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Testing sonification with granular synthesis and visual reconstruction with spectrograms of the MARSIS instrument

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Abstract

In the context of an artistic project for the Guggenheim Museum in a collaboration with the European Space Agency and the International Space Station, experiments were conducted to translate ionospheric data of Mars taken by the Mars Advanced Radar for Subsurface and Ionosphere Sounding instrument of the Mars Express probe. Given the complexity of raw numerical data, we opted to work with processed spectrograms as source material. Experimentation was done with direct translation from images to sound, and testing the spectrum of the resulting sounds to verify whether it was possible to accurately reconstruct the initial visual data. For the mapping, each pixel was translated into a small sound grain that forms a continuous sound using granular synthesis. Various strategies were employed to reduce timbral and rhythmic artifacts. The final result was a series of sounds whose spectral analysis reproduces the input data with great accuracy. The ionograms contain interesting features from an artistic point of view, so they were used as part of *Chasmata*, a large music composition.

1 Introduction

The origin of this sonification experiment lies in the composition of *Chasmata*, a large multimedia suite for 120 saxophones, live electronics, mobile orchestra, and multiprojection in the Frank Gehry's Atrium at the Guggenheim Museum Bilbao. The piece was created in collaboration with the composer Ángel Arranz. This performance was a highlight of the museum's XX Anniversary celebration, involving the European Space Agency (ESA), researchers from various institutes, and two astronauts: Pedro Duque, who participated from the museum, and Paolo Nespoli, who contributed a message while in microgravity aboard the International Space Station.

The creation of musical compositions related to Mars was carried out in various ways, ranging from mere suggestion to the literal translation of data. Visual and auditory pieces were created from the orography, and different datasets from ESA repositories were explored to find interesting material for faithful sonification [3]. From a purely artistic perspective, it is uncommon to find musical results from the direct translation of scientific data into sound. However, the Mars ionospheric data from Mars Express exhibited very interesting characteristics for exploration as a sound source, treating the probe and the Martian ionosphere as a huge musical instrument.

2 MARSIS data features

The MARSIS (Mars Advanced Radar for Subsurface and Ionosphere Sounding) instrument is aboard the ESA's Mars Express probe [1]. We used datasets from the Active Ionospheric Sounding mode, which is an operational mode to determine the time delay versus frequency in the lower frequency bands, used to detect echoes from the topside of the ionosphere [4, 8]. An ionogram (Fig. 1) is a graphic representation of the delay time between the MARSIS radar pulse transmission and its echo reception versus carrier frequency. It contains many features, but the main one is the ionospheric trace (feature labeled b), from which the main scientific data, the vertical electron density profiles of the ionosphere, can be retrieved.

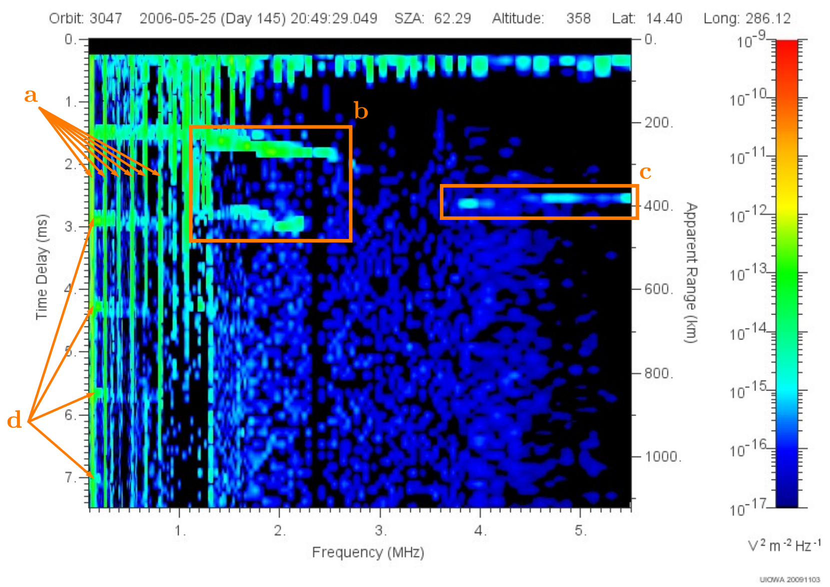

Figure 1: Main structures of the ionograms marked in orange: a) Harmonics produced by the interaction between MARSIS antennas and the ionosphere. b) Ionospheric traces around 1-3 MHz. c) Line at high frequencies due to reflection from Mars' surface. d) Horizontal lines from electrons accelerated by the antennas' electric field interacting with the ambient magnetic field (cyclotron echoes).

