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SONIC REPRESENTATION OF RESERVOIR ELECTRICAL AND HYDRAULIC CONDUCTIVITY VARIATIONS

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ABSTRACT

Electrical and hydraulic conductivities in the reservoir environment can vary over many orders of magnitude over very small distances, while human vision is limited to perception of a Cartesian space in which the perceptual scales in all directions are commensurate. This means that visual plots of electrical or hydraulic conductivity variations with respect to a spatial coordinate must plot the logarithm of the data versus one or more spatial coordinates. This traditional visualization scheme, which is facilitated by the contemporary use of graphical workstations, exchanges precision for ease of data presentation, since the logarithmic mapping smoothes the data. This may be a good thing if gross earth structures are targeted, but it can be counterproductive if truly high-resolution mapping of the earth is desired. Since the frequency and amplitude dynamic range of the human ear is many orders of magnitude, alternative sonic data presentations preserve the true scale of the data. In these presentations, traditional log strip charts serve as visual "scores" while a "sonification" presents the data in auditory, or "musical", form. There are many natural maps of conductivity data into sound realizations, with a wide range of possible timbres and ensembles possible for correlating large data sets. These maps have natural extensions to fractal conductivity distributions. A trial piano sonification of induction well-log data, presented for your listening pleasure, maintains the scale of the induction data and presents the information in listenable form, reminiscent of some contemporary composed music.

We conjecture that with the increasing availability of inexpensive electronic synthesizers, true multi-media capabilities, and virtual reality work-stations, that all geophysical data will be mapped to many dimensional perceptual media which best preserve their true geometric scales. In the case of reservoir distributions of electrical and hydraulic conductivities, the "pure" presentation media will be sound, perhaps with an accompanying score for those who sight read. We further conjecture that the linguistic and musical aptitude of humans for detecting and remembering structure in sound strings will lead to increased precision in reservoir description and analysis.

Remember, you heard it here first!

INTRODUCTION TO SONIC DATA REPRESENTATION

The idea of auditory representation of physical phenomena is not new. At the very beginning of Western science, Pythagorean cosmology used musically analogies. At the dawn of the contemporary era, Kepler (1619) examined musical analogies of planetary movement. Purposeful contemporary sonic representations of physical data include musical representations of geomagnetic variations (Saito et al., 1996), protein structure (Dunn and Clark, 1999), and anesthesiology data (Fitch and Kramer, 1994). James (1993) discusses the relationship between music and science throughout western history.

General contemporary studies of the technology of sonification are also available. Zipf (1949) and Moles(1966) give an information theoretic analysis of sonic data streams, speech, and music. O'Donnell and Bisnovatyi (2000) discuss some of the technical issues in computer-user auditory interaction. Burns (1997) gives a synopsis of algorithmic music, which is of interest in data sonification. These references suggest that there are interesting analogues between sound and other data sets - but why is this correspondence of use in reservoir geophysics?

Geotechnical analysis involves large amounts of many kinds of data which must be interpreted in terms of a complicated model in many different petrophysical parameters. In the parlance of inversion theory, we need to invert an N-dimensional data space to an M-dimensional space, where both M and N are large. Such problems are the rule in physical, biological, and engineering studies before the approximation mill starts to crank the interpretation problems down to human size - hopefully without grinding up vital information in the process. One of the big problems with the analysis of such data sets is the difficulty in perceiving data sets of large dimensionality. A great deal of work has been done to facilitate visualization of such data, using creative graphical displays (Tufte, 1983, 1990, 1997). Useful as these approachs are, humans perceive more than three-dimensions routinely in every-day life - and they use five senses for their perceptions.

Given the propensity of humans to do what is technically possible, there will be a day in which the five senses are all stimulated electronically for business and recreation. For the present, though, technical means of presenting sonic representations of data exist and will be used for geophysical data representation in the near future.

Our purpose in this paper is discuss possible bases for sonification of electrical and hydrologic parameters. We first briefly review the perceptual basis of sonic data representations and their synergy with visual data representation. We then discuss some possible mathematical mappings from electrical and permeability data space to sonic data space.

Sounds can arise from natural sources, from language, from musical systems, or from electronic sources. In our discussion, we are not necessarily tied to any particular musical system or theory.

PERCEPTUAL BASIS OF SONIC DATA REPRESENTATION

The literature of psychoacoustics is large and growing and must be addressed in effective sonification. We present a highly abbreviated and simplified discussion of some of the perceptual issues in sonification. Roederer (1995) and Zwicker and Fastl (1990) are good references for more information on this subject.

In making a mapping from geophysical data to a sonic representation, it is important to assess precision and dynamic range of sonic preception.

