UNITED NATIONS
OFFICE FOR OUTER SPACE AFFAIRS

SONIFICATION: A TOOL FOR RESEARCH, OUTREACH AND INCLUSION IN SPACE SCIENCES

A SPECIAL REPORT BY THE SPACE FOR PERSONS WITH DISABILITIES PROJECT
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COVER DESCRIPTION

The cover is an artistic depiction of a sonification of the Omega Nebula image taken by the Hubble Space Telescope. Also known as the Swan Nebula, it consists of newly born stars embedded in wavelike patterns of gas. The image is presented in duotone colours and retains the beautiful structure of the nebula. The ocean wave-like front of the nebula is overlaid with multiple columns of bars following the upward trajectory of the wavefront to represent the frequency visualisation of a sound equalizer. The Omega Nebula is still visible throughout the sound equalizer visualisation to underscore the nexus of sound and astronomical data.

Image credit: NASA

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Sonification: a tool for research, outreach and inclusion in space sciences

UNITED NATIONS
Vienna, 2023

"Our world is confronting a cascade of crises that are disproportionally impacting persons with disabilities.
We need transformative solutions to rescue the Sustainable Development Goals and leave no one behind. This requires greater public-private sector collaboration to develop strategies for, with and by persons with disabilities. The cornerstone of this cooperation must be the active participation of persons with disabilities in their full diversity, and their full inclusion in all decision-making processes.
Innovation and technology can be powerful tools for inclusion. They can enhance access to information, education, and lifelong learning. And they can open new avenues for persons with disabilities to participate in the workforce and society at large on an equal basis.
[…]
On this day and every day, let us work together in finding innovative solutions to build an accessible and equitable world for all."

António Guterres
United Nations Secretary-General
International Day of Persons with Disabilities 2022

Contents

Foreword

The 2030 Agenda for Sustainable Development pledges to “leave no one behind”, where the dignity of an individual and equality among all is a fundamental principle cutting across the three pillars of the work of the United Nations: Development, Human Rights and Peace and Security. In this regard, it is critical to ensure the full and equal participation of persons with disabilities in all spheres of society, including in space.

The United Nations Office for Outer Space Affairs is committed to advancing efforts towards disability inclusion in space. The importance of science, technology and innovation will only grow in the future. We must ensure that every individual is empowered to access space information and contribute to international cooperation in the exploration and peaceful use of space. For too long persons with disabilities have been excluded from full participation in space sciences.

An estimated one billion people, or 15% of the world's population experience some form of disability. Many of whom are prevented from joining the wider society in education or employment due to discrimination, stigma and lack of support and assistance amongst other barriers. The adoption of the Convention on the Rights of Persons with Disabilities created a human rights-based blueprint for achieving disability inclusion, enhancing efforts by numerous stakeholders to create an equitable world. Within space, each of us has the responsibility to work towards this future and advocate for the rights of persons with disabilities.

For blind and visually impaired (BVI) persons, there are huge barriers to accessing the opportunities afforded by space. This report addresses one such barrier: the sector’s reliance on data visualisation for research, outreach, and education. The power of spectacular images of space to inspire and spark curiosity is unquestionable, but by assuming that sight is the only way to explore space we exclude the BVI community, who have equal right to full participation in space sciences. By exploring different ways to interpret and communicate data we open doorways to new discoveries and a more inclusive future.

Sonification, a technique in which non-verbal sound is used to interpret, analyse, and communicate data, is a powerful tool for equitable access to space. This report aims to provide a comprehensive overview of sonification in terms of its contribution to space science and accessibility, challenges in mainstreaming, and makes recommendations to address these issues, in particular with the goal of developing and implementing sonification as a universal tool for space science research and communication that is accessible to BVI researchers. This report hopes to stimulate a global dialogue and shift the paradigm in attitudes and approaches to persons with disabilities in space.

This report is a small but important step in improving our understanding of accessibility in space science. Although much work is still to be done on the road to an inclusive future, we are not alone. From the United Nations to scientific institutions, the private sector, as well as individuals, there are many stakeholders committed to mainstreaming disability and advocating for tools like sonification. Only by working together can we build a truly diverse and inclusive space sector for the benefit of everyone.

Mr. Niklas Hedman

Acting Director, Office for Outer Space Affairs

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Glossary of terms

Blind and visually impaired (BVI): A term referring to people with blindness or vision impairment as defined by the World Health Organisation (WHO) International Classification of Diseases[1]. Globally, at least 2.2 billion people have vision impairment. A person's experience will vary depending on many different factors.

Persons with disabilities: Persons with long-term physical, mental, intellectual or sensory impairments which in interaction with various barriers may hinder their full and effective participation in society on an equal basis with others[2].

Universal design: The design of products, environments, programmes and services to be usable by all people, to the greatest extent possible, without the need for adaptation or specialized design. Universal Design shall not exclude assistive devices for particular groups of persons with disabilities where this is needed[3].

Sonification: Translation of data into non-verbal sound to facilitate interpretation and communication[4].

[1] WHO fact sheet on blindness and vision impairment dated 13 October 2022.
[2] Convention on the Rights of Persons with Disabilities, Article 1.
[3] Convention on the Rights of Persons with Disabilities, Article 2.
[4] See Section 2.1 for a full discussion of the definition of sonification.

Chapter 1: Introduction

1.1 Context

This report was prepared by the United Nations Office for Outer Space Affairs (UNOOSA) Space for Persons with Disabilities project implemented by the Space Applications Section. The report reviews the status and potential of sonification for promoting disability inclusion in space science, and benefits for enhancing scientific work by researchers with or without disabilities. The report draws together a review of current literature and the results of expert consultations to give a comprehensive overview of the status of the field and make recommendations for the future development of sonification tools as universal tools for space science research and communication, conducted in such a way as to render space sciences more accessible to blind and visually impaired (BVI) researchers.

By demonstrating the role of sonification in facilitating disability inclusion in space science, the report raises awareness of accessible tools and opportunities and support decision-makers to enable and encourage the development and use of sonification. This research also contributes to the implementation of the Sustainable Development Goals (SDGs), in particular SDG 10: Reduced Inequalities. It aligns with the United Nations Convention on the Rights of Persons with Disabilities (CRPD) to promote, protect and ensure the full and equal enjoyment of all human rights and fundamental freedoms by all persons with disabilities, including the rights to accessibility and participation in society. In a larger context, this report hopes to stimulate a global dialogue and shift the paradigm in attitudes and approaches to persons with disabilities in space.

The aims of this report are:

- To demonstrate the contribution of sonification to scientific research and disability inclusion in space science;
- To identify key challenges that need to be addressed to realise the full potential of sonification; and
- To make recommendations for decision-makers wishing to support the use and development of sonification as a tool for scientific research and inclusion.

The recommendations made in Chapter 6 of this report are consistent with the CRPD, in particular:

- Recognizing the importance for persons with disabilities of their individual autonomy and independence, including the freedom to make their own choices (Preamble (n));
- Full and effective participation and inclusion in society (Article 3, General Principles (c)); and
- To undertake or promote research and development of, and to promote the availability and use of new technologies, including information and communications technologies, mobility aids, devices and assistive technologies, suitable for persons with disabilities, giving priority to technologies at an affordable cost (Article 4, General Obligations (g)).

The first chapters of this report will introduce the methodology of this research report and the concept of sonification. This is followed by a discussion of the advantages and challenges of using sonification. Next, steps to mainstreaming sonification and recommendations for decision-makers are identified. The annex of the report lists existing work using sonification in space sciences, as well as the events and community spaces that facilitate international, multidisciplinary collaboration in the field of sonification. Three projects representing the use of sonification in outreach, research and archives are also highlighted in the feature articles.

1.2 Methodology

This section presents the research methodology and sources of information for this report:

- **Literature review**

A review of current literature on sonification in space science and accessibility in Science, Technology, Engineering and Mathematics (STEM) fields was conducted via an online search for relevant papers and recommendations made by experts in the field.

- **Publicly available materials**

A wide range of recorded talks and lectures on sonification is available publicly. A selection of these is listed in Annex C. Talks by sonification practitioners, aimed at a variety of audiences, were used to gain an understanding of the current state of the field, find relevant literature, and identify sonification projects and experts in the field.

- **Expert consultation**

To give a representative overview of the field, a wide range of relevant experts and sonification users have been consulted. Forty interviews were held with experts between May and December 2022. Most of these consultations were with individuals working directly with sonification, including a number of those leading projects listed in Annex C. Other categories include individuals with expertise in inclusivity in STEM, or multisensory work other than sonification. The individuals consulted include both sighted and BVI individuals. This report also draws upon discussions and lessons learnt from the Audible Universe 2021 and 2022 workshops (Annex B and Harrison et al., 2022b).

- **Webinar**

Insights gleaned from the public webinar "Sonification: a tool for research, outreach and inclusion in space sciences" organised by UNOOSA on 17 November 2022 were included in this report[5]. The panel discussion brought together professional astronomers and experts in sound perception, science communication and accessibility to discuss the current state of sonification in space science, challenges in implementation, recommendations on how to facilitate the advancement and adoption of sonification in space science research and outreach, and what to expect in the coming years.

[5] "Sonification: a tool for research, outreach and inclusion in space sciences" is an online event organised by UNOOSA in November 2022. This online event aims to explore sonification as a tool that has the potential to contribute to scientific research, outreach and disability inclusion. This event comprises of two segments. Segment one showcases a diverse range of sonification projects in space sciences while segment two is an online panel discussion where experts unpack the complexities surrounding the use of sonification in space sciences. The video recordings for segment 1 and segment 2 are available on UNOOSA YouTube channel.

Chapter 2: Sonification background

> ***Actually, humans are blind to much of the light that comes from the universe. From infrared to ultraviolet, sighted eyes are sensitive to only a narrow band of light located almost in the middle of the spectrum.***
>
> ***Wanda Díaz-Merced***

Space sciences are commonly believed to be highly visual subjects, yet there is a long history of radio astronomy and time-dependent signals from the universe that do not naturally lend themselves to visual representations. Much of the electro-magnetic spectrum is invisible to the human eye, yet people have mostly chosen to represent the inherently digital data visually. Awe-inspiring images are widely used to engage non-expert audiences, exciting curiosity and hoping to inspire the next generation of scientists. Data analysis often relies on visual representations from telescope images to data plots.

The ramifications of this are twofold. Firstly, it limits the possibilities of data analysis to the capabilities of visual perception. Secondly, BVI persons are prevented from fully accessing or engaging in space science. In recent decades there has therefore been a move by some in space sciences to widen the sensory parameters of space sciences through a process called sonification.

Sonification, most simply defined as the practice of mapping data onto sound, is a technique that has been used in a wide variety of scientific fields, from seismography to neuroscience, as well as space science (Supper, 2012). Sonification has been growing in popularity and usage since the 1980s. The first International Conference for Auditory Display (ICAD) in 1992 is considered the "formal" beginning of sonification as a defined field (Supper, 2012; Scaletti, 2017). Within space science, sonification remains an emerging technology and is not in mainstream use. Annex C outlines sonification projects reviewed for this report.

2.1 Defining sonification

The definition underlying a sonification tool influences its goals, methodology, design, and evaluation (Worrall, 2019). Sonification is also a highly multidisciplinary field, in which artists, educators, science communicators and scientists intersect and collaborate. This has sometimes created difficulties in community efforts to define sonification and demarcate artistic and scientific boundaries.

Is sonification a scientific discipline, an interdisciplinary community, a cutting-edge practice, a research methodology, a technological tool, a practical application, a popular mass medium? All of these terms have been invoked to describe sonification.

Supper, 2012: 100

Supper (2012) explores the evolution of definitions of sonification in detail, identifying Scaletti (1994) as one of the first mainstream definitions of sonification. Scaletti's definition is as follows:

> *"a mapping of numerically represented relations in some domain under study to relations in an acoustic domain for the purposes of interpreting, understanding, or communicating relations in the domain under study."* *(224)*

This definition is notable for the inclusion of two elements: the mapping technique, and the interpretation and communication of relations. Supper identifies Kramer et al. (1997)'s report for the US National Science Foundation as providing the following widely cited definition:

> *"Sonification is defined as the use of nonspeech audio to convey information. More specifically, sonification is the transformation of data relations into perceived relations in an acoustic signal for the purposes of facilitating communication or interpretation. By its very nature, sonification is interdisciplinary, integrating concepts from human perception, acoustics, design, the arts, and engineering." (3)*

Criticisms of this definition have focused on the broad definition of what may be considered a sonification (Supper, 2012). At ICAD 2008, Herman (2008) suggested that work should have to meet specific criteria:

> *"The sound reflects objective properties or relations in the input data. The transformation is systematic. This means that there is a precise definition provided of how the data (and optional interactions) cause the sound to change. The sonification is reproducible: given the same data and identical interactions (or triggers) the resulting sound has to be structurally identical. The system can intentionally be used with different data, and also be used in repetition with the same data." (Hermann, 2008: 2)*

The exclusion or inclusion of artistic sonification has been debated in the field. The challenge of demarcating the boundaries of sonification, particularly regarding the art/science boundary, affects efforts to achieve scientific acceptance of sonification.

