The development of an acoustic probe to measure the thickness of ferro-manganese crusts

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***Abstract*—This paper describes the development of an acoustic probe designed to perform *in-situ* measurements of ferro-manganese crust thickness at depths of up to 3000 m. It is planned that this device will operate at low altitudes off the seafloor, mounted onboard an underwater vehicle, and continuously map the crust thickness of regions extending over several kilometres. A prototype probe has been developed together with an algorithm that automatically detects the reflections from the top and bottom surfaces of a layer of crust and measures its thickness. The performance of the system is demonstrated through a series of laboratory experiments carried out using crust samples obtained during the NT09-02 Leg 2 of the R/V Natsushima. First, the ability of the system to measure crust thickness at various ranges to the target is assessed. Next, the effects of pressure are investigated in an experiment where the thicknesses of several crust samples are measured at pressures between 0.1 and 30 MPa. Finally, the sub-bottom profiles of a number of crust samples, with and without substrates attached are measured.**

I. Introduction

Cobalt rich, ferro-manganese crust deposits occur throughout the pacific on seamounts, guyots and plateaus in areas that have been kept free of sedimentation for periods extending over millions of years [1]. The crusts are generally found at depths between 1000 and 3000 m, and are formed by oxidised minerals that precipitate out of the ambient seawater to form a continuous layer of deposit. These deposits can extend over several tens of kilometres, blanketing an underlying hard-rock substrate. The crust layers are typically no more than 150 mm thick, but can be as thick as 250 mm in places, with growth rates ranging from 4 to 7 mm/Ma depending on gravity processes, pH, sediment cover and ocean currents [2]. The crusts consist mainly of Fe and Mn oxides, but are rich in Co, Ni, Cu and contain traces of Pt, making them the focus of much attention as a potential target for mining [3]. However, since the thicknesses of the crust layers can vary anywhere between 10 and 250 mm, a method to accurately measure crust thickness on a regional scale is sought in order to determine their value as a mineral resource. In this research, the authors seek to develop an acoustic probe to perform *in-situ* measurements of ferro-manganese crusts thickness. It is planned that this device will operate at low altitudes off the seafloor, mounted onboard an autonomous underwater vehicle (AUV), and continuously map the crust thickness of regions extending over several kilometres.

This paper describes the development of a prototype acoustic device, and presents a study to demonstrate the feasibility of remote acoustic measurement of ferro-manganese crust thickness. A 3000 m depth rated, high frequency prototype probe has been developed together with an algorithm to automatically measure the thickness of the crusts. In this paper, the performance of the proposed system is demonstrated through a series of laboratory experiments using ferro-manganese crust samples obtained during the NT09-02 Leg 2 of the R/V Natsushima (see figure 1). The effects of distance to target and ambient pressure on the accuracy of the measurement of crust thickness are assessed and the sub-bottom profiles of a number of ferro-manganese crust samples, both with and without their substrates, are obtained. Based on this prototype, an ocean going probe is being developed to perform high-resolution, continuous measurements of ferro-manganese crust thickness *in-situ* at depths of up to 3000 m.

II. Problem Formulation

An acoustic reflection occurs at any boundary where there is a change in acoustic impedance. Therefore, assuming that the acoustic propagation velocity within a target object is known, and as long as there is some contrast in acoustic impedance between the target and the media either side of it, it is possible to compute the target's thickness by measuring the time of flight between the acoustic reflections that take place at its top and bottom surfaces. However, ferro-manganese crusts grow on a wide variety of substrates, and subsequently the level

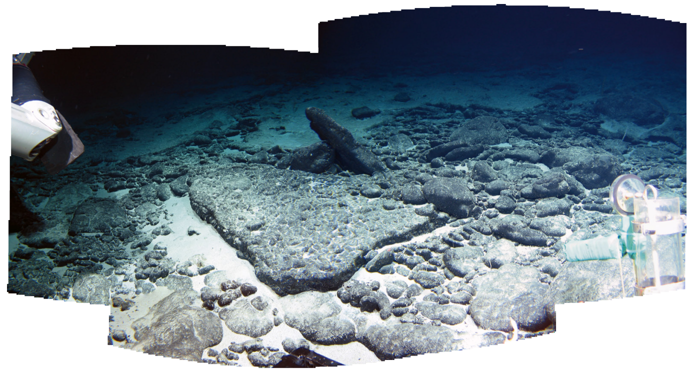

Fig. 1. Photo of crust deposits taken during NT09-02 Leg 2.

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of contrast can vary significantly between different regions [4], [5]. In cases where there is little contrast in impedance between the crusts and their substrate, reflections occurring at their boundary may be too small to detect and acoustic measurement of crust thickness may not be possible. However, in the case of fresh basalt, phosphorite and certain types of breccia substrate, a sufficient contrast in impedance can be expected and acoustic measurement of crust thickness may be possible. Even in these cases, measurement will still be complicated by seafloor roughness and the fact that the crusts being measured can be as thin as 10 mm.

With regard to the physical geometry of the crusts, the acoustic devices used in most sub-bottom applications are designed to detect features several metres beneath the seafloor, typically operating at frequencies of less than 10 kHz in order to achieve deep penetration. As such they do not have sufficient resolution to discretise layers only a few centimetres thick. In the case of manganese crusts, this is further complicated by the roughness of the surfaces that exist on a variety of scales, with bumps of similar or even greater magnitude than the thickness of the crusts themselves. Under these conditions, the high energy acoustic reflections from the undulating surfaces cannot be resolved in time from the much weaker reflections of the crust-substrate interface. When subject to these limitations, low-frequency signals do not have the necessary spatial or temporal resolution to resolve the thickness of thin, bumpy crusts. The authors propose to overcome these issues by operating a high-frequency transducer, at low altitudes off the seafloor using an underwater vehicle to maintain the range to the target.

