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Development and evaluation of an ultralow-noise sensor system for marine electric field measurements

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ABSTRACT

In this paper, we describe the development of an ultralow-noise sensor system consisting of non-polarizable Ag/AgCl electrodes and a chopper amplifier for detecting marine electric field signals. Ag/AgCl electrodes were fabricated using a constant current density to clean the electrode cores and were then electrolytically chloridized by applying a constant potential. An amplifier was developed using the chopper stabilization (CHS) technique to reduce the $1/f$ noise and the initial offset. To achieve ultralow-noise performance, we took advantage of newly developed materials in the fabrication of Ag/AgCl electrodes and proposed a residual ripple reduction loop to decrease the modulated noise and the offset of the chopper amplifier. Typical measured noise levels are 0.6 nV/rt(Hz) for the Ag/AgCl electrodes and 0.55 nV/rt(Hz) for the chopper amplifier at 1 Hz. The source resistance between pairs of Ag/AgCl electrodes is approximately 5 Ω. The offset potential is typically ±0.1 mV with a drift of less than 5 μV/day. The chopper amplifier had an offset voltage below 0.2 μV with a −3 dB bandwidth from 0.01 Hz to 40 Hz and a variable gain from 80 dB to 120 dB to achieve a large dynamic range. This sensor system is used for marine electric field measurements with high precision.

1. Introduction

Marine electromagnetic (EM) methods have been used extensively over the last 10 years, including in the commercial application of marine magnetotelluric (MT) and marine controlled-source electromagnetic (CSEM) soundings for offshore hydrocarbon exploration [1,2]. Seafloor electric field measurements are essential for both the marine MT and CSEM methods. However, induction in conductive seawater attenuates the magnetotelluric fields, causing a dramatic loss of electric field power on the seafloor at frequencies greater than 1 mHz [3]. As a result, the natural marine electric field signal is similar to the noise floor of the electric fields (0.1 nV/m) at approximately 1 Hz in typical continental shelf environments. The ability to detect electric fields on the deep seafloor requires an ultralow-noise level. Thus, the noise level of the recording instrument must be sufficiently low as to not significantly distort the signals, and the instrumental resolution must be capable of providing an accurate and reliable description of these signals [4]. With an increasing number of marine electromagnetic surveys in the deep ocean, carefully designed electric field sensors and amplifiers with much lower noise levels are needed to improve detection accuracy.

Marine electric field measurements require two electrical contacts with seawater. Non-polarizable Ag/AgCl electrodes have excellent electrochemical characteristics, such as a very high ion exchange reaction current and a lack of polarization at a low current density, and are considered the optimal type of electrode for marine geophysical surveys [5]. The three classic methods for Ag/AgCl electrode construction are electrolytic, thermal and thermal electrolytic fabrication [6]. Thermal Ag/AgCl electrodes have a reversible electrochemical process and have been studied for different applications [7,8]. Ag/AgCl electrodes with less resistance at low frequencies, stable potentials and lower noise levels can be obtained using electrolytic chloriding [9]. Filloux used Ag/AgCl electrodes for the first marine MT survey and described a “water chopper” recorder to remove drift and self-potential [4]. Webb et al. designed an electrolytic Ag/AgCl electrode by applying a constant current during anodizing [10]. Constable obtained a noise level of below 1 nV/rt(Hz) at 1 Hz on the deep seafloor using the same method [3,11]. Electromagnetic Geoservices (EMGS) has used

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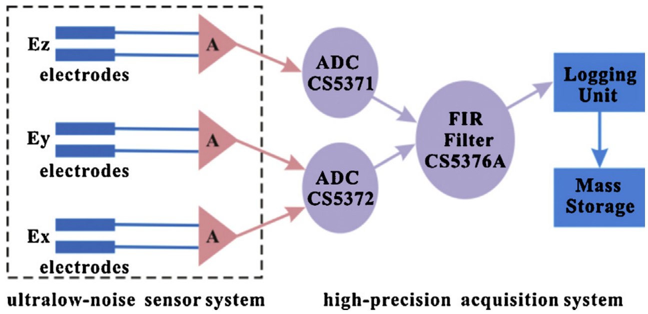

Fig. 1. A simplified block diagram of the signal measurement system. The dashed box shows the ultralow-noise sensor system.