This report does not seek to define sonification or set criteria for validity. However, the work discussed here broadly fits into a definition provided by Bardelli et al. (2021), which follows a similar structure to Scaletti (1994), and Kramer et al. (1997):

"Sonification is the transformation of data into acoustic signals, namely a way to represent data values and relations as perceivable non-verbal sounds, with the aim to facilitate their communication and interpretation." (171)

2.2 A multisensory history

Although sight has historically been the primary sense used in space sciences, there are examples that demonstrate that the use of sound existed prior to 1992. Early examples of using sound to understand space phenomena include the 1932 discovery by K. Jansky that telephone communications were being disrupted by radio waves from the centre of the Milky Way – a finding that led to the discovery of the Galaxy's supermassive black hole and the beginning of radio astronomy, and the 1964 discovery by A. Penzias and R. Wilson that cosmic background radiation was causing noise disturbance to their antenna observations (Zanella et al., 2022). The British Antarctic Survey's *Sounds of Space* project draws on work that began in the 1950s, creating music from radio waves and space weather storms picked up by Very Low Frequency receivers (Meredith, 2019; Meredith et al., 2022). Some have pointed to Kepler's *Music of the Spheres* to argue that sound has always had relevance to those seeking to understand the cosmos.

The 1979 Voyager-2 mission is often cited as an early example of the use of sonification in space sciences. While traversing Saturn's rings, the spacecraft developed a problem. When visual displays of data proved hard to interpret, the data was played through a music synthesizer instead. The resulting "machine-gunning sound" enabled engineers to diagnose a problem with the spacecraft caused by collisions with micro-meteoroids (Barras & Kramer, 1999).

Today, sonification is part of a move towards multisensory engagement with space in which "the sense of sight tells only a small part of the cosmic story" (Arcand et al., 2019: 2). Touch, hearing, and even taste (Trotta et al., 2020) have been used to enhance exploration and understanding of space science for both expert and non-expert audiences. The use of sound for accessibility has also increased in recent decades, with projects like Microsoft's *Soundscape*, which enables sound-based navigation.

Modern sonification is a highly multidisciplinary field. Artists, educators, science communicators and researchers are engaged in sonification work across multiple subjects. While the focus of this report is on sonification in space sciences, there remains variation within that subset. The goal and intended audience of a sonification strongly affects how it is constructed. Broadly speaking, there are three categories:

- **Artistic sonification**

  The primary goal is artistic expression, to push the boundaries of music, to creatively explore data, or both. There may be an element of engaging the public with science or music in a new way, but these types of sonifications are primarily musical and their creators do not necessarily limit the extent to which they manipulate the sounds beyond the core data. An example is *Sound of Earth's Magnetic Field*, an audio representation of Earth's magnetic field over the past 100,000 years, designed by scientists from the Technical University of Denmark, using signals measured by the European Space Agency's Swarm satellite mission (Annex C). This audio installation was played in a public square in Copenhagen, Denmark.

- **Sonification for outreach and education**

  This is a common category of sonification, drawing on the ability of sound, especially as a relatively unusual tool for science communication, to engage non-expert audiences. The goal of these types of sonifications is usually either to inspire curiosity about STEM subjects or to communicate a specific learning objective, or both. For example, in May 2022, NASA tweeted a sonification of the black hole at the centre of the galaxy cluster known as Perseus as part of the agency's efforts to use social media to communicate complex scientific discoveries the public. The attached audio has been played 173 million times on Twitter as of 23 Dec 2022[6].

- **Sonification for scientific research**

  A smaller subset of sonification work is engaged in creating or using sonification as a data analysis tool, drawing on the advantages of audio perception and sonification's accessibility to researchers who are blind or vision impaired. Wanda Díaz-Merced, a blind astronomer, developed and applied a sonification technique for use in her doctoral research, demonstrating the ability of sonification to support identification of signals in noisy data. Sonification has been used to study plasma patterns in the Earth's uppermost atmosphere. The goal of sonification for scientific research is to understand the underlying phenomenon of data by analysing it with sound. Therefore, the sound mapping is grounded in technical accuracy; sound represents the original data accurately and the sonifications may be done interactively and iteratively to facilitate comprehensive exploration of the data.

Zanella et al. (2022) identified a fourth category in which accessibility is a primary objective. That category has not been included in this report as projects from each of the other three categories commonly include accessibility as a secondary goal.

There are projects that fall into multiple categories; often, these projects involve people whose usual focus is on one or the other category, such as a musician and scientist working together, but may also be the work of an individual who is, for example, a scientist passionate about science communication and outreach, or a scientist with musical training. This framework informs the layout of Figure 1.

> “ ***There are three main broad areas of applications of this technique to scientific data, considering the receptor and objective of the output, all of them with wide common overlapping areas: a) analysis by means of sound of any kind of data; b) pedagogical and dissemination purposes; c) source of inspiration for artistic creations and public engagement. Depending on the public and aim of the sonification, the acoustic complexity and the clear presence of the data will have different weights.*** ”
>
> ***García-Benito & Pérez-Montero, 2022: 2***

[6] A sample of the sound of black hole is available here.

2.3 Existing work

Figure 1 provides an overview of sonification projects reviewed for this report, divided into three categories defined by the primary goal of each project: artistic, outreach and education, and scientific research. There is considerable overlap between categories; categorisation is based on projects' primary goals, and should not be taken as a definitive categorisation, but as a system to aid understanding. A detailed description of each project and links to relevant resources are provided in Annex C[7].

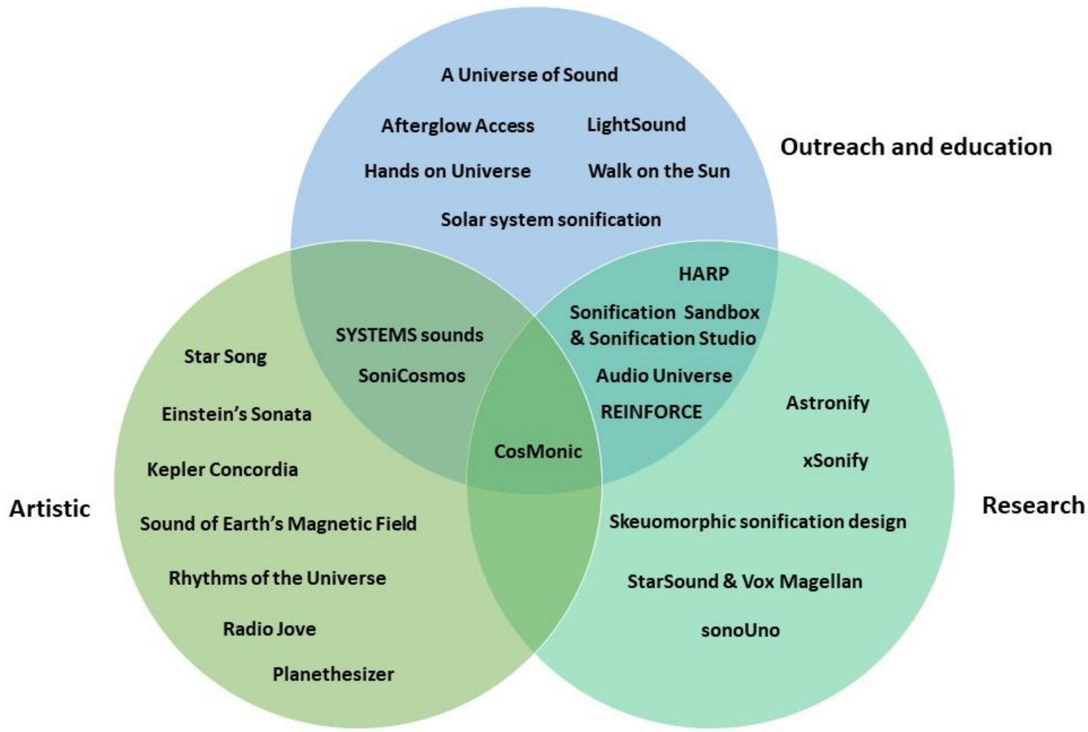

Figure 1: Venn diagram demonstrating different types of sonification projects based on their primary goals divided into the sets "artistic", "outreach and education" and "research".

Artistic

- Einstein's Sonata
- Kepler Concordia
- Planethesizer
- Radio Jove
- Rhythms of the Universe
- Sounds of Earth's Magnetic Field
- Star Song

[7] The projects listed here are the result of a review of current literature on sonification in space sciences and interviews with individuals leading or otherwise involved in the projects. The design, value, or impact of these projects is not assessed. They are presented here to give an overview of the current state of the field. Any project that may have been missed is not a statement on its value or importance but a limitation of the scope of this project.

Outreach and education

- A Universe of Sound
- Afterglow Access
- Hands on Universe
- LightSound
- Solar system sonification
- Walk on the Sun

Research

- Astronify
- sonoUno
- Skeuomorphic sonification design
- StarSound and Vox Magellan
- xSonify

Overlap between artistic and outreach and education

- SoniCosmos
- SYSTEM Sounds

Overlap between outreach and education and research

- Audio Universe
- Heliophysics Audified: Resonances in Plasmas (HARP)
- REsearch Infrastructures FOR Citizens in Europe (REINFORCE)
- Sonification Sandbox and Sonification Studio

Overlap between artistic, outreach and education, and research

- CosMonic

For an alternative overview, see Zanella et al. (2022), which reviewed 98 existing applications of sonification collated into the *Data Sonification Archive* [8] with the tag "astronomy", via a community effort. They identify the first conscious effort to sonify space science as the work of Donald Gurnett from 1962 to 2012, who sonified data from space missions like Cassini and Voyager. According to their findings, 8 to 19 new projects have been launched each year since 2016. Most have a primary goal of public engagement (36% of those assessed) or research (26%). Only 13% listed making astronomy accessible to BVI as a primary goal, with 22% listing it as a secondary goal. 79% were designed for the general public. 64% used a multisensory approach where sound is combined with other modalities.

This remainder of this report will focus primarily on sonification in space sciences for research, and briefly touch on outreach and education. The following sections will cover some key concepts and outline the advantages and challenges of using sonification in space sciences.

[8] The Data Sonification Archive is a curated living database currently showing 417 sonification examples across multiple domains created from 1991 till present. A search for astronomy returns 119 examples as of 14 April 2023.

2.4 Key concepts

The key underlying concepts in this report are:

- Although sonification is not a mainstream scientific tool, it is successfully in use in the scientific practice of a small group of scientists. It is therefore appropriate to talk about its value and applications in the present tense, as opposed to hypothetical future potential.
- Sonification is a counterpart of data visualisation.
- It is not sufficient to just hear the data; using sonification to enable interpretation requires specific design considerations.
- Sonification has been used extensively in outreach and education. However, there remain significant barriers to sonification gaining legitimacy as a research tool, despite successful application by some researchers.
- Implementing Universal Design principles is more inclusive, and often more affordable and simpler than developing specialized software or hardware for persons with disabilities. Sonification in practice should therefore be informed by a universal design approach.

Sonification and visualisation

Treating sonification as analogous to visualisation is part of normalising its use and understanding how to utilise it effectively. However, it will take time for sonification as a field to develop norms, conventions and standards for data representation similar to those in the field of data visualisation. Moreover, as with data visualisation, sonification requires training and skill to produce, understand, and interpret.

Sonification is not a replacement for visualisation. Many practitioners advocate for the integration of sound into multisensory experiences and data analysis. Supper (2012) notes that "an underlying assumption of sonification is that an auditory display and analysis of scientific datasets might be helpful for blind scientists, but also that it might yield a more thorough comprehension of certain scientific data and phenomena, for sighted as well as blind scientists" (12). Sonification is a potential solution to the proliferation of large, complex, multidimensional datasets in space sciences which require new approaches to data analysis to tackle effectively.

Chapter 3: Advantages of sonification

Sonification draws on the advantages of sound for representing, analysing, and communicating data. While sonification presents specific advantages to BVI individuals who cannot use visualisation methods, most advantages of sonification are applicable to all hearing users. These advantages fit into four broad categories: sound perception, accessibility, engagement and complex data analysis.

3.1 Sound perception

Arguments for sonification often call on research into sound perception as evidence of the need to expand beyond visual-only data analysis. The way humans perceive sound has multiple benefits applicable to space science and data analysis.

