct to current data analysis techniques to enrich and improve the perception of events in space science, physics and numerical data. In space science, any signature that has no meaning and is pervasive is classified as noise. According to Starck (2002) the major areas of image and signal processing applications in astronomy and space science are:

1. Visualisation
2. Filtering
3. De-convolution - a method used to correct instrumental effects of observing conditions
4. Compression
5. Mathematical morphology
6. Edge Detection
7. Segmentation and Pattern Recognition
8. Multidimensional Pattern Recognition
9. Hough and Radon transforms, leading to 3D tomography and other applications

One of the most important challenges in space science numerical data analysis is the need to perceptualise, identify and interpret space extended data - data sets spanning dozens of orders of magnitude, and weak unknown signals. This section discusses space science data exploration methods and acquaints the reader with the needs and challenges which space scientists face when performing data exploration.

In this era of petascale astronomy (Hassan, 2012), scientific data visualisation techniques have to enable features of the data to be identified that would otherwise have remained unnoticed. (Spence, 2001), (Hassan, 2012) and (Palomino, 2003) all agree that there is a very subtle distinction between scientific visualisation and the closely related field of information visualisation. In scientific visualisation the data source is scientific enquiry. Since its conception (Frenkel 1988)(McCormick, Defanti and Brown 1987)(DeFanti, Brown and McCormick 1989) scientific visualisation has been a process of turning numerical data into images which can be analysed or inspected; it is characterised by perceptualization, identification, interpretation and interaction with the data that determine the direction of the next stage.

This thesis acknowledges the difference between scientific visualisation from the important field of information visualisation, framing scientific visualisations as to illustrate scientific enquiry originated data, enabling scientists to better understand, and draw insight from their data. On the same token, it recognises the important field of information visualisation as a tool and technique for conveying abstract data in simple ways. This abstract data is not generated by scientific enquiry (Hassan A. H. 2013).

For the purposes of the research this thesis will only focus on scientific perceptualization of space science data. In space science, the interaction with the data occurs during processing; the interaction or processing is framed by the visual perceptualization of the data and determines the direction of the next stage. Consequently, this highlights challenges in effective data mining, data interaction, data perceptualization and data display. The interaction is limited by the numerical data analysis packages currently available and the resolution of currently available displays.

Efforts have been made to develop ways to interact and process large amounts of data without overwhelming the computer architecture. An example is the CYBERSKA (Scientific 2013)(Federl, et al. 2011) prototype which uses a distributed management system, DMS, architecture where data is distributed over several archive sites, each holding only a portion of the overall data which provides efficient access to the archive as a whole.

Space Science data exploration has been limited to visual perceptualisation. As mentioned in the review of space science sonification prototypes, the first sonification prototype for the exploration and analysis of space science data was launched in 2005 by Robert Candey, with the initial intent of providing blind users a capability to access this kind of numerical data and analyse it at the same knowledge level as their peers. Results of space science data analysed using Candey's prototype led to the finding of signatures that had been obscured visually from sighted peers leading to the notion that the sonification techniques may benefit the sighted aswell. The findings using sound were corroborated by peers and published, see Chapter 5.

As mentioned in the previous chapter, space scientists, approach the data with a problem at hand. A perceptualization and interaction occurs through mathematics and visualisation, for the explorer to search for the relevant portion of the data. This approach defines the processing and interaction with the data, which at the same time defines the data gathering, data transformation and display. This visualisation of data is mathematically defined. For this reason, many papers can be found which use different and mathematically defined techniques adopted by various astronomers for interacting, perceptualizing and analysing their data. This interaction is limited by the display and capabilities of the data reduction tools used by space physicist, e.g. IDL, OCTAVE, SCILAB, MATLAB, etc.

No more than 10 papers have been written in space science regarding space science visualisation, their author's are as follows: (Hassan, 2012), (Hassan 2011), (Palomino 2003), (Federl 2011), (Leech and Jenness 2005), (Dubinski 2008), (Kapferer and Riser 2008), (Li, Fu and Hanson 2008), and (Fluke, Barnes and Jones 2009). Candey, (2005) is the only publisher to publish a paper on the creation of a sonification prototype for the scientific exploration of space data using sound as an adjunct to the visual display for the space science community.

Space Science will always be data-driven, (Szalay 2012). Each data set in space physics has dozens of properties spanning dozens of orders in magnitude (McGuire 2013), (NASA 2013), (Earth-Science 2011) and (Astrophysics 2011). Some examples of these are position, velocity, mass, density, temperature and intensity. According to (Gardner 2012), in order to perceptualise and analyse data, space scientists write scripts to mathematically process and render 2 or 3 dimensional plots.

In Space science, data is collected; transformed or modified by using various numerical methods, which best facilitate the exploration of the data. These modifications are the result of interaction and perceptualization of the data during processing. Frequently, this is predetermined by a known problem at hand and the data is subsequently rendered on screen. This is confirmed by the existence of scientific visualisation models (Watson,1990 ). Watson evaluated scientific visualisation models and proposed a new one. Watson's model serves to differentiate scientific visualisation from information visualisation and involves the entire process of scientific investigation of graphical rendering, from directly mapping data to rendering an image and human interaction.

### 2.3.1 Most Common Scientific Visualisation Techniques Used By Space Physicists

Hassan and Flurke (Hassan A. H., *et al*., 2013), summarise scientific visualisation techniques used in Space Science as:

1. Time series
2. Points
3. Splats
4. Isosurfaces
5. Volume rendering

#### 2.3.1.1 Points

Plotting points on the screen as fixed width pixels is often the most straightforward representation; however, this approach is limited by the available resolution and pixel density of the display (Tall and Winkelmann 2012).

#### 2.3.1.2 Splats

Visualisation technique commonly used for volume rendering often rendered with a Gaussian intensity profile to replace point-like objects. (Westover 1990) .

#### 2.3.1.3 Isosurfaces

According to Hassan, as a visualisation tool an isosurface produces three-dimensional equivalent of contouring. Commonly astrophysicists use matching cubes (Hassan A. H., *et al*., 2013),(Lorensen and Cline 1987)(Montani, Scateni and Scopigno 1994),matching tetrahedra (Bloomenthal 1994) multi-resolution isosurface extraction (Gerstner and Pajarola, 2000), and surface wavefront propagation (Wood *et al.*, 2000) methods for calculating an isosurface from a dataset.

#### 2.3.1.4 Volume Rendering

According to Hassan (Hassan A. H., *et al*., 2013) in his paper on data visualisaiton and astrophsics (Hassan A. H., *et al*., 2013), volume rendering is used as mean to achieve a global view of the dataset. Taking into cosideration that this a purely visual technique authors like Hassan assert this technique may display visually indistintive surfaces (K¨ahler 2002). Neverthelss as a visual technique it is limited by screen resolution.

It is worthwhile noting that in this chapter, current data analysis techniques assume the data is either non-linear or non-stationary. Space physics data is both non-stationary and non-linear. An assumption of either linearisation or stationarisation buffers any signature contained within the noise which does not fit into the assumption, making it more difficult to perceptualise or identify the signal with the senses as the processing advances.

### 2.3.2 The origin of Space Science Data

The problem the astrophysicists has at hand, perceptualisation, interpretation and origin of the data has an impact on the choice of perceptualization and processing technique used. One way to look at space science data, (Hassan A. H., 2013), and (Hassan and Fluke 2011) (Brunner, et al. 2002)is to consider its origin or physical source, including:

- Imaging data - two-dimensional within a narrow wavelength range at a particular epoch (Hassan and Fluke 2011).
- Catalogues - secondary parameters determined from processing of image data, coordinates, fluxes and sizes (Hassan and Fluke 2011)
- Spectroscopic data and associated products - includes 1D and 3D spectral data cubes, data on distances obtained from redshifts and chemical composition of sources(Hassan and Fluke 2011)
- Studies in the time domain - including observations of moving objects, variable and transient sources which require multiple observations at different epochs, or synoptic surveys (Hassan and Fluke 2011).

- Numerical simulations from theory - these can include properties such as spatial position, velocity, mass, density, temperature, and particle type. These properties may also be presented with explicit time dependence through the use of "snapshot" outputs (Hassan and Fluke 2011)

For space scientists, data exploration and perceptualization originates mostly from the acquisition of measurements, and relies on the nature of the data and its mathematical processing allowing it to fit CPUs and screen resolutions. Measurements can be classified as either remote or *in situ* Remote measurements are of distant conditions that propagate to the sensor.

One example of this is photometric points measured by photometers whereas *in situ* measurements are generated from conditions directly encountered by the sensor, such as the field measured by an orbiting magnetometer (Nylund and Holland 1999). For any of those cases, the data received by the space scientist does not resemble the data acquired by the satellite.  Before the final rendering of *in situ* or remote data, the data goes through several numerical processing. Once it reaches the space scientists hands it goes through several further numerical processing and perceptualizations before the next stage of the data analysis takes place.  All of this is based on current data analysis techniques, for instance buffering any possible unexpected signals manifesting in the data which has not been identified visually during the early stages of data processing (see section 2.3.1).

For example an image in space science a display format must be chosen which is most appropriate for perceptualizing and interpreting the data features. According to

(Nylund and Holland 1999) (Hassan and Fluke 2011), commonly colour visualisation is the method used to address this two demands. It is the numerical processing techniques to process, delete detectors and sensor noise, such as the ones discussed below, and the always increasing size of data sets, which are of concern to space scientists when analysing data. The numerical processing techniques used today either buffer or delete signals which may convey important information about the interstellar medium.

Once the information is filtered, it will not be displayed, regardless of the visualisation technique used. An early perceptualization of any important signal living in the data will provide space scientists with a broader opportunity to find scientifically meaningful information in the data which may otherwise be missed.

In the appendix the reader will find a list of the platforms such as satellites, sensors instruments, data sets and types of data that space scientists use to create multimedia products and can be found in the NASA, JAXA, ESA, KASI, CONAE, ASI web pages. This list is also available at the Scientific Visualisation Studio web page at NASA Goddard Space Flight Center, (Huang, Shen and Long 1998)(Listing of all Satellites 2013)

Efforts are done to find numerical transformations that will not further buffer the signal in the data. One example is the Hilbert Huang transform. This transform relies on the empirical orthogonal function (defined later in this Chapter) and an adaptive base of expansion (Camp, Cannizzo and Numat 2012) (Huang, Shen and Long 1998).

Space agencies around the world are now putting more of their data online, making it available for public use. With all space agencies, once satellites acquire data, a process of filtering takes place before it is made available for further analysis. It is worthwhile pointing out that according to the usability and evaluation studies discussed in this dissertation, the participants expressed their need to explore the data as naively as possible, with gaps, zeroes, and no filtering.

### 2.3.3 Signal and Noise in Space Physics Data

According to the literature review for space physics data processing, space physics data is characterised by the presence of noise (Starck, 2007), (Nylund 1999) and (Hassan et, al., 2013). Frequently, the detector's noise is known and can be filtered from the signal, e.g. common noise distribution is determined by its variance.

Signal is what astronomers and space scientists term as the scientifically interesting part of the data; it is compressible by definition (Hanson Andrew J. Chi-Wing Fu 2000)(Zhefan Jin 2010), and (Starck 2007) (Starck and Murtagh 2002) (Starck and Murtagh 2001). It has to be differentiated from noise or clutter (Starck 2007) and by definition is not compressible. Noise is unwanted and is always present. For that reason noise is often estimated and then filtered from the data. However, the signal may be embedded within the noise and may be then filtered or buffered from the data. For this a reason a reliable estimation of noise is very important in astronomy and space physics.

Noise modelling algorithms have been developed for this reason and following are a list of some of the noise these models cover:

1. Gaussian Noise.
2. Poisson Noise.
3. Non-stationary additive Noise.
4. Multiplicative Noise.
5. Non-Stationary multiplicative noise.
6. Stationary Correlated Noise.
7. Undefined Stationary Noise.
8. Unknown Noise.

Space physics also faces the problem of traditional analysis method limitations. Traditional data analysis methods for the analysis of space-plasmas are based around linear or stationary assumptions. The latter assumes its probability distribution does not change when shifted in time or space. As a result, parameters such as the mean and variance, if they exist, do not change over time or position. For example, wavelet analysis and the Wagner-Ville distribution (Flandrin *et al.*, 2003), (Greochenig *et al.*, 2001) (Huang, Shen and Long 1998) (Huang, Shen and Long 1998) were designed for linear but non-stationary data. Additionally, various nonlinear time-series-analysis methods (Tong, 1990), (Kantz and Schreiber, 1997) and (Diks, 1999) are only applicable for nonlinear but stationary and deterministic systems (Huang, Shen and Long 1998). The space scientist then approaches the data knowing the traditional data analysis technique to use to display the expected signal. This detaches space science from being a science exploring for the unknown to become a science searching for the expected.

Some data reduction transforms such as Karhunen-Loeve's, often referred to as eigenvector, Hotteling transform or Principal Component Analysis, (PCA) (Starck and Murtagh 2006) (Karhunen, 1947), (Levy, 1948) and (Hotteling, 1933) . It is analogous to FFT and represents a function on a bounded interval and is a representation of stochastic processes as an infinite linear combination of orthogonal functions.

In space science the data is both: nonlinear and non-stationary. It is then important to distinguish noise or clutter from signal early during the data processing and perceptualization as it may help to prevent shadowing of any important signal in the data which may be masked by noise.

For nonlinear and non-stationary systems, the probability distribution may change locally and when shifted in time and space, other assumptions applied buffer and obscure important signal embedded in the data. The processing and perceptualization occurs at every step and leads the next stage in the data processing. The use of multimodal perceptualization through attention control mechanisms, to approach space science data may augment any signature embedded in the data and may ease the identification of clutter or noise from the signal.

### 2.3.4 Review of non-stationary data processing methods

The following sub-section lists some non-stationary data processing methods. It is worth noting that even though these processing methods are non-stationary, each is based on linear assumptions causing piecewise linearisation, leakage, and buffering of signal which may be of importance. The techniques are:

1. Spectrogram.
2. Wavelet analysis.
3. Wigner–Ville distribution.
4. Evolutionary spectrum.
5. Empirical orthogonal function.

#### 2.3.4.1 Spectrogram

The spectrogram is a time window-width Fourier spectral analysis technique. It is used to get a time–frequency distribution. It completely depends on the traditional Fourier spectral analysis; the data then is assumed to be piecewise stationary.

#### 2.3.4.2 Wavelet Analysis

The wavelet analysis approach is a time-frequency transform, like the Fourier spectral analysis. A wavelet is a kind of mathematical function used to divide a given function into different frequency components and study each component with a resolution which matches its scale. A wavelet transform is the representation of a function by wavelets. The wavelets are scaled and translated copies, known as "daughter wavelets". These are of a finite-length or fast-decaying oscillating waveform referred to as the "mother wavelet”.

It is used for representing functions which have discontinuities and have sharp peaks. The latter constitutes one advantage of wavelets over Fourier. Fourier transforms decompose the signal into sine and cosine waves; the wavelet transform uses functions that are localised in both real and Fourier space. According to Huang (Huang, Shen and Long 1998) “the resolution of the wavelet is compromised by the uniform distribution of all the scales which generates leakage distorting the frequency time distribution".

#### 2.3.4.3 Wigner–Ville Distribution

According to Huang (Huang, Shen and Long 1998), the Wigner–Ville distribution is another time-frequency analysis. This is a spectrogram with better time-frequency resolution. The problem with this method is the existence of severe cross terms as indicated by the existence of a negative power for some frequency ranges. Although this can be eliminated by using the Kernel method (Cohen 1995), the result is basically a windowed Fourier analysis. It therefore suffers all the limitations of a Fourier analysis.

#### 2.3.4.4 Evolutionary Spectrum

With sharp presicion Huang again asserts (Huang, Shen and Long 1998): "The basic idea is to extend the classic Fourier spectral analysis to a more generalised basis; from sine or cosine to a family of orthogonal functions. The basic idea is to extend the classic Fourier spectral analysis to a more generalised basis; from sine or cosine to a family of orthogonal functions $\{\varphi(\omega, t)\}$ indexed by time, t, and defined for all real ω, the frequency. Evolutionary spectral analysis is very popular in the earthquake community (see, for example, (Liu 1970), (Liu 1971), (Liu 1973) and (Lin & Cai 1995)".

There is not systematic method to define the basis of expantion $\{\varphi (\omega, t)\}$. Then in principle the basis of expansion has to be defined a posteriory and constructing an evolutionary spectrum from the given data is very difficult, if not impossible. The application of this method have changed the approach from data analysis to data simulation.

#### 2.3.4.5 Empirical Orthogonal Function

The empirical orthogonal function expansion (EOF) is also known as the principal component analysis, or singular value decomposition method (Huang, Shen and Long 1998). For any real $z(x, t)$, the EOF will reduce it to $z(x, t) = \sum_{1}^{n} a_k(t) f_k(x)$. Within this is the orthonormal basis, $\{f_k\}$, the collection of the empirical Eigen functions defined by $C \cdot f_k = \lambda_k f_k$ where C is the sum of the inner products of the variable (Huang, Shen and Long 1998). For this method the expansion basis is derived from the data (*a posteriori*) wich makes it more efficient than the methods discussed previously.

The EOF, only gives a distribution of the variance in the modes defined by $\{f_k\}$, but this distribution by itself does not suggest scales or frequency content of the signal (Huang, Shen and Long 1998). A single component out of a non-unique decomposition, even if the basis is orthogonal, does not usually contain physical meaning (Huang, Shen and Long 1998). Other authors has proposed the Fourier transform of the EOF (Vautard & Ghil 1989). For this to work, it is important to be sure that each EOF component is piece wise stationary.

Other than the above methods, there are also useful but very specialized methods such as least square estimation of the trend, smoothing by moving averaging, and differencing to generate stationary data. The reader may find information on those in any signal processing book.

### 2.3.5 Conclusions

In this section, the data processing and visualisation methods used by space scientists were presented in preparation to plot data so as to facilitate the data exploration directed to scientific enquiry. This section also outlined the fact that the interesting part of the data may be masked by noise and filtering or numerical processing techniques may delete it further. This means space scientists need new techniques such as sonification and multimodal perceptualisation, to search for the signatures embedded within the noise.

All of the above mentioned areas of application of image and signal processing in astronomy and space physics are validated visually. Because these data sets are so huge and signal may be anywhere within them, the high costs of data mining algorithms (Lupton Robert, 2011) and (Solutions inc, 2012) have lead Astronomers to employ sophisticated data mining algorithms often at prohibitively high computational costs (GNUplot, 2012).

The tools for visualisation and exploration are used to rapidly and intuitively inspect very large data sets to identify regions of interest within which to apply time-consuming algorithms. The data exploration tools are limited to the processing and displaying of 2D images or for the generation of meaningful 2D and 3D plots. The space physics community needs new methods for facilitating more dynamic inspections of large data sets. All efforts have been directed to the further development of high performance architectures such as multi-core CPUs, powerful graphic cards and interoperability.

Interoperability allows different applications to operate simultaneously on a shared data set. This generates collaborative workflows permitting several users to work simultaneously on the same data set, exchanging information and visualisation experiences. Combining attention control mechanisms integrating multimodal perceptualisation to data exploration is a novel approach not attempted before in space physics data analysis and may become a tool allowing scientists to visualise changes and trends obscured to the eye avoiding the high computational costs.

## 2.4 Sonification

This section presents a review of sonification techniques applied to the analysis of space physics/physics data and numerical data as found in the International Community on Auditory Display, ICAD. If the reader wants to read basic information on the theory of sonification, psychoacoustics, auralization, direct mapping sonification, model based sonification etc, please refer to the Sonification Handbook published by the International Community of Auditory Display in 2011 (ICAD).

Sonification is a form of information display. A literature review on sonification techniques for 2D data-analysis and/or mapping shows that they are all based on linear and/or stationary assumptions. Moreover the majority of the papers written over the two decades of existence of the ICAD have been focused on the technicalities of sonification and not very much on the use of sonification perception applied to tasks that are relevant and practical to the user. In case of this thesis it is to mimic an exploration task similar to tasks performed by scientists, as it is to use sonification to improve perception in work related tasks in astrophysics. A somewhat similar approach has been taken for sonification as used in medical science for the identification of diseased tissue in magnetic resonance imaging (MRI) images (Martins 1996). Another relevant experiment is concerned with the use of sonification towards the identification of malignancy (Mauney 2004) (Nattkemper 2003) (Edwards, et al. 2010) and a paper on neuroscience sonification of neural data (Chang, Wang and jonathan 2010) .

Pauletto (Pauletto and Hunt 2006) researched the use of sonification for the exploration and analysis of EMG data gathered real time. According to Pauletto and Hunt, EMG data analysis is time consuming. Pauletto used sonification to convey known[3] parameters in the data that are of interest to clinical practioners. One aim of this research is to study if it is possible to meaningfully map EMG data to sound parameters in order to create an informative sound display of the data (Pauletto and Hunt 2006) . The authors studied known parameters in the data and test to see if these can be detected in a sound-only display. Even though the participants found the sonification fatiguing to listen to, they considered it appropiate to represent EMG data, when searching (mining) for known characteristics of EMG data.

A paper on sonification of numerical fluid dynamics simulation (E. Childs 2001) documents the creation of a prototype TEACH-L to link the numerical output of the

[3] Meaning the scientist knew what s/he is looking for or expecting to find.

Computational Fluid Dynamic Flow to sound. The reader must take into account that simulated data does not contain unpredictability (non-linearisation) and the noise pervasiveness that characterise space physics data which is the interest of this dissertation. In space science, simulated data serves to provide the probability of finding signal in the data. Sturm (2000), used quantum physics and Newtonian models combined with musical composition to convey parameters in quantum physics de Broglie simulated data. The simulation presented in Sturm paper is not an accurate model of particle systems.

In another paper Sturm (Sturm 2002) documented the sonification of spectral ocean data. Sturm's work, which greatly inspired this thesis research, originated from artistic curiosity. His work used spectral information of buoy measurements over time, which conveys information on the energy content of a measurement, variations over time, and the distance it originated. Other works on non-simulated data were performed previously on the sonification of Ocean waves (Berger, Ben-Tal and Daniels 2009) , (Dombois 2001) and seismic data (Saue and Fjeld 1997) but Sturm was the first one presenting the sonification of spectral data.

A study compared the effectiveness of two auditory display designs for conveying the relationship between discrete and continuous data (McCormick and Flowers 2007). The latter is a major concern for space scientists as it has a direct impact on data transformations. Using simulated data, participants judged the relationship between simulated data representing "sea temperature," (a continuous variable) and "storm occurrence" (a categorical variable) by rating the strength of covariation between these variables and qualitatively describing the relationship for one of two types of auditory displays. To do this, subjects utilised one of two auditory data display formats and made judgments of the relationships displayed. The first method (Guitar) integrated the discrete and continuous data more than the second method (Woodblock). For both display formats, perceived strength of the relationship was positively correlated with the actual strength of the relationship. These correlations were stronger in the integrated condition than in the separate stream condition. The correlations remained positive but were weaker when the stimuli with the strongest relationships were removed. In this regard, the two conditions produced statistically equivalent results. Many subjects demonstrated difficulty in perceiving the correct relationship when the relationship was weak.

Nees and Walker (Nees and Walker 2008) report experiments in which participants were only exposed to auditory graphs of a stock price over the course of a 10 hour period. A second study examined the effects of the same manipulations on a local trend identification task, in which participants were asked to identify whether the data was increasing, decreasing, or staying the same over a given 1 hour period. in the trading day, then being asked to estimate the price of the stock at a randomly selected hour of the trading day. Nees and Walker documented the strategies participants used to obtain the desired information from the auditory graphs. With a participation of around 130 volunteers from the psychology department, the experiment had good statistical power. Regardless, Nees and Walker acknowledge limitations in the study. Their coding scheme was simply designed to detect the presence or absence of a particular strategy, a participant's failure to mention using a strategy does not mean that the participant did not use that particular strategy. Nees and Walker also report that participants may have been biased as a result of training and instruction taking place before the studies.

Many more experiments are documented at ICAD on attempts to use sound for auditory graph design and the draw of information from auditory graphs (Stockman, Nickerson and Hind 2005), (Walker and Nees 2005), (Nees and Walker 2006), (Mansur, Blatner and Joy 1985), (Flowers and Hauer, The ear's versus the eye's potential to assess characteristics of numeric data: Are we too visuocentric? 1992), (Flowers, Buhman and Turnage 1997), (Brown and Brewster 2003), (E. Childs 2005), (Peres and Lane 2005) and (Flowers 2005).

Training using sonification has been researched on the basis of finding preconceived patterns and trends and has not focused on developing a training paradigm that would allow users to use sound (as a stand-alone cue or multimodally) to augment perception or to use it as an adjunct to data visualisation to improve the identification of events, specially events masked by noise.

Devallez studied the effect of speech auditory cues on visual perceived order and depth (Devallez, Rocchesso and Fontana 2007). The stimulus consisted on two overlapping squares, one blue and one red, in the middle of a white background. Each visual stimulus was paired with a speech auditory stimulus of the words “red” and “blue”. People had to identify which square appeared in front of the other. Devallez reported no visual-audio interaction effect on the perception of visual depth.

On the same token, Ecker and Heler (Ecker and Heller 2005) performed an experiment in which the stimulus was an ambiguous visual signal consisting of a rolling ball that could either roll back in depth on the floor of a box, or jump in the frontal plane. Moreover, other ball's paths of different types and curvature in between were also presented to the subjects. The moving ball was either shown alone, accompanied with the sound of a ball rolling, or the sound of a ball hitting the ground. Ecker and Heler found that sound influenced the perception of the ball's trajectory, depending on the type of sound. Results of Devallez experiment do not conflict with previous investigations as Devallez used speech sound and static stimuli. Ecker and Heler used dynamic visual and audio cues (ball rolling). The dynamic information from both senses may reinforce the auditory-visual unity (Devallez, Rocchesso and Fontana 2007).

Another paper on audio-visual interaction examined the ability of human subjects to localise visual, auditory and combined visual-auditory targets under conditions of normal and degraded vision (Hairston, et al. 2003). These authors report that localisation presicion under conditions of normal vision, was equivalent for visual and combined visual-auditory targets, and was significantly worse for auditory targets. In contrast, under conditions of induced myopia, the auditory performance was not affected while the visual localisation performance was degraded by an average of 25%. However, during induced myopia, multisensory (i.e. visual-auditory) localisation performance was significantly improved as compared to visual performance. These autors evidenced a "multisensory-mediated enhancement in human localisation ability, and illustrate the cross-modal benefits that can be obtained when spatial information in one sense is compromised or ambiguous" (Hairston, et al. 2003). Visual ambiguity imposes a cognitive load on the performer that inhibit mechanisms of attention wich at the same time affects their performance when identifying events in the visual field.

As mentioned earlier the research on the use of sound alone or as an adjunct to visualisation is an active area of research that has been mostly limited to technical details on how to convey known parameters contained in 2D and 3D graphs. The research by Flowers and his colleagues has shown through a series of studies that auditory and visual displays of time series data, (Flowers and Hauer 1995), distribution of single samples(Flowers and Hauer, The ear's versus the eye's potential to assess characteristics of numeric data: Are we too visuocentric? 1992), (Flowers and Hauer, Sound alternatives to visual graphics for exploratory data analysis 1993), periodic numerical data (Turnage, et al. 1996) and bivariate scatterplots (Flowers, Buhman and Turnage 1997) show almost no difference in terms of subjects' abilities to identity and understand the data distributions.

Walker and his associates tested individual differences in the ability to comprehend auditory graphs (Walker and Mauney 2002) and the effects on performance of sonified labels, axes, and tick marks on the interpretation of auditory graphs (Smith and Walker 2002). Researchers such as (Scaletti and Craig 1990), (Brown and Brewster 2003), (Walker, Kramer and Lane 2000) (Walker and Nees 2005), (Peres and Lane 2003) also tested the effect on human performance of the use of sound to explore auditory graphs. In addition, researchers have also investigated the psychoacoustic parameters that affect the construction and the subsequent perception of auditory graphs (Neuhoff, Kramer and Wayand 2000), (Walker, Kramer and Lane 2000). The importance of dynamic human interaction when exploring datasets with sound (Hunt and Hermann 2004) is an emerging area of research. During the protracted literature review done to complete this thesis, no evidence was found on the use of combined attention mechanisms, towards the augmentation of human perception to explore, understand, and interpret 2D and 3D numerical graphs.

Herman, Meinkle and Ritter published a paper describing a new approach to render sonifications for high dimensional data called principal curve sonification (Hermann, Meinickle and Ritter 2000) The authors aim is to use sonification to provide the user a mean to perceive the "main" structure of the data distribution. This technique may be of use for a more statistical-general approach to numerical data than to space physics data where the space physicists is trying to find any signal that may be embedded in the data. The technique proposed by these authors allows for dimensionality reduction while maintaining the main structure of the data. In sum this technique may be appropriate to observe how the data evolutions over time in terms of curvatures.

Hermann and Ritter (2005), equally suggest the use of a sonification technique named Model Base Sonification. This innovative use of sonification rests on the fact that sound evolves in time. Then as it evolves in time, a mathematical function may describe the evolution of the sound produced by the sonification of a data set. The understanding of the evolution of the sound over time may be associated with physical parameters of the data itself. The author of this sonification model, points out that sonification and visualisation place a cognitive load on the user. One of the applications of the Model Based Sonification, (MBS), is a model created by Herman (2008) called the Crystallization Model. The Crystallization Model is based on a Euclidian Vector spatial model. The model space is a Euclidian vector space of pre-defined elements, for crystal growth in which start the crystallization in a Euclidian space. It defines each data point as a point on a Euclidian Vector.

The reader should note, Euclidian space vectors assume linear transformations, which preserve linear relationships between variables. That relationship changes for systems like astrophysical plasmas where non-linearity (meaning that linear relationships between vectors changes and for instance change the correlation between them). In fact, this model based sonification seems promising for system that do not change suddenly, as it predicts the trajectories of particles given a number of conditions.

A new sonification technique presented at the ICAD 2009, is called “Entropy Sonification” (Ramakrishnan and Greenwood 2009). According to the authors, it is a way of guiding the listener to the significant information in the data set using rhythmic variation and accentuation, a standard tool from music composition and therefore very likely to be familiar to many listeners. So even if the listener does not necessarily know what the sound is telling him or her about the data, s/he at least knows what to pay attention to (Ramakrishnan and Greenwood 2009).The entropy sonification technique has been presented on the basis of which techniques to use in order to bring data to the foreground of a sonification and push uninteresting data to the background. In other terms, it will lead to the interaction/perception of the sound stimuli by the listener.

The research on which this dissertation is based, uses sonification techniques to analyse Gamma Ray Data, Magnetic Fluctuation Data, Radio Data, xRay data and to pursue experiments in perception in order to focus on the perception, interpretation understanding and intelligibility of signals contained in the data with the ultimate aim of assisting the researcher in performing a more detailed analysis of space physics data.

The sonification community, especially in the papers on sonification of numerical data presented in the ICAD conference series, has mostly been focused on the technicalities of sonification and only a few studies focus on the perception of the sounds (at least for sonification of numerical data) simulating tasks. The exploration of multimodal interaction (sound as an adjunct to visualisation), and research on how to use multimodal interaction and to allocate attention to better perceptualize data, seems neglected in the auditory display community.

In 2011 a paper appeared in ICAD in which the authors focused on the technicalities of sonifying the Cosmic Microwave Background (CMB). The paper covers in length some very basic aspects of the CMB, which is understandable given the fact that the ICAD community is comprised of a small group of members who are mainly non space physicists. In the paper the authors focused on sonification rendering, it does not report a usability evaluation.

This dissertation focuses on the need to develop perception integration tools (multi-modal perceptualization) using sound as an adjunct to visualisation to aid the target audience (space physicists) to find fleeting, non-persistent, masked events in 1 and 2 dimensional data that may lead them to further discoveries. The reader may note that the nature of space physics plasmas is its non-linearity, noise pervasiveness, unpredictability for example when dealing with turbulence in space physics plasmas the fundamental may not be the lowest component. Imposing waveforms on the data will buffer information of importance.

As an application of sonification, a simulation of the early universe was developed in Ohio, to convey a phase transition that occurred shortly after the Big Bang (Winters et.al 2011). They sonified the Electroweak Baryogenesis bubble nucleation using Supercolider. The authors of this paper relied on human perception for their integration of science and aesthetics, which lead them to the unexpected benefit of being useful in debugging the code used for the simulation.

Nick Bearman added sonification to the statistics R analysis environment, using Csound, http://playitbyr.org/. This was presented at the 2012 ICAD conference. This sonification effort is inspired by Sonification efforts done at Bell Labs in 1975. It is applied to statistics and at least explicitly does not mention human perception.

### 2.4.1 Existing Sonification Techniques to Analyze Numerical Data

#### 2.4.1.1 Parameter Mapping Sonification

Parameter mapping Sonification (PMSon), (Florian Grond, 2012) is a sonification rendering technique in order to associate information with auditory parameters for the purpose of data display. According to the authors of the Parameter Sonification chapter in the Sonification Handbook, predetermined intermediary associations can be established between one or more attributes of the information under scrutiny and its resulting auditory display. Some of its characteristics are:

According to the same authors the associations mentioned in the previous paragraph and may be scaled to adapt to perceptual features of human hearing. It directly uses the human interpretative mapping decision process allowing for a wide range of different sonification displays. According to the authors this offers precision of the display but relies on issues that are emotive, intuitive and aesthetic.

Features of the Data: While working with numerical data. The researcher needs to know the features of the data (continuous, discrete, dimensions, channels, topological structure, etc). Basically the data display depends on this analysis.

Data Preparation: The features of the data are met by the structure of the of the sound synthesis parameters. This step consists of the following parts and may be influenced by perception:

I. Calculating derivatives as complementary information to map.
II. Extracting events from the data.
III. Connecting Data to Sound: Map data features to Sound Synthesis parameters to understand parameters in the data.

The authors assert that an acoustic event is defined as a signal generation function that shapes amplitude and spectral envelopes. (Florian Grond, 2012).

Direct Parameter sonification is a technique smartly relying on human perception. Its flaw is that it relies on using current data analysis techniques to extract events from the data before the data is mapped to sound. This technique is not intended for exploration of the data, it is intended to understand parameters in the data through acoustic associations.

### 2.4.1.2 Model-Based Sonification

This technique developed by Thomas Hermann (Hermann, 2011) uses a mathematical model to describe the temporal evolution of a system. The information contained here is available at Model Based Sonification chapter in the Sonification Handbook. According to the authoirs the acoustic response depends on the temporal evolution of the model. The acoustic response is generated by actions defined by the model and its associated with the model dynamics. In other words as the model evolves in time, the parameters of the data change in time. The listening mode changes from musical listening to signification listening as listeners assign meaning to the acoustic output. For example, the beat of a drum, the deeper the beat, the more energy is added to a system. It allows for exploration of evolution of a system in time given a user defined mathematical function. The Model Based Sonification framework is defined by the following six components (Hermann, 2011):

Model Setup: Bridges static data to systems (acoustic model) that vary in time. The acoustic model makes the sound. (Hermann, 2011)

Model Dynamics: The equation of motion for the model describes how the data changes in time. To create the model dynamics you need the equation that describes the system. (Hermann, 2011)

Model Excitation: in this step, Term excitation is used as an interaction term of user and model. The listener performs a physical action, and receives an acoustic reaction that may be associated with data parameters. For example, one physical action, say squeezing a bottle, may be performed in many different ways leading to different characterisations of the data. (Hermann, 2011)

Initial State: Defines data first stage and/or position before interaction. Model Link Variables: Link the equations in the dynamic model to the sound signal. (Hermann, 2011)

As mentioned in section 2.2, imposing a wave form to space physics data potentially will buffer any unexpected signal living in data. The basis of expansion for space physics data has to be adaptive. Model Based sonificaiton only allows for exploration of evolution of a system in time given a user defined mathematical function. The model based sonification as proposed by Herman may serve for explorations if the scientist knows the changes being looked for. For non linear and non stationary systems the probability distribution may change locally and when shifted in time and space. To impose a data wave form (as in Model Base Sonification) will assume that probability distribution does not change when shifted in time or space. As a result parameters such as the mean and variance, if they exist, do not change over time or position.

In 2007 de Campo, (de Campo 2007) proposed a variation of the sonification techniques above: Sonification by Continuous Data Representation, by Discrete Point Data Representation, and by Model-Based Data Representation.

Based on these categories, de Campo proposes a sonification design map based on movement on the design space to allow the user to find signatures in the data that were not known beforehand as perceptual entities in the sound. The design map enables the researcher to engage in systematic reasoning about applying different sonification strategies to his/her task or problem based on dimensionality and perceptual concepts.

These strategies include sonification techniques like model based sonification, parameter mapping sonification and audification. His approach defines overlapping areas of these three sonification strategies. De Campo asserts that “reasoning about data aspects and making well informed initial choices based on perceptual givens can help to develop a clearer formulation of useful tasks”. This last assertion has applications in space physics as the signal of interest may be anywhere in the data and the choices for the sonification design are based on perceptual approaches. De Campo performed experiments in which three teams used the design map space to explore data. The teams chose how to create the sonification and the paper only mentions how one of the teams decided what initial sonification approach to use (“Team B chose to do audification following one sonification expert’s request” (de Campo 2007)). The paper does not report the results of the data exploration or the nature of the data sonified. This results are inconclusive as participants choose to use audification and not sonification.

The initial approach to space physics data is always to perceptualize to glean insight from the data. This step decides the next steps in the data mathematical processing and analysis.

### 2.4.2 Conclusions

This section portrayed some of the existent sonification techniques reviewed and provided examples of sonification techniques applied recently to numerical and scientific data. The bridging of the sciences and the arts are acquiring strength because of its aesthetics. Human perception and cognition are only superficially covered and most of the papers published on sonification of numerical data (ICAD.org) are concerned with sound rendering and conveying expected information.

# 3 Sonification Prototype xSonify

## 3.1 Introduction

Space science data, requires the space scientist to perceptualize data containing more information than can be conveniently displayed at one time on a single screen. The goal of the Sonification prototype is to allow a target audience of space scientists to perceive data in a multimodal fashion. This will be accomplished by employing sound as an adjunct to data visualisation in an endeavour to have sonification accepted as a scientific tool for data exploration.

One of the research questions in this dissertation asks: does sound used as an adjunct to current data visualisation techniques augment the perception of signatures in space physics data masked by noise? This together with, the evaluation of sonification prototypes for space physics in Chapter 2 and results of focus group, prompts the questions:

1. Why it has not been widely used in the space science community?
2. Can a prototype be developed which space scientists could use to explore their data using sound and graphics and will fulfill their data exploration needs?

Sonifications should be easy to use (B. Walker 2012), on the same token, the platforms allowing us to sonify space physics data should be easy to use and understand so the researcher will engage in data exploration and not on data formatting. This thesis introduction and the chapter on data exploration techniques used by space physicists outlined some of the limitations space scientists face in the detailed analysis of space data. Hassan (Hassan A. H., 2013) mentions that space science Big

Data[4] has data volumes that are orders of magnitude larger than astronomers and existing astronomy software are accustomed to dealing with, requiring new software and perceptualization approaches.

Holland (Stuart R. Nylund 1999) mentions that space science data as received on the ground very often bear little resemblance to the original sensor measurements needed to support, study and analysis. For example, according to Hassan (Hassan A. H., 2013), before the data are available for researchers use, they have been fragmented through buffering, intermixing and encoded to fit the most information into the limited telemetry bandwidth (Stuart R. Nylund 1999) and (Starck 2007). Then the space data is ready for analysis by the space physicists and the data is transformed and condensed further to address the researcher's questions. As explained in chapter two, this mathematical transformation may shadow or buffer signals that may be embedded within noise. However, limited visual displays and techniques may filter the data further. Multimodal perceptualization (for this thesis sound as an adjunct to visualisation) may prevent further filtering by facilitating the identification of signal that is masked by noise or away from the direction of gaze. These prototypes (in this thesis a sonification prototype) should make easier the perceptualization and interpretation of the data.

According to Stuart, as well as creating views that the scientists need, these prototypes must be easy to operate and sufficiently quick in producing results (Stuart R.

[4] Data sets too large to be handled with on-hand analysis, processing and visualization tools.

Nylund 1999). Tedious or confusing interfaces and long processing delays only distract or frustrate the researcher's focus on on science (Stuart R. Nylund 1999).