This work focuses on the development of a practical tool to make accurate remote measurements of manganese crusts with thicknesses greater than 30 mm, since these are of most interest as a potential mineral resource. In order to achieve this, a high-frequency acoustic probe has been developed together with an algorithm to automatically determine the thickness of the target crusts. In our previous work, an acoustic beam of frequency 100 kHz with a footprint of 20 mm on its target was found to provide a suitable balance between resolution and signal attenuation when measuring crusts with thicknesses in the range of interest [6]. In this work, an amplitude modulated 100 kHz probing wave is generated using 1 MHz primaries to achieve a narrow beam and increase the range of operation of the system. However, even though underwater vehicles are capable of maintaining low altitudes, small changes in the distance to the target are to be expected due to undulations of the seafloor, and it is important that the developed probe has a sufficient depth of focus to compensate for this. The first experiment described in this paper assesses the ability of the system to measure crust thickness at various distances to the target. Next, the effects of pressure are investigated in an experiment where the thicknesses of several crust samples are measured at pressures between 0.1 and 30 MPa. Finally, the sub-bottom profiles of a number of crust samples, both with and without substrates are measured and the average thicknesses of the crust layers are computed.

III. Sample preparation

Variations in crust geometry and the underlying substrate rock types greatly complicate the acoustic measurement of ferro-manganese crust thickness. Further complications arise concerning the development of a device to measure crust thickness, due to the difficulty in obtaining high quality samples with which to perform experiments. The crusts are fragile and easily damaged during sampling and storage, and often their condition is not sufficient for the measured acoustic properties to be representative of their *in-situ* acoustic characteristics. For example, the use of dredges for sampling can cause cracks and small hairline fractures within the sample. Such features will greatly affect their acoustic behaviour, causing internal reflections and dissipating the acoustic signal within the sample. Similarly, if the samples are allowed to dry during storage, they will inevitably contain voids and pockets of air and it will not be possible to completely restore them to their

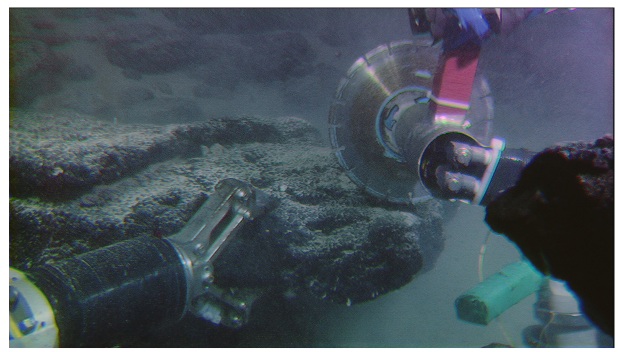
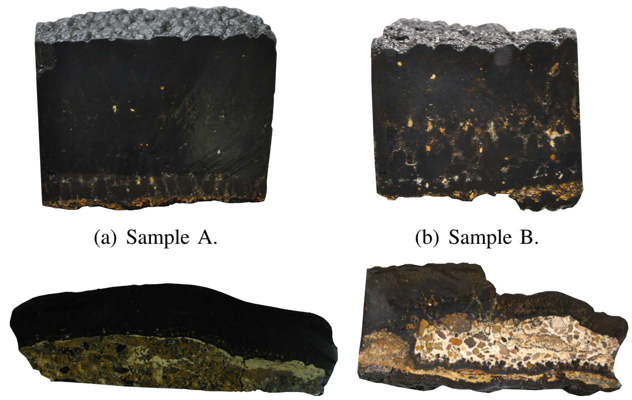


Fig. 2. Sampling of manganese crusts using the ROV Hyperdolphin.



(a) Sample A. (b) Sample B.

(c) Sample C. (d) Sample D.

Fig. 3. Crust samples used in this investigation.

TABLE I
Details of samples used in this study.

Sample	Dimensions (mm)	Mass (g)	Description
A	$115 \times 110 \times 93$	2400	Crust
B	$95 \times 80 \times 71$	1200	Crust
C	$280 \times 65 \times 85$	3200	Crust and substrate
D	$200 \times 60 \times 100$	2000	Crust and substrate

original state. It should be noted that such features would not be expected in the ambient seafloor environments where ferro-manganese crusts are formed. Therefore, the first stage of this research was to obtain high quality ferro-manganese crust samples with which to carry out acoustic investigations.

Sampling of ferro-manganese crusts was performed using the ROV Hyperdolphin of JAMSTEC, during the NT09-02 Leg 2 of the R/V Natsushima. During the cruise, a total of more than 700 kg of crust were sampled from depths of between 900 and 3000 m over 7 dives with the ROV (figure 2). Care was taken to not crack or damage the crusts with the ROV manipulator during sampling, and maintain the samples in good condition during storage once they had been retrieved. Of these, 18 samples, with a variety of substrates, surface structures and thicknesses were selected for acoustic investigation. These were chosen specifically to be representative of the ferro-manganese crust types observed during the cruise. Once these samples were brought onboard the R/V Natsushima, they were immediately washed and immersed in water. The samples were then stored at low temperatures in order to maintain their condition and allow for representative acoustic characterisation. This paper describes experiments carried out on four samples, shown in figure 3, retrieved during this cruise. The dimensions and physical characteristics of these samples are given in table I.

IV. PROBE

A 3000 m depth rated, high frequency probe has been developed as a prototype to demonstrate remote acoustic measurement of manganese crust thickness. The probe, pictured in figure 4, has a spherically focused transducer of diameter 100 mm and a focal length of 500 mm. The transducer consists of an annular array of 1 MHz 1-3 piezoelectric composite elements for transmission, with a 100 kHz receiver array built-in along the same axis. The probe transmits a 1 MHz, high frequency amplitude modulated signal in order to generate a narrow 100 kHz beam that penetrates the target. The echoes of the low frequency component are detected using the on-axis 100 kHz receiver. The oil-filled probe design is pressure compensated to operate at depths of up to 3000 m.

