What is the sound of the Earth? First steps into EMusic

Antonio Menghini[1*] and Stefano Pontani[2] demonstrate the conversion of Airborne EM (AEM) data into music by data normalization and applying the Musical Instrument Digital Interface (MIDI) routine.

The musical examples that accompany this article can be found online at: http://soundcloud.com/eagepublications

We show the possibility of transforming Airborne EM (AEM) data into music, by means of the simple procedure of data normalization and the application of Musical Instrument Digital Interface (MIDI) routine. For this introductory work, named 'EMusic', we exploit the ability of the MIDI protocol to translate numerical values (voltage response) into musical pitches. It is possible to use the large amount of data collected by airborne systems, in order to make easier the comprehension of EM method (for a didactic purpose), to assess quickly the quality of data (for a technical purpose) and, last, but not least, to compose musical pieces (creative purpose). Through preliminary and short samples, we show that it is really possible to achieve a 'sound' of a particular geological setting, characterized by a specific musical signature, which could support the data interpretation. It is possible to expand greatly this procedure, also considering other geophysical methods. We point out future steps that could be taken.

The idea of transforming scientific data into music (sonification) is not new: as reported by Dell'Aversana (2013), many authors dealt with this topic, mainly by processing seismic data (see further references in the quoted paper). The same author presented music samples extracted from earthquake and volcanic activity, processed through the Musical Instrument Digital Interface (MIDI) protocol. In a second paper, published in 2014, he applied this idea to seismic prospection for detecting gas-filled channels, faults and geological formations, using rhythmic features that reflect the spectral analysis of data. Finally, he suggested that this approach can be applied to any kind of geophysical data and that sonification can complement, not substitute, standard geophysical processing and interpretation routines.

We completely agree with this last statement, as, if we refer to the AEM dataset, it is much easier to inspect the huge amount of info through the eye rather than the ear: in a typical portion of flight that is considered for standard processing, there can be about 200-300 soundings; if we keep, for the sake of clarity, at least a listening time spacing of 1 second per sounding, we would get more than three minutes of music that should be analysed. On the contrary, standard procedures of accurate processing, for the same amount of data, would require much less time, in the order of tenths of seconds. This means that it would be impossible to achieve a realistic processing procedure by means of audio applications. Our idea is that sonification can only support data interpretation, since it would be possible to get a fast and preliminary evaluation about the quality of data, the level of EM noise, and the general background geological setting, before starting the standard processing workflow.

On the other hand, we are convinced that sonification can play a useful role for didactic purposes: the complicated physics behind EM methods can be more easily explained to students. The understanding of complicated formulas, such as the Maxwell's or Schelkunoff's equations, would be greatly facilitated by means of musical analysis, and further examples will show how to achieve this goal.

At the same time there is a creative aspect of the question, since it is really possible to extract the 'effective' sound of the subsurface: in the EM methods, we excite the Earth through the eddy currents induced by a transmitter, in a manner similar to the vibrations caused by the percussion of a tuning fork. This means that hours and hours of music can be played automatically, by simply manipulating AEM data acquired all over the world, in the most disparate geological scenarios. On the other hand, EMusic would follow very well in the wake of 'serial music' and of many contemporary musical streams, advocating the automatic composition of music, without any (or with a really negligible) action from the composer: Arvo Pärt, in his 'Tabula rasa' showed how it is possible to build a complex piece by using simple 'quasi-mathematical' rules (in this case he adopted the triad of A minor, i.e. only A, C and E notes, to start a simple mechanism that enables the music to generate itself without any intervention).

