SONIFICATION OF *TESS* DATA VALIDATION TIMESERIES FILES

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ABSTRACT

In August 2022, the Transiting Exoplanet Survey Satellite (TESS) will start its fifth year of exploration having observed and analyze more than a million stars in the search of extrasolar planets around both celestial hemispheres. At this time, with 5,767 declared TESS objects of interest (TOI), the total number of confirmed planets that appear in peer-reviewed journals exceeds 220.

This article describes the prototype design and domain conversion strategies used for the sonification of Data Validation Timeseries (DVT) files from TESS mission. Focused on 132 examples of publicly available lightcurves from stars hosting at least one planet confirmed during the first four years of TESS observations, the resulting proposal allows the multi-modal and multi-channel automatic interactive aural exploration of astronomical variables, generating sequences of complete soundscapes from target variables stored in each DVT file, which can be controlled in terms of complexity and balance. Aesthetics and inspiring aspects of Sonification are also open for discussion.

1. INTRODUCTION

The Transiting Exoplanet Survey Satellite (TESS) is an MIT-led NASA mission oriented to the discovery and observation of transiting planets by an all-sky survey. TESS observes the sky in sectors that measure 24x96 degrees, obtaining full-frame images collected every 30 minutes, and two-minute cadence target pixel time-series from around 20,000 stars per sector during about 27 days (two orbits of the satellite). It is currently exploring sector 53 and its huge amount of data aimed at detecting and observing exoplanets, as well as the smallest details of the observations, are publicly available at TESS Mission web page [1].

With such an overwhelming database in mind, this article describes an automatic interactive multi-channel sonification tool designed for the multi-modal exploration of Data Validation Timeseries (DVT) files used on TESS mission to identify objects of interest with planetary transit candidates. The prototype design aims to launch the proposal of using the sonification of astronomical variables for the creation of complete soundscapes where target parameters, such as the effective Temperature or the Metallicity of a star, generate a sound environment to interact with. This kind of approach has been designed on the narrow interdisciplinary space between sonification and musification, as a sonification-driven sound generation module for a work in progress project oriented to music composition based on *Deep Learning* and required to deepen some aesthetics aspects of Sonification that are presented here to feed the current open discussion about this topic. The final musical project is expected to produce automatic compositions framed into the Spectralism[2] and Algorithmic Music aesthetics[3] while the prototype is expected to be also useful in the monitoring stellar catalogs, in aural correlation analysis of astronomical variables and as an engaging resource in educational and accessibility contexts related to Astronomy and STEM.

```
TELESCOP= 'TESS     '           / telescope
INSTRUME= 'TESS Photometer'     / detector type
DATA_REL=                     2 / data release version number
OBJECT  = 'TIC 55650590'        / string version of target id
TICID   =              55650590 / unique tess target identifier
SECTOR  =                     2 / Observing sector
PXTABLE =                   129 / pixel table id
RESFILE = 'tess2018234235059-s0002-s0002-0000000055650590-00109_dvt.fi
ts.gz' / c
DVVERSN = 'spoc-3.3.37-20181001' / DV Subversion revision number
NUMTCES =                     1 / number of TCEs found
SECTORS = '001     '            / bit-vector string of 17 0/1 chars
RADESYS = 'ICRS    '            / reference frame of celestial coordina
tes
RA_OBJ  =  73.7371900000000000 / [deg] right ascension
DEC_OBJ = -62.5223690000000000 / [deg] declination
EQUINOX =                2000.0 / equinox of celestial coordinate syste
m
PMRA    =                       / [mas/yr] RA proper motion
PMDEC   =                       / [mas/yr] Dec proper motion
PMTOTAL =                       / [mas/yr] total proper motion
TESSMAG =           12.47200012 / [mag] TESS magnitude
TEFF    =         3358.00000000 / [K] Effective temperature
LOGG    =                       / [cm/s2] log10 surface gravity
MH      =                       / [log10([M/H])] metallicity
RADIUS  =                       / [solar radii] stellar radius
```

Figure 1: Fragment of metadata extracted from the header of TIC 55650590. TESS data validation timeseries file from *STScI* archive [4].