From pictures to current data processing technologies, by far the human brain is still the most powerful tool for the perusal of large data sets. And at the end of the day, it is a human analyzing the data and deciding. Space Science data processing professionals agree that current automated data analysis and processing tools will not be a replacement for the human brain (Hassan A. H., 2013). Current automated data analysis and processing tools can only detect known features and data characteristics. With the 'discovery of the unknowns' which is space science's major objective, space scientists need a method to summarise such massive data sets into a simple, more easily interpreted form (Hassan A. H., 2013) in which weak signals, that are masked, may look similar to noise, that may be away from the direction of gaze and/or weak, may become salient. Then the challenges space scientists face when performing data analysis may naively be categorised as:

1. Structural design: Challenges or elements of the interface that cause problems to the user;
2. Data formatting: this refers to data formatting that prepares the data as acquired by the spacecraft, and formatting the signal to be salient in the data;
3. Perceptualization Techniques.

In Chapter 2 this thesis presented different current data analysis techniques for the exploration of space data. No space science data analysis technique addresses formally, the use of multimodal perceptualization as useful tool to better the exploration of space science data sets. These requirements suggest the need for a space science multimodal perceptualization sonification prototype, that is user-centred, can handle the most common data formats used by Space Scientists and will provide the user with the option of multimodally interacting with data sets.

This chapter presents the work done which extends the development of the Sonification prototype xSonify by the development of a user-centred prototype. The development of the xSonify prototype began at NASA Goddard Space Flight Centre and was developed in the hope of giving the blind a tool for analysing data.

This eventually led to the idea that sighted people could also benefit from Sonification. It appeared more efficient in extracting important information from multidimensional data sets than just simply viewing plots of changing colours. Sighted people could use two senses instead of one to extract information while blind users should be more highly attuned to listening to those sounds by default. This should allow both sighted and blind users to be aware of the same events, allowing them to discuss findings based on similar knowledge.

XSonify was developed in JAVA, the JAVA sound API and MIDI as the standard for sound generation and handling. There is a JAVA class that builds a function named createSequence, this stores each single MIDI event with its mapped value in the data structure. This forms tracks, and multiple tracks form sequences. The raw data (loaded by the researcher) is stored in xSonify's internal data structure and can be considered as the initial starting point of the data's analysis. This data structure is used to build a transformed data structure with values mapped into a value range between 0 and 1. The advantage of this procedure is to make the data available in an independent form regardless of their ranges and scales. For more details the reader may access the documentation on xSonify, worked by Anton Schertenleib and available at http://spdf.gsfc.nasa.gov/research/sonification/documents/Alltogether.pdf

As mentioned earlier, the prototype provides the opportunity to display numerical data as sound with the help of three different audible attributes. The attributes fall under the category of pitch, volume and the rhythm of the sound generated. In order to start the Sonification process the numerical data values have to be converted into values of the internal data structure. The data values of this structure are floating point variables in the range of 0.0 to 1.0. The smallest value is represented by 0.0 and the largest value is 1.0. This scaling allows every single data point contained in the data loaded by the researcher, to be transformed into sound regardless of the units or range used. This is very important for space physics data as the data values may span dozens of orders of magnitude.

### 3.1.1 Data Pipe Line

Because the data spans dozens of orders of magnitude that may risk the data to be imperceptible, the data pipe line used by xsonify is addressed here (for more details the reader may access the documentation below on xSonify available at http://spdf.gsfc.nasa.gov/research/sonification/documents/Alltogether.pdf

Ed Chi (Chi and Riedl 1998), worked on a way how to display a visualisation process and named it the “Data Pipeline”. Analogously to this process Sylvain Daude(Sylvain and Laurence 2003) and Laurence Nigay presented a Sonification process which transforms and prepares the raw data to be finally sonified.

1.From Data To Data View: Data Transformation:

In this step the raw data will be mapped value by value into a range of values between $0 < x < 1$. This process can be considered as a kind of standardisation of values which is necessary to make the data available, independent from their unit and scale.

From Data To Abstract Sound Space: Sonification Transformation

During this step the data are prepared according to the chosen Sonification modus. Every value will be assigned to a certain position at a “time line”. This “time line” represents the time line of the Sonification sequence which will be played in xSonifying the MIDI player.

FromAbstract Sound Space to Sonic: Auditory Display Transformation

This is the part where the signal is finally displayed on a physical device. In xSonify this is the part where the MIDI sequence will be transmitted to the MIDI player and played.”

To better understand the idea of sonification, xSonify takes advantage of the MIDI support from JAVA. If for instance one wished to display numerical data information by the dint of the pitch of a musical instrument, the value 0.0 would represent the lowest frequency and a value of 1.0 the highest frequency, defined by the settings.

Each tone represents one value and the whole sequence of different tones accordingly, the whole dataset. In the case of the space physics data, the events originate from a file that is stored as a standard MIDI files. The file is converted into a track; every track is played by an instrument which consists of MIDI events or collection of MIDI events. A MIDI event is a note, and each note consists of at least a note_on or a note_off event. The MIDI file is read and then performed by a software sequencer. The sequencer performs its sound by sending MIDI messages to a synthesizer that will play the notes stored in the MIDI file.

The author of this dissertation did not make any changes to the sonification rendering techniques of the original xSonify prototype. For more information on the used technologies the reader may read section 3.5 and 4.2 of the xSonify documentation section at the spdf page (spdf.gsf.nasa.gov/research/sonification/documents). In chapter 5 the reader will find examples of sound techniques used to approach and analyse space science data.

In order to support researchers in gaining better results, the application needs to have the ability to transform or rather to change the data to suit their purposes. For the execution of transformations, xSonify provides the user with a selection of different functions and an interface to GNU Octave. This is an environment for numerical computation which plots the data into xSonify for Sonification. GNU Octave is analogous to MATLAB and is distributed free. Every result of applying such a function can be seen immediately as a 2D plot and later-on heard during playing back a sequence.

Technically, the prototype allows users to hear and see 2D numerical plots. Examples of sonification techniques employed to perceptualize space science data are included in Chapter 5.

xSonify allows the user to import ASCII data. During the second year of research the prototype and sonification techniques were extended and could analyse FITS astronomy data sets corresponding to High Energy space physics data and Ex Hydra as well as improving the usability of the application

The author of this thesis advised and actively participated in the original design of xSonify. For purposes of this thesis, the aim of the application is to provide space physicists with a multimodal perceptualization sonification prototype that will not frustrate their research.

The application has been improved to allow the user to assign different sonification, or different instruments to each dataset. This option is necessary if the user wants to distinguish the different datasets or variables while listening to them at the same time (L. Brown 2003).

XSonify has many novel characteristics brought about and put into action during this research to suit target audience needs. These characteristics are not implemented in other Sonification prototypes such as Sonipy (Worral, 2009), the Sonification sandbox (Davidson, 2009) and the Sonification prototypes for space physics data mentioned earlier in the literature review. xSonify is the first Sonification prototype capable of mapping and sonifying any data saved in text and Fits format as well as from several NASA archives such as VISBARD, CDAweb+ and CDAweb which use the Java Sound API to generate MIDI output. xSonify is the first prototype of its kind accessing data from all the missions included in the data base of the space physics data facility (SPDF).

During the research performed for this dissertation the prototype was modified to save the data as audio and text and allows the user to mark regions of interest, save values in textual format and allow for the import of a variety of data formats.

### 3.1.2 Focus group and usability evaluations

Astrophysics data reduction and analysis requires large and difficult mathematical transformations, perhaps implying to populate the data analysis tool with mathematical functions and visualisations, at risk of taking the user out of the loop. What this really means is that making intelligent software for astrophysics data analysis implies indeed that it will be a usable intuitive product.

The focus group and usability evaluation results which were used to lead the development of the prototype can be found later in this chapter. Given the feedback from the target audience the reader will find in the usability evaluation presented in this chapter, the application has been improved to save the Sonifications in ".wav", ".au" or ".aiff" format dependant on the user’s Sonification settings. In the appendix, the reader will find the functionalities added to the xSonify strictly following the focus group and usability evaluation results. As the Sonification technologies have remained unchanged the reader may refer to the original documentation of the xSonify at the Space Physics Data Facility. Information regarding the different standards employed to bring the original algorithm to completion can be found at http://spdf.gsfc.nasa.gov/research/Sonification/Sonification.html.

The improvements to the prototype were completely user-centred. The methods employed for the usability evaluations were think aloud, combined with remote usability testing. These were performed so as to gain a better understanding of space scientist's usability needs as their domain can be perceived as complex.

A study by (Folstad 2007) compares the results of group expert usability evaluations carried out by usability professionals and domain experts on three different domain-specific mobile applications. The results showed that domain experts identified fewer, but more severe usability problems compared to the usability professionals who had no domain expertise. While Folstad is cautious about generalising his results given the limited scope, the results suggested that domain experts make higher-impact findings than usability professionals in usability inspections. For this reason the participants in the usability studies presented here were PhD space physicists working at space research institutions with major publications, and were given the opportunity to be remotely monitored so that their participation would not affect their busy schedules and their data interaction would resemble their daily interaction with data.

The Sonification prototypes developed earlier for the sonification of space-physics data, mentioned in the literature review, (e.g STEREO, LARGE HADRON COLLIDER, etc), were each built for one specific data type, such as Kepler data (http://oklo.org). These were designed with a focus on the graphical interface and utilities resulting in prototypes built around the data and not the user. The prototypes performed the work of mapping a very specific data format into sound remarkably well, but did not meet the needs of space scientists during data analysis (see chapter on review of sonification prototypes in space physics). Most of the sonification prototypes for space science mentioned in the literature review have been built with the purpose of using Sonification for outreach purposes.

This thesis, prototype development consisted of 3 main stages:

- Stage 1 – Carry out focus group discussions to determine what the priorities of data analysis would be for the target audience;
- Stage 2 – To prioritise requirements according to their importance, usefulness and difficulty of implementation, and produce the next version for further testing;
- Stage 3 – Conduct usability evaluations.

As the initial xSonify prototype was created by a developer who had no training in space physics, the author of this dissertation, who has extensive training in space physics, decided to redesign it using input from the focus and usability evaluation groups. These groups were composed firstly of PhD space scientists with post Doctoral publications. They were working at major observatories and space science research institutions and were ideally suited candidates as those were the intended target audience.  The focus group concentrated on the topic of needs in space science data exploration. The idea behind this was to capture interaction in use case scenarios, which can be used to identify priorities. The use case scenario discussed was the user's needs and challenges when performing data exploration.

### 3.1.3 Results of the focus group and usability evaluations

This section presents the results of a focus group and usability evaluation. In the literature review, this thesis outlined 7 sonification prototypes created for the sonification of space physics data. Each prototype may be used only with one kind of data set.

In order to create effective sonifications which will be usable, intuitive (B. Walker 2012) and useful to space physicists, user studies need to be undertaken to fully understand their needs and requirements and to create a prototype which will not engage the space physicist in data formatting as this may frustrate them. The focus group and usability evaluation research presented in this section portrays the results leading to the development of the xSonify prototype previously described.

There are few field studies conducted with sonification by end users, although this is vital if sonification tools are to be refined to meet the needs of these specific clients. The user study presented in this section innovates by engaging the participants in a real user task. This will facilitate to gather information on user case scenario to understand how the user performs the work and coping strategies. The latter will support the coding and for instance the prioritising of user centred development to the prototype.

Eleven PhD-level space scientists with publications in the field and employed at major observatories participated in this study. All the participants were willing to be part of both the focus group and the usability evaluation.

As a result of the literature review the focus group topic set for discussion with the volunteers centred on:

1. Data types used by space scientists.
2. The step-by-step process space scientists follow for data analysis, e.g. filtering techniques, data selection.
3. The user's challenges and needs for data analysis.

During the usability evaluation the participants had the flexibility of using data sets of their choice to capture interaction in user case scenarios.

### 3.1.4 First Stage: Recruiting Process

The volunteers in the focus group were recruited via email and given the time constraints and the busy schedules of the target audience; a set goal of five volunteers was agreed. A copy of the email which was sent out can be found in the Appendix. Eleven volunteers reported to the focus group evaluation and subsequently participated in the usability evaluation. They were divided in two groups, one focus group evaluation of five participants and the other of six. Focus group data was recorded as an audio file, transcribed and analysed. Participants talked about the step-by-step process when doing data analysis, the challenges they face when performing data analysis in the form of personal anecdotes and their need when doing data analysis.

Following the focus group evaluation and prototype improvements, a .jar file containing the sonification software was provided to the participants during one-to-one workshops in their offices for purposes of usability evaluation. A data log monitoring the data usage was saved by the prototype providing low and medium granularity information that serve to determine if the focus group needs were met. The workshops consisted of training on how to use the xSonify software, download data to it, how to select its various settings, how to playback data sequences and how to save the data as a sound file to disk. The eleven space scientists used the sonification prototype with their own data at their leisure after the focus group discussion.

### 3.1.5 Focus Group Results

#### 3.1.5.1 Type of Data Analysed

The dataset contains a detailed description of the steps taken by participants and problems they face when performing data analysis. For example: "I want to explore the data before any of the mathematical processing takes place"

The data were analysed in two main stages: discovery and coding (Taylor and Bogdan, 1984). In the discovery stage we got familiar with the data and identified the main themes and concepts. To do so, attention was paid to those issues that were especially problematic for users when performing data analysis and interacting with prototype.

The datasets contained two main indicators pointing to these problematic situations: problems reported by the participant (e.g. “I got confused over the formatting of the data”), verbal expresions of users that denoted problems (e.g. “when analysing data from (mission x), I had to build the prototype (participant referring to an experience using a prototype from a mission) then had to find and import some binaries, lost days getting that done”).

To do the categorization the process was categorical coded by classifying reported problems and challenges according to the situations described in the introduction to identify challenging situations.

Data was coded in an emergent way, whereas the researcher compared the notes submitted by two independent coleagues. In this way, the categories describing problematic situations emerged without any intentional prejudice. The following categories that determined problematic situations when analysing data using current available prototypes and techniques emerged: unfulfilled goal, data formatting strategies, perceptualization techniques and, Information structural design.

#### 3.1.5.2 Categories

Unfulfilled goal: This refers to data reduction and perceptualization the user has not been able to perform.

Data formatting strategies: This refers to data formatting that prepares the data as acquired by the spacecrafts, and formatting to make or not, signal to be salient in the data.

Information structural Design: This category refers to those elements of the graphic user interface, which cause users problems.

Perceptualization techniques: This refers to techniques used or proposed by the participant to get more from their data employing their senses.

| **Volunteer** | **Interest** | | | **Purpose/Need** | **Data Type** |
|---|---|---|---|---|---|
| **Fictitious Name** | **Research** | **Curiosity** | **Education** | | |
| **Darin** | X | | | Wants to increase resolution of data visualisation. | Kepler Time Series Data |
| **Wen** | 1.1. | | X | To get an idea of how all parameters in a data set are changing with respect to each other so that information can be gathered more quickly than taking the time to listen to each variable separately | Asteroseismology |
| **Margie** | X | | | Some changes that could not be evident just by looking at the data. It will always be better if you add another way of data characterisation. | X-Ray data |
| **Tom** | X | | | Wants to prepare a Sonification library of pulsar data, as it may be easier to classify the pulsar by sound. | Pulsar Data |
| **Marc** | | x | | Curiosity | |
| **Jason** | X | | | | Kepler Time Series |

| | | | | | |
|---|---|---|---|---|---|
| **Douglas** | X | | | to consider two or more parameters in conjunction with each other - looking at how one changes with respect to the others | Heliophysics |
| **Josh** | X | | | | Kepler Time Series |
| **Juan** | X | | | Melodies develop which will give insight of events in the data | X-Ray Data |
| **Lisa** | X | | | Determine Transits on Kepler Data | RR Lyrae light curves |
| **Matthew** | X | | | I am interested on hearing pure sine waves and the silence in the data for example a gap in the data because of the solar cycle | Light Curves |
| **Emma** | X | | | I am interested to do a mapping to timbre perhaps using filters, or other sound parameters that would draw out the highlighting features. | Seismology |

Once the responses from qualitative observation of this focus group evaluation were completed, the participant's interest and purpose to use sonification as an adjunct to visualisation were taken and classified in three main groups. These responses are detailed in table one and the three categories are as follows:

1. Research
2. Curiosity
3. Education/Outreach

**Table 1: Table of Focus group participants' reasons for using sonification and their expected use of sonification.**

The data types used by the volunteers are also detailed in table 1 and the theme discussed in the focus groups were always directed to ways each of them could listen to the data in order to avoid formatting the data and help make a signature of their interest salient, e.g. "frequency and time variations as a function of pitch can be grouped and then extracted from the data, this step may be compared to decomposing the data into different simple modes of oscillation."

Another example of this is when talking about the step by step process used by space scientists for data reduction; the participants described how to listen for noise when the signal and noise were both ambiguous. In the discussion, the focus group participants suggested to each other how to listen to different data sets and ascertain how to find different parameters being sought at the time.

100% of the participants agreed that there were five main stages of data analysis:

- Stage 1 – The first stage is visualisation[5] of the data. This visualisation is done to spot apparent signatures that may be of interest.
- Stage 2 - The second stage is filtering of the data to remove noise.
- Stage 3 - The third stage is to correct for instrumental effects.
- Stage 4 – The fourth step is to use mathematical morphology which is a set of filtering and segmenting tools used to visualise[6] digital images.
- Stage 5 – The fifth stage is to visualise the data again.

Participants expressed the desire to use Sonification at every step of the process as most of the time the data published by space agencies does not resemble the original data acquired by the satellites. The participants stated how and why they would use sonification in their field as described earlier in Table 1. Nine out of

[5] With visualization meaning to plot the data as acquired with no filtering.
[6] With visualization meaning to plot the data visually.

the eleven participants would use Sonification solely for research purposes as opposed to outreach as the latter is not their main interest. Two categories were identified from the discussion: perceptualization and visualisation techniques. 100% of the participants strongly wanted to increase the resolution of their data to be able to see and hear signatures in the data for data mining purposes. 100% of the participants discussed perceptualization techniques as an approach for seeking signatures in their data as described in Table 1.

During the focus group, participants said that it was imperative for a prototype not to limit their analysis by the display, data type, mathematical morphology, platform or cost. The prototype has to bring them to the correct data exploration fast and without investing time in formatting the data._

### 3.1.6 Usability Evaluation

Given the focus group discussion and literature review, the usability evaluation gathered qualitative data on:

1. Understandability - Recognising the tools operability and applicability.
2. Learnability - attributes that bear on the users' effort for learning the application. In the case of this research, this means if the user is able to use the prototype functionalities unassisted and if the user is able to perform the exploration of the data without investing further time in data formatting, or writing code. Remote data logging during the participant interaction with the data monitored and recorded console output and runtime exceptions to file. Two data logging sessions were saved on the participant's computer desktop one for interaction with the prototype and the other for run time errors and exceptions.
3. Operability - Is the volunteer able to use the Sonification and visualisation options in the tool to adjust the data to match their perception?

### 3.1.6.1 Aims and Methods

The aim was to observe the effectiveness, efficiency and satisfaction with which astrophysicists can achieve their goals and use the xSonify prototype to explore data from local or remote files, sonify the data and explore it. The main methods used were:

1. Understandability – Think Aloud consisting of one-to-one 30 minute workshops with each participant.
2. Learnability - attributes that bear on the users' effort for learning the application. In the case of this research, this means if the user is able to use the prototype functionalities unassisted and if the user is able to perform the exploration of the data without investing further time in data formatting, or writing code. Remote data logging during the participant interaction with the data monitored and recorded console output and runtime exceptions to file. Two data loggings were saved on the participants computer desktop one for interaction with the prototype and the other for runtime errors and exeptions.
3. Operability – To get physical evidence that the users were successfully exploring the data we provided a target for participants to meet during the tasks. Participants provided with a WAV, AIFF or AU file after their data exploration. These files are kept in a password protected folder.

The usability evaluation used participants who were recruited for the focus group reported previously. The outcome of these focus groups and details of space scientists needs are detailed in Section 3.5.2 of this report. The usability evaluation intended to mimic exactly the data exploration followed by space scientists on their daily exploration of data. During the usability evaluation the task consisted of:

- Data import from the common data format web, (CDAweb) Space Physics Data Facility, and/or fits or txt data.
- Mapping and exploration of data in a user choice plot and Sonification modi such as with volume, pitch or timbre.
- Play back of data.

The participant had the flexibility of using data sets of their choice. To overcome any unexpected events, additional to the one-to-one workshops, the usability evaluation groups were provided with a link to a digital “DropBox” where they could find a copy of the prototype in “.jar” format. A help file consisting of a brief prototype description, system navigational instructions, and a 2D data set corresponding to GRB 04/12/19, (Gamma Ray Burst, 04/12/19) from the High Energy Space physic archive, (HEASARCH) was include. A copy of the help file is available in the appendix section of this thesis.

During the workshop, the participants either imported data from the Space Physics Data Facility (SPDF), using the xSonify or used their own data. When loading data from the SPDF, the participant imported data from a satellite of their choice. Sometimes the participant provided the data to be imported. In case the participant did not have a data file, the backup file provided in the DropBox was used. Participants sonified the data, played back the sonification, which was remotely monitored, and proceeded to save the data to disk in ".WAV", ".AU" or ".AIFF" format using the prototype.

These workshops were done in their respective offices where participants perform their research. After the workshops, participants were permitted to use the prototype at their leisure in their offices.

### 3.1.6.2 Results

Generally, and as they literally expressed during the focus groups, they wanted to hear the data as naively as possible, with the gaps in the data if present and when there were no data points or zeroes presented. For example, this could happen when there is a gap in the sun solar cycle. Participants also expressed the need to explore the data in a time effective manner and "the desire to spot signatures that are ambiguous and or embedded in noise especially in large data sets". Other comments included "the need to explore for the unexpected in the data before applying any filtering or morphology".

The Console.txt file created to monitor the user navigation of the prototype as a standalone showed that ten of the eleven volunteers tried their own data on the prototype. Seven of those ten trying their own data, tried more than one data set from all of them having more than 17, 000 data points. Of those ten, two tried more than one data type, namely ".txt" and. fits.

The Console.txt file consists of a print out of the user navigation, buttons pressed, sonification mappings used and values marked amongst other things. One volunteer imported data from the Coordinated Data Facility. The mapping of the data was done in pitch. Six of the eleven volunteers did not use the rhythm option and only one participant saved the sonified data as a MIDI output. The rest of the participants saved the file in ".WAV" format. The participants praised the prototype as it allowed them to try more than one data type.

Participants said that sonification allowed them to invest more time looking at the data to “make sense of it” in large data sets comprising of hundreds of thousands of data points. The participants liked that the prototype permitted them to import the data easily and explore the data, which in turn gave them a chance to further mathematically transform the data if desired through the GNU Octave interface using basic line command in C. Participant’s expressed satisfaction to the fact that the only requirement to import and plot the data is for the data to be formatted as columns; the first column, the x-axis to be positive numbers and the rest of the columns, the y-axis, to be either positive or negative numbers. Equally, they liked how the prototype plots as many columns as desired against time and choose which ones they wished to hear, plot or mathematically transform. Eight participants expressed the interaction with sound brought them to think on possible transformations and correlations they had not considered previously. [7]

[7] Participants were promised that their correlations and details of data sets explored would not be presented in this research.

#### 3.1.6.3 Discussion

The analysis of the data collected during the focus group confirms that space physicists are frustrated when performing data analysis due to:

1. The forced engagement in data formatting to fit software architectures.
2. The desire to analyse the data to seek for events which may be masked by noise or by the current data analysis techniques available or that are away from their direction of gaze.

The categories found in Section 3.5 are confirmed by the literature review in Chapter 2 and the introduction of Chapter 3 of this dissertation. The categories found in this research include the limitations faced by space physicists in research listed in this thesis introduction. For example “The absence of efficient techniques with adaptive basis for the detailed analysis of nonlinear and non-stationary data” is included in category Data formatting strategies. By categorising the different challenges of space physicists when performing data analysis helps identify solutions which do not depend on the underlying technology.

*On the relationship of interest and purpose for the use of multimodal perceptualization, sound as an adjunct to visualisation:*

By being able to establish a relationship between the purpose of using sound as an adjunct to visualisation and the main interest of the researcher, education, research, curiosity, as detailed in table 1, one could infer that the data analysis needs, require prioritising. For instance the author of this thesis understood the “purpose” as an “unfulfilled goal”.

Identifying the user's needs of this research brought about the development of a user centred prototype for analysing space physics using multimodal perceptualization, sound as an adjunct to visualisation and which could support its users and target those aspects which cause frustration when performing data analysis.

### 3.1.7 Conclusions

In this chapter we presented the Sonification prototype xSonify, created at first at NASA Goddard Space Flight Centre and later converted into a user-centred prototype at the University of Glasgow in Scotland. To understand user needs and issues for the prototype, a focus group and usability evaluation were conducted. The results of these studies have shown some of the needs of space scientists have been met by giving them a better understanding of the data. The focus group research and the usability evaluations showed that space scientists need an improvement in the resolution of their data analysis. This means that they wish to explore the data as naively as possible, before any filtering or transformation takes place, as it risks the loss of important but perceptually ambiguous information embedded in the data.

This chapter presented such an approach from a prototype perspective. It is to be proven if sound as an adjunct to visualisation augments the sensitivity to space science signal from the perspective of perception experiments and this will be addressed in future chapters. Psychology experiments have proven that the auditory cortex can be profoundly engaged in processing non-auditory signals, particularly when those signals are being attended to (Shinn-Cunningham, 2008). The latter has to be proved from the perspective of a space physics signal detection experiment with manipulated and no manipulated data. This also may open a path to the multimodal exploration of such data sets through training.

To sum up, the space scientists believed in the potential of Sonification to augment signatures in data masked by noise, for performing data mining and to get insight into certain non-obvious events in the data as detailed in Table 1 of this document. This has been shown through their willingness to participate in the focus groups and usability evaluations regardless of their busy schedules. The xSonify prototype is the first space physics data analysis sonification tool developed around the user and not around the data.

This user study shows that in this field, Space scientists are searching for new ways to approach their data. The improved version of the sonification prototype xSonify provides the target audience with an application that will take them directly to the execution of their science and will provide multimodal perceptualization of the data that as the volunteers said, "may bring forth other correlations not thought of at the time of data gathering".

# 4 Use of perceptualization techniques to analyse space science data sets

## 4.1 Introduction

This chapter presents attempts to use the sonification prototype presented in Chapter three to approach data acquired with satellites. The creation of a prototype that is user-centered means that it is usable and, in the case of this research, will help the scientists to explore their data, augmenting their sensitivity to events that may have been masked or not thought of before the data analysis began. The reader should remember from Chapter 2 that space physics data analysis involves a perceptualisation that decides the next stage of the data analysis. For those purposes scientists working at the Center for Astrophysics who volunteered to take part in the experiments reported in Chapter 3 were motivated to share any findings found in the data using sound and/or the sonification prototype. In space physics before any findings are submitted to peer rewiew for publication, there is a process of scrutinization, spanning a very long time.

Dr.Alilcia Sodebergh used the prototype and reported the publication of two papers (July 2013), a radio interview and a presentation at the American Astronomical Society Meeting held in January 2014, of findings using the techniques developed towards this thesis, (sound as an adjunct to visualisation). The papers and links to radio interview and transcription are listed in the Conclusions chapter. This section attempts to provide examples of practical use of sound as an adjunct to visualisation to approach different examples of noisy space physics data.

Time series, power spectra, magnetic fluctuation and radio data were explored using sonification in the search for signatures[8]. The data types analysed in this chapter are only a handful of the diversity of data types space scientists analyse. Due to time restraints, easily available data that exemplifies the data most used by space physicists was used. These included: FITS, time series, power spectra, magnetic fluctuation and radio data to assess the effectiveness of the use of sound to explore the data in the search for signatures/changes/events in both manipulated[9] and not manipulated[10] data.

The sonification evaluation presented in this chapter began with SPDF, CDF, and ASCII data formats for solar wind and radio data as xSonify was built originally for that data type. During the summer of 2010, sonification techniques were tested with FITS format data, with the hope of extending the use of sonification and xSonify capabilities to High Energy astrophysics data. FITS (FITS the astronomical image and table format 2011)(Flexible Image Transport System) is a standardised data format, which is widely used in astronomy. Although originally conceived as simply a standard interchange format for digital images, FITS files are now often used as a working data format and can be used to store ASCII or binary tabular data, in addition to images and spectra. Detailed information on the FITS format can be obtained

[8] The interesting part of the data. It has to be differentiated from noise or clutter.
[9] Manipulated data refers to data in which an experimenter has intentionally hidden a signal for identification by a participant.
[10] Data acquired by satellites in which no experimenter has hidden any signal for identification.

from the NRAO[11] FITS archive or from the FITS support office at Goddard Space Flight Center http://fits.gsfc.nasa.gov/fits_samples.html (FITS the astronomical image and table format 2011).

Briefly, a FITS file consists of a sequence of one or more Header and Data Units (HDUs). A header is composed of ASCII card images that are usually read into a string array variable. The header describes the content of the associated data unit, which might be a spectrum an image or tabular data in ASCII or binary format. Image and vector data can be present in any HDU, but tabular data cannot appear in the first HDU. The HDUs following the first (or primary) HDU are also known as extensions and thus a FITS file containing tabular data must contain at least one extension.

The Interactive Data Language (IDL) programming language astronomy library contains four different sets of procedures for reading, writing and modifying FITS files. The reason for having four different methods of FITS I/O with IDL is partly historical, as different groups developed the software independently. However, each method also has its own strengths and weakness for any particular task.

The reader may notice that the data analyst in this section (the author) only used sonification to approach the data.  This is because the data analyst is blind.  At the same time the reader should note that results were presented to a sighted audience that validated the results through exposing themselves to the data sonification and visuali-

11 National Radio Astronomy Observatory.

sation and by performing numerical validation.

The analysis of the data presented in this chapter has the following order:

1. Analysis of data that had already been analysed by sighted astrophysicists. In this thesis, results from sonification of the data are presented as well as new periods that had been overlooked by sighted post-doctoral astrophysicists using currently available techniques.

2. Analysis of data to perform a frequency study of the noise floor by acquiring data from a constellation of satellites. The report includes the numerical and auditory validation of findings by other astrophysicists.

3. Analysis of time series radio data. The report includes the numerical and auditory validation of findings by other astrophysicists.

## 4.2 X-Ray Data

During the usability evaluation at the Harvard-Smithsonian Center for Astrophysics, astronomers provided X-ray data corresponding to Chandra EX-Hydra to be explored using sonification. The data set had been previously explored extensively by post-doctoral astrophysicists. EX-Hydra is a cataclysmic variable (CV), star, of the polar type. CVs are binary systems that consist of a normal star and a white dwarf. They are typically small - a typical binary system is roughly the size of the Earth-Moon system - with an orbital period in the range 1-10 hrs. The companion star, a more or less normal star like our Sun, loses material onto the white dwarf by accretion.

The reader may note this data has been approached with a problem at hand. This section reports the result of searching the event of interest using sound and the identification of two known events in the data. The latter gives more credibility to the events identified using multimodal perceptualisation.

There are two principal energy sources in a cataclysmic variable: accretion and nuclear fusion. Since the white dwarf is very dense, the gravitational potential energy is enormous and it is converted into X-rays during the accretion process. The efficiency of this process is typically around 0.03% i.e. the energy released in X-rays is about 0.03% of the energy which would be released by the total annihilation of the same quantity of matter. The fusion of 4 hydrogen nuclei into a Helium nucleus has an efficiency of 0.7%. This is much lower than accretion onto neutron stars (~10%), or black holes (up to ~40%), observed in X-Ray binary systems but still high enough to make CVs much brighter in X-ray than typical stellar coronae.

The analysis task was to find quasi-periodic oscillations. Quasi-periodic oscillations (QPO) are important as those may be present in any space plasma data as the solar wind. The latter have been a challenge for high energy scientists as they are very difficult to unravel. The QPO phenomenon promises to help astronomers understand the innermost regions of accretion disks and masses, radii and spin periods of white dwarfs, neutron stars, and blackholes. QPO are of utmost interest to high energy space scientists as they may help test Einstein's theory of general relativity which makes predictions that differ most from those of Newtonian gravity when the gravitational force is strongest or when rotation is fastest (when a phenomenon called the

Lense-Thrring effect comes into play)[12]. Normally a QPO is identified by performing a power spectrum of the times-series of the X-ray data. A QPO on the other hand, appears as a broader peak sometimes with a Lorentzian shape. The data analysed had been already characterised using different mathematical transformations and Alias[13]. (Many thanks to Dr.Juan Gerardo Luna and Dr. Nancy Brickhouse who trusted the author of this thesis with their data.)

### 4.2.1 Perceptualisation Technique Used

The aim of this work was to use sonification to find already characterised periods plus report if new periods were identified with the sonification technique. Normally, this is done by displaying consecutive power spectra to visualise the time evolution of the QPO frequency. The time series and power spectra of the XE-Hydra light curve data were mapped to sound, using the xSonify prototype, to analyse the frequency content of the data. The registry space spanned (the relative high or low frequency of discrete or noise sound) would give information on instantaneous frequency changes. The notes are approached as the product of several frequencies e.g. harmonics, fundamentals etc. Temporal fluctuation information is portrayed as a simultaneously sounded cluster of pitches. Each data set was mapped in pitch each time for phase, frequency, time variation and harmonic perception (Grochening 2001). The different spans were grouped and then extracted from the data. Given the human ability to transform the disturbance reaching it from the space domain to the

[12] Also known as frame dragging in which the orbit of a small body orbiting around a rotating massive one is slightly perturbed by the rotation of the massive rotating body.

[13] Referring to error or distortion.ex: in space physics temporal resolution sets a cutoff frequencuency, the so called nyquist frequency, which is half of the sampling frequency, for fourier analysis. In order to resolve a waveform, the sampling frequency should be at least twince the wave frequency. If frequencies above the nyquist frequency are present when a signal is digitized it appears to oscillate at the frequency below the nyquist frequency. Such signal is called aliased.

frequency domain, this step may lead to decomposing the data into its different simple modes of oscillation. Those oscillations may or may not be symmetric to the local mean but we know the data may have many co-existing oscillation modes superimposed on each other characterised by variable amplitude and frequency as functions of time. The latter then may produce the instantaneous frequencies.

Those correspond to spin and orbit parameters that have to be extracted from the data noise to be characterised given local conditions. The data were mapped in pitch, for comfort[14] the volume set at 70% of the Jslider range (4db); the timbre selected to hear the data was voice Oh (midi patch 77), because of the range of the human voice and because if needed it may lend itself to be used to relate physical parameters in the data to the voice. (See Figure 11 below for range of harmonics and fundamental frequency).

[14] Meaning the volume at which the data listener felt most comfortable listening to the data.

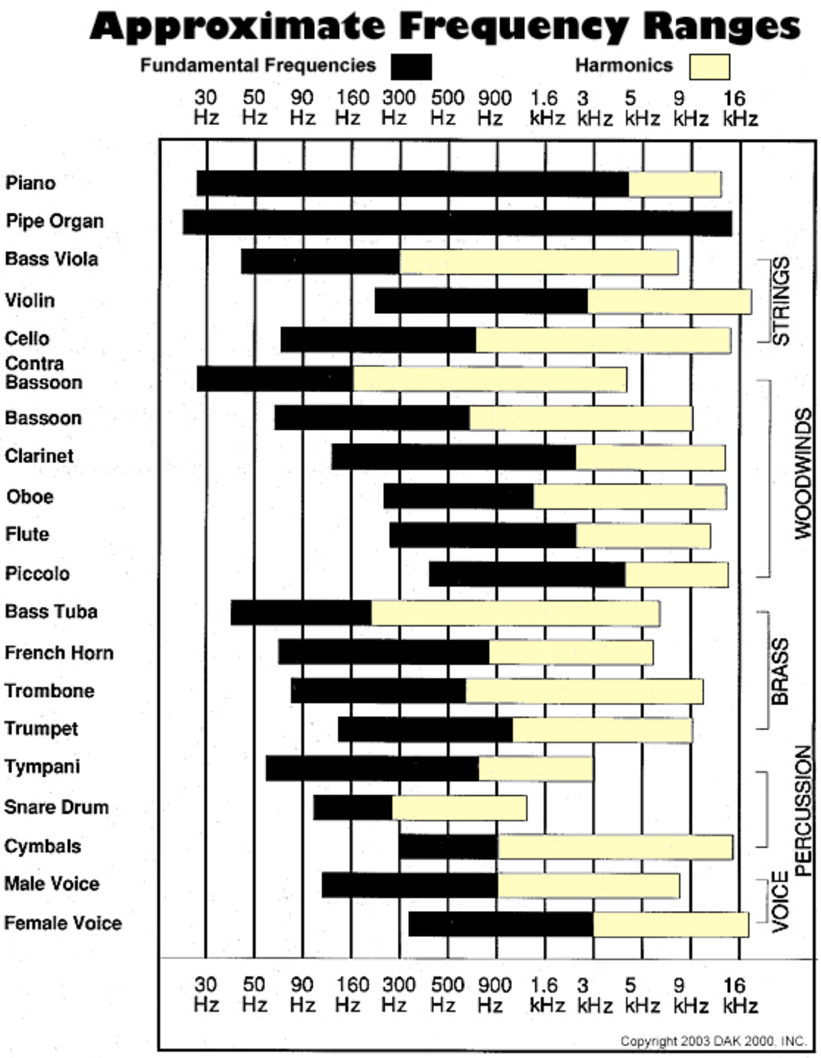



**Figure 11 Fundamental frequency ranges for different instruments and voice.**

(DAK Industries 2012)

Twelve hours of data, acquired at a sampling rate resolution of 1 second were converted from FITS to txt and imported into xSonify. The data were heard in sets of 4,000 with continuous segments of the data set overlapping by ten minutes with the previous one. As a reference for the musical note to data frequency conversion, the listener established that the C and C sharps corresponded to frequencies of 4-5 MHz

### 4.2.2 Results

By extracting the harmonics and paying attention to frequencies in the MHz range, frequencies distributed within 2.4-5 MHz with periods oscillating between 9 seconds and 98 minutes were identified. Frequencies between 0.5 Hz and 1.3 Hz could be heard. The charts below illustrate the harmonics heard when applying the sonification settings previously described.

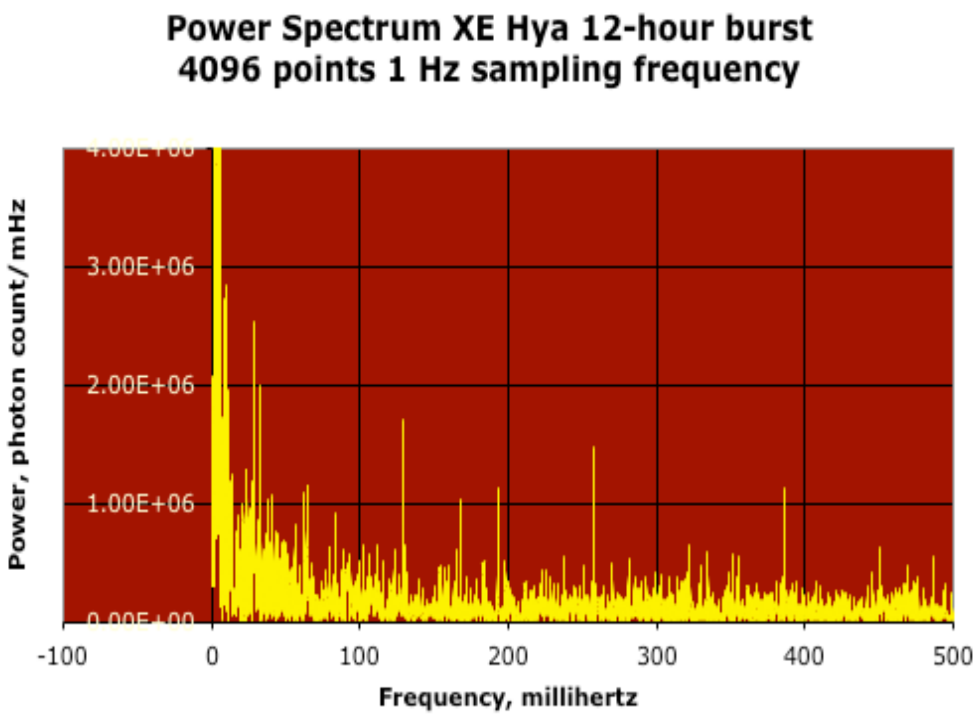



**Figure 12 Power Spectrum EX Hydra 12 hour burst.**

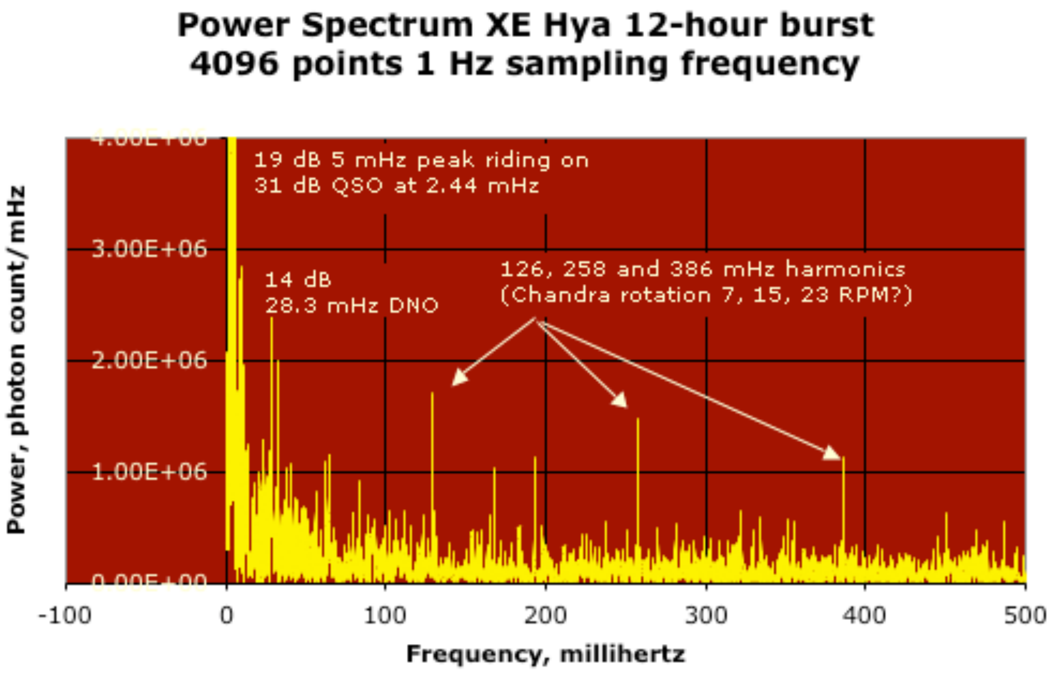



**Figure 13 Power Spectrum EX Hydra.**

Figure 13 shows the power spectrum of the 12-hour burst (corresponding to May 30, 2007), and has the dc-component suppressed, so what the reader sees near the beginning is a real peak. It is off-scale so the reader can see the weaker peaks throughout the 500 MHz sampling range. The readers are shown a close-up of the strong peak, which is what is suspected to be the QPO at 2.44 MHz, which is 31 dB above the noise (the noise level at 100,000 is estimated visually on a zoomed-in graph). Sonification at a 19 dB peak at 5 MHz was also identified. A few of the peaks look like they are harmonics. Those may be from Chandra's rotation which may rotate anywhere between 4 to 15 RPM. Even though the antenna does not rotate out of view of the target, vibrations will be microphonically imposed on the detector.