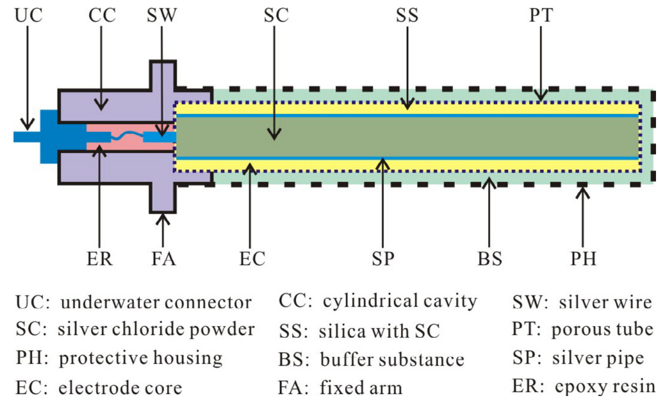

Fig. 2. Diagram of the interior of a cylindrical Ag/AgCl electrode. The electrode mainly contains electrode core (EC), cylindrical cavity (CC), fixed arm (FA), protective housing (PH) and underwater connector (UC). The electrode core is made up of silver wire (SW), porous tube (PT), silver pipe (SP) and the mixture of the silica and silver chloride powder.

electric field sensors from Ultra Electronics, which provides various low-noise electrodes for geophysical electromagnetic surveying. Other improved approaches for fabricating Ag/AgCl reference electrodes have been studied [12–15].

To measure low-amplitude and low-frequency (0.1 Hz to 10 Hz) electrical signals using Ag/AgCl electrodes, we must develop an ultralow-noise amplifier [11]. Most amplifiers are restricted by offsets and $1/f$ noise, which dominates at low frequencies and limits the minimum detectable signal. The conventional solutions for $1/f$ noise and offset are the auto-zero (AZ), correlated double sampling (CDS) and CHS techniques [16]. AZ increases the noise density in the band above the original thermal noise floor due to aliasing or folding back of the broadband thermal noise [17]. CDS is a specific case of AZ. CHS decreases the effects of amplifier noise and offset without affecting the baseband noise floor, and has been widely used in precision amplifier design due to its low noise levels [18]. However, conventional chopper amplifiers are unable to adequately remove the ripple caused by signal demodulation which may be considered as a very low-frequency noise source. Several techniques have been proposed to eliminate these ripples, such as the resistance balancing circuit technique [19], a continuous-time AC-coupled loop [20], a combination of chopping and correlated double sampling [21] and a charge injection suppression loop [22].

In this paper, we describe a novel method to improve the performance of Ag/AgCl electrodes, including their noise level, repeatability and stability. During the anodizing process, we applied both a fixed current density and potential. A constant current density was used for cleaning to achieve a low noise level, and the constant potential was used to increase the repeatability and stability of the Ag/AgCl electrodes. We also present an ultralow-noise chopper amplifier matched with Ag/AgCl electrodes. An outer chopper with an electronic switch detector was used to reduce the modulated $1/f$ noise and offset. Data from the Ag/AgCl electrodes and chopper amplifier demonstrate their ultralow-noise performance as a result of the improved approach and the residual ripple reduction loop. This research is a significant step towards improving the noise level and resolution of seafloor electric field instruments and towards increasing the accuracy of marine electric field measurements.

2. Sensor system description

A simplified block diagram showing the three components of the electric field signal (Ex, Ey, Ez) measurement system is given in Fig. 1. The measurement system essentially consists of an ultralow-noise sensor system and a high-precision acquisition system. As shown in the dashed box, each channel of an ultralow-noise sensor system contains two Ag/AgCl electrodes and a chopper amplifier.

2.1. Electrode mechanism

Ag/AgCl electrodes, which are normally represented by $Ag|AgCl|Cl^-$, consist of metallic silver (Ag), solid silver chloride (AgCl) and an electrolytic solution containing a soluble chloride [6]. The reversible reaction between Ag, AgCl and the electrolytic solution can be written as

$$AgCl + e^- \rightleftharpoons Ag + Cl^- \quad (1)$$

During measurement, small induced currents have an insignificant effect on the measured potential due to the large exchange current density.

The potential is given using the Nernst equation [9]:

$$E = E^0 - \frac{RT}{F}\ln a_{Cl^-} \quad (2)$$

where constant E^0 is the standard potential of the Ag/AgCl electrode, R is the constant of the perfect gas, T is the absolute temperature, F is the Faraday constant and a_{Cl^-} is the chloride-ion activity.

Eq. (2) shows that the potential of the Ag/AgCl electrodes is determined by the activity of the Cl^- ions. Therefore, it is necessary to maintain a constant concentration of Cl^- ions in the electrodes during fabrication.

2.2. Electrode fabrication

The fabrication of Ag/AgCl electrodes involves three main steps: (i) preparation of the electrode core, (ii) conversion of Ag to AgCl by anodization and (iii) construction of the Ag/AgCl electrode. The configuration of a cylindrical Ag/AgCl electrode is illustrated in Fig. 2.

2.2.1. Preparation of electrode cores

Prior to electrode core preparation, the materials (silver wire and silver pipe, 99.99% purity) were immersed in dilute nitric acid to remove surface contaminants and then rinsed thoroughly with deionized water. The silver wire was then connected to the top of the silver pipe with a hard link, and the bottom of the pipe was glued into a porous tube that was closed at the bottom. The interior of the silver pipe was packed with AgCl powder, and the space between the silver pipe and the porous tube was tightly packed with a mixture of AgCl and silica. The top of the porous tube was sealed with epoxy resin, completing the electrode core, and was soaked in distilled water to improve the contact.