Low Noise Ag/AgCl Electric Field Sensor System for Marine CSEM and MT Applications

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Introduction

Imaging deep hydrocarbon targets using Controlled Source Electromagnetic (CSEM) or Marine Magnetotellurics (MMT) techniques demands very high sensitivity and low noise electric field sensors for the sea bed nodes that are commonly used [1].

Ultra Electronics has extensive experience with low noise Ag/AgCl electric field sensors for marine use, primarily for vessel signature management [2]. The sensors have been adapted to CSEM and MMT use and operate at up to 4000m water depth.

EMGS has developed a matching low noise, low power chopper amplifier for the frequency range 0.5mHz-20Hz.

In this paper we report from field tests in deep water, and compare with laboratory data.

Sensor description

It is relatively straightforward to make electric field measurements in sea water by means of two electrical contact points made with the seawater, with connections to a measuring device. The electric field value measured will be along the direction of the line between the two contacts. The simple expression for the electric field, expressed in volts per metre, is given by this voltage divided by the separation distance. The contact points, or electrodes, are designed in such a way that they produce a minimal voltage when the sensor is placed in zero field, and this contact voltage has a very small variation, or self-noise. The voltage measured by a two-electrode sensor depends on the electrode spacing. Sensors can be configured as single, two or three axis units.

Choice of Sensing Element

There are two main types of electrode that can be used to measure electric fields in seawater.
1. Inert e.g. carbon, titanium, platinum and gold.
2. Chloride forming e.g. silver, cadmium, lead and copper.

Materials which are inert in seawater in general are characterised as polarisable and have potentials which vary widely depending on the surface condition of the electrode and the current drawn from it. They are not suitable for low noise sensors at very low frequency.

The second type of materials forms chlorides in seawater. They are non-polarisable and as such have relatively constant potentials when small changes in current occur. Many of the chloride type electrodes are poisonous. Ag/AgCl however is robust and has excellent long term stability. It has been used for cathodic protection monitoring for over 40 years.

All sensor types are subject to gradual marine fouling. In general such growth is minimised by the presence of a cap which shields the electrode whilst still allowing the sensor to function. Ag/AgCl electrodes exhibit an additional protective effect due to the presence of silver ions which act as a biocide to reduce marine growth. Trials have shown negligible marine growth in over 500 days of submersion in the sea.

Figure 1 Ultra Electronics Electric Field Sensor

Ultra Electronics utilises specially developed silver / silver chloride electrodes which have self-noise levels below the nanovolt region, with offset voltages of the order of a few microvolts. The electrodes have been developed to have a low contact resistance with the seawater even at DC. This ensures very low noise levels at frequencies well below 1Hz. The specially developed housing for the electrodes allows these properties to be retained, even after prolonged immersion in the sea. The electrodes are encapsulated, and contained in their own electrolyte. Contact with the seawater is via a porous barrier, which excludes gross ingress of contaminants. It also greatly reduces the problem of flow noise, which otherwise arises when an electrolyte flows past an electrode sensing surface. The reliability of the sensors has been shown to be very good over many years of operation in these various installations. The actual construction of the electrode elements is very strong and resistant to shock and vibration. This gives them a very high reliability, in contrast to some other electrode types.

The Sensor Electrode Noise Voltage

At frequencies above approximately 0.1Hz, the noise spectrum is flat, and results from the thermal noise of the electrode pair impedance. Below 0.1Hz, there are two sources of noise; one is a result of competing electrochemical processes on the electrode surfaces; the other is the long term difference in temperature and salt concentration between the two electrodes.

Sensor Impedance Characteristics

If we look at the equivalent circuit of an electric field sensor we see that it has a frequency dependent characteristic, this is as a result of the Helmholtz layer that is formed between electrode and the electrolyte interfaces [3].