The figures above have a very strong signal at 2.44 MHz, not reported previously in literature. If this can be corroborated, then this would indicate the discovery of a new QPO, not seen before. This was found on 12 hours of the data. If there is new physics more research has to be done to figure out what it means. There are some possibilities: probably something happening at the inner edge of the accretion disk, possibly a type of plasma instability. The magnetic field of the white dwarf is thought to truncate the accretion disk at some radius (or order of 5 to 10 stellar radii), and this might move in and out if the magnetic field's strength changes.

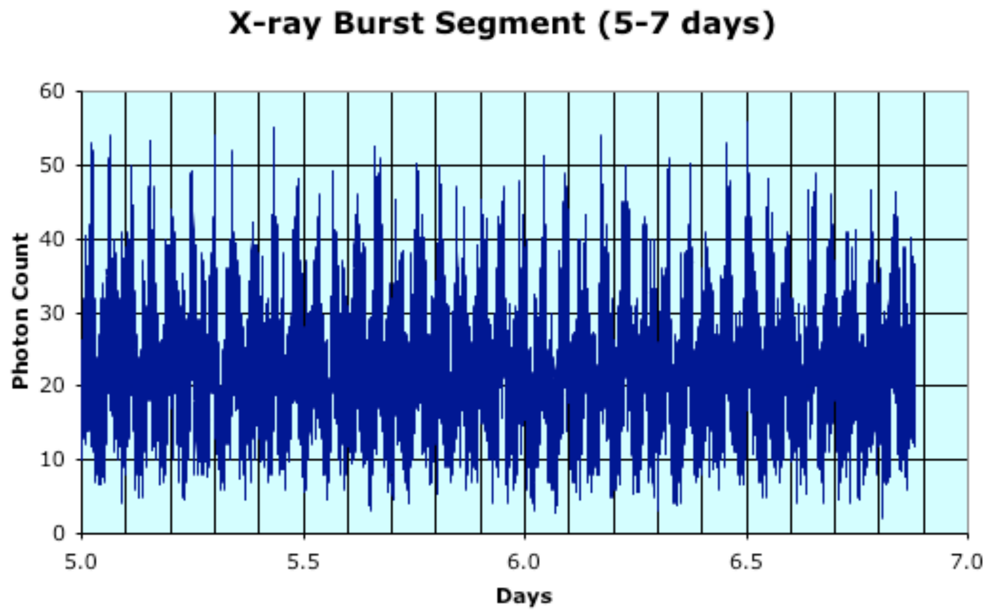



**Figure 14 2-day-long burst.**

Figures 14 and 15 correspond to two time series files, one is a 2-day-long burst and the other is a 12-hour close-up. The 1-hr white dwarf rotation (67 minutes) is easily seen; the orbital period (98 minutes) of the big star is not as easy to see. A better FFT will clearly show the 98 minutes orbital period heard in the data.

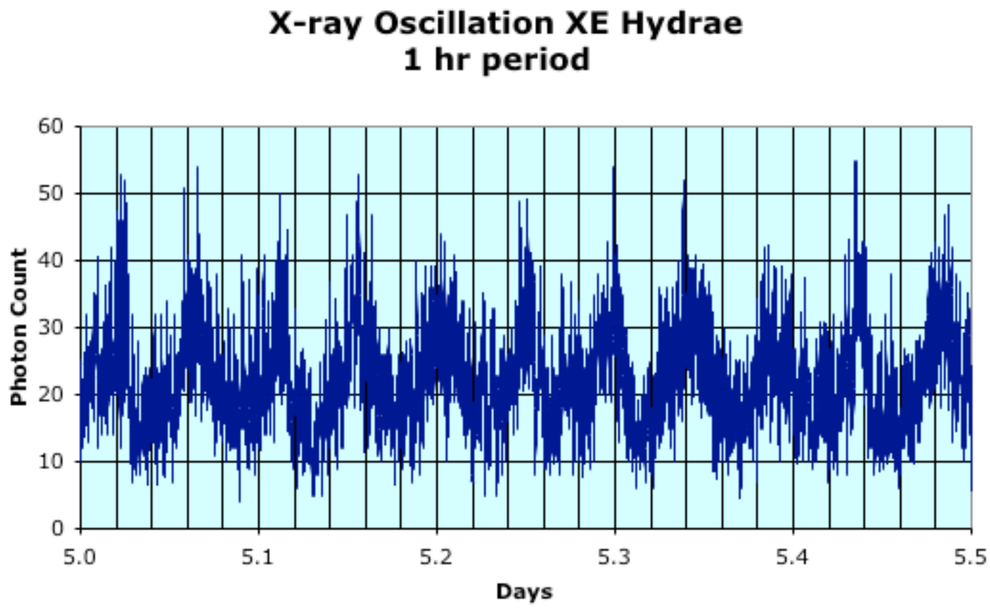



**Figure 15 12-hour close-up.**

### 4.2.3 Conclusions

A sonification technique used to analyse X-Ray data proved to help space scientists in the exploration of data to identify known parameters (like orbital periods and spin rotation), and for the identification of new QPO's.

If the new period 6.8 min (2.44 MHz) holds up this might indicate some kind of oscillation at the inner edge of the accretion disk. For a Keplerian orbit, this is at about 8 times the white dwarf radius, close to what is assumed to be the distance at which the magnetic field of the white dwarf truncates the disk. Not every paper in the literature agrees that there is an accretion disk in EX Hydra.

So far this technique to decompose this data into its different frequency components to search for QPO's testeded to be effective. Regularly decomposition of the data is time consuming and may buffer signal[15]. Studies on timbre and rhythm perception have to be integrated to increase sensitivity to signal detection in space physics data. Experiments on perception have to be performed in order to establish a base line to allow the comparison of detection of signatures in sonified data, visual data and sonification as an adjunct to data visualisation cues. The latter is to help interested target audiences to have interaction with the data that will lead to augmenting the quality of data analysis.

## 4.3 Sonification and perceptualisation of Solar Wind, ACE, WIND, GOES data

The previous section (4.1) presented the sonification and analysis of X-Ray data to study the behaviour of the noise floor and searching for signal of interest (QPO). This section presents the sonification of particle and magnetic fluctuation data on the progress of the impact of a solar flare on the solar wind. This will help to determine parameters of the solar wind and in the case of this data set, changes as the burst approaches different satellites, i.e. widening the variety of data types of analysis and application of sonification to other space science data sets. This section presents the use of direct parameter mapping sonification techniques (Florian Grond, 2012) to analyse the impact of a major solar flare (X17 Halloween Storm), on the solar plasma, in particular, the solar wind between the Sun and the Earth and the astrophysical cavity called the Earth's magnetosphere. The focus is on sonification settings used to analyse the X17 flare and its associated halo Coronal Mass Ejection (CME),

[15] See chapter 2.2

initiated October 28, 2003. Particle flux and magnetic fluctuation data are extracted from a constellation of satellites: ACE, (Advanced Composition Explorer), (ACE, 2006), the WIND, (Zsabo, 2005) space probe, and the GOES, (NASA-NOAA, 2012). The sonification showed expected and non-expected changes in the power spectra. The sounds were characterised using FFT algorithms.

As mentioned in chapter 2 space physics data is characterized by the presence of noise that masks signal embedded in the data. Solar wind data is regularly analysed employing FFT analysis to generate a power spectra (to produce a log Power vrs Log Frequency distribution). It is used by space scientists to study the behaviour of the noise floor. Being analogue to FFT it assumes the data to be piece-wise stationary and may buffer[16] signal specially if it is unexpected.

### 4.3.1 Background

Solar flares are tremendous explosions on the surface of the Sun. A billion megatons of TNT energy is released across the entire electromagnetic spectrum in just a few minutes. Twisted and sheared magnetic field lines near sunspots can cross and reconnect with the explosive release of energy. The strength and direction of the magnetic field is measured with the Marshall Space Flight Centre's Vector Magnetograph.

A constant stream of particles flowing $10^6$ mph from the Sun's corona extends beyond Pluto's orbit and deforms Earth's magnetic field. Solar wind deflected—like a

[16] See chapter 2.2 for details on data analysis techniques.

stream diverted around a boulder—by our planet's magnetic field forms a tear-drop-shaped cavity in the solar wind flow, the magnetosphere, which contains highly dilute plasmas. Its size depends on the velocity, density, and IMF (Interplanetary Magnetic field) of the solar wind.

The Earth's magnetosphere typically extends to around 10 times the radius of Earth in the sunward or "upstream" direction, and hundreds of Earth radii in the direction away from the Sun, or "downstream." How the magnetosphere responds to the continuous buffeting by the solar wind depends strongly on the direction and strength of the IMF.

When the magnetic orientation of the IMF[17] is opposite that of Earth's magnetic field on the sunward face of the magnetosphere , the two magnetic fields slam together and can cancel each other out. This annihilation process is called magnetic reconnection. Reconnection is the primary process by which Earth's magnetic shield is breached and energy is transferred from the solar wind to the magnetosphere.

This transfer of energy in turn drives the flow of plasma within the magnetosphere and leads to the build-up of magnetic energy in the magnetotail—the downstream portion of the magnetosphere, which looks like the tail of a comet. The energy stored in the tail is then explosively released in events known as magnetospheric substorms. During substorms, the magnetic field lines in the magnetotail behave like elastic bands that are stretched and then abruptly released, snapping back to their original configuration (Carbone 2012).

[17] IMF= Interplanetary Magnetic Field

The reconnection of stretched and stressed magnetic field lines in the tail is an important element of this process. Some of the energy released in substorms drives powerful electrical currents that inject several billion watts of power into the upper atmosphere and produce spectacular displays of the aurora borealis and aurora australis—the northern and southern lights.

Heliophysics data are acquired at a very high sampling rate averaging from 1 second to hours. Regularly this data is analysed by performing power spectra (see chapter two for more on power spectra). To visualise periodicities developing over time for very high sampling rate data requires high resolution displays and CPU power (see chapter two for more details). The approach of using sound as an adjunct to visualisation may give heliophysicists a tool for data exploration that may reduce the CPU cost, giving space scientists a broader appreciation of the data. This may reduce the buffering of important signals embedded in the data that may be masked by the numerical transformations resulting from the visual perceptualisation of the data occurring during the data analysis. This is very important as this perceptualisation of the data determines the direction of the next data analysis process.

This section presents the exploration of using sound from power spectra data. Results and validations of spectral index identified help to follow a major solar event and determine its impact on the interstellar plasma.

For turbulent plasmas like the solar wind, the fundamental may not be the lowest component of a waveform. In turbulent interestelar space media, subharmonics occur where the fundamental is not the lowest frequency, i.e. subharmonics are actually at lower frequencies. When a wave passes through plasma, the electrons respond to the electric field by oscillating and re-radiating at the wave frequency; this is the origin of the refractive index when expressed in terms of the resonant frequency of plasma. The response of the electrons is affected by the presence of a magnetic field, which forces the electrons into curved paths. The amplitude of the electron response will give an idea of the direction of the field. Imposing a waveform into the data as described in Chapter 2 may mask this important change to the space scientist.

Ranking of a solar flare is based on its peak burst X-ray intensity (I) measured at the Earth in the 0.1 to 0.8 nm wavelength band (Table 26).

| Class | I (Watts/square meter) |
|---|---|
| **B** | $I < 10^{-6}$ |
| **C** | $10^{-6} < I < 10^{-5}$ |
| M | $10^{-5} < I < 10^{-4}$ |
| **X** | $I > 10^{-4}$ |

**Table 26 Ranking of a solar flare is based on its peak burst X-ray intensity (I).**

A multiplier is used to indicate the level within each class. For example, a class M6 flare has a peak power density 6 x $10^{-5}$ Watts/$m^2$.

The Solar Wind Observatory Reports [18]

| Event Date and Time | Flare Class | Shock Arrival Time | Hours Elapsed |
|---|---|---|---|

[18] Space Weather Highlights: Preliminary Report and Forecast of Solar Geophysical Data, published by the National Weather Service's Space Environment Center

| | | | |
|---|---|---|---|
| Oct 26, 2003 1819 UTC | X1 | Oct 28, 2003 0130 UTC (ACE) | 1.5 |
| Oct 28, 2003 1110 UTC | X17 | Oct 29, 2003 0559 UTC (ACE) | 30 |
| Oct 29, 2003 2049 UTC | X10 | Oct 30, 2003 1600 UTC (Earth) | 64 |

**Table 27 Time Line Construction of Flares October 2003.**

The power of a signal (antenna voltage, magnetic field fluctuation etc.), depends on the frequency f processes in plasma, and is reflected in the spectral index. Changes might be tracked through its monitoring:

$$P = f^{-a}$$

Where the exponent is the spectral index (in this case p = -a and is called the Spectral Index). Some examples of the Power Law, $f^{p}$, include:

Random Noise p = -1

Radio spectra

- Thermal sources, (p > 0).
- Synchronous sources, (p < 0).
- Radio Scintillation, (p = -7/3).

### 4.3.2 Sonification/Perceptualisation technique used

The power spectrum was mapped into sound using the xsonify prototype, giving special emphasis to the harmonic content of the sound and restricting the sonification to decade windows between 10-1000 MHz, detecting frequency-averaged levels and descending tones. The sonification mapping (timbre, volume, etc) was as for the X-ray data presented in the previous section. The data was mapped in pitch, using as a timbre voice Oh (midi patch 77). The descending tones heard would correspond to spectral indices (relating the flux density of a radio source to its frequency), which in turn tell us something about the physical processes in the plasma.

The approach focused on instantaneous changes using sound and the notes produced by a timbre in terms of a sum of a number of distinct frequencies, e.g. harmonics, fundamentals, partials, etc. Satellite time-series data were searched for and changes were heard in the Spectral Index of the space plasmas. The sonification showed expected and non-expected changes in the power spectra. The sounds were characterised using FFT algorithms.

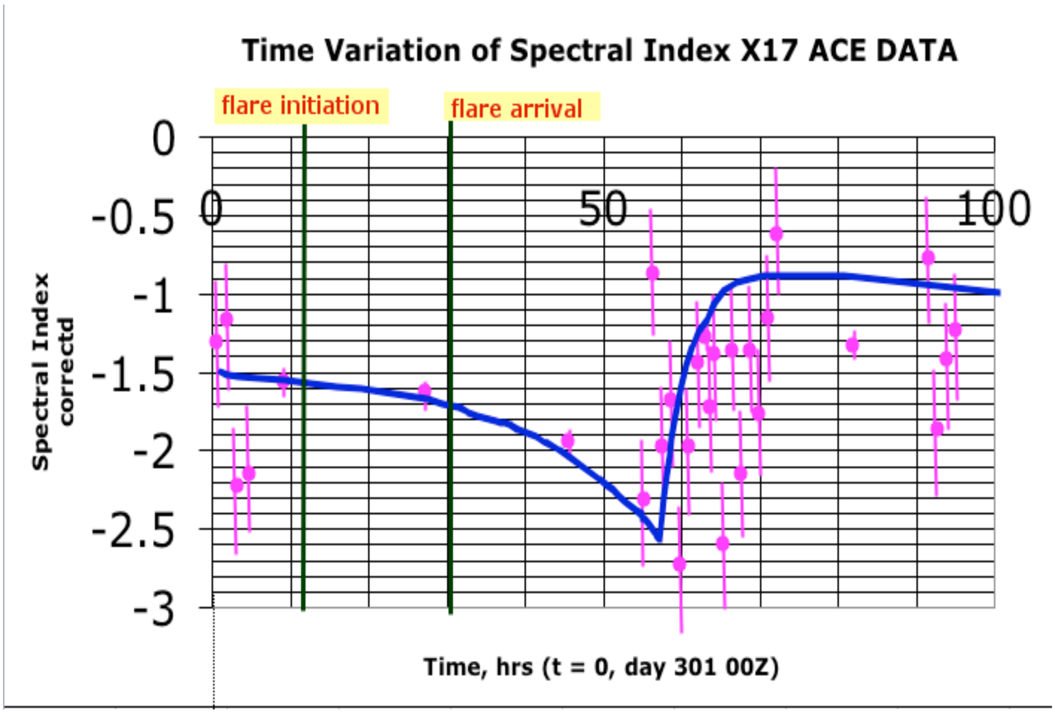
### 4.3.3 Results

The ACE spacecraft is sampling the solar wind in the vicinity of Earth's magnetic field boundary which gives a characteristic length of about 1 AU (Astronomical Unit), with spherical or cylindrical geometry. For an electromagnetic transverse wave of any kind, the fundamental should be around $c/2\pi R_{S\text{-}L1}$ or 324.5 μHz; i.e. in the order of 100 MHz or 0.1 MHz. Published values include this: 0.4, 0.7, 1.0, and 1.3

MHz[19].

Experimental results support calculated values with predominant resonances seen in the 0.35 +/- 0.05 MHz band. The WIND spacecraft was near L2 at the time of the X17 flare arrival ~200 earth radii and with an effective radius < 200 $R_E$ and a lower bound of fundamental ($c/400\pi R_E$) ~37 MHz.

Experimental observations indicate resonances consistent with this estimate; the strongest bands are around 20-22 and 30-34 MHz and 68 MHz (probably a harmonic) (see Figure 16).




[19] Alfven waves (Surveys in Geophysics, 2005), Robert L. McPherron, Volume 26, p. 545–592

**Figure 16 Mapping of descending tones heard corresponding to Spectral Indexes.**

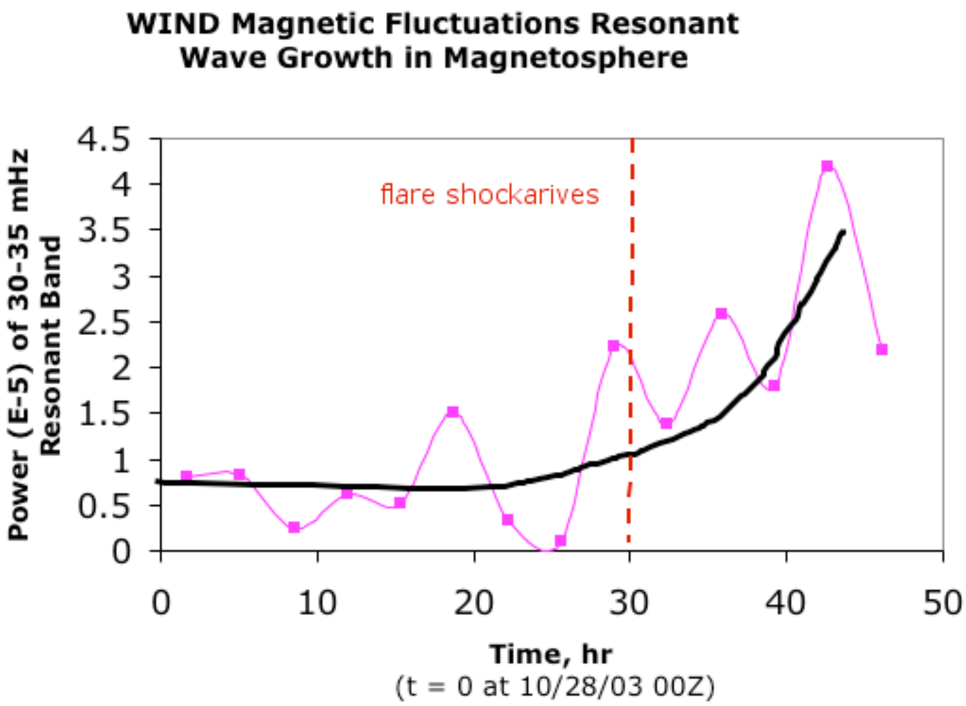



**Figure 17 Wind magnetic fluctuations resonant wave growth in magnetosphere.**

Quasi-oscillatory may be due to some kind of trapping mechanism at reconnection point. Spectral Parameter Analysis, p = -5/3, characteristic of turbulent plasma (see figure 16 and 17). Figure 17 shows shock arrival to WIND satellite and the exitation of the plasma afterwards.

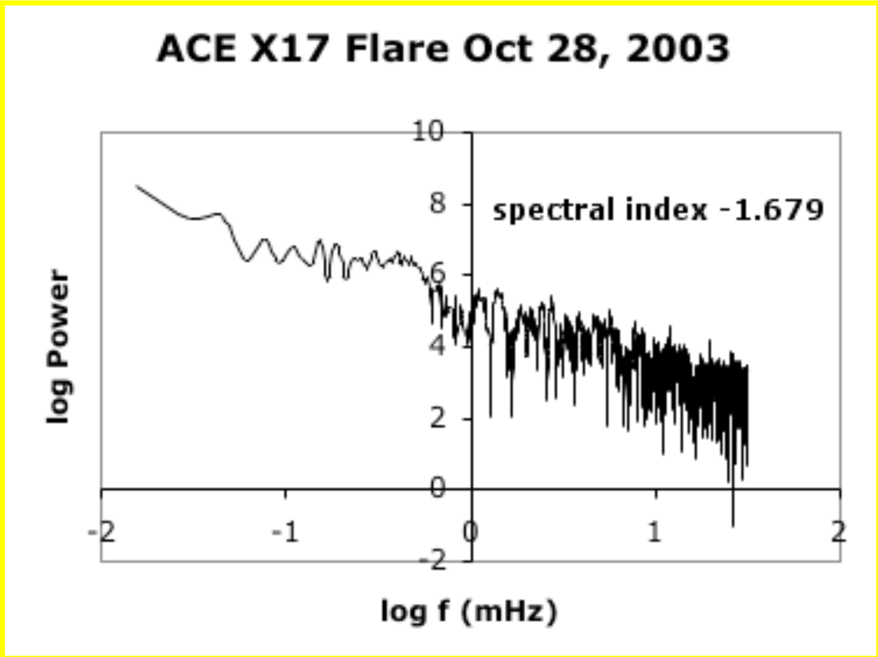



**Figure 18 Temporal evolution of Power Law Plot (solar Wind ACE)**

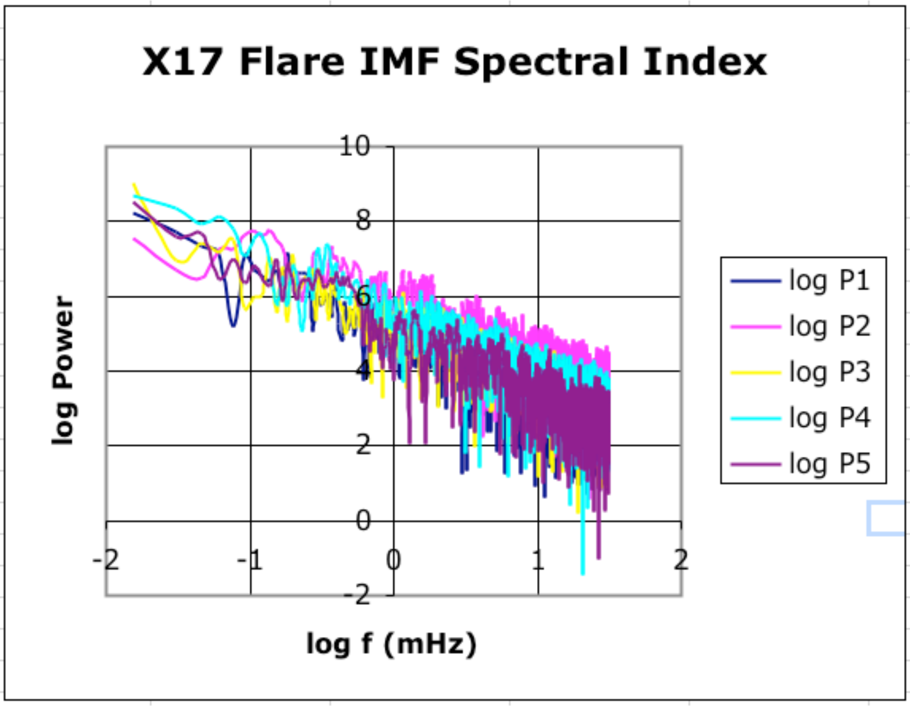



**Figure 19 Interplanetary Magnetic Field Spectral Index.**

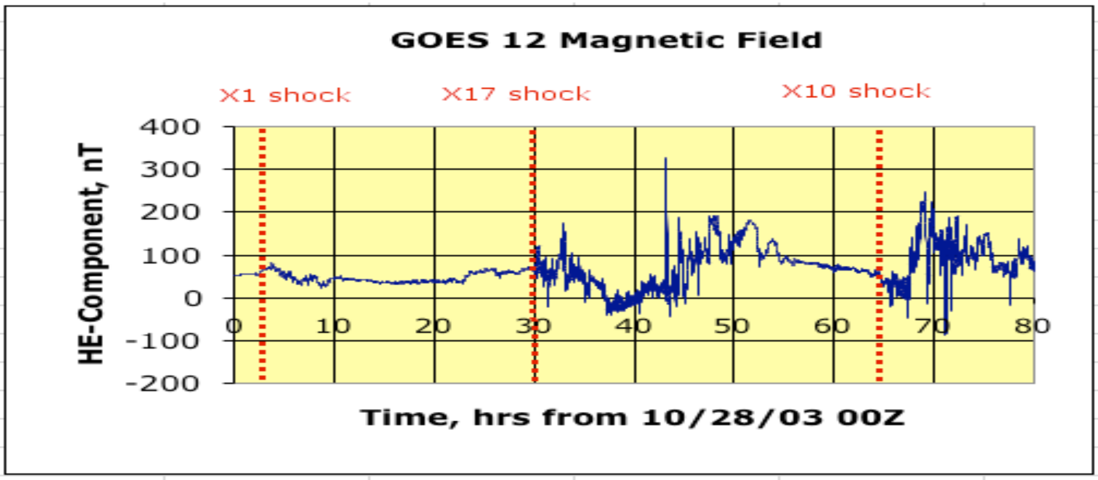



**Figure 20 Interplanetary fluctuation aftershock.**

Looking at Figure 20 it is worthwhile noting that: the delay in magnetic fluctuation aftershock arrival => importance of orientation of the interplanetary magnetic field.

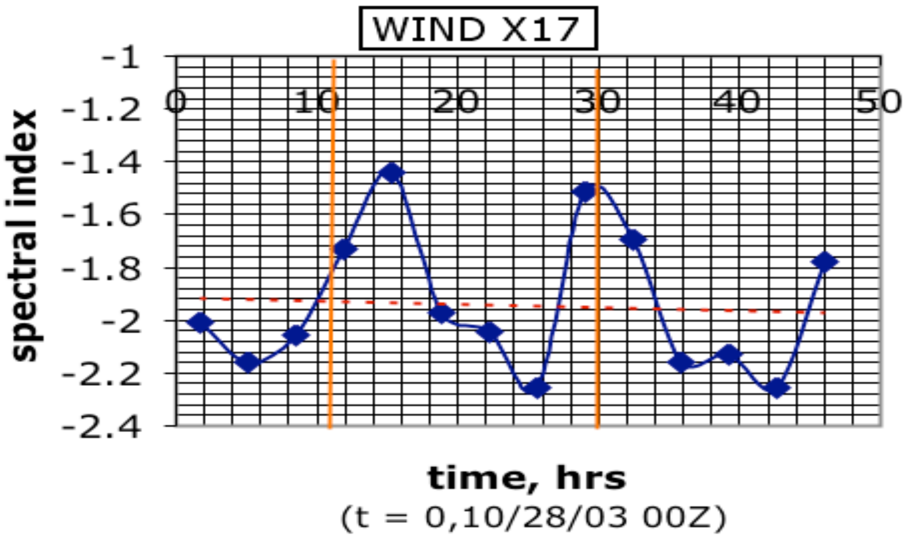



**Figure 21 Inside the magnetosphere.**

Looking at Figure 21 it can be seen that it is not as turbulent inside the magnetosphere, (p = –1.9 +/- 0.4). Particle injection where the tails thins and magnetic reconnection provides a path for turbulent plasma, (p = -1.5). Note correspondence of our tones heard and the IMF (interplanetary magnetic field spectral index). Particle injection where the tail thins and magnetic reconnection provides a path for turbulent plasma, (p = –1.5).

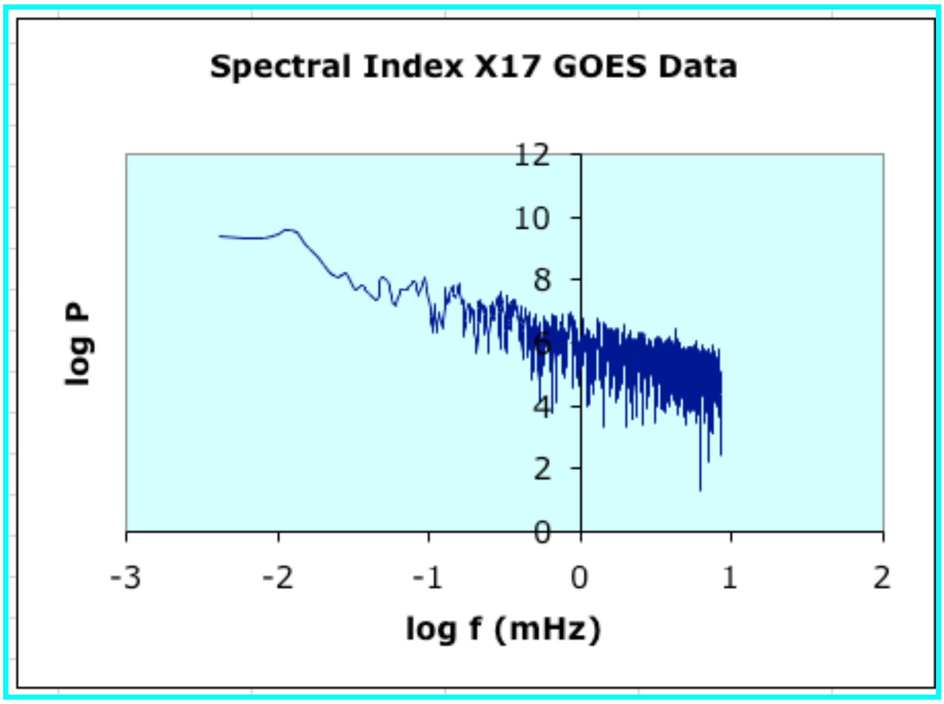



**Figure 22 A Preliminary spectral index of -1.20.**

It is expected the spectral index becomes more negative as the shock arrives to the satellites, e.g. during solar flares (Figure 22). The GOES satellite data preliminary Spectral Index -1.20 was not as negative as heard in the sonification. Sonification might be indicating events for which characterisation of the descending tones have to be developed. Listening to turbulent data can be meaningfully done in frequency space and it might also be possible to detect the differences in phase velocity. Listening to the power spectra may also be meaningful in the frequency space, by restricting the hear-to-decade windows between 10-1000 MHz. The descending tones and frequency average levels will correspond to the spectral index.

Direct Mapping Sonification (Florian Grond, 2012) has so far been useful to detect unexpected changes in the data analysed e.g. Kolmogorov power spectra -5/3 in slow solar wind swift data. Sonification provides an accessible tool to examine the impact of a major solar flare on the solar wind, magnetosphere, and ionosphere. It is necessary to develop a three-dimensional analysis of fast solar wind and slow solar wind using sound for extraction of vector components for further correlations.

Energy transfers from particles to waves (turbulent cascade), as p goes from -1.5 to -2 or lower. The transfer seems to lag behind the passage of the shock, p oscillating wildly and randomising the plasma.

This section successfully presents characterisation of the sonification using Fourier transformations and provides an approximation to the physics in the data, (turbulent cascade mechanisms etc). Sonification might be indicating local changes better characterised with non-stationary data assumptions. Documentation on how to listen to different space-physics data sets and sonification techniques has to be developed to extend sonification as a reliable data analysis tool to the entire scientific community. Currently, perception experiments are being designed and carried out to prove that sonification techniques may be used as an adjunct to space physics data visualisation by the sighted.

With sonification the impact of a solar flare on the solar wind, magnetopause and ionosphere was examined. Power spectral density analysis supports turbulent cascade mechanism for particle-wave interaction.

## 4.4 Sonification in the Analysis of Magnetic Field Fluctuations: Messenger Crossing Data Second Flyby

The following presents a frequency analysis using sonification techniques as applied to Messenger Magnetic Fluctuation Data to determine gradients in the inner heliosphere. Solar physicists requested to sonify frequency magnetic fluctuation crossing data to determine gradients in the inner heliosphere. The vector components (radial, tangential and perpendicular) of the magnetic field intensity were sonified. The radial (Br), tangential (Bt), and perpendicular (Bz), components were sonified throughout the approach and departure of Venus (3/10/07-5/22/07) and Mercury (12/20/07-1/13/08).

A female blind listener in the age range 31-40, having a tonal native language, heard the data and characterised the behaviour of the vector components.

### 4.4.1 Perceptualisation Technique

The gradient of interest is a strongly solar cycle dependent characteristic. The power spectra of the magnetic fluctuation data were sonified in order to analyse the frequency content of the data. The relative high or low frequency of discrete or noise sound would give information on instantaneous frequency changes. The notes are approached as the product of several frequencies, harmonics, fundamentals, etc. Magnetic temporal fluctuation information is portrayed as a simultaneously sounded cluster of pitches. Each data set was mapped in pitch active each time for phase, frequency and time variations. The different spans were grouped and then extracted from the data. Those correspond to systematic parameters that have to be extracted from the data to remain with the gradients of interest.

90 sets of 24 hour data sets were sonified. Each set of data comprised of 86200 data points. The data were heard in sets of two hours, each set of two hours overlapping by ten minutes with the previous one. The data time resolution was 1 second. The C and C sharps correspond to 40 MHz.

### 4.4.2 Results

#### 4.4.2.1 Cumulative monthly magnetic field fluctuations

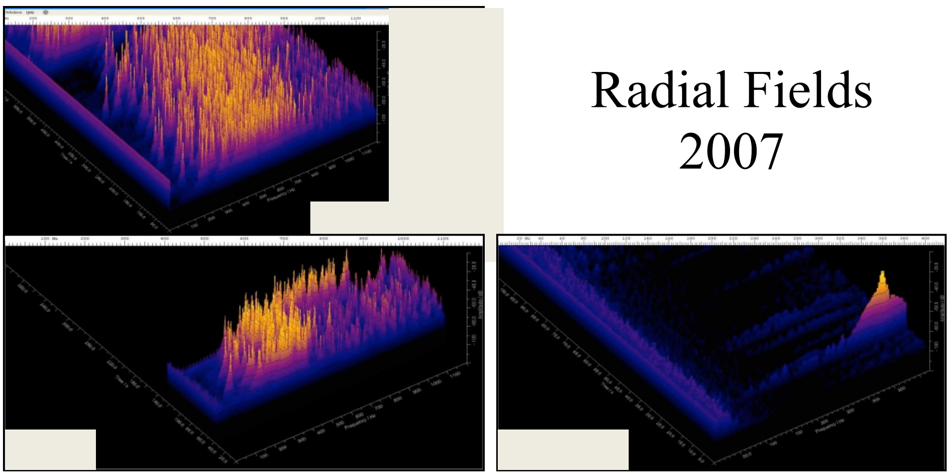



**Figure 23 Radial magnetic fields. Messenger April, July and August 2007.**

**Br April 2007**

Frequencies are distributed densely between 30 and 90 MHz from about 75 to 500 units of time (the time scale runs from 50 to 700 (Eastern Standard Time) corresponding to the continuous days analysed), then there is an abrupt break, at least at the lower frequencies, until at around 600 time units. With the noise floor at –100 dB, the peaks at 800 x $10^{-4}$ Hz or 80 MHz were between 0 and –10dB. The data are shown in Figure 23.

Br July 2007

On sonification, an unexpected diminishing of the frequency intensity as well as the distribution was noticed. The strongest was heard at around the 30-50 MHz band, but extended to 90 MHz at the end of the month.

Br August 2007

There was a small gap around 3-7 MHz throughout the whole run. The data is very sparse with much lower or non-detectable noise floor. There is a noticeable blade of frequency at 40 MHz (-10 dB).

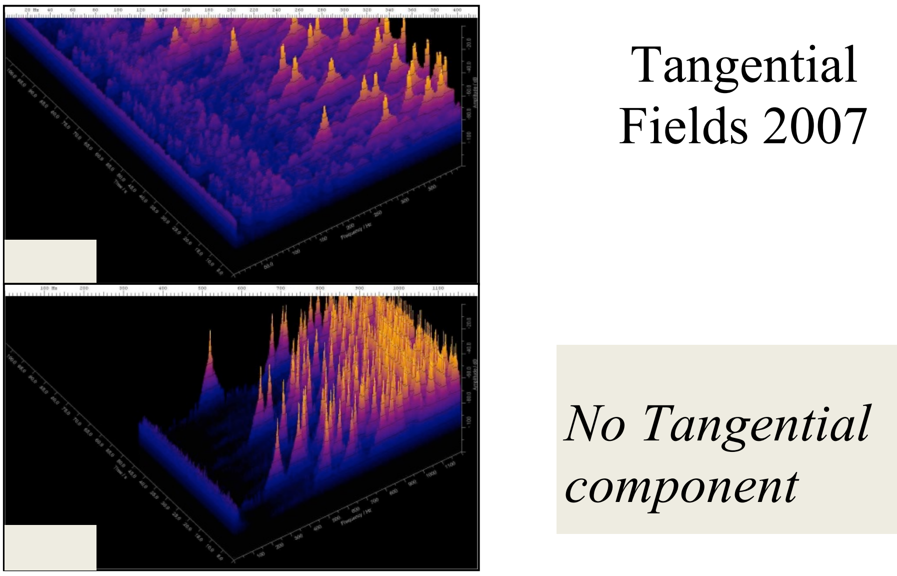



**Figure 24 Tangential magnetic fields. April and July Messenger Crossing data.**

Bt April 2007

The frequencies are far sparser and broader than Br April 2007. Peaks are between 20 and 40 MHz becoming quiescent after 80 time units. The data are shown in Figure 24.

Bt July 2007

The frequency scale is up to 130 MHz. There is a rapidly growing density of resonances starting at 35 MHz becoming more dense along the time axis at higher frequencies.

Bt August 2007

The data is file missing; No data available for Bt component of magnetic field so it could not be analysed.

