SEEKING A REFERENCE FRAME FOR CARTOGRAPHIC SONIFICATION

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ABSTRACT

Sonification of geospatial data must situate data values in two (or three) dimensional space. The need to position data values in space distinguishes geospatial data from other multi-dimensional data sets. While cartographers have extensive experience preparing geospatial data for visual display, the use of sonification is less common. Beyond availability of tools or visual bias, an incomplete understanding of the implications of parameter mappings that cross conceptual data categories limits the application of sonification to geospatial data. To catalyze the use of audio in cartography, this paper explores existing examples of parameter mapping sonification through the framework of the geographic data cube. More widespread adoption of auditory displays would diversify map design techniques, enhance accessibility of geospatial data, and may also provide new perspective for application to non-geospatial data sets.

Index Terms— cartography, geography, geospatial data, map, parameter mapping, sonification, audio

1. INTRODUCTION

Geospatial data are characterized by their position in space and time. Consideration of the spatio-temporal properties of data reveals patterns that could be missed when treating locations or time values as generic numeric variables in a multi-variate data set. Typical assumptions of independence between observations do not hold due to spatial and temporal autocorrelation. Further, parameter mappings that overlook organization of data along spatial or temporal dimensions compel the listener to mentally reconstruct that organization. The strong temporal qualities of audio have provided a natural parameter mapping for time series data (e.g., [1]); but, the effective representation of (geo-)spatial data and the use of spatial audio remain open questions. Organization of data and sonification into binary categories of “spatial” and “non-spatial” [2] take an initial step toward addressing the peculiar needs of geospatial data, but further examination of the “spatial” category is warranted.

Specialized systems have emerged to handle geospatial data. Geographic information systems combine data structures and computer algorithms to support the unique needs of geospatial data storage, processing, and efficient query. Statistical methods that accommodate spatial and temporal autocorrelation have been designed (e.g., [3]). Evidence from psychology and neuroscience suggests that the human brain has specialized mechanisms for encoding and processing spatial data (e.g., [4]). And, design and use of maps have been studied as communication channels for geospatial data (e.g., [5]).

Thematic maps and reference (or navigation) maps constitute two common types of geographic map. Thematic maps depict the location of attribute values over geographic space. Among their varied purposes, thematic maps encourage the map reader to notice spatial patterns. For example, a map of Oregon that depicts population density shows the majority of the population living on the west side of the state (Figure 1). The map does not explicitly declare this pattern; the map reader interprets the information they perceive from the map. In contrast, navigational maps facilitate route learning, guide movement through the physical environment. Experience navigating through physical space inspires a metaphor for exploration of a data space [6], creating a connection between the two map types. But this paper challenges that connection and emphasizes sonification of geospatial data in thematic maps.

Auditory display of geospatial data is not a new idea. Although the majority of modern cartographic display techniques fall in the realm of graphic design, widespread and inexpensive

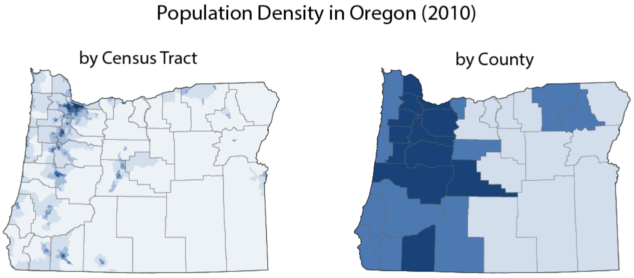

Figure 1: Maps of population density in the state of Oregon are graphic examples of thematic maps. These maps use color to depict population density (*attribute*): darker colors indicate higher population density. Geographic coordinates (*location*) determine the positions of features within the map. Notably, both maps depict the same underlying data. Data recorded by Census tracts (left) have been aggregated by county (right) to demonstrate one type of cartographic generalization. *Data Source: U.S. Census Bureau*