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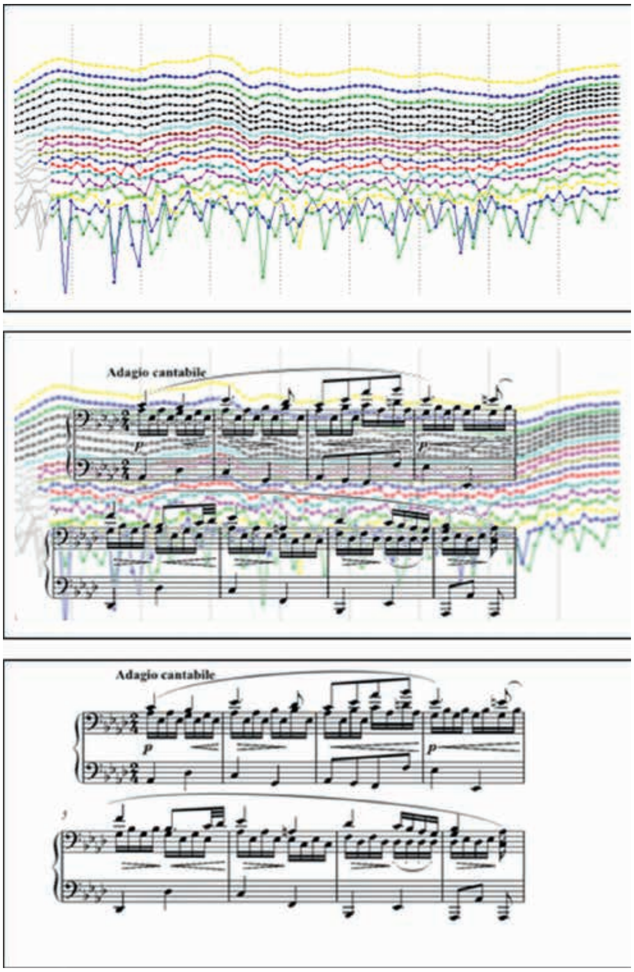

Figure 1 *Voltage responses acquired along a portion of an AEM flight compared with a musical piece.*

Indeed, automatic creation of music was already tried by W.A. Mozart, since 1787, when he wrote the instructions and the rules of a musical system able to transform the possible combinations of the dice game into notes (http://outsidethebox93.org/Projects/MozartDiceGame/). Thus, there is nothing really new in prospect.

From geophysics to music

Time Domain EM methods use a direct electric current, flowing into an insulated transmitting loop and generating a static primary magnetic field. The abrupt switch off of the transmitter current causes a rapid decay to zero of the primary magnetic field, so that secondary electric currents (eddy currents) are induced in the Earth. According to the Lenz's Law, the eddy currents act to oppose the decrease in the primary magnetic field and spread out like horizontal 'smoke-rings' in the subsurface. The fast decay of these fields causes the birth of a secondary magnetic field that is measured by means of an induction coil. The voltage decay (i.e. the 'transient') is measured as a function of time; depth of investigation increases with acquisition time, as at later times the current will proceed deeper into the ground. The inversion of voltage data collected at different acquisition times produces a 1D model of the subsurface, in terms of resistivity. For a detailed explanation of the method see Ward and Hohmann (1988), Spies and Frischknecht (1991), Christiansen et al. (2009).

In the AEM prospecting (Siemon et al., 2009) we can collect a huge amount of data, by flying with a helicopter or a fixed-wing system, carrying both the transmitting loop and the receiver coil. The AEM data are binned along the flight with a sampling time of about 1-1.5 seconds, which translates to every 20-30 m. Details about AEM data processing are presented by Auken et al. (2009).

There is a particular feature of AEM data that makes their sonification easier: it is enough to see a typical response of voltage acquired along a portion of a flight, showing all the gates acquired as a stream. If one substitutes the voltage values with musical notes, it is easy to get a musical phrase on a pentagram (Figure 1). Hence, the pitch of any instrument (i.e. the gate of the EM receiver) is strictly linked with the voltage response.

Since the dynamic range of voltage is really wide, depending not only on the ground resistivity, but also on the altitude of the system, we must adopt a logarithmic scale. Also the sound frequencies associated to musical pitches are distributed in a non-linear scale (according $\log_2$).

The MIDI pitch values are linked with frequency through the following equations:

$$f = 440 * 2^{(m-69)/12} \tag{1}$$

$$m = 69 + 12 \log_2 (f/440) \tag{2}$$

where f = frequency and m = MIDI pitch

This is to say, that we must distribute all the range within the MIDI span between 0 and 127 units, that correspond to the frequency range 8,176-12543,854 Hz. Indeed the audible span is limited to 10-110 MIDI units.

