In Quest for the Schumann Resonances: Measurements of the Natural Electromagnetic Spectrum

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Abstract

The aim of this project was to determine whether the characteristic frequencies of the so-called Schumann resonances can be detected in the ELF range of magnetotelluric data collected at the Earlyburn test site, situated fifteen miles south of Edinburgh. It was done in order to examine the viability of the site for further testing of electromagnetic equipment and methods in terms of the impact of cultural noise on the natural spectrum and for monitoring frequency fluctuations in the Schumann resonances. Measurements of the three spatial components of the magnetic field as well as the horizontal components of the electric field have been carried out over a period of five days using the S.P.A.M. MkIII data acquisition system. Data processing comprises splitting the data into time series of uniform length, calculating raw power spectra using FFT, the stacking of raw spectra in order to improve the signal-to-noise ratio and the removal of the filter functions from the spectra. The first four commonly measured Schumann resonances can easily be found at 7.8 Hz, 14.0 Hz, 19.8 Hz and 26.3 Hz in the spectra of all horizontal field components within the frequency band 4 Hz - 16 Hz. Up to six resonances are detected within band 16 Hz - 128 Hz, revealing two higher frequencies of 32 Hz and 40 Hz. The B_y component turns out to provide the best quality spectra. Sharp line spectra at the harmonics of 1 Hz are superimposed on the continuous spectra of B_x and B_z, giving rise to speculation about insufficient grounding or the influence of power lines or electric fences nearby. Further measurements with different timing are recommended to resolve frequency variations of the resonances.

Experimental set-up

The experimental set-up is the one of a classic magnetotelluric survey. Induction coils for the B_x, B_y and B_z components of the magnetic field were dug in just below the surface. $Cu/CuSO_4$ electrodes were deployed in two perpendicular, cross-shaped lines. The S.P.A.M. Base Box, the hard disk drives and the batteries were placed inside an onsite building and connected to the Remote Box that stayed with the sensors. Measurements were taken during days 24 to 29 of 1996. All eight frequency bands were recorded using the timer option of the S.P.A.M. and covering a total frequency range between 2^{-7} Hz and 128 Hz. Data collection was split into three separate runs due to a battery change after two days, but only the first two runs have been examined in this project.

Band	HP freq	LP freq	Nyquist freq	Sampling freq
0	16 Hz	128 Hz	256 Hz	512 Hz
1	4 Hz	16 Hz	32 Hz	64 Hz

Table1: Characteristics of the frequency bands used during the experiment

Notch filters were enabled for all sensors at 50 Hz during the first run and at 50 Hz and 150 Hz during the second run in order to suppress the mains frequency and its first odd harmonic. The timing for data collection within the two bands was set according to the following tables:

Run 1	**Total length** 01:40:40							
Band	**Start time day024**	**End time day024**	**Timing**	**Length of sequence**	**Length of seq./ samples**	**Total data length**	**Total length/ samples**	**No. of time series(4096)**
0	13:40:22	15:21:02	every 10 min	00:00:64	32768	00:11:44	360448	88
1	13:40:22	?	continuous	01:40:40	386560	01:40:40	386560	94

Table 2: Characteristics of the first recording run

Run 2	**Total length** 45:08:53							
Band	**Start time day024**	**End time day026**	**Timing**	**Length of sequence**	**Length of seq./ samples**	**Total data length**	**Total length/ samples**	**No. of time series(4096)**
0	17:00:38	14:01:41	every hour	00:00:64	32768	00:49:04	1507328	368
1	17:01:00	14:09:31	every hour	00:08:32	32768	06:32:32	1507328	368

Table 3: Characteristics of the second recording run

Run 1 started on day 24 at lunch time, run 2 started on the same day in the afternoon and went on until the afternoon of day 26. Run 3 started in the afternoon of day 26 and went on until the afternoon of day 29.

Data processing

In order to derive suitable power spectra from the huge amount of data recorded, a whole number of data processing steps had to be carried out. Data collection of all eight frequency bands in two recording phases over a period of two days reached a total of more than 166 MB of binary time series data. Bearing in mind that the first five modes of the Schumann resonances are commonly measured within a frequency range between 7.8 Hz and 32.5 Hz, only the first two frequency bands were taken into consideration. They cover the ranges of 4 Hz to 16 Hz and 16 Hz to 128 Hz and in the following are referred to as band 0 and band 1, respectively.