- The "cocktail party" effect: The ability to identify and prioritise sounds in a noisy environment. This effect is highly relevant to leading-edge research using large, noisy datasets that are difficult to reduce or analyse with automated tools (Cooke et al., 2019). Increased sensitivity to events in noisy data was demonstrated by Díaz-Merced (2013). It is also possible to perceive multiple sounds simultaneously (Lunn & Hunt, 2011);
- Sound is inherently multidimensional, offering control over parameters such as pitch, timbre, amplitude, and duration. This can be used to represent multiple data parameters in one sound (Cooke et al., 2019; Tucker Brown et al., 2022; Zanella et al. 2022);
- Sound offers higher temporal resolution (Quinton et al., 2020) and is more appropriate than visual analysis for time-based information, patterns, and transient changes (Zanella et al., 2022). Human hearing also covers a larger frequency range than the visual system (Archer et al., 2018). Sound can convey the dynamics of a process and directly represent time-dependent phenomena;
- Sound can communicate spatial location[9]; and
- The ears are always active and can operate in the background, therefore it is possible to listen to a sonification while engaged in other tasks, which has potential, for example, in supporting analysis of large datasets where the researcher is sufficiently familiar with the sound signature of the signal of interest and is alerted by the ears to specific parts of the dataset.

[9] See Harrison et al. (2022) for a practical use of sound's spatial properties.

3.2 Accessibility

> ***Astronomy is based on light and more important, astronomy education is largely based on beautiful images. Teaching astronomy to visually impaired people is therefore a major challenge.***
>
> ***Weferling, 2006: 102***

The current reliance on images, videos and animations excludes BVI persons from full participation in space sciences at any level (Bonne et al., 2018; Pérez-Montero, 2019). Sound-based science communication and research therefore has potential to enable participation in space science by BVI persons. Several BVI astronomers are currently making use of sonification in their research or outreach activities[10].

Moreover, multimodal approaches have benefits beyond the BVI community, providing benefits to people with or without disabilities. Assistive technologies have a strong record of universal benefit following expansion beyond the disability community; voice recognition and captioning are well-known examples.

In practice, work is ongoing within the space science community to leverage multisensory learning to improve disability inclusion, including two projects led by blind astronomers, *AstroAccessible* and *Tactile Universe*. The *AstroAccessible* project aims to "improve the teaching and popularization of astronomy among blind and visually disabled people by helping teachers and scientists to be more conscious of the need to extend their activities to all groups" (Pérez-Montero, 2019: 114-115). *AstroAccessible* develops resources and materials for describing astronomical objects using touch and audio, including verbal explanations, and high contrast images for people with partial sight (Pérez-Montero et al., 2017; 2022).

Tactile Universe is a UK-based project using tactile resources to demonstrate to BVI communities that astrophysics can be accessible to them. The presence of a blind astronomer in the position of a tangible role model is identified as an important element of this project (Bonne et al., 2018).

A further initiative, the *Sensing the Dynamic Universe* project, focuses on improving accessibility of software and digital content in astronomy for multiple disability groups, including BVI people (Díaz-Merced et al., 2020).

Unlike traditional planetarium shows where visuals play the leading role, the soundtrack is of primary importance in the planetarium show *Audio Universe: Tour of the Solar System* (Annex C2). Audiences can listen to the stars appear and hear the planets orbit in an immersive experience that is educational, enjoyable and accessible. Sonification is not an add-on but a key feature for accessibility.

[10] See 2016 TEDTalk "How a blind astronomer found a way to hear the stars" with speaker Wanda Díaz-Merced. See also Díaz-Merced (2013).

3.3 Engagement

> ***Attractive images provide good reinforcement for explanations of astronomical concepts. When people look at them, they find them beautiful, strange, curious, rare, […] It turns out that sounds can play the same outreach role as astronomical images.***
>
> ***Ballesteros & Luque, 2006: 1***

Awe-inspiring images are a powerful engagement tool for attracting non-expert audiences to complex subjects and stimulating interest in students of astronomy (Ballesteros & Luque, 2006). Sonification provides an alternative or additional way of inspiring curiosity and wonder. Ballora (2014) describes this "wow" factor as an important part of the appeal of sonification, and Supper (2014) describes the ability of sonification to create an experience that allows people to engage with hard-to-grasp concepts and access some of the fascination and excitement of doing science without expert knowledge. On one hand, this engagement through sonification could be a motivating factor that encourages further step towards acquiring expert knowledge and tools to deepen understanding of the subject. However, on the other hand, it could hinder efforts to present sonification as "real" science (Supper, 2014). Further research is required to understand the impact of multisensory learning tools on student engagement.

3.4 Complex data analysis

> ***Continued exploration into data sonification is essential for optimising and managing large and multidimensional data sets, and performing the most accurate and faster human-based data analyses.***
>
> ***Cooke et al., 2019: 256***

The need to analyse large, complex, noisy, and/or temporally changing datasets is often given as evidence of the need for data sonification (Supper, 2012). The amount of data available is a key issue: "there is essentially more astronomical data available than there are astronomers to process it" (Lunn & Hunt, 2011: 8). Astronomers often deal with large datasets, tracking multiple important parameters, and often with significant noise obscuring the relevant signal. New methods for data analysis are therefore appealing as a way of finding new insights and tackling the overabundance of data (Quinton et al., 2020). Adding sound to the astronomer's toolkit can essentially increase the "bandwidth" of data analysis and reveal patterns and phenomena obscured by a visual-only approach (Candey et al., 2005; Lunn & Hunt, 2011). It allows better identification of patterns or signals in large and multidimensional astronomical datasets.

A specific example of this is the application of sonification in the *Deeper Wider Faster* project, which aims to detect and study fast transients. Hundreds of potential transient candidates are identified every few minutes, and high priority candidates must be confirmed swiftly. Cooke et al. (2019) argue that incorporating data sonification can enhance discovery and enable participation by BVI researchers and the public.

Chapter 4: Challenges to mainstreaming sonification

Despite these advantages and the 30 years of research since the first ICAD meeting, sonification remains on the periphery of scientific practice.

The 2017 ICAD keynote lecture by Carla Scaletti, titled "Why sonification is a joke", tackled the question of why sonification remains outside of the mainstream, and how to take steps toward scientific legitimacy. Scaletti argued that sonification is one of three pillars of human auditory communication, equal to speech and music, but is not treated seriously or adequately trained. She also argued that all data mapping is adaptive technology because humans cannot hear or see most of the dynamic processes in the universe unaided. Sonification is another variation on the ways processes are mapped and interpreted. Why, then, does the treatment of sonification in scientific communities differ from that of data visualisation?

This section explores the barriers to mainstream integration of sonification in scientific practice, and the challenges that remain to be addressed by future work.

4.1 Design challenges

Sonification design is challenging, and ultimately depends on the goals of the project, the intended users, and the data source. Setting a clear goal for the sonification and knowledge of the perceptual processes that will render it meaningful are crucial elements of sonification design (Barass & Kramer, 1999; Worrall, 2019).

4.1.1 Standardisation

The lack of standardisation in sonification design is a core challenge. Zanella et al. (2022) described a lack of standardisation as a "major limitation" and argued that when projects are focused on the public, they focus "more on inspiring the audience and conveying a single message rather than being related to the underlying data" whereas "the opposite is true for projects meant for researchers". They found that "there have been little-to-no attempts during the development of these tools to do extensive testing to establish the best approach to sound mapping".

The 2021 Audible Universe workshop brought together 55 experts working in sonification to identify key areas of concern for the field. They argued that both standardisation and customisation are essential for enabling effective, recognizable sonification design, and user control (Harrison et al., 2022b). Currently there is a lack of standardisation in sonification design, whereas data visualisation benefits from a long history of developing conventions and consensus. This issue is compounded by the subjectivity of sound perception. And while it is now possible to sonify a plot or 2D image, there are outstanding issues around sonifying contextual information such as legends, axis labels and tickmarks on plots, and how to provide both a rapid overview of the data and the ability to "zoom in" and interrogate points of interest. In some specific cases of sonification for data analysis, conventions on what the time development or frequency of the sound represents and common methods for implementing a default configuration combined with interactive user control are already emerging, but this is a limited occurrence. Solving these design problems is an important step towards sonification becoming a mainstream scientific tool.

4.1.2 Usability

To establish sonification as a scientific tool the most important feature required of sonification is to enable the analysis of the data and the underlying phenomena of the data. This means that it must always be possible to adjust the sonification iteratively and quickly such that the best representation of the data can be found. Additionally, the sonification must be available in an interactive manner, enabling the user to either quickly scan through the sonification or focus purposefully on a particular part of the sonification. The usefulness of sonifications for analysis of large datasets will be further enhanced by increasing ease of use.

4.1.3 User needs

Current sonification work caters to a range of users from individual scientists to planetarium visitors. Understanding the needs of different user groups, the impact of factors such as cultural background, disability, and training on perceptions of sonification, and evaluating the efficacy of sonification with different user groups, is a significant challenge. Efforts toward wider adoption of sonification in scientific research is also challenging partly due to the inadequacy of existing sonification tools to meet the demanding requirements of large quantitative data analysis.

4.1.4 Designing for BVI users

Accounting for the needs of BVI users and testing sonification tools with the community is a necessary but challenging part of sonification work aimed at increasing disability inclusion in space science. The BVI community is not a homogenous group, thus every individual will have different needs and interact with a sonification differently. A group of BVI users may include people who are blind or have varying degree of partial sightedness., whose blindness or visual impairment is congenital or adventitious. For persons who are adventitiously blind or adventitiously partially sighted, their experience of the world is also influenced by the age of onset of the impairment.

Moreover, testing sonifications for scientific use is a separate challenge because there are very few BVI scientists in space science. Consultation and testing with BVI individuals are however necessary parts of sonification design and pilot studies. The sonification must be meaningful to BVI users, and the tools and resources associated with it must also be accessible. This has not always been the case (Garcia et al., 2019).

4.2 Testing

> “ ***Proof that the sonification methods and tools being developed are effective in achieving their goals will be crucial for wider adoption.*** ”
>
> ***Zanella et al., 2022: 2***

Effective sonification design must be supported by rigorous evaluation and user testing. The 2021 Audible Universe workshop also identified a lack of scientifically driven experiments to test the efficacy of sonification projects (Harrison et al., 2022b). Each of the sonification projects listed in Annex C of this report has different approaches to evaluation, often with small groups of users, though the findings are usually not published.

The lack of testing is a major barrier to bringing sonification into mainstream use. Tucker Brown et al. (2022) conducted the first large-scale efficacy testing of a new sonification method in astronomy, testing the Astronify platform with 192 participants, using 18 mock light curves to evaluate the ability of both expert and non-expert users to identify signals in the data. More systematic, scientifically rigorous evaluation of sonification tools and methods is required for the field to expand into mainstream scientific practice.

4.3 Training

Similar to viewing images, listening to sonification requires training, practice, and skill. Tucker Brown et al. (2022) concluded in their assessment of the Astronify sonification tool that "we must expect at least some level of training and experience for sonification to be used effectively in the professional astronomical setting."

Understanding how much training is required and how to integrate sonification training into different levels of education, from early years to university courses, remains a challenge. Scaletti (2017) argued that the first generation of "natural" sonification users will result when active and analytical listening is taught from an early age - users who neither question the legitimacy of sound nor expect an experience above an informative one.

Interpretation of visual data is taught from a young age to the extent that one might be unaware of the training behind one's ability to interpret a plot (García-Benito & Pérez-Montero, 2022). Sonification will continue to perform unfavourably against data visualisations in comparative tests because of the inequality in training and background knowledge. However, until there is greater consensus around sonification methods it will not be possible to create sonification-specific effective training programmes beyond elements from existing fields such as sound design and active listening.

4.4 Expertise required

The multidisciplinary nature of sonification work is both a necessity and a strength of the field, enabling collaboration and shared learning across disciplines. However, it also presents a challenge. There must be experts in sound design as well as experts from the field of study providing the data. Experts with backgrounds in differing disciplines may have different goals and scientific norms around areas such as project design and evaluation (Supper, 2012).

> ***"One of the greatest difficulties found in the development of sonification tools lies in the conjunction of multiple interdisciplinary aspects required to ensure the final usefulness of the prototype."***
>
> ***Garcia Riber, 2018: 224***

Collaborations between astronomers and artists, for example, can be beneficial in bridging the science-society gap. Noting the potential tension between musical and scientific goals, the different expectations for the resulting sonification must be carefully balanced. Regarding the space sciences in particular, the information from the astrophysical background should drive the data such that information is not lost, which requires expertise from the researchers of the field. Conveying this information may be done using different auditory representations which requires expertise from sound designers. Both must work together to ensure that the sonification is in the audible range for the human ear and represents the data accurately[11].

The requirement to include multiple forms of expertise from fields such as psychology, sociology, software development, and education, also increases the cost and logistical complexity of sonification work. It may also be challenging to find experts in some fields such as disability inclusion and accessible software design, which may be less visible and outside of the usual scientific networks available to researchers.

