Acoustic in-ice positioning in the Enceladus Explorer project

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Introduction

One of the most challenging tasks for humanity is the search for extraterrestrial life. A promising candidate for this search is Enceladus, a Saturn moon, which is completely covered by an ice crust. Recently, the Cassini spacecraft found evidence for a large underground ocean of liquid water at the south pole of Enceladus [1]. In earlier measurements Cassini found frozen water particles, salt and organic molecules in geysir-like jets ejected near the south pole [2]. The combination of both observations strengthens the possibility of the existence of extraterrestrial life on Enceladus. For further investigation it becomes essential to probe the liquid water directly. The Enceladus Explorer Project has been funded by the German Space Agency DLR as a first step toward the accomplishment of such a mission.

Enceladus Explorer project

The goal of the Enceladus Explorer project is to develop a maneuverable probe for a terrestrial test scenario where samples are to be taken from a subglacial water pocket at the Blood Falls in Antarctica in November 2014 [3]. The used probe is called "IceMole". Within the Enceladus Explorer project it has been successfully tested during two field tests, one on the Morteratsch Glacier in Switzerland in June 2013 and one on the Canada Glacier in Antarctica in November 2013. Prior to the final test there will be another field test in June 2014 on the Morteratsch Glacier in Switzerland.

IceMole

The IceMole is a melting probe with an ice screw for forward thrust [4]. Partial heating of the IceMole head allows to drive curved trajectories through the ice. To monitor and control these trajectories a navigation system has been developed. This navigation system consists of an inertial measurement unit and a magnetometer as well as an acoustic navigation system containing an ultrasonic reconnaissance system, which explores the fore-field of the probe and an acoustic positioning system, which determines the absolute position of the IceMole [3].

Acoustic Postitioning System

The Acoustic Positioning System (APS) uses six ultrasound emitters embedded in the upper ice layers as well as four ultrasound receivers in the IceMole head. The position of the IceMole is determined by measuring the arrival times of the emitted pulses, converting them into distances and using trilateration to calculate the position. A sketch of the APS method is shown in figure 1. The ultrasound emitters are commercial sonar transducers which emit sinus bursts with a frequency of 18 kHz and a length of 11 periods [5]. Each ultrasound receiver [6] consists of a piezo element whose signals are directly processed by the APS front end electronics [7]. The current front end electronics filters out frequencies below 10 kHz and above 300 kHz and therefore has a rather broad passband [6]. The sensor design is shown in figure 2. The desired detection range of the system is at least 100 m [3].

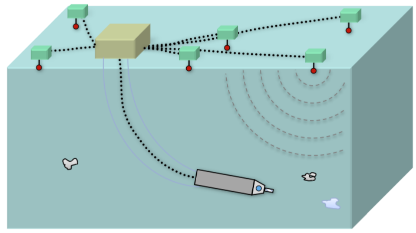

Figure 1: Sketch of the APS measurement technique: Emitters form a net on the ice surface. Receivers are situated in the head of the probe and measure the arrival time of the emitted signal [3].

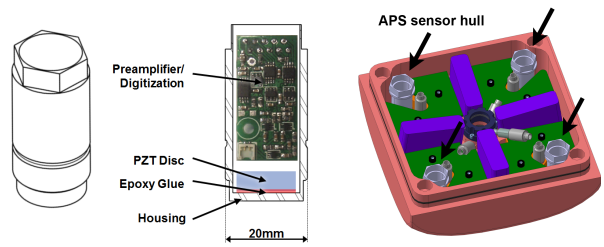

Figure 2: Sensor design: The piezo element with the current front end electronics is situated in the APS sensor hull (left). The sensor hulls are integrated in the IceMole head [3] (right).