This restriction of the frequency bands still leaves a quantity of about 78 MB of binary data to be looked at; a fact which shows already that a method had to be developped which allowed to process these data easily and efficiently, to look at the data quality at an arbitrary stage of processing and to present the results in a reasonable way. The approach being taken here comprises splitting up the continuous data into single time series of suitable length, adjusting the units, calculating raw power spectra for a number of single time series - in this case for a whole run within a given band - and stacking the raw spectra in order to average out unwanted noise.

Results

In view of the large number of spectra produced, only the most characteristic power spectra from the very last stage of data processing are presented within this article. A sample raw spectrum is given for reasons of comparison. Band 1 spectra are generally displayed over the full range of spectral estimates, thereby covering a frequency range between 0 Hz and the Nyquist frequency of 32 Hz. Band 0 spectra, however, are displayed only up to the low pass frequency of 128 Hz, thereby covering the range between 0 Hz and half the Nyquist frequency of 256 Hz. This is done in order to emphasize the lower part of band 0 where the Schumann resonances are expected, and to avoid confusion about overcorrections in the spectra at the 150 Hz notch filters.

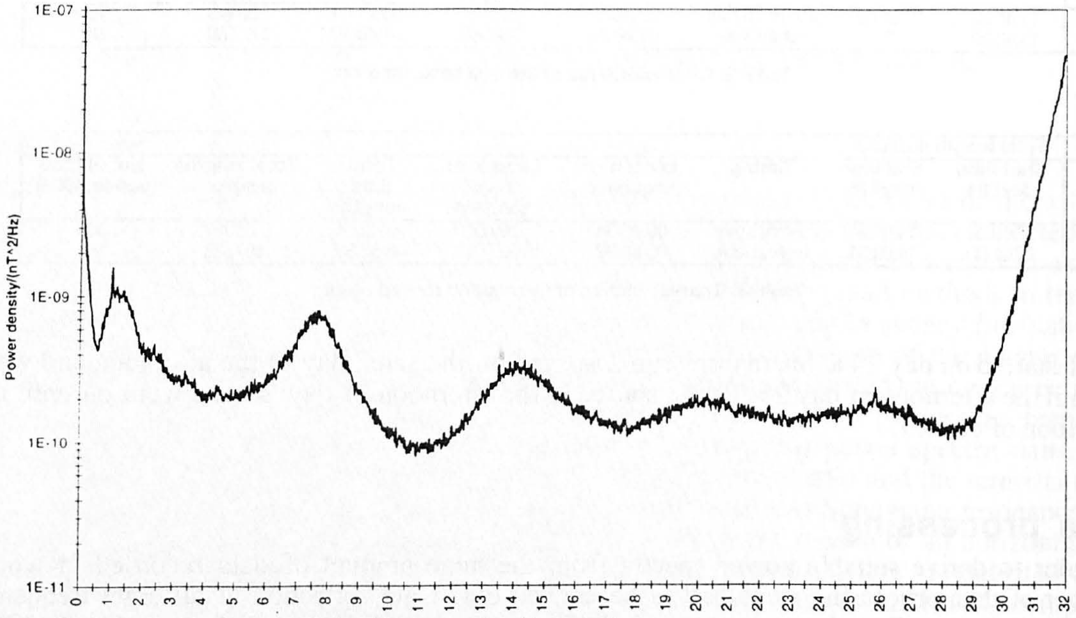

Figure 1: B_y component, band 1, run 2, 323-fold stack, band pass removed

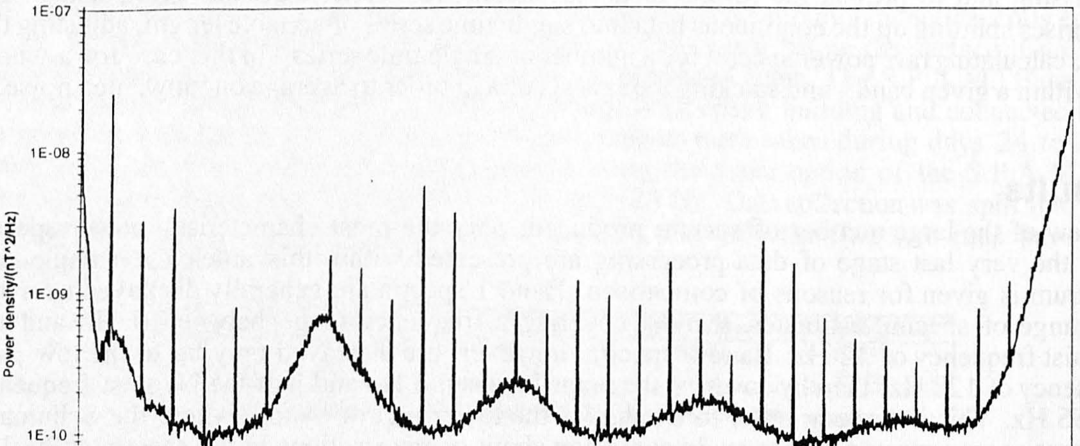

Figure 2: B_x component, band 1, run 2, 323-fold stack, band pass removed

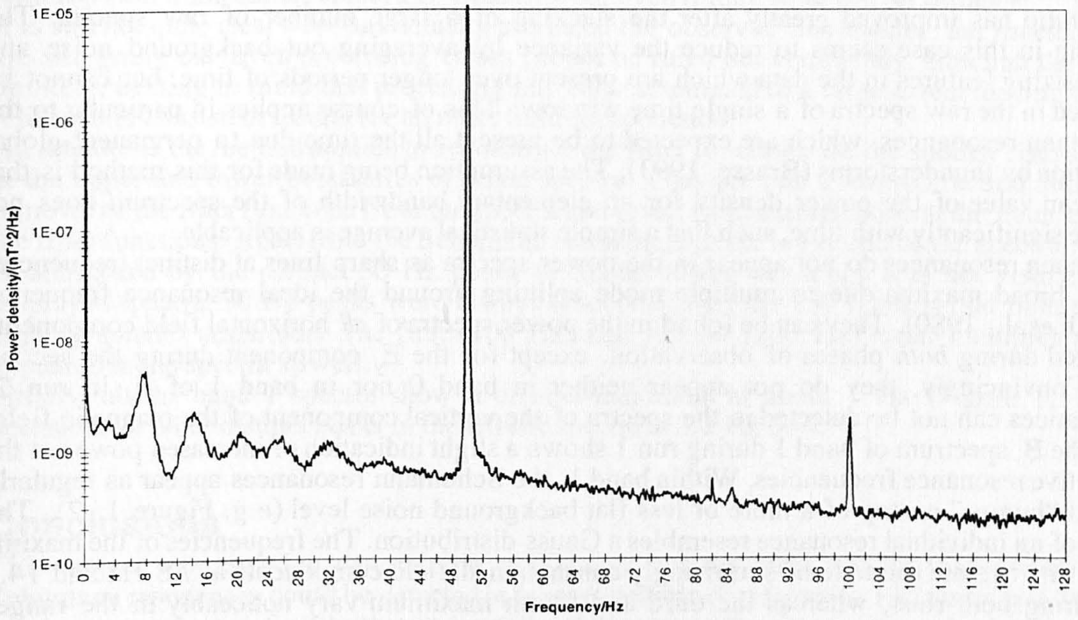

Figure 3: B_y component, band 0, run 2, 330-fold stack, band pass removed

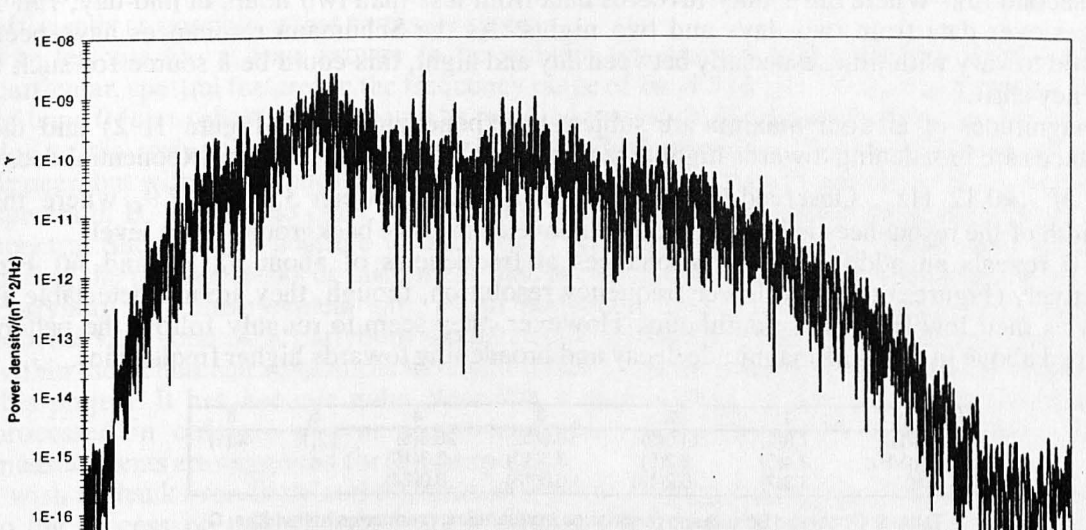

Figure 4: Sample raw power spectrum. B_x component, band 1, run 1.

Interpretation