2. CONTEXT AND PROPOSAL

The sonification of Astronomy and Astrophysics data is a field in exponential expansion that generates results of the highest quality both in the musical and scientific fields [5]. Institutional projects like *Astronify* from the STScI [6], *Sound from Around the Milky Way* [7] and *A Universe of Sound* [8] from NASA's Chandra X-ray Center, coexist with research teams developing compositions, studies and tools that contribute to establish the current state of the art in this topic. Works like *CosMonic* from the IAA-CSIC [9], *Sonification of Dark Matter* by Bonet et al. [10], *Sonification of the zCOSMOS Galaxy Dataset* by Bardelli et al. [11], *Sonification*

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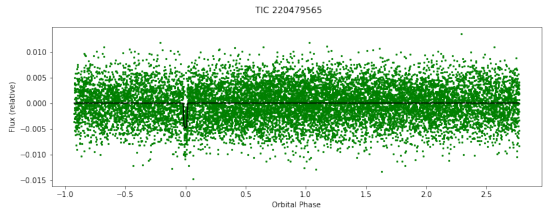

Figure 2: Folded lightcurve and transit model for TIC 220479565, an eccentric sub-Neptune transiting a M2 dwarf.

of Planetary Orbits in Asteroid Belts by Quinton et al. [12] and the revision of tools like *x-sonify* by Garcia et al. [13] or *Sonification Sandbox* by Walker [14], leading to *Highcharts Sonification Studio* by Cantrell et al. [15], are highlighted examples of what draws the international sonification landscape in which the proposal of this article could be framed.

In an effort to contribute to this solid ecosystem of proposals and using the TOI catalog as case study, this work aims to provide a tool for easily *view and listen* to the information contained in the catalogs in a sequential and automatic monitoring way, offering a music-based auditory perspective of stellar properties which can be used to identify salient targets in preliminary massive catalog analysis and variable correlation detection between selected groups of objects under study.

3. TESS DATA VALIDATION TIMESERIES FILES

TESS Data Validation Timeseries (DVT) files are the result of a preliminary analysis of possibly transit-like periodic signals found in data that are used in the process of planet transit confirmation. In this process, the variations of brightness flux registered by the telescope and stored in two-minute cadence light curves, are analyzed by a Transit Planet Search (TPS) module that creates Threshold Crossing Events (TCE), which could be "consistent with transiting planets but also with eclipsing binaries, variable stars or even noise in the data" [16]. The purpose of these files is to archive the time series related to data validation that are involved with transit search and TCE modeling, providing a primary HDU with metadata and one FITS extension HDU for each TCE found in the lightcurve of the observed object, as well as an additional extension with statistics about the search. All the details about FITS file structure can be consulted in [17].

Light curves in DVT Timeseries present some preprocessing that includes the removal of harmonics, level adjustment, normalization, and stitching between sectors. All the details about the data structure are described in TESS science data products documentation [18, 19]. *Figure 2* shows the folded lightcurve and transit model for TIC 220479565, confirmed as "a sub-Neptune close to the transition between super-Earths and sub-Neptunes transiting the M2 dwarf TOI- 269 (TIC 220479565, V = 14.4 mag, J = 10.9 mag, Rstar = 0.40 Rsun, Mstar = 0.39 Msun, d = 57 pc). The exoplanet candidate has been identified in multiple TESS sectors, and validated with high-precision spectroscopy from HARPS and ground-based photometric follow-up from ExTrA and LCO-CTIO" [20].

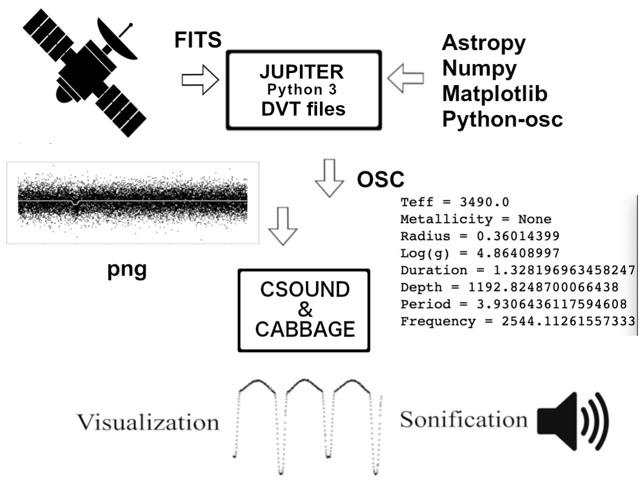

Figure 3: Block diagram showing the computing engine.