Fig. 4. 3000 m depth rated spherically focused transducer array.

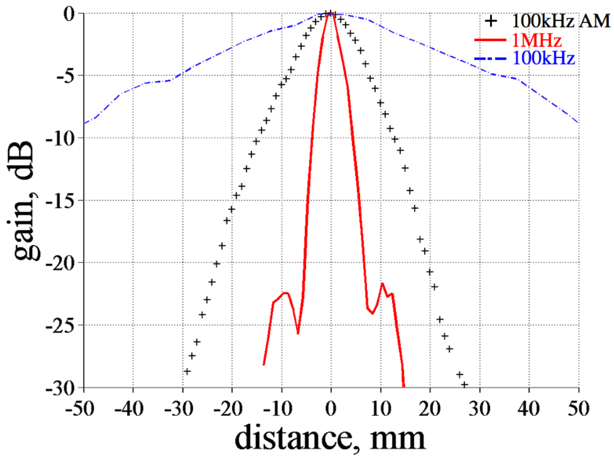


Fig. 5. One-way beam pattern measured at a range of 500 mm.

Figure 5 shows the beam pattern of the probe measured using a broadband hydrophone (RESON TC-4038). The hydrophone was placed at the focal length, 500 mm from the transducer and scanned laterally in steps of 1 mm. The high frequency 1 MHz and low frequency 100 kHz components of the transmitted amplitude modulated signal were separated using a band-pass filter, and the corresponding beam patterns are plotted by the solid line and crosses respectively. It can be seen that the 100 kHz component that penetrates the target, denoted as 100 kHz AM, is narrow with a -3 dB beam width of 15 mm at its focal length. It is also noted that no significant side lobes are observed in the measured signal. The dotted line represents the beam pattern of the 100 kHz receiver array used to detect the echoes of the transmitted signal. The sampling rate of the system is set to 0.5 MHz for the experiments described in this paper.

V. MEASUREMENT ALGORITHM

Since the aim of this research is to develop a system to continuously map the thickness of ferro-manganese crusts of regions extending over several kilometres, it is necessary to develop an algorithm to automatically process the vast amounts of data recorded. In order to achieve this, a simple software based peak detection algorithm has been developed and is implemented to automatically measure the thickness of the crusts. The algorithm, illustrated in figure 6, recognises peaks in the acoustic data based on envelope detection of the reflected signal, $S(t)$, where each signal represents a discrete set of data containing the acoustic reflections that occur within a fixed period after a single transmission. The algorithm first takes the modulus of the reflected signal and applies a low-pass filter to extract the low-frequency envelope, $|S(t)|_{filter}$. At this point, the algorithm uses the following condition to check that the signal has a sufficient signal-noise-ratio for the peak detection algorithm to work reliably,

$$\frac{\overline{|S(t)|_{filter}}}{\max |S(t)|_{filter}} < k_{S/N}, \quad (1)$$

where $k_{S/N}$ is a fixed constant less than 1. If the above condition is satisfied, a step window function is used to detect the peaks using an adaptive threshold which is modified according to the maximum amplitude of the signal. The threshold for the top and bottom peaks are set as follows:

$$\sigma_{top} = k_{top} \max |S(t)|_{filter}, \quad (2)$$
$$\sigma_{bot} = k_{bot} \max |S(t)|_{filter}, \quad (3)$$

where k_{top} and k_{bot} are fixed constants of value less than 1. Next, a window function is used to search for the first peak using the following condition,

$$\textbf{if} \left(\max_{t=t_k}^{t_k+n} |S(t)|_{filter} - \sigma_{top} > 0 \right)$$
$$t_{top} = \left\{ t : \max_{t=t_k}^{t_k+n} |S(t)|_{filter} \right\}$$
$$\textbf{else}$$
$$t_k = t_k + \frac{n}{2}, \quad (4)$$

where t_k points at the beginning of each search and n is the width of the window. If condition (4) is satisfied, the peak is labelled as the top surface reflection and the time at which it occurred is stored as t_{top}. If the condition is not satisfied, the search shifts half a window width and the process is repeated iteratively until the end of the signal is reached. In the case of a positive result, the algorithm next searches for the bottom surface reflection as follows:

$$\textbf{if} \left(\max_{t=t_{min}}^{t_{max}} |S(t)|_{filter} - \sigma_{bot} > 0 \right)$$
$$t_{bot} = \left\{ t : \max_{t=t_{min}}^{t_{max}} |S(t)|_{filter} \right\}. \quad (5)$$

The size of the search window for the bottom surface is bound by t_{min} and t_{max}, where in this study the lower bound is defined since discussion is limited to crusts thicker than 30 mm, and the upper bound is based on the fact that crusts are rarely reported with thicknesses greater than 250 mm. If condition (5) is satisfied, then the thickness of crust is measured based on the time of flight between the reflections, $\Delta t = t_{bot} - t_{top}$, using the p-wave velocity, c_p, in the crusts, as follows:

$$d = c_p \frac{\Delta t}{2}, \quad (6)$$

where an average value of $c_p = 2680\, m/s$ was measured for the crusts obtained during the cruise.

It should be noted that in this algorithm, the following assumptions are made implicitly:

- the target's uppermost surface is manganese crust, and
- the crust deposit is formed by a single continuous layer.

The first condition can be confirmed locally using visual images of the seafloor obtained by the underwater vehicle on which the acoustic device is mounted. The second condition is generally true considering the mechanisms understood to be behind the formation of manganese crusts.