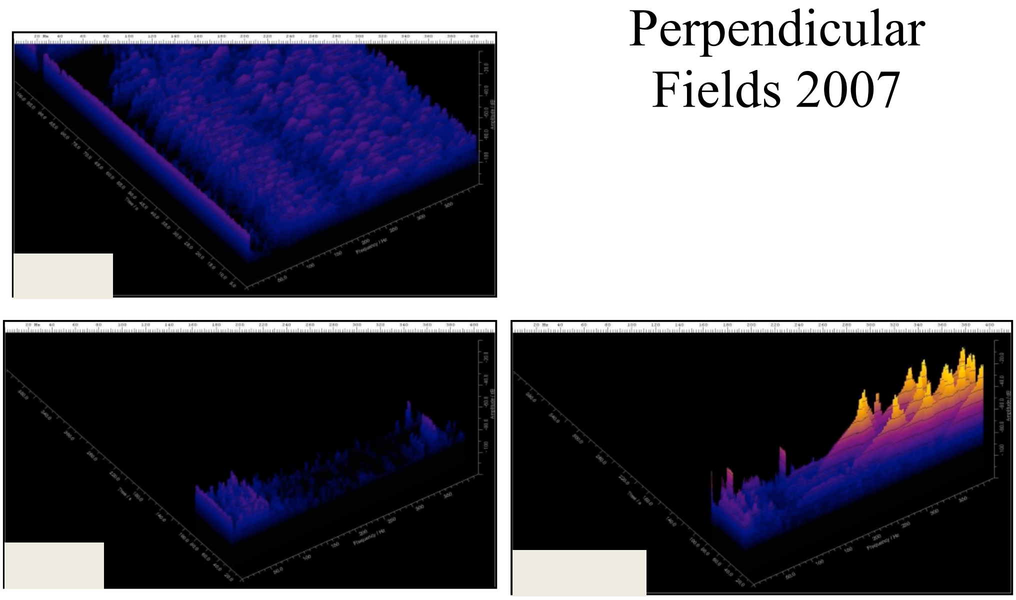



**Figure 25 Perpendicular magnetic field components. Messenger crossing data.**

Bz April 2007

The same scale is shown as for Bt April 2007. There is a quiet noise floor. Density of frequencies at 11-17 MHz and then again 25-35 MHz. Between 60 and 100 time units, there is a slight blanking of the low frequencies, below 15 MHz.

Bz July 2007

It is interesting to note that the z-component remains very diminished and slightly shifted through July (5-7.5 MHz and 35-40 MHz).

Bz August 2007

August shows a sudden growth, 25-40 MHz.

### 4.4.3 Discussion

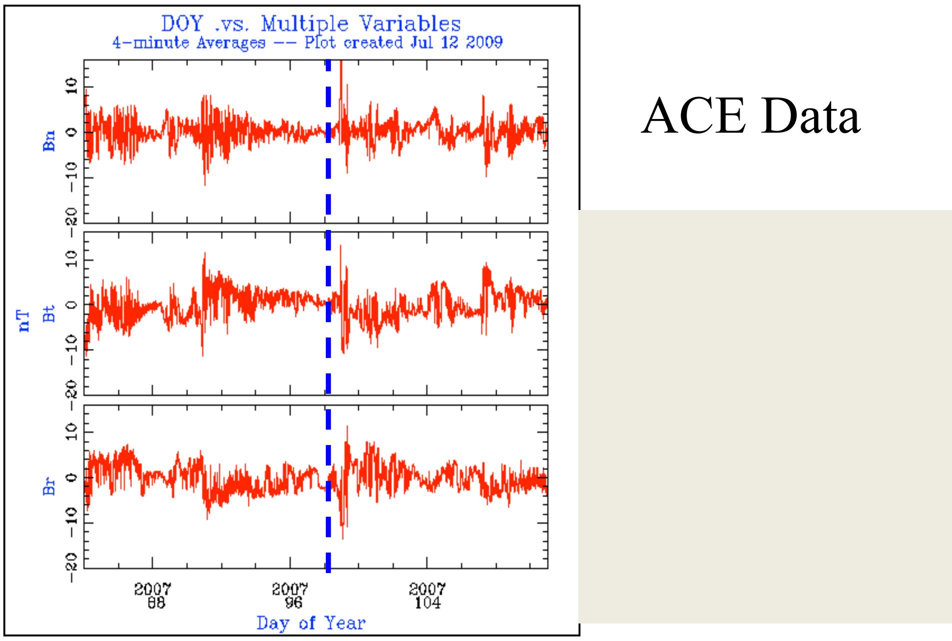



**Figure 26 ACE Interplanetary Magnetic Field Data.**

Normally, the vector components, Br, Bt and Bz values are very different. To validate the perceived noted behaviour, previously described in the data, a comparison between April 6$^{th}$ and April 8$^{th}$, 2007 was performed. The latter was done because all vector components produce marked increases in frequencies for the latter day. Solar and Heliospheric Observatory (SOHO) data does not show anything remarkable except for a sun spot group 0951, but is only responsible for the B-class X-ray bursts.

However, Advanced Composition Explorer (ACE) data did show a slight increase in the magnetic field variation (all components) (Figure 26).

Days 96 and 98 corresponded to April the 6$^{th}$ and 8$^{th}$ on the B-field plot. A disturbance is noted on day 99, but keeping in mind the great difference in distance from the sun between Messenger and ACE in April (about 0.5 and 1 AU, respectively.), the disturbance, which is likely due to an increased particle flux from solar flaring, would arrive at Messenger a day earlier than at ACE. This puts the time of arrival of the magnetic disturbance at messenger at day 98 or April 8$^{th}$. Because of the closer proximity of the sun, the disturbance may have been more concentrated (less dispersed). Currently, this is the hypothesis to explain the differences in the frequency analysis between April 6$^{th}$ and 8$^{th}$, 2007.

### 4.4.4 Conclusions

Messenger data for the first flyby has been sonified in order to identify systematic parameters; further data validation gathering from a constellation of satellites validated the sonifications: ACE, GOES, THEMIS and WIND.

The changes heard (April 6$^{th}$ and 8$^{th}$) may correspond to stellar outflow. The frequencies heard at 30 MHz correspond to the solar wind frequencies validating the perceptualisation technique.

The Messenger data analysis using sonification proved useful in comparing the behaviour of the vector of magnetic field fluctuation data. The comparison of the radial components of the magnetic field using sonification gave a good approximation of the progress of an outflow as it arrived to the ACE satellite. The sonification allows the author to test if the perceptualisation technique was accurate. The latter as ACE data was listened to in order to corroborate events. Upon reporting the un-usual behaviour of the radial, tangential, and perpendicular component of the vectors, e.g. radial component intensity diminished as the spacecraft approached the Sun when is expected to increase its intensity) sighted scientists verified the data and found that the data being saved at the archives was not real. The planetary division worked on the data and corrected the errors.

The use of sound to approach magnetic fluctuation data in frequency space successfully gave an insight of the behaviour of the vectors components. The latter further validates this dissertation proposal of the usefulness of using sound as an adjunct to visualisation to approach data sets.

## 4.5 Radio Data: Sonification for the Analysis of Plasma Bubbles at 21 MHz

Plasmas of the ionosphere, of interplanetary space and of the interstellar medium all contain irregularities. Propagation of electromagnetic waves, like optical or radio waves, through a medium with random fluctuations in Refractive Index results in amplitude and phase fluctuations. These variations may be displayed via sonification, using changes in sounds to represent the data variations. This is particularly useful for extending science to visually impaired people.

Radio Frequency radiation is emitted by billions of extraterrestrial sources. Some of these frequencies pass through Earth's atmosphere right into our domain on the ground. This brings information about these objects through the large portion of the electromagnetic (EM) spectrum. Radio radiation allows us to look at objects that emit relatively low energy. This includes dust and gases in the galaxy and solar system. To space scientists, radio has 100 times more observable wavelengths than optical. There are several sources of noise in radio astronomy. Firstly, there is the noise associated with objects in space. Any object will emit EM radiation at varying intensities and frequencies therefore generating a random noise background level. Secondly, there are man-made signals which affect into our frequencies of interest e.g. electric blankets, cell phones, laptops, digital cameras, etc. Thirdly are the electronic noise sources brought about by quantum fluctuations within chips and other electronics.

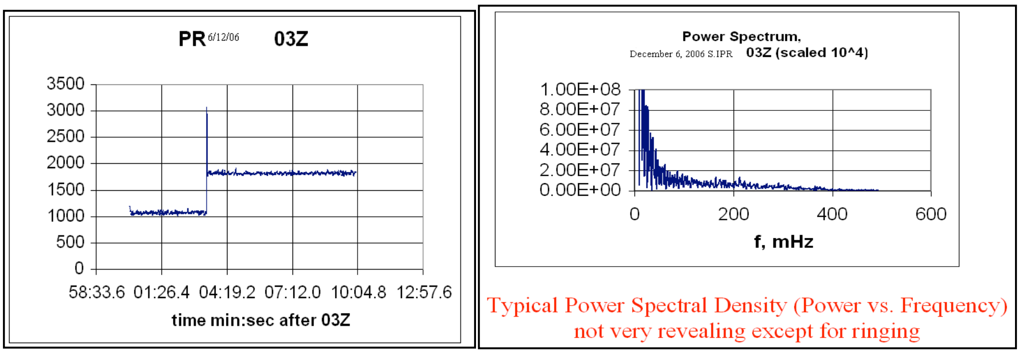
Chapter 2 reviews the different types of noise and the struggle space scientists face in eradicating pervasive noise. In many radio astronomy observation programs, the signal is many times smaller than the background noise and the signal must be detected using a variety of techniques. Larger antennas have larger collection areas for gathering more signals and have longer integration times (for averaging of data etc). Sonification used as an adjunct to visualisation may offer the space scientists an alternative to better identify signal from noise. This section presents an exploration of radio data using sound.

### 4.5.1 Method and instrumentation

Data presented here were collected by means of the improved Radio Jove receiver, RF-2001A, located at the grounds of the Rosa Cecilia Benitez Elementary School in Caguas, Puerto Rico. The students performed an experiment suggested by Dr. John Mannone from the University of Tennessee, for the detection of plasma bubbles in the ionosphere. A local oscillator generates a waveform at frequencies around 20.1 MHz (19.950-20.250 MHz). The incoming signals are amplified by a factor of 10. The receiver input circuitry is designed for a 50 Ohm antenna.

The double dipole antenna (Radio Jove) is 10 feet above the ground, aligned east-west, in-phase, so the beam is directly overhead. The maximum gain for a horizontal dipole is 7.3 dB, beam width is 115 degrees. The data was mapped to sound, by means of the xSonify Prototype developed for the purpose of this thesis.

This experiment required a radio telescope centred at 20 MHz to be located close to the magnetic equator. The closest radio telescope to the magnetic equator at 20 MHz radio background noise was Shirohisa Ikeda Observatory Puerto Rico. Data was gathered on December the 6th, 2006, at 11 pm local time to generate signal strength versus time data set.




Interplanetary Magnetic Field Data: **4 Minute Averages** (27-day Bartels rotations).The blue dashed line shows April 8, 2007.
http://www.srl.caltech.edu/ACE/ASC/level2/lvl2DATA_MAG.html

**Figure 27 Shirohisa Ikeda Observatory Puerto Rico, Signal Strength versus Time Graph.**

December the 6th 2006 at 11:00 pm local time, at 10 minutes time series sampled at 1 Hz (990 +/- 7 MHz) during "heard" event.

The typical power spectral density (Power vs. Frequency) was not very revealing except for ringing. Frequency plots were more revealing and are displayed in fig. 27.

### 4.5.2 Perceptualisation/Sonification Technique

On December 6th, 2006, data were gathered for the detection of charge deficient holes (plasma bubbles) in the ionosphere. Data were collected hourly for a period before sunset until after sunrise (6 pm to 6 am Atlantic Standard Time (AST)). Arbitrarily, the antenna signal was sampled for the first 10 minutes of each hour. The sampling rate was 1 Hz. 12 sets of base line were collected. Fig. 27 shows the sample recorded at 11 pm AST.

The data were collected and the power spectra sonified in the frequency space, as in the frequency analysis where discrete resonances, combs and bands are exposed by holding the volume constant and the pitch active. These settings were used for sonification based on the fact that exited cavity modes lead to resonant lines: fundamental vibration and its harmonics that might be picked by the ear. The volume range was kept at 4 dB (70% of its 100 range), the tempo was at 4 bpm and an observation log was filled during the hearing of the sonification.

Various types of scintillation lead to different spectral indices: the quiet sky - 0.65, typical ionospheric scintillation - 8/3, plasma bubbles - range 2-8 with average 4, tropospheric scintillation - 11/3, interstellar scintillation - like ionospheric without seasonal or geographic restrictions. The power spectrum in Power vs. Frequency plot – an example shown in previous figure – is not very informative. The Spectral Index p is obtained from log Power vs. log Frequency plot; the spectral behaviour is examined from the range 100-1000 MHz.

### 4.5.3 Results

On sound perceptualisation perceptualisation(Henrietta Mustovic 2003)(Justus and List 2005)an increase in the baseline pitch was recorded at 11:00 pm local time (03Z), coinciding with ionospheric recombination time. Though the plasma bubbles only survive around 30 minutes, the antenna is seeing numerous irregularities (future experiments will acquire more data over a shorter time interval and at higher sampling rate). Figure 28 presents the examined spectral regions before and after this event. Spectral Index p = 5 for plasma bubbles over San Juan, Puerto Rico.

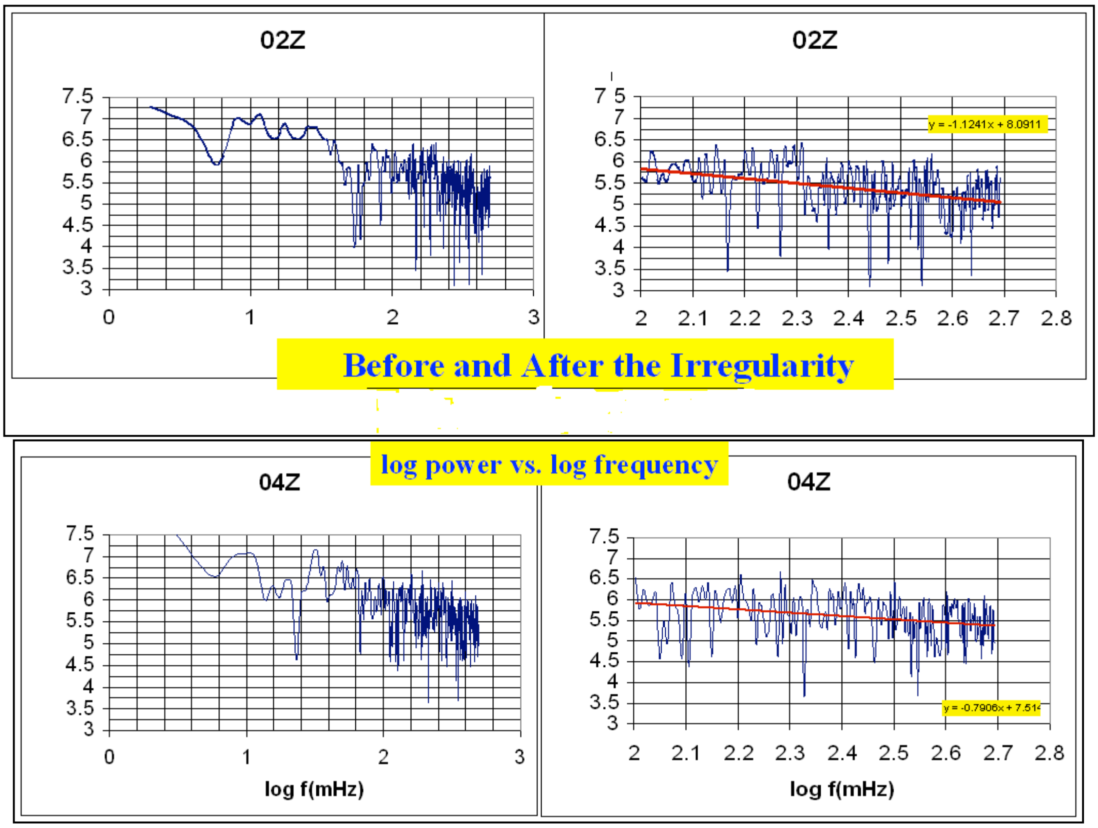
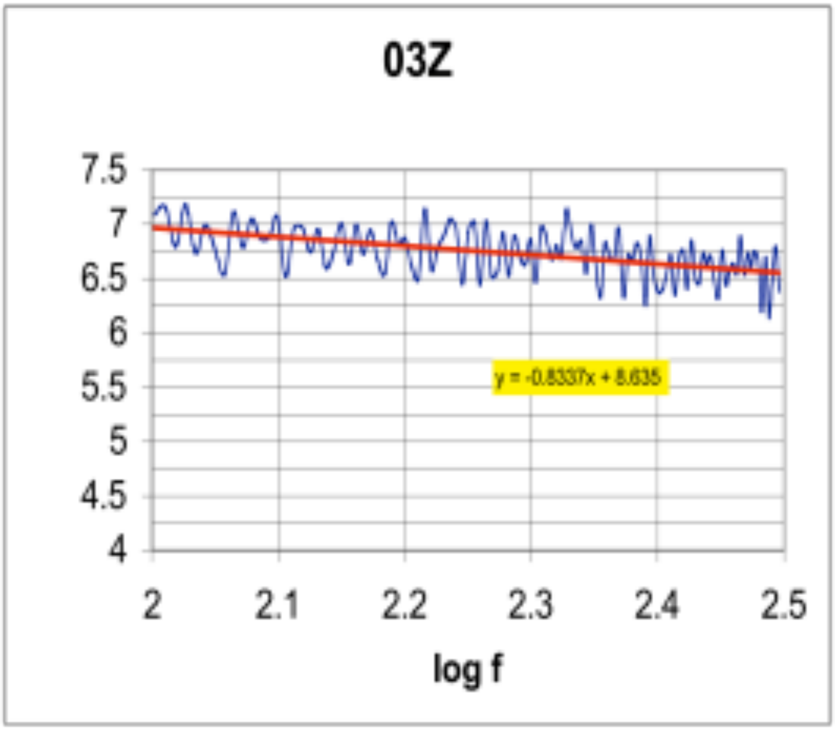



**Figure 28 Power Spectra of regions before and after the irregularity confirms the pitch changes heard.**



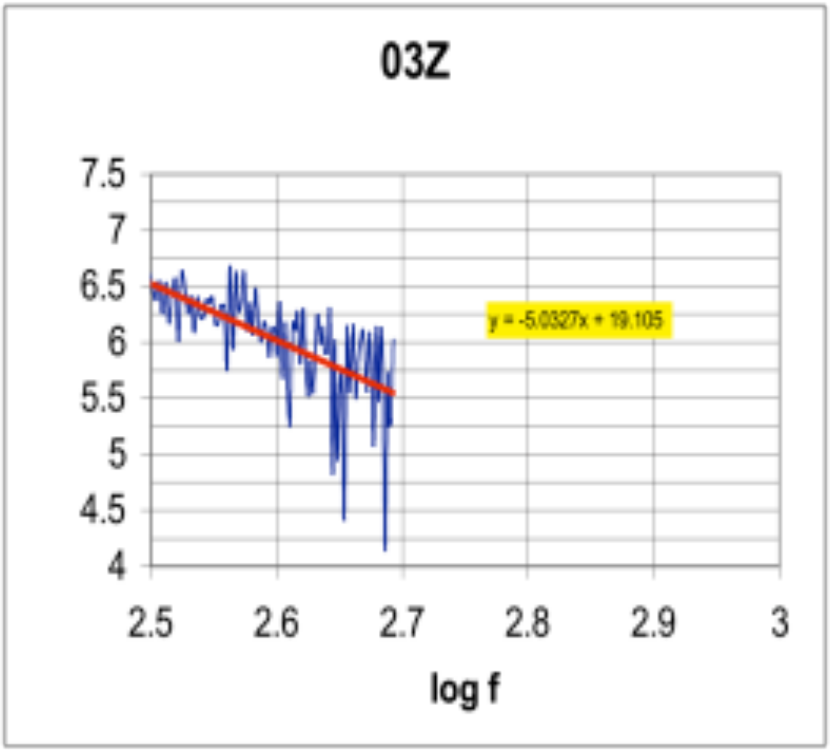




**Figure 29 Major changes are indicated in the condition of the ionized layer during the measurement interval.**

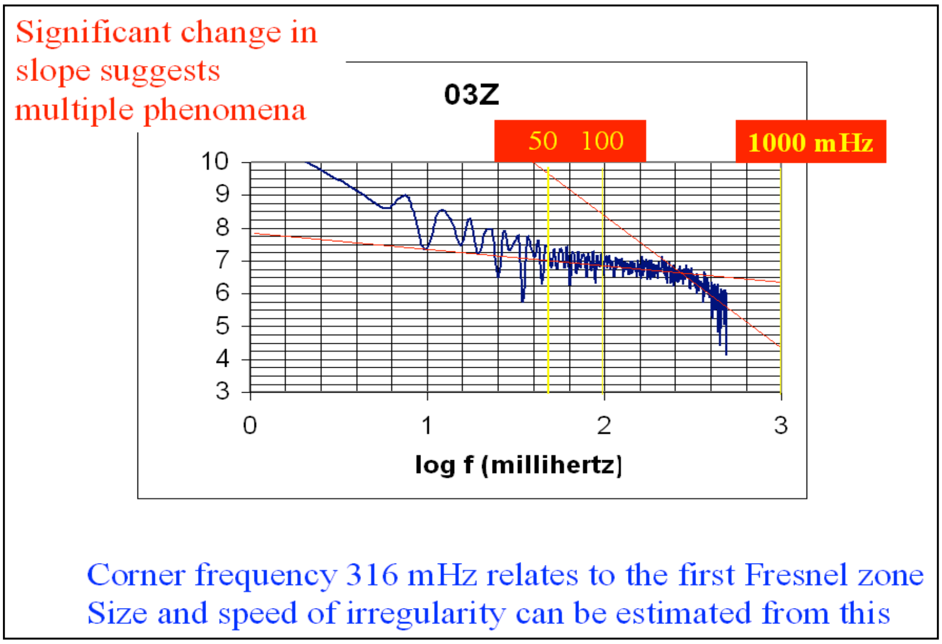



**Figure 30 Post-sunset (-01Z) and Pre-midnight(+04Z).**

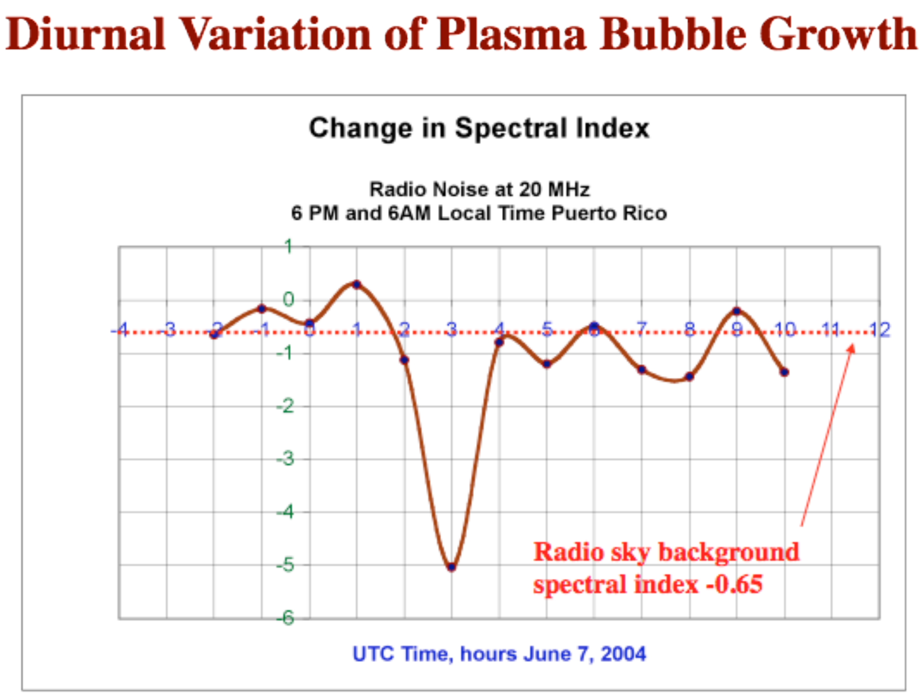



**Figure 31 Growth of Suspected Plasma Bubbles.**

### 4.5.4 Conclusions

In the context of using sound to analyse radio data, frequency domain analysis using sonification especially over a particular range, revealed some very interesting features interpretable in terms of scintillation (radio twinkling). More baseline studies, acquired at higher sampling rates have to be done to corroborate the findings. Auditory exploration of data via sonification is promising for complex or rapidly/temporally changing data sets, for data exploration, especially with large datasets, and for exploring datasets in frequency rather than spatial dimensions.

When using sonification, listening to turbulent data can be meaningfully done in frequency space and it might also be possible to detect the differences in phase velocity. The power spectrum is difficult to listen to, but as shown for solar data, restricting hearing to decade windows between 10-1000 MHz would probably would enable one to detect frequency-averaged levels and descending tones and other changes in slope. These would correspond to spectral indices, which in turn, revealing something about the physical processes in the plasma.

The Radio Data sonification analysis presented in this section successfully helped to get an idea of changes in spectral index.

## 4.6 **Overall Conclusions**

This chapter presented four examples of data analysis using sound towards answering the research question: Does sound used as an adjunct to current data visualisation, augment the perception of signatures in space physics data masked by noise?. This section presented samples of data analyzed from the persepective of a practical approach to the exploration of space science numerical data using sound. The data presented in this section, was acquired by satellites as published by the space agencies data archives. The exploration of the data using sound proved to be effective for:

1. The search of QPO's that has been previously overlooked.
2. The analysis of the impact of a Coronal Mass Ejection (CME), on the Solar Wind.
3. The study of crossing data (Messenger Space Craft) showed that the data was not real and lead the team to debug the data.
4. The Perceptualisation of radio data searching for disturbances in the ionosphere.

The approach showed events that were either overlooked or unexpected in the data. This section also introduced the reader briefly to scientific papers and media publications from other space scientists using the sonification prototype to approach their data.

The techniques presented in this section proved effective on augmenting sensitivity to signal detection as applied to the particular examples presented here. The reader should keep in mind that this data was choosen only by availability and its common use by target audience (Space science data is acquired in situ or remote[20], by satelittes (e.g. ACE, Chandra, WIND), ground observatories (e.g. radio astronomy)). It has to be tested by carefully designed perception experiments if sound increases space scientists sensitivity to signal detection.

[20] See section 2.2.3

# 5 Perception Experiments

## 5.1 Introduction

Humans are continuously exploring, monitoring and experiencing information through sensory signals from multiple modalities. They engage in a perceptual judgment, resulting in a complex mapping of sensory signals. According to Massaro and Cowan (Massaro and Cowan 1993) (Massaro, Book Review: What Are Musical Paradox and Illusion? 2007) two stages occur between stimulus and response: sensory and decision. The stimulus is decoded to produce a sensory event as an output. This output is information used to make a decision that will lead to a response. The response is then the output of the sensory process and not of the stimuli.

This chapter presents experiments in which sound as an adjunct to data visualisation is seen as a process of physiological input systems. The subject interprets the stimulus (belief bias) and selects how to respond (decision bias), (Massaro & Cowan, 1993). The first, belief bias, has to do with the sensory process and the second, decision bias, with the decision process (O'Hare, 1991). As mentioned in chapter 2, space science data analysis involves a process of perceptualisation that determines the next stage of the data analysis. As mentioned in section 2.2 an early perceptualization of any signal living in space physics data will broaden the probabilities of finding events in the data. In this context, the experiment presented here investigates and compares multimodal, bi-modal and unimodal stimuli to augment visually presented 2D data, in terms of associating it with sensitivity to signal detection (e.g. fleeting, non-persistent changes) so that the graphical signatures can be heard and not just seen with the eyes. This thesis proposes that the use of sound as an adjunct to visual display will augment visually presented data in the form of 2 dimensional graphs, by linking it to sensitivity of signal detection, e.g. fleeting, non-persistent changes. In this way, the graphical signatures can be heard and not just seen with the eyes.

Baldacci (Baldacci, Mega and Burr, 2006) evidenced that visual perceptual clutter leads to an increase in judgment errors and also to an increase in perceived signal strength and decision confidence on erroneous trials. In their studies, Baldacci *et al.* tested and evidenced that, in a cluttered visual environment; erroneously perceived stimuli should be seen at higher signal strength than when the target is presented in isolation. In their experiments, observers were briefly presented with a circular array of grating patches, all vertical except for the target, and were asked to identify the direction of target tilt (without necessarily knowing which of the targets was tilted). Participants reported simultaneously the direction and magnitude of the tilt of a target grating presented either alone, or together with vertical distractor stimuli (visual noise). When presented in isolation, observers perceived isolated targets as only slightly tilted on error trials, and had little confidence in their decision. When the target was embedded in visual clutter , participants perceived it to be strongly tilted on error trials, and had high confidence in their (erroneous) decisions. They also tested that not only discriminability thresholds worsen when visual perceptual clutter is present, but ‘‘observers make more high confidence errors when there are many distractors than when there are few’’.

The same principles could be extended to much more complex decisions like the detection of signal embedded in noise in astrophysics data. If the decision-maker has to monitor a low signal to noise ratio source on the basis of intensity and angle of visual fiel, and if each event is cluttered by dynamically changing visual noise, then according to this authors there will be a high probability that the decision will be erroneous and made with high confidence. High-confidence errors can have major consequences, as it implies a desicion indirectly proportional to uncertainty. As mentioned in Chapter 2, in space physics the signal as acquired by the satellites or ground observatories, is embedded in noise that becomes visual noise when plotted for analysis. Space scientist data analysis deals with the cognitive load of the noise that not only affects their judgement and confidence when identifying the signal but, at the same time, triggers mechanisms of attention that inhibit peripheral sensitivity (Schneps, 2007).

It has been proved by Magnetic Resonance Imaging (Schwartz, 2005) that task load in the periphery of the visual field suppresses perception in the centre, and task load in the centre is found to affect detection in the periphery, suggesting that the centre and the periphery interfere under attention task load (Inhoff, 2006), (Martinez-Conde, 2006), (Posner, 1994) and (Rucci, 2007). In the case of astrophysics, the signal may be anywhere in the data (periphery or centre), for example if the data analysis is computationally expensive, time sensitive (among others), visual perceptualisation of any signal living in the data may be compromised.

The interest in exploring the potential of using sound encoding of numerical data has increased[21]. Data sets are becoming too large to be handled with current visualisation tools as discussed in Chapter 2. Each event in the interstellar medium is the product of a number of oscillatory modes. Those events may be quasi-periodic, non-persistent, masked by noise, fleeting, etc. Traditional techniques for the analysis of space physics data such as radio, particle, magnetic fluctuation and X-ray are based on visual exploration of data[22]. Additionally, various nonlinear time-series-analysis methods (Tong, 1990), (Kantz and Schreiber, 1997), (Diks, 1999) were designed for nonlinear but stationary and deterministic systems (see Chapter 2 for more Information).

Space scientists base the data analysis on fitting the data to waveforms determined by the problem at hand, linearising and or estationarizing the data (mean and variance do not change if they exist). Unfortunately, in most real systems, either natural or human-made, data are most likely to be nonlinear and non-stationary.

Space physics and its graphical representations have mostly been visual and or uni-modal. The size of space physics datasets is always increasing, saturating the visual perceptual system when rendering for visual display. Another limitation is that, even the best computer screens available on the market today have a limited spatial resolution. This limitation affects the useful dynamic range of the display, reducing the

[21] See papers published at ICAD.org
[22] See chapter 2 - Review of Data Visualisation Methods Used in Space physics for a more detailed explanation

amount of data scientists can study at any one time. Scientists currently work around this limitation by filtering the data, so as to display only the information they believe is important to the problem at hand. But since this involves making some *a priori* choices about the results they are searching for, discoveries may be missed.

Van Ee demonstrated using a novel paradigm that congruent auditory or tactile information, and combined auditory–tactile information, aids attentional control over competing visual stimuli and *vice versa*, (v. B. van Ee, 2009). Van Ee studied attentional selection, using perceptually ambiguous stimuli in a novel multisensory paradigm that combined competing auditory and visual stimuli. They demonstrate that the ability to select, and attentively hold, one of the competing alternatives in either sensory modality is greatly enhanced when there is a matching cross-modal stimulus, (v. B. van Ee, 2009). In those experiments, the competing visual rivalry was an ambiguous concentric pattern in one eye and a non-ambiguous rotating radial pattern in the other.

In the Van Ee experiments, the mean multimodal attention gain, amounted to 29.3% +/- 5.8% indicating that the subjects were more successful in perceiving the visual ambiguous pattern when a matched sound was present as opposed to when sound was omitted. The same attention related change was calculated for a non-ambiguous pattern with an unmatched sound present, (-3.8 +/- 3.8%) and indicated that the presence of the unmatched sound decreased the ability to visually perceive the pattern.

Van Ee proved that congruent sound aids attentional control over visual ambiguity. Van Ee demonstrated the latter by exposing volunteers to binocular rivalry with sound and no sound under passive and non-passive conditions. Van Ee also performed experiments in which volunteers were exposed to the sound and binocular rivalry and found that the mere presence of a matched sound did not automatically trigger the ability to select and hold looming visual stimuli. Instead, He found that an explicit act of attention to the audio stimulus is required to have control over the visual stimulus. Moreover, it has been shown that a sound presented in synchrony with a visual stimulus in tasks requiring the detection of visual targets enhances the sensitivity to specific visual features like contrast (Lippert, Logothetis and Kayser 2007), intensity (Stein, 1996) (Stein, et al. 2009), and pattern configuration(Vroomen and de Gelder 2000).

This framework is used in this thesis to prove or disprove, that the use of sound as an adjunct to visualisation is associated with sensitivity to space science signal detection. In that sense if the precense of a congruent sound aids to disambiguate an ambiguous visual stimuli, it may be possible for the presence of sound to aid astrophysicists to disambiguate space science data. Van Ee instructed volunteers to pay attention to either the centre of the visual field, the sound or the visual pattern.

The innovation in this thesis is on presenting dynamically changing ambiguous visual patterns and using the above mentioned results to show that sound aids signal detection over a dynamically changing visual cue. Three experiments were conducted for this purpose. The first experiment creates a base line, using unimodal stimuli, visual and audio separately, and then both stimuli together. The second and third experiments add a third visually congruent cue, which is a red-line sweeping across the spectra at the same rate the sound is played, making the sound physically congruent with the ambiguous visual cue and providing an explicit control over the audio stimuli.

The ever-increasing sampling rate of space science data generates datasets containing several hundreds of thousands of data points. The scientifically interesting part of the data or signal may be anywhere in a dataset. This data is characterised by the presence of noise (Starck, 2007), which is always present.

Most of the time, knowledge is available on the detector's noise so the noise may be filtered (e.g. common noise distribution is determined by its variance) to remain with signal, and it has to be differentiated from noise or clutter (Starck and Murtagh, 2006) and by definition is not compressible.

The signal may be non-persistent, fleeting, quasi-periodic, masked by noise, for example. For this reason, noise is estimated and filtered from the data. Astronomy calls for the holistic integration of visuospatial extended information, sensitivity to fleeting changes occurring away from the direction of gaze and masked by noise.

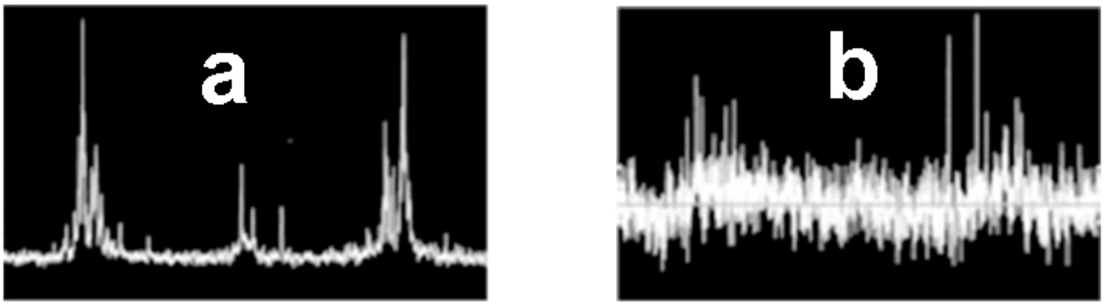



**Figure 1 (a) high and low (b) Signal-to-noise Ratio example of molecular gas orbiting the centre of a galaxy.**

The experiments in this Chapter determined the signal-to-noise (S/N) thresholds where participants could correctly identify the presence of a simulated double-peaked "black hole" pattern and which was obscured by visual and the audio Gaussian noise generated from the participant's performance, as illustrated in Figure 1.

In the case of the black hole task, the high-spatial frequency noise (overlying the low-spatial frequency "signal") may act as a cognitive load that triggers mechanisms of attention that inhibit peripheral sensitivity. Though it may be difficult to precisely demarcate a centre to periphery boundary, for the purposes of this discussion, and in accordance with the literature review, with regards to the experiments presented in this research the centre to periphery boundary is taken to be at ~8°; where changes in attention response become pronounced (Plainis, Murray & Chauhan, 2001) and (Schwartz *et al.*, 2005).

The experiments presented here are based on the empirical measurement of performance based on correct answers. Given the research question serving as motivation to this section: Is sonification as an adjunct to data visualisation effective in allowing users to identify signatures in 2 dimensional space physics data sets, masked by noise? For this purpose, the visual Black Hole paradigm designed by Schneps (Schneps, 2007) was modified. Their experiments determined the visual signal-to-noise (S/N) thresholds for which participants could correctly identify the presence of a simulated double-peaked "black hole" pattern which was obscured by visual Gaussian noise. This paradigm was modified to evaluate participants' performance when experiencing audio and visual presentations of the same type of simulated double peak data. Three experiments were conducted.

### 5.1.1 Experiment 1

Visual stimuli presented at a static visual angle of 8 degrees. Feedback cues:

a) Visual

b) Audio

c) Visual and Audio together. Visual stimuli presented at a static visual angle of 8 degrees and congruent with the sound.

### 5.1.2 Experiment 2

Given the results of Experiment 1, these experiment were conducted with the presentations of 4 cues. Visual stimuli were again presented at a static visual angle of 8 degrees. Feedback cues:

a) Visual
b) Audio
c) Visual and audio together (visual and audio presentations synchronized)
D) Visual and Audio together with a red-line sweeping across the spectra at the rate the sonification is played (visual, audio and red line synchronized).

### 5.1.3 Experiment 3

Given the results from the previous 2 experiments, Experiment 3 was conducted with the presentation of 4 cues that serve as stimuli but incorporating a range of alternate degrees of visual angles. Visual stimuli presented at a dynamic changing visual angle of either, 8, 16 or 24 degrees for 1000 ms. Feedback cues:

a) Visual
b) Audio
c) Visual and audio together (visual and audio presentations synchronized)
d) Visual and Audio together with a red-line sweeping across the spectra synchronized with the sound played. Visual, audio and red line synchronized.

Some abbreviations are used to describe some of the experiment condition sets. These are as follows:

- A = audio only
- V = visual only
- AV = audio and visual only
- AVR = audio, visual and red-line

In the experiments presented in this section, the tasks, which consisted of the presentation of four cues, were used to compare user performance when trying to identify the signal in the presence of masking noise when experiencing each of those cues.

The users responded to the cues using the keyboard. A threshold analysis algorithm called QUEST, (Quick Unbiased and Efficient Statistical Three) (Shih, 2011) is used to calculate accuracy of these forms of thresholds.

A staircase algorithm monitored the responses and dynamically varied the amplitude of the "signal" Gaussians until a threshold at which participants responded correctly at 75% of the trials could be ascertained (determined each subject's 75% threshold sensitivity for the correct identification for each condition). A Bayesian adaptive staircase procedure (Watson, 1983) which uses all previous trials to estimate the parameter T, the threshold, of psychometric function, was used to measure S-N sensitivity thresholds in the black hole task for each of the three span conditions in the task (8°, 16°, and 24°).

The experiments presented in this chapter investigate the hypothesis that sound as an adjunct to data visualisation will increase participants' sensitivity to identify the presence of a simulated double-peaked "black hole" pattern in simulated data, when those signals are changing in intensity and visual field angle. This research used a task which simulated the process astronomers adopt to search for the characteristic indicators of black holes (Kondratko, 2006). The task derives from the idea that a Black Hole exists in the centre of each galaxy.  The molecular gas around the Black Hole emits symmetric double peak spectra, which is characteristic with the presence of a Black hole. This signal was simulated for the experiments.