4. SEQUENTIAL MULTI-VARIABLE SOUNDSCAPE SONIFICATION

Multi-track recording is nowadays a standard technique in music industry even in the most classical environments [21], providing a way of controlling the balance between sources *a posteriori*, minimizing leakage (the quantity of sound of one instrument that is picked up by the microphone of another instrument) and enhancing tiny details in every sound recorded [22]. Once the recording is finished, all the tracks are passed through a mixing console to elaborate a final mix in which every aspect has been fine-tuned [23]. This consolidated optimization of the recording and mixing process is proposed here for discussion as an inspiring design paradigm for the sonification of multi-variable auditory representations. Basic frequency mappings from each astronomical variable to each synthesized sound are suggested in the implementation, to minimize the complexity in the analysis of the proposal which displays different variables of an object of interest merged within a complex sonification controllable soundscape.

According to the suggestions of Flowers(2005) [24] related to *Sequential Comparisons of Sonified Data*, the addition of an automatic sequential exploration engine to this multi-track soundscape from DVT file concept, converts the proposal in a continuous multi-modal exploration and monitoring tool that allows trend identification and perception of the harmonic or inharmonic correlations between variables and even between different objects under study.

5. PIPELINE AND MAPPING DESCRIPTION

Figure 3 shows the block diagram of the implemented *FITS2OSC* pipeline [25], that connects the main *Python* kernel which runs over *Jupiter notebook* [26] and sends OSC [27] messages and images to *CSound* [28] audio software synthesizers.

Regarding the audio part of the process, the values of every target variable are extracted from the DVT files using *astropy* [29, 30] and *numpy* [31] libraries, to be converted into float values that are sent via OSC with *python-osc* [32] to *CSound*, where independent instruments generate the sonification of each variable to conform the final soundscape.

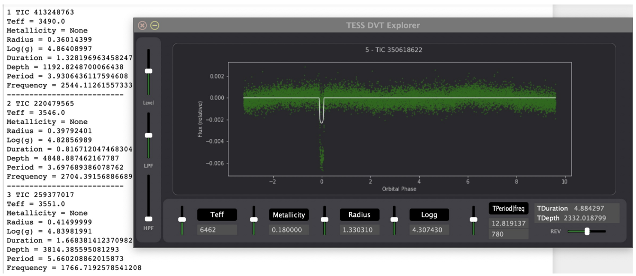

Figure 4: Prototype user interface screenshot during the sonification of TIC 350618622.

Table 1: Target star variables to CSound Instruments mapping.

Variable	Freq. factor	CSound Opcode	Amp. factor
Teff	1/2	oscil	1/20
Metallicity	+/- 10000	dust2	1/2
Radius	100	fmb3	1
Logg	100	buzz	1/4
TPeriod	1/10000	fmvoice	1/2

In reference to the graphic display, the folded lightcurves stored in FITS extensions for each TCE are used in the multimodal representation of every object. In this sense, *Figure 2* is also an example of the png files generated with *matplotlib* [33] and incorporated in the prototype's UI. As can be seen in *Figure 4*, in addition to the light curve representation, the user interface is provided with level and mute controls for each instrument, as well as with frequency adjustable *Hi pass* and *Low pass* filters plus a reverberation module oriented to provide a music-inspired sonification and to allow its use in musical applications.

The mapping strategy used in this study follows an *as direct as possible* paradigm, trying to reduce this process to the introduction of multiplication factors which adjust the domain conversion of astronomical variables into sound variables. No mental models [34] are used in this first prototype -as for instance, commonly applied in the sonification of mass quantity-, to maintain the numerical approach and to reduce the inferences needed in the comprehension of the complete soundscape.

Table 1 lists target variables, *CSound* opcodes [35] and domain correction factors used in frequency and amplitude mapping. Duration and depth of each detected transit has been mapped to duration and amplitude of each synthesized soundscape to generate a music inspired sequence of sonifications.

The next link provide a short video demonstration showing the behavior and possibilities of the prototype.

