Southern Horizons in Time-Domain Astronomy
Proceedings IAU Symposium No. 339, 2019
E. Griffin, ed.

doi:10.1017/S1743921318002703

Exploring Data Sonification to Enable, Enhance, and Accelerate the Analysis of Big, Noisy, and Multi-Dimensional Data

WORKSHOP 9

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Abstract. We explore the properties of sound and human sound recognition as a means to enhance and accelerate visual-only data analysis methods. The aim of this work is to enable and improve the analysis of large data sets, data requiring rapid analysis, multi-dimensional data, and signal detection in data with low signal-to-noise ratio. We present a prototype tool, `StarSound`, to sonify data such as astronomical transient light curves, spectra, and power spectra. Stereophonic sound is used to 'visualise' and localise the data under examination, and 3-D sound is discussed in conjunction with virtual reality technology, as a means to enhance analysis efficiency and efficacy, including rapid data assessment and training machine learning software. In addition, we explore the use of higher-order harmonics as a means to examine simultaneously multi-dimensional data sets. Such an approach can allow the data to be interpreted in a holistic manner and facilitates the discovery of previously unseen connections and relationships. Furthermore, we exploit the capability of the human brain for selective or focused hearing that enables the identification of desired signals in noisy data, or amidst similar or more significant signals. Finally, we provide research examples that benefit directly from data sonification. The work presented here aims to help tackle the challenges of the upcoming era of Big Data and help optimise, speed up and expand aspects of data analysis requiring human interaction.

Keywords. Methods: data analysis, miscellaneous, techniques: sociology of astronomy

1. Introduction

Effective analysis and interpretation of Big Data is particularly relevant in astronomy, where advances in technology are leading to ever larger data sets. For example, the Square Kilometre Array will produce, per unit of time, an amount of radio astronomy data that will far surpass the current global internet traffic§. Present-day technologies are simply not up to the task of gathering, processing and making sense of such large volumes of information in real time. In an attempt to address this problem, some technology companies, e.g., IBM, have proposed the use of cognitive systems, defined as systems capable of learning from their interaction with data and humans, while continuously programming themselves. However, it is unclear whether cognitive systems can evolve sufficiently, or appropriately, to emulate the complex functioning of human cognition

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§ https://protect-au.mimecast.com/s/bg3FClxwjxs2m70ziGgRzu?domain=skatelescope.org

during decision-making, especially when faced with uncertainty or equal-valued choices. Automated analysis, recognition algorithms and objective parameters are typically based on known behaviour and phenomena and, thus, are not capable of recognising or evaluating objects or events properly outside expectations. As a result, humans will continue to perform key roles in data identification and interpretation for the foreseeable future, such as identifying unexpected objects and events, recognising the importance of outliers, training machine-learning software, and ultimately deciding what is relevant and important in the data.

The interaction of researchers with their data is limited by factors such as the available numerical data analysis packages, human eye physiology, and display resolution and design. Consequently, large data sets, along with the demands of real-time analysis, require exploration into new or enhanced human-based analysis techniques and tools. Common data analysis approaches involve searching for spatial and temporal coherence, i.e., identifying relationships between signals at different points in space or moments in time. The Modality Precision or Modality Appropriateness hypothesis (Welch & Warren 1986) states that discrepancies are always resolved in favour of the more precise or more appropriate modality. In spatial tasks, the visual modality usually dominates because of its higher precision in determining spatial information. However, for temporal judgments sound usually dominates over vision as the more appropriate modality (Shams 2000).

Recent ventures into data sonification or audification include studies of ionosphere plasma bubbles and dwarf novæ (Díaz-Merced *et al.* 2008; Tutchton *et al.* 2012), as well as the presentation of gravitational wave signals and fast radio bursts. Through carefully designed perception experiments, Diaz-Merced showed that the use of sound as an adjunct to visual display increases sensitivity to events in noisy 1-D data that otherwise would have remained unnoticed by the human eye (Díaz-Merced 2013). Moreover, Schwartz *et al.* (2005) find evidence that attention task load in the periphery of the visual field hinders perception in the centre, and vice-versa, demonstrating that the centre and the periphery interfere (Posner & Dehaene 1994; Inhoff *et al.* 2006; Martinez-Conde *et al.* 2006; Rucci *et al.* 2007). For data that are time sensitive, complex, cluttered, etc., visual perception of signal at the periphery of the visual field may be compromised. These efforts have explored only a fraction of the advantages sound can provide in data analysis (see Hermann *et al.* 2011, for a comprehensive review).

In this Workshop we (1) presented our proto-type software interface designed to conduct conventional 1-D data analysis and sonically augment visual analyses for faster, more accurate assessments, (2) described simultaneous many-parameter analyses exploiting higher-order harmonics that define tone quality, and (3) explored rapid signal identification in noisy data, exploiting human selective hearing. We discussed future directions, including the use of 3-D sound and virtual reality modalities. We note that an estimated 1 in ∼200 people are blind (Bourne *et al.* 2017)†. Data sonification greatly enhances the productivity of vision-impaired researchers and enables the sighted or vision-impaired public to participate, and to participate more effectively, in citizen-science programmes.