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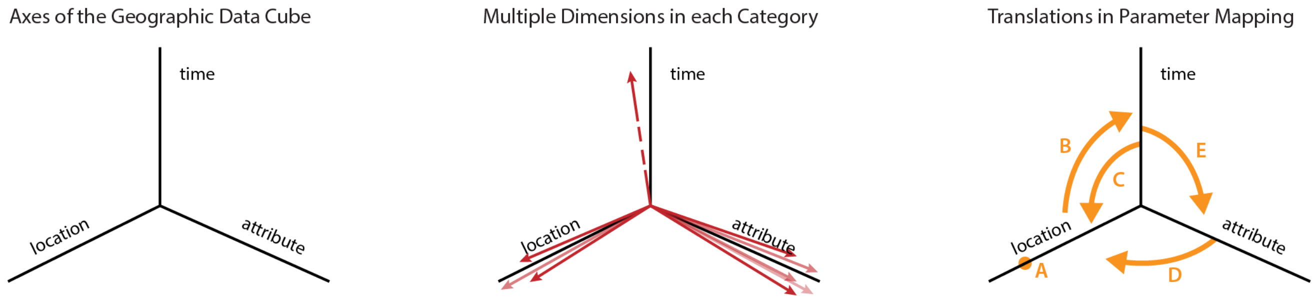

Figure 2: Conceptual categorization of data across location, time, and attribute (left) is an established framework for organizing geospatial data [7]. Each of these categories may be further subdivided across multiple dimensions (center). The number of dimensions depends on the specific data set under consideration. Displays of geospatial data create parameter mappings that stay within or translate across the axes of the geographic data cube (right). For example, depiction of data location to screen coordinates demonstrates a mapping within the location axis (A). And among many possible examples of translations: turn-by-turn directions translate spatial information into a temporal sequence (B), time series data represented as line graphs convert time into a spatial location on the x-axis (C), scatterplots translate attribute values into locations (D), and time series data may be represented with a color attribute in a static graphic (E).

sound synthesis in the early 1990s prompted cartographers to consider auditory displays. In parallel with expanded use of audio in more general human-computer interfaces, cartographers used sound to represent uncertainty in remote sensing data [8] and to highlight anomalies in data [9]. However, initial interest and optimism about the use of audio in geospatial data displays has waned. Recent availability of browser-based audio tools revived some interest in augmenting web-based interactive maps with auditory elements (see review in [10]). Still, proliferation of visual displays and challenges in the design of effective parameter mappings for sonification of spatial data, have meant that the use of sonification in cartographic design has been low.

To support more widespread adoption of sonification in cartography, this paper draws attention to parameter mappings that cross the conceptual category boundary between data location and the temporal dimension of an auditory display. The next section provides a brief overview of geospatial data, associated data transformation techniques, and example cartographic design guidelines. The third section considers existing sonification approaches to (geo-)spatial data, highlighting the role of space and time in those displays. A final section reflects on the current status of sonification in cartography, posing an open question about the implications of cross-category parameter mappings.

2. GEOSPATIAL DATA AND CARTOGRAPHY

Geographers and cartographers have a long history of organizing, transforming, and representing geospatial data. The discussion revolves around the location and time axes of the geographic data cube as a context in which to examine the application of parameter mapping sonification to geospatial data.

2.1. The Geographic Data Cube

An emphasis on location, or position within a two (or three) dimensional reference frame, distinguishes geospatial data from other multi-dimensional data sets. The geographic data cube [7], an established conceptual framework from geography, organizes data in three categories: attribute, time, and spatial location. The three axes represent three categories of data inherent and necessary to any geospatial data set (Figure 2, left). Omitting any category is detrimental to interpretation of the data set. For example, a temperature attribute value carries little information without the context of when and where the observation was recorded. While all three categories are necessary, a category may be held constant for a given map product. As a case in point, the maps in Figure 1 depict a range of locations and attribute values, while holding time constant (the year 2010).

The three categories each consist of one or more dimensions (Figure 2, center). Of particular interest in the case of geospatial data is the location axis that has two or more dimensions. A location may be recorded as two-dimensional coordinates on the surface of the earth, and elevation may be added as a third location dimension. Notably these dimensions of spatial location are orthogonal to one another, and values along these dimensions tend to be autocorrelated: "everything is related to everything else, but near things are more related than distant things" (Tobler's first law of geography, [11]).

2.2. Cartographic Processing

Cartographers have developed techniques to transform geospatial data in preparation for display in geographic maps. Two such techniques, projections and generalization, are described here. Projections, or systematic translations of spherical geographic coordinates (e.g., latitude and longitude) into two-dimensional planar (page or screen) coordinates, are standardized data transformations. Locations in the physical world have a one-to-one mapping with locations the two-dimensional frame (although relationships between locations are inevitably, but predictably, distorted). Even though projection introduces error in the location data, the resulting two-dimensional model has been applied to good effect in helping people conceptually understand and reason about phenomena on the surface of the earth.