4.5 Cultural barriers

> ***In the past few years, sonification has received considerable media attention; sonification concerts, public talks and magazine articles, all promising that sonification will allow listeners to tap into the sublime, have flourished. This popularity is in stark contrast with the contested status of sonification in the sciences, where a small interdisciplinary community is still struggling for scientific acceptance.***
>
> ***Garcia Riber, 2018: 224***

The lack of scientific legitimacy is a major barrier to mainstream uptake of sonification. While sonification is celebrated in some spaces and used by institutions such as NASA's Chandra X-ray Center for the *A Universe of Sound* project, progress towards acceptance remains slow, as there is a perception that sonification is a "gimmick" rather than a serious scientific tool (Neuhoff, 2019; Noel-Storr & Willebrands, 2022). This view is reinforced by the popular description that sonification is "novel" even though the development is more than 30 years in progress. Multiple people consulted for this report recounted experiencing scepticism or hostility from other scientists, research institutions, and funding providers. Sonification faces accusations of a lack of evidence base or being appropriate only for outreach and education work. Researchers seeking to use sonification in their work, therefore, must put considerable time and energy into justifying their methods before they are able to conduct their work, an additional hurdle for BVI scientists who already face barriers to their full participation in space science.

Scientific practice consists of norms and standards derived from decades of research and debate. These norms are expressed at all levels from seeking funding to publishing research.

[11] It is worth pointing out that this is not a problem exclusive to sonification. Visual representations also are manipulations of the underlying data and the presentation of these data (visually) varies dramatically depending on the primary purpose. Years of experience underpin how experts produce visualisations for these different purposes.

Supper (2012) argued that for sonification to succeed in breaching scientific norms, balancing work outside the norm with working within mainstream science is required to effect change. This tension is exacerbated for BVI scientists, whose needs may exclude them from the mainstream scientific community already. Supper argued that the lack of scientific legitimacy of the research method means that "getting too involved in sonification work can therefore be a threat for one's career prospects", compounding issues such as the precarity of work for early career researchers. For BVI researchers who already face limitations in the types of science they can pursue, using sonification as the foundation of a career comes with considerable risk.

4.6 Funding

Making effective sonifications requires time and resources, both of which must be funded. The need for and scarcity of funding is not a challenge unique to sonification. Access to funding is a requirement for all scientific research and was a concern for many of the scientists consulted for this report. The difficulty of finding funding providers appropriate to sonification projects is a major barrier. The lack of scientific legitimacy is an obstacle in acquiring funding for sonification work as a scientific project, while grants available for outreach or accessibility work are often small and inappropriate for leading-edge scientific work. Furthermore, due to the multidisciplinary nature of sonification, it is often difficult to seek funding or sustain funding from funders who are accustomed to a strictly scientific or artistic field.

Chapter 5: Path to mainstreaming

> ***In order to create a niche in which sonification can be regarded as an acceptable way of analysing and representing scientific data, much work needs to be done: transforming data into sound, making it sound good, developing and relaying listening skills, familiarising oneself with different scientific specialisations from which the data are taken, building up and defining a field.***
>
> ***Supper, 2012: 112***

Despite the challenges described in the previous chapter, the benefits of sonification as a tool for enhancing current scientific practice and supporting disability inclusion demonstrate that it is worth continuing to develop the field to actualise this potential.

Mainstreaming sonification does not imply the replacement of data visualisation, nor does it make sonification a mandatory application in all circumstances. It means sonification could be considered an accepted tool in the toolbox.

One may ask what elements have enabled the mainstreaming of sonification in other scientific fields that could be applied to space sciences? We may draw some observations from three broad categories of equipment observed in most laboratories; standard devices that could be found almost anywhere, such as printers or centrifuges; domain-specific equipment, usually mass-produced but targeted for specific types of scientific work; and bespoke devices that were custom-designed to answer a specific question. Sonification-enabled perceptualisation of the data improves our understanding of the data and facilitates discovery that may not have been possible through standardised graphing tools or existing domain-specific modelling tools. Sonification could therefore start off as a bespoke built-for purpose tool and be gradually integrated into existing research tools, archives and major astronomical software.

Ironically, the most credible and widely used examples of sonification are the ones that are so ubiquitous that they are hardly noticeable, such as the beeps of indicators or variable feedback from interactive wands or probes. In the long run, one measure of the success of sonification in space science will be when it is no longer seen as a novelty but simply part of everyone's toolbox for understanding the universe.

However, mainstreaming sonification requires it to be seen as scientifically legitimate and gaining scientific legitimacy is challenging. It involves breaking a difficult cycle; a tool must prove its worth to be accepted by the scientific community, but to prove its worth those using that tool need to acquire funding and institutional support, and publish in academic journals, all of which requires acceptance of the tool's value and scientific legitimacy.

As clearly defined goals, methods, and evaluation strategies are important elements of convincing the scientific community of the legitimacy of sonification (Neuhoff, 2019), a first step to acceptance would involve improving the design and the evaluation process of sonification projects. Other suggestions include the publication of peer-reviewed articles, and inclusion of sonified data in academic conferences and journal (Barass & Kramer, 1999; Tucker Brown et al., 2022; Noel-Storr & Willebrand, 2022; Zanella et al., 2022). Producing novel scientific results from sonification will be an important step in the journey toward the acceptance of sonification as a legitimate scientific practice.

Supper (2012) described the path to academic legitimacy as requiring practitioners and policy makers within the field to accept the value offered by a particular tool or approach, but argued that a further step is required of sonification; it must flourish and be accepted outside the field of sonification as well as within it; successfully applying sonification in a range of scientific disciplines, and demonstrating its value as a universal tool will be key to its success.

Following literature review and expert consultation, recommendations to mainstream sonification were identified in the next chapter.

Chapter 6: Recommendations

The policy goals relating to sonification define the appropriate pathways and factors to consider. For instance, if the goal is to increase accessibility of space sciences for BVI individuals, sonification has to be embedded in policy infrastructure that enables inclusivity more broadly, including supporting use of sonification in schools and universities, and creating accessible environments for students and scientists. If the goal is to use sonification to support work bridging the science/society divide, the focus may be relatively more on funding and resources to enable collaboration between educators, scientists, and informal learning institutions like museums and science festivals.

The recommendations in this section assume the goal of developing and implementing sonification tools as universal tools for space science research and communication, conducted in such a way as to render space science more accessible to BVI researchers. It is not intended as a prescriptive list of technical requirements for developers of sonification projects although some basic elements are introduced. This section is aimed at a broad range of stakeholders, each with a unique role to play in supporting the use of sonification for scientific research and accessibility.

It should be noted that work is ongoing in all the following areas, but more is needed, or should be supported to realise the potential of sonification and take full advantage of past and current work in this area.

6.1 Support the development of sonification as a tool for scientific research

The design of sonification projects is extremely important. Appropriate project design is necessary for ensuring success and for supporting efforts towards gaining scientific legitimacy. Researchers working on sonification should ensure their work is of the highest rigor, just like in any other discipline. From a policy perspective, institutions and funding bodies can encourage or require certain factors to be considered in projects seeking to develop sonification tools to foster an environment of quality, and support with appropriate funding. The following subsections identify some areas which could be pursued to develop sonification as a tool for scientific research and overcome latent scepticism.

6.1.1 Clear goals and target users

Projects should have clearly identified goals and target users; the “why” of the project and its design should be made explicit. Sonification should be done with clarity of intention. Sonification used in research should enable a clear understanding of the data for scientists and include a key or legend to make the sonification comprehensible and reproducible, just as it is expected for visualisations of data. Both the use of sonification for outreach and for research work can reinforce the expectation for the use of sound in research and research communication and as such make astronomy more inclusive.

6.1.2 Multidisciplinary consultation

Consultation with experts in a range of appropriate fields, such as sound perception, sound design, psychoacoustics and user experience and design should be a keystone of sonification work. Sonification also benefits from being an international field. International partnerships and collaborations and sharing of information and best practices globally should be encouraged to create awareness of and momentum for sonification work. The more people who are working on data sonification, the better the tools will become.

6.1.3 User testing and evaluation

Rigorous approaches to user testing and evaluation should be included. The choice of method depends on the questions to be answered and could be informed by evaluation methods in the psychoacoustics and experimental psychology field[12]. For most outreach projects, testing and evaluation could include conducting pre- and post-test surveys with participants and control groups or using standardised testing to evaluate the use of sonification as a teaching tool. Where accessibility is a goal, persons with appropriate expertise should be consulted and BVI individuals should be involved in design and testing at all stages.

6.1.4 Balance standardisation and customisation with a set of basic guidelines

Discussions around an agreed upon basic guidelines to expedite or facilitate the mapping of data to sound in a transparent way for scientific research should be encouraged. Over the years, many individuals, teams and institutions have experimented with their own sonification methodologies for specific purposes. This has led to an explosion of new knowledge and lessons learnt could be shared on an international platform. Sonification in space sciences is still in the early stage and standardising things too early limits the ability of the field to explore possibilities. In fact, "brainstorming" before "norming" is a first step in any innovation process. In view of this, practitioners in sonification could aim for a set of basic guidelines to enable the mapping of raw data to a wide variety of sonic representations that most clearly bring out patterns in the data, so one can explore the data in an interactive and iterative way. The mapping should be as transparent and natural to the researcher as plotting a histogram is with current technology. Any guideline or standard should be flexible and allow for a certain level of customisation in the mapping to ensure its adaptability. Industry standards applicable to sound design should be consulted.

6.2 Apply universal design

Many sonification tools are already successfully used for artistic, educational, and scientific purposes (Annex C). However, these tools are primarily limited to a small subset of institutions and researchers and the design may not have been originally designed with accessibility as a top priority. The recommendations in this section pertain to addressing this issue with the concept of accessibility and universal design in mind.

Article 2 of CRPD defines Universal Design as the design of products, environments, programmes and services to be usable by all people, to the greatest extent possible, without the need for adaptation or specialized design.

[12] Refer to Misdariis et al. (2022) for a technical discussion on how sound perception, sound design, psychoacoustics and experimental psychology could inform the methodology of sonification for astronomy. Table 1 describes specific questions related to the sonification of astronomical data and corresponding evaluation methods.

Article 4 of CRPD holds that State Parties will "undertake or promote research and development of universally designed goods, services, equipment and facilities […] which should require the minimum possible adaptation and the least cost to meet the specific needs of a person with disabilities, to promote their availability and use, and to promote universal design in the development of standards and guidelines". The UN Flagship Report on Disability and Sustainable Development Goals emphasises that "implementing Universal Design principles is more inclusive, affordable and often simpler than developing specialized software or hardware for persons with disabilities". Sonification would thus be best implemented in practice if it is informed by a Universal Design approach.

The recommendations in this section pertain to achieving that goal. First, an outline of the 7 Principles of Universal Design is cited from the Centre for Excellence in Universal Design with additional notes on relevance to sonification provided in brief. The purpose of the Principles is to guide the design of environments, products and communications.

Principle 1: Equitable use

The design is useful and marketable to people with diverse abilities.

Example guidance: Provide the same means of use for all users; identical whenever possible, equivalent when not. Avoid segregating or stigmatizing any users. Make the design appealing to all users.

Relevance to sonification: Offering sonification as a valid, useful tool for all scientists, not limited to BVI users. Encourage familiarity with and training in sonification for all to facilitate integration of sonification users into the wider research community.

Principle 2: Flexibility in use

The design accommodates a wide range of individual preferences and abilities.

Example guidance: Provide choice in methods of use.

Relevance to sonification: Sonification tools should be designed to offer flexibility and user control in all elements. Sonification tools should be as flexible and responsive to user needs as visualisation equivalents.

Principle 3: Simple and intuitive use

Eliminate unnecessary complexities. Use of the design is easy to understand, regardless of the user's experience, knowledge, language skills, or current concentration level.

Example guidance: Be consistent with user expectations and intuition.

Relevance to sonification: Tools for data analysis will require a certain amount of background knowledge and training consistent with that required to use other data analysis methods. However, creating consistent training and standards for sonification is important for facilitating the use of sonification as a mainstream scientific tool.

Principle 4: Perceptible information

The design communicates necessary information effectively to the user, regardless of ambient conditions or the user's sensory abilities.

Example guidance: Provide compatibility with a variety of techniques or devices used by people with sensory limitations.

Relevance to sonification: Information required to use sonification tools and understand sonifications should be provided in a way that accounts for different sensory abilities and is compatible with devices such as screen readers and haptic tools.

Principles 5 – 7 (tolerance for error, low physical effort, and size and space for approach and use) primarily apply to physical environments. However, these principles should be considered in elements of sonification design such as the hardware required for full use of sonification tools, and user experience design and task flows.

Achieving universal design requires not only the existence of tools that enable full, inclusive access to scientific research, but a level of acceptance within the scientific community that provides low-effort access to sonification for anyone who needs it, and for that sonification to be useful to people with diverse abilities.

6.3 Integrate sonification into education system and standard scientific training

Sonification could bring sustainable benefits if integrated into the education system and standard scientific training. Training is crucial to enable the scientific community to use sonification effectively. Training is required for learning techniques of mapping the data to audible sound, as well as for developing the ability to listen attentively to the information transmitted by the sound. As consensus builds around sonification methods, it would also be possible to create systematic training programmes specific to certain space science disciplines. Developing evidence-based training programmes to enable use of sonification by current and future scientists should be prioritised. Trainings could be in the form of crash-courses and self-training modules for professionals who would like to expand their toolboxes to include data sonification as well as university courses. Training in programming and the science and mathematics of sound would provide strong foundation for those wishing to advance in the field of sonification. Additionally, integrating active and analytical listening at earlier ages would help to establish data sonification as another natural data analysis, interpretation and communication method. However, more research is required regarding best practice and impact of multisensory learning, and options for teaching sonification in early education.