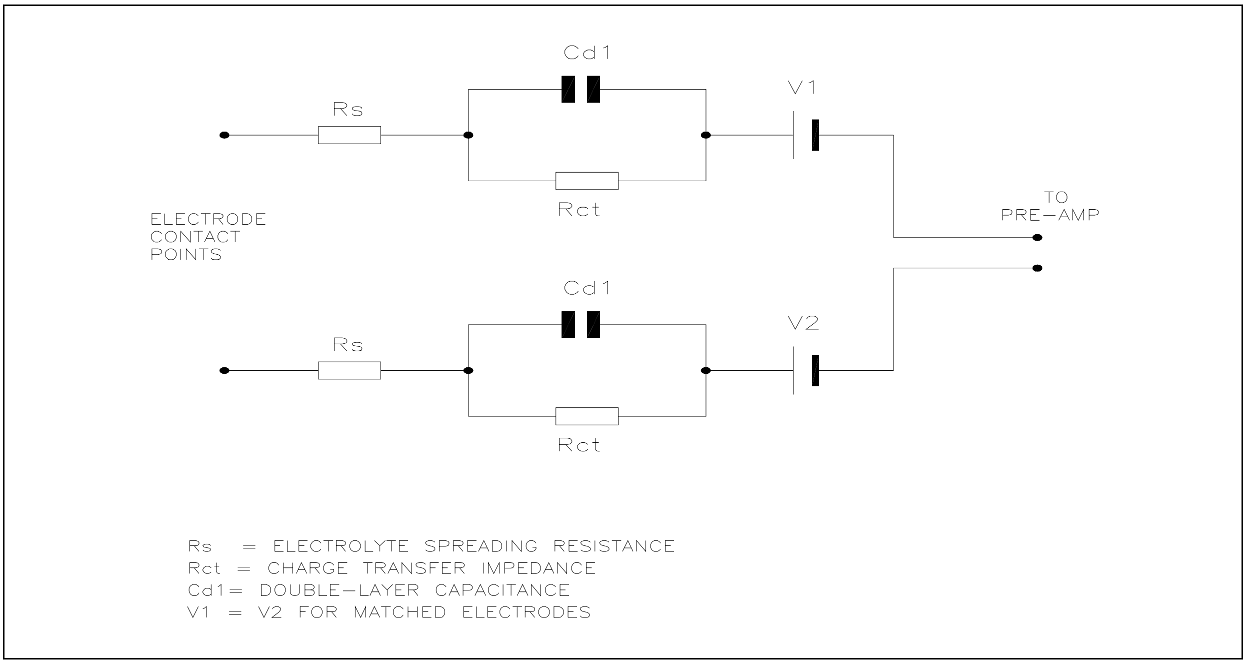

Figure 2 Sensor equivalent circuit

This causes many electrodes to show capacitive effects at low frequencies, i.e. the imaginary component of the impedance increases, and introduces errors when making low frequency measurements. CSEM and MT systems require accurate phase information, which requires the imaginary component of the electrode impedance to remain small. The Ag/AgCl electrodes manufactured by Ultra have a low imaginary component to frequencies of 0.001Hz and below. Measurement of the real and imaginary impedance is carried out at Ultra as part of the production testing on CSEM electrodes using a technique developed by EMGS. Figure 3 shows the typical characteristics of an Ultra electrode pair.