Print and screen technologies have traditionally necessitated the dimension reduction from three to two dimensions for map production. Even through the physical world is three dimensional and 3D rendering technologies are emerging, the most common map displays – maps printed on paper, displayed on computer screens – are still constrained to a two dimensional spatial plane. Although this spatial dimension reduction affords a simplified special case of geospatial data, projection may not be required for auditory representations [2] and may be propagating a visual bias into auditory display design.

As a second example, generalization eliminates unnecessary clutter or emphasizes specific characteristics of the data [12], and may be applied to data from any of the three data cube categories. Cartographers have developed many generalization routines for geospatial data in visual displays, and analogous approaches have also been applied in sonification, e.g., by emphasizing "distinct" data values [6]. Generalization transforms data into a simpler or alternative form. The degree to which such tools are applied depends on several factors including display technology and modality.

Generalization helps focus attention on the message that the map was designed to convey, but introduces error and removes detail (compare, e.g., the two maps in Figure 1). In some sonification prototypes, heavy-handed generalization or simplification has made evaluation feasible, but researchers recognize that it is not realistic data (e.g., [13]) and is not functionally equivalent to its visual or tactile counterparts. While arbitrarily reducing data complexity is not a long term solution, generalization may still play a role in the design of an effective parameter mapping.

2.3. Symbolization of Geospatial Data

Map symbolization, and more generally graphic or sonification design processes, creates relationships between data values and display values. This section briefly describes the treatment of location and time data in typical cartographic design, and considers how these approaches do or do not apply to auditory displays. In some cases, a direct relationship exists between the data and an analogous display parameter, but a direct relationship is not strictly necessary, and mappings may cross the boundaries outlined by the categories of the geographic data cube (Figure 2, right).

Cartographic design commonly presents geospatial locations as corresponding locations within a graphic map display. The spatial arrangement of light receptors in the retina of the eye and the projection of that two dimensional organization into higher level processing areas of the brain [14] further support a direct mapping of the location of geospatial data to location within a visual display. Similarly, this "easy" choice for representing location is also observed in tactile map graphics: the position of symbols on the map correspond to location in the real world.

The relative ease with which humans visually perceive spatial relationships has also lead to the use of location to depict non-spatial data. For example, *attribute* values are represented by a *location* in space in a scatterplot ("spatialization", [15]) or iconographic display [16]. While the translation across axes of the geographic data cube can be effective, there is still a correlation between the ease and usability of a display and the alignment between the dimensionality of the data and that of the display.

However, this approach does not directly generalize to auditory displays. Despite what may appear at a cursory glance to be an easy direct mapping of location attributes of the data to monaural or binaural spatial audio cues, on closer inspection, several limitations become apparent. On the plus side, spatialized audio targets the human ability to localize sounds [17] and can "leverage the natural affordances of the space and the user's location within the sound field" [18]. When applied to sonification of non-spatial data, spatialized audio has been reported to facilitate segregation between data streams [6, 19] and to provide orienting cues for the use of a haptic mouse in the absence of visual feedback [13]. But, spatialized audio is relative to the listener, and relies on either distance cues or elevation cues to determine a position in a two dimensional space. The egocentric perspective that relies on distance cues may be sub-optimal for communicating relationships between data points (e.g., [20]) and accuracy of perceived location varies across different axes of physical space (e.g., poor resolution in conveying elevation [21, 22]). These nuances highlight open questions about the use of spatialized audio to depict geospatial data.

As an alternative to spatialized audio, cartography has explored depiction of one of the spatial dimensions on the time axis. Time has been used to depict both temporal and spatial data. Interactive maps have provided functionality to produce animations of geospatial data that change over time (see review in [23]). Animated visual displays are consistent with the general recommendation to use time to represent temporal data [24]. As cartographers and sonification designers explored stand-alone auditory displays of geospatial data, the time dimension was also co-opted for the display of location. In 2000, Saue [6] proposed the idea of spatial data "temporalization," which translates location data into the time dimension of an auditory display using a metaphor of walking through an environment. The depiction of location data over time has since been a common approach to sonification of geospatial data (either alone or with redundant location information from other sensory modalities). A drawback to this approach however, is that the reduction of two dimensional space to a linear sequence takes longer to perceive than a visual display of the same data and data that is spatially proximal may be separated by extended time intervals. The listener faces the challenging task of remembering a long sequence of data values and mentally reconstructing two dimensional space. And in the context of accessibility, the resulting display, which may take more than a minute to render depending on the size of the data set, lacks functional equivalence with its visual counterpart, which might take only a few seconds to perceive and mentally process.