It is noted that there could be resistance to participate in sound training due to the perceived difficulty of training people who are used to visual representation. One way to convince people that they can be trained to extract meaning from sound is by demonstrating that they already have the innate ability to derive some information from data mapped to sound. Using an anecdote as illustration, a coin-flipping sonification experiment was introduced to a general audience where head was mapped to a high-pitch event and tail was mapped to a low-pitch event. After listening to what a "fair coin" sounds like, the audience was able to identify that an unknown coin was biased, and the direction in which it was biased. Knowing that it is possible to improve with practice is sufficient motivation to begin the learning process. As with any form of practice, the accumulation of small gains over an extended period of time is key to mastery.

Sonification training should ideally be taught to everyone, not just BVI persons. Data sonification is also a form of communication and only works if there is a two-way understanding. If a BVI researcher is using sonification, it is essential that the counterpart, be it an adviser, a fellow researcher or audience in a conference, is also capable of understanding and interpreting sonifications so they can communicate results with each other effectively.

6.4 Integrate sonification into infrastructure of research and academic work

For sonification to be widely used in professional settings, it should be integrated into the infrastructure of academic work, such as journals, conference presentations, data archives and educational resources. Ensuring that sonifications as well as sonifications which accompany visualisations are a common occurrence will help shift the mentality regarding the use of audible data and habituate the ears of researchers to audible information.

For example, Nature Astronomy published its first article with embedded sonification in 2022 (Zanella et al., 2022). This article is the latest in a series of articles on the use of sonification. However, more progress and collaborations with various stakeholders, such as publishers, web developers and content creators are required. The development of guidelines, procedures, standards, and frameworks for sonification to be included in journals, including but not limited to specifications for presentation format, audio description, legends and explanatory notes, are necessary. To ensure a high degree of usability by persons with disabilities, these should be guided by international accessibility guidelines and standards such as the W3C accessibility standards for web content[13], and best practices such as accessible publishing guidelines for e-publications[14], and MathJax[15] for equations.

Sonification should be integrated into existing research tools, archives and major astronomical software, not just the outputs and communications. This way the community does not need to make a special effort to download bespoke software but can simply try sonification as a possible function or option within the usual tools or archives they are already accessing with ease and convenience[16].

Another suggestion is to ensure the availability of reliable equipment and IT support to enable the playing of audio by presenters at conferences.

6.5 Improve funding and institutional support for sonification research and accessibility

Funding is crucial to progress in any field. Sonification, as described in the Chapter 4, has faced particular difficulties in this regard, relating to a lack of available funding and scepticism from scientific institutions and funding bodies. The following five recommendations are aimed at improving funding access and institutional support for sonification research and accessibility.

First, funding bodies should be open to supporting sonification as an emerging technology, breaking the cycle whereby innovative scientific results are required to access future funding.

[13] The Web Accessibility Initiative (WAI) is an initiative of the World Wide Web Consortium (W3C).
[14] AccessiblePublishing.ca is a repository of resources for accessible publishing developed by the National Network for Equitable Library Service (NNELS), a digital public library of books for Canadians with print disabilities.
[15] MathJax is a JavaScript display engine for mathematics that works in all browsers. No setup for screen reader is required.
[16] The Astronify project which aims to integrate sonification options for data alongside visual previews in Mikulski Archive for Space Telescopes (MAST) archive is an example of how archives may be sonified to remove barriers to BVI researcher's participation in scientific research (Annex A2).

Moreover, encouraging research and development for accessibility is consistent with Article 2 of CRPD.

Second, flexible funding is required that accounts for sonification's position as a multidisciplinary tool, addressing the issue whereby sonification is viewed as an exclusively outreach-related activity and therefore relegated to funding streams that are insufficient and inappropriate for funding scientific research. Such funding should not only apply to the research project per se, but also to the organisation of workshops, conferences and other community-building activities that foster multidisciplinary interactions, including allowance to cover the accessibility needs of persons with disabilities (see Chapter 6.8).

Third, reasonable expectations regarding the progress of sonification as a field relative to data visualisation should be established. Data visualisation is a highly developed field with over two hundred years of history. Sonification is an active field with significant potential, but will not "catch up" overnight, especially without support from institutions and funding bodies.

Fourth, persons with disabilities and their needs should be considered as a central part of the scientific community and funding structures. For example, scientists seeking project funding should be empowered to build in allowance for potential postgraduate students or postdoctoral researchers who are disabled and therefore have specific funding needs.

Finally, acknowledging that there may not be an immediate pay-off in terms of publication or grant renewals in addition to potential risk to one's career, it may help to include members at both ends of the spectrum of experience in the research team, such as a leader whose career and reputation is well-established for whom risk-taking would be seen as bold leadership, rather than a risky career move, and early career researchers, students or post-docs who are open to sonification. This may help to create a conducive environment for the successful application of sonification.

6.6 Foster multidisciplinary scientific culture, network and collaboration

Collaborations and networks drive multidisciplinary research and facilitate exchange of knowledge between researchers which could accelerate progress in this field as well as ensure sustainability of ideas and prevent the problem of "reinventing the wheel" when earlier initiatives fade away. At its foundation, this must be supported by a culture of open-mindedness and respect for the knowledge, expertise, and speciality of each participant. Where differences in scientific approach may arise, computer modelling has been suggested as a common ground where nearly all specialities can meet. It provides a common language and platform where experts from many areas share an understanding and ways of working. Sonification, based on the mathematics of sound, would thrive in such an environment.

6.7 Industry taking the lead

The adoption of sonification by technology companies may also be an important driver and signal of the relevance of sonification. The popularity of voice-controlled assistants[17], now standard on personal devices, demonstrates the power of industry in mainstreaming

[17] Examples include Siri, a voice-controlled assistant on Apple devices, as well as Amazon's Alexa, Microsoft's Cortana and Google's Google Assistant.

technologies previously considered only relevant to persons with disabilities. Moreover, demand from industry for employees with these skillsets would encourage the allocation of resources by educational institutions to offer sonification-related courses as students need to be trained to graduate with the skills and knowledge needed to work with sonification in industry roles. Examining from a different angle, increased vision and related health problems due to prolonged usage of screen devices and aging population may present an additional reason to pursue auditory display techniques and sonification as a market opportunity which may have positive spill-over effects on other sound-related technologies. Making sonification usable, effective and useful for everyone, with the knock-on benefit of universal design helping persons with access needs, could be a pragmatic approach to mainstreaming sonification.

6.8 A holistic approach to accessibility

> ***The specific needs of scientists with disabilities is discipline dependent. It is not sufficient to provide accommodations but necessary to create the tools that encourage, support, and promote maximum performance for each individual. Inclusion and accommodation are critical to empowering individuals to live independently, be employed and contribute to society. In a scientific field, to not address access to bibliographic and data resources for individuals with disabilities may be a violation of human rights.***
>
> ***Garcia et al., 2019: 2***

Beyond applying universal design, taking full advantage of the potential of sonification for accessibility requires that it be integrated into a holistic approach to accessibility, considering the diverse needs of persons with disabilities. Aarnio et al. (2019) refer to this as focusing on the "Astronomical Environment" rather than specific individuals or conditions, tackling systematic barriers to access rather than accommodating individuals. Including sonification in a holistic approach to accessibility in space sciences is part of addressing such barriers.

It should be recognised that people have multiple intersecting social identities and may therefore experience intersecting barriers to their full participation in research and the scientific community. These experiences and diverse needs need to be considered when developing sonification tools and when using sonification as part of a project of increasing accessibility. It is beyond the scope of this report to account for all these needs or describe all available methods for meeting those needs. However, this section provides a non-exhaustive list of recommendations for maximising the contribution of sonification to accessibility in space sciences.

First, regarding sonification for accessible outreach, the first barrier is reaching a diverse audience. Informal science education in spaces like science museums and festivals has been suggested to primarily reach more enfranchised groups in society, although participation information is not always available (Dawson, 2014). In the United Kingdom for instance, the

Department for Digital, Culture, Media, and Sport (DCMS) *Taking Part* survey in 2015/16 found that 46.8% of respondents who had a long-standing illness or disability had visited a museum in the past 12 months compared to 55.1% without. In terms of lower socio-economic group vs upper socio-economic group, the split was 37.4% versus 61.5%[18]. Outreach projects with accessibility as a core goal should make specific efforts to reach disenfranchised groups and include an assessment of demographic reach.

Second, addressing the issue of isolation. Where there is, for example, only one BVI individual in an academic department, they may feel isolated and find it harder to advocate for their needs (Beck-Winchatz & Riccobono, 2008). Moreover, if their peers are not aware of or accepting of sonification as a legitimate scientific tool, this may reduce a BVI individual's ability to make effective use of sonification in their career. Solving this may take two approaches: creating accessible environments and research cultures to attract more researchers with disabilities, and enabling networking between institutions (see DAIS, Annex B).

Third, acknowledging and addressing the multiple barriers faced by persons with disabilities in pursuing careers in space sciences (Aarnio et al., 2019). Respect for inherent dignity and individual autonomy, including the freedom to make one's own choices, is a principle of Article 3 of CRPD. However, persons with disabilities may experience a lack of autonomy, as career choices may be shaped by barriers to participation rather than interest or skill. Persons with disabilities also face challenges such as physically inaccessible buildings, or the extra costs of assistive technology and other forms of support. This limits opportunities for professional development and can be hard to measure as statistics are drawn from those already in academic careers, as opposed to those excluded from them (Garcia et al., 2019).

Sonification can act to open areas of scientific research for BVI researchers. It is therefore necessary to provide specific pastoral, funding, and resource-based support to individuals with disabilities, and build institutional cultures and sonification frameworks that prioritise researcher autonomy and professional development.

Fourth, accessibility should be a requirement for all elements of academic and scientific culture. Sonification tools are insufficient if the original data, journal articles, and conferences, are inaccessible to BVI researchers. For example, the American Astronomical Society provides guidance and resources for making astronomical work accessible and produced a White Paper on Accessible Astronomy (Aarnio et al., 2019). Other work includes Casado et al.'s (2020) guidance on how to give accessible presentations; common practices such as using white backgrounds and image-heavy presentations can render conference presentations inaccessible.

Finally, other modalities such as spatiality, haptics or 3D-printed materials may be utilised to complement sonification in providing a multisensorial approach to understanding the universe.

[18] Analysed using Department for Culture, Media and Sport (DCMS), 2016, Taking Part Survey, London, online data analysis tools.

Chapter 7: Conclusion

Sonification is a tool for the analysis, interpretation, and communication of data with significant potential for improving the accessibility of space sciences for BVI people. Moreover, the advantages of sonification are applicable to all users, irrespective of sensory abilities, particularly in relation to enhancing analysis of the large, complex, multidimensional datasets characteristic of space sciences. Considerable work has been done to develop and use sonification tools, including by BVI researchers, since the 1980s. This work encompasses projects with artistic, outreach, and scientific goals, and is multidisciplinary and international. Researchers are connected by a series of conferences and communities dedicated to sharing knowledge, facilitating collaboration, and advocating for sonification.

Despite the advantages of sonification and progress in the field, it faces numerous serious challenges in mainstream integration, including latent scepticism. To address these challenges, this report provides recommendations for decision-makers with the aim of maximising the benefits of sonification for scientific research and inclusion; support the development of sonification as a tool for scientific research, apply universal design, integrate sonification into education system and standard scientific training, integrate sonification into infrastructure of research and academia work, improve funding and institutional support for sonification research and accessibility, foster a multidisciplinary scientific culture, network and collaboration, industry taking the lead and encouraging a holistic approach to accessibility.

Sonification presents an opportunity to make real progress in ensuring all individuals can enjoy equal access to knowledge and equitable participation in space science. Mainstreaming sonification is a step towards building an inclusive future and contributing to achieving the Sustainable Development Goals.

Annex A. Feature articles

A1. A Universe of Sound: Translating NASA's Chandra X-ray data into sound

Figure 3: Galactic Centre image used to create the sonification described in this feature article. The image is overlaid with an artistic rendering of sound waves. The key feature of this image is the supermassive black hole in the lower right, which appears as a bright area in the image, and as a crescendo of sound in the sonified version. The image is a composite, combining X-ray data, infrared data, and optical data from three telescopes. Credit: X-ray: NASA/CXC/SAO; Optical: NASA/STScI; IR: Spitzer NASA/JPL-Caltech.