Three experiments were conducted and details of these can be seen in Table 2. In the first, participants took part in conditions: 1, 2 and 3. In the second they took part in conditions: 1, 2, 3 and 4. In both experiments the separation of the two Gaussian signals did not change (Non-Dynamic Visual, NDV), being set at 8°. In the third experiment participants took part in conditions 1, 2, 3 and 4 varying the separation of the two Gaussian signals by 8°, 16° or 24° randomly (Dynamic Visual, DV).

| **Condition Set** | **Condition** | **Experiment 1 NDV** | **Experiment 2 NDV** | **Experiment 3 DV** |
|---|---|---|---|---|
| **1** | **V** | X | X | X |
| **2** | **A** | X | X | X |
| **3** | **AVR** | | X | X |
| **4** | **AV** | X | X | X |

**Table 2 Conditions versus Experiment Table. DV= Dynamic Visual, NDV= Non-Dynamic Visual.**

## 5.2 Experiment Description

Visual and Audio graphs of artificial "radio spectra" served as stimuli. Auditory stimuli were presented through Sennheiser HD 215 headphones. The volume of the sounds was adjusted to ensure participant comfort by 0 to 4dB. Stimuli were presented on a 20-inch Apple Cinema flat-screen LCD monitor viewed at a distance of 70 cm, with a resolution of 1680 by 1050 pixels and a refresh rate of 60 Hz. Stimulus presentation and data acquisition were controlled by custom software using Matlab (The Mathworks, Natick, Massachusetts), and the Psychophysics Toolbox (Brainard, 1997).

The visual stimuli (visual graph), based on the paradigm designed by Schneps and Pomplun (Schneps, 2007), were shown as white lines (luminance: 360 cd/m$^2$) on an otherwise black screen (3 cd/m$^2$). The width of this line was approximately 0.1° of visual angle, and the graph subtended 30° horizontally and 3° vertically.

In 'noise-only' stimuli, the vertical position of the graph at each horizontal pixel position was determined by Gaussian noise, and the graph was scaled to subtend 3° vertically. In 'signal' stimuli, a signal consisting of two positive, upward peaks was added to the noise before the scaling was performed. These peaks were modeled by identical Gaussian functions with standard deviations of 0.5° and variable, but equal, peak elevation. The quotient of peak elevation and standard deviation of the Gaussian noise in a given stimulus was operationally defined as its signal-to-noise ratio (S/N). The two peaks always occurred to the left and to the right of the centre at identical eccentricity. The span separating the peaks was 8° for Experiment 1 and 2 and 8°, 16°, or 24°, with random jitter in the span modeled by Gaussian noise with a standard deviation of 1.0°, for Experiment 3.

## 5.3 Experiment 1

The sonification prototype translated the continuous visual stimuli data (noise, signal + noise) into sound. The sound was created by using a weighted sum of the square wave and sine waveforms. In this way the listener will hear less edges and more of the fundamental tone when the sine is added. This will be because the square wave is composed essentially of the fundamental (F1) and an infinite series of odd harmonics The sonification of the data was defined by the following parameters:

1. Waveform modulation = 0 (if no waveform modulation, this is the waveform being used (0 = sine, 1 = square)
2. Stereo = 0 (no pan stereo = 0)
3. FadeDuration = 0.07 Cuts into the stimulus not to increase the overall duration of the stimulus.
4. Carrier frequency (for amplitude modulation) 880 Hz To avoid distortion.
5. Minimum frequency (for pitch modulation) = 110 Hz To avoid aliasing distortion (e.g over tone).
6. Octave range for pitch modulation = 6. Given literature review a 6 of an octave is recommended not to produce distortion.
7. Sample Rate = 22050 Hz. Used to preserve the noise.

The participants performed five blocks of trials for each condition and in random order. Each block consisted of 15 trials, with the presentation of each spectrum for 1000 ms. Participants were instructed to press the ‘S’ button on a computer keyboard if they believed that the current stimulus contained a signal and to press ‘N’ if they thought that there was no signal. There was no time limit imposed on participant responses. Immediately after pressing the button, participants were acoustically informed whether their response was correct (800 Hz sound played for 20 ms) or incorrect (400 Hz sound played for 100 ms).

Participants were allowed to move their eyes freely throughout the experiment and their heads were positioned with their heads centred on the screen using a chinrest for comfort at 70 cm from the screen. The first trial in each block presented a signal at a signal-to-noise ratio of 10, which proved to be quite easy to identify. The remaining trials were aimed at estimating the signal-to-noise threshold at which the subject gave correct responses in 75% of the trials.

This estimation was performed using the QUEST staircase procedure (Watson, 1983), (Pelli, 1987) with an initial threshold estimate of 1.5 (signal-to-noise ratio of 10) and parameters $\beta = 3$, (slope of psychometric function), $\delta = 0.01$[23] and $\gamma = 0.3$, (probability of success at 0 intensity). The threshold update between trials was based on the quantile method and the final estimate was determined by the mean method (Pelli, 1987).

### 5.3.1 First Experiment: 3 Conditions ND

The first experiment created the baseline. Separation of the Gaussians was 8° with equal eccentricity. Eleven space scientists age 20-45 took part in the study. None of the participants had participated in experiments related to this research before. They were recruited via an e-mail to scientists at the Centre for Astrophysics in Massachusetts and through personal contacts. They were paid $10 an hour in Amazon gift cer-

[23] Beta controls the steepness of the Weibull function. Many vision studies use Michelson contrast to control the visibility of the stimulus. It turns out that psychometric functions for 2afc detection as a function of contrast have a beta of roughly 3 for a remarkably wide range of targets and conditions (Nachmias, 1981). The psychometric function is sigmoidal, with a flat floor, a rise, and a flat ceiling. To estimate threshold you want all your trials near the steepest (roughly speaking) part of the rise. To estimate beta, the steepness of the rise, you want to have most of your trials at the corners, where the rise begins and where it ends. Observers occasionally make errors regardless of how intense the stimulus. The possibility of these blinks, "finger mistakes," or whatever can be accommodated by specifying an upper asymptote, I-δ, to the probability of a success. The assumed psychometric function then becomes $PT(x) = \min[1 - \delta, WT(x)]$. Where WT is the Weibull psychometric function. The parameter δ, like δ and λ, must be chosen before the experiment, and should be set to the estimated probability of a failure well above threshold. Literature recommends a value of .01 (Watson 1983).

tificates upon completion of the experiment. Participants were screened for normal or corrected-to-normal vision and hearing, accurate colour vision, normal cognitive function, and for any history of neurological disorders. All the participants were PhD-educated space scientists with post-PhD publications.

This experiment observed the effect of conditions 1 (visual cue only), 2 (audio cue only) and 3(visual and audio together), on participant's performance, with the hypothesis that sound as an adjunct to data visualisation will increase participants sensitivity to allocate signatures (identify the presence of a simulated double-peaked "black hole" pattern) in simulated black hole space physics data, when those signals are changing in intensity.

#### 5.3.1.1 Instructions conveyed to participants

The following are the instructions given to the participants where the text given in italics details the procedural instructions for the experiment coordinators.

You will be using the keyboard to respond to visual and audio cues. The visual cues will be presented to you on the computer screen and the auditory cues will be presented through headphones. Some cues will contain a signal and other will not—these will be simply noise. If you detect a signal, you will respond by pressing an S on the keyboard (indicated by the gummy on the keyboard). If you do not detect a signal and the cue is only noise, you will respond by pressing the N key on the keyboard (indicated by the fuzzy green dot on the keyboard).

Sometimes you will see and hear the data (see the charts and hear the sound - signal with noise, noise only, low signal on noise), other times you will only see the data, and other times you will hear the data. The signal loudness and intensity will vary (increase or decrease) randomly.

Now what do we mean by a signal? Signal is the sonification and visualisation of a black hole numerical data stream and will look like this. *(Show the first image on paper "signal present", withdraw the paper from the volunteer sight and say: "The audio cue will sound like this" (play sound here)*. The visual and audio cue will look and sound like this *(show the image and play the sound)*. Sometimes the signal will be really strong, others not so strong and will look like this *(point at image labelled "maybe" on the paper and play the sound)* even though it is fussy it contains signal. The audio signal will be presented, and the signal visualisation will be presented.

The task gets harder over time. Remember, we are not evaluating you; it is the audio and visual cues that are being evaluated. This session will last about 45 minutes. If at any point you wish to stop the testing for any reason, please just let me know and ask me to stop. Thank you for participating."

After the instructions were given, the participants were encouraged to ask questions. When they understood the task, a five minute practice session followed, where the participants took part in typical experimental conditions. The practice sessions were performed using the same conditions as the main experiment. All subjects gave informed consent according to procedures approved by the Harvard University Research Subjects Review Board

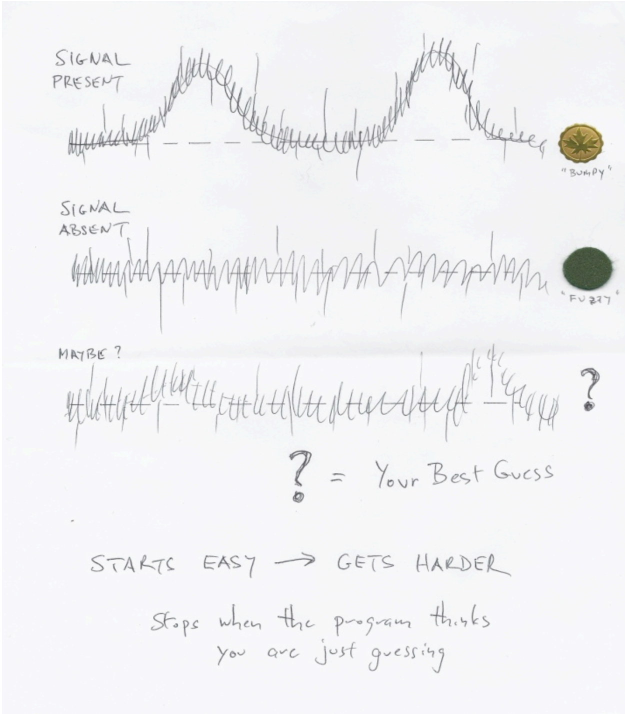



**Figure 2. Illustration shown to participants when giving instructions before the practice session.**

### 5.3.1.2 Experiment One ND[24]

An artificial black hole "signal" consisting of a pair of symmetrically placed Gaussians separated by fixed span of 8° was used (see Figure 3). This span is where changes in attention response are more pronounced. In addition to this, a variable amount of Gaussian-random noise was also added. The latter was displayed either visually on a computer screen with or without sound through headphones or audibly only. Participants were shown either a "signal" or "noise" as an image flashed on the screen and or audio for 1000 ms. Participants pressed a key to register their yes or no responses to indicate whether they thought that the spectrum they were presented with contained  a “signal” or "noise".

[24] ND=No dynamic visual

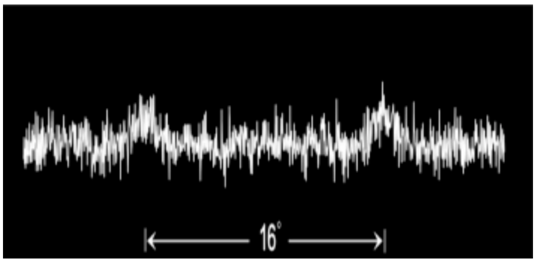



**Figure 3. Visual Cue experiment example with visual angle of 16 degrees.**

In the visual condition, a graph was shown on a screen and participants were asked to indicate whether they thought a signal was present. The auditory conditions were the same, except that participants heard an audio version of the graph. In the third condition, participants were presented with both modalities simultaneously. The experiment took approximately 45 minutes.

### 5.3.1.3 Results from Experiment 1

A repeated-measures one-way ANOVA, based on correct responses over the three conditions, was conducted to observe the effect on the participants' and individual differences in their performances. The distribution of mean for the threshold per condition was calculated (see Table 3). Table 4 shows the mean signal-to-noise thresholds for the different conditions. The mean distribution N=11 favored condition 1) over condition 2) and favored condition 3) over condition 1) and 2). However, one way anova results showed no significance f(1.5, 14.7) = .806, p = .215.

| Subject | Condition 1 (V) | Condition 2 (S) | Condition 3 (V+S) |
|---|---|---|---|
| p1 | 0.538 | 0.727 | 0.443 |
| p1 | 0.538 | 0.727 | 0.443 |
| p2 | 0.421 | 0.58 | 1.529 |
| p3 | 0.666 | 0.611 | 0.489 |
| p4 | 0.801 | 1.3 | 0.949 |
| p5 | 0.846 | 0.804 | 0.592 |
| p6 | 0.55 | 0.765 | 0.588 |
| p7 | 1.141 | 0.749 | 0.743 |
| p8 | 0.62 | 0.642 | 0.531 |
| p10 | 0.343 | 0.798 | 0.883 |
| p11 | 0.613 | 0.126 | 0.704 |
| p12 | 0.557 | 0.57 | 0.607 |
| p13 | 0.536 | 0.877 | 0.68 |
| p14 | 0.714 | 0.975 | 0.266 |

**Table 3 Average Threshold per Volunteer per Stimuli.**

| Experiment | S-to-N Threshold Condition 1 (V) | S-to-N Threshold Condition 2 (A) | S-to-N Threshold Condition 3 (AV) |
|---|---|---|---|
| **1** | 0.66 | 0.784 | 0.651 |
| **Standard Error** | 0.07 | 0.065 | 0.052 |

**Table 4 Calculated Mean per stimuli (excluding subjects with unreliable data).**

### 5.3.2 Discussion

None of the conditions (1, 2 or 3) differed significantly. The average performance of the visual and audio cues together suggests that sound as an adjunct to visualisation may increase sensitivity to signal detection. This needs to be investigated further to see if the effect is real.

The average threshold performance is directly proportional to the average signal intensity and volunteers could correctly identify this lower signal-to-noise ratio for AV condition. These results neither support deVallez's experiments nor contradict Ecker and Heler's experiments described previously in the Sonification review. As in Ecker’s experiment, the black hole task signal gets more ambiguous as the task progresses and dynamically changes its intensity. This means that not only the noise level increases but the signal strength changes dynamically.

As mentioned earlier in this chapter, If the decision-maker has to monitor a dynamically changing signal to noise ratio source on the basis of intensity and visual angle, and if each event is cluttered by dynamically changing visual noise, then according to this authors there will be a high probability that the decision will be erroneous and made with high confidence. As demonstrated by Baldacci and Burr, discriminability thresholds worsen when visual perceptual clutter is present, but ‘‘observers make more high confidence errors when there are many distractors than when there are few’’. Space science data analysis deals with the cognitive load of the noise that not only affects their judgement and confidence when identifying the signal but at the same time triggers mechanisms of attention that inhibit peripheral sensitivity (Schneps, 2007). Interestingly to note that the lower signal to noise correctly identified, based on the data, corresponds to AV stimuli.

Another experiment repeating the same conditions will increase the statistical power and probability to corroborate our results. The volunteer’s verbalized Conditions 2 and 3 were harder at the beginning because they were not used to the task. Equally all the participants said they felt Conditions 2 and 3 were more useful as the S/N ratio decreased. Therefore a second experiment was conducted.

## 5.4 Second Experiment: 4 Conditions Nd

The second experiment repeats Experiment 1 but also explores the effect of another information input on performance. The third stimuli being a red-line sweeping across the visual graph at the rate the sonification was played, to unite visual and auditory focus. User performance tests were then conducted using this new cue condition whereby, the participants were presented with audio, visual and the red-line stimuli synchronised as a red-line sweeping across the graph.

It was hypothesised that a moving target on the screen, congruent with the audio, may induce attention allocation, leading to audio-visual capture that will help towards the identification of the black hole signal in the data. This could prove especially true if the signal-to-noise ratio is really small. It was predicted that space scientists using sound as an adjunct to visualisation and a third congruent cue (the red-line sweeping across the spectra) would be able to detect the presence of "signal" at lower S/N thresholds as compared to the first experiment.

The moving line functions as congruent stimuli that may elicit attention control (van Ee. 2009). According to van Ee's findings, the moving red-line would force control over the audio stimuli, making the sound congruent with the visual cue. In this experiment, the noise masked the signal so the signal-to-noise ratio was very small making the visual signal ambiguous when present. Then if the moving line is helping, it will be noted at the pairwise comparisons.

As mentioned in this chapter's introduction, it has been demonstrated in the literature (van Ee, 2009), (O'LEARY and RHODES 1984) that congruent auditory or tactile information, and combined auditory–tactile information, aids attention control over competing visual stimuli and *vice versa*. Van Ee also found that congruent sound, aids attention control over visual ambiguity and correspondingly, a congruent visual pattern aids in control over ambiguous sounds. In this thesis, experiment findings are used to help space scientists to overcome visual ambiguity in the detection[25] of signal embedded in noisy space science data. In the case of these experiments, the ambiguous competing stimuli is the noise floor, which as its visual ambiguity increases, the user is forced to allocate attention to the auditory cues to make sense of the stimuli. The red line becomes a physical means to allocate attention and not to create the impression that a source is moving from one side of a soundstage to the other.

In the second experiment these findings are used as a framework to add the red-line as a third modal cue and observe its effects on participant performance. The black hole paradigm designed for the three experiments is a dynamic task requiring participants to divide attention among multiple dynamically changing stimuli (signal-to-noise ratio changing) (Johnson, 2003). It was expected the red-line stimuli would give the participants a means to allocate attention to correlate the audio to a particular change in the visual graph yielding performance improvements compared to the first experiment.

As before, the separation of the Gaussians was fixed at 8° with equal eccentricity. The experiment again used a within-subjects design and the settings, instructions and

[25] Detection, in this thesis refers to the entry of information concerning the presence of a signal into a system that allows the subject to report the existence of the signal by an arbitrary response indicated by the experimenter. We mean to distinguish detection in this sense from more limited automatic responses that may occur to the event. Posner, M. I., Snyder, R. C., & Davidson, B. J. (1980). Attention and the Detection of Signals. *Journal of Experimental Psychology: General , 109* (2), 160-174.

design were the same as those of the first experiment with the exception that the red-line cue was added. Fourteen participants, aged 20-45, from the Centre for Astrophysics participated in the experiment and none of them had participated in any of the previous experiments. They were recruited via an email to scientists at the Centre for Astrophysics in Massachusetts and personal contacts. They were paid $10 in Amazon gift certificates upon completion. Participants were screened for normal or corrected-to-normal vision and hearing, for accurate colour vision, normal cognitive function, and to verify that they had no history of neurological disorder. All the participants were PhD-level space scientists with post PhD publications. The experiment took 50 minutes.

This experiment observes the effect of the 4 conditions on performance and compares results with Experiment 1, towards the hypothesis that sound as an adjunct to visualisation can help space scientists to identify signatures in 2D numerical graphed data.

Feedback cues:

a) Visual
b) Audio
c) Visual and audio together (visual and audio presentations synchronized)

Visual and Audio together with a red-line sweeping across the spectra synchronized with the sound played. Visual, audio and red line synchronized.

### 5.4.1 Results

A repeated-measures ANOVA with factor "condition" (levels 1-4) yielded the result:

f(2.19, 28.5) = 4.83; $P < 0.012$ ; $p < 0.05$, and thus the null hypothesis can be rejected. Raw data can be seen in Table 5. Table 6 compares the signal-to-noise thresholds for Experiments 1 and 2. Table 7 shows the effect sizes and Table 8 shows the paired differences between the conditions in Experiment 2.

| **Subject** | **Cond1** | **Cond2** | **Cond3** | **Cond4** |
|---|---|---|---|---|
| **p1** | 0.378 | 0.493 | 0.365 | 0.393 |
| **p2** | 0.406 | 0.495 | 0.382 | 0.457 |
| **p3** | 0.408 | 0.503 | 0.419 | 0.469 |
| **p4** | 0.415 | 0.52 | 0.433 | 0.483 |
| **p5** | 0.443 | 0.569 | 0.46 | 0.49 |
| **p6** | 0.45 | 0.58 | 0.475 | 0.508 |
| **p7** | 0.461 | 0.6 | 0.483 | 0.536 |
| **p8** | 0.473 | 0.61 | 0.495 | 0.554 |
| **p9** | 0.473 | 0.626 | 0.502 | 0.578 |
| **p10** | 0.482 | 0.638 | 0.506 | 0.579 |
| **p11** | 0.536 | 0.663 | 0.511 | 0.595 |
| **p12** | 0.554 | 0.672 | 0.59 | 0.599 |
| **p13** | 0.634 | 0.739 | 0.607 | 0.666 |
| **p14** | 0.664 | 0.744 | 0.955 | 0.685 |
| **Average** | 0.484071429 | 0.603714286 | 0.513071429 | 0.542285714 |

**Table 5 Average threshold per participant per condition in Experiment 2 (NO dynamic visual).**

| **Experiment** | **S-to-N Threshold Condition 1 (V)** | **S-to-N Threshold Condition 2 (A)** | **S-to-N Threshold Condition 3 (AV)** | **S-to-N Threshold Condition 4 (AVR)** |
|---|---|---|---|---|
| **1** | 0.66 | 0.784 | 0.651 | N\A |
| **2** | 0.484071429 | 0.603714286 | 0.513071429 | 0.542285714 |

Table 6 Average thresholds in Experiment 1 and 2 for comparison.**Table 7 Experiment 2 Effect size (4 conditions No Dynamic Visual,ND).**

| Paired sample statistics Paired Differences | | | |
|---|---|---|---|
| 95% Confidence Interval of the Difference | | | |
| **Pairs** | **Conditions** | **Mean** | **Sig. (2-tailed)** |
| **1** | 1 – 2 | -0.11964 | 0.004 |
| **2** | 1 – 4 | -0.05821 | 0.036 |
| **3** | 1 – 3 | -0.029 0 | 0.520 |
| **4** | 2 – 4 | 0.06143 | 0.044 |
| **5** | 2 – 3 | 0.09064 | 0.016 |
| **6** | 3 – 4 | 0.02921 | 0.361 |

**Table 8 Paired differences between conditions in Experiment 2.**

| Effect Size ND | V versus A | A versus AVR | AV versus AVR |
|---|---|---|---|
| | 0.69 | 0.53 | 0.25 |

The results above show there is a significant difference in mean values across the four experimental conditions. The paired differences in Table 8 show significant differences for conditions 1 vs. 2, conditions 1 vs. 4, conditions 2 vs. 4, and conditions 2 vs. 3. This T-test paired differences mean that:

1. Audio (A) lead to better performance than Visual (V) $p = 0.004$.
2. Audio-Visual with Red Line (AVR) lead to better performance than Visual (V) $p = 0.036$
3. Audio-Visual with RedLine (AVR) lead to better performance than Audio (A) $p = 0.044$
4. Audio-Visual lead to better performance than Audio (A). $p= 0.016$

The reader may find that AVR did not lead to better performance than AV (p = .361 > .05). Indicating then it is the synchronizity of displays over the ambuity and not the red line the cause of the performance improvement.

| **Total** | **56 scores** | **K= 6 classes** | | |
|---|---|---|---|---|
| **per cond** | 14 | K=3 | | |
| **claas width .1** | | | | |
| **Cond 1 V** | | | | |
| **thresholds** | **Count Freq** | **Cumulative freq** | **Relative freq** | **%Freq** |
| **0.3-0.4** | 1 | 1 | 0.071428571 | 7.142857143 |
| **0.4-0.5** | 9 | 10 | 0.642857143 | 64.28571429 |
| **0.5-0.6** | 2 | 13 | 0.142857143 | 14.28571429 |
| **0.6-0.7** | 2 | 15 | 0.142857143 | 14.28571429 |
| **Total** | | | 1 | 100 |
| | | | | |
| **cond A** | | | | |
| **0.3-0.4** | 0 | 0 | 0 | |
| **0.4-0.5** | 2 | 2 | 0.142857143 | 14.28571429 |
| **0.5-0.6** | 4 | 6 | 0.285714286 | 28.57142857 |
| **0.6-0.7** | 6 | 12 | 0.428571429 | 42.85714286 |
| **0.7-0.8** | 2 | 14 | 0.142857143 | 14.28571429 |
| **Total** | | | 1 | 100 |
| | | | | |
| **cond AV** | | | | |
| **0.3-0.4** | 2 | 2 | 0.142857143 | 14.28571429 |
| **0.4-0.5** | 6 | 8 | 0.428571429 | 42.85714286 |

| | | | | |
|---|---|---|---|---|
| **0.5-0.6** | 4 | 12 | 0.285714286 | 28.57142857 |
| **0.6-0.7** | 1 | 13 | 0.071428571 | 7.142857143 |
| **0.9-1.0** | 1 | 14 | 0.071428571 | 7.142857143 |
| **Total** | | | 1 | 100 |
| **Cond AVR** | | | | |
| **0.3-0.4** | 1 | 1 | 0.071428571 | 7.142857143 |
| **0.4-0.5** | 4 | 5 | 0.285714286 | 28.57142857 |
| **0.5-0.6** | 7 | 12 | 0.5 | 50 |
| **0.6-0.7** | 2 | 14 | 0.142857143 | 14.28571429 |
| **Total** | | | 1 | 100 |

**Table 9 Relative and Cumulative frequency tables per Condition Experiment 2.**

Table 9 shows the relative and cumulative frequencies for thresholds/Performance per condition to illustrates the distribution of thresholds per per signal to noise ratio.

**Figure 4 % frequency Signal-to-noise Ratio (threshold) Visual and Audio Condition Experiment 2 NDV**

**Figure 5 % frequency signal-to-noise ratio (threshold) Audio-Visual-Red Line condition and Audio-Visual Experiment 2 NDV.**

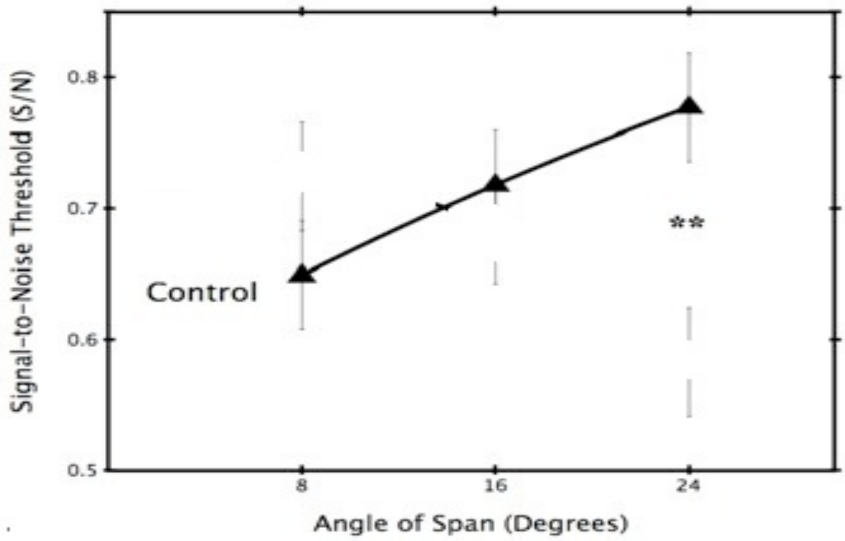



**Figure 6 Signal-to-noise ratio (threshold) Schneps, 2007).**

Figure 6 shows the average threshold for astrophysicists participating in the Black Hole experiment detection for static visual angles of 8, 16, and 24 degrees as reported by Schneps (Schneps, 2007). Schneps's experiments resulted in an average threshold or signal-to-noise ratio detected correctly by participants of .66 for a static visual angle of 8 degrees. This result agrees with the result in Experiment 1 in this thesis for visual stimuli at 8 degrees of visual angle. Schneps volunteers experienced one visual angle per experiment.

The average signal-to-noise ratio (threshold) identified by the participants in the audio visual condition is .51 (see table 6). Audio-Visual condition Frequency percentage (see table 9) is 14.3% at signal-to-noise ratio range (threshold) of .3-.4, (see table 9 and figure 4 and 5), as opposed to V with a percentage frequency of 7% at a signal to noise ratio range of .3-.4 ( see table below) .

| Class(Signal/Noise ratio) | Visual | Audio | AV | AVR |
|---|---|---|---|---|
| 0.33-0.49 | 7.14 | 0 | 14.28 | 7.14 |
| 0.49-0.65 | 64.28 | 14.28 | 42.85 | 28.57 |
| 0.65-0.81 | 14.28 | 28.57 | 28.57 | 50 |
| 0.6-0.7 | 14.28 | 42.85 | 7.14 | 14.28 |
| 0.7-0.8 | 0 | 14.28 | 0 | 0 |
| .9-1.0 | 0 | 0 | 7.14 | 0 |
| Total | 100 | 100 | 100 | 100 |

**Table 1 % frequency distribution of signa-to-noise ratios per condition Exp. 2 NDV**

Participants stated the red-line was a distraction as they knew where to expect the signal. Participant threshold average improved for the four conditions. This verbal reports repeated by all the participants are indicators that they are aware of the event, and were able to align attention to it (Posner, Snyder and Davidson 1980).

### 5.4.1.1 On Cross-Modal Effects

Experiment 2 presents in random order, to the participant, 4 stimuli as opposed to experiment 1 which presents 3 stimuli. Donohue (Donohue *et al.*, 2013) performed experiments on Cross-Modal effects. Like Van Ee (van Ee, 2009), her results proved that response accuracy was only modulated by congruency. In her experiments, Donohue employed a cross-modal audio-visual task in which manipulated the within-trial stimulus-onset-asynchronies (SOAs) of the stimulus-component inputs, the grouping of the SOAs (blocked vs. random), the attended modality (auditory or visual), and the congruency of the Stroop colour-word stimuli (congruent, incongruent, neutral) to assess how these factors interact within a multisensory context.

Donohue's findings are based on the fact that visual processing tends to be faster than auditory processing as reflected by RTs (Molholm, *et al.*, 2004), (Yuval-Greenberg and Deouell, 2009) (Donohue *et al.*, 2013). Second, there is a general pattern of asymmetry between the magnitudes of conflict effects observed in cross-modal contexts, in that incongruent visual stimuli generally produce more interference on the processing of relevant auditory stimuli, than *vice versa* (Molholm, *et al.*, 2004), (Yuval-Greenberg and Deouell, 2009), (Stuart and Carrasco, 1993), (Roelofs, 2005)(Donohue *et al.*, 2013). According to Donohue cross-modal asymmetries may be found in instances of uncertainty, wherein the more reliable modality 'wins' (e.g., a shift in the auditory percept toward a more spatially reliable visual stimulus, as in the ventriloquist effect (Alais and Burr, 2004), (Bertelson and Radeau, 1981). Indeed, when Yuval-Greenberg and Doeuell degraded their visual stimuli making them more difficult to identify, the visual conflict effect on auditory processing diminished, evidencing that the visual information was not being relied on as heavily (Yuval-Greenberg and Deouell, 2009)(Donohue *et al.*, 2013). This is analog to the task performed in experiment 2. Space scientists with postdoctoral publications have an average experience time of 10 years (Ericsson and & Charness 1994) (Ericsson K. Anders 1993) (K. A. Ericsson 2009) (Chase W.G. and Ericsson 1982). Then applying Ericsson assertions to target audience, space scientists with this level of expertise do not commit so many big errors and is used to identify the kind of signal being sought using a particular data analysis technique of their choice. In the case of this experiment the participant is not only identifying but also analysing as ambiguity increases, being the signal more difficult to identify.

### 5.4.2 Conclusions

The Black Hole task presents the data for 1 second. In this time, a person can perform at most 4 fixations and because the signal is fixed at 8 degrees of visual angle, participants said that the sweep-line becomes nothing more than a distraction adding to their cognitive load; they knew the visual location of the signal in the data.

Paired differences for experiment 2 indicate that audio (A) leads to better performance than visual (V) ($p = 0.004$). BothRedLine (AVR) leads to better performance than visual (V) ($p = 0.036$). Audio-Visual (AV) leading to better performance than audio (A) ($p = 0.016$) and AudioVisual RedLine (AVR) leading to better performance than audio ($p = 0.044$). The reader should note that BothRedLine (AVR) did not lead to better performance than Both (AV) stimuli ($p = 0.361$).

With this experiment setup, (fixed visual angle), participants could at least partially rely on the absolute positions of the peaks wich is like a decision about two local signals. The reader should note that Experiment 1 resulted in to no significant differences, see Table 4 to compare the average thresholds per condition.

The question is if the volunteers were using the red line? Given the paired differences results the red line did not lead to better performance than Audio-Visual stimuli. If the volunteers were using the red line implicitly then the sweep-line helped the user understand where they were in the context of the entire data set and to exert control over the audio stimuli as ambiguity increases. Then as visual ambiguity increases the audio becomes the more reliable modality. As a side note, it may be important to note that during debrief all the participants said they re-played the sound in their heads before selecting an answer. None of the participants said they re-played the visual image in their heads. Participants were asked if they did.

The participants were highly trained to visualise space physics data but the experiment exposed them to a no - dynamic audio/visual rendering (changing signal-to-noise ratio and static visual angle). Then if the positions of the Gaussians change randomly as the signal-to-noise ratio change, i.e. making the visual cue more ambiguous, an improvement in performance or signal detection is expected.

## 5.5 Third Experiment: 4 Conditions Dv[26]

The third experiment explored the effects of using multimodal (audio and visual) cues to explore the effect of sound as an adjunct to visualisation on exploring data masked by noise for which signal position is randomly iterated. The separation of the two Gaussian signals was change to be either 8°, 16° or 24° and participants therefore do not know what stimulus eccentricities to expect. In this case, they would actually have to analyse symmetry, just as space scientists do when looking for black holes.

Twelve volunteer space scientists aged 20-45 were recruited and screened in a similar fashion to the previous 2 experiments. As before none of the volunteers had participated in any of the previous experiments.

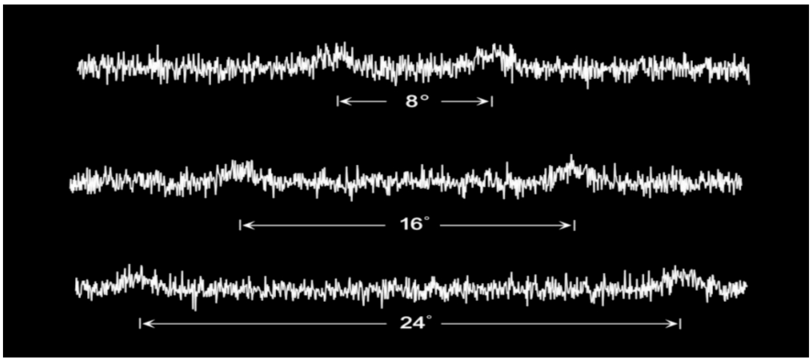



**Figure 7 Experiment 3 Iterated Visual Angles Presented to Volunteers.**

Experiment settings and cues were as for Experiment 2 with the exception that the position of the signal was dynamically iterated between angles of 8°, 16° and 24°.

[26] DV=Dynamic Visual

Feedback cues:

a) Visual
b) Audio
c) Visual and audio together (visual and audio presentations synchronized)

Visual and Audio together with a red-line sweeping across the spectra synchronized with the sound played. Visual, audio and red line synchronized.

If experiment 2 resulted in significance across conditions at a static visual angle of 8°, where changes in attention response become pronounced (Plainis, Murray & Chauhan, 2001) and (Schwartz *et al.*, 2005). Experiment 3 hypothesises that sound used as a third multimodal cue will help space scientists by increasing their sensitivity to signal when the data analysis requires symmetry analysis to identify signal.

### 5.5.1 Results

A repeated-measures one-way ANOVA, based on condition resulted in a significant main effect; f (2.11,23.21) = 3.47; p=.009 < .05. Variance analysis S=12, N=60 produced significance across the 4 conditions p = .009, rejecting the null hypothesis (see table 16 for pair wise comparisons). In Condition 4 (AVR), average signal-to-noise ratio was marginally favoured over condition 1, 2 and 3 (see Table 10).

| **Experiment 3** | **Condition 1 (V)** | **Condition 2 (A)** | **Condition 3 (AV)** | **Condition 4 (AVR)** |
|---|---|---|---|---|

| (Mean) Threshold | 0.65542 | 0.63300 | 0.54892 | 0.53142 |
|---|---|---|---|---|
| **Std deviation** | 0.157803 | 0.115934 | 0.148118 | 0.112911 |
| **N** | 12 | 12 | 12 | 12 |

**Table 10 Average threshold for Experiment 3.**

Table 10 shows the data favours condition 3 (visual and audio), and condition 4 (visual and audio with red line) as better performance.

| | **Cond1** | **Cond2** | **Cond3** | **Cond4** |
|---|---|---|---|---|
| **Subject** | **Visual** | **Auditory** | **Vis/Aud** | **Vis/Aud/Redline** |
| 1 | 0.348 | 0.498 | 0.435 | 0.33 |
| 2 | 0.48 | 0.518 | 0.45 | 0.431 |
| 3 | 0.507 | 0.519 | 0.451 | 0.444 |
| 4 | 0.539 | 0.531 | 0.459 | 0.492 |
| 5 | 0.683 | 0.564 | 0.486 | 0.5 |
| 6 | 0.683 | 0.591 | 0.491 | 0.513 |
| 7 | 0.699 | 0.636 | 0.493 | 0.518 |
| 8 | 0.713 | 0.674 | 0.535 | 0.529 |
| 9 | 0.714 | 0.675 | 0.584 | 0.578 |
| 10 | 0.765 | 0.764 | 0.6 | 0.607 |
| 11 | 0.841 | 0.79 | 0.63 | 0.688 |
| 12 | 0.893 | 0.836 | 0.873 | 0.747 |
| | 0.655416667 | 0.633 | 0.548916667 | 0.531416667 |

**Table 11 Average signal-to-noise ratio (thresholds) for Experiment 3 (AVR Dynamic visual).**

| | | | | |
|---|---|---|---|---|
| 48 scores | | K= 6 | | |
| Per cond 12 | | K= 4 | | |
| Signal noise ratio | | | | |
| .33-.49 | 2 | 1 | 5 | 3 |
| .49-.65 | 2 | 6 | 6 | 8 |
| .65-.81 | 6 | 4 | 0 | 1 |
| .81-.97 | 2 | 1 | 1 | 0 |
| | | | | |
| Cum freq | 2 | 1 | 5 | 3 |
| | 4 | 7 | 11 | 11 |
| | 10 | 11 | | 12 |
| | 12 | 12 | 12 | |
| | | | | |
| Rel. Freq | 0.166666667 | 0.083333333 | 0.416666667 | 0.25 |
| | 0.166666667 | 0.5 | 0.5 | 0.666666667 |
| | 0.5 | 0.333333333 | 0 | 0.083333333 |
| | 0.166666667 | 0.083333333 | 0.083333333 | 0 |
| Total | 1 | 1 | 1 | 1 |
| | | | | |
| Cum Rel freq. | 0.1666667 | 0.083333333 | 0.416666667 | 0.25 |
| | 0.333333333 | 0.583333333 | 0.916666667 | 0.916666667 |
| | 0.833333333 | 0.916666667 | 0.916666667 | 0 |
| Total | 1 | 1 | 1 | 1 |
| | | | | |

| | | | | |
|---|---|---|---|---|
| **% Frequency** | 16.66666667 | 8.333333333 | 41.66666667 | 25 |
| | 16.66666667 | 50 | 50 | 66.66666667 |
| | 50 | 33.33333333 | 0 | 8.333333333 |
| | 16.66666667 | 8.333333333 | 8.333333333 | 0 |
| | 100 | 100 | 100 | 100 |

**Table 242 Frequency, Relative Frequency and % Frequency distribution from Raw data.**

**Figure 8 Pie Chart % frequency for signal-to-noise ratio (thresholds) per condition.**

**Figure 9 % frequency for signal-to-noise ratio (threshold) per condition.**

| Effect Size DV | V versus A | A versus AVR | AV versus AVR |
|---|---|---|---|
| | 0.4953 | 0.9633 | 0.36 |

**Table 15 Experiment 3, effect size.**

| Paired Samples Test | | | | |
|---|---|---|---|---|
| | Paired Differences | T | Df | Sig. (2- |

| | | | | | 95% Confidence Interval of the Difference | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Mean | Std. Deviation | Std. Error Mean | Lower | Upper | | | |
| Pair 1 | Visual – Auditory | .022417 | .151049 | .043604 | -.073555 | .118388 | .514 | 11 | .617 |
| Pair 2 | Visual – BothRedLine | .124000 | .095421 | .027546 | .063373 | .184627 | 4.502 | 11 | .001 |
| Pair 3 | Visual – AV | .106500 | .179742 | .051887 | -.007703 | .220703 | 2.053 | 11 | .065 |
| Pair 4 | Auditory – AVR | .101583 | .126374 | .036481 | .021289 | .181877 | 2.785 | 11 | .018 |
| Pair 5 | Auditory – AV | .084083 | .213916 | .061752 | -.051832 | .219999 | 1.362 | 11 | .201 |
| Pair 6 | BothRedLine – AV | -.017500 | .171789 | .049591 | -.126650 | .091650 | -.353 | 11 | .731 |

**Table 16 Experiment 3 ( 4 conditions Dinamic Visual) shows the difference between the conditions.**

The result of Experiment 3 shows that performance is affected by the conditions. T-tests show that condition AVR [27] leads to better performance than Auditory (p = .018) or Visual (p = .001) and there is a tendency of AV, (Both), leading to better performance than Visual). T-test also show BothRedLine (AVR) did not lead to better

[27] AVR=Audio/visual with redline.

than both (p = .731).

| Class(Signal/Noise ratio) | Visual | Audio | AV | AVR |
|---|---|---|---|---|
| .33-.49 | 16.66666667 | 8.333333333 | 41.66666667 | 25 |
| .49-.65 | 16.66666667 | 50 | 50 | 66.66666667 |
| .65-.81 | 50 | 33.33333333 | 0 | 8.333333333 |
| .81-.97 | 16.66666667 | 8.333333333 | 8.333333333 | 0 |
| | 100 | 100 | 100 | 100 |

**Table 17 % frequency distribution of signal-to-noise ratios per condition in Exp 3 DVR**

Table 17 and Figures 8,9 illustrate the frequency distribution per signal to noise range per condition for Experiment 3. Table 15 shows the calculation of those frequency distributions from the raw data. 41% of the signal identified in AV condition occurred at a signal-to-noise ratio (threshold) of 0.33-0.49 for dynamically changing stimuli. Table 17 shows the threshold or signal-to-noise ratio, in which participants could identify correctly the presence of a signal. The reader may appreciate that the lowest signal-to-noise ratio occurs in average (see table 10) for Condition 4 (AVR) but the frequency distribution shows to be the highest at, signal to noise ratio (threshold) range of 0.33 - 0.49 for AV condition (41.6 percentage frequency distribution), as opposed to conditions V, AV and AVR with much lower frequency distribution. The latter as shown by the frequency analysis distribution[28] on table 17 (see footnote below). This is very important because in Experiment 3 the participants did not have the expectation factor as the signal was iterating dynamically between 8, 16 and 24 degrees of visual angle. The signal-to-noise ratio or threshold identified by participants is much lower than the signal-to-noise threshold reported by Schneps (see Figure 8). Participants for Schneps experiments were post doc astrophysicists with post doc publications in the field.