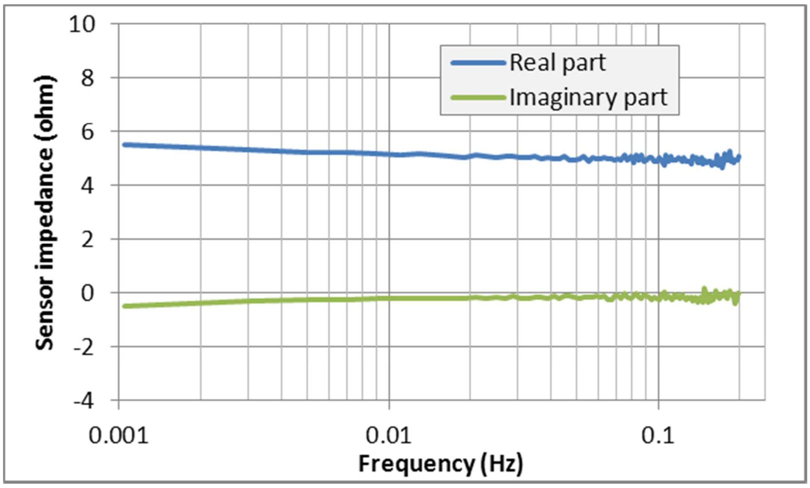

Figure 3 Complex sensor impedance vs frequency. Water conductivity 45mS/cm

Amplifier description

In marine CSEM and MT the frequency band is from sub mHz to over 10Hz. Most source frequency spectrums have a fundamental frequency lower than 1Hz. Ordinary amplifiers suffer from 1/f noise in this low frequency band. To remove this noise, EMGS uses a chopper stabilized amplifier design. Before any amplification of the signal occurs, the signal is shifted in frequency to a band with no 1/f noise using a square wave amplitude modulator. A similar type of modulator is applied to shift the signal back to the original frequency band after amplification.

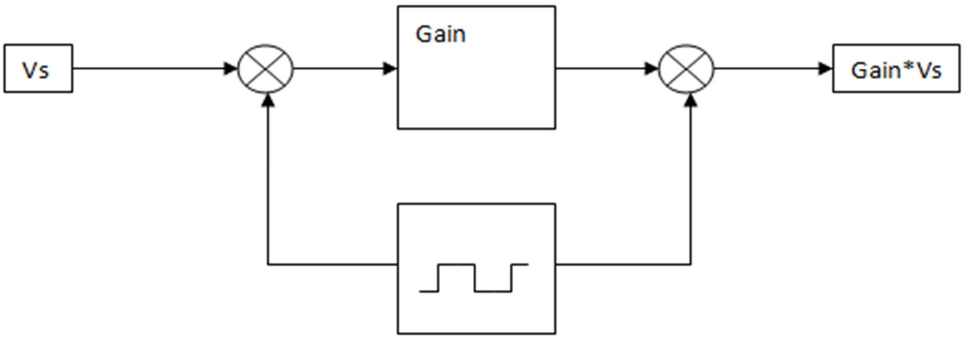

Figure 4 Chopper stabilized amplifier

The modulator is implemented with low R_{on} FET switches to reduce the thermal noise level. The amplifier noise with shorted input is about $0.34\, nV/\sqrt{Hz}$ @0.1Hz and with a 4Ω termination $0.45\, nV/\sqrt{Hz}$ @0.1 Hz, see Figure 6. The thermal noise from the resistor at room temperature is $0.25\, nV/\sqrt{Hz}$, and thus the amplifier noise with 4Ω load is $\sqrt{0.45^2 - 0.25^2}\; nV/\sqrt{Hz} = 0.37\, nV/\sqrt{Hz} @ 0.1Hz$ [4]. This implies that the amplifier is well matched to a 4Ω sensor pair, but that the amplifier noise is slightly higher than the thermal noise from the sensor pair. The current consumption is about 3mA at ±5V, which makes the amplifier ideal for battery powered system such as CSEM /MMT receivers.

The amplifier has a single pole low cut filter at ~4mHz, and an anti-aliasing filter with a cutoff frequency of 10Hz. The resulting frequency response (magnitude only) is shown in Figure 5 below. All the noise data shown in this paper has been corrected for the amplifier frequency response.

The amplifier has variable gain which provides sufficient dynamic range for the recording of ultra low noise data as well as the high amplitudes found when the towed source is passing directly over the receiver. All the noise data shown has been recorded with maximum gain setting.