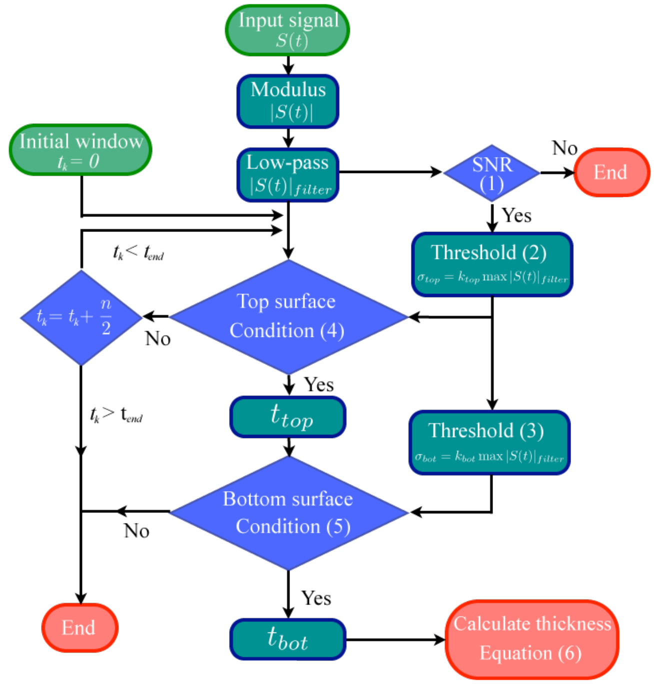


Fig. 6. Peak detection and crust thickness measurement algorithm.

VI. Experiments

A series of experiments were carried out in order to investigate the performance of the acoustic probe and the measurement algorithm described in the preceding sections. First, the ability to measure the thickness of a crust sample at various distances along the probe's longitudinal centreline is assessed. Next, the thicknesses of two crust samples are measured at pressures from 0.1 to 30 MPa to investigate the effects of pressure on the performance of the probe and on the acoustic characteristics of the crusts. Finally, the sub-bottom profiles of four crust samples are measured at atmospheric pressure in order to assess the robustness of the algorithm when scanning continuous layers, and investigate the feasibility of measuring crusts with various substrates.

A. Longitudinal range

The thickness of a 93 mm thick crust sample, sample A, was measured at various longitudinal distances from the probe. The sample was placed along the centreline of the probe and the distance to the target was varied from 250 mm to 1050 mm in steps of 50 mm. The experiment was performed in an acrylic tank of dimensions $1.8 \times 0.6 \times 0.75$ m, as shown in figure 7. The acoustic reflections recorded by the receiver array are plotted in figure 8. For clarity of presentation the plots have been offset vertically according to the distance between the probe and the top surface of the crust. It can be seen that as the sample moves further away from the probe, the reflections from its surfaces move further back in time. The reflections seen at 1350 μs are of the back wall of the tank. For separations larger than 650 mm it was necessary to move the probe away from the sample and so the distance to the tank wall increases.

The measurement algorithm was applied to all the data obtained during the experiment. Figures 9(a), (b) and (c) show the reflections from the sample recorded for separations of 250 mm, 500 mm and 1050 mm respectively. The dotted lines show the raw data recorded by the system at a sampling rate of 0.5 MHz. The solid lines show the low-frequency envelopes extracted using the measurement algorithm. The crosses denote the locations of the peaks corresponding to the top, S_{top}, and bottom, S_{bot}, surfaces of the sample as detected by the algorithm. In all cases, both surfaces were correctly identified. However, as the distance between the sample and probe moves away from the focal length of the system at 500 mm, the quality of the recorded signal starts to decrease. Figures 10 and 11 show the variation of the peak amplitudes for the top and bottom surfaces, and the thicknesses measured by the algorithm as the distance to the target changes. The measurement of thickness by the algorithm is most accurate near the focal length. However, even though the algorithm remains robust and correctly identifies both the top and bottom surfaces of the crust in all cases, as the distance between the probe and sample moves away from the focal length, the surface reflections become smaller in amplitude and longer in time, making it more difficult for the algorithm to accurately identify the locations of the top and bottom surface peaks. This effect is thought to be due to a combination of the beam having a larger footprint on the sample away from the focal length, and due to scattering of the reflected signal caused by surface roughness resulting in a smaller proportion of the reflected signal being detected by the receiver array as the distance to the target increases. It is suggested that techniques such as dynamic beam focusing could be introduced to elucidate the first point and improve the overall accuracy of the system.

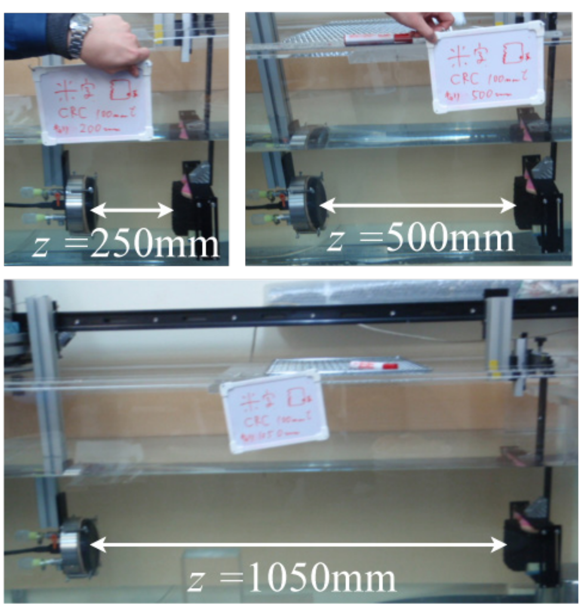


Fig. 7. Experimental set-up for measurement of sample A at various distances.