`https://vimeo.com/702224818`

6. INTERDISCIPLINARY AESTHETICS

Dealing with Sonification challenges naturally involves considering multidisciplinary aspects that strongly affect the final representation and its potential use. As highlighted by Walker et al. [36] many critical questions should be resolved to generate useful sonifications. Although the translation of data into music can lead to the loss of information and the distraction from the object of study, in an attempt to establish some acceptable reference points that allow receivers to understand the information contained in a sonificated message, music has been pointed as a potential global background knowledge that can help the audience in the identification of correlations between the sounds and the data and to increase engaging levels [37]. Even the implicit knowledge of musical structures [38] and the existence of music-specific neural networks in human brain [39] are rich areas of investigation. Perani et al. studies suggest that "the neural architecture underlying music processing in newborns is sensitive to changes in tonal key as well as to differences in consonance and dissonance" [40], which can lead to demonstrate that most of the basic musical expressions are already understood by the human being in the first days of life.

Taking into account all of these factors, the development of the prototype described in this article points to the exploration of an equilibrium between abstract and classic musical forms of sound that can contribute to the generation of sonifications with a certain degree of abstraction but accessible enough by the audience to narrow misinterpretations [41] and to allow connections between the sounds perceived and the underlying data. In this sense, and moving around Vickers' *Aesthetic Perspective Space* [42], Spectral music inspired sonifications are here proposed as an aesthetic solution with the potential to accurately preserve data relationships in the mapping while producing music sounding sonifications with a moderate level of abstraction that invite the listener to focus the attention in the object of study, highlighting the message over the form and reducing distraction and fatigue induced by long time exposures.

7. LISTENING TO OBJECTS OF INTEREST

Table 2 presents the coordinates and links to reference publications describing some of the Tess Objects of Interest (*TOI*) used in the sonification. TIC 172900988 is a binary system with a period close to 19.7 days and an eccentricity close to 0.45, that hosts a transiting circumbinary planet detected from sector 21. It transited the primary star and then five days later it transited the secondary star [43]. HIP 67522 b is a confirmed transiting hot Jupiter orbiting TIC 166527623 (Teff = 5650, M = 1.2Me) in the 10 to 20 Myr old Sco-Cen OB association [44]. TIC 257060897b is an inflated system having one of the smallest densities known so far [45]. TOI-2445 b is a super Earth exoplanet that orbits an M-type star. Its mass is 2.1 Earths and it takes 0.4 days to complete one orbit around TIC 439867639 [46]. TOI-2427.01 is a 1.80 Re planet candidate with a 1.31 day orbital period orbiting a K dwarf(TIC 142937186) that is 28.5 pc away and has a V magnitude of 10.30 [47]. TOI-2406 b is a sub-Neptune orbiting the thick-disk, mid-M dwarf star TIC 212957629. The stars low metallicity and the relatively large size and short period of the planet, make TOI-2406 b an unusual outcome of planet formation, and its characterization provides an important observational constraint for formation models [48]. TOI-2337 b is a massive, uninflated planet (1.6 MJ, 0.9 RJ) on the shortest period orbit (P = 2.9943 days) ever observed around a red giant (3.2 Rsun, 1.4 Msun) star [49]. TOI-2257 b (TIC 198485881) is a long-period (35 days) sub-Neptune orbiting an M3 star at 57.8 pc. Its transit depth is large enough (0.4%) to be detected with medium-size, ground-based telescopes[50]. *AU Mic* (TIC 441420236) hosts a young nearby exoplanet system that serves as a useful laboratory for probing and characterizing young exoplanetary systems that could present additional non transiting planets that need to be confirmed. The model seem to be consistent with a compact resonant multi-planet chain in a 4:6:9 period [51]. TOI-2202 is an early K-type star with a mass of 0.82 the mass