This outcome can be simply achieved, by means of logarithmic transformation. A simple formula could be:

$$X_N = 10 + [\mathrm{Log}\,(X/X_{MIN}) * 100/\mathrm{Log}\,(X_{MAX}/X_{MIN})]$$

Where

X_N = normalized value

X = measured voltage value

X_{MAX} = maximum voltage value

X_{MIN} = minimum voltage value

The choice of X_{MAX} and X_{MIN} is fundamental: if we are interested in assessing only the dataset within a single survey, we can use those data collected in the field. While, if we would compare different responses of different surveys, we should fix wider limits, able to include all the potential voltage values that can be measured on the Earth. It is not so easy, but we could start thinking about a higher limit due to seawater, and a lower limit due to noise or highly resistive rocks. This issue is very similar to the choice of the palette for representing resistivity or conductivity variations: usually the colour scale is set according to the single survey, in order to enhance local anomalies, while it is nearly impossible to fix a unique one for any dataset.

The frequency of sampling can be chosen by the MIDI operator, but it could be set with the same time interval used for binning the stream-data: usually soundings are extracted every 1-1.5 sec, which is a reasonable interval between notes making them easily distinguishable.

The number of notes that can be played (like instruments of a musical ensemble) depend on how many gates are available, so that for a system able to use only a few ones, e.g. frequency domain systems, one can get a simpler outcome (like a chamber music ensemble). In the case of many gates, one can get a more rich and complex sound (like a complete symphonic orchestra).

Let the geophysicists play: some beginnings

But let us do a step back: if we start from a homogeneous half-space and focus our attention to no more than four gates (notes), we could get a chord (Figure 2, modified from Christiansen et al., 2006). Audio Sample_1 shows the chord we get from a conductive (10 ohm-m) halfspace (orange notes): the high pitches prevail, since we record a high voltage response. If we adopt the A key, it shows itself an A7sus chord (without the 5th). This outcome must be considered only in a relative way. In fact, if we repeat this operation for the resistive (100 ohm-m) half-space (blue notes), we get, for the same four acquisition times, a lower tone, by getting a chord of DbMI(b5) (Audio Sample_2): it is now clearer, also for anyone who has poor knowledge in physics, the relationship between these two different geophysical models.

It is also interesting to evaluate the difference between an H-model (conductor between two resistors) and a K-model (resistor between two conductors). As Audio Sample_3 and Sample_4 display, the difference is not so obvious, as it depends on units of measurements and other parameters, since these are actual data collected from a real survey. However, the contrast is easily distinguishable in a relative sense, as we get a BbMA7(#5) for the H-model and a DbMI7(b5) for the K-model. We can state that EMusic is effectively closer to jazz music, characterized by sharp alterations of the key

If we consider actual data, we can extract a more complex sound. Audio Sample_5 was composed by means of a TEM sounding collected on a volcanic dome in Central Italy, Cimini Mountain, Viterbo (Figure 3a), by using Geonics Protem 57 equipment. In this case, we unrolled the chord obtained by sonification, so that we have distributed the single notes, to create an arpeggio. The pitches were located exactly at the center of each time gate of a single transient, but after having applied a time expansion of the order of 20,000, so as to make distinguishable the different sounds. Thus, in this case, we are able to really follow the eddy currents' travel into the subsurface and to get a real perception of the response collected by the receiver coil with the elapse of time. In detail, the initial sharp sound represents the end of the time-on, during which the current is injected into the transmitting loop, followed by a pause, representing the time elapsed before the first measurement of voltage. Then, we can listen to the descending pitches, as the signal decays more and more, with increasing spacing between the gates, as they are set according to an exponential scale. This makes immediate the concept of vertical resolution in TEM sounding, which decreases with time, i.e. with exploration depths. For creative purposes, we applied a feedback effect to the notes, to create a sort of echo.