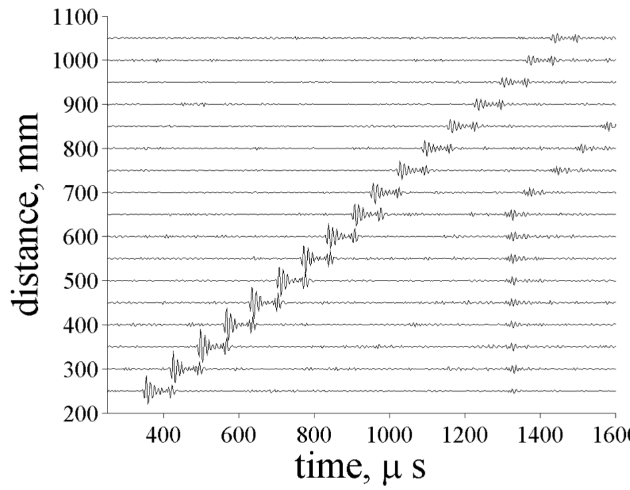
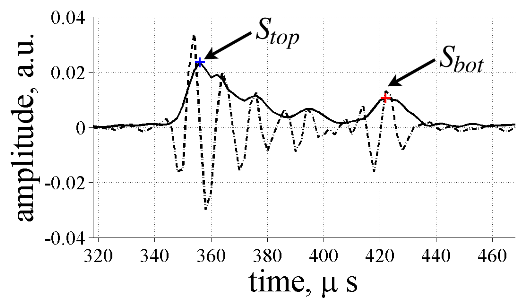
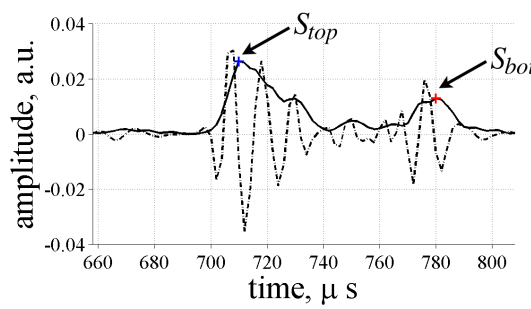


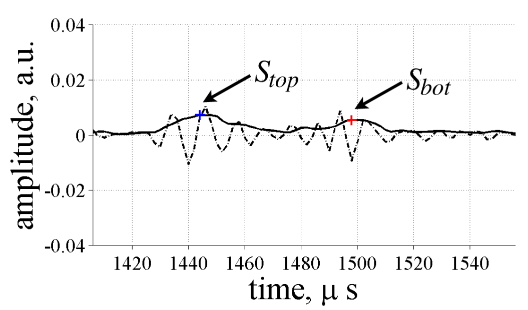
Fig. 8. Acoustic reflections from sample A at various distances.



(a) z =250 mm



(b) z =500 mm



(c) z =1050 mm

Fig. 9. Reflections from top and bottom surfaces of sample A.

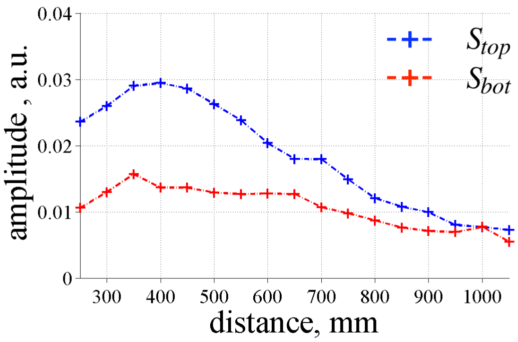


Fig. 10. Amplitude of top and bottom surface peaks of sample A at various distances.

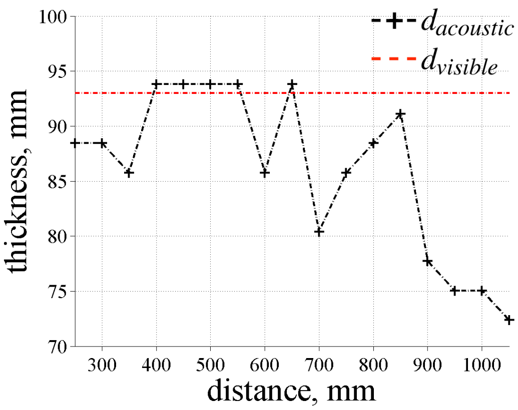


Fig. 11. Automatic measurement of the thickness of sample A at various distances.

B. Measurement under pressure

One area of concern for *in-situ* measurement of crust thickness is that the acoustic properties of the crusts may change with pressure. In order to investigate this point and verify the performance of the acoustic probe under pressure, an experiment was performed where the thicknesses of samples A and C were measured at various pressures up to an equivalent ocean depth of 3000 m. The pressure chamber used in the experiment had a diameter of 525 mm and a length of 1200 mm. An aluminium frame was used to align the system with the samples held at a distance of 500 mm from the probe using a mount with a 100 mm diameter opening so as to not obstruct the acoustic path. It can be seen from figure 5 that the beam width of the transmitted signal is sufficiently narrow that the sample mount has no effect on the results obtained. The experimental set-up is shown in figure 12.

In the experiments, the pressure was increased from 0.1 MPa to 30 MPa, and reduced back down to atmospheric conditions over a period of 54 minutes. During this period acoustic measurements were made continuously throughout the entire pressure cycle. The results of the thickness measurement for sample A are presented in figure 13. For clarity of presentation, only the data obtained at 5 MPa intervals is shown and the recorded signals have been offset vertically according to the pressure at the time of measurement. It can be seen that as the pressure increases the signals move forwards in time due to an increase in the speed of sound in water. Figures 14 and 15 show the peaks detected by the algorithm and the resulting thicknesses measured when applied to all of the data recorded during the up and down pressure cycles of the experiment. A constant value of 2680 m/s has been used for the p-wave velocity in the crust. No effects of pressure can be seen in the height of the peaks or the measured thickness of the sample. It can be inferred from the results that effects of pressure on the acoustic impedance, attenuation and acoustic velocity of the crust are negligable for the purposes of this study.