The visual and audio capture was shown to cause a larger effect on Experiment 3 (see table 14), which tended to mimic the kind of scene space scientists face when analysing 2D data. Future research could explore whether a carefully designed training session would result in the visual and audio capture to be more significant.

| Experiment | S-to-N Threshold V | S-to-N Threshold A | S-to-N Threshold AVR | S-to-N Threshold AV |
|---|---|---|---|---|
| 1 ND | .660 | .784 | | .651 |
| 2 ND | .484 | .603 | .542 | .513 |
| 3 DV | .655 | .633 | .531 | .549 |

**Table 18 Comparison Table Experiments 1, 2, and 3 average signal intensity (threshold) detection.**

[28] It was intended to show a more robust statistical analysis. e.g. multimodal gain. Accessibility issues and time constraints prevented the author from showing a more robust statistical analysis.

Table 18 shows a comparison of the three experiments presented in this section. For Experiment 1 static visual angle of 8 degrees and 3 conditions the data supported a marginal lower signal-to-noise ratio but produced no statistical significance difference among the conditions. For experiment 3, Distribution of frequency % showed that the signal to noise ratio identified the most was at lower signal-to-noise ratios (0.31) for AV condition. For Experiment 3, the same conditions were repeated plus another condition (visual and audio with red line), producing significant differences among the conditions.

It is interesting to note that the participants found it difficult to transition from visual condition to any other. The reader should remember the order of the conditions and visual angle iteration were completely random (8, 16 or 24 degrees of visual angle).

Participants reported relying more on the sound as the experiment progressed and signal-to-noise ratio was lower. This is evidenced from the data, as the calculated averages were lower for multimodal sensitivity than for unimodal sensitivity[29]. This indicates the signal-to-noise ratio perceived correctly was lower when presented multimodally (see table 17). One participant said they closed their eyes when signal-to-noise ratio was very low as the graph presented was a visually

[29] refer to tables 16, 17, and 18. It was intended to do a more robust statistics analysis issues related to accesibility and time constraints prevented it.

ambiguous cue (increased visual ambiguity). This is seen as an attempt to make sense of the cue, because of the stimuli that they could control by switching the audio on or off (open and close the eyes). Another observation was that none of the participants removed their headphones at any time. Qualitatevely seems the audio was beign weighted more heavily than visual when the visual condition was not reliable. Unfortunately a multimodal gain calculation could not be performed for this experiment given accessibility.

One particular participant reported to open and close their eyes when searching the data, for all the conditions. Another participant reported to close his eyes and not paying attention to the visual cues. The reader should remember that participants are not used to use sound for analyzing data. As discussed earlier Erickson affirms that it takes this scientists ~ 10 years to reach a point where they may identify signal easily through any data analysis technique. This contributes greatly to the fact that audio was not performing better.

All the participants reported that they developed a technique to scan the data during Conditions 2, 3, and 4. They reported that they listened to the sound only focusing on a particular change especially when the signal-to-noise ratio got very low, i.e. when the signal was visually confusing and ambiguous. They reported to listen for one characteristic change in the data and if it was present, they then relied on there being a second symmetric lump. Equally all the participants reported that they replayed the sound in their heads when they were uncertain when using Conditions 2, 3 and 4. Participants mentioned that they relied on the visual signal if the signal-to-noise ratio was high (visual signal being very evident)[30].

In general for Condition 2, 3, and 4 they got the pattern then figured out the signal, played it back in their head quickly looking for the signal again and then used their eyes to find it.

### 5.5.2 Conclusions

As mentioned earlier, the red-line together with the audio-visual cue helps the user to exert more control over the auditory stimuli to make sense of the data as visual ambiguity increases. The reader should remember that for experiment 2 and experiment 3, AVR, (Both red line), stimulus did not lead to better performance than AV (Both). At high visual ambiguity the dominant sense is not the visual but the audio. It causes a modality capture, which at the same time helps the participant to orientate in the context of a large data set of varying content. This is especially evident in very low signal-to-noise ratios, as the signal, if present, can be very ambiguous. This is because AVR, (Both redline), and AV (Both) cues are synchronised, resembling the congruent multimodal stimulus that aids attention control over competing visually ambiguous stimuli (van Ee, 2009). This may imply a contribution to effective displays.

As a side note the utterances reported may be an indicator that people may have been using memory in advanced ways to compare patterns observed to patterns memo-

[30] A statistical analysis is needed to test this utterances. Time constraints and accessibility issues prevented the author from it.

rised. People with poor memory cannot use such strategies; this could be an interesting theme to research on effective displays. A paradigm designed for that purposes and a robust statistical analysis are needed to test that.

The three experiments so far presented, answer effectively this thesis research question: Does sound used as an adjunct to data visualisation, augment sensitivity to the perception of signatures in data masked by noise? Experiment 1 showed no significance among the 3 conditions experienced by the participants. Experiment 2 and 3 resulted in significance across the conditions. Especially in experiment 3 in which participants had to analyze symmetry. The 3 experiments presented in this section address the research question in terms of the effectiveness of the use sound as an adjunct to visualization to increase sensitivity to signal occurring at attended, unattended, or unexpected locations, extended in space, when the occurrence of the signal is in presence of a dynamically changing competing cognitive load (noise) that makes the signal visually ambiguous.

Experiment 2 and 3 address the research question in terms of combining multimodal perceptualization (sound as an adjunct to visualisation) and attention control mechanisms, to help allocate attention to identify visually ambiguous signal. Experiment 2 and 3 added a third congruent cue making the visual and the audio congruent. Experiment 2 resulted in significance across the 4 conditions at a static visual angle of 8 degrees (see table). The average performance for experiment 2 outperformed the average performance reported by Schneps. Experiment 3 resulted in significance across conditions (see table 18) at a dynamic visual iterating randomly between 8, 16 and 24 degrees of visual angle. (see table 18).

## 5.6 Training Experiments

The previous sections brought experimental evidence that using sound as congruent cue, increases sensitivity to signal detection in astrophysics data. The 21st century found us without a training paradigm for space scientists to polish the skill[31] of using sound to perform data exploration. Focus group and usability evaluation reported in chapter 3, supports the interest of Space Scientists to use multimodal perceptualisation to perform a more thorough data analysis. These scientists have extensive visual training on data analysis. The busy schedules, large data sets (to mention some) require a low learning curve when reffering to new softwares as stated in chapter 3, so they may focus on their data analysis. This also applies to polishing the audio and visualisation perceptualisation techniques to perceive events in the data. Then if the use of sound as an adjunct to visualisation increases sensitivity to signal perception and if according to Ericcson this is proportional to experience, then to be effective it has to have a low learning curve. This section brings the perspective of training to polish the human natural ability of using sound as an adjunct to visual display but

[31] "Skill acquisition refers to a form of prolonged learning about a family of events. Through many pairings of similar stimuli with particular responses, a person can begin to develop knowledge representations of how to respond in certain situations. These representations have some form of privileged status in memory because they can be retrieved more easily and reliably than memories of single events. Thus, skilled behaviours can become routinized and even automatic under some conditions. The range of behaviours that can be considered to involve skill acquisition could potentially include all responses that are not innate. That is, any response that can be learned can potentially be refined with practice, given the right conditions." Speelman, C., & Kirsner, K. (2008). Skill acquisition: History, questions, and theories. In C. peelman, & K. Kirsner, *Beyond the Learning Curve: The construction of mind.* Oxford Scholarship Online." Speelman, C., & Kirsner, K. (2008). Skill acquisition: History, questions, and theories. In C. peelman, & K. Kirsner, *Beyond the Learning Curve: The construction of mind.* Oxford Scholarship Online.

directed (in the case of this research) to analyse space science data.

Human beings mature from a world where people receive information multimodally from birth (Bearne 2003). Children grow-up and live in a multimodal environment where they become competent in making sense of the world through signs. As human beings we come from a world of meanings expressed in “numerous ways and in countless forms in our early years to a much more one-dimensional world” (Vincent, 2006), of visual interpretation.

In the case of this research, the target audience is trained to visualise the physics data and its representations using their eyes, not their ears. Space physics as a field of study and its graphical representations are visually presented. As this field is so closely related to mathematics, visualisation of space physics data may be directly related to the fact that, since primary school, mathematical representations have been delivered visually. In that context, space physicists read the graphical representations to extract information; their work requires analysis and meaning generated from symbols.

Complex skills, such as searching for signatures in space physics data or problem solving are made up of multiple components, which need to be learnt and integrated before skill is acquired (Johnson 2003). Such skills take time to develop and are more dependent on the nature of training and the background of the performer (Johnson, 2003). Focus group and usability evaluation (see chapter 3), reported utterances where participants recommended to each other how to listen for particular events.

Participants were not focused on exploring for the unknown but on finding suspected events. As stated on section 2.2 it is agred that the basis of expansion for space physics data has to be adaptive (Huang, Shen and Long 1998). The reader should keep in mind that participants in experiments reported in chapter 3 had unmet expectations emerging from a problem at hand that has not been solved. They were consulting to each other how to listen. Effective training giving them a starting point is mandatory if the use of sound as an adjunct to visualisation may be effective data analysis option for space physics.

Burton (2003) says that “reading is like listening with the eyes as it involves two types of comprehension: literal, from word meanings, sentence meanings and understanding the main idea; and inferential. Burton (2003) also asserts that reading may be the analogue to listening to verbal representations.

In sonification, with or without visual accompaniment, these assertions may be equivalent to reading with our ears. This research examines how sound could be used as an adjunct to space physics data set visualisations by using the human senses of sight and hearing to identify signatures in the data, especially signatures that are ambiguous or masked by noise.

Studies on multimodal (audio-visual) interaction directed at training using sound to perform a task, are somehow limited on performing preconceived patterns and trends (attend an activity to learn through repetition and how it is supposed to be done).

Normally, the focus is put on repeating a task and then testing if the task was performed. Evaluating the effects of the training when performing a task in which a stimuli dynamically changes in intensity (such as with visual and audio noise and visual angle) is never done; as in the case of exploration of space science data. Unintentionally it precludes any form of change-powered learning. Studies on Physics expertise by Anzai *et al.* (1991) showed that physics novices work backwards and experts work forwards (Anzai *et al.*, 1991), (Anzai and Yokohama, 1984).

According to Anzai and Yokohama, Experts represent the problem towards the solution as they read the problem. Novices are less likely (or more difficult) to decide or build a representation along the way. Experts, use the representation as an aid, while according to this research, the novice lacks the organised knowledge base and the ability to build a representation that may act as a cue (Anzai *et al.*, 1991), (Anzai and Yokohama, 1984). By the time a question regarding the problem is presented experts are often able to retrieve a solution plan from memory based on this representation (Larkin, et al. 1980)(Popovic, 2006). Taking the latter into consideration a number of training techniques were reviewed:

- Part-task training (Frederiksen and White, 1989).
- Minimal training (Carrol, Quiñones and Ehrenstein, 1997)
- Fractionalisation training (Schneider, 1985) (Schneider and & Detweiler, The role of practice in dual-task performance: Toward workload modeling in a connectionist/control architecture 1988).
- Integrative training (Frederiksen and White, 1989), (Frederiksen and White, 1999).
- Whole task training.
- Massed Practice.
- Distributed Practice.

In these training techniques, participants undertake the training sessions then transfer sessions with no consolidation time in-between. After a protracted search the only evidence on using sound as an adjunct to visualisation to perform a task which may change in content (like identifying signals in space physics data sets) has been found in Morse code operators. Because every message can be different, the copying of high speed Morse code depends on the perceptual ability to parse the 'dits' and 'dahs' that make up the message and to group these symbols into conceptual units (motor ability to quickly type the message and the strategic ability to copy behind) (Wisher, Sabol and Kern, 1995).

Astronomers perform analogous tasks. For example, they must make go/no-go decisions as data arrives from the telescope. These decisions could be to either spend more telescope time on a given galaxy, or to cut their losses and move on to another candidate. Such decisions are often based on visual hunches made by human observers. This may be seen when astronomers use a process to search for a spectral signature indicating the presence of black holes. The task derives from the observation that many galaxies, including our own, contain massive black holes at their centres, buried within dense cusps of stars (Braatz, *et al.*, 2004), (Kondratko, 2006).

As only a relatively small fraction of candidate galaxies present readily detectable emission signatures and discovery surveys may cover tens to thousands of targets along with the fact that the maser spectra varies in position of signal and intensity, the autonomous processes based on statistical tests are not fully reliable (see Chapter 2).

Although there are few publications to support it, it is said that Morse code operators practice to achieve instant recognition of the letters (Pierpont, 2001), (Ericsson and & Charness, 1994). Some trained Morse code operators have been able to write down from hearing 100% of a message while carrying on another conversation.

Research on training has shown a direct proportion between deliberate efforts to improve and improvement of performance (Ericsson and & Charness, 1994). Carrol (1997) affirms that training environments should permit users to: get started fast, to think and improvise, embed information in real tasks, to relate new information to what they already know and support error recognition and recovery. In other words, training should elicit active learning while providing support to keep learners involved in useful tasks while building knowledge on what they already know.

This thesis explores sound as an adjunct to data visualisation and looks at making sense of the data with the purpose of augmenting the signatures in the data.

This section attempts to develop a training paradigm in which the target audience is trained to build skills by multimodally interacting and perceptualizing 2D data sets, strengthening and building skills based on error. The latter is more effective because it permits the participant to recognise errors and to transfer and use the learning (Carrol, Quiñones and Ehrenstein, 1997). The multimodal perceptualization uses sound as an adjunct to data visualisation. The question addressed by this thesis is:

Does sonification used as an adjunct to data visualisation, augment sensitivity to the perception of signatures in data masked by noise?

To answer this question, the following additional questions had to be answered:

a) Is sonification used as an adjunct to visualisation effective in increasing sensitivity to signals occurring at attended, unattended, or unexpected locations, extended in space, when the occurrence of the signal is in presence of a dynamically changing competing cognitive load (noise) that makes the signal visually ambiguous?

b) How can multimodal perceptualization (sound as an adjunct to visualisation) and attention control mechanisms, be combined to help allocate attention to identify visually ambiguous signal?

To answer question (a) and (b) above perception experiments were carried and reported (see sections 4.1 to 4.5). The existant generation of space physicists is trained completely to visualize the scientific data to be analyzed. The generation of future space scientists, will most likely be trained to visualize the numerical data. This will change if a training paradigm exists that will bring science to rely on using multimodal perceptualisation and will provide where to direct their practice. As said earlier in this chapter, complex skills as numerical data analysis are acquired over time.

Then as the space science community is not accostumed to use mutimodal perceptualisation to analyze the data it is worth exploring if it is possible to develop a training paradigm for those purposes.

Our research question for this chapter towards answering the main research question is: Is it possible to train our target audience to multimodally, (using sound as an adjunct to data visualisation) interact and perceptualize 2D datasets to identify, (augment) signatures in 2D numerical data? In this context, the training treatment designed should help users interpret the “signs” and build meaning. The latter achieved on building skills based on error.

The evidence for transfer (which refers to changes in learning in one situation due to prior learning in another situation) from training on a demanding working memory task to measures of performance (Jaeggy, *et al.*, 2008), serves as a framework for the training intervention used in the experiment. Jaeggy asserts that transfer can result even when the trained task is entirely different from the performance test itself.

Jaeggy (2008) and Ericsson (1994,2009) demonstrated that the extent of performance improvement directly depends on the amount of training; the more training, the more improvement in performance. That is, the training effect is dosage-dependent. Jaeggy used a recently proposed hypothesis by Halford (Halford, Cowan and Andrews, 2007) as a framework for the design of a transfer study where they would like to improve performance by means of a working memory task. In their work, they submitted the volunteers to a working memory training intervention. The training intervention relied on binding processes and attention control. Their analyses of the training functions showed that all training groups improved in their performance on the working memory task.

Anderson (1982) and Ericsson (1993) defined practice as exposure to a task. For the purpose of this chapter, the thesis will differentiate practice from training, defining training as the acquisition of techniques to carry out a task and practice as the exposure to a task for a given period of time prior to the formal execution of the task. Galton (1869) claims that motivation and perseverance are necessary to perform in any work. According to Ericsson, "the attainment of a level of performance for individuals in a given domain is not attained automatically as a function of extended experience, but the level of performance can be increased even by highly experienced (Galton, 1869) (Johnson, 2003) individuals as a result of deliberate efforts to improve" (Ericsson K. Anders 1993).

A protracted Literature review on training and practice suggests this research has been directed to expectations and current goals. There is a need transfer of the trained task to tasks in the future. No training process found in the literature review has given the trainees the opportunity to refine methods (Ericsson K. Anders, 1993). During task practice or training the participants should receive continuous informative feedback and knowledge of performance progress. In the absence of adequate feedback, efficient learning is difficult and improvement only minimal (Ericsson K. Anders 1993). The subject needs to be given the opportunity to build up memory (declarative memory and working memory, etc.) through consolidation.

In the procedure used for the experiment presented in this section, this stage of research is directed to the research of the use of sound as an adjunct to visual display to improve performance as a result of training efforts. It is a framework of researching training that will facilitate the acquisition of characteristics (skills) and transferred to a data exploration skill which changes dynamically. The participants learned what to ignore and what information not to ignore; they discerned information relevant to the skill or the task.

This section presents the results of a training experiment and explores whether threshold improvement is possible given feedback based on error. The participants had to identify the presence of signal in manipulated data; the visual display was dynamic, meaning that the position of the signal was iterated randomly in a similar fashion to Experiment 3 above. In this experiment, the participants knew what information was relevant, as they were given a baseline during the practice and clear instructions. The target audience is highly trained to visualise space physics 2D data. Regardless if they are self-trained or explicitly taught, they practice this kind of data analysis through self-motivation.

All the participants were in post doctoral or doctoral positions, implying a number of years of post graduate experience in visualising data. 16 new volunteers, space scientists from the Center for Astrophysics participated in the training and after training sessions. This section reports the results based on analysis of means and variance within a 2 way repeated measures ANOVA, reporting significance and thresholds before and after training.

### 5.6.1 Experimental Design

This experiment investigates the hypothesis that training based on feedback and error may improve the use of sound as an adjunct to data visualisation by helping participants to allocate signatures by identifying the presence of a simulated double-peaked “blac khole” pattern in simulated Black Hole space physics data. This research used a task simulating the process astronomers use to search for the characteristic indicators of black holes. The experiment determined the signal-to-noise (S/N) thresholds for which participants could correctly identify the presence of a simulated double-peaked “black hole” pattern which was obscured by visual and audio Gaussian noise.

For this purpose, the experiments were based on the visual black-hole paradigm designed by Schneps and Pomplun (Schneps, 2007). They experimentally determined the visual signal-to-noise (S/N) thresholds for which participants could correctly identify the presence of a simulated double-peaked black hole pattern which was obscured by visual Gaussian noise. The paradigm was modified to evaluate the performance of audio and visual presentation of the same type of simulated double peak data.

In this experiment, the task consisted of the presentation of four cues:

1. Sonification of the data.
2. Visualisation of data.
3. Synchronized visual and audio presentation.
4. Visual and audio presentation synchronized with a red line sweeping across the graph at the rate the sonification was played, to compare user performance.

The order of conditions was completely random as perception experiments reported on section 4. The participants responded to the cues using a keyboard and a threshold analysis using the QUEST algorithm, (Quick Unbiased and Efficient Statistical Three (Shih, 2011)) was used to calculate accuracy in the form of thresholds. The values of the psychometric function were as for perception experiments reported in section 4.5.

Auditory stimuli were presented through Sennheiser HD 215 headphones. The volume of the sound was adjusted to ensure participant comfort from 0 to 4 dB. As for perception experiments reported on section 4.1 to 4.5, the C code in matlab, translated a continuous signal into sound. Following the same parameters defined for the perception experiments reported on sections 4.1 to 4.5 created, the sound.

The following parameters define the sound in all the experiments presented in this thesis: (if the reader wants more information please refer to sections 4.1 to 4.5).

Waveform modulation = 0. If there is no waveform modulation, this is the waveform used (0 = sine, 1 = square).

1. Stereo = 0, (no pan stereo = 0).
2. FadeDuration = 0.07.
3. cf = 880Hz (carrier frequency for amplitude modulation (Hz)).
4. mf = 110Hz (minimum frequency for pitch modulation).
5. oct = 6 (octave range for pitch modulation).
6. Sample frequency = 22050 Hz.

The visual stimuli were presented on a 20-inch Apple Cinema flat-screen LCD monitor viewed at a distance of 70 cm, with a resolution of 1680 by 1050 pixels and a refresh rate of 60 Hz. Stimulus presentation and data acquisition were controlled by custom software using Matlab, (The Mathworks, Natick, Massachusetts) and the Psychophysics Toolbox (Brainard, 1997).

### 5.6.2 Procedure

Visual and Audio graphs of artificial "radio spectra" were simulated, (similar to Experiments 1, 2 and 3) for this experiment and served as stimuli in the present study. The visual stimuli, (visual graphs), based on the paradigm designed by Schneps and Pomplun, (Schneps, 2007), was shown as a white line (luminance: 360 cd/m2) on an otherwise black screen (3 cd/m2). The width of this line was approximately 0.1° of visual angle, and the graph subtended 30° horizontally and 3° vertically. In 'noise-only' stimuli, the vertical position of the graph at each horizontal pixel position was determined by Gaussian noise and the graph was scaled to subtend 3° vertically. In 'signal' stimuli, a signal consisting of two positive upward peaks was added to the noise before the scaling was performed. These peaks were modelled by identical Gaussian functions using a standard deviation of 0.5° and variable but equal peak elevation. The quotient of peak elevation and standard deviation of the Gaussian noise in a given stimulus was operationally defined as its signal-to-noise ratio (S/N). The two peaks always occurred to the left and to the right of the centre at identical eccentricity. The span separating the peaks were either 8°, 16° or 24° with random jitter in the span modelled by Gaussian noise and having a standard deviation of 1.0°.

The participants performed two sessions: a training session and an after training session conducted 24 hours later. In each session the participants performed five blocks of trials, for each condition and in random order. Each block consisted of 15 trials, with the presentation of each spectrum for 1000 ms. Participants were instructed to press the 'S' button on a computer keyboard if they believed that the current spectrum contained a signal and to press 'N' if they thought that there was no signal.

There were no time limits imposed for the participants' responses. Immediately after pressing the button, participants were acoustically informed whether their response was correct (800 Hz sound played for 20 ms) or incorrect (400 Hz sound played for 100 ms). If their response was incorrect, a visual prompt was displayed on their screen giving them the option to re-play the previous cue for a maximum of 5 times but not allowing them to change their answer. This was to give them the opportunity to review their error.

Participants were allowed to move their eyes freely throughout the experiment. The first trial in each block presented a signal at a signal-to-noise ratio of 10, which was very easy to identify. The remaining trials were aimed at estimating the signal-to-noise threshold at which the subject gave correct responses in 75% of the trials. This estimation was performed using the QUEST staircase procedure (Pelli, 1987), (Watson, 1983) with an initial threshold estimate of 1.5 and parameters $\beta = 3$, $\delta = 0.01$ and $\gamma = 0.3$. The threshold update between trials was based on the quantile method and the final estimate was determined by the mean method (Pelli, 1987).

Before each session participants received instructions that included a description of the auditory and visual graph and task. To provide a baseline of the task participants were exposed to a 3 minute practice. The practice gave the participants the opportunity to experience the 4 stimuli in random order and practice to answer.

The participants performed 20 blocks of trials for each condition: 1, 2, 3 and 4 with spans of 8°, 16°, or 24° and delivered in random order. Instructions, consent form and stimuli were as for Experiment 3 with the exception that participants had the option to replay any wrong answered cue up to a maximum of 5 times. Abbreviations are used to describe some of the experiment condition sets as described below and earlier in this thesis and are as follows:

- A = audio only.
- V = visual only.
- AV = audio and visual.
- AVR = audio, visual and red-line.

Conditions are show in Table 21. The after-training experiment comprised of the same conditions as the training session. The opportunity to experience the cue after a wrong response was removed. This did not give the participants the opportunity to review their incorrect answers and build skills based on error, hindering the participant's opportunity to refine methods by removing immediate informative feedback and knowledge of results of their performance. In the absence of adequate feedback, efficient learning is impossible and improvement only minimal even for highly motivated subjects. Hence mere repetition of an activity will not automatically lead to improvement especially in accuracy of performance (Trowbridge and Cason, 1932).

This experiment measures tthe signal-to-noise threshold at which the subject give correct responses towards the hypothesis that training based on error will help target audience to use sound as an ajunct to visualisation to analyze astrophysics data.

| Session | Condition | Dependent Variable |
|---|---|---|
| **1** | **1** | T1 = training session V |
| | **2** | T2 = training session A |
| | **3** | T3 = training session AVR |

| | | |
|---|---|---|
| | **4** | T4 = training session AV |
| **2** | **1** | AT1 = after training session V |
| | **2** | AT2 = after training session audio only |
| | **3** | AT3 = after training session AVR |
| | **4** | AT4 = after training session AV |

**Table 21 - Between subjects factors in the training experiment.**

### 5.6.3 Results

A 2 way ANOVA (Training (T) and after training (AT)) resulted in significance on both, the main effect of training ($F (1; 15) = 6.50$, $p < 0.05$) and the main effect of condition ($F (3; 45) = 5.05$, $p < 0.005$). As expected, performance improves from the first (T) to the second (AT) session. However, there was no interaction between the two factors ($F (3; 45) < 1$, $p > 0.4$), indicating that training did not have differential effects on the four conditions.

Computation of 16 different t-tests testing were performed for differences between conditions before training, after training, and before vs. after training for the same conditions. Only four of these tests yielded significant results:

T 1(V) < T1(A), $t(15) = 2.89$, $p < 0.05$

AT(V) < AT(A), $t(15) = 2.41$, $p < 0.05$

AT(A) > AT(AV), $t(15) = 4.23$, $p < 0.005$

AT(A) > AT(AVR), $t(15) = 2.80$, $p < 0.05$

Qualitatively, it seems that all the conditions except condition 1 (Visual) benefit from training. SPSS does not work with screen readers which make it impossible to present a multimodal gain chart and do more specific statistics.

| | T(V) | T(A) | T(AV) | T(AVR) | AT(V) | AT(A) | AT(AV) | AT(AVR) |
|---|---|---|---|---|---|---|---|---|
| P1 | 0.72 | 0.72 | 0.56 | 0.55 | 0.72 | 0.72 | 0.56 | 0.55 |
| P2 | 0.6 | 0.55 | 0.86 | 0.59 | 0.71 | 0.69 | 0.56 | 0.51 |
| P3 | 0.66 | 0.74 | 0.55 | 0.57 | 0.73 | 0.64 | 0.43 | 0.55 |
| P5 | 0.55 | 0.72 | 0.58 | 0.52 | 0.46 | 0.51 | 0.37 | 0.49 |
| P6 | 0.59 | 0.61 | 0.45 | 0.42 | 0.41 | 0.67 | 0.46 | 0.48 |
| P9 | 0.51 | 0.87 | 0.62 | 1.02 | 0.58 | 0.88 | 0.67 | 0.57 |
| p10 | 0.49 | 0.63 | 0.44 | 0.32 | 0.56 | 0.45 | 0.73 | 0.53 |
| p11 | 0.64 | 0.82 | 1.24 | 0.63 | 0.47 | 0.8 | 0.46 | 0.53 |
| p12 | 0.53 | 0.49 | 0.5 | 0.53 | 0.53 | 0.57 | 0.54 | 0.49 |
| p13 | 0.65 | 1.3 | 0.52 | 0.46 | 0.61 | 0.66 | 0.62 | 0.51 |
| p14 | 0.55 | 0.59 | 0.79 | 1.35 | 0.49 | 0.79 | 0.58 | 0.65 |
| p15 | 0.47 | 0.85 | 0.66 | 0.72 | 0.6 | 0.71 | 0.58 | 0.57 |
| p16 | 0.37 | 0.56 | 0.38 | 0.41 | 0.5 | 0.53 | 0.49 | 0.42 |
| p17 | 0.73 | 0.66 | 0.68 | 0.86 | 0.71 | 0.73 | 0.66 | 0.63 |
| p18 | 0.57 | 1.24 | 0.43 | 0.47 | 0.4 | 0.66 | 0.49 | 0.5 |
| p19 | 0.55 | 0.52 | 0.53 | 0.41 | 0.51 | 0.42 | 0.56 | 0.56 |

**Table 22 Average Thresholds (signal-to-noise ratio) per condition before and after training).**

Schneps *et al.* (2007) supplied Figure 8 which plots the results of the black hole experiment performed with a control group of PhD space physicists screened alike and experiencing only visual cues. In their experiment they calculated the signal-to-noise threshold by visual angles of $8^0$, $16^0$ and $24^0$. Schneps *et al.* (2007) used an average threshold (visual angle fixed at $8^0$) for their control group which comprised of PhD astronomers and who were screened in the same manner as were those used for the experiments presented in this thesis. Schneps results, yielded a poorer performance than in Experiments 2, 3, and 4 designed for this thesis. The results show an improvement from training (T) session to After training (AT) session. But it did not, show interaction between the two factors indicating that training did not have differential effects on the four conditions. Important it is to notice experiment 3 average thresholds (section 4.5) are very similar to exper iment 4 AT average threshold results.

Ericsson and Charness (Ericsson and & Charness 1994) assert that, when the time interval between scientists' first accepted publication and their most valued publication is measured, it averages more than 10 years and implies an even longer preparation period. Even for the most successful ("talented") individuals, the major domains of expertise are sufficiently complex that mastery of them requires approximately 10 years of essentially full-time focus, which corresponds to several thousands of hours of practice (Ericsson and & Charness 1994). Ericsson (K. A. Ericsson 2009) also asserts that for more experienced individuals large mistakes become increasingly rare, performance appears to be smoother and the learner no longer needs to concentrate as hard to perform the task. This is analogue to space physicists participating in the study presented in this section. The longer a space scientists use a particular data analysis technique, the quality of the signal identification increases. As a result the experienced space scientist can tipically recognize a sought signal whereas in the task presented for the training treatment ,(T) and (AT) , the target audience had to evaluate rather than recognize. In that context, experiments with longer training periods are necessesary to conclusively assert the effectiveness of training.

| **Paired Samples Test** | | **Results** |
|---|---|---|
| **Pair 1** | **T1 – T2** | 0.011 |
| **Pair 2** | **T1 – T3** | 0.571 |
| **Pair 3** | **T1 – T4** | 0.457 |
| **Pair 4** | **T2 – T3** | 0.178 |
| **Pair 5** | **T2 – T4** | 0.131 |
| **Pair 6** | **T3 – T4** | 0.987 |
| **Pair 7** | **AT1 – AT2** | 0.029 |
| **Pair 8** | **AT1 – AT3** | 0.288 |
| **Pair 9** | **AT1 – AT4** | 0.656 |
| **Pair 10** | **AT2 – AT3** | 0.001 |
| **Pair 11** | **AT2 – AT4** | 0.013 |
| **Pair 12** | **AT3 – AT4** | 0.478 |
| **Pair 13** | **T1 - AT1** | 0.653 |
| **Pair 14** | **T2 - AT2** | 0.145 |
| **Pair 15** | **T3 - AT3** | 0.175 |
| **Pair 16** | **T4 - AT4** | 0.302 |

**Table 23 Paired samples T-tests for the training experiment.**

The reader may remember that experiment 3 T-tests, results showed that (AVR) [32] lead to better performance than Auditory ($p = .018$) or Visual ($p = .001$) and resulted in a tendency of AV, (Both), leading to better performance than Visual). T-test also show BothRedLine (AVR) was not better than both ($p = .731$).

Training session T test analysis shows during training session, audio (T2) lead to better performance than visual (T1), T(V) < T(A), $t(15) = 2.89$, $p=0.011$, $< 0.05$. T test shows that AV ( T3), and AVR (T4) did not lead to better performance than visual or audio (see table 23). Like in experiment 2 and 3, T4 (AVR) did not lead to better performance than T3(AV) and AT4 did not lead to better performance than AT3.

After Training session t test analysis, shows that audio (AT2) leads to better performance than visual (AT1) $t(15) = 2.41$, $p = 0.029 < 0.05$ Evidencing that with more training the audio performance will improve; AT3 (AV) leads to better performance than AT2 (A) $t(15) = 4.23$, $p = 0.001 < 0.005$ , and AT4 (AVR ) leads to better performance than AT2(A) $t(15) = 2.80$, $p = 0.013 < 0.05$.

Once again (like for experiment 2 and 3), AVR did not lead to better performance than AV in either T and AT sessions.

The Training session (T) was a complex task requiring to integrate many skills. Participants were analyzing, evaluating and generating a response. This setting exposes

[32] AVR=Audio/visual with redline.

(by choice) the volunteer to fail, by imposing a cognitive load on the volunteer, which may undermine participants immediate ability to do integrative thinking.

The after training session resembles completely experiment 3, with the exeption that participants had a training session (24 hours before) and consolidation time (sleep) before hand. The after training session is key to show if participants' performance improve. According to the t-test analysis conditions AT2 (A), AT3(AV), and AT4(AVR) improve (See table 23). Frequency percentage distribution will be necessary in order to check in which condition the lowest signal to noise ratios were identified (as shown for experiment 2 and 3).

This discovery may have implications in the fields of designing effective training treatments, design of effective training and displays to aid people with learning disabilities, data mining and ambiguity. Other aspects that may be benefited from computerised effective training intervention using sound and sight is the acquisition of skills, say, prosody in people with cognitive disorders or improvement of communication skills in people suffering from Aphasia and Apraxia.

Participants commented that every time they repeated the cue after a wrong answer for conditions 1 (V), 3 (AVR), and 4 (AV), they were trying to visualise (find with their eyes) where they had made the mistake. Participants also stated that the after training session was much more challenging than the initial training session. According to the results the average performances were much better during the after training session.

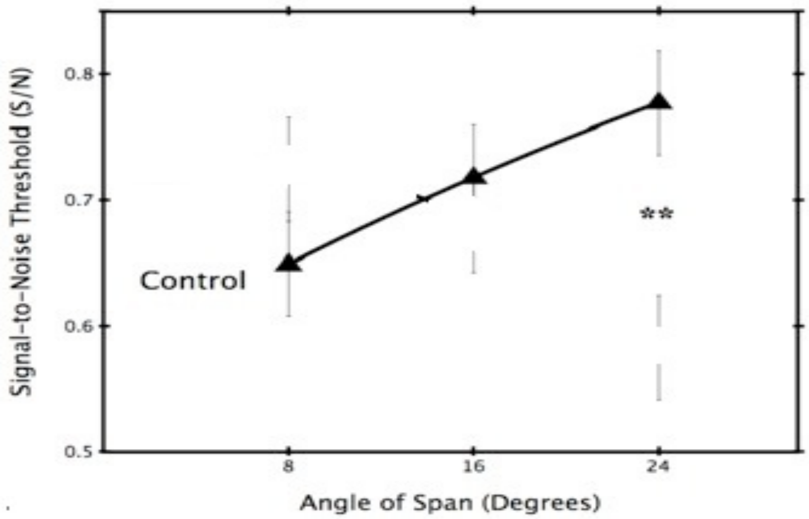



**Figure 10 Signal-to-noise ratio per angle of span (Schneps 2007).**

### 5.6.4 Conclusions

Experiment 3 serves as control group experiencing the paradigm once. Future research will have a control group experiencing the paradigm twice with no training for a better control of variables and address the effect of repetition. This is to discard the possibility of the improvement in performance to be incidental, due to mere repetition or as an effect of the training treatment, (being able to review answers, consolidation time, etc.).

It is widely known that auditory skills may be improved. The results presented in this section indicate that performance in signal detection is improved when using sound as an adjunct to visualisation. The results presented may preliminary open the path to research on training treatments to elicit multimodal perceptualization for the exploration, analysis of space physics data.

The higher ability of performers in the after training sessions stems from an improved ability to detect changes and adjust efforts to cope with changing task demands.

## 5.7 Conclusions from the Perception Experiments

| Experiment | S-to-N Threshold V | S-to-N Threshold A | S-to-N Threshold AVR | S-to-N Threshold AV |
|---|---|---|---|---|
| **1** | 0.660 | 0.784 | | 0.651 |
| **2** | 0.484 | 0.603 | 0.542 | 0.513 |
| **3** | 0.655 | 0.633 | 0.531 | 0.549 |
| **Training (T)** | 0.574 | 0.741 | 0.613 | 0.612 |
| **After Training (AT)** | 0.5617 | 0.6527 | 0.5331 | 0.5485 |

**Table 24 - Comparison of the Experiments: 2 (ND and 4 conditions); 3 (DV and 4 conditions); Training session (T) and (AT) DV and 4 conditions.**

The table above shows the average performance for each condition for the experiments. Note that the average performance for Experiment 1 (NDV $8^0$ visual angle) matches the average threshold obtained by Schneps and Pomplun in their experiments (see Figure 8). Schneps only used visual condition and one static visual angle. Also note that the average performance improves for sessions T and AT. Comparing After Training experiment results with experiment 3 (section 4.5), which serves as a base line; there is no meaningful change among the mean thresholds. It is necessary to do a threshold frequency distribution per condition for T and AT sessions and a multimodal gain calculation (for all the experiments in this section) defined as: increase in single stimuli condition/ increase in more than one stimuli condition. Ericcson (Ericsson and & Charness 1994) asserts experts acquire skill in memory to meet specific demands of encoding and accessibility in specific activities. Consolidation time provided the participants with a mean to organize acquired knowledge and refine procedures and strategies, and it "allows participants to find a way around limits on working memory demanded by the limited capacity of short-term memory in a given domain" (Kandel Erick R 2012). During the Training session the participant had the chance to review answers, re-organize, refine and consolidate knowledge. But their ability to recognize and identify the signal embedded in the noise had a strong component on their ability to recognize and identify the signal, on the basis of their previous knowledge identifying signal. Undoubtedly T-test analysis results show that all conditions improved at AT session. The experiments presented in this section prove that the use of sound as as adjunct to visual display increase the sensitivity to signal detection (see table 3 and 4 below). It is inconclusive about the effects of the particular training treatment designed for this research. But it is conclusive on the improvement of multimodal perceptualisation and auditory perceptualisation after training (see pairwise comparisons on Table 23). This is important for other tasks in science such as trying to find very small changes in x-ray images or minute changes in visually noisy images or geological data.

| Class (signal/ Noise ratio) | Visual | Audio | AV | AVR |
|---|---|---|---|---|
| 0.3-0.4 | 7.14 | 0 | 14.28 | 7.14 |
| 0.4.0.5 | 64.28 | 14.28 | 42.85 | 28.57 |
| 0.5-0.6 | 14.28 | 28.57 | 28.57 | 50 |
| 0.6-0.7 | 14.28 | 42.85 | 7.14 | 14.28 |
| 0.7-0.8 | 0 | 14.28 | 7.14 | 0 |
| | 100 | 100 | 100 | 100 |

**Table 3 Frequency % distribution signal to noise ratio experiment 2.**

| Class (Signal/ Noise ratio) | Visual | Audio | AV | AVR |
|---|---|---|---|---|
| **.33-.49** | 16.66666667 | 8.333333333 | 41.66666667 | 25 |
| **.49-.65** | 16.66666667 | 50 | 50 | 66.66666667 |
| **.65-.81** | 50 | 33.33333333 | 0 | 8.333333333 |
| **.81-.97** | 16.66666667 | 8.333333333 | 8.333333333 | 0 |
| | 100 | 100 | 100 | 100 |

**Table 4 Frequency % distribution signal to noise ratio experiment 3.**

The results of the experiments if corroborated may imply that sound used as an adjunct to visualisation used as a congruent cue aid attention control over a competing visually ambiguous stimuli, is associated with sensitivity to changes, (away from the direction of gaze, non-persistent, clouded by noise, weak, quasi-periodic, etc). This could prove to be especially true in visually ambiguous data, (low signal-to-noise ratio and when masked by noise).

