COROT LIGHT CURVE AMBSONICS/BINAURAL SONIFICATION

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ABSTRACT

This work describes the design and implementation strategies used in the development of an interactive spatialized multimodal display for the exploration of the light curves from the Convection, Rotation and planetary Transits (CoRoT) archive from the Institut d'Astrophysique Spatiale (IAS). The application displays the representations in a user-selectable Ambisonics or Binaural configuration based on the actual coordinates of the objects. Each sonification is based on a symbolic spectral-type to musical-note mapping strategy, providing musical aesthetics and auditory spectral differentiation capability. The UI shows the footprint of 474 objects from the CoRoT N2 legacy data release and a sequential representation of its light curves. It is designed to be used in outreach activities and archival accessibility improvement. The work includes a user study with 40 participants experienced and non-experienced in Astronomy and Music, that analyzes the usefulness of the proposal for auditory stellar spectra classification with the support of training videos. Although the results should be considered indicative, they suggest that non-experienced participants can retrieve useful information through sound to complete the task with an average success rate around 0.47, while experienced participants do it with an average success rate around 0.72.

1. INTRODUCTION

Space telescope mission products can be divided into two wide categories, raw or unprocessed data and science ready processed data. The first category includes original recorded information required on specific applications and in-depth research [1]. Through data reduction and calibration processes, the astronomical objects and their attributes are extracted from the raw data to provide labeled products ready for science use [2]. These processed products include information such as the telescope used, the date and time of the observation, the coordinates and spectral type of the objects, or the RMS level of the recorded signal, allowing instant access through databases and information systems like Exo-Dat [3].

Aligned with the need of an inclusive research scenario expressed by Casado [4], to move forward toward truly accessible astronomy[5], this work explores the sonification possibilities of easy-access tagged information stored in the headers of the N2 light curves from the Rotation and planetary Transits (CoRoT) archive from the Institut d'Astrophysique Spatiale (IAS) [6]. The final goal is to propose inclusive complementary exploration methodologies that could make archive scientific-ready data accessible to anyone, providing a preliminary summarized real time sonification [7] to help in the search of case studies that could be analyzed in-depth using accurate methodologies such as those described in Tutchton et al. [8], Tucker et al. [9], or tools like Sonouno [10], Highcharts sonification studio [11], STRAUSS [12] , Astronify [13], or Sonifigrapher [14].

The interdependence of data, sound, science, and music exposed by Barret[15] is also explored in this work to propose the spatialized musical exploration of the CoRoT archive as a resource that could foster public engagement in Astronomy. The use of Binaural audio and Head Related Transfer Functions (HRTF) in sonification has been proposed [16], analyzed [17], and developed to create accurate positional mappings [18] along with sound spatialization techniques such as Ambisonics or Vector Base Amplitud Panning (VBAP), that have also been used to create immersive public representations of meteorological [19], stock market [20], multichannel EEG [21], and geospatial data [22].

The sonification prototype presented in the following sections includes user-switchable first order Ambisonics or Binaural spatialization [23] linked to the actual coordinates of the represented objects, enhancing the connection with the audience through immersive audio and allowing spatialization for researchers using headphones. The proposal is aimed at providing an auditory representation that could summarize the information related to the spectral type and best fit period of the light curves from the CoRoT archive. It is expected to be useful for auditory spectral classification and live outreach public demonstrations, and could be implemented in massive archives to provide fast auditory information about the type of star and the main period detected in its light curve. A demonstration video showing the Binaural exploration of the CoRoT archive is provided at: `https://vimeo.com/921824459`

2. THE IAS COROT ARCHIVE

The CoRoT space mission was led by the Centre national d'études spatiales (CNES) with European Space Agency (ESA) participation between December 2006 and June 2014. Aimed at analyzing stellar physics and searching for exoplanets, CoRoT was pioneer on detecting rocky planets outside the Solar System. This work uses 474 EN2_STAR_MON products (previously called exoplanet channel) [24], containing the information about monochromatic stars with all the pixels of each target added to provide single light curves. The files are publicly available at the CoRoT web page [25] and at Strasbourg astronomical Data Center (CDS) [26]

Table 1: Spectral-type to musical-note mapping strategy used for the sonification of the seven types of stellar spectra of Harvard classification.