The raw power spectra calculated from single time series show very large variance in the power density estimates (Figure 4). The first remarkable result of the processing is that the signal-to-noise ratio has improved greatly after the stacking of a large number of raw spectra. The stacking in this case seems to reduce the variance by averaging out background noise and emphasizing features in the data which are present over longer periods of time, but cannot be resolved in the raw spectra of a single time window. This of course applies in particular to the Schumann resonances, which are expected to be present all the time due to permanent global excitation by thunderstorms (Brasse, 1993). The assumption being made for this method is that the mean value of the power density for an elementary bandwidth of the spectrum does not change significantly with time, such that a simple statistical average is applicable.

Schumann resonances do not appear in the power spectra as sharp lines at distinct frequencies but as broad maxima due to multiple mode splitting around the ideal resonance frequency (Bliokh et al., 1980). They can be found in the power spectra of *all* horizontal field components recorded during *both* phases of observation, except for the E_y component during the second run. Convincingly, they do not appear neither in band 0 nor in band 1 of E_y in run 2. Resonances can not be detected in the spectra of the vertical component of the magnetic field. Only the B_z spectrum of band 1 during run 1 shows a slight indication of increased power at the respective resonance frequencies. Within band 1, the Schumann resonances appear as regularly shaped "bumps" on top of a more or less flat background noise level (e.g. Figure 1, 2). The shape of an individual resonance resembles a Gauss distribution. The frequencies of the maxima of the first two are found to be surprisingly constant in all field components at 7.8 Hz and 14.1 Hz during both runs, whereas