We could have also used the start and the end of each time gate, instead of the centre: by this way it would be more intuitive to capture the effective functioning of the geophysical instrument and the meaning of the relationship between the

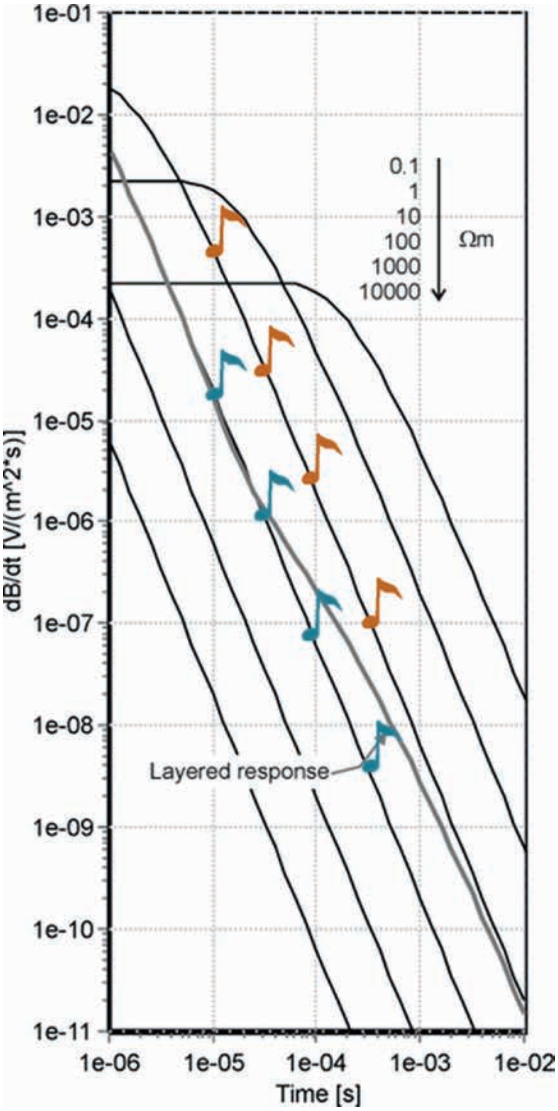

Figure 2 *Half-space curves of the impulse response (dB/dt). For the 10 ohm-m homogeneous half-space we picked four green notes, while for the 100 ohm-m the blue notes. Notice that the acquisition times are the same for the two cases (modified from Christiansen et al., 2006).*

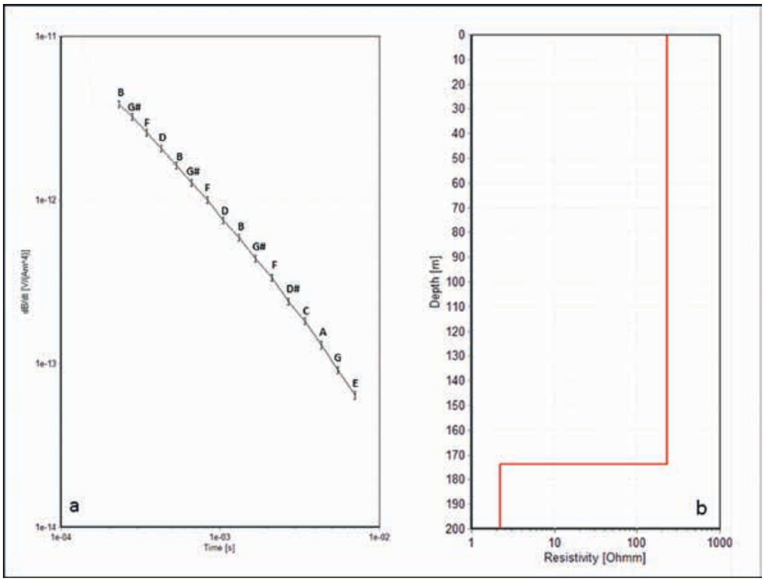

***Figure 3** Voltage response of a TEM sounding performed with Geonics Protem 57 equipment, with relative pitches (a) and corresponding 1D model (b)*

width of the acquisition gates and the signal-to-noise ratio (the gate widths increase with time, since the signal weakens).