Spectral type	O	B	A	F	G	K	M
Musical note	C	B	A	F	G	D	E
(Latin)	Do	Si	La	Fa	Sol	Re	Mi

via vizier [27]. The light curves are archived using the following nomenclature:
<COROTID>_<START_DATE>_<END_DATE>.fits

3. SPECTRAL CLASSIFICATION AND *BOX LEAST SQUARES* PERIODOGRAM ANALYSIS

Stellar spectra can be classified according to their absorption features and effective temperature using Harvard spectral classification. This system uses the sequence O, B, A, F, G, K, M running from the hottest stars (more than 28,000K) to the coolest ones (less than 3,500K). Within each spectral type, 10 additional subclasses numbered from 0 to 9 allow the classification of the spectra based on the strength of their absorption lines [28]. An additional luminosity class is required to differentiate stars with the same temperature but with different luminosity. The Morgan-Keenan classification [29] use roman numbers to differentiate between extremely luminous super-giant stars (class *I*) and the main sequence dwarf stars (class *V*).

Box-fitting Least-Squares (BLS) periodogram analysis is one of the standard statistical methods to search periodicity in irregularly sampled data [30]. This method fits the input time series to periodic "box" shaped functions which represent better than sines and cosines the behavior of a light curve during a transit (the pass of an object between a source of light and the observer), making it useful in the search of transiting exoplanets or detached eclipsing binaries [31]. *Python's astropy* library [32, 33] allows the implementation of the standard and generalized *Box Least Squares* periodograms. All the documentation, key functionality, common tools, and statistical processes used for performing astronomical calculations in *Python* are available at *astropy:docs* [34].

4. TECHNICAL DESCRIPTION

The sonification prototype proposed in this work consists of two modules implemented in Jupyter notebook [35], which pre-process and launch the archive exploration, and a CSound/Cabbage [36] multimodal display with a UI that allows the sound control of the sonifications "on the fly". The first pre-processing module reads the data from each fits file [37] of the CoRoT archive, calculates the best fit period found in each light curve, and save the data into numpy arrays. The launching module reads the pre-processed arrays, generates the graphical representations of the light curve, and sends MIDI notes and OSC messages "in real time" to the sound synthesizer. *Figure 1* shows the variables and output files used for the sonification of each light curve. The complete system is publicly available following Open Science practices at:
`https://github.com/AuditoryVO/CoRoT_Explorer`

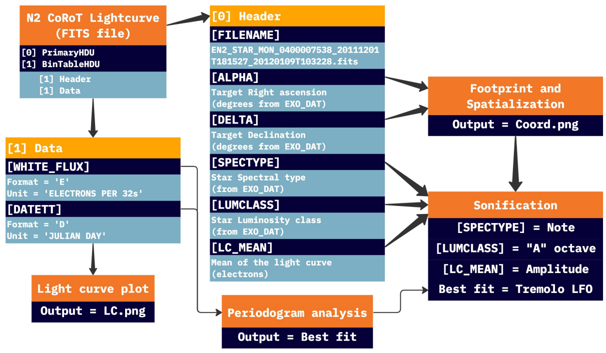

Figure 1: Variables extracted from the FITS file of each object. The chart includes description, output files, and mapping.

5. SONIFICATION DESIGN

Table 1 shows the symbolic mapping strategy adopted to provide an intuitive conversion into sound of the spectral classes of the objects included in the archive (labeled using the Harvard and Morgan-Keenan classification). It is basically an almost direct correspondence between the seven spectral classes of the Harvard classification and the seven notes of C major scale. The subdivision numbers are used to control the octaves of the notes, assigning the lowest pitches to the hottest stars (number 0), and the highest pitches to the cooler ones (number 9).