Next, the experiment was repeated using sample C. This sample consists of both crust and substrate, with an average visible crust thickness of 47 mm. The substrate is composed of angular fragments of debris flow deposit, or breccia. The acoustic impedance of the crust and substrate for this sample were measured to be 4.9 kg/cm^3 m/s and 10.9 kg/cm^3 m/s respectively, and so there is sufficient contrast to expect a detectable acoustic reflection from the interface. The signals recorded for pressures of 0.1 MPa to 30 MPa are plotted in figure 16. The peak detection algorithm was applied to the data obtained, as illustrated in figure 17. The reflection from the substrate interface is somewhat weaker, and longer in time compared to the reflection from the bottom surface of sample A. However, the algorithm was able to detect the location of the bottom surface of the crust for all the data recorded. Figures 18 and 19 show the peak heights and the thickness of the sample measured using the algorithm. As in the case of sample A, there appears to be no significant effect of pressure on the measurement. It is noted that the measured thickness is somewhat larger than the average thickness of the visible crust. However, the thickness of the visible crust varies between 40 mm and 60 mm and the exact location of the measurement made in the experiment could not be accurately determined with the set-up used.

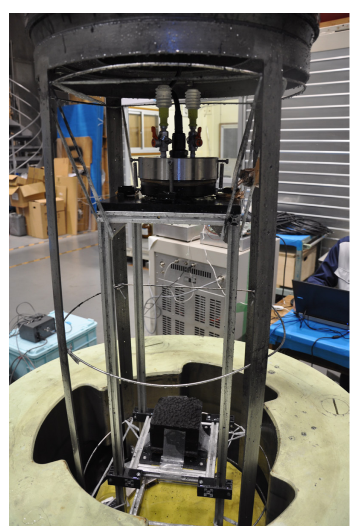


Fig. 12. Set-up for high pressure experiments.

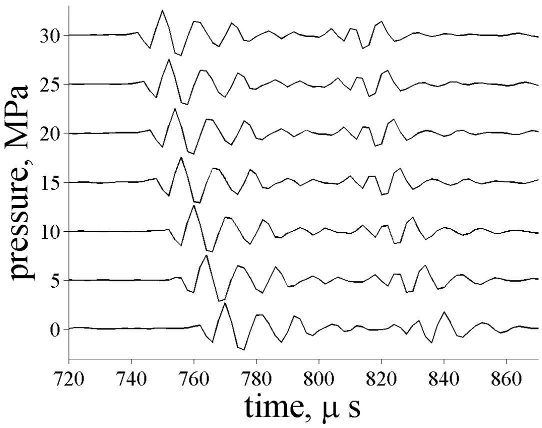


Fig. 13. Acoustic reflections from sample A at various pressures.

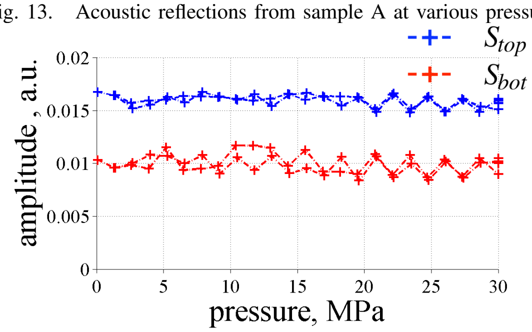


Fig. 14. Top and bottom surface peaks of sample A at various pressures.

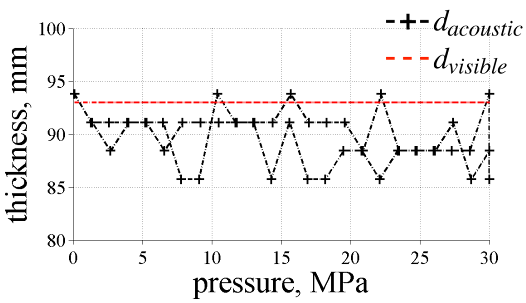


Fig. 15. Crust thickness of sample A measured at various pressures.

C. Transverse scan

The final series of experiments measures the sub-bottom profiles of samples A, B, C and D. The samples were placed 500 mm away from the probe, and were scanned laterally in steps of 1 mm. The experiment was performed at atmospheric pressure using the acrylic tank described earlier. In the case of samples A and B the entire sample was scanned. For samples C and D, it was not possible to scan the entire sample due to limitations in the available space. These samples were scanned a distance of 150 and 130 mm respectively. The acoustic profiles recorded for each sample are shown in figure 20. The proposed algorithm was applied to all the data obtained. The peaks detected by the algorithm and corresponding thicknesses measured are plotted for each of the samples in figures 21 and 22 respectively. The average thicknesses of the crusts

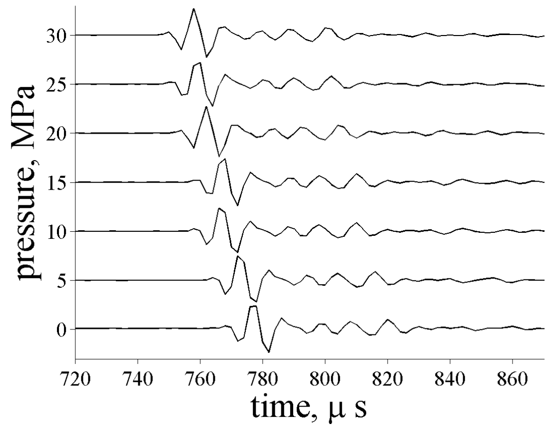


Fig. 16. Acoustic reflections from sample C at various pressures.

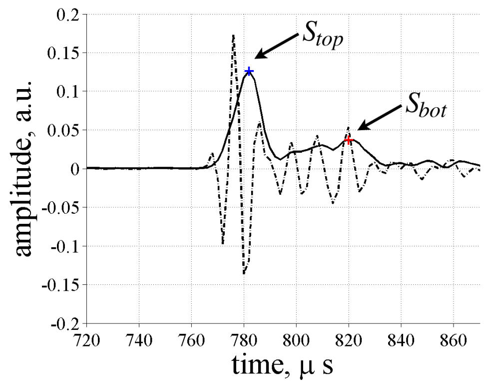


Fig. 17. Reflections from top and bottom surfaces of sample C's crust.