Tone data representation is has a large dynamic range, since human perception of pure tones extends from approximately 20 Hz to 16,000 Hz. For monaural presentation, measured tonal resolution of pure, enduring tones from 800 Hz. to 5000 Hz is approximately .5%. This resolution decays to approximately 3% at 100 Hz. If two tones, f_1 and $f_2 = f_1 + ?$, are played at once, they are distinguishable clearly and pleasantly if ? is greater than a critical band width $?_{CB}$. For smaller frequency differences, the two frequencies are perceived as beats or "rough" tone superposition. The critical band width $?_{CB}$ lies between a tone and a minor third for the frequency range from 800 Hz. to 5000 Hz.

These limits can be reduced by stereo presentation, by introducing some spectral content to the dominant tones, or by varying the duration of the tones. For example, dichotic presentation of f_1 and f_2 in different ears eliminates beat sounds. For actual musical instruments tones are not simple, are not steady, and a stereo effect is present - all of which decrease the perceptual limit.

Data can also be represented by tone amplitudes, instrument timbres, and vector sound. Each sonification scheme will have perceptual limitations imposed by the auditory space and the transfer function of the human ear. Hearing illusions can result from particular characteristics of the sound stream.

Reservoir data can consist of various physical property logs measured in numerous wells, 4D seismic data, geological sections, and miscellaneous tables and figures. Taken together, such data collections are multi-dimensional, where the dimensionality can be very large. Biomedical, economic, and engineering data can also be radically multi-dimensional. A great deal of science and art has been spent trying to develop effective means of representing these complex data sets visually on a surface (see, e.g., Tufte, 1983, 1990, 1997) However, sound is a natural means of representing multi-dimensional data, as we all will attest. Whether the sounds originate from a symphony orchestra, a pipe organ, a choir, a rock band, or a cocktail party, the average listener can discern multiple voices - i.e. data dimensions. Although a trained listener, such as a symphony conductor, is much better at this than most, it should not be difficult for an average listener to perceive at least ten dimensions. Imagine, for example, an ensemble piece for bagpipe, soprano, bass, barking dog, howling dog, squealing pig, fire siren, church bells, violin, trumpet, clarinet, and piano. Each dimension of this 14 dimensional data space should be painfully distinguishable to untrained listeners, supposing that some little attention to phasing is made.

The multidimensionality of sound representation is increased by the vectorial nature of sound. That is, we can detect from whence a sound originates. With multi-sourcing, it is possible to move sound about. Recent advances in acoustic antenna technology even permit aimed, highly focussed sound beams (Yoneyama et al., 1983; Pompei, 1999).

Imagine then that a virtual reality display is supplemented by a set of loudspeakers, which project interpolated sounds to an observer moving through the virtual display. This corresponds to a multi-media, many-dimensional display of the reservoir environment. The Evans and Sutherland StarRider system, with 6 cameras and 6 sound channels, approximates such a system.

We also speculate that visual and sonic data are remembered differently, with different degrees of precision. Most people seem to be more facile in memorizing sound streams, such as tunes or poems, than visual scenes. Exceptions occur, such as the extraordinary abilities of some autistic individuals to memorized large amounts of visual data (T. Grandin, Pers. Comm.). This difference in cognitive retension of data might be important in designing data fusion techniques.

SONIFICATION OF RESISTIVITY AND PERMEABILITY DATA

a) Point by Point Pitch Mapping

When data ranges over orders of magnitude, such as is the case for electrical resistivity or permeability data, then a particularly nice means of representing it by sound is to map it data point by data point to the tone of some instrument. If more than one data stream is present, then the sonic representation can be an ensemble. For linear maps, appropriate dilation and offset values can be applied to map the measured resistivity range into the audible range. The use of non-linear maps maps is particularly intriguing, with the non-linearity giving the possibility of "special effects" geared to recognition of particular data features. Information is maintained as long as there is a formation analyst with "perfect pitch". Recent research indicates that such individuals are common among native speakers of tonal languages.

b) Sonification by Data Projection

Another method of sonifying data which varies with respect to one or more spatial dimensions is to project it onto a sample space as a function of frequency or time. To illustrate how this might be done, consider the case of a resistivity or permeability log, which would be a sequence of delta functions of varying amplitudes. This is equivalent to a D^+ conductivity distribution with respect to depth, as discussed by Parker (1980) and Parker and Whaler (1981). This distribution then has an MT response with respect to frequency as measured on the Earth's surface, which can be sonically realized. With well-heads distributed over the surface, then the sonic projection would be a sound "surface". Unfortunately, the non-uniqueness of the D^+ inverse problem means that we cannot uniquely discriminate between various logs based on finite amounts of projected data. Of course, other physical response mechanisms could be used to perform the projection.

c) Data "Drums"

A third possible means of sonifying data is to use the geometric structure of the data to construct an analogous instrument which might then be sounded. A direct example of this would be to convert the shape of a two-dimensional object into a drum and then represent the shape by the sound of the drum. A classical problem in Spectral Geometry involves whether one might "hear" the shape of such a drum (Kac, 1966). Gordon, Webb, and Wolpert (1992) and Gordon and Webb (1996) demonstrate that two drum shapes can give the same sound. Hence, while a sonification of a geometric shape might be of practical interest, it gives a non-unique representation of the object.