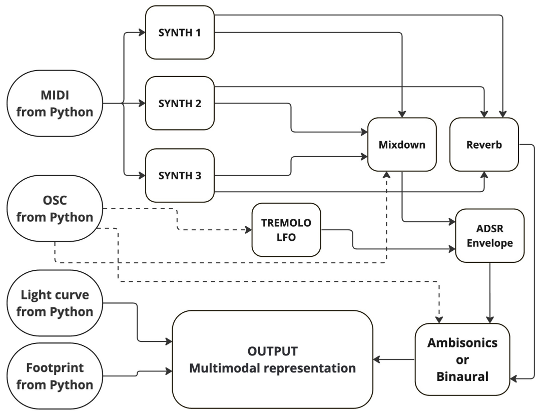

Figure 2: Block diagram of the sonification synthesizer implemented in CSound/Cabbage. Continuous lines represent MIDI, audio and image connections, dashed lines represent OSC connections

This approach is expected to simplify the necessary explanations for audiences without knowledge on Astronomy thanks to the interdisciplinary symbolic coincidence. An additional constant note (A) is reproduced in octaves that are controlled by the Morgan-Keenan luminosity class (expressed in roman numbers from *I* corresponding to super-giant stars, to V corresponding to dwarf stars). The amplitude of each note is modulated by the mean flux of each light curve. Finally, a *Box-fitting Least-Squares* periodogram analysis calculates the best fit period detected in the light curve, which is mapped to the oscillation frequency of a tremolo effect. The luminosity class, best fit period, and amplitude sonifications can be interactively bypassed.

As can be seen in *Figure 2*, the sound generation module consists of three independent synthesizers that cover the spectral range equivalent to 9 octaves from K0 (interpreted as D0) to G8 (interpreted as G8). The *CSound* opcodes [38] *fmb3* and *vco2* cover the low and middle frequency ranges. For the highest notes the *oscil3* opcode was added [39]. All of them receive the activation MIDI notes sent by the *Python* sonification module, which also sends via OSC the variables that control the frequency of the tremolo associated to the periodogram analysis, the proportion and amplitudes of the sound generators associated to the mean flux of the light curve, the coordinates of each object for the spatialization, and the refreshing rate that drives the sequential representation.

6. SPATIALIZATION

Aimed at providing an immersive sonification experience for the exploration of the CoRoT archive, the prototype includes a user-switchable Ambisonics/Binaural configuration.

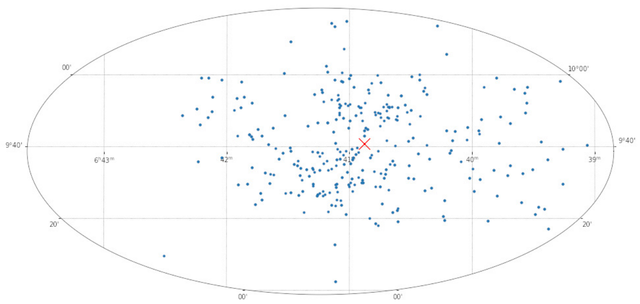

Figure 3: IAS CoRoT archive footprint (blue dots) and centroid spatialization coordinate reference position (red cross) at RA 100.2196 DEC 9.6773 (degrees).

The Ambisonics setup is suitable for educational or public outreach activities but does not support headphone playback. The complementary Binaural approach provides spatialization for researchers and laptop users wearing headphones. *Figure 3* shows the footprint of the complete CoRoT archive and the centroid spatialization coordinate reference position established at RA 100.2196 DEC 9.6773 degrees to provide a centered immersive perspective.

6.1. Ambisonics Sonification

Ambisonics technique consists of shaping a sound field to represent virtual sound sources in 3D space. In this format, the sound source is encoded and stored in a variable number of channels called *B-format* not related to the number of speakers or channels used in the final projection. First order Ambisonics uses 4 channel B-format, second order uses 9 channels, and third order 16. Higher order codifications in general lead to better space resolution [40]. The final immersive representation requires a decodification process to convert the B-format into the final audio signals that feed the chosen speaker configuration. First-order Ambisonics require a minimum of 4 speakers for a correct representation, second-order 6 or 9 speakers if 3D is needed, and third-order 16 for 3D representations [41].