2. Sonification Techniques

2.1. *One-dimensional data*

Conceived in late August 2017, the `StarSound` prototype is a sonification tool designed to assist both sighted and non-sighted researchers in identifying and interpreting quickly trends in complex data sets. Developed using MaxMSP (Puckette 1988, 1991), a graphical programming environment often employed in the development of real-time musical applications, `StarSound` consists of a single interface through which sighted users can

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† see also: World Health Organization, Global Data on Visual Impairments 2010, 2012

	Instrument	Instrument	Tone	Mode	Tone	Tone	Instrument	Mode
	Pitch	Pitch	Pitch	Pitch	Amp	Pitch	Map	Amp
	MAG	MAGERR	UL	#MJD	MAG	MAGERR	UL	#MJD
	mute	mute	muted	muted	mute	mute	muted	muted
Raw Data								
Raw	21.0260	0.0630	0.0000	57599.1992	0.0000	0.1700	22.0370	57599.1992
Min	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Max	21.9970	0.1700	22.5280	57599.2422	21.9970	0.1700	22.5280	57599.2422
Raw Data Limit								
Min	16.0000	0.0200	17.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Max	23.0000	0.1700	23.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Hz					440.		440.	440.
Scaling								
HzLo	1760.0000	110.0000	1760.0000	220.0000		330.0000	385.0000	
HzHi	55.0000	220.0000	55.0000	220.0000		330.0000	385.0000	
ApLo	0.2000	0.0000	0.2000	0.2000	0.2000	0.2000	0.2000	0.2000
ApHi	0.8000	0.7000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000

Figure 1. Image of the `StarSound` graphical user interface in an example configuration. Across the top, from left to right, the interface offers the following menu options; loading a data set, viewing and clearing a data set, and loading a configuration file. Below that is the scanning slider and two tabs for switching between the 16 available sonification modules. Each sonification module consists of a tone generator or musical instrument selection. A predefined pitch table is provided for mapping and listening to data quickly. From there, users may wish to fine-tune or define their own pitch range. Once a data and configuration file is loaded, the *Play* feature can be used to listen to the results of the data sonification from start to finish. Alternatively, the *GoTo* option can be used to jump directly to a point of interest, or the user can scan the data manually with the left/right keys on a computer keyboard or the scanning slider, which can be mapped directly to a stereo panning algorithm including external mouse or trackpad input. Further options include turning on the *Voice* accessibility for reporting the sonified data index – a pulsing option which acts like a metronome for repeated listening.

tailor, but also fine-tune their sonification environment (see Figure 1). Acknowledging that most non-sighted users may find the interface difficult to navigate, an important design feature is that it also allows direct interaction with the software, in real-time, via the editing of a text-based configuration file. The configuration file lists every feature and mappable parameter within the application. One advantage of this technique is that any text-based editor can be used and consequently does not require any specialist knowledge to use. The software also features a Voice accessibility option for reporting the index of the currently sonified data point.

A common 1-D application is the sonification of astronomical transient or variable source light-curves (brightness vs. time; Section 3). One option for presentation is to assign pitch to the brightness of the object (holding volume constant), such as higher pitch for brighter magnitude, as it is often intuitive to attribute a higher pitch to an upward direction, so typical light-curves present brighter magnitudes toward the top of the plots. The light-curve data are then heard as an even succession of tones in time, as the time of the observations are assigned to the elements of the time series. For example, a light-curve representing an object rising and falling in brightness over time is heard as sound rising and falling in pitch over time. The data are presented as a sped-up (time-lapse) version of the data acquisition, which can also be designed to be reflective of data acquired in unevenly-spaced epochs. Other examples of standard 1-D sonification analysis are the power spectra (power vs. frequency) and electromagnetic spectra (intensity vs. time) of astrophysical objects (Díaz-Merced *et al.* 2008).

To assess better the data and to help visualise the corresponding 1-D data as typically plotted, `StarSound` has an option to present the tones in stereo, a slidebar or trackpad-activated control to move back and forth through the data, and an ability to mark data point locations. These capabilities aid the listener to the data location, spatially, on an imaginary plot in the mind and help to enable more rapid and more natural interrogation of the data, as the user can move directly to the location of specific data points of interest. Finally, the combination of data sonification with visual plots enables quicker classification of data exhibiting similar behaviour, enhances data quality assessments, and helps discriminate aspects of the data that are difficult to discern using visual cues alone.

2.2. *Multi-parametric data*

The presentation of data on 2-D plots is central to the analysis and interpretation of astronomical data and the communication of results. Often several parameters are analysed and the results are presented in a number of 2-D plots or, in some cases, 3-D plots (with or without animation). Capturing multi-parametric information is challenging, and is typically done by varying symbol size, colour, and shape and/or presenting the parameters, two at a time, against each other on multiple plots. That mode of presentation becomes bulky and inefficient when dealing with more than a few parameters. Moreover, such data presentations have the weakness of obscuring or over complicating connections between the multiple parameters where the ability to recognise these connections lies at the core of understanding and appreciating the underlying physics.