Much of the universe is too distant to visit in person. Exploration of space by telescopes enables us to "travel" to faraway objects to better understand the astronomical objects and phenomena. Light, from radio waves to X-rays and gamma rays, is often the data source and "messenger'". Modern telescopes collect their data in digital form using unique codes of ones and zeroes. These inherently digital data are then often turned into images for professional use or consumption by the public. This almost always requires an essential step of "translation'" because most of the light detected by telescopes is invisible to the unaided human eye.

The sonification project led by NASA's Chandra X-ray Center explores the potential to experience these data through hearing instead, by translating astronomical data into sound. One of the first pieces created for this project featured data from the centre of the Milky Way galaxy, where a supermassive black hole is located (Figure 3). The positions and brightness of the sources, which included stars, nebula and so on, are translated into sound as the cursor moves across the image from left to right. Light from objects towards the top of the image are heard as higher pitches than those lower down, while the intensity of the light controls the volume. Stars and other compact sources are converted to individual notes while extended objects like clouds of gas and dust produce an evolving drone. As the listener reaches the supermassive black hole, Sagittarius A*, in the lower right region of the image, the increasing brightness results in a crescendo.

Users can listen to data from this region of the Galactic Center, roughly 400 light years across, as "solos" from Chandra as well as two other space-based NASA observatories - the Hubble and Spitzer Space Telescopes - or together as an ensemble in which each telescope plays a different instrument that harmonizes together. Each telescope reveals different phenomena. Hubble sees energetic regions where stars are being born, and reveals hundreds of thousands of stars, the Spitzer data show cooler clouds of dust containing complex structures, and X-rays from Chandra reveal gas heated to millions of degrees from stellar explosions and outflows from the supermassive black hole Sagittarius A*. Listen to the Galactic Center sonification, as well as others, on the Chandra X-ray website.

This sonification was led by the Chandra X-ray Center (CXC) and further supported as part of the NASA's Universe of Learning (UoL) programme. The collaboration was driven by visualisation scientist Dr. Kimberly Arcand (CXC), astrophysicist Dr. Matt Russo and musician Andrew Santaguida (of the SYSTEM Sounds project.)

Contributing author: Kimberly Arcand, Chandra X-ray Center

A2. Astronify: Sonifying MAST for astrophysical research

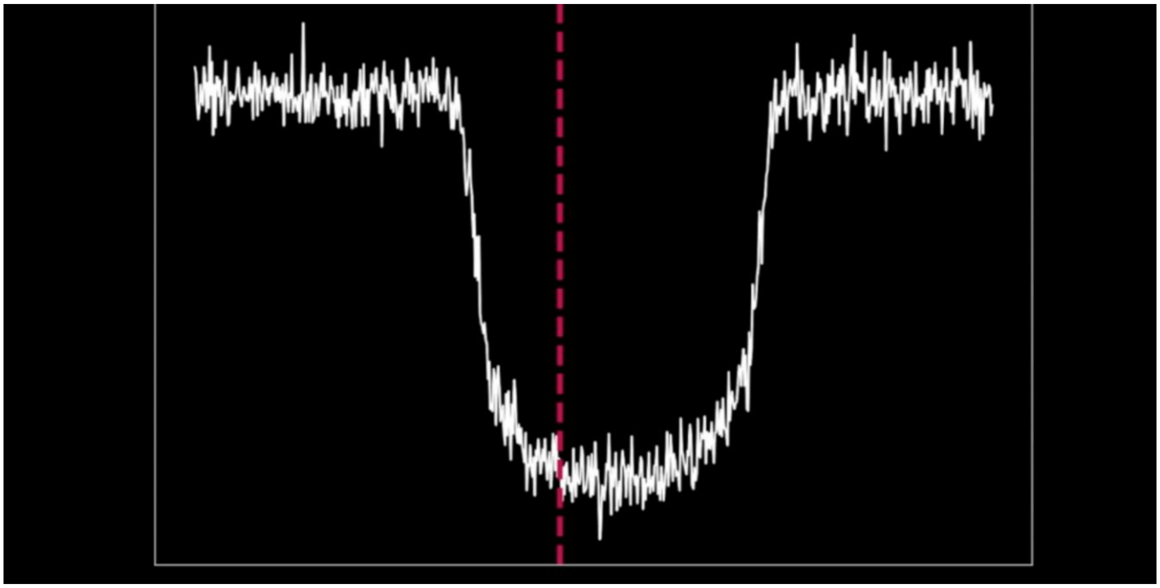

Figure 4: In this figure, the data of a transiting exoplanet is plotted, measuring the brightness of the star over time with the Kepler space telescope. The individual measurements are not shown as data points but are instead connected by lines between them. The figure is taken from a video created that combined the output of Astronify with a visual plot of the data being sonified. Credit: Astronify.

Astronify is an open-source Python package to produce data from the Mikulski Archive for Space Telescopes (MAST) in a sonified format. The sonifications it produces are intended to be used for research purposes, and thus the primary goal is to ensure the sonifications accurately represent the underlying data.

Astronify represents each data point by a note that has a specified pitch frequency, duration, and interval between the notes. These can all be configured with the software depending on each user's preferences or analysis needs.

A key feature of Astronify is active effort made to connect with relevant audiences. One of Astronify's core principles was to network and engage BVI astronomy professionals and enthusiasts to design and test the software. Astronify's development therefore included consultation with more than a dozen BVI individuals and interaction with a global network of people interested in developing sonification for education, outreach, and research in science fields. One-on-one user testing sessions were critical to the success of the project and helped avoid mistakes. Engagement with BVI professionals frequently corrected assumptions about the viability of tools or techniques relied upon by the (non-BVI) team. For example, Jupyter notebooks, a tool MAST uses extensively for analysis tutorials with Python code, were originally planned for making notebook tutorials for Astronify. Upon learning that Jupyter notebooks do not work with screen readers, the team were able to change plans regarding documentation early in the project.

Besides one-on-one interactive sessions to gather user feedback, a game-show-style test was created where users could play various sonifications and answer a survey, so feedback could be received from many people asynchronously. The sounds were played through YouTube videos and embedded in a SurveyMonkey form, both of which are accessible to screen readers. This approach enabled large-scale testing with the general public without the expense of one-on-one interactive sessions, both of which were considered important sources of feedback. The game element also contributed to positive engagement with students, the general public, or professionals, by introducing an audience-participation component to presentations.

Astronify was funded as part of a semi-annual call for research projects at the Space Telescope Science Institute (STScI), where MAST resides. STScI staff are able to propose for funding to conduct modest-scale projects, often those that are prototypes, seed-projects, or otherwise “difficult-to-impossible” to obtain funding for via other means. This support was instrumental in enabling the development of Astronify by facilitating buy-back of staff time to dedicate to the project.

Future development of Astronify includes the integration of sonification options for data alongside visual previews in MAST. This is an important step to opening astronomy to more BVI professionals as equal access to both sonified and visual archive data will remove one long-standing hurdle to BVI astronomers’ participation in scientific research.

Contributing author: Scott Fleming, Space Telescope Science Institute

A3. StarSound and VoxMagellan: Designed for BVI-accessible astrophysical research

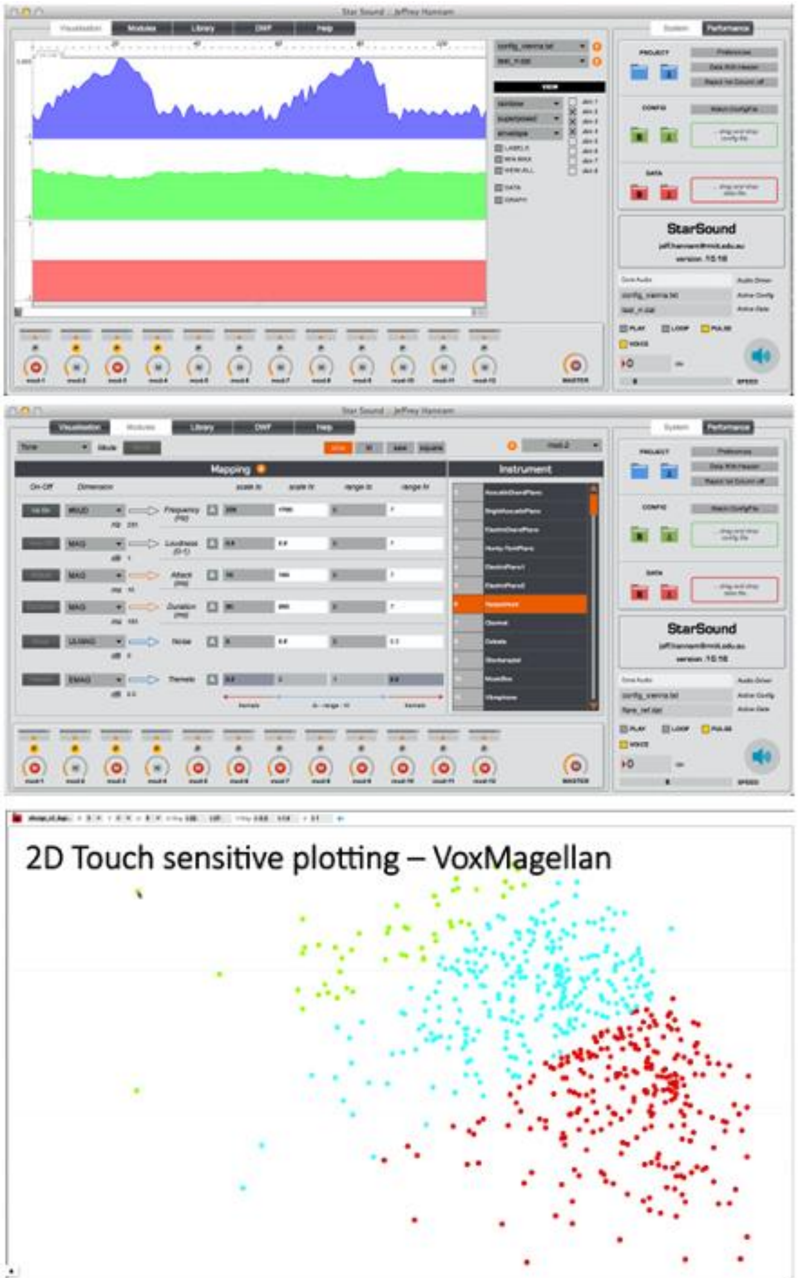

Figure 5:

(Upper) The StarSound visualisation page showing the first of the five tool tabs. This tab includes a data visualisation window, here showing three discrete data channels being sonified (blue, green and red traces), controls for modifying visual features of the plot and project administration (to the right), and 12 channels (with panning stereo) and controls for starting, stopping and moving back and forth through the data (along the bottom).

(Centre) The second tab replaces the data visualisation window with controls to modify the properties of the sound.

(Bottom) VoxMagellan rendering of a 2-D multidimensional data set showing a plot of galaxy colours (y-axis) vs. brightness (x-axis) based on certain selection criteria (green, cyan, and red). Here, the colours are assigned to distinct sounds to easily identify each population, which has different properties. For each data point a second sound is overlaid to provide additional information (here, the strength of a certain spectroscopic feature).

Numerous aesthetically appealing sonifications based on scientific data have proven successful in capturing attention and stimulating curiosity in outreach and pedagogical applications. However, despite some ground-breaking successes (Díaz-Merced et al., 2008; Tutchton et al., 2012), and isolated innovative applications (Hansen et al., 2020), sonification is yet to be widely adopted as a tool in research. Efforts toward this goal have been frustrated, at least in part, by the inability of existing sonification tools to meet the demanding requirements of quantitative data analysis. Designed from the start with accessibility for BVI astrophysical researchers in mind, it is exactly this challenge that StarSound and VoxMagellan aim to address.

The StarSound sonification tool is designed to assist sighted and BVI researchers in quickly identifying and interpreting trends and features in complex one-dimensional datasets, such as time series or spectroscopic data. Similarly, VoxMagellan provides users with an accessible touch-based system for exploring 2-D images and multidimensional data using sound. Importantly for research applications, both packages include the ability to mark and navigate between data points of interest and allow for the audible reporting of data values on a point-by-point basis. These features assist the BVI researcher in creating a mental image of the data space and enable quantitative interrogation that is both rapid and intuitive.

A key feature of StarSound and VoxMagellan is that the sonic rendering of the image is not limited to the visually displayed information but can incorporate as many as ten or more channels of data per pixel, thus providing a genuine means to encode and transmit multiparametric information beyond the capabilities of a visual-only approach (Foran et al., 2022).

In high-redshift galaxy research, StarSound has been used for the verification and initial analysis of the rest-frame ultraviolet spectra of distant (redshift $z \sim 2-3$) star-forming galaxies (upper panel of Figure 1), and VoxMagellan for 2-D plot multiparametric investigation of relationships between the physical, kinematic, and environmental properties of these same galaxies and the Lyman-α transition of hydrogen (lower panel of Figure 1).

Future directions for StarSound and VoxMagellan include the implementation of virtual and augmented reality technologies with ambisonics (3-D sonification) and haptic feedback to expand the sensory experience into more dimensions and modalities.