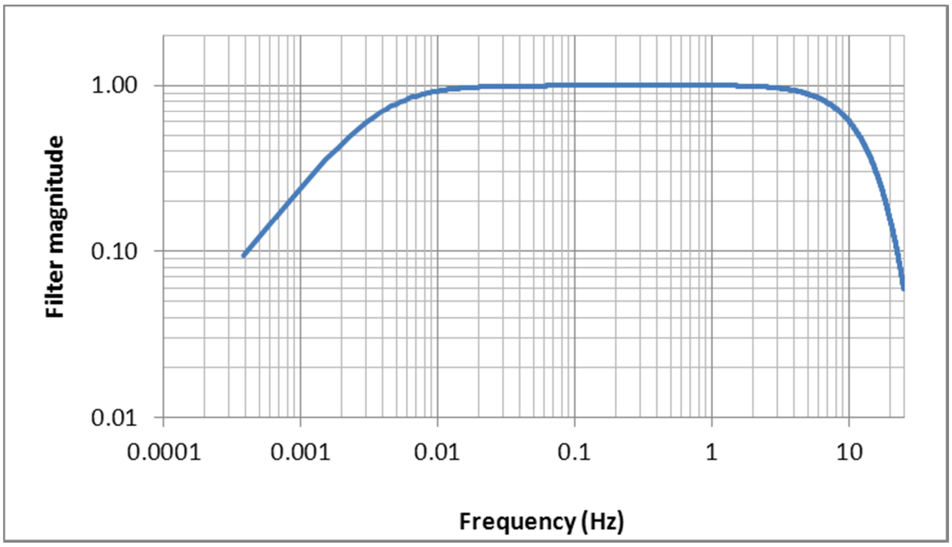

Figure 5 Amplifier transfer function. There is a low cut filter at around 4mHz, and anti-aliasing filter with cutoff at 10Hz

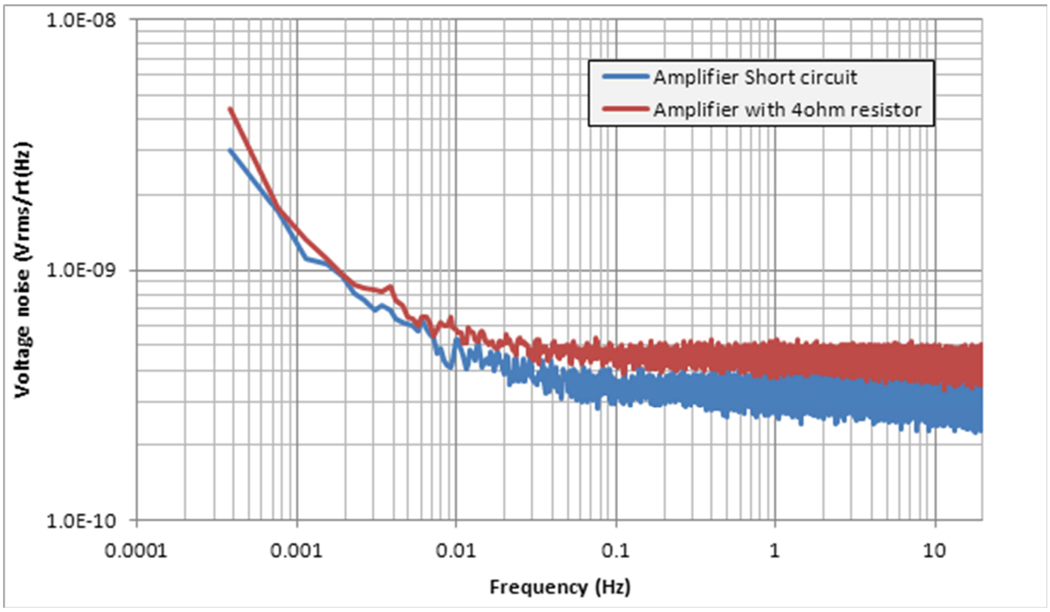

Figure 6 Noise floor for amplifier with short circuit input and with 4Ω resistor on the input. The data are compensated for the amplifier frequency response