The next section expounds on the auditory display of geospatial data, reviewing a number of sonification examples.

3. SONIFICATION OF GEOSPATIAL DATA

As sound production and real-time audio rendering became possible in computer hardware and later through software, sonification emerged as a feasible data display modality across many application domains [25, 26]. Although researchers have recognized the challenge of presenting multiple variables in a single audio stream (e.g., [24]), there are also many success stories. Sonification has been used to depict large, complex, and multi-dimensional scientific data sets including recordings of solar winds [27] and climate data [28]. Still under investigation is effective and efficient sonification of geospatial data.

Amid ongoing advances in technology and expanding adoption of sonification across multiple disciplines, geographers too considered ways to incorporate audio into map design. Audio was viewed as a "largely untapped medium for the communication of cartographic data" [8] and a "means of expanding the representational repertoire of cartography and visualization" [9].

Geographic applications began pairing auditory representations of non-spatial data with visual map displays. For example, Fisher [8] represented uncertainty information associated with classified remote sensing data, and Krygier [29] augmented animated graphics with redundant information through natural sounds. Over the following decades, however, interest among cartographers waned.

Although the introduction of audio capability in web browsers spurred interest in multimedia mapping (see review in [10]), initial difficulties adopting audio into cartographic design had already set the tone. Some geographers and cartographers came to doubt the potential of auditory displays to represent of spatial data over non-trivial spatial extents [30], or grew skeptical of any non-visual display of geospatial data [31]. Rather than justification for jumping ship and abandoning sonification, however, this skepticism could indicate a lack of an appropriate design. And, not all have abandoned auditory map display: "Rather, the use of sound forces us to rethink the very concept of the map as primarily a visual image of space that serves as a simple conveyer of information" [32].

The remainder of this section explores three groups of examples, organized by the role that audio plays in the display: audio-enhanced displays, multimodal displays, and stand-alone sonification.

In audio-enhanced displays, sonification of attribute data accompanies or enhances another display modality. Location information is conveyed through, e.g., vision [30, 10]. Interaction with a mouse, touchpad, or stylus triggers playback of an audio recording or renders a data value in audio that is specific to the selected location. For example, in an interactive web map the map user triggers rendering of a parameterized note or playback of a pre-recorded audio clip by selecting a location using a mouse-click or tapping a touchscreen. Within this group of audio-enhanced displays, the role of sonification is limited to the display of isolated non-spatial data values. The audio component of the display cannot stand alone; the display relies on an alternate display modality to communicate spatial location - the aspect of the data that makes it (geo-)spatial. And, the map reader must mentally integrate disparate sensory input streams to interpret the complete set of spatial and non-spatial data attributes.

In other multimodal displays, the auditory component of the display conveys partial or redundant information about spatial location. Location data is depicted in a two dimensional plane through, e.g., proprioceptive feedback [33, 34, 35, 36, 37, 38, 39], or a haptic device [40, 13]. While such audio-enhanced displays have found some success communicating spatial data, evaluations have found that users have difficulty interpreting spatial patterns, without a companion visual or tactile display [41, 38] or without providing contextual clues about the specific layout [42].