The ability to analyse and interpret multi-parametric data is of great potential utility to the field of galaxy formation and evolution. For example, one area of our research investigates the relationships between the Lyman-α transition of hydrogen and over 10 properties of high-redshift galaxies. Lyman-α has been shown in our work, and in previous work, to have direct relationships to seemingly unconnected internal and external properties, such as galaxy colour, kinematics, age, large-scale spatial distribution, morphology, gas outflows, mass, and interactions (Shapley *et al.* 2003; Cooke 2009; Law *et al.* 2012a,b; Cooke *et al.* 2013; Foran *et al.* 2018). Obtaining spectra of high-redshift galaxies is challenging as a result of their faintness. Because Lyman-α is often their most prominent spectral feature, understanding the complicated relationships between Lyman-α and the multiple observables provides a means to probe the very early Universe and to understand the processes of galaxy formation and evolution.

By exploiting properties of sound, data sonification may provide a way of presenting and analysing multiple parameters simultaneously. If a trumpet or flute were to play the same note (same frequency) at the same volume and duration, the human ear could discriminate between the two sounds and identify the associated instrument. This is because the instruments produce overtones, or higher-order harmonics of the fundamental frequency, at differing strengths (for example, see Elliott *et al.* 2013, and their Figure 4). The combined sound produces the tone quality, or timbre, of the instrument, and that unique set of strengths of the higher-order harmonics is what the human ear instantly interprets in order to identify the sound. The concept we are pursuing here is to assign a different data parameter to each harmonic frequency with appropriate scaling to enable the resulting tone to carry instantaneously the full information of the multiple parameters of an object of interest. With training, the researcher would be able to recognise the values of the multiple parameters of each data point from a single tone. Objects can thus be selected or vetted on their properties as a whole, or in part, based on their tonal qualities. By that means, data sonification can enable an identification and understanding of the multiple relationships between many parameters in an organized way, leading to clearer insight into the underlying physical connections as a whole.

2.3. *Extracting signal in noisy data*

Leading-edge research often pushes the limits of technology, resulting in the need to examine data that have a low signal-to-noise ratio (S/N). Such data, by definition, are difficult to reduce and analyse and often too difficult for automation of the analysis process, thus, leaving the job for human researchers. In addition, current large surveys are producing data in large volumes that are too great to be examined by humans using conventional methods. Data sonification can help examine low S/N data in ways that enhance the efficiency of visual analysis on is own, speed up the analysing process, and enable the detection of signal that can be missed when only visual inspection is employed.

Writing software to identify and classify signals in low S/N data is very difficult and, to date, inefficient. Moreover, often the aim is to single out a specific signal in a noisy data set of similarly significant signals. The human brain is very adept at identifying known or recognisable sounds amidst noise – a phemonenon commonly referred to as the 'cocktail party' effect (e.g., Bregman 1990). Humans are capable of selective hearing, which is the ability to detect and focus on a desired sound in a noisy environment consisting of similarly significant, or more significant, sounds. Moreover, humans can hear data faster than they can visualise them, and data sonification can take advantage of human non-linear listening (Rychtáriková *et al.* 2016). We aim to capitalise on these capabilities for identifying astrophysical sources in noisy data. Efforts similar to this approach include the sonification of fast radio-burst data, and gravitational-wave audification.

3. Applications

Data sonification has great potential utility for astronomy and other science disciplines, as well as business, government and the military. In this Workshop we discussed the research in which we are implementing data sonification, e.g., our multi-parameter galaxy research (Section 2.2), and our Deeper, Wider, Faster (DWF) programme†; see p. 135.

DWF coordinates over 40 telescopes worldwide and in space, including radio to gamma-ray facilities and particle and gravitational-wave detectors, to detect and study fast transients with durations of milliseconds to hours. Because of the fast, and often unknown, nature of the transient sources, DWF coordinates high-cadence simultaneous observations of targeted fields at all wavelengths. The data are processed in real time (seconds), producing hundreds of transient candidates every few minutes throughout an observing run. The optical images and evolving light-curves are analysed via software and human inspection by a team of researchers locally and worldwide. High-priority candidates must be confirmed within minutes after the light hits the telescopes to enable other facilities to react and obtain deep spectroscopy or imaging before the events fade.

The urgency of the data analysis motivates research into the fastest and most accurate methods of candidate identification and confirmation. Data sonification is being incorporated to enhance and accelerate discovery, while enabling visually-impaired researchers and the general public to participate. The large volume of data produced by the DWF

† http://www.dwfprogram.altervista.org/

programme, and the need for very rapid transient identification, necessitates enhanced means of analysis. The DWF programme is a current example of the new approaches and real-time data products that will be produced in future programmes. Lessons learned from DWF, as well as our high-redshift galaxy research, will have direct applications to Big Data analyses and upcoming large surveys such as the SKA and LSST. Continued exploration into data sonification is essential for optimising and managing large and multi-dimensional data sets, and performing the most accurate and fastest human-based data analyses.

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