Drums can also be constructed in fractal shapes. This representation is discussed by Brossard and Carmona (1986), Lapidus (1991a,b; 1993; 1994), Lapidus and Pomerance (1993), Lapidus and van Frankenhuysen (2000), Sapoval (1989), Sapoval et al. (1991), and Sapoval and Gobron (1993).

d) Data "Strings"

Another possible sonification strategy is to consider a well log as a sequence of discrete fractal data "strings", which are then "plucked", "struck", or "bowed" simultaneously or sequentially in a manner necessary to give a particular sound quality (Fletcher and Rossing, 1998) .

One sonification would result when all the data is interpolated and the interpolant is plucked. The theoretical basis for this sonification has been developed in papers by Lapidus (1991a,b); Lapidus and Pomerance (1993); and Lapidus(1994).

e) Equivalent circuits

Fletcher and Rossing (1998), among others, model the relationship between pressures and acoustic volume flows in musical instruments by equivalent linear and nonlinear circuits. Now many geophysical and reservoir processes also can be modeled with equivalent circuits. For example, the 1D and 2D magnetotelluric or fluid flow equations have transmission line or surface representations (e.g. Madden, 1972), which have acoustic equation counterparts. These acoustic equations could be used to design linear or surface instruments which would "play" the sonification of the physical flow.

EXAMPLE OF DATA SONIFICATION

As an example of the principles discussed in this paper, a suite of geophysical logs from ODP drill sites exemplifying Milankovitch frequencies has been sonified at the University of Utah Computer Music laboratory. A cassette of this sonification together with a description of the well logs can be had upon inquiry.

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APPENDIX : ARE SONIFICATIONS MUSIC?

Although our work is not concerned primarily with aesthetic considerations, the authors have noticed a resemblance of geophysical sonifications with purposeful artistic productions. Drawing inspiration from Duke Ellington (" If it sounds good, it is good") , we might postulate " If it sounds like music composed by humans, it is music". The musical structure of sonified resistivity data does suggest contemporary aspects of purposeful music.

One formal basis for discussing the relationship between data sonification and music is the fractal nature of both resistivity and permeability data (Barton, 1989; Cahn, 1989; Hewitt, 1986), and the fractal nature of music and speech (Voss and Clarke,1975; Voss, 1989). Hence we might expect some resemblance between our algorithmic sonifications and artistic music - especially contemporary music exploring the mathematical aspects of composition.

But still, can "rock" music be great music?

Consider the lengthy and perhaps controversal passage from Lévi-Strauss (1997, p. 86), concerning fractal algorithmic music and aesthetic value, contained below:

" ...To limit myself to a single example, the fractal character of a musical composition results from the fact that the relations between a small number of continguous notes is repeated unchanged when those fragments are compared with more extensive passages from the same piece.

This sort of construction can be observed in the work of the great masters. Already Balzac noted that " in Beethoven the effects are , so to speak, distributed in advance... the orchestral parts in Beethoven's symphonies follow orders given in the general interest and subordinated to admirably well conceived plans." A contemporary musicologist, Charles Rosen, explains the same matter in terms that could almost be borrowed from the language of the theory of fractals:

> This is perhaps Beethoven's greatest innovation in structure; the large modulations are built form the same material as the smallest detail, and set off in such a way that their kinship is immediately audible... One has the feeling that one is hearing the structure.

A little later he comes back and speaks of how " the most typical ornamental device is turned into an essential element of large scale structure."

However as already noted, fractal algorithms do not have the ability to engender, whether in painting or in music, more than those minor genres which I have called decorative - even if , in terms of their refinement and complexity, fractals often exceed, relative to painting at least, anything actually created by decorators. A large gap separates these often fascinating objects from an authentic painting or piece of music. The distance is, in fact, insurmountable. But does this, in principle, have to be the case? In this regard, one might note that the screening mechanisms necessary to generate fractals present an analogy with those implemented in stages by the same organs and nerve centers, which transmit to the brain only some of the peripheral impressions they register.

If it is so that the brain abstracts invariant properties out of these primary givens (but inflected by experience, individual history, and so on), could not the work of art then be the result of a feedback from the cerebral schema projected onto the work, which thereby fuses the thought object and sense impression?"

So perhaps, great music does contain its own meaning, a meaning which may not be present in petrophysical properties. For alternate discussions of aesthetic meaning versus information content, see Moles (1966) and Josephson and Carpenter (1992; 1994).