Table 2: Example list with coordinates and publication references

Name	RA(2000)	DEC(2000)	Ref.
TIC 172900988	08:34:38.80737	+31:33:14.6804	[43]
TIC 166527623	13:50:06.27970	-40:50:08.8811	[44]
TIC 257060897	15:10:07.66974	+72:42:37.2466	[45]
TIC 439867639	02:53:15.81819	+00:03:08.7844	[46]
TIC 142937186	03:29:09.83348	+31:21:46.9614	[47]
TIC 212957629	00:35:13.21911	-03:22:14.2880	[48]
TIC 230001847	19:22:28.79651	+60:51:13.9011	[49]
TIC 257060897	12:58:57.68144	+77:39:41.6896	[50]
TIC 441420236	20:45:09.53250	-31:20:27.2379	[51]
TIC 358107516	03:24:54.86176	-73:57:27.2632	[52]
TIC 176956893	06:43:19.94322	-66:56:51.6331	[53]
TIC 298663873	18:31:46.49083	+56:39:03.0671	[54]
TIC 237913194	01:29:46.95650	-60:44:23.8365	[55]
TIC 27491137	14:29:34.24261	+39:47:25.5433	[56]
TIC 188589164	15:58:18.79764	+35:24:24.2798	[57]

of the sun, a radius of 0.79 the radius of the sun, and solar-like metallicity. This system is very interesting because it presents two warm Jovian-mass planets orbiting near the 2:1 mean motion resonance, which is a rare configuration [52]. TIC 176956893 is a massive evolved subgiant (M= 1.53 MJ, R= 2.90 RJ) hosting a hot Jupiter that was flagged as a false positive by the *TESS Quick-Look Pipeline* due to periodic systematics introducing a spurious depth difference between even and odd transits. Combining space-based TESS photometry, ground-based photometry, and ground-based radial velocity measurements, TOI2184 b has been finally reported as an orbiting planet, demonstrating the feasibility of detecting planets around faint post-main sequence stars (TESS magnitude greater than 12 with TESS bandpass = 600 - 1000 nm, centered on 786.5 nm, the traditional Cousins I-band central wavelength) [53]. TOI-2180 b is a 2.8 MJ giant planet orbiting a slightly evolved G5 host star (TIC 298663873) [54]. TIC 237913194 b, with a mass of MP= 1.942 MJ and a radius of RP= 1.117 RJ, implying a bulk density similar to Neptunes, orbits a G-type star (M= 1.026 Msun,V= 12.1 mag) with a period of 15.17 days on one of the most eccentric orbits of all known warm giants (e0.58) [55]. TOI-2076 is a transiting three-planet system of sub-Neptunes orbiting the bright (G = 8.9 mag), young (340mp80 Myr) K-type star TIC 27491137. Although a validated planetary system, the orbits of the two outer planets were unconstrained as only two non-consecutive transits were seen in TESS photometry. This left 11 and 7 possible period aliases for each. To reveal the true orbits of these two long-period planets, space-based and ground-based photometric follow-up of TOI-2076 c and d with CHEOPS, SAINT-EX, and LCO telescopes was required [56]. GJ 3929 b, is a hot Earth-sized planet orbiting the nearby M3.5 V dwarf star, GJ 3929 (TIC 188589164, TOI-2013). Joint modelling of photometric observations from TESS sectors 24 and 25 together with 73 spectroscopic observations from CARMENES and follow-up transit observations from SAINT-EX, LCOGT, and OSN yields a planet radius of Rb=1.150 Re, a mass of Mb=1.21 Me, and an orbital period of Pb=2.6162745 days. The resulting density is compatible with the Earth's mean density of about 5.5 g/cm3. Due to the apparent brightness of the host star (J=8.7 mag) and its small size, GJ 3929 b is a promising target for atmospheric characterization with the JWST [57].

The next link provides a sequential auditory representation of 132 TOI, including the above mentioned, that host at least one planet confirmed during the exploration of 48 sectors of the *TESS* mission.

`https://vimeo.com/702520208`

8. FRAMEWORK AND FUTURE DESIGNS

Continuing with the exploration and development of tools and techniques focused in the interdisciplinary field between Music and Astronomy and with the main goal of building a solid proposal for an Auditory Virtual Observatory in which this article is framed, some of the improvements planned to be included in future designs will be addressed to incorporate Virtual Observatory (VO) tools like Aladin widget, Vizier and Pyvo access in the prototypes, as well as binaural and ambisonic spatialization of the sonification soundscapes. More demonstration videos of the overall project are also available in the next link.

`https://vimeo.com/user82659899`

To conclude, it is worth mentioning that all the prototypes of this research are expected to be tested in the next stage of the investigation by non-specialized and specialized users in both fields, Music and Astronomy.

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