Contributing authors: Garry Foran[1], Jeff Hannam[2], and Jeff Cooke[1]
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[2] Spatial Information Architecture Laboratory, RMIT University, Australia

Annex B. Events/Community space

Sonification is a multidisciplinary field. Spaces for collaboration are therefore important to the development of the field. Community networks are also important for BVI researchers, helping address the isolation issue discussed in Chapter 6. This annex lists some of the relevant networks and events.

International Community for Auditory Display

The annual meeting of the International Community for Auditory Display (ICAD) is an important interdisciplinary community for people working with sonification, and a source of advocacy for scientific legitimacy of sonification. The importance of ICAD is such that it has been referred to as the birthplace of the sonification community, and its founder Gregory Kramer as the 'grandfather' of the field (Supper 2012). ICAD's proceedings are open source and provide a necessary space for publishing research on sonification while acceptance by mainstream academic publishers remains low.

The Audible Universe

'The Audible Universe' is a workshop held online in 2021 and subsequently in a hybrid format at the Lorentz Center Oort in Leiden, The Netherlands, in 2022. The workshop brings together experts from different backgrounds, including astronomy, sound computing, sound design, sound perception and educators, with the goal of discussing and consolidating current attempts at sonification of astronomical data and set a common ground among different disciplines. More information is available at the 2021 workshop and 2022 workshop webpages.

Astronomy Beyond the Common Senses

'Astronomy Beyond the Common Senses for Accessibility and Inclusion' aims to bring together people working on multisensory research and other work in astronomy, bridging gaps between people who may be working in isolation with limited resources. The first workshop was held in Colombia in 2016, and the second was held virtually in 2021. By drawing together an international community of people this workshop aims to develop strategies for future work, enable effective sharing of existing resources and learning, and motivate institutions to support work beyond the visual. Talks and posters from the 2021 workshop can be viewed on the workshop website.

Sonification World Chat

Sonification World Chat is a community of over 100 people. Much like the afore-mentioned events, the goal of the Sonification World Chat is to prevent people working in isolation and help move the field forward by bringing diverse groups of people together. This include monthly meeting to discuss and share information on applying sonification to scientific data to provide accessibility for people who are blind or visually impaired. A key challenge for spaces like this is turning them into self-sustaining communities.

Disabled Academics in Space (DAIS)

DAIS is a peer-networking and support group for professionals in space related fields who identify as disabled or chronically ill. The membership is primarily academics, with others such as educators and science writers. It is a particularly important space for early career researchers seeking advice on navigating academic careers. DAIS seeks to provide connection and support for individuals who may be the only persons with disabilities in their institutions.

Annex C. List of projects

Annex C lists 25 sonification projects researched for this report grouped into three categories as defined by their primary goal.

C1. Primary goal: Scientific research

Afterglow Access	
Aims	Enabling BVI people to explore images captured by space telescopes.
Description	Afterglow Access is a complete browser-based astronomy image and data analysis sonification software tool developed as part of IDATA's project to improve the accessibility of astronomical science. The software is screen-reader accessible and designed to be easily translated into multiple languages, in line with IDATA's focus on space research and development. Development followed user-centred design, with direct involvement from BVI and sighted students and their teachers.
Output example	Afterglow Access Demo
Resources	Afterglow Access webpage Blind Abilities podcast episode on Afterglow Access Afterglow Access talk on Sonification World YouTube Channel Detailed breakdown of the user-centred design process
Project coordinators	IDATA (Innovators Developing Accessible Tools in Astronomy) project. Tim Spuck, Associated Universities, Inc.

Astronify	
Aims	Improving access to astronomical data in the MAST archive
Description	Astronify is a Python software package designed for sonification of astronomical data. It is primarily intended for use by scientists. Currently the package can sonify data series and will ultimately grow to encompass a range of sonification functionality. A game designed to teach people to interpret sonifications was also produced. Development involved testing with BVI people and dedicated testing by UX/UI designer and inclusive education and outreach specialist. Astronify is the subject of the first large-scale efficacy testing of a sonification method by Tucker Brown et al. (2022). Astronify was used to sonify mock light curves, which were then tested with 192 expert and non-expert participants, alongside visualisations and a combination of sonifications and visualisations. Broadly, the findings of this evaluation were that training and experience is needed for sonification to be effectively used by professionals. It is difficult to assess efficacy of sonifications versus plots for those with professional training because of the significant inequality in training provision for sonification compared to traditional data representation and analysis methods. However, people with no professional level training performed equally with both sonified and visual data.
Output example	Downloadable sonifications and explanations available via STScI
Resources	Astronify website Astronify on GitHub

	STScI Public Lecture Series lecture by the authors of Astronify with demonstrations MAST Archive
Project coordinators	Space Telescope Science Institute. Scott Fleming, Jennifer Kotler, Kate Meredith, Clara Brasseur

Sonification Sandbox & Sonification Studio	
Aims	An interdisciplinary research group, focused on development and evaluation of auditory and multimodal interfaces with a focus on sonification.
Description	The Georgia Institute of Technology Sonification Lab has three strands of research; 1) Sonification and auditory displays, including studying perception of audio displays and interpretation of sonifications; 2) Human-Computer Interaction (HCI) in non-traditional interfaces, including sound, tactile, voice and vibration modalities; 3) Psychological and social factors in the adoption and use of technology. The Sonification Lab produced Sonification Sandbox and its successor Sonification Studio, a collaboration with Highcharts, which is currently in development. Other research projects include the development of auditory graphs, and sonifying the 2017 solar eclipse. On the artistic side, the Sonification Lab also created a sonification of data from NASA's Kepler space telescope for a musical composition at the behest of the artist (Winton et al., 2012).
Output example	2017 solar eclipse
Resources	Sonification Lab website Sonification Studio website Auditory graphs project page
Project coordinators	Georgia Institute of Technology Sonification Lab. Bruce Walker

Heliophysics Audified: Resonances in Plasmas (HARP)	
Aims	Using sonification and citizen science to engage a wider audience in space science research
Description	HARP is a NASA-funded pilot study to engage citizen scientists in space science research. HARP will develop a web-based interface to facilitate analysis of spacecraft data converted into sound (audification). It expands upon a previous project by Martin Archer called "Magnetospheric Undulations Sonified Incorporating Citizen Scientists" (MUSICS) in which high school students used sonified data from NOAA satellites and discovered a new type of plasma wave (Archer et al., 2018). MUSICS and HARP draw on the potential of both sonification and citizen science for tackling large amounts of data in a reduced time frame compared to visual analysis. The audification method was evaluated via public survey. The Graphical User Interface is currently undergoing beta testing by university students in the US. Data events submitted by citizen scientists are compared with each other and evaluated by HARP scientists.
Output example	HARP citizen science tool YouTube video
Resources	HARP website

	[NASA THEMIS satellites (data source)]
Project coordinators	Space Science Institute. Michael Hartinger, James Harold, Anne Holland, Robert Alexander, Martin Archer, Robert Candey, Shane Coyle, Emmanuel Masongsong, Xueling Shi, Evaldas Vidugiris

REsearch Infrastructures FOR Citizens in Europe (REINFORCE)	
Aims	Extending the senses used in scientific work beyond the visual, including the participation of BVI people
Description	REINFORCE is a EU funded citizen science project aimed at reducing the gap between science and society, with a specific focus on inclusive research. REINFORCE contains four distinct research projects from different physical fields. Among these, GWitchHunters is concerned with gravitational wave data. REINFORCE will compare the discrimination value between background noise and signal for sonifications, visualisations and both combined.
Resources	[REINFORCE project website] [REINFORCE webinar YouTube video] [GWitchHunters webpage]
Project coordinators	Coordinated by the European Gravitational Observatory (EGO), with 10 additional partner organisations, supported by the European Union's Horizon 2020 SWAFS 'Science with and for Society' programme

xSonify	
Aims	Improving accessibility of space science research for BVI students and researchers.
Description	xSonify is an open-source Java application developed to extend access of the NASA Space Physics Data Facility to BVI students and researchers (Candey et al., 2006). xSonify was developed to analyse time-varying one-dimensional data. The aim was to create a flexible, versatile, open-source software that could be used for scientific research. The tool was evaluated by a committee of users and experts in assistive interfaces, including BVI and sighted users. xSonify is notable for the involvement and use of the software by Wanda Díaz-Merced, a blind astronomer and pioneer in the field of sonification for space science research. User-centred design, particularly when considered the needs of BVI users, was a key part of this project and SonoUno, which was developed from xSonify.
Output example	Notably used by Wanda Díaz-Merced in her doctoral thesis, in which sonification was used to produce new results (Díaz-Merced, 2013).
Resources	[xSonify on SourceForge]
Project coordinators	Robert Candey, Anton Schertenleib, Wanda Díaz-Merced

sonoUno	
Aims	Bringing multimodal access to astrophysical data to all people and aspects of expertise, irrespective of their performance styles or functional diversity through creating a user-centred sonification package for astrophysical research.
Description	sonoUno is a sonification tool that allows people with different sensory styles to explore scientific data. It was developed from lessons learned from earlier sonification tools such as xSonify, Sonification Sandbox, and StarSound. The development of sonoUno was user-centred for groups containing sighted, BVI, professional, and non-expert people. User testing was also carried out by specialists in astronomical science. sonoUno can input images, .txt, and .csv data files. The user interface design is modular, enabling users to modify the graphical and sound interface. Parameters mapped to pitch, and volume and timbre can be changed.
Output example	Sonifications of various datasets using sonoUno
Resources	sonoUno website sonoUno user manual sonoUno on GitHub
Project coordinators	Johanna Casado, Gonzalo De La Vega, Wanda Díaz-Merced, Poshak Gandhi, Beatriz García

Skeuomorphic Sonification Design of Astronomical Data	
Aims	Employ user-centred methods and skeuomormorphism to design sonifications for a variety of astronomical data.
Description	Multiple sonification models and one planetarium show were created by employing user-centred methods in which end users were involved throughout the design process. The sonification designs were based upon the use of keywords or concepts mentioned by astronomers to describe their data. This technique helps the users to be able to associate the sonification to the data more quickly since familiar sounds are easier to comprehend. For example, the sound of flowing water was used to represent water vapour in the atmosphere of an Exoplanet situated in the Habitable Zone of an Exosolar system; the sound of sand being blown by the wind was used to represent dust clouds in accretion discs; and the sound of cracking ice mapped to data was used to represent colliding asteroids. Psychoacoustics were used to create these skeuomorphic representations and spatial mapping was used to mimic the movements of celestial entities to give a more accurate representation of the data. Spatial mapping was highly effective at representing the temporal qualities of these astronomical phenomena. End user design helps to create effective and comprehensible sonifications for the user. Projects included a sonified model of the solar system for the Esplora Planetarium in Malta (Quinton et al., 2016), a sonification of an exoplanetary atmosphere (Quinton et al., 2020), the sonification of planetary orbits in asteroid belts (Quinton et al., 2021a), and the sonification of exosolar system accretion discs (Quinton et al., 2021b).
Output example	Sonification of asteroid collisions on Soundcloud
Resources	Michael Quinton on Soundcloud

Project coordinators	Michael Quinton, Iain McGregor, David Benyon

StarSound & Vox Magellan	
Aims	To create a sonification tool that meets the demanding requirements of quantitative data analysis and improves accessibility for BVI astrophysical researchers.
Description	StarSound and its successor Vox Magellan are sonification tools for astronomical research. StarSound sonified 1D data, and its successor Vox Magellan works with 2D data and images. Vox Magellan is also able to work directly from a data stream without rendering a visual plot, and is touch-sensitive, scaling plots to computer trackpads/touchpads and enabling navigation by touch. StarSound has been used primarily in analysis of Light Curves. Development of these tools has focused on meaningful interaction with data, enabling researchers to identify areas of interest and interrogate the relevant data points. Cooke et al. (2019) plan to use these platforms in the Deeper Wider Faster citizen science programme, which monitors transients. Human confirmation of potential transient candidates is required to be very fast, and they last a very short amount of time, so the hope is that audible monitoring will support this research more effectively than visual monitoring.
Output example	Example implemented in an article in fortytwomagazine
Resources	StarSound website Talk on StarSound and Vox Magellan by Jeff Cooke (2021) via Sonification World YouTube channel
Project coordinators	Jeff Hannam, Garry Foran, Jeff Cooke

C2. Primary goal: Outreach and education

Audio Universe	
Aims	Improving accessibility of astronomical science using sonification, in both research and outreach.
Description	Audio Universe is a collection of tools and resources for scientists, the public, and educators interested in working with sonification. There are three strands to the Audio Universe project; developing multisensory tools and methods for scientific research; creating accessible, multisensory outreach and education resources; and increasing accessibility of astronomical science. The tool used for the sonifications is the Python package STRAUSS (Sonification Tools and Resources for Astronomers Using Sound Synthesis). The *Tour of the Solar System* planetarium show was developed with input from scientists, a composer, and members of the BVI community. The show was piloted with BVI audiences and adapted based on this feedback. Feedback from the BVI community, BVI astronomers, and Qualified Teachers of Visually Impaired children (QTVI) was sought at various stages of development (Harrison et al., 2022). The planetarium show premiered in 2021.