Laboratory data

We have measured the noise level for a sensor pair in the laboratory. The sensors were placed with short separation in water with conductivity 50mS/cm. The sensor tank was placed inside an aluminium container with added thermal insulation and magnetic shielding. Data were logged for several days, and the resulting noise floor is shown in Figure 7 below, compared to the amplifier noise floor (shorted and with 4Ω termination). We see that the noise floor is limited by thermal noise from the impedance between the sensor electrodes and amplifier noise for frequencies down to 0.1Hz, but increases somewhat for lower frequencies. We do not know how much of the increase which is due to sensor noise and how much is due to environmental noise penetrating the shielding.

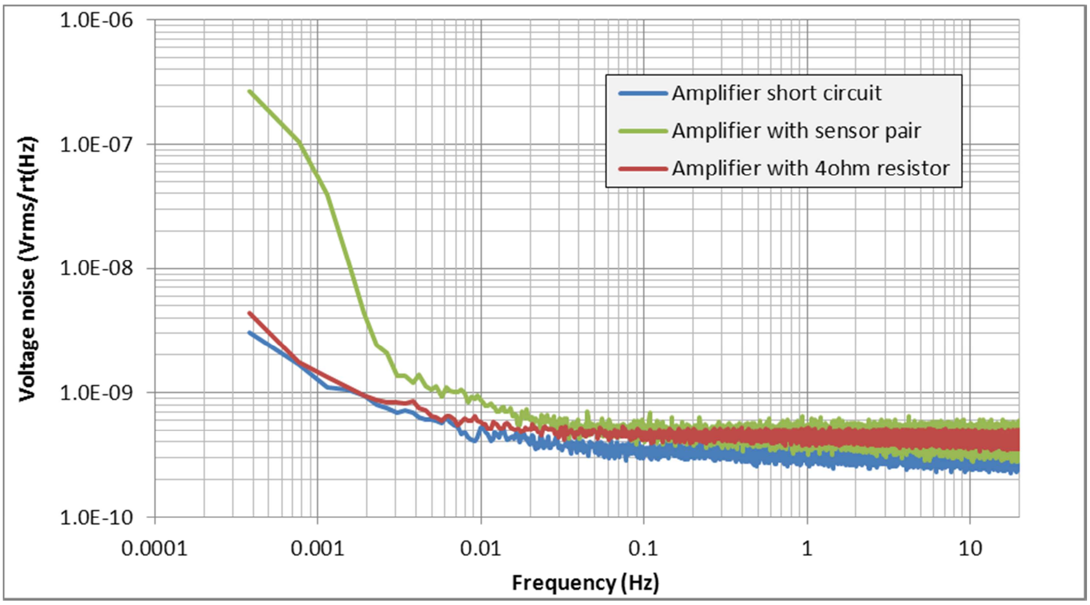

Figure 7 Sensor noise floor, compared to the noise level with a 4Ω resistor and shorted amplifier

Field data

Ultra E field sensors were in December 2010 installed on three EMGS receivers onboard M/S Boa Galatea, and have been dropped as test receivers on most of the surveys made with this vessel since. We show some examples of the data we have recorded.

Figure 8 shows a picture of one of the test receivers with Ultra E sensors being deployed. Figure 9 shows a Magnitude vs Offset (MVO) plot for a tow line, the signal frequency used is 0.9375Hz. Also shown is a noise estimate around the source frequency in units of V/m. A stacking time of 100s was used for the MVO and the noise estimate. On out-tow (right hand side of peak) the EX sensor pair has a noise level of around 4.5pV/m at this frequency. Figure 10 shows the noise estimate on out-tow vs source frequency, found from a set of plots similar to that in Figure 9. The water depth was 1100m in this case.