As an end and side note to this chapter, physics and its related fields have become an elite science open for people that may adapt to the current perceptualization and visualisation techniques available to succeed in the field.  Petascale space science has brought space scientists to engage in multimodally perceptualizing the data, which will open the field of space science to other kind of learners.

# 6 Conclusions

This chapter summarizes the main findings of the PhD research. The research set out to explore if the use of sound as an adjunct to visualisation helps space scientists identify signals in 2D astrophysics data, especially signals masked by competing visual noise. This chapter presents the findings from 3 perspectives:

1) User needs
2) Satellite data analysis
3) Perception experiments

This research has identified challenges encountered by space physicists when exploring 2D space physics data. The work has also sought to prove by using perception experiments if the use of sound as an adjunct to visual display augments the detection of signals in space physics 2D data. The general theoretical literature about this subject in psychology supports the argument that the auditory cortex can be profoundly engaged in processing non-auditory signals, particularly when those signals are being attended to (Shinn-Cunningham, 2008). Psychology experiments also proved that congruent sound aids attentional control over visual ambiguity. These ideas motivated the approach taken in this thesis.

Through perception experiments, focus groups and usability evaluations this dissertation tried to answer the following question:

> Does sound used as an adjunct to current data visualisation, augment the perception of signatures in space physics data masked by noise?

To answer this question, the following additional questions had to be answered:

c) Is sound used as an adjunct to visualisation effective in increasing sensitivity to signals occurring at attended, unattended, unexpected locations, extended in space, when the occurrence of the signal is in presence of a dynamically changing competing cognitive load (noise), that makes the signal visually ambiguous?

d) How can multimodal perceptualization (sound as an adjunct to visualisation) and attention control mechanisms, be combined to help allocate attention to identify visually ambiguous signals?

## 6.1 User Needs Perspective

This thesis presents evidence that sound as an adjunct to visual display helps astrophysicists in the identification of signal embedded in noise. For the purposes of exploring this, a review of the target audience's needs, perception experiments and space physics data analysis were conducted. The sonification tools used for space physics are often intuitively developed by space scientists with a need to explore data in a different way. The prototypes are not user-centred but focus on the type of data to be explored. This raises the need for developing a user-centred sonification prototype that may be used by a wider audience inside the space physics community and that will make use of human computer interaction knowledge. The system has to provide for the user to: get to the data analysis fast, without cognitively overwhelming the user and/or without limiting the user to a limited number of mathematical conditions or states. Of course, this means that it needs to accept a wide diversity of data formats and allow the user to adjust the sonification parameters towards maximizing sensitivity to signal detection.

The sonification tools reviewed in the literature review map and aurally display the data. The tools were built around the type of data set to be sonified and not around the needs of the target user (space scientists) during data analysis. Most of the sonification prototypes for space science in the literature review have been built with the purpose of using sonification for outreach purposes, rather than data analysis. Undeniably, the emergence of these prototypes has underlined the need space scientists have for alternate ways to analyse their data by using multimodal perceptualization to augment signatures in the data and even to identify if a signal is real or not. This should be seen as an effort to complement the always-developing technology with human abilities. This means space scientists need new techniques such as sonification and multimodal perceptualisation to search for the signatures embedded within the noise.

The literature review, focus groups and usability evaluations carried as part of this research evidence that all of the mentioned areas of application of image and signal processing in astronomy and space physics are validated visually. The tools for visualisation and exploration are used to rapidly and intuitively inspect very large data sets to identify regions of interest within which to apply time-consuming algorithms. The data exploration tools are limited to the processing and displaying of 2D images or for the generation of meaningful 2D and 3D plots. The space physics community needs new methods for facilitating more dynamic inspections of large data sets. So far in space physics, efforts have been directed to the further development of high performance architectures such as multi-core CPUs, powerful graphic cards and interoperability (see Chapter 2).

The analysis of the data collected during the focus groups confirms that space physicists are frustrated when performing data analysis due to:

1. The forced engagement in data formatting to fit software architectures;
2. The desire to analyse the data to search for events which may be masked by noise, by the current data analysis techniques used or that are away from their direction of gaze.

Identifying user needs brought about the development of a user-centred prototype for analysing space physics using multimodal perceptualization, sound as an adjunct to visualization, which could support its users and target those aspects which cause frustration when performing data analysis.

To understand user needs and issues for the prototype, focus groups and usability evaluations were conducted. The results of these studies have shown that they wish to explore the data as naively as possible, before any filtering or transformation takes place, otherwise there is a risk of the loss of important but perceptually ambiguous information embedded in the data.

The literature review and xSonify chapters presented such an approach from a user needs perspective. Later, the thesis addressed if sound as an adjunct to visualisation augmented the sensitivity to signals from the perspective of perception and training experiments. This thesis presented carefully designed experiments to explore this from the perspective of a space physics signal detection task with manipulated and non-manipulated data.

The studies showed that in this field, space scientists are searching for new ways to approach their data. The improved version of the sonification prototype provides space scientists with an application that will take them directly to the execution of their science and will provide multimodal perceptualization of the data that as the volunteers said, "may bring forth other correlations not thought of at the time of data gathering".

## 6.2 Data Analysis Perspective

Once the sonification protoype reached a release stage it was imperative to test its efficacy for carrying data analysis. The latter was done by:

1. Finding available data that exemplifies the data most used by space physicists. These included: FITS, time series, power spectra, magnetic fluctuation and radio data to assess the effectiveness of the use of sound to explore the data in the search for signatures/changes/events in both manipulated and un-manipulated data.

2. Motivating space scientists to use the sonification prototype for data analysis and share results. This section is placed here for the sake of future readers seeking guidance on how to use sound to approach space physics data.

Dr. Alicia Sodeberg, team leader at the supernova forensics group at the Center for Astrophysics in Massachusetts, reported to the author of this thesis and at National Public Radio broadcast about her listening to supernova data: "When Soderberg listens to these songs, she started to hear things. Things she hadn't noticed when she looked at the data." The reader may find the full transcription and radio interview at http://www.npr.org/blogs/thetwo-way/2014/01/10/261397236/dying-stars-write-their-own-swan-songs. The findings published by the super nova forensic team are below including links to the supernova sounds:

1. The Fast and Furious Decay of the Peculiar Type Ic Supernova 2005ek

M. R. Drout, A. M. Soderberg, P. A. Mazzali, J. T. Parrent, R. Margutti, D. Milisavljevic, N. E. Sanders, R. Chornock, R. J. Foley, R. P. Kirshner, A. V. Filippenko, W. Li, P. J. Brown, S. B. Cenko, S. Chakraborti, P. Challis, A. Friedman, M. Ganeshalingam, M. Hicken, C. Jensen, M. Modjaz, H. B. Perets, J. M. Silverman, D. S. Wong. arXiv:1306.2337v2 [astro-ph.HE] 11 Jul 2013.

2.A panchromatic view of the restless SN2009ip reveals the explosive ejection of a massive star envelope

R. Margutti, D. Milisavljevic, A.M. Soderberg, R. Chornock, B.A. Zauderer, K. Murase, C. Guidorzi, N.E. Sanders, P. Kuin, C. Fransson, E.M. Levesque, P. Chandra, E. Berger, F.B. Bianco, P. J. Brown, P. Challis, E. Chatzopoulos, C.C. Cheung, C. Choi, L. Chomiuk, N. Chugai, C. Contreras, M.R. Drout, R. Fesen, R.J. Foley, W. Fong, A.S. Friedman, C. Gall, N. Gehrels, J. Hjorth, E. Hsiao, R. Kirshner, M. Im, G. Leloudas, R. Lunnan, G.H. Marion, J. Martin, N. Morrell, K. F. Neugent,

N. Omodei, M.M. Phillips, A. Rest, J.M. Silverman, J. Strader, M.D. Stritzinger, T. Szalai, N.B. Utterback, J. Vinko, J.C. Wheeler, D. Arnett, S. Campana, R. Chevalier, A. Ginsburg, A. Kamble, P.W.A. Roming, T. Pritchard, G. Stringfellow. arXiv:1306.0038v1 [astro-ph.HE] 31 May 2013

Links to the sounds corresponding to the papers above may be found at: http://arxiv.org/a/friedman_a_1

The data analyst for the data presented in Chapter 4 only used sonification to approach the data because the data analyst was the author who happens to be blind. At the same time, the reader should note that results were presented to a sighted audience that validated the results through exposing themselves to the data sonification and visualisation by performing numerical validation. The analysis of the data presented contained:

1. Analysis of data that had already been analysed by sighted astrophysicists. Results from sonification of the data is presented as well as new periods that had been overlooked by sighted post-doctoral astrophysicists using currently available techniques;

2. Analysis of data to perform a frequency study of the noise floor by acquiring data from a constellation of satellites. Results include the numerical and auditory validation of findings by sighted astrophysicists.

3. Analysis of time series radio data. The results include the numerical and auditory validation of findings by sighted astrophysicists.

## 6.3 Perception Experiment Perspective

Data sets are becoming too large to be handled with current visualisation tools, as discussed in Chapter 2. Each event in the interstellar medium is the product of a number of oscillatory modes. Those events may be quasi-periodic, non-persistent, masked by noise, fleeting, etc. Traditional techniques for the analysis of space physics data such as radio, particle, magnetic fluctuation and X-ray are based on visual exploration of data. Additionally, various nonlinear time-series-analysis methods (Tong, 1990), (J.S., 1993) (Kantz and Schreiber, 1997), (Diks, 1999) were designed for nonlinear but stationary and deterministic systems.

Space scientists base their data analysis on fitting the data to waveforms determined by the problem at hand, linearising and or stationarizing the data. Unfortunately, in most real systems, either natural or human-made, data are most likely to be nonlinear and non-stationary.

Space physics and its graphical representations have mostly been visual and unimodal. The size of space physics data sets is always increasing, saturating the visual perceptual system when rendering for visual display. Another limitation is that, even the best computer screens available on the market today are limited to a range of spatial resolution. This limitation affects the useful dynamic range of the display, reducing the amount of data scientists can study at any one time. Scientists currently work around this limitation by filtering the data, so as to display only the information they believe is important to the problem at hand. But since this involves making some *a priori* choices about the results they are searching for, discoveries may be missed.

The experiments presented in this thesis were based on the empirical measurement of performance . The visual Black Hole paradigm designed by Schneps and Pomplun (Schneps, 2007) was modified to evaluate participant's performance when experiencing audio and visual presentations of the same type of simulated double peak data. Three experiments were conducted:

### 6.3.1 Experiment 1

Visual stimuli presented at a static visual angle of 8 degrees

a) Visual

b) Audio

c) Visual and Audio together. Visual stimuli presented at a static visual angle of 8 degrees and congruent with the sound.

### 6.3.2 Experiment 2

Given the results of Experiment 1, these experiment were conducted with the presentations of 4 cues, which serve as stimuli. Visual stimuli were presented at a static visual angle of 8 degrees.

a) Visual.

b) Audio.

c) Visual and audio together. (visual and audio presentations synchronized)

d) Visual and Audio together with a red-line sweeping across the spectra at the rate the sonification is played (Visual, audio and red line synchronized).

### 6.3.3 Experiment 3

Given the results from the previous 2 experiments, Experiment 3 was conducted with the presentation of 4 cues that serve as stimuli but incorporating a range of alternate degrees of visual angles. Visual stimuli presented at a dynamic changing visual angle of either, 8, 16 or 24 degrees for 1000 ms.

e) Visual
f) Audio
g) Visual and audio together (visual and audio presentations synchronized).
h) Visual and Audio together with a red-line sweeping across the spectra synchronized with the sound played (Visual, audio and red line synchronized).

In Experiment 1, none of the conditions (a, b or c) differed significantly. The results were inconclusive but suggested that, with further support, sound could augment visualisation.

These results neither support deVallez's (Devallez, Rocchesso and Fontana 2007) experiments nor contradict Ecker and Heler's (Ecker and Heller 2005) experiments described previously in the Sonification chapter. As in Ecker experiment, the black hole task signal gets more ambiguous as the task progresses and dynamically changes its intensity. This means that not only the noise level increases but also the signal strength changes dynamically.

As mentioned earlier, If the decision-maker has to monitor a low signal to noise ratio source on the basis of intensity, and if each event is cluttered by dynamically changing visual noise and position, then according to this authors there will be a high probability that the decision will be erroneous and made with high confidence. High-confidence errors can have major consequences, as it implies a desicion indirectly proportional to uncertainty. As demonstrated by Baldacci and Burr, discriminability thresholds worsen when visual perceptual clutter is present, but ‘‘observers make more high confidence errors when there are many distractors than when there are few’’ (Baldacci, Mega and Burr 2006). Space science data analysis deals with the cognitive load of the noise that not only affects their judgement and confidence when identifying the signal but at the same time triggers mechanisms of attention that inhibit peripheral sensitivity (Schneps, 2007).

Experiment 2 data analysis (repeated-measures ANOVA with factor "condition" (levels 1-4) yielded the result: $f(2.19, 28.5) = 4.83$; $P < 0.012$ ; $p < 0.05$, showing significance and thus the null hypothesis can be rejected.

The paired difference table shows significant differences for conditions 1 vs. 2, conditions 1 vs. 4, conditions 2 vs. 4, and conditions 2 vs. 3. Paired differences for experiment 2 indicate that audio (A) leads to better performance than visual (V) ($p = 0.004$). BothRedLine (AVR) leads to better performance than visual (V) ($p = 0.036$). Audio-Visual (AV) leading to better performance than audio (A) ($p = 0.016$) and AudioVisual RedLine (AVR) leading to better performance than audio ($p = 0.044$).

The reader should note that BothRedLine (AVR) did not lead to better performance than Both (AV) stimuli ($p = 0.361$).

Experiment 2 resulted in average; signal-to-noise ratio (threshold) identified by the participants in the audiovisual condition is .51 (see table 6). Audio-Visual condition Frequency percentage (see table 9) is 14.3% at signal-to-noise ratio range (threshold) of .3-.4, (see table 9 and figure 4 and 5), as opposed to V with a percentage frequency of 7% at a signal to noise ratio range of .3-.4

Given the results, the red line did not lead to better performance than the Audio-Visual stimuli. If the volunteers were using the red line implicitly then the sweep-line helped the user understand where they were in the context of the entire data set and to exert control over the audio stimuli as ambiguity increases. All the participants verbalized that the red line was a distractor. This is an indicator that participants were aware of the event, in such cases, according to Posner (Posner, Snyder and Davidson 1980) the participant is able to align attention with the expected event and for instance the red line becomes a distractor. Then as visual ambiguity increases, the audio becomes the more reliable modality. As a side note, it may be important to note that during debrief all the participants said they re-played the sound in their heads before selecting an answer. None of the participants said they re-played the visual image in their heads.

Donohue (2013) performed experiments on Cross-Modal effects. Like Van EE

(2009), her results proved that response accuracy was only modulated by congruency.

Donohue's findings are based on the fact that visual processing tends to be faster than auditory processing as reflected by RTs (Molholm, *et al.*, 2004), (Yuval-Greenberg and Deouell, 2009) (Donohue *et al.*, 2013). Second, there is a general pattern of asymmetry between the magnitudes of conflict effects observed in cross-modal contexts, in that incongruent visual stimuli generally produce more interference on the processing of relevant auditory stimuli, than *vice versa* (Molholm, *et al.*, 2004), (Yuval-Greenberg and Deouell, 2009), (Stuart and Carrasco, 1993), (Roelofs, 2005)(Donohue *et al.*, 2013). According to Donohue, cross-modal asymmetries may be found in instances of uncertainty, wherein the more reliable modality 'wins' (e.g., a shift in the auditory percept toward a more spatially reliable visual stimulus, as in the ventriloquist effect (Alais and Burr, 2004), (Bertelson and Radeau, 1981). Earlier it is mentioned that, when Yuval-Greenberg and Doeuell degraded their visual stimuli making them more difficult to identify, the visual conflict effect on auditory processing diminished, evidencing that the visual information was not being relied on as heavily (Yuval-Greenberg and Deouell, 2009)(Donohue *et al.*, 2013).

This is analog to the task performed in experiment 2.  Space scientists with postdoctoral publications have an average experience time of 10 years (Ericsson and & Charness 1994) (Ericsson K. Anders 1993) (K. A. Ericsson 2009) (Chase W.G. and Ericsson 1982). Then applying Ericsson assertions to target audience, space scientists with this level of expertise do not commit so many big errors and is used to identify and interpret the kind of signal being sought using a particular data analysis technique of their choice. In the case of this experiment the participant is not only identifying but also analysing as ambiguity increases, being the signal more difficult to identify.

Then like in the experiments presented in this thesis, as visual ambiguity increases (as the noise level increased and the signal intensity decreased) the synchronized audio becomes the more reliable modality, increasing then sensitivity to signal detection.

Experiment 3 explored the effects of using multimodal (audio and visual) cues to explore the effect of sound as an adjunct to visualisation on exploring data masked by noise for which signal position is randomly iterated. The Experiment resulted in statistical significance across the 4 conditions. Condition 4 (AVR) had a threshold average (mean) signal to noise ratio that was lower than for the audio, visual and audio/visual conditions.

The result of Experiment 3, shows a repeated-measures one-way ANOVA, based on condition resulted in a significant main effect; $f(2.11,23.21) = 3.47$; $p=.009 < .05$. Variance analysis $S=12$, $N=60$ produced significance across the 4 conditions $p = .009$, rejecting the null hypothesis (see table 16 for pair wise comparisons). In Condition 4 (AVR), signal-to-noise (Mean) was favoured over condition 1, 2 and 3 (see Table 10 reproduced below).

| **Experiment 3** | **Condition 1 (V)** | **Condition 2 (A)** | **Condition 3 (AV)** | **Condition 4 (AVR)** |
|---|---|---|---|---|
| **(Mean) Threshold** | 0.65542 | 0.63300 | 0.54892 | 0.53142 |
| **Std deviation** | 0.157803 | 0.115934 | 0.148118 | 0.112911 |

| | | | | |
|---|---|---|---|---|
| **N** | 12 | 12 | 12 | 12 |

**Table 5 Reproduction of table 10 (Mean) threshold per condition experiment 3 DV**

T-Test Paired sample statistics (Paired Differences) shows that performance is significantly affected by the conditions. T-tests show that condition AVR [33] leads to better performance than Auditory (p = .018) or Visual (p = .001) and there is a tendency of AV, (Both), leading to better performance than Visual). T-test also show BothRedLine (AVR) did not lead to better than both (p = .731).

The frequency distribution per condition for Experiment 3, shows a 41% at signal to noise ratio of 0.33 -0.49 with dynamically changing stimuli. The lowest signal to noise threshold in table 5 above occurs condition 4 (AVR) but the frequency distribution is higher at a signal to noise ratio of 0.33 - 0.49 for AV (41.66%) condition as opposed to conditions V, AV and AVR. This is very important because in Experiment 3, the participants did not have the expectation factor as the signal was iterating dynamically between 8, 16 and 24 degrees of visual angle. The signal to noise ratios or thresholds identified by participants is much lower than signal to noise threshold reported by Schneps for either experiment 2 and experiment 3 (see Figure 8). This, together with experiments T-tests that AVR condition was not performing better than AV condition, supports strong evidence that sound used as an adjunct to visualisation increases sensitivity to signal dectetion.

[33] AVR=Audio/visual with redline.

Baldaccis principle extends to complex decisions like the detection of signal embedded in noise in astrophysics data. If the decision-maker has to monitor a low signal to noise ratio source on the basis of intensity and angle of visual fiel, and if each event is cluttered by dynamically changing visual noise, then according to this authors there will be a high probability that the decision will be erroneous and made with high confidence. High-confidence errors can have major consequences, as it implies a desicion indirectly proportional to uncertainty (not only referring to statistical uncertaintiy but embracing perceptual uncertainty). As mentioned in Chapter 2, in space physics the signal as acquired by the satellites or ground observatories, is embedded in noise that becomes visual noise when plotted for analysis. Space scientist data analysis deals with the cognitive load of the noise that not only affects their judgement and confidence when identifying the signal but, at the same time, triggers mechanisms of attention that inhibit peripheral sensitivity (Schneps, 2007). High-confidence errors are critical in space physics as it may lead to erroneous discoveries. As mentioned in Chapter 2, in space physics the signal as acquired by the satellites is embedded in noise that becomes visual noise when plotted for analysis. The use of the synchronized stimuli helped astrophysicists in their judgement when identifying the signal and triggering mechanisms of attention helping the astrophysicist to identify signal at the periphery and centre of the visual field.

In Experiment 3 the visual and audio capture was shown to cause a larger effect on Dynamic visual, which tended to mimic the kind of scene space scientists face when analysing 2D data. Future research could explore whether a carefully designed training session would result in the visual and audio capture to be more significant.

Table 5, in Chapter 4 shows an average threshold comparison of the three experiments. For Experiment 1, Static visual angle of 8 degrees and 3 conditions produced no statistical significance difference among the conditions. For Experiment 2, the same conditions were repeated plus the additiona of another condition (visual and audio with red line). Both experiments used stimuli at a visual static angle of 8 degrees, but Experiment two producing significant differences among the conditions. On petition of my supervisor the significant differences listed on table 6, below were: T-Test Paired sample statistics (Paired Differences) shows that performance is significantly affected by the conditions T-tests show that condition AVR [34] leads to better performance than Auditory (p = .018) or Visual (p = .001) and there is a tendency of AV, (Both), leading to better performance than Visual). T-test also show BothRedLine (AVR) did not lead to better than both (p = .731).

| **Paired Samples Test** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **Paired Differences** | | | | | | | |
| | | | | **95% Confidence Interval of the Difference** | | | | |
| | **Mean** | **Std. Deviation** | **Std. Error Mean** | **Lower** | **Upper** | **T** | **Df** | **Sig. (2-tailed)** |

[34] AVR=Audio/visual with redline.

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Pair 1** | **Visual – Auditory** | .022417 | .151049 | .043604 | -.073555 | .118388 | .514 | 11 | .617 |
| **Pair 2** | **Visual – AVR** | .124000 | .095421 | .027546 | .063373 | .184627 | 4.502 | 11 | .001 |
| **Pair 3** | **Visual – AV** | .106500 | .179742 | .051887 | -.007703 | .220703 | 2.053 | 11 | .065 |
| **Pair 4** | **Auditory – AVR** | .101583 | .126374 | .036481 | .021289 | .181877 | 2.785 | 11 | .018 |
| **Pair 5** | **Auditory – AV** | .084083 | .213916 | .061752 | -.051832 | .219999 | 1.362 | 11 | .201 |
| **Pair 6** | **BothRed-Line – AV** | -.017500 | .171789 | .049591 | -.126650 | .091650 | -.353 | 11 | .731 |

**Table 6 Paired differences for Experiment 3. Note significance for pairs Visual-BothRedLine, Auditory-AuditoryBothRedLIne**

As mentioned earlier, the redline together with the audio-visual cue helps the user to exert more control over the presented stimuli to make sense of the data as visual ambiguity increases. At such time, the dominant sense is not the visual but the audio. Like in the Yuval-Greenberg and Doeuell experiments, with an ambiguous visual stimuli making it more difficult to identify, the visual conflict effect on auditory processing diminished substantially, finding that the visual information was not being weighted as heavily (Yuval-Greenberg and Deouell, 2009). Audio then becomes the more reliable modality as visual ambiguity increases, causing a modality capture, which at the same time helps the participant to orientate in the context of a large data set of varying content. This is especially evident in very low signal to noise ratios, as the signal, if present, can be very ambiguous. This is because the cues are synchronised, resembling the congruent multimodal stimulus that aids attention control over competing visually ambiguous stimuli (van Ee, 2009). This may imply a contribution to effective displays.

The reader may remember that experiment 3 T-tests, results showed that (AVR) [35] lead to better performance than Auditory ($p = .018$) or Visual ($p = .001$) and resulted in a tendency of AV, (Both), leading to better performance than Visual). T-test also show BothRedLine (AVR) was not better than both ($p = .731$)._Training session T test analysis shows during training session, audio (T2) lead to better performance than visual (T1), T(V) < T(A), $t(15) = 2.89$, $p=0.011$, $< 0.05$. T test shows that AV ( T3), and AVR (T4) did not lead to better performance than visual or audio (see table 23). Like in experiment 2 and 3, T4 (AVR) did not lead to better performance than T3(AV) and AT4 did not lead to better performance than AT3.

After Training session t test analysis, shows that audio (AT2) leads to better performance than visual (AT1) $t(15) = 2.41$, $p = 0.029 < 0.05$ Evidencing that with more training the audio performance will improve; AT3 (AV) leads to better performance than AT2 (A) $t(15) = 4.23$, $p = 0.001 < 0.005$ , and AT4 (AVR ) leads to better performance than AT2(A) $t(15) = 2.80$, $p = 0.013 < 0.05$.

[35] AVR=Audio/visual with redline.

Once again (like for experiment 2 and 3), AVR did not lead to better performance than AV in either T and AT sessions.

As a side note, the tendency for the Audio-Visual condition effect to be stronger than AVR and visual may be an indicator that people may have been using memory in advanced ways to compare patterns observed to patterns memorised. People with poor memory cannot use such strategies; this could be an interesting theme to research on effective displays.

Schneps *et al.* (2007) gives Figure 8 which plots the results of the black hole experiment performed with a control group of PhD space physicists screened alike and experiencing only visual cues. In their experiment, they calculated the signal to noise threshold by visual angles of $8^0$, $16^0$ and $24^0$. Schneps *et al.*, (2007) used an average threshold (visual angle fixed at $8^0$), for their control group. The results yielded a poorer performance than in Experiments 2, 3, and 4 designed for this thesis. This implies that the use of the sound as an adjunct to visualisation aids astrophysicists in their search for knowledge in numerical data. This discovery may have implications in the fields of designing displays to aid people with learning disabilities, data mining and ambiguity. Other aspects that may be benefited from such computerised training intervention using sound and sight is the acquisition of skills, possibly prosody in people with cognitive disorders or improvement of communication skills in people suffering from Aphasia and Apraxia.

The results of the perception and training experiments imply that sound used as an adjunct to visualisation when a third multimodal congruent cue is added to aid attention control over a competing visually ambiguous stimuli, may be associated with sensitivity to changes away from the direction of gaze, non-persistent, clouded by noise, weak, quasi-periodic, etc. This could prove to be especially true in visually ambiguous data, (low signal to noise ratio and when masked by noise).

Training experiments in Chapter 4 use Experiment 3 as control group experiencing the paradigm once. Even though results of training experiment show that average discriminability thresholds improve after the training treatment, and T-tests show that all conditions improve except the visual conditon. Although the experiment lacked a control group experiencing the paradigm twice with no training for a better control of variables and to address the effect of repetition. This is to discard the possibility of the improvement in performance to be incidental, due to mere repetition or as an effect of the training treatment (being able to review answers, consolidation time, etc).

It is widely known that auditory skills may be improved. The results presented in this thesis from the perspective of User Needs, Data Analysis and Perception Experiments indicate that performance (sensitivity) in signal detection is improved when using sound as an adjunct to visualisation. The results presented may open the path to research on training treatments to elicit multimodal perceptualization for the exploration, analysis of space physics data. This results also lead to a contribution to the field of learning and ability to detect changes and adjust efforts to cope with changing task demands.

## 6.4 Limitations of the thesis

The approach taken to use sound as an adjunct to visualisation has been shown to be effective. However, it has some limitations that have to be considered.

This thesis tested the effectiveness of using sound as an adjunct to visualisation from the perspective of a sonified signal synchronized with the visual display. Sensitivity to signal detection using sound has to be tested further from the perspective of sound parameters eg. Timbre, etc. The experiments presented in this thesis showed that sensitivity to signal detection in astrophysics data increases from the perspective of multimodal perceptualisation and not from the perspective of combining sound parameters to augment further the signal detection. The approach taken ensures that the use of sound as an adjunct to visualisation was rigorously tested. The experiments in this thesis did not test directly if signal recognition rates were faster or lower given the conditions (dynamically changing stimuli or no dynamically changing stimuli). The training experiments did result in significant differences among conditions showing that performance improved despite the fact that auditory attention is not a well-practiced task and so it may not be easily done. Training has to be carefully investigated as, for our target audience, the domain of expertise is sufficiently complex that mastery requires approximately 10 years of essentially full-time focus, which corresponds to several thousands of hours of practice(Ericsson and & Charness 1994). Ericsson (K. A. Ericsson 2009) also asserts that for more experienced individuals, large mistakes become increasingly rare, performance appears to be smoother and the learner no longer needs to concentrate as hard to perform the task. This is analogous to space physicists participating in the study presented in the training experiments. The longer a space scientist uses a particular data analysis technique, the quality of the signal identification increases. As a result, the experienced space scientist can tipically recognize a sought signal whereas in the task presented for the training treatment, the target audience had to evaluate rather than recognize. The training treatment has to be evaluated from the perspective of consolidation that will lead the target audience to achieve a level of expertise. This will require a longitudinal study to test how long it would take to achieve mastery or sufficient level of expertise as compared to astrophysicists using visualisation only.

It has to be further investigated if there are situations (as applied to target audience signal recognition) when the sound may not be useful or where the auditory attention may become ambiguous, as described by Barras & Best(Barrass and Best 2008).

## 6.5 Future Work

This thesis presented real life applications of the use of sound as an adjunct to visual display for space physics data, which has never been done before. This section will briefly discuss a few of the many options for future work in this area:

1. To investigate the possibility of monitoring different astrophysics data paramaters using sound as an adjunct to visualisation. This is a common task for space scientists. For example monitoring different vector components[36] to compare how those vectors change. Section 4.4 did the analysis of perpen-

[36] Mathematics & Physics **a quantity having direction as well as magnitude, esp. as determining the position of one point in space relative to another.**

dicular, tangential and radial vectors but the analysis was done one vector component at the time. A technique using attention mechanisns was not specifically developed for this common task (Seagull, Wickens and Loeb 200). The author wanted to present multimodal attention gain for all the experiments as defined earlier in chapter three but accessibility circumstances prevented the author from presenting those. As future work it will be good to prepare a multimodal attention gain analysis for all the conditions presented in the experiments.

2. To investigate if tactile information could be an additional augmentation to visualisation, and to see how it combines with auditory feedback to enhance visualisation in space physics.

3. To design a set of guidelines to get the target audience started on the use of sound as an adjunct to visual display. The International Astronomical Union requires a set of guidelines to be created to get space physicists started in the use sound as an adjunct to visual display. (The reader must remember Chapter 4's focus on providing a starting point to future users of the resources presented in this thesis).

It is listed in the literature that responses in the auditory cortex depend no only on the acoustic stimuli presented, but also on the behavioural context ((Hromádka and Zador 2007), T., Zador, A.M., ( 2007) A future work that will greatly benefit human compute interaction interphases will be to understand how factors like attention, motivation etc, modulate human computer interaction ( e.g. responses, performance etc). This will help to understand and design better interphases. In the case of space science, interphases that will not frustrate the researchers will to do research. The latter is known from a neurological perspective. For example Hubel et.al. 1959 (Hubel, Henson and Galambos 1959) performed the earliest experiments on how animal behavioural or attentional state can play a crucial role in shaping neuronal responses, specifically the auditory cortex. The authors described "cells" that appear to be sensitive to auditory stimuli only if the "subject" pays attention to a sound source. One of the first studies to employ what is now the standard paradigm for studying the neural correlates of attention was developed by Robert Galambos's laboratory (Picton et al., 1971 ). The study was conducted not in an animal model, but in humans, using electroencephalogram (EEG) recording techniques. Even though attention is difficult to quantify, their results lead to to the conclusion that neural processes responsible for attention play an important role in determining whether or not a given acoustic stimulus proves adequate. Years later, Picton, (Picton et al 1971) conducted experiments on humans using EEG recording techniques to compare click-evocked cortical responses under two behavioural conditions. Picton and colleagues found that the evoked response was larger when subjects attended to the auditory stimuli.

Human computer interaction experiments where only the attentional state is varied so the effect of the attention modulation may be isolated, may present actual evidence on how performance, sensitivities and responses vary, given different attention controlled stimuli and also audio controlled stimuli. Modality gain calculation when using different stimuli may help to gain an understanding of the effort and work load on the user when performing the task at hand.

The latter are just a few of the subjects future work may take. As data acquisition is constantly improving, this may divert in the future. It is clear that it is a human interacting with space physics data and that in the near future no technique or technology has been developed to replace the human brain for this kind of analysis. In the end, the signal detection depends on how effectively the space scientist recognizes what is important or not in the data. In that context, the work on attention control mechanisns and the prevention of cognitive overload will be of utomost importance. Commonly, software for space data detection is designed by people with no knowledge of Human Computer Interaction leaving the user out of the loop and, for instance, not meeting the target audience needs.

The experiments presented in this thesis evidence and answer the research question: Does sound used as an adjunct to data visualisation, augment sensitivity to the perception of signatures in data masked by noise? This thesis achieves the latter from the perspective of User Needs, Data Analysis and Perception Experiments. This thesis offers evidence, through practical experiments resembling daily tasks executed by space scientists, that the use of sound as an adjunct to visual display together with a third congruent cue can increase the sensitivity to signal detection in data changing in content, e.g. amplitude, visual angle, noise content. The latter may also be important for other tasks in science such as trying to find very small changes in x-ray images or minute changes in visually noisy images.

## 6.6 Contribution to Knowledge

To sum up the work presented in this thesis is the first work addressing the needs of space scientists when performing data analysis from the perspective of the user. Employing grounding theory this thesis presents a focus group and usability study leading to identify the major challenges of space scientists when using currently available technologies to perform numerical data analysis (chapter 3). The Target audience is astronomers and astrophysicists aiming to explore the data more throughly. Participants of the focus group and usability study presented in chapter three, were post doctoral people with publications in the field. This is a mean of 13 years of visual training for mathematics at school level, a mean of 4-5 years of visual training during the Bachelors and if they went directly to the doctorate a mean of 3-4 years of visual data analysis ( add 2 or 4 more years if masters is done). The access to the target audience to perform, focus group and usability evaluation lead to the identification of categories (challenges) affecting directly the uncertainty, performance and possibility of discoveries when the target audience perform data analysis.

The thesis then presents the use of the categories reported in chapter three to build a multimodal perception prototype for space science data analysis. In chapter three, the thesis presents the considerations to build the prototype (e.g information architecture, data pipeline etc). On chapter four, the thesis presents evidence of the use of sound as an adjunct to visualisation to analyze/perceive space science numerical data. Perceptualisation strategies, and numerical validation of results are presented.

This thesis presents the perspective of the use of multimodal perception from the perspective of carefully designed experiments. The results of 3 perception experiments where attention control mechanisms were varied, encouraged that the use of sound as an adjunct to visualisation increases sensitivity to signal detection, specially if the position of the signal and the quantity of visual noise change randomly. This thesis innovates by presenting results of multimodal perception experiments, from the perspective of an actual task. Earlier psychology experiments using sonification, sound as an adjunct to visualisation, present results from theoretical perspective (see literature review) and from perspectives that have no application in daily life. This thesis presents qualitative and quantitative evidence, that the use of multimodal perceptualisation (use of sound as an adjunct to visualisation) increases sensitivity to the detection of signal in space science data masked by noise.

Those results encouraged the development of a training paradigm to train space physicists as space physics is a highly visual field. A discussion of existent training techniques and results from applying training based on error is presented. The thesis reports improvement from the Training Task to After Training task but the 2 way ANOVA lead to no differential effects between conditions (Training and After Training conditions).

As mentioned earlier, target audience has a mean of 21 years of visual training in mathematics before achieving expertise. Space physics data analysis is a complex skill. Complex skills, such as searching for signatures in space physics data or problem solving are made up of multiple components, which need to be learnt and integrated before skill is acquired (Johnson 2003). Such skills take time to develop and are more dependent on the nature of training and the background of the performer (Johnson, 2003). Evidence of plateaus in learning curves does appear regularly in the literature, particularly where the tasks being performed involve the acquisition of many skill components that may be acquired at different rates (Speelman and Kirsner 2008). These plateaus represented periods during training where subjects' performance did not improve. Then, according to Ericsson, space scientists with this level of expertise do not commit so many big errors because they are used to identify the kind of signal being sought using a particular data analysis technique of their choice. In all the perception experiments participants were restructuring their skill to overcome plateaus. Plateaus according to the Ericsson (Ericsson K. Anders 1993) (A. K. Ericsson 2009) (Ericsson and & Charness 1994) (K.-R. Ericsson 1993) (K.-R. Ericsson 1993) are not an inevitable characteristic of skill acquisition. With extended efforts, subjects could restructure their skill to overcome Plateaus.

In space science the signal identification tasks involve (among others), (1) the cognitive processing involved in orienting to and selecting among specific items or responding to infrequent changes in what is presented, (2) It also involves the mental effort dedicated to this processing, and (3) the state of alertness or readiness to process additional items (Matthews Davies, Westerman, & Stammers 2000; Washburn, Taglialatela, Rice, & Smith 2004). The task may involve items with high or low signal to noise ratio, ambiguity and uncertainty in presentation and may also involve the presence or absence of background signals and visual noise.  Space Scientists' tasks require attention that can be auditory and/or visual, may involve one or more items to identify what must be maintained in working memory, may involve frequent or rare items, and may demand a higher-level situation awareness. All of these tasks demands can influence target audience performance.

This thesis is a contribution to the understanding of mulditmodal perception and its effects on target audience performance. (e.g. creations of better interfaces for individuals who prefer or perform better using one or two modalities (e.g. visual and audio detection) over another (e.g. visual detection).

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# 8 Appendices

## 8.1 Functionalities added to the xSonify

i) Capability to scroll back and forward in the chart area.

j) Added a Mouse Motion Listener to the Plot Graph Panel to allow the user to make marks on the chart as sonifications are played.

k) Added a Mouse Listener to the position Jslider to make possible the scrolling back and forth as the sonification is played (Stethoscope functionality)

l) Added a functionality to increase the tempo speed as the sonifications are played.

m) Added a functionality for the user to see what values are being sonified and values marked. This capability save the values marked on the console via the Mouse Listener.

n) Improved the Speech support for accessibility by the blind.

o) Increased the resolution of the Chart area by modifying the Gridbag constraints.

p) Added a Zoom in/Zoom out capability allowing the user to increase and decrease screen resolution as the sonification is played.

q) Improved the Data retrieval functionality.

r) Shortcut Keys

s) Increase the chart plotting area resolution.

The xSonification prototype has been modified to save in your computer two files. A file called “console.txt”, copy to the console the sonification settings used by the volunteer. The latter will serve the programmer to track the user interaction with the prototype. Another file called “out.txt” will be created and saved. The out.txt file tracks the bugs. Those two files will help to improve the prototype and will allow us to monitor the easiness of use and usefulness of the prototype. With your authorization we will like to copy those two files on the day of the usability evaluation survey.

For the purposes of a simple usability evaluation, the task consists on: 1) data import from the cda web Space Physics Data Facility/ and or ascii data 2) Mapping of Data in a user selected sonification modi (Volume, Pitch and Timbre), 3) play back of data. Some graphics has been included, in this document as well as an explanation of each. You will find a file called GRB, this file consists of a txt file corresponding to the light curve of GRB 04/12/19 acquired with the swift satellite. Preferably the volunteer will use his/her own data but you may use the data provided for the usability purpose.

### 8.1.1 Navigation

The following navigation constitutes the help file given to the usability evaluation participants (see chapter 3). The instructions were compiled by a visually impaired intern.

The explanation is intended to be inclusive for everyone. The prototype development consists of 3 stages: 1) Focus Group Discussion and individual cases discussion to determine target audience priorities for data analysis. 2) Prioritize the requirements according to their importance, usefulness and difficulty of implementation, and produce the next version for further testing. 3) Usability Evaluation.