As raw data were quite complex to process, we decided to attempt sonification directly from the ionograms, which have well-distinguishable and differentiable features, which appeared interesting for sonification. Such structure were considered analogous to sounds with potentially musical properties, such as a powerful attack, richness and variety in harmonics, variable dynamics, strong low-frequency pulses, and an interesting overall temporal evolution.

Data used in this study are freely available at the ESA Planetary Science Archive (PSA), storaged under the "browse" products of the MARSIS-AIS data.

3 Sonification objectives

Considering these data characteristics, three scientific and artistic objectives were pursued:

- Test the possibility of recreating a sound from the image of an ionogram, with a spectrum that faithfully matches the original data.
- Develop an ergonomic sonification in terms of time, frequency, and intensity that allows for auditory distinction of the ionogram's features.
- Obtain sound representations with sufficient quality and variety to serve as raw material for use in musical compositions.

4 Methods

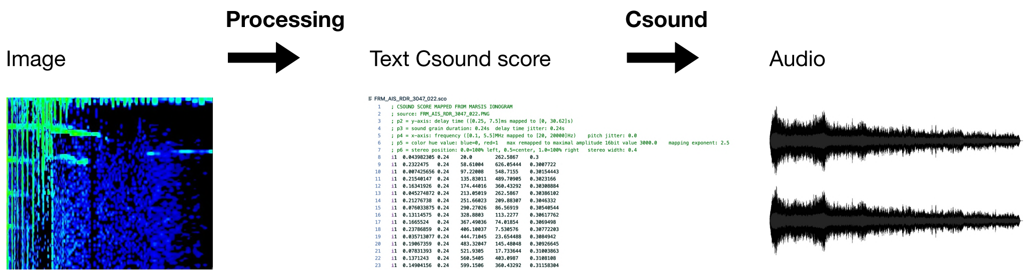

Figure 2: Pipeline for translating ionograms to a score of small sound grains using Processing, and compiling it with Csound to obtain a stereo audio file.

We chose granular synthesis for image sonification, which is a sound synthesis technique that involves breaking down audio signals into small segments called grains [7]. These grains are reassembled to create complex, evolving textures and timbres, allowing for extensive control over the sound's characteristics. Each pixel was translated into a small sinusoidal sound particle with energy concentrated at a single frequency. The process is equivalent to an inverse Fourier transform, with certain adjustments to adapt the sound to human auditory perception, and with temporal jittering measures to minimize the occurrence of spurious frequencies due to sampling.

The sound synthesis thus consisted of mapping the information contained in each pixel to a small sound grain to form a global sound created by the addition of tens of thousands of sound particles called grains. A pipeline was created using a small script with Processing that converted each image into a Csound score (Fig. 2). Csound is a classic programming language for sound synthesis, still renowned for its precision and reliability. In Csound, a score is the list of events passed to the synthesizer to create the sound file. The method consists of the following steps:

1. Reading the hue level of each pixel.
2. Mapping pixels into sound grains, as explained in Section 5.
3. Writing the events in a Csound score, if their corresponding mapped amplitude > 0.
4. Adding a header detailing the input data and the mapping parameters.
5. Synthesizing audio to a soundfile from Csound scores.
6. Listening and analyzing the results to refine the mapping parameters.

5 Mapping ionogram pixels to sound grains

The processes of mapping to sound parameters are detailed below. Table 1 provides a condensed summary of these conversions. These are the considerations taken for each parameter, aiming to find a balance between data fidelity and suitability for psychoacoustic factors:

Table 1: Optimal value ranges tested for the sonification of MARSIS ionograms.

Spectrum parameter	Data min.	Data max.	Mapped min.	Mapped max.
Total time	0 ms	7.5 ms	0 s	30 ± 10 s
Time interval per pixel	0.017 ms	0.017 ms	0.06 s	0.06 s
Sound duration per pixel	–	–	$(0.2 - 0.06)$ s	$(0.2 + 0.06)$ s
Frequency	0.1 MHz	5.5 MHz	30 ± 10 Hz	17 ± 2 kHz
Amplitude[a] (color hue)	0 (blue)	1 (green)	0	7.6% of 16 bit range
Stereo panning	–	–	$25 \pm 10\%$ Left	$25 \pm 10\%$ Right

[a]The ionogram data do not use the full hue color range, but only the colors between blue and green, which correspond to the range from 10^{-17} to 10^{-13} $V^2m^{-2}Hz^{-2}$, normalized to values between 0 and 1.