the third and fourth maximum vary noticeably in the ranges [19.8...20.3 Hz] and [26.3...26.6 Hz], respectively. They seem to be slightly higher particularly during the second run. A possible explanation for these minor deviations might be the fact that frequencies beyond 16 Hz in band 1 have undergone low pass filtering. Filter functions have been determined experimentally in order to reestablish the original spectrum, a process which might have distorted the positions of the maxima. Another possibility is of course fluctuation of the resonances with time, bearing in mind that the deviations are observed in the second run. Where run 1 only involves data from less than two hours at mid-day, run 2 averages over data from two days and two nights. As the Schumann resonances have been observed to vary with time, especially between day and night, this could be a source for such a frequency shift.

The magnitudes of all four maxima are subject to exponential decay (Figure 1, 2) and the resonances are broadening towards higher frequencies. Curve fitting gives an exponential decay factor of $\lambda \cong 0.12\ \mathrm{Hz}^{-1}$. Observed Q factors, $Q=f_n/\Delta f_n$ are between 3.3 and 7.9, where the halfwidth of the resonances is being measured above an average background noise level.

Band 0 reveals an additional two resonances at frequencies of about 32 Hz and 40 Hz, respectively (Figure 3). Due to lower frequency resolution, though, they are not detectable as clearly as their low frequency neighbours. However, they seem to roughly follow the pattern described above in terms of magnitude decay and broadening towards higher frequencies.

n	1	2	3	4	5	6
f(n)/Hz	7.8(2)	14.0(2)	19.8(5)	26.3(5)	32(1)	40(1)
Δf(n)/Hz	2.4(5)	2.2(5)	3.3(10)	3.3(10)	-	-
Q(n)	3.3(7)	6.2(14)	6.0(18)	8.0(24)	-	-

Table 2: Observed Schumann resonance frequencies, resonance halfwidths, Q factors and their errors., 5 and 6 estimated from Figure 3.