The number of examples of stand-alone sonification of (geo-)spatial data is more limited. Stand-alone auditory displays encode sufficient information in the auditory stream to convey location information independent of other display modalities. Flowers, Buhman, and Turnage [43] used frequency and time as two axes for an auditory display of scatterplots, depictions of (non-geographic) data points within a two-dimensional space. Alty and Rigas introduced *AudioGraph* [42], which used pairs of notes to represent coordinate locations within a display. Timbre indicated which axis is being represented and frequency encoded location along that axis. A virtual cursor traced shapes in the display, playing a pair of notes at each vertex. Specifically to display geospatial data, Zhao et al. implemented a stand-alone auditory display in *iSonic* [21] that traverses the two dimensional geographic space following pre-established scan patterns. A virtual cursor moves through the display as auditory feedback indicates the data value at the cursor location. As the sounds play, the listener must mentally assemble the individual notes to recreate the two dimensional arrangement of objects in the display. Reports from evaluation of the *AudioGraph* display indicate some success communicating spatial information, but also difficulty interpreting overall patterns [42]. Over several years of development, the *iSonic* interface seems to have moved away from the audio-only display in favor of an interactive display with a spatial input device [35]. Such findings are consistent with other evaluations of non-visual display in which a heavy burden is placed on users' working memory [44].

The parameter mappings employed in the examples mentioned in this section are summarized in Table 1. The table lists the location and attribute categories present in the data set (none of the example sonifications depicted temporal data), along with the respective auditory dimension in which that data was encoded. Listed parameter mappings are available in the respective systems, but may not be concurrently available. The set of examples is not intended to be exhaustive, but to illustrate the variety of approaches that have been explored. The next section reflects on trends among these example systems and poses an open question for future research.

4. REFLECTION AND OUTSTANDING CHALLENGES

The examples of geospatial data sonification listed above show diversity among parameter mappings, and shows that translations across categories of data and display dimensions are common. The categories themselves were not mutually exclusive. Amplitude, for example was used in a way that mimicked distance (*location*) in the physical world with closer features represented as louder sounds [34, 13]. But, amplitude was also used in a way that mimicked magnitude (*attribute*) [37, 10]. Both uses employ intuitive metaphors, and there is no single rule to assign amplitude to a category of display dimension. Within the location category, special attention is draw to the distinction between egocentric and allocentric perspectives. Differences between the two perspectives have implications for interpretation of the display. Beyond categorization as spatial and non-spatial, parameter mappings may also need to address or accommodate the alignment of perspectives between the data and the display. Acknowledging the limitations of a simplified account of the examples, this summary offers one interpretation and provides a basis for discussion; for full details of the parameter mappings and their respective display systems, readers are referred to the original papers.

With an exponential number of possible combinations, the selection of auditory dimensions to serve as such a reference frame is neither obvious, nor trivial. Selecting a parameter mapping is complicated by perceptual limits on the number of auditory events that can be processed concurrently [45] and interactions between auditory dimensions (e.g., [46, 24]). Further, results from empirical evaluation of sonification parameters by experiment must be applied with caution when removed from the laboratory and applied to real-world data [46, 13] or generalized from pure tones to more complex musical sounds [47]. A two-dimensional auditory reference frame to support effective and efficient auditory displays of geospatial data is still illusive.

Table 1: Existing implementations of (geo-)spatial data sonification provide examples of parameter mapping sonification representing location and attribute data (none of the example systems depicted temporal data). Grey highlighting and **bold font** emphasize egocentric location information and translation across axes of the geographic data cube, respectively.

Reference, Content Domain *(System)*	**Location**	**Attribute**
Audio-enhanced Displays (no auditory display of spatial location)		
Bearman and Fisher [30], elevation, uncertainty *(ArcGIS extension)*		data value → frequency
Brauen [10], multiple airborne pollutants		data value → amplitude, audio clip
Audio-enhanced Displays (with complementary visual, proprioceptive, tactile, or haptic display of location data)		
Krueger and Gilden [33], named polygon features *(KnowWhere™)*	relative location → **audio icon**	data value → speech
Daunys and Lauruska [34], shapes of polygon features	distance → amplitude relative location → **audio icon**	data value → speech data value → audio clip
Zhao et al. [35], choropleth map *(iSonic)*	x-location → azimuth	data value → frequency, speech, timbre
Nasir [36], surface contours *(Geo-Sonf)*	direction → azimuth, direction → **time**, distance → **frequency**, **number of notes**	
Adhitya and Kuuskankare [37], multiple building attributes *(Sonified Urban Masterplan)*	movement → **onset time**, distance → **duration**	data value → frequency, timbre, amplitude
Brittell, Young, and Lobben [38], choropleth map *(mGIS)*	relative location → **audio icon**	data value → frequency
Kaklanis, Votis, and Tzovaras [40], reference maps *(Open Touch/Sound Maps)*	direction → azimuth, distance → **frequency**, relative location → **audio icon**	data value → speech
Geronazzo et al. [13], guided pointing, object location	relative location → azimuth relative location → elevation distance → amplitude	
Schito and Fabrikant [39], elevation	x-location → azimuth, **frequency** y-location → **waveform**, distance → **frequency** relative location → **time**	data value → **duration**, frequency
Audio Displays (stand-alone auditory display of spatial location)		
Flowers, Buhman, and Turnage [43], scatterplot	x-location → **time**, y-location → **frequency**	
Alty and Rigas [42], geometric shapes *(AudioGraph)*	coordinate value → **frequency**, coordinate axis → **timbre**, shape → **time/order**	
Zhao et al. [21], choropleth map *(iSonic)* [temporalization]	location → **onset time** relative location → **audio icon** x-coordinate → azimuth y-coordinate → frequency	data value → frequency, timbre