- Time: Creating a continuum based on sound grains considering that a literal translation of each pixel's position creates spurious frequencies derived from the period associated with the pixel columns. To avoid this, a stochastic deviation is applied to the start point of each sound grain. Additionally, each sound particle has an amplitude envelope to produce an overlap with adjacent particles, creating the perception of a continuous sound whose spectrum evolves as a whole.

- Frequency: In the example in Fig. 3, the full range of human hearing is applied, though this should be adjusted based on the audio device's characteristics and the user's perceptual range (with age, the theoretical 20 kHz limit decreases). In these ionograms, relevant information lies in the mid-to-low range of the spectrum, so the upper limit is not critical.

- Amplitude: Finding a good amplitude range and applying an exponential factor to enhance spectral features and avoid masking effects. The mapping to audio amplitudes is done by applying an additional parameter, $ampMappingFactor$, typically between 2 and 3, which applies an exponential correction to accentuate the dynamic difference and make the important features of the graph more perceptible:

$$sonifiedAmp = 0.076 \cdot 2^{bitDepth-1} \cdot normalizedAmp^{ampMappingFactor} \tag{1}$$

  where $sonifiedAmp$ is the amplitude value for the sound particle, $bitDepth$ is the bit depth of the sample format of each audio sample, $normalizedAmp$ is the hue color value read from each pixel of the graph and normalized in the range $[0, 1]$, and $ampMappingFactor$ is an exponent to accentuate the dynamic relief of the mapping.

- Stereo panning: The spatial location of each sound grain does not represent any specific data feature; however, adding a stereophonic dimension to the sound particles enhances the perception of layers and features. A continuous frequency-based distribution is applied, positioning lower frequencies to the left and progressively shifting higher frequencies to the right. Extreme panning is avoided to preserve sound compactness.

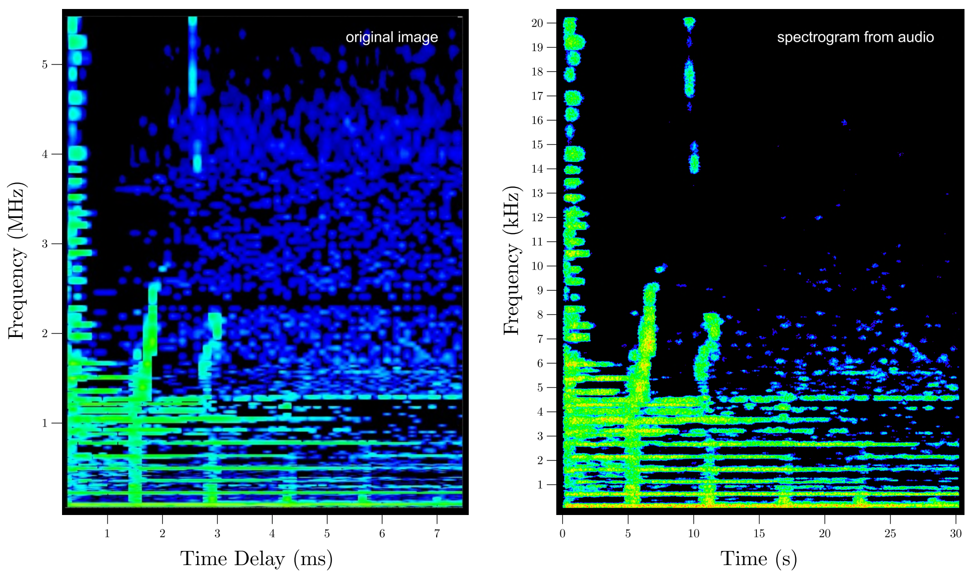

Figure 3: Comparison of an original ionogram with the spectrogram of its sonification. The graphs have been rotated 90 degrees to provide a more intuitive representation of the sound, with time on the horizontal axis.

6 Results

To evaluate the accuracy and fidelity of the sonification, spectral analyses of the generated sounds were performed using the same color palette and equivalent parameters for the fast Fourier transform. Considering the inherent information carried by spectral analysis, the comparison of spectrograms is clearly satisfactory due to its fidelity to the original picture. In Fig. 3, it can be observed that the correction applied in Equation 1 has reduced the background noise in blue.

With the automation of the process for accessing datasets corresponding to complete orbits of the Mars Express, several hundred ionograms were sonified. The source code used, along with hundreds of sonifications with the source ionograms, the Csound scores, and the sound spectra, are available on Internet Archive [5, 6]. Additionally, a video version of the oral presentation of this talk given at the XVI Scientific Meeting of the Sociedad Española de Astronomía (SEA) can be found here.

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