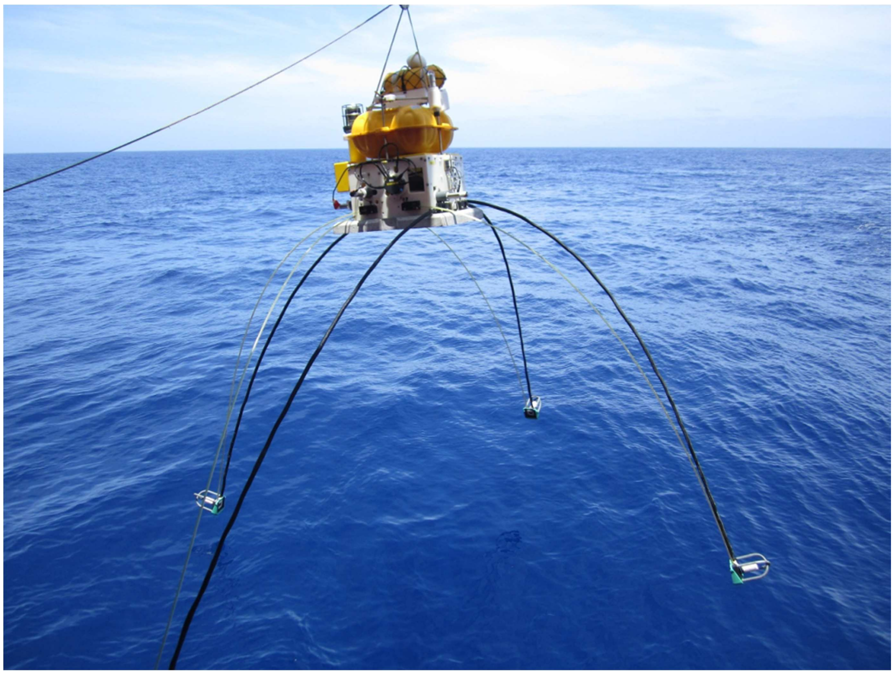

Figure 8 A receiver with Ultra E sensors being deployed

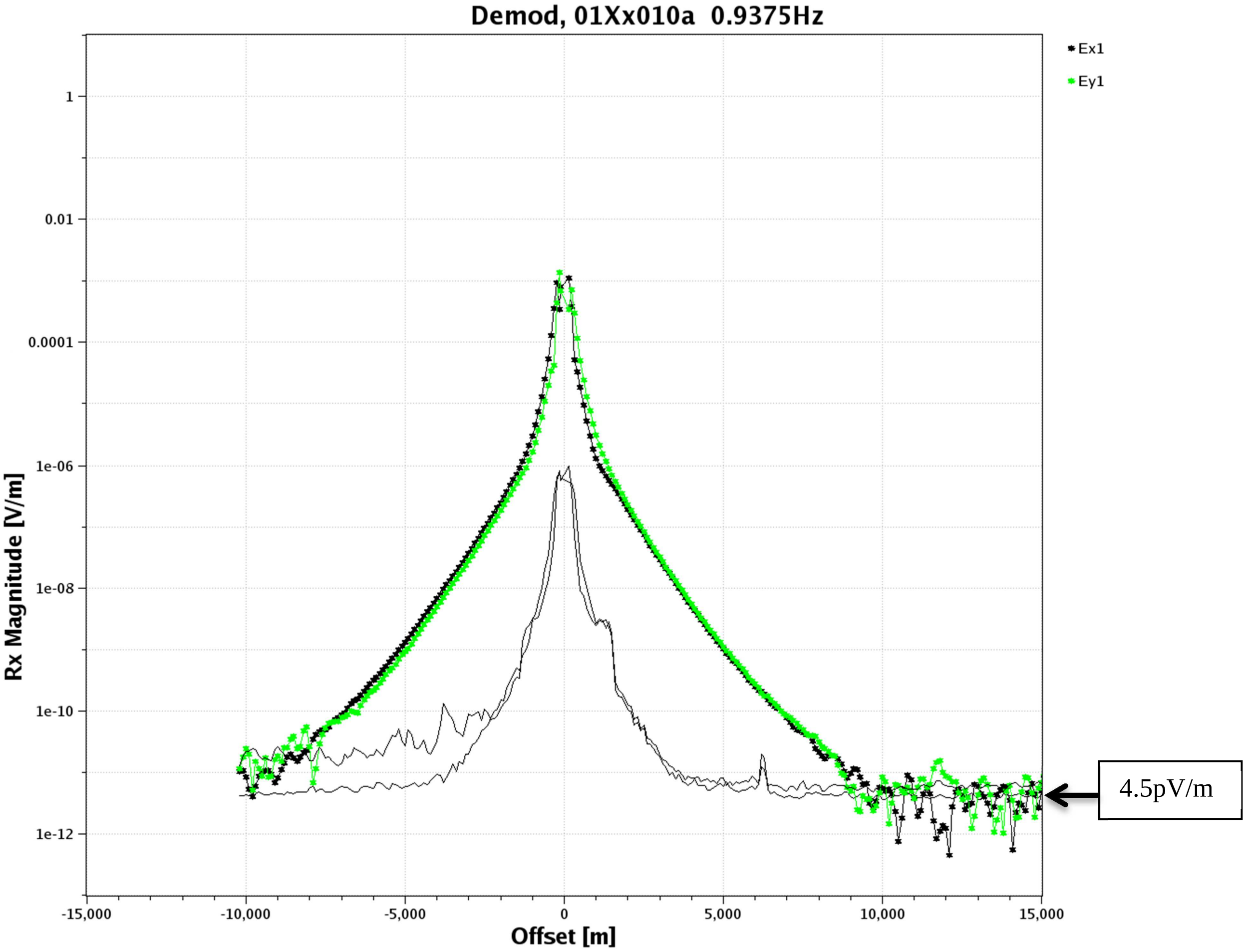

Figure 9 Magnitude vs Offset at 0.9375Hz and noise estimate at the same frequency (100s stacking)