Output example	Audio Universe: Tour of the Solar System - Full Show on YouTube
Resources	Audio Universe website STRAUSS on GitHub Tour of the Solar System webpage
Project coordinators	Chris Harrison, James Trayford, Nicolas Bonne, Anita Zanella, Enrique Pérez Montero, Sean Dougherty, Patrick O'Neill

A Universe of Sound	
Aims	Encouraging non-expert/public users to explore telescope data.
Description	The *A Universe of Sound* project provides sonifications of images from NASA's Chandra X-ray observatory and other telescopes. Most sonifications allow the listener to select between optical, x-ray, infrared, and composite image sonifications. The sonification is accompanied by an image, with visual aids to demonstrate which part of the image corresponds to sound.
Output example	A Universe of Sound website
Resources	Chandra X-ray Observatory website
Project coordinators	NASA Chandra X-Ray Observatory. Kimberly Arcand

CosMonic	
Aims	This sonification project aims to facilitate analysis by means of sounds of all types of data, be a source of inspiration for artistic creations and a source for pedagogical and dissemination purposes.
Description	CosMonic (COSmos harMONIC) is a tool for sonification of data and combines audio with animations in a complementary manner to reach a larger audience. The tool is not limited to sonifying astronomical data and users can input their own data. CosMonic has produced simple custom use-cases for AstroAccessible, the inclusive astronomy project led by Enrique Pérez-Montero, described as "painting graphs with sound" (García-Benito & Pérez-Montero, 2022). The YouTube playlist of sonification examples includes an auditory description of the sonification for each video.
Output example	M33 Rotation curve sonification YouTube Video
Resources	CosMonic webpage English CosMonic YouTube channel Spanish CosMonic YouTube channel
Project coordinators	Rubén García-Benito

Hands on Universe and Dark Matter Multisensory Experience	
Aims	Lowering barriers to public access to astronomy, cosmology and astrophysics.
Description	The *Hands on Universe* was a multisensory public engagement project, engaging all senses to experience and conceptualise the universe. For the Cheltenham Science Festival exhibit, the project lead also worked with the Royal National Institute of the Blind. The *Dark Matter MultiSensory Experience* was an immersive experience at the Science Museum 'Lates' (2018) and Great Exhibition Road Festival (2019). Visitors entered an inflatable planetarium and

	explored dark matter via timed visual, auditory, tactile, olfactory, and gustatory stimuli (Trotta 2018).
Output example	Dark Matter: A Multisensorial Experience YouTube Video
Resources	Roberto Trotta webpage: Multisensory Cosmology
Project coordinators	Roberto Trotta, Marianna Obrist and team from SCHI Lab at the University of Sussex/UCL.

LightSound	
Aims	Enabling BVI people to observe solar eclipses
Description	LightSound is a device for the real-time sonification of a solar eclipse and maps the light intensity to sound volume. It was developed for the Great American Solar Eclipse in 2017. Initially, 3 devices were made. The original design was developed further for the 2019 South American solar eclipse and was awarded an International Astronomical Union Special Project Grant and an ESO grant, enabling distribution of more devices across Argentina and Chile. Another five devices were constructed at Apadilangit: Universe Awareness Malaysia. These devices are designed to be simple and cost-effective to assemble: One such LightSound device costs roughly US$70 in components and requires only a soldering iron to assemble (Bieryla et al 2020).
Output example	LightSound 2020 Experience YouTube video
Resources	Apadilangit: Universe Awareness Malaysia subpage on the LightSound Device
Project coordinators	Allyson Bieryla

Solar System Sonification	
Aims	Creating an accessible, multimodal planetarium display.
Description	Tomlinson et al. (2017) designed an auditory model of the solar system for a planetarium show, mapping planetary characteristics to sound parameters such as pitch, amplitude, and spatial position. Desired learning outcomes were identified through semi-structured interviews with five teachers or educators. Understanding scale was a common issue, so the team focused on relating details such as mass, temperature, and distance between objects. The final models provided two views of the solar system. In the first, the user was positioned on the sun, and the sonification focused on planetary mass, length of years, days, and distance from the sun. In the second, the user was positioned on a planet, and could learn details such as number of moons or rings, and planetary temperature and gravitational force. Use of the planetarium's speaker system allowed spatial presentation of sound. A PowerPoint was included to provide visual anchors for attendees, and narration provided context.
Resources	Solar system sonification: Exploring Earth and its Neighbours through Sound
Project coordinators	Brianna Tomlinson, R. Michael Winters, Christopher Latina, Smruthi Bhat, Milap Rane, Bruce Walker

SoniCosmos	
Aims	Sonification of the zCOSMOS dataset for data exploration, inclusion and artistic creativity.
Description	SoniCosmos refers to the sonification of the zCOSMOS dataset, which contains data on almost 20,000 galaxies. The result is a journey through time and space that demonstrates the change in star formation through time. "Ecological metaphors" are used to connect the sonification with users' real-world experience (Bardelli et al., 2021). A multidisciplinary team was involved in the development, namely physicists and astronomers, computer scientists, artists and sound-and-music computing experts, and sound design experts. SoniCosmos is a way of tackling the challenges of working big data and presenting the many different parameters of interest in the study of how galaxies develop. In this project, artistic, scientific and outreach goals are of equal importance.
Output example	Examples from sonification of zCOSMOS Galaxy dataset SoniCosmos excerpt YouTube video
Resources	Presentation of SoniCosmos YouTube video
Project coordinators	Sandro Bardelli, Maurizio Rinaldi, Giorgio Presti, Claudia Ferretti.

SYSTEM Sounds	
Aims	Inspiring and educating the public on scientific concepts and ideas in an accessible way using sound.
Description	SYSTEM Sounds is a science-art project that creates sound-based representations of astronomical phenomena. These include sonifications of Chandra-X-ray data, sonifications of James Webb Space Telescope imagery and data, and virtual instruments using sonifications of astronomical objects such as Trappist-1 planets. Sonifications can be listened to online, and in-person shows and exhibits. The System Sounds webpage showcases tutorials on sonification and the coding activity *NASA's Space Jam* which allows "making music with planets".
Output example	Trappist-1 planets
Resources	SYSTEM Sounds website TEDTalk: a Musical Tour of the Universe Sonification Tutorials NASA's Space Jam Coding Activity The Sonic Orbiter, an arcade-style exhibit at the Ontario Science Centre, for exploring the surface of the moon via sound
Project coordinators	Matt Russo, Andrew Santaguida, Dan Tamayo

Walk on the Sun	
Aims	Improving accessibility and learning outcomes by engaging the whole body in the learning experience
Description	*Walk on the Sun* was an immersive, interactive science museum exhibit, combining sonification and visuals. Participants moved across images projected on the floor, triggering sonifications of the pixels they were walking over. The images were taking from the NASA Solar Terrestrial Relations Observatory (STEREO) spacecraft images. Colour

	was mapped to instrument type, brightness to pitch, and physical location to panning position of the sound. A prototype was first demonstrated to two bling students at Keene State College in 2008. The exhibit was funded by a Space Telescope Space Science Institute NASA Ideas Grant and was toured around the US. Over 50,000 people experienced the exhibit, of which roughly 1,000 were blind or visually impaired. The exhibit was installed in 2009 in the McAuliffe-Shepherd Discovery Center in New Hampshire.
Resources	Walk on the sun: an interactive image sonification exhibit
Project coordinators	Design Rhythmics Sonification Research Lab

C3. Primary goal: Artistic

Einstein's Sonata	
Aims	Expressing part of the output of the planned LISA mission in a creative and accessible way.
Description	Einstein's Sonata is a sonification of simulated gravitational wave data for ESA's future Laser Interferometer Space Antenna (LISA) mission. This project aimed to "contribute to the cultural heritage" of both art and science communities, and inspire and educate public audiences about scientific concepts in an engaging and accessible way. *Einstein's Sonata* combines sound and visual elements. The gravitational wave data was first mapped onto an abstract space model before generating music notation from it. It was performed at the Festival della Scienza, Genoa, in October 2021.
Output example	Trailer to Einstein's Sonata
Resources	Einstein's Sonata reimagines gravitational waves to inspire new audiences
Project coordinators	Andrea Valle, Valeriya Korol, Samantha Stella

Kepler Concordia	
Aims	Celebrating 400th anniversary of Kepler's *Harmonices Mundi* by enabling musical exploration of astronomical data and ideas.
Description	Kepler Concordia is a virtual instrument designed to work through extended-reality platforms, enabling multisensory play and exploration of astrophysical data. It is being created by a team of programmers, artists, musicians, and engineers. An early prototype was developed at a 2019 hackathon (Snook et al., 2020), using generated link lines between Jupiter and Uranus, and Venus and Earth (Snook et al., 2018).
Resources	Kepler Concordia website
Project coordinators	Kelly Snook, Tarik Barri, Joachim Goßmann, Jason Potts, Margaret Schedel, Hartmut Warm

Planethesizer	
Aims	Creative exploration of data and dissemination among non-expert publics.
Description	Planethesizer is a "model-based virtual instrument" (García-Riber, 2018: 219) with which users could compose their own music from sonified data. The data used was light flux data from seven exoplanets orbiting the star Trappist-1. It was sonified via musical software synthesis. Planethesizer was evaluated with Sound Technology students, and compositions and performance evaluation were presented for the sonification concert at ICAD 2018.
Resources	Planethesizer prototype on the Internet Archive.
Project coordinators	Adrián García Riber

Radio Jove	
Aims	Exploring how sound can be used to understand astronomical ideas and applying artistic perspectives to scientific data.
Description	Radio Jove is broadcasting live sounds from radio telescopes on internet and radio. It is part of the NASA INSPIRE project and focuses on observations of natural radio emissions from Jupiter, the Sun, the Earth, and the radio background noise from the Milky Way galaxy. Radio kits can be ordered as a radio telescope package and the receptors can be tuned to different parts of the radio spectrum in which astronomical objects can be heard. Radio Jove uses the 'Radio-Sky Spectrograph (RSS)' free Windows program for recording and reviewing radio frequency spectagrams. Radio Jove offers training for using the radio kits and hosts an archive of previously recorded data.
Output example	Radio Jove Live Stream on YouTube
Resources	Radio Jove website Radio Jove Data Archive Radio-Sky Spectrograph homepage NASA INSPIRE project
Project coordinators	Honor Harger, Adam Hyde (r a d i o q u a l i a)

Rhythms of the Universe	
Aims	Artistic exploration of the cosmos.
Description	*Rhythm of the Universe* was designed as a multisensory exploration of the universe. This project was primarily artistic, creating sonifications that were compelling with a secondary concern for their informative value. Rhythms of the Universe explored different astronomical phenomena such as pulsars, planets, gravitational waves, and solar winds. Different sonification methods were applied to each astronomical phenomenon. The result was a short film; however, it is not available online anymore.
Resources	Rhythms of the Universe IMDB entry
Project coordinators	Mark Ballora

Sound of Earth's Magnetic Field	
Aims	Creating awareness about Earth's magnetic field and its fluctuations over time.
Description	The project is an audio representation of Earth's magnetic field over the past 100,000 years. It was prepared for a public square in Denmark, on which 32 speakers are dug into the ground and hooked up to a 32-channel sound system so that each speaker can be controlled individually. The audio installation played for a week in October 2022 at Solbjerg Square, Copenhagen. Time series of data representing the field fluctuations at 32 different locations on the planet were prepared at the Technical University of Denmark's division for geomagnetism. Data from ESA's Swarm satellites, as well as other sources, were used to manipulate and control a sonic representation of the core field. The soundtrack is an artist rendition of the magnetic field and is meant to give the listener an impression of a living planet in constant flux. Audio recordings of natural sounds were combined with the soundtrack, and the data was mapped to various parameters of the playback.
Resources	The scary sound of Earth's magnetic field
Project coordinators	Technical University of Denmark; Klaus Nielsen, Nikolai Linden-Vörnle, Clemens Kloss

Star Song	
Aims	Exploring musical composition to endow sonified scientific data with meaning.
Description	The project examines the socio-psychological bases of the transformation of sound into music. Nine musical pieces in a variety of musical styles were composed from the sonified x-ray data from the EX Hydrae binary system recorded by the Chandra X-ray Observatory The compositions were played and recorded in a trio (Volkmar Studtrucker, piano; Gerhard Sonnert, bass; and Hans-Peter Albrecht, drums).
Output example	Star Song website subpage with musical compositions
Resources	Star Song website
Project coordinators	Gerhard Sonnert, Wanda Díaz-Merced, Volkmar Studtrucker

Annex D. Resources

D1. Publications

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"In all our actions, our goal is clear: a world in which all persons can enjoy equal opportunities, participate in decision-making and truly benefit from economic, social, political and cultural life. That is a goal worth fighting for."

António Guterres
United Nations Secretary-General
2020

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