Throughout all the measurements, the B_x and B_z continuous spectra are superimposed by sharp line spectra of 1 Hz multiples. These line spectra occur in both frequency bands at exact frequencies of 1.0 Hz, 2.0 Hz, 3.0 Hz, and so on. They are not of uniform amplitude but seem to be envelopped more or less periodically. Thus, the time domain signal must have been periodic with a period of 1 s, consisting of short impulses like occurring in electrical switching processes. One might possibly think of an electric fence in East-West direction, which, being excited every second, would in fact create a magnetic field with only B_x and B_z components and, more importantly, in theory create a similar spectrum. However, it is most unlikely that this fence should be exactly parallel to the B_y direction such that it does not induce at least a very tiny B_y field at all - which it obviously does not, since the B_y spectra are completely flat and continuous. Furthermore, it is unlikely that such a fence should not have perpendicular parts which would immediately create a B_y field as well, even if they were at a far distance.

It is still not quite clear what has actually produced the observed line spectra, but investigations are still going on. Even processing errors cannot be ruled out completely, although they seem unlikely, bearing in mind that processing has been automated to a large extent leading to very reliable and consistent results for all other field components.

An artefact of the method applied to reconstruct the filter functions are the sudden rises or falls at the upper and lower boundaries of some spectra. They are due to overcorrection during the removal of the filter functions from the spectra and result from extrapolation at the outer ends of the filter functions. Apart from the Schumann resonances in the lower end of the spectra, band 0 is dominated by the distinct 50 Hz peaks of mains power. Although it is not visible in the displayed spectra, 50 Hz peaks were always associated by their 150 Hz first odd multiple at a slightly smaller amplitude. The first (100 Hz) and second (200 Hz) even multiples always appeared in the spectra as well.

Finally, all the band 1 spectra show a distinct maximum at about 1 Hz (Figure 1, 2) and occasionally other distinct peaks in the telluric spectra at 3.0 Hz or 5.7 Hz.

Conclusions

This project was aimed at determining whether or not the characteristic frequencies of the Schumann resonances could be detected in magnetotelluric data from the Earlyburn test site. The results show most definitely that at least six Schumann resonances appear in the spectra of horizontal field components of Earlyburn data. The vertical magnetic field contains only slight indications of the Schumann frequencies. Observed resonance frequencies and Q factors match their commonly measured counterparts very well within their error boundaries. Generally, great enhancements in data quality were made by stacking the raw power spectra of time series collected during two runs of about two hours and about 48 hours, respectively, and thereby improving the signal-to-noise ratio of the spectra. Data processing has been carried out as efficiently as possible at that particular stage.

The test site has at least proven to be suitable for spectral analysis of the ELF range. In particular, spectral features in the frequency range of band 1 (4 Hz - 16 Hz) and the lower parts of band 0 (up to about 40 Hz) could be resolved very well. Electromagnetic noise is found to be due to the mains frequency of 50 Hz and its odd harmonics. The even harmonics do also appear, but with magnitudes being lower by several orders. Apart from the 1 Hz harmonics line spectra in B_x and B_z, no other distinct noise was detected that could have spoilt parts of the spectra. Should it be possible to trace the 1 Hz harmonics down to insufficient grounding during the measurements or instrument malfunction, it would certainly increase the worth of Earlyburn as a measurement site, as all horizontal field components seem to continuously provide very good data. Earlyburn should also be suitable for monitoring frequency fluctuations within the Schumann resonances although it has not been tried to determine such variations in this project. It has become quite clear that a vast amount of data has to be acquired and processed in order to determine resonance frequencies with sufficient accuracy. Further measurements are suggested for this purpose.

I wish to thank everybody at the Department of Geology and Geophysics who has contributed to the success of this project. I am grateful to Roger J. Banks for setting the challenge, organising the measurements and patiently answering my questions during the work. The project would not have been possible without the encouragement and support provided by the Magnetotellurics Laboratory crew. I wish to thank Graham Dawes for setting up the measurements and his numerous ideas about data enhancement, Oliver Ritter for providing references and software, his continuous support and numerous discussions and Darcy Nascimiento for his time, support and endless humour.

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