In this approach we use first order Ambisonics (FOA), requiring the codification into a B-format with three basic dimensions (a_0, a_{11}, a_{12}), and its decodification to eight final audio signals feeding the proposed eight speakers setup. To implement this configuration in CSound a user defined opcode (UDO) [42] has been developed. The equations that ruled the codification can be expressed as shown in *Equation 1*, where φ represents the angle of the polar coordinates of each represented point, and a_0, $a_{1,1}$, and $a_{1,2}$ the encoded B-format signals. Right ascension (RA) of the actual coordinates of each sky object is used as φ in the final implementation.

$$a_0 = Source(mono) \tag{1a}$$
$$a_{1,1} = X = Source \cdot cos\varphi \tag{1b}$$
$$a_{1,2} = Y = Source \cdot sin\varphi \tag{1c}$$

The decodification equations for eight speakers symmetrically placed on a circle can be expressed as shown in *Equation 2*, with a_n representing the output signal feeding the "n" speaker, spaced $\phi_n = 45 \cdot (n-1)$ degrees.

$$a_n = 2/3(a_0/2 + a_{1,1} \cdot cos\phi_n + a_{1,2} \cdot sin\phi_n) \tag{2}$$

A direct mapping of right ascension to azimuth coordinates was used to provide 2D representations correlated to a flat screen projection of the visuals (RA = AZ = φ). This configuration was found after intensive testing as the most adequate approach to meet user expectations. Preliminary tests revealed how accurate conversion of right ascension and declination to azimuth and elevation produced sonifications not correlated to the sky sphere shown in the graphical representation (it requires the introduction of user's location reference coordinates, which potentially produces variable results).

6.2. Binaural Sonification

Human hearing uses both ears to estimate the location of a source by analyzing the sound perceived in one ear (monoaural cues) and by comparison with the sound received in both ears (binaural cues). The alterations of a sound from the source to our ears can be characterized using Head Related Transfer Functions (HRTF) [43]. Through the convolution of a sound source with the HRTF for the two ears, Binaural systems allow the spatialization of static locations at HRTF measured points and the interpolation of the response to the rest of the virtual sound space [44].

In general, the relationship between the sound source and the signal reaching the listener ears can be expressed in terms of the azimuth (AZ) and elevation (EL) angles, the distance to the source (d), and the angular frequency (w), as shown in *Equation 3*:

$$Y_{L,R}(AZ, EL, d, w) = H_{L,R}(AZ, EL, d, w)X_{L,R}(w) \tag{3}$$

where $Y_{L,R}$ is the audio spectra of acoustic signals at listener's ears, $H_{L,R}$ is the HRTF and $X_{L,R}$ is the spectrum of the sound source.

In this approach we use the binaural *hrtfmove2 Csound* opcode [45] to represent the sky sphere through azimuth and elevation angles extracted from the sky coordinates of each light curve. The opcode provides 3D binaural audio for headphones

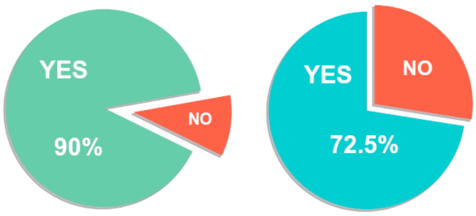

Figure 4: Qualitative feedback from 40 participants, 90% of the complete sample considered that the proposal could be useful in outreach activities for introducing the types of stellar spectra (left), and 72.5% declared their interest in listening to more astronomical sonifications after completing the survey (right).

with improved low frequency phase accuracy using HRTF based filters [46]. It also uses the Woodworth spherical head model, that considers the head as a perfect sphere with antipodal ears, and assumes an infinite source distance, relating interaural time and level differences to the azimuth and elevation angles [47], and reducing the general expression to *Equation 4*.

$$Y_{\text{L,R}}(AZ, EL, w) = H_{\text{L,R}}(AZ, EL, w) X_{\text{L,R}}(w) \tag{4}$$

Equation 5, represents the variables used as inputs (right), to obtain the *hrtfmove2* opcode binaural output (left) in *CSound*'s coding style (RA = AZ, DEC = EL).

$$[Bin_{\text{L,R}}] < hrtfmove2 < [Synth, RA, DEC, HRTF_{\text{L,R}}] \tag{5}$$

7. EVALUATION

Aimed at evaluating if the proposed sonification model can be useful for the auditory classification of stellar spectra, an online user study was conducted from March to May 2024. A survey of 16 questions and two self-training videos with sonification examples was distributed to volunteer participants including students from astronomy and data science university courses, musicians, astronomers, and personal contacts of the authors.