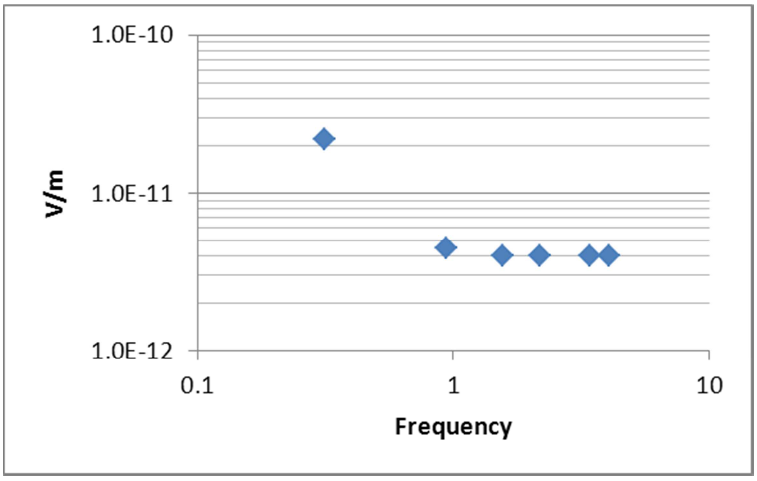

Figure 10 Estimated noise vs frequency for the E field with 100s stacking

One of the test receivers was modified to have two sensor pair in the EX direction (i.e. with no EY sensor). The purpose of this was to investigate the correlation between the channels, and from that evaluate what is actual signal on the seabed, and what is system noise. The receiver was dropped at almost 2500m water depth, and data recorded for ~3 weeks. An example of the results is shown in Figure 11 below. The red and blue curves are the amplitude spectral density for the field strength (i.e. the recorded voltage divided by an arm length of 8m). The green curve is the amplitude spectral density of the difference between the two channels, $(EX1 - EX2)/\sqrt{2}$. If the two sensor signals have the same amplitude, but are uncorrelated, for example consisting of thermal noise, the spectral density of the difference will be the same as for the individual channels. This seems to be the case at frequencies above ~0.1Hz. The part of the signal that is the same for both channels will be removed in the subtraction and will not contribute to the spectral density of the difference. This will be the case for towed source signal and MT signal. We see that below ~0.05Hz, the spectrums for the two channels are very similar, and the difference spectrum is a factor ~50 below the two channels. This shows that the recorded signal is actual signal, likely MT signal, and not system noise.

For MT measurements, the MT noise acts as the excitation source, and therefore it is important that the sensor noise is significantly below the MT noise in the frequency of interest to enable the secondary signals generated by the conductivity anomalies below the sea bed to be characterised.

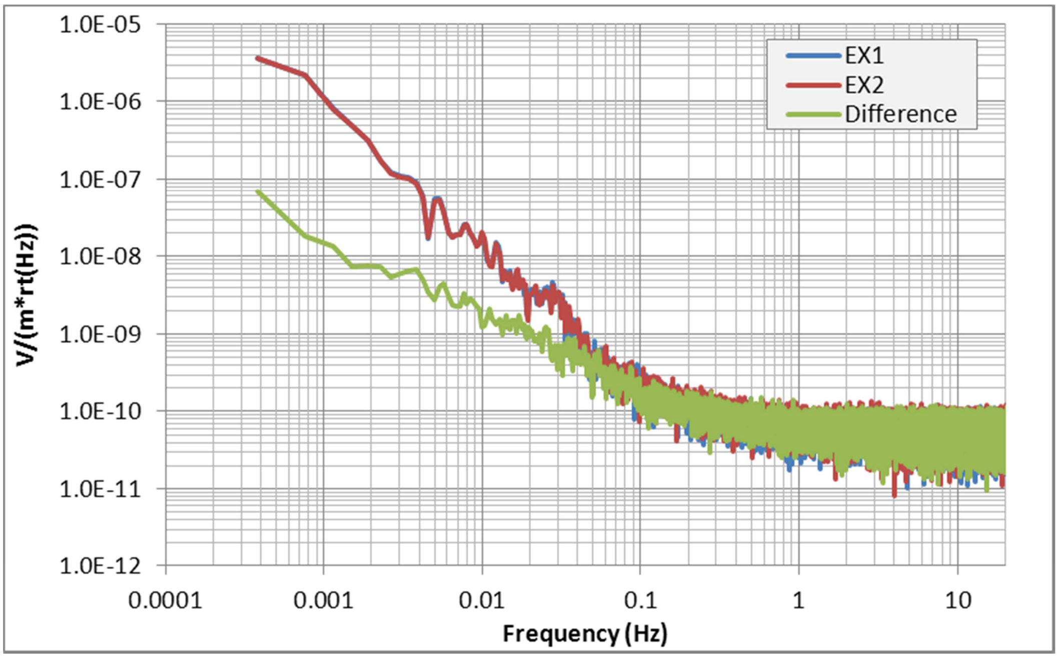

Figure 11 Amplitude spectral density for the two senor pairs compared to the difference between the sensors (divided by $\sqrt{2}$)

Conclusions

We have demonstrated low noise amplifiers suitable for MMT and CSEM applications in the range from below 0.5mHz to above 10Hz.

We have demonstrated Ag/AgCl E field sensors with noise level less than $1\, nV/\sqrt{Hz}$ down to 10mHz in the laboratory, and down to ~0.1Hz on the seabed. We have also shown that on the seabed, the sensor noise in the range 0.001Hz to 0.01 Hz is less than the background MT noise in deep water.

The sensors and amplifiers have shown stable performance in the field during a six month period.

References

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