It is funny to recognize a steady repetition of the following notes: B, G#, F and D (that is a Ddim7 chord) until 45 seconds. We must keep in mind that this is due to how we define minimum and maximum values to extract the pitches and how the gates timing is set, so that with other TEM equipment, even if we had taken into account actual current and Tx and Rx size (that means 'to normalize' the data), we would have got a different sound; but, if we always use the same equipment, we can state that this is the sound of the resistivity model shown in Figure 3b. We expect that most of the sound comes from the conductive clay substratum (about 2 ohm-m) resting at more than 170 m deep, as the first volcanic layer is greatly resistive (more than 200 ohm-m): when we start to listen, the eddy currents have already reached almost to the bottom of the volcanics. In order to capture the effective sound of lavic dome, we should have used higher repetition rates, so as to acquire earlier times.

Audio Sample_6 shows the audio signature of a real 3D effect, due to a vertical conductor. The plot of voltage data shows the typical pattern (Figure 4) with two peaks at the flanks of a trough, centered over the conductor. It would be easy through an audio inspection of an AEM dataset to provide preliminary info about the presence of potential targets (e.g. for mining application). The location of the target is over the lower tone sound, flanked by the two adjacent higher chords. A similar outcome might be caused by galvanic coupling, due to man-made infrastructures. This is an approach very similar to 'bump' detection, since we get only a qualitative outcome, but no model. Of course, this will not be the exact musical response of any vertical conductor, since it will depend also on the way of data normalization: the same AEM equipment might provide different responses; moreover the effective altitude flight can modify the sound substantially, so that we could get different audio footprints. However, within the same project, we could expect roughly the same musical appearance.

It must be noticed that the musical outcome confirms very well the asymmetric feature of the anomaly, which is located along a sharp resistivity contrast: the voltage response on the right side is much higher. The ear is able to get this info.

If we work with an entire flight, we can extract complex musical tracks. By this way, we can follow the geological variations also in the lateral direction. Audio Sample_7 shows an example of data collected in Siberia, for kimberlite detection: the conductive feature (20-50 ohm-m) of the tuffitic and pyroclastic coverage above the kimberlite is well marked by the higher tones at about 50 sec. The background is characterized by low tones, as hard rocks with high resistivity (between 200 and 1000 ohm-m) prevail, so that the sound anomaly due to the crater cap is well pronounced. It should be noted that we selected just five gates, for the sake of clarity.

The second example (Audio Sample_8) comes from Namibia and it refers to an AEM prospect for hydrogeological purposes. Here, there is no clear 'bump' anomalies, but a more flat sound, with some interesting variations, due mainly to the uprising of a deep conductor, due to salt water, causing an enhancing of the tones. Indeed, the most relevant difference with the Siberian dataset is the higher pitches, since we are dealing with mean resistivity of about 50 ohm-m, with the deep conductor reaching values below 10 ohm-m. In this case, we considered seven gates, but we could have selected many more instruments.

These AEM examples show another didactic feature of EMusic: we used a time spacing of 1 second, i.e. the same used to extract single soundings along the flight, so that it can provide an exact idea about what is the effective lateral resolution of an airborne system. It must be noted that we have cropped just a small portion of audio data, for size limitations, but it is easily achievable for the export of minutes of EMusic.

The next steps

As previously stated, we think that the most important application of AEM sonification is for didactic purposes. Regarding data processing, it could represent a support for preliminary assessment, but probably it will not greatly improve the current workflow.

On the contrary, we believe that EMusic could facilitate the comprehension of hard concepts by students:

(1) Vertical resolution – it increases with the number of instruments. Thin targets can be detected only if we have sufficient numbers, so as to catch the small audio variations within a single chord (i.e. a single sounding).

(2) Lateral resolution – it depends on the frequency of sampling, so that a narrow target can be resolved only if the pitches density is adequate.

(3) Relationship between geological setting and EM response – a flat music, with small changes all over the track, would reveal a simple geology (until 1D conditions), while an uneven trend would be typical of complex structures. For example, a fault will be marked by a sudden change of sound.

(4) Effect of data processing – by comparing AEM data before and after decoupling and denoising, it is easier to appreciate the positive role of processing: the sharp anomalies, like those ones in Audio Sample_5, will disappear after processing. The same will occur for the effect of late noise assessment: before processing the music will be really noisy, with a marked background of low tones that disturb the listener; after data processing we will get a cleaner and sharper sound.