Optimization of the signal detection

The main challenge in analyzing the raw data is to find a robust method for a precise determination of the arrival time of the signal. The five sigma method (FSM) searches for the first time where the noise level is surpassed by a factor of five. The noise level is defined as the standard deviation of the first millisecond of data, which is recorded before a signal is being transmitted. The APS reduces the noise by averaging over 32 waveforms and thus reducing miss-identifications. However if the noise level is too high or if there are other large signals recorded beside the emitted one the FSM fails. A waveform where

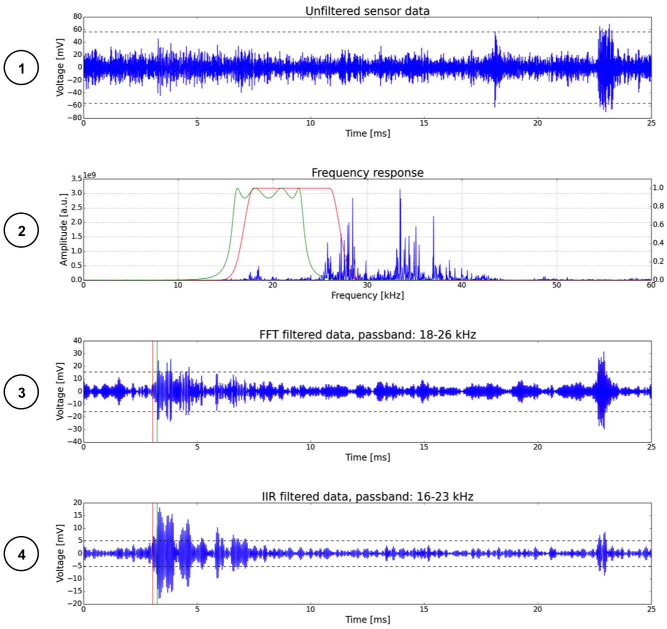

Figure 3: (1) Measured data averaged over 32 waveforms, (2) Fourier spectrum of the data, frequency response of the Fourier filter (red) and the IIR filter (green), (3) Fourier filtered data, (4) IIR filtered data. The dashed horizontal lines indicate five times the standard deviation of the noise. The vertical lines mark the determined arrival time. The different plots will be explained more precisely in the chapter on the optimization of the signal detection.

such problems occur is shown in figure 3.1. The data was taken during the field test in Antarctica with a distance between emitter and receiver of about 7 m. Therefore one expects to detect a signal at around 3 ms, including 1 ms of noise. It is obvious that no signal exceeds the noise level at around 3 ms. Instead there are two other signals at the end of the waveform, which are detected by the FSM. Closer investigations using a time resolved Fourier spectrum indicate that those signals have a broad frequency range, typically between 20 kHz and 60 kHz, in contradiction to the emitted signal at 18 kHz. Therefore those signals are transient signals which most likely originate from cracks within the glacier. Furthermore it becomes clear that the noise level after averaging is still to high to achieve the desired detection. Both transient signals and noise can be reduced by the use of frequency filters. The currently used filter is a Fourier filter with a passband of 18 kHz to 26 kHz. The Fourier spectrum of the measured data as well as in red the frequency response of the Fourier filter is shown in figure 3.2. Figure 3.3 shows the Fourier filtered data. After filtering, the expected signal at about 3 ms can be found by the FSM. The transient signals at the end of the waveform could be reduced but are still quite dominant. This shows that the use of frequency filters is recommendable and is to be investigated further. The performed design study verifies that an infinite impulse response (IIR) filter [8] with a passband of 16 kHz to 23 kHz and a Chebyshev type 1 filter design [8] as shown in green in figure 3.2 gives the best results. Figure 3.4 shows the IIR filtered data. The signal at about 3 ms can be found by the FSM and the transient signals at the end of the waveform were able to be significantly reduced in comparison to the emitted signal. To compare the noise reduction of different filters the best choice is to look at the signal-to-noise ratio (SNR). The SNR of the Fourier filtered data is about 7.8 while for the IIR filtered data the SNR is about 17.7 which is a factor of 2.3 higher. The investigation of the optimal filter characteristics was done as a design study for the development of new sensor electronics for APS. The results strongly suggest the use of analog filters in future APS sensor electronics.

Summary & Outlook

In this contribution a design study for the use of analog filters in the APS sensor electronics was presented. The differences between the compared filters were pointed out on the basis of data, which was taken during the field test in Antarctica. It was shown that the use of analog filters in the APS sensor electronics is absolutely recommended. Based on the design studies, improved front end electronics with an optimized two stage analog filter were developed and are in production. First test measurements with a prototype in the laboratory indicate an improvement compared to the old front end electronics. Further test measurements will be done during the field test in Switzerland in June 2014 to confirm this improvement under realistic conditions.

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