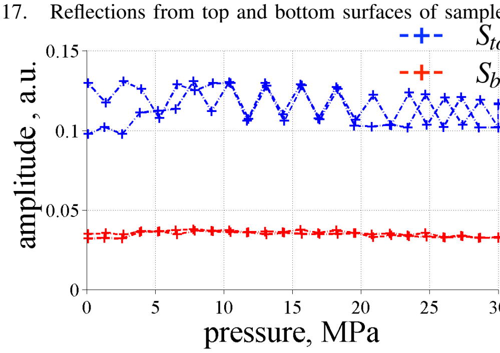


Fig. 18. Top and bottom surface peaks of sample C at various pressures.

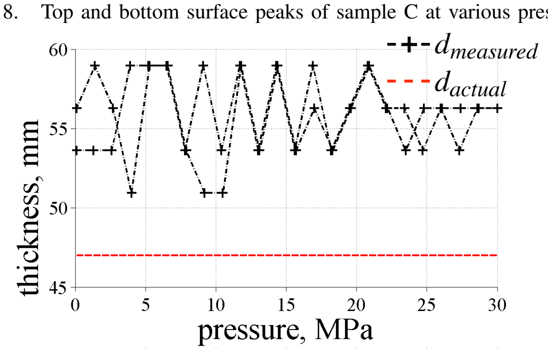
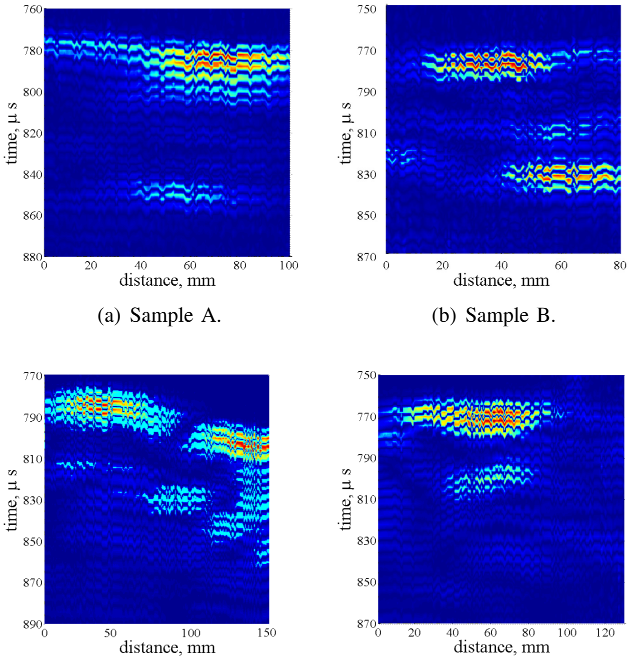


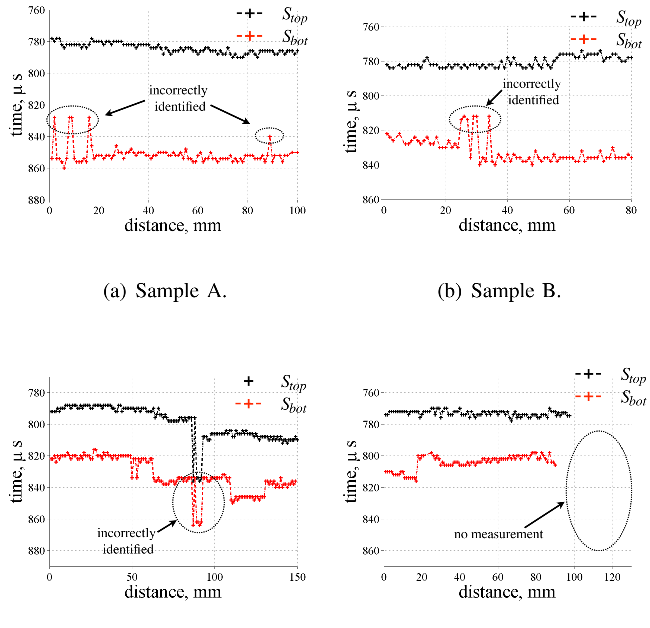
Fig. 19. Crust thickness of sample C measured at various pressures.



(a) Sample A. (b) Sample B.

(c) Sample C. (d) Sample D.

Fig. 20. Acoustic profiles of crust samples A to D.



(a) Sample A. (b) Sample B.

(c) Sample C. (d) Sample D.

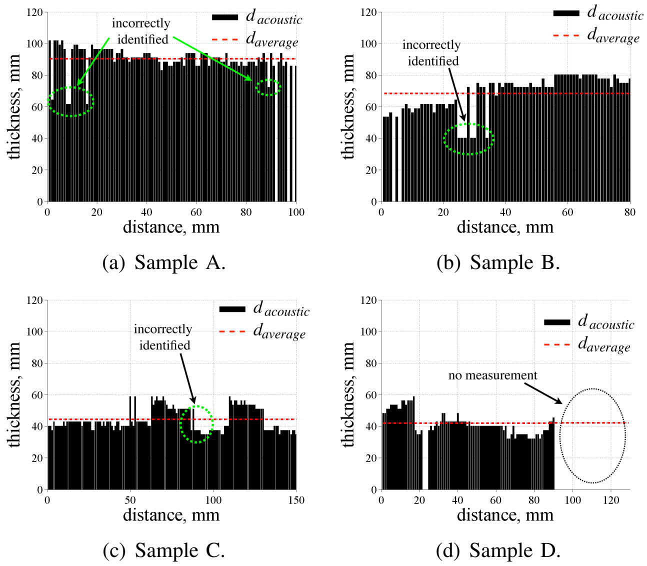
Fig. 21. Automatically detected profiles of crust samples A to D.

are calculated based on measurements where both the top and bottom surfaces of the crusts could be detected. These results are shown in table II alongside the percentage of detection, which is defined as the ratio of the number of thickness measurements made against the total number of signals analysed by the algorithm. The values obtained for the measured thicknesses are compared to the average thicknesses of the visible crusts. In the case of samples A and B, the average thicknesses could be determined by light sectioning of the top and bottom surfaces. However, for samples C and D, the visible crust was measured by taking the average of the thicknesses measured at ten different locations. As such the values given are intended only to serve as a guide and should not be used to infer the quantitative accuracy of the acoustic measurements made by this system.