In the case of geospatial data, the need for data patterns to be simultaneously interpreted across multiple dimensions poses a unique problem. The goal is not to encourage separation or perceptual streaming, but to organize data within a two (or three) dimensional frame and communicate patterns that occur across those dimensions (c.f., [6, 19]). Recall at this point that the objective of thematic maps is to communicate a general spatial pattern.

A trend across the (geo-)spatial sonification examples is reliance on time or temporal order. The sonification follows a cursor through the display controlled by either an interactive spatial input device or a pre-established scan path. The supporting metaphor of movement through a space occupied by sound sources offer both affordances from real world experience and appealing simplicity in implementation. But the resulting sequential exploration is susceptible to variable or ambiguous interpretations prompted by spurious depiction of distance between locations that are proximally located (pre-planned and automated scan patterns) or emergent texture and patterns that are intertwined with the speed of movement (user-controlled spatial input devices). Time that elapses during movement directly corresponds with the timing of auditory events. This interplay between space and time leads to emergent properties of the sound, creating textures and patterns [16, 24, 37] that can be difficult to anticipate from the underlying data.

Harnessing the power of these emergent patterns means striking a balance between a parameter mapping that is "exact and rigorous" [48] and one that is more fluid: "It should be stressed that the sound tracks need to be constructed according to their own sound logic and cannot simply be reduced to the structure of data or other map variables" [49]. Again for an application in which general patterns are of interest, the ability to extract a single data value with high precision is not a goal of the display. For sonification designers who are steeped in a visual tradition, such as that of cartography, finding such a balance will require conscious effort to mitigate visual bias (e.g., [50]).

Even though geospatial data are not inherently visual, an occular-centric trend in cartography and GIS has emphasized visual displays. Mainstream cartographic designs often focus on graphic displays, and occasionally later append an auditory component of the display. The auditory display is an afterthought. It is subject to the decisions that were made to optimize the graphic display. A conscious effort is required to avoid temptations to translate visual displays into audio. Without diminishing the value of visual displays, the focus on map graphics allows implicit assumptions in the way that sighted researchers think about geospatial data to persist unnoticed and to creep into the tools for map production. For example, the implementation of the GeoTools library [51] tightly integrates the spatial data representations with the Swing graphics library [52], which is good for code optimization in implementing visual map displays but can complicate efforts to explore auditory displays that still rely on functionality to handle geospatial data. Map production that targets auditory displays earlier in the design process can help reverse some of the embedded visual bias.

In practice, the dominance of visual maps in print and on computer screens has lead to a scarcity of alternative cartographic display techniques and a reduction in accessibility of geospatial data, particularly for people with disabilities [53]. As noted in the context of multidimensional astronomy data, however, auditory display enhanced both accessibility for researchers who are blind, and conveyed patterns beyond those apparent in visual displays [25, 54]. Visual displays of geospatial data are good, but not sufficient to support a diverse population of map readers and growing volumes of scientific data. With efficient and usable designs, auditory displays could make a substantial contribution to the cartographer's toolbox.

Using the geographic data cube to describe the structure of cartographic sonification reveals an open question: how does translation across the conceptual boundaries of the geographic data cube influence communication of geospatial data through sonification? By investigating this question, geographers and cartographers can join musicians and sound designers in pursuing ways to think about auditory patterns that emerge from sonification of multi-dimensional data sets. A pursuit that seeks a reference frame for cartographic sonification at the intersection of exact science and expressive art.

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