(5) Anomalous decay rates, far from the expected $t^{-5/2}$, due to noise, Induced Polarization, Superparamagnetism or 3D distorsion – if we keep the same time gate spacing for a single sounding, we will get more 'compact' chords, with single notes that rest one close to the others, due to the lower transient decay.

(6) Joint analysis of vertical Z and horizontal (X,Y) components of the secondary magnetic field can support diagnostic evaluation of the data, by adding, e.g., a choir ensemble (X response) over the orchestra (Z response).

Indeed, these will be our next steps from the didactic point of view.

We are thinking also of building a sort of musical library, by working on the sonification of the most common mining and structural targets, or of the most frequent geological structures (sulphide deposits, tabular orebodies, dykes, bends, faults, seawater intrusion and so on). This performance will be carried out by considering different AEM equipments, in different geological scenarios.

From the creative side, we will consider the use of specific musical scales, besides the 12-tone approach, so as to arrange a kind of 'modal' tuning. By this way, one could previously fix what mood wish to use, according to, e.g. local scales, so as to make more appealing the musical outcome of AEM data: imagine applying a Phrygian scale for a Spanish or Latin American dataset, a blues scale for US data or Arabian moods for Middle-East surveys. It will be enough to insert the data only into selected ranges of MIDI pitches, each of them associated to a note of the selected scale.

Another idea will be to add geomagnetic data, which are usually collected during an AEM survey, by inserting them as a distinct sound, e.g. a human voice or a piano, like a soloist. It will be a kind of 'joint' data interpretation.

Together with the Art Republic Foundation Studio, an Italian musical association, we are preparing a series of concerts that will be held next summer in woods and parks. This project was named ((E))Mago. By means of the preliminary

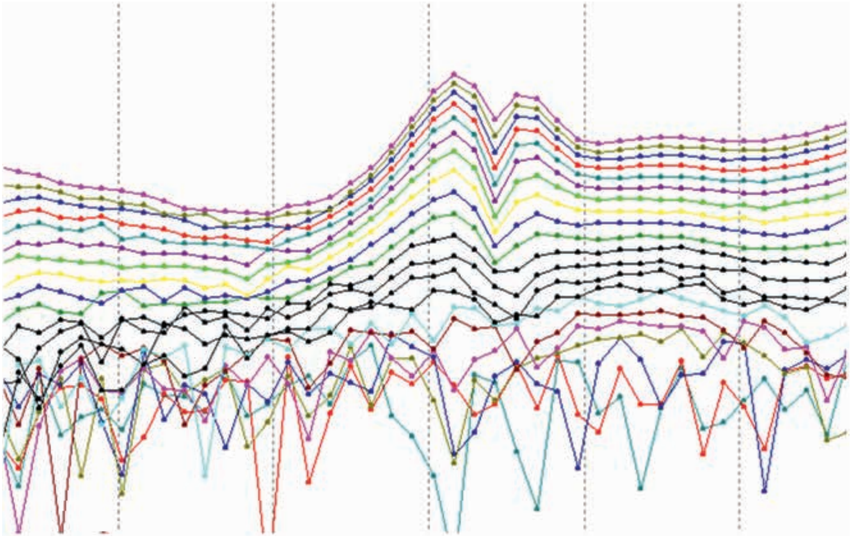

Figure 4 *Example of 3D distorsion due to coupling, along an AEM survey.*

acquisition of ground TEM data, we will be able to arrange on-site a soundtrack reflecting the geology of the area (as shown by Audio Sample_5), over which the musicians will play, being inspired by the effective 'sound' of the place. The Earth will provide the basic palette that the musicians will be able to manipulate to create their extemporary composition.

One of the purposes of this project is also to use these musical-geophysical events as a denunciation tool, by selecting particular sites worthy of attention from a public community (e.g. abandoned or polluted areas, ruined historical and archaeological sites).

Conclusions

This introductory work aims to provide just a preliminary overview of what could be drawn from the sonification of EM data. More detailed analysis of the musical response of geological and structural structures must be carried out and the simple audio samples attached to this paper must be considered just as starting points that can be greatly improved.

For now we would stress that the educational power of this approach is huge. It is important that people, and above all future generations, understand that behind complicated formulas and concepts there can be a world of beauty, connecting science with the arts.

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