For sample A, the average acoustically measured thickness was 90.2 mm, which is within 2.8 mm of the average thickness of the visible crust. The algorithm successfully detected both the top and bottom surfaces of the crust and computed its thickness for 97 % of the data analysed. For 5 % of the measurements the algorithm incorrectly identified reflections that occurred part way through the visible thickness of the crust as the bottom surface. In the remaining cases the top and bottom surfaces were correctly identified.

For sample B, the average thickness measured by the algorithm was 68.4 mm, which is within 3 mm of the visible crust thickness. In this case, the algorithm measured the thickness for 96 % of the data analysed. The profile for this sample contains a strong reflection that originates part way through the visible crust region. It is possible that a layer of sediment exists partially within the crust, though this cannot be easily confirmed visually. In most cases the peak detection algorithm correctly identifies the bottom surface of the sample since the reflections from the bottom are generally stronger than those occurring part way through the crust. However for 8 % of the data analysed, the reflections from the intermediate region are stronger than the reflections from the bottom of the sample, and in these cases the intermediate reflections are incorrectly identified as the bottom surface.

The profile measured for sample C gives an average crust thickness of 44.3 mm, which is within 2.7 mm of the visible crust thickness. The algorithm measured thickness for all of the data analysed and correctly identified the crust-substrate interface in most case. However, between 80 to 100 mm of the scan, the sample's top surface has a noticeable change in its profile, and the reflections from this region are weak due to interference between reflections from different spatial features of the boundary. The acoustic signals in this region penetrate the sample with a strong reflection taking place at the substrate interface. This type of interaction between the incident wave and sub-wavelength spatial features of the surfaces was reported in our previous work [6]. Here, this effect causes the algorithm to incorrectly identify the interface as the top surface, and reflections occurring within the substrate as the bottom surface of the crust. Surfaces were incorrectly identified in 5 % of the signals measured. It is suggested, that it may be possible to overcome this problem and automatically deduce that these identifications are incorrect even if the actual shape of the target is not known, by checking for local continuity between adjacent measurements.



(a) Sample A. (b) Sample B.

(c) Sample C. (d) Sample D.

Fig. 22. Automatically measured crust thicknesses for samples A to D.

TABLE II
RESULTS OF ACOUSTIC MEASUREMENTS.

Sample	$d_{average}$ (mm)	$d_{visible}$ (mm)	$\triangle d$ (mm)	% detection
A	90.2	93.0	-2.8	97
B	68.4	71.4	-3	96
C	44.3	47.0 *	-2.7 *	100
D	41.9	44.7 *	-2.8 *	67

* *These values are intended as a guide, and should not be used to infer the quantitative accuracy of the acoustic measurements.*

In the case of sample D, all the signals recorded beyond a scan distance of 99 mm were judged by the algorithm to have an insufficient signal-to-noise ratio to perform reliable peak detection. It can be seen that the reflections recorded in this region are weak. It is thought that this is due to the sharp incline of the top surface of the crust causing most of the signal to be reflected away from the probe. The average thickness of the crust measured where detection was possible was calculated to be 41.9 mm, which is within 2.8 mm of the average thickness of the crust visible in this region. However, even though the algorithm gave a reasonably accurate result, measurements could only be performed for 67 % of the data obtained due to the reasons mentioned above.

VII. Conclusion

This paper has described the development of a 3000 m depth rated prototype acoustic probe designed to measure the thickness of ferro-manganese crusts. A peak detection algorithm was implemented to automatically detect the top and bottom surfaces of the crusts. The system was used to measure the thickness of four crust samples obtained during NT09-02 Leg 2 of the R/V Natsushima. The experiments performed demonstrate that the developed system can reliably measure manganese crusts thicker than 30 mm at various ranges, pressures as well as measure the thickness of crusts with a breccia substrate. The sub-bottom profiles and average thicknesses of crusts automatically extracted by the algorithm agree well with the actual dimensions of the visible crust layers for samples both with and without a substrate attached. In future work, the authors will investigate to what extent these results can be generalised to other types of substrate rock.

During this study, it was demonstrated that the acoustic behaviour of manganese crusts does not change significantly with pressure. Although the developed algorithm was shown to be robust, the quality of the acoustic reflections recorded by the probe degraded as the distance to the target moved away from the probe's focal length. It is suggested that techniques such as dynamic beam focusing should be introduced to elucidate this problem. For the cases where the proposed system incorrectly identified the top and bottom surfaces of the crusts, further refinements could be made to take into account the results of neighbouring measurements when processing the signals during a continuous scan. In addition to demonstrating remote measurement of crust thickness, the fact that the measurement made in this study were performed automatically suggests that wide area mapping of manganese crust thickness is feasible. Furthermore, the automation of data processing suggests the possibility of using this information to modify the behaviour of an AUV used to survey crusts in real-time. Based on the work described in this paper, an ocean going probe is under development and it is intended that this system will be mounted on an underwater robot and deployed at sea to make *in-situ* measurements of manganese crust thickness.

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