Once the user clicks on the .jar file 2 Graphic User Interface will show. One is called Capture Sound and the second one is the sonification window. The capture sound allows the user to capture the playing the data and save it as a digital format (.WAV, .AU, .TIFF.).

The file will be saved under the name Sonified with the extension the user has selected. The user may also save the data as Midi file from the file menu item “export data” option.

xSonify – The Application

This chapter describes the functionality of xSonify followed by the detailed structure and technical inner life.

### 8.1.2 How xSonify Works

Before I explain the handling of xSonify I would like to give a general overview how the application works. The program provides basically the opportunity to display numerical data as sound with the help of three different kinds of sound attributes. Attributes like the pitch, the volume and the rhythm of sound.

To realise the idea of Sonification, xSonify takes advantage of the MIDI support from JAVA. To display the information of numerical data for instance by dint of the pitch of a played music instrument the smallest value (0.0f) represents the lowest frequency and the largest value (1.0f) the highest frequency according to the settings. Each tone represents one value and the whole sequence of different tones accordingly the whole dataset.

In order to start the Sonification process the numerical values are converted into values of the internal data structure. The data values of this structure are floating point variables in the range from 0.0f to 1.0f.

0.0f represents therefore the smallest and 1.0f the largest value of the original data.

The user can also assign different Sonification modi or different instruments to each dataset. This option is necessary if the user wants to distinguish the different datasets while listening to them at the same time.

Sonification provides naturally also a chance for blind scientists to work with data and needs speech support. xSonify provides the user optionally with its own speech support software – independent from commercial screen reader software.

## How to Work With xSonify

Basically the application is based on two main windows called Capture-Sound and XSonify. The main window is separated in different sections. Starting with the menu bar, the “Sonification Object” section and the “Player Control” section.

To work with the application the user has to import the data the user wants to sonify. In order to do that, the user has two options:

they may use the function “File => Import Data” which is based on a resource toolkit from the application ViSBARD. With this function the user can access a remote database or a local file in order to retrieve the data. Both ways handle files with the formats like *.cdf and *.vba.

The second option to retrieve data is with the function “File => Import Data

Textfile”. This option simply reads a text file with the data according to the file structure explained earlier

Import Data

Import data: Imports data from local files or from remote databases via the Internet. The remote data sets are from the Space Physics Data Facility at Goddard Space Flight Center (GSFC). The data base has access to all the data files pertaining to missions monitored by NASA GSFC. Single results of measurements from spacecraft instruments can be selected by their corresponding variables in a specific time frame. The result will be transformed into MIDI sequences to be played with a selection of different instruments from the sound-bank accessed from the XSonify graphical user interface.

How to import data from the Space Physics Data Facility Data Base:

1. In the File menu item select the Import Data Option. A GUI appears when the import data button is clicked. This GUI allows the user to interact with several archives from spacecraft instruments.

2. Navigate to the add Local File(s) Button or the Add Remote Files

Button.

The Add Local files button open files already saved in the hard drive of the computer. These files might only be SPDF, txt and Fits format. This GUI is straightforward and behaves as the GUI to open a file from a windows directory.

The Add Remote Files button open files via Internet from several space-crafts instruments at the Space Physics Data Facility in Maryland. This functionality will be extended to the High Energy Space physics Service ARCHive ( HEASARCH)

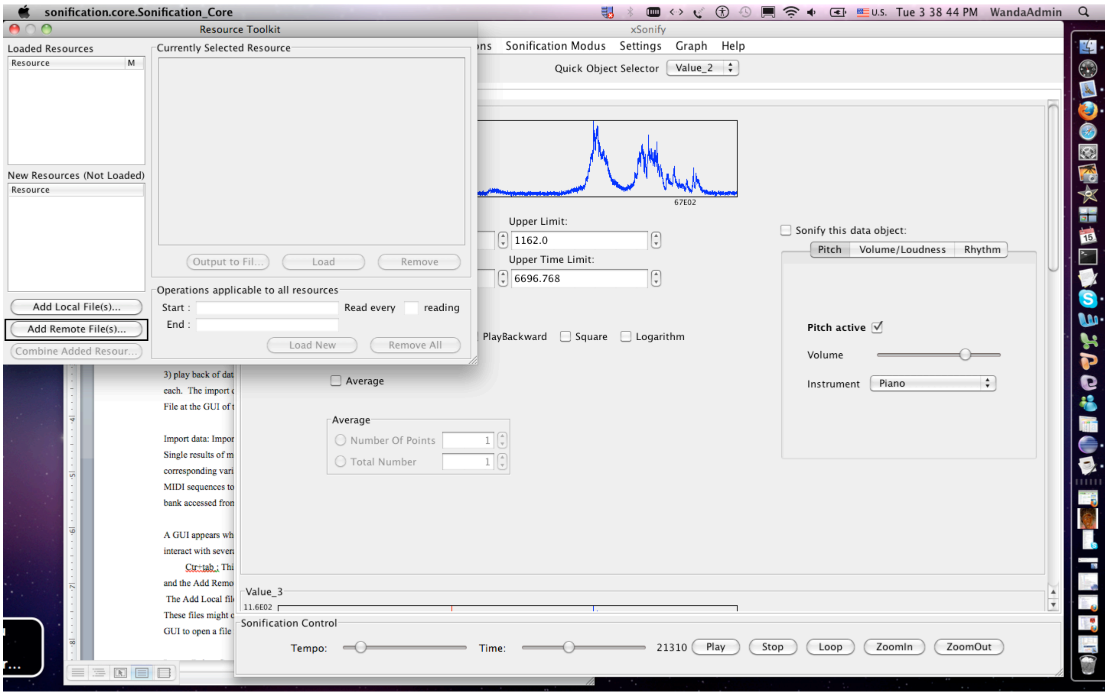


**Figure 32 Screenshot of Interface (open file)**

3. Open remote file button: Opens a GUI allowing the user to select a

web service to access the data. It prompts to select one of the following web service from a combo-Box http://cdaweb.gsfc.nasa.gov/ or http://sscweb.gsfc.nasa.gov/

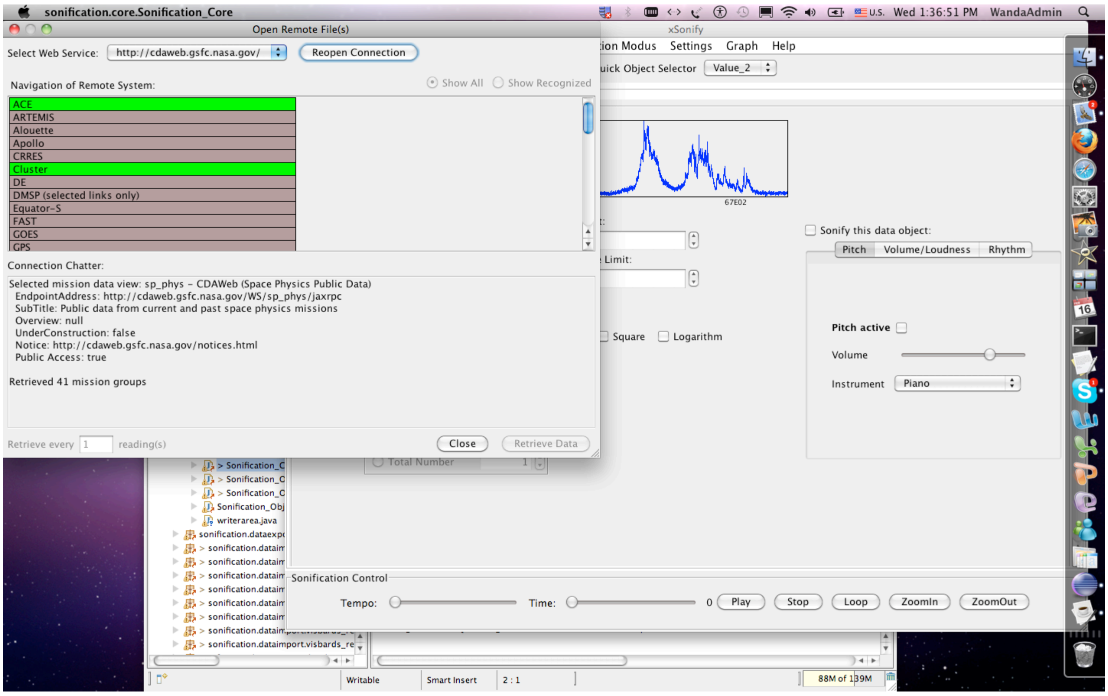


**Figure 33 Screenshot of Interface (add remote files)**

Image: Graphic User Interface of XSonify add remote files GUI active

Open Connection Button: accessed either with the tab key or the combination ctr + Tab. This key opens the connection with the web service selected.

The screen reader user will hear the prompt: getting view description.

Show all and/or show recognised: Follows the reopen connection button once the tab key is pressed. This option allows the user to access the description of the devices and or the data contained in the archives respectively.

Navigation of Remote System Box: Is active at the edit prompt. This Box contains the list of all the spacecrafts/data sets available. To access any of the data archives for any mission use the mouse or press the tab key and the up arrow key at the same time. Pressing on the name of the spacecraft (in green) follow a list of measurement devices contained in it in Brown, once the list shows after the edit prompt it is possible to navigate through it using the tab key and the up and/or down arrow key. Pressing on those will follow a list of different capabilities/experiments the measurement device has. Pressing on the specific data, a box appears asking for: start date (refers to starting date and time) in year month day and Hours minutes seconds.

For example if the data wanted is from May 23 2005 at 1:00 pm to May 25 2005 it has to be written as 2005-05-23, 01:00:00 (the time is optional). Likewise once pressed the tab command the program ask for the ending data in the same format. The retrieve data button will not be active if the data is not written correctly. In such an instance the users depending on the screen reader will notice that the screen reader will ignore the button.

Following the user will find the options to select the data parameters, select your options by using the mouse or using the space key and navigate through those using the tab key.

If the button “choose the recognised” is selected the list of spacecrafts will show at the first mouse/space bar click a description of the measurement collection devices contained by the spacecraft appears in a box below the list.

Using the mouse or tab button access the Retrieve Data Button that might be active if the date and hour has been written well. The data will be downloaded to the XSonify GUI.

To go back to the main GUI and hear the data just press the load button or navigate to it by using the alt and tab keys.

Importing ASCII Data

XSonify allow the user to load ASCII data. This opens a world of possibilities for mathematic / science/physics teachers of sighted and not sighted students and for amateur radio astronomers as the users of the NASA Radio JOVE project.

The capability of importing data from text file is accessed from the file menu item at the main GUI (see list of shortcut keys) the data retrieval is straight forward and the navigation through the retrieval window is much like the navigation to retrieve a document from e.g. the My Documents directory to the notepad capability in a text editor environment.

The file imported to XSonify has to be formatted as columns of only numerical data. The plot generated at the Graphic User Interface Sonification Window will be a plot where the x axis will be the first left column of the data imported. For example if I import a document that has 4 columns, (1,2,3,4) the sonification window will plot 3 charts in which column 1 will be the x axis for all the charts, and column 2,3,4, will be the Y axis respectively. The user may sonify and all of the charts plotted at the same time.

The Main Window in xSonify

The text files uploaded to XSonify has had to be previously saved as text (MS DOS if navigating in windows) or as windows compatible text file if working on an Apple Macintosh Computer.

After the data are successfully imported the Sonification procedure can begin. The new imported data create for each Sonification object one panel. The “Quick Object Selector” provides an overview of the existing data objects and the user can select the requested data object directly without scrolling to it.

Each Sonification object panel exists of a data plot which plots the data as a simple diagram. Later on during the play-back a cursor (red line) displays the current position in the sequence. It is also possible to define bounds of the displayed object.

xSonify provides also a pool of functions  which can be applied to the corresponding object.

On the right side of each Sonification object a tabbed field with the choice of three Sonification modi including their appropriate settings enables the user to add the specific Sonification object to the sequence. It is only possible to apply one modus for one Sonification object. If none of the three modi is selected the whole Sonification object will not be considered for the Sonification procedure.

The sequence will be created and played after a click on the “Play” button in the “Sonification Control” panel. The play-back can be interrupted or changed into an endless loop. It is also possible to change the play-back-speed and to move the current position directly by moving the sliders.

The GUI components and their actions can be optionally read by xSonify. Independent from screen reader software this feature opens up visually impaired people the usage of this application.

During the play black the user may mark point of interest by bringing the mouse cursor to the chart area and clicking. This will mark the position of interest to the user and the value will be saved in the console. The position marked will be determined by the position of the red line and not by the position of the mouse on the chart.

The user may navigate back and forth during the play back by interacting with the Time slider located at the bottom left side of the graphic user interfase.

Equally the user may increase and decrease the tempo by interacting with the Tempo slider located at the bottom right side of the graphical user interface

Sonification Modus: Pitch

Historically, to display information in an acoustic way one would choose the pitch attribute of sound. The lowness and highness of a sound (the frequency) respectively contains in that case the information. Pitch is highly distinguishable and is one of the most effective ways of differentiating order with sound. On average, individuals can easily distinguish 48 to 60 pitches over at least four or five octaves, and this implies that pitch, divided up by octaves can be used to represent more than a single variable in a sonic display (Yeung, 1980, 1121).

But beside all the positive aspects of this Sonification method there are also things which have to be considered.

– Judgments of pitch will vary somewhat from person to person. –

Western music has traditionally employed a scale of eight octaves comprised of twelve pitches each; extreme pitches, however, are hard to distinguish.

– Mapping with pitch is appropriate for ordinal data. In addition, pitch may imply direction, where, for example, an increasing pitch represents upward movement.

– Tonal sharps and flats can be used to some effect also, possibly to represent a second variable such as variations in data quality. Every twelfth pitch has the same pitch colour (chroma) and this may serve to represent nominal or ordinal data (Weber, 1993b). Pitch, then, can represent quantitative data, primarily ordinal. Time can be added to pitch to create a sound graph which tracks ordinal change in data over time.

Sonification Modus: Volume/Loudness

The second parameter of sound which is used to hear the data is the volume of a certain tone. According to the current values in the data sequence the volume/ loudness is measured in terms of the decibel and implies an ordinal difference. The average human can just detect a one decibel sound, can detect differences in loudness of about three decibels, and can tolerate up to approximately 100 decibels (e.g. the loudness of a jet taking off). Loudness is inherently ordered and thus seems appropriate for representing ordinal level data. Loudness may be used to imply direction and can be varied over time to represent ordinal change in data over time (e.g. to alert one to important but infrequently occurring phenomena).

It is known that humans usually become unconscious of constant sounds (Buxton, 1990, 125). For example, although the hum of a computer's fan in becomes inaudible soon after switching it on, even a slight variation in the fan will be instantly noticed. This effect can be used to represent information where a quiet tone represents a steady state and any variation represents change.

Sonification Modus: Rhythm

The last modus in our software application is the idea to use a certain rhythm of a beat instrument to display the information. During this modus the whole range of data values are fragmented into a certain number of groups. Default amount of groups are 20 but can be changed in the average panel. The idea is that every group has the value of the average of all values inside a group and the value represents a certain rhythm.

According to the sound attribute overview in the introduction of this Chapter this modus covers the sound attributes “Duration” and “Rate Of Change”.

• Duration: The length of time a sound is (or isn't) heard. Duration refers to the length of a single sound (or silence) and can represent some quantity mapped to that duration. Silence must be used in tandem with duration if one is to distinguish the duration of multiple sounds (Yeung, 1980, 1122). Duration is naturally ordinal.

• Rate of Change: The relation between the durations of sound and silence over time. Rate of change is primarily a function of the varying (or unvarying) durations of sounds/silences in a series of ordered sounds over time and can represent consistent or inconsistent change in the phenomena being represented.

Tong, H. Non-linear time series: a dynamical system approach. Oxford, Oxford University Press.

List of the data sets available for data visualisation

Following is a list of shortcut keys compiled to help the user to navigate through the Graphic User Interface of the Xsonify :

8.1.2.1 List of XSonify shortcut keys at the GUI

Alt + I Import Data

Alt + t import data from text file

alt + I look in combo box

alt + N name of archive

alt+t type of archive ( txt, all etc)

Alt+o open archive

alt + c cancel

Alt + E export sequence

Alt +I save in

Alt + S save button

alt+N file name

alt+t type of file

alt+ c cancel button

alt+s save button

Alt+c Player control

ctrl+p    Play sequence

ctrl +s stop sequence

ctrl+ l loop...makes an infinite loop of the data

alt+shif+= increase speed

alt+shif+- decrease speed

alt+shift+. Position forwards

alt+shift+, position backwards

alt+u Functions

alt+shift+A standard

alt+shift+N inverse

alt+shift+Q square

alt+shift+B backward

alt+shift+L logarithm

alt+o sonification modus

alt+shift+p pitch select

alt+shift+v increase pitch velocity

alt+V decrease pitch velocity

alt+shift+o Volume select

alt+shift+r increase volume frequence (Press the three keys continuously for the frequence to increment) this has to be changed for the frequence to be increased with the arrows)

Alt+r decrease volume frequence (press continuously)

alt+shift+h rhythm select

alt+shift+v increase rhythm velocity

alt+v Decrease Rhythm velocity

alt+shift+m increase bit per minute minimum

alt+v decrease bit per minute minimum

alt+shift+x Increase bit per minute maximum

alt+x decrease bit per minute maximum

alt+shif+r increse rhythm frequence

alt+r Decrease rhythm frequence

8.1.2.2 Navigation of xSonify as written by Volunteer:

The visually impaired participant tested this prototype earned her access to Space physics data archives and analysis. Following is the written explanation on how to navigate the prototype as written by the volunteer.

The import data option is retrieved by either pressing the alt-I keys or from the menu File at the GUI of the xSonify.

Import data: Imports data from local files or from remote databases via the Internet. Single results of measurements from spacecraft instruments can be selected by their corresponding variables in a specific time frame. The result will be transformed into MIDI sequences to be played with a selection of different instruments from the sound-bank accessed from the xSonify graphical user interface.

A GUI appears when the import data button is clicked. This GUI allows the user to interact with several archives from spacecraft instruments.

Ctr+tab: This key combination allows the user to navigate to the add Local File(s) Button and the Add Remote Files Button.

The Add Local files button open files already saved in the hard drive of the computer. These files might only be SPDF, txt and Fits format. This GUI is straightforward and behaves as the GUI to open a file from a windows directory.

The Add Remote Files button open files via Internet from several space-crafts instruments at the Space Physics Data Facility in Maryland. (This functionality was extended to the High Energy Space physics Service ARCHive (HEASARCH) during our 3rd year of research.

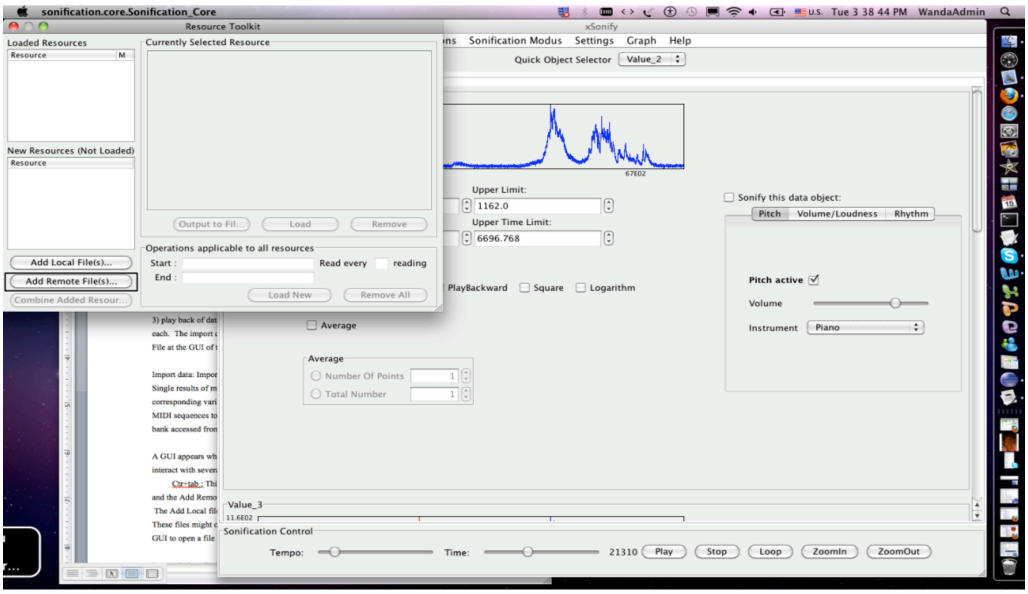


**Figure 34. Graphic User Interface shown when selecting the Import Data option from menu bar at xSonify main GUI. Add Remote files button high lightened. It imports data from the Space Physics Data Facility (SPDF)**

Open remote file button: Opens a GUI allowing the user to select a web service to access the data. It prompts to select one of the following web services from a combo-Box http://cdaweb.gsfc.nasa.gov/ or http://sscweb.gsfc.nasa.gov/

Image: Graphic User Interface of xSonify add remote files GUI active

Open Connection Button: accessed either with the tab key or the combination ctr + Tab. This key opens the connection with the web service selected.

The screen reader user will hear the prompt: getting view description.

Show all and/or show Recognized: Follows the reopen connection button once the tab key is pressed. This option allows the user to access the description of the devices and or the data contained in the archives respectively.

Navigation of Remote System Box: Is active at the edit prompt. This Box contains the list of all the spacecrafts/data sets available. To access any of the data archives for any mission use the mouse or press the tab key and the up arrow key at the same time. Pressing on the name of the spacecraft (in green) follow a list of measurement devices contained in it in Brown. When the list shows after the edit prompt it is possible to navigate through it using the tab key and the up and/or down arrow key. Pressing on those will follow a list of different capabilities/experiments the measurement device has. Pressing on the specific data, a box appears asking for:  start date (refers to starting date and time) in year month day and Hours minutes seconds.

For example if the data wanted is from May 23 2005 at 1:00 pm to May 25 2005 it has to be written as 2005-05-23, 01:00:00 (the time is optional). Likewise once pressed the tab command the program ask for the ending data in the same format. The retrieve data button will not be active if the data is not written correctly.  In such an instance the users depending on the screen reader will notice that the screen reader will ignore the button.

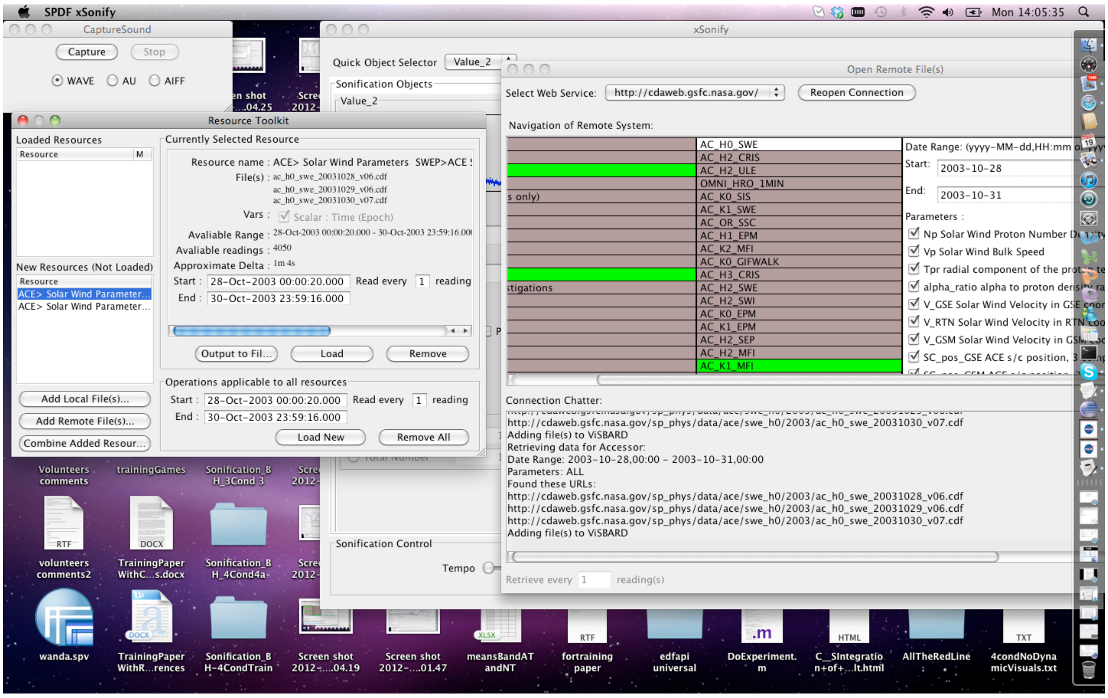


**Figure 35 GUI for the add remote data. The green and brown buttons previously described and the information panel is visible**

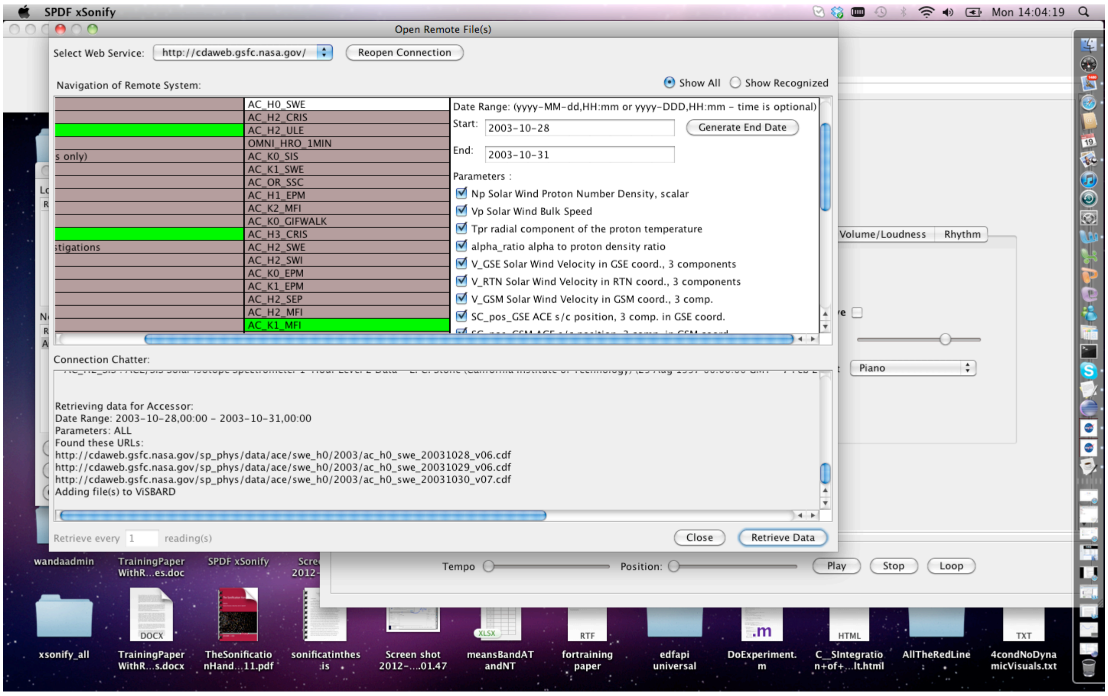

Figure 36 GUI for selection of variables to plot, date and time range desired (TOP).

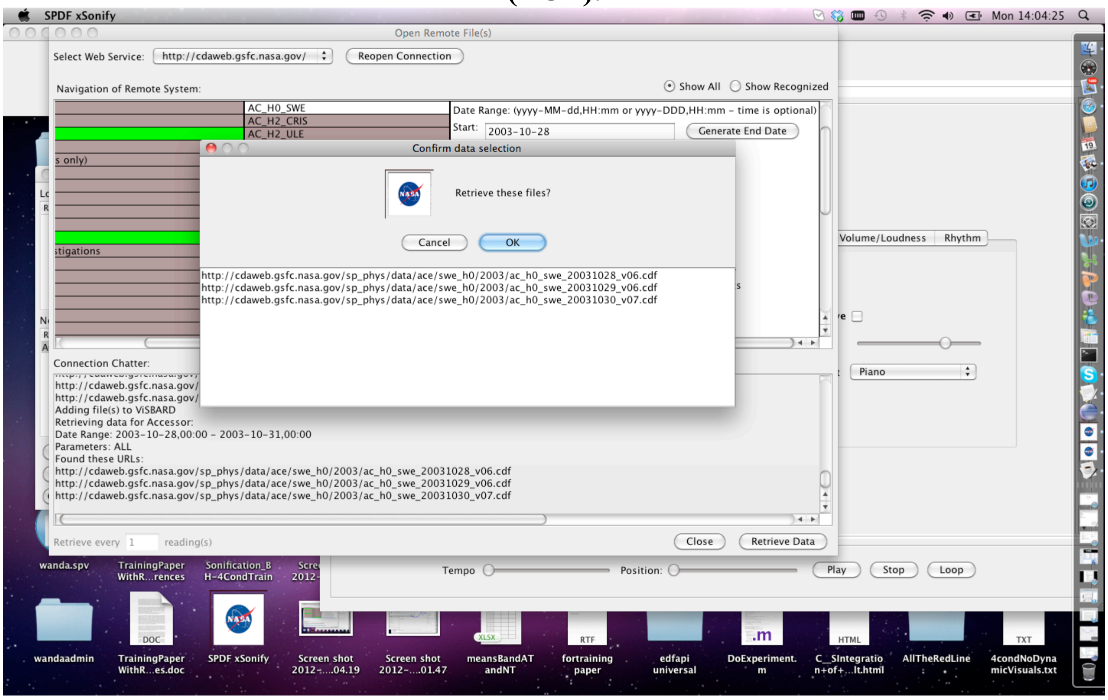

Figure 37 GUI shown to confirm the files to be retrieved after selection of variables to plot, date and time range.

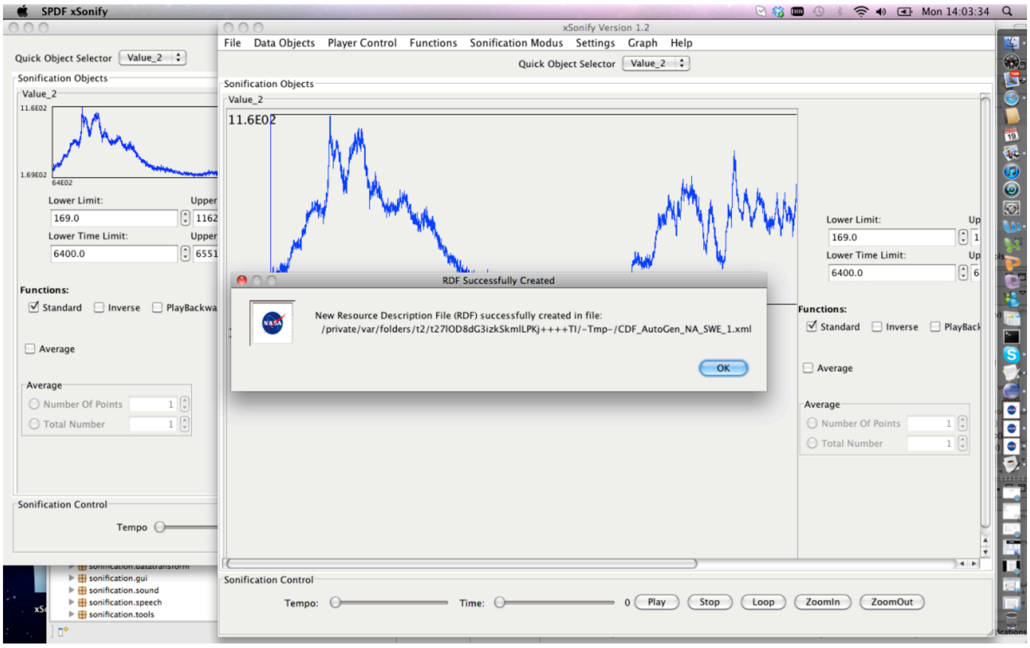


Figure 38 Message Shown after pressing the retrieve data button

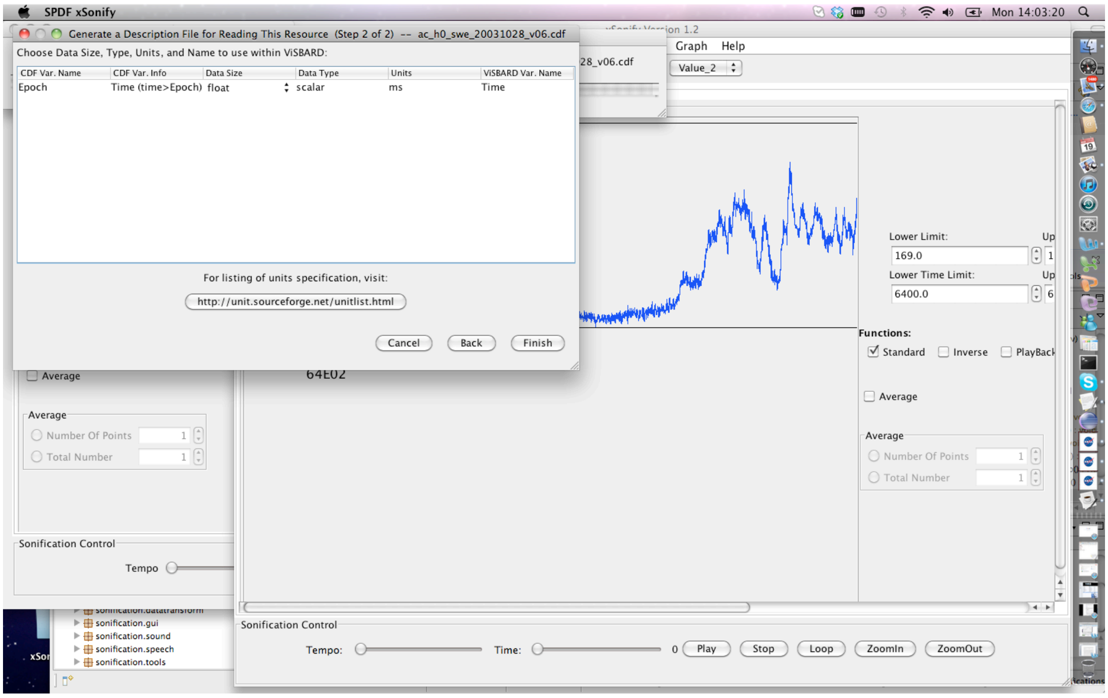


Figure 39 Step necessary to import data from SPDF to xSonify the first time.

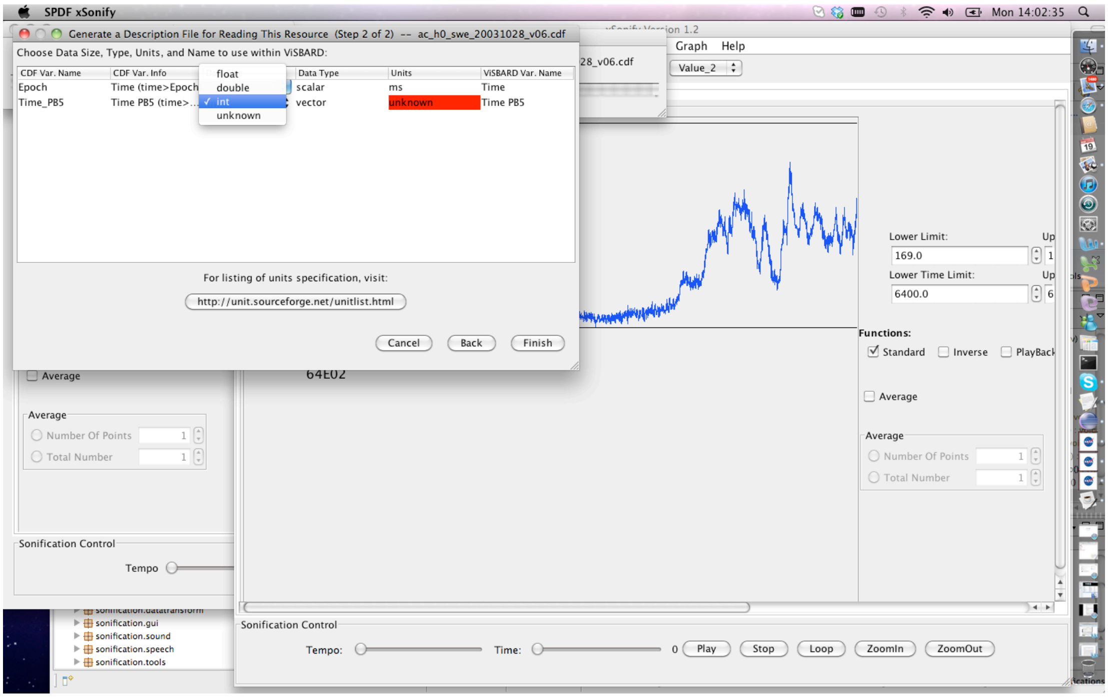


**Figure 40 Step necessary to import data to xSonify from SPDF. Selections of Units.**

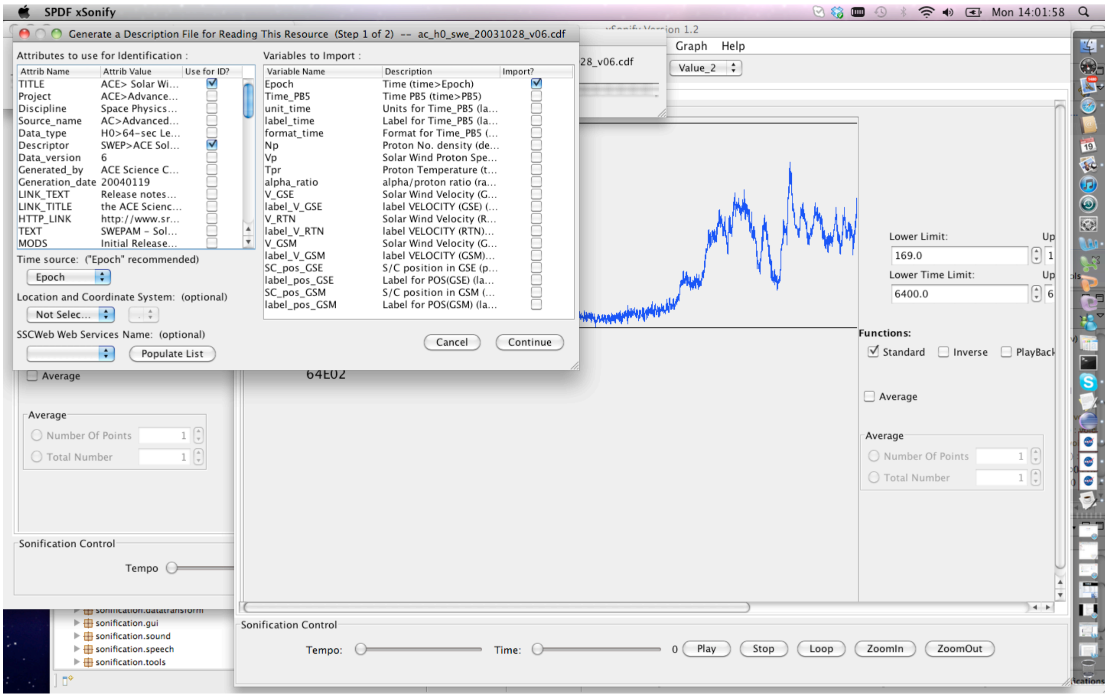


**Figure 41 Necessary step for importing data the first time from the Space Physics Data Facility to xSonify. Generating description file (headers for the data).**

The user will find the options to select the data parameters select your options by using the mouse or using the space key and navigate through those using the tab key.

If the button “choose the recognised” is selected the list of spacecrafts will show at the first mouse/space bar click a description of the measurement collection devices contained by the spacecraft appears in a box below the list.

Using the mouse or tab button access the Retrieve Data Button that might be active if the date and hour has been written well. The data will be downloaded to the xSonify GUI.
Image: Xsonify GUI with remote data retrieval data parameters, date and hour active. To go back to the main GUI and hear the data just press the load button or navigate to it by using the alt and tab keys.

XSonify allows the user to load ASCII data. This opens a world of possibilities for mathematic / science/physics teachers of sighted and non sighted students and for amateur radio astronomers such as the users of the NASA Radio JOVE project.

The capability of importing data from text file is accessed from the file menu at the GUI (see list of shortcut keys) the data retrieval is straight forward and the navigation through the retrieval window is much like the navigation to retrieve a document from (for example) the My Documents directory to the notepad capability in a text editor environment.

The text files uploaded to XSonify has had to be saved as text (MS DOS if navigating in windows). That option is found as “save as type” once the save as button is activated or pressing the alt and the t key together. The xSonify help file has a complete list of all the shortcut keys to access the files (included in the appendix).

The capability of importing data from FITS files may be accessed from the file menu at the GUI. The internal data structure of the FITS file converter class changes the FITS file into a text file and then load it to the xSonify. This capability is accessed from the file menu Item.