The questionnaire asked 8 questions through videos focused on auditory spectral classification (4 using the sonification prototype described in this article and four using another approach using artificial intelligence [48]), 6 demographic control questions, and 2 additional qualitative questions asking about the usefulness of the proposal and the interest of the participants in listening to more sonifications. All the questions were presented shuffled and the use of headphones was recommended even if they were not essential. No prior knowledge was required to participate. The self-training videos used an approach close to Infosonics [49], complementing the sonifications with spoken guiding labels that provide context and references [50]. The questionnaire is available at: `https://forms.office.com/e/veisXfB6fw`

7.1. Results

A total number of 40 responses were obtained mainly from Spain, with some participants from Germany, Chile and United States. 18 participants declared having experience in Astronomy and/or Music, and 22 declared no prior knowledge in these topics. The non-experienced group was randomly down-sampled to allow direct comparisons, so the final results and conclusions represent the

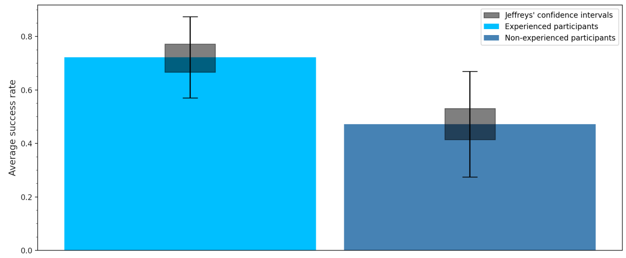

Figure 5: Average success rate for 18 experienced (left) and 18 non-experienced participants (right).

feedback of 36 participants, 18 experienced including two blind or low vision participants (BLV), and 18 with no previous experience. Nevertheless, the study should be considered as indicative as the sample is too small to offer statistical significance.

The average success rate of the 40 participants for the four questions was 0.56, with a Jeffreys confidence interval of (0.52, 0.59) and 68.3 % of uncertainty, suggesting that the approach could be useful for the proposed classification task.

Attending the results recorded from the qualitative questions shown in *Figure 4*, 90.00 % of the 40 participants considered that the sonifications can be useful in outreach activities for introducing the types of stellar spectra, and 72.50 % of the participants declared interest in listening to more sonifications of astronomical data after completing the survey.

To provide further analysis of their responses, the participants were subdivided into two groups, experienced and non-experienced, based on their relationship with Music and Astronomy. The experienced group, understood as familiarized with the data or trained in paying attention to sound, was formed by 18 amateur and professional astronomers or amateur and professional musicians. The non-experienced group was formed by 18 randomly sampled participants (from the initial group of 22), that declared no relationship with Astronomy nor Music.

As shown in *Figure 5*, the experienced group obtained an average success rate of 0.72 with a Jeffreys confidence interval of (0.66, 0.77) and 68.3 % of uncertainty, 1.53 times higher than the average success rate of the non-experienced group that obtained a 0.47 of success with a confidence interval of (0.41, 0.53), for the same percentage of uncertainty.

The notably better results of the experienced participants seem to confirm that prior knowledge fosters the understanding of the sonifications [51, 52]. The acceptable results of the non-experienced group seem to suggest that even without prior knowledge, and despite the difficulty in differentiating sounds declared by some participants, the self-training videos could be an effective tool to use this approach for inclusive citizen projects.

In the experienced group, 88.88% of the participants found the sonifications useful in outreach activities for introducing the types of stellar spectra, and 83.33% declared interest in listening to more sonifications of astronomical data after completing the survey. In the non-experienced group, 88.88% of the participants found the sonifications useful, and 66.66% declared interest in listening to more sonifications. The success rate of question 1 was notably higher than the success rate of question 4 in all groups of participants regardless of their experience level, what seems to suggests that most of the participants were able to distinguish salient auditory representations.

Table 2: Summary of success rates and qualitative feedback by groups of participants showing standard deviation and confidence intervals. Notice that the subgroups are extracted and balanced from the global group for comparative purposes.

Group	Participants	Success rate	Conf-low	Conf-high	Std	Useful (%)	Want more (%)
Global	40	0.5562	0.5167	0.5950	0.1519	90.0	72.5
Experienced	18	0.7222	0.6666	0.7716	0.1977	88.88	83.33
Non-experienced	18	0.4722	0.4142	0.5310	0.1064	88.88	66.66
AstroMus	4	0.8125	0.6977	0.8895	0.2239	75	100
Musicians	4	0.6250	0.4999	0.7350	0.1443	100	100
Astronomers	4	0.5625	0.4384	0.6790	0.3750	75	50
4-Non-exp	4	0.5	0.3788	0.6212	0.2886	75	50

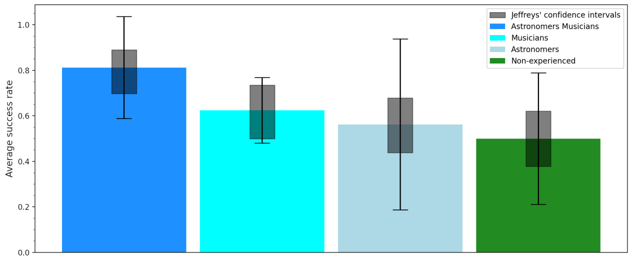

Figure 6: Four samples subgroup analysis. Average success rate for astronomers musicians (left), musicians (center-left), astronomers (center-right), and non-experienced (right).

An additional analysis within the experienced group was performed to estimate potential differences in responses of astronomers, musicians, astronomers musicians, and non-experienced participants. The original sample included 4 astronomers and 4 astronomers musicians, what forced to 4 the number of musicians and non experienced participants used to establish the comparison (randomly selected from the original subgroup of 10 and 22 participants, respectively). *Figure 6* shows how, as expected, astronomers musicians performed significantly better, presenting an average success rate of 0.81 vs the 0.62 obtained by musicians, the 0.56 obtained by astronomers, and the 0.5 obtained by non-experienced participants. All the results can be found summarized in *Table 2*.

8. CONCLUSION AND PROSPECTIVE

This work describes a proposal for the spatialized multimodal exploration of the IAS CoRoT light curve archive based on the possibilities of the symbolic conversion of spectral types into musical notes. Providing Ambisonics and Binaural sound spatialization the prototype could be useful on both, public science outreach activities and personal computer headphones based analysis. Future improvements of the Binaural representation could explore the influence of customized Head-Related Transfer Functions. The ideal scenario should include personalizing HRTF, which has been proven to significantly impact spatialization [53].

On the other hand, the use of alternative 2D Ambisonics representation makes it possible to communicate results to larger audiences using the same analysis tool, which could foster science dissemination, exhibitions and educational or artistic installations. Future developments could increase the order of the codification to improve the spatial accuracy of the representation. In both formats, the contribution provides an immersive perspective that could be implemented in near future massive open access astronomical archives.

The work also includes a user study aimed at evaluating the potential of the methodology for the classification of spectral types by experienced and non-experienced users. Although a higher number of participants is required to obtain solid conclusions, the results obtained from 40 participants seem to reveal a good acceptance of the proposal with 90% of the participants considering it useful for introducing spectral classification to non-experienced audience in outreach activities, and 72.5% declaring interest in listening to more sonifications after completing the survey.

The average success rates obtained by self-declared experienced participants in Astronomy or Music were 1.53 times higher than those obtained by self-declared non-experienced, the respective average success rates obtained were 0.72 and 0.47. Within the experienced group, astronomers musicians reported the best results. This tendency seems to confirm the importance of prior knowledge for a complete understanding of the sonifications [54]. Nevertheless, an average success rate of 0.56 for all the participants seems to suggest that users could retrieve information from sound using this approach, which could be useful for auditory spectral classification (even by non-experienced users with enough training), and that could be applied in the development of inclusive citizen science projects.

Additional feedback from professional astronomers suggested that the alternative mapping used for the sonifications (based on the symbolic notation of *Table 1*), was slightly disorienting due to the expectation of a pitch-to-temperature association of the spectral types in decreasing order from *O* to *M*. Although the goal of this study was to analyze in a broad scope whether basic musical knowledge could help in classification tasks, the highlighted association should be considered in future developments specifically addressed to professional astronomers.

Ongoing perceptual experiments are being conducted to analyze the possibilities of deep learning sonification applied to stellar and galaxy spectral classification. This near future studies include experiments on sound location within binaural environments as well as classification tasks aimed at identifying through sound the shape and age of galaxies, and the spectral type of stars to be compared with the results presented in this article.

9. ACKNOWLEDGMENT

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