An Apparatus for Monitoring Sea Ice Thickness Based on Coplanar Multi-Electrode Capacitance Sensor

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Keywords: Coplanar, Multi-electrode capacitance, Sea ice, Antarctic.

Abstract: This study describes an apparatus for in situ measurement of centimeter-accurate changes in the sea ice thickness in Antarctica. The apparatus consists of a rod-shaped measurement sensor based on coplanar multi-electrode capacitance sensing technology. In use, it is vertically installed into the sea ice to realize automatic monitoring of increases in sea ice thickness. It is suitable for monitoring fixed measurement sites on ice that are not deformed. The apparatus presented was tested on landfast ice and ice cap near China's Zhongshan Station (East Antarctica) for approximately 6 months during the austral autumn and winter. Data on the coastal sea ice thickness at the Zhongshan Station for 6 months was obtained. An analysis of the data verifies the reliability and accuracy of the apparatus for monitoring Antarctic sea ice. Application experiments prove that the apparatus can realize the automatic monitoring of sea ice thickness on fixed sites and provides a new method of monitoring sea ice thickness.

1 INTRODUCTION

Sea ice thickness directly affects the thermodynamic interaction of the atmosphere and marine environments. It has long been considered a key indicator reflecting climate change in polar regions. However, little is known about ice thickness changes. Sea ice plays an important role in the global radiation balance and global climate due to its smooth surface and the accumulated snow thereon. Moreover, continuous, real-time automatic monitoring of ice thickness on fixed sites is a difficult problem in ice thickness detection technology. At present, four methods are mainly employed in sea ice thickness observation. These are, manual hole-drilling measurements, remote sensing measurements, sonar measurements, and airborne (ship) electromagnetic sensing measurements.

Manual hole-drilling was the earliest ice thickness measurement used. The method is highly accurate, very reliable, and has been widely used. However, it cannot realize fixed-site real-time measurement. Moreover, it requires high labor intensity and shows low efficiency. Thus, it is merely used to make measurements at key points. In addition, this method cannot be used during ice forming and thawing periods for the sake of safety.

Remote sensing refers to the measurement of a wide range of ice structures using measurement devices carried by satellites Satellite remote sensing contributes much to the monitoring of a wide range of ice and is widely utilized. However, due to the satellite's altitude, picture resolution is low. Therefore, this method can only be used to obtain characteristic ice information on a large scale. It is not capable of acquiring ice parameters on medium and smaller scales. Furthermore, it is relatively easily influenced by weather.

In sonar measurement, a high frequency transducer is used to emit different forms of signals and the time-delay between the reflected signals from the ice-air and ice-water interfaces detected. The ice thickness can then be calculated from the time difference between the echo signals from the two interfaces and the sound velocity in the ice in the measurement area. This method shows the optimum under-ice resolution and can avoid the influence of ice properties. However, it is only able to detect the ice thickness below the waterline of the ice layer.

Airborne (ship) radar measurements began to be used in sea ice observation in the middle 1980s. In

Zhang, L. and Dou, Y.
An Apparatus for Monitoring Sea Ice Thickness Based on Coplanar Multi-Electrode Capacitance Sensor.
In *3rd International Conference on Electromechanical Control Technology and Transportation (ICECTT 2018)*, pages 467-475
ISBN: 978-989-758-312-4

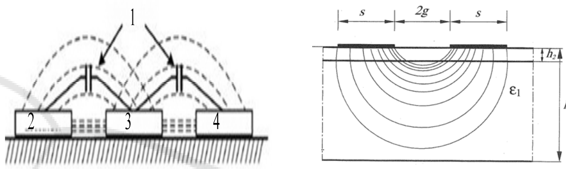
this method, the ice thickness is obtained by analyzing electromagnetic echo signals and calculating the distance between the upper and lower surfaces of the ice. The main commercial products used include the EM-31 ice and snow detector, etc. The method can be directly applied in moving situations and can collect a large amount of data in a short period of time without damage to the ice. Thus, the influences of summer and device installation on the ice melting rate are reduced. However, in this method, the contours or 'ups and downs' of the ice surface are all included in the bottom surface morphology.

The members of our team have developed a fixed-site magnetostrictive sea ice thickness measurement device. The device was adopted to monitor the sea ice near Zhongshan Station for more than half a year and is capable of monitoring sea ice thickness to a precision of ±2 mm. Unfortunately, due to certain factors, such as the inability of the power supply used to provide the long-term, unattended mechanical power the system requires, the equipment is still at present in a state of improvement. Therefore, a new device is designed in the current study to measure changes in the snow/ice thickness at fixed sites. It aims to monitor the sea ice thickness in time to a precision of 1 cm. Moreover, the power consumption of its power supply is low. A 12 V spirally-wound lead acid battery with a capacity of 80 Ah can ensure normal working of the whole device set for one year. In addition, the whole device set has a low cost and is suitable for being laid on a large area of sea ice. This device was applied to the ice surface and ice cap near Zhongshan Station.

This study first introduces the basic principles involved, as well as the design and production process used to construct the system for ice thickness detection by coplanar multi-electrode capacitance sensors and corresponding system. Then, it discusses application of this apparatus in the detection tests carried out on the sea ice near Zhongshan Station. The accuracy of the apparatus is also analyzed. Finally, the in situ application and problems encountered with it are discussed and solutions and improvement measures for these problems outlined.

2 BASIC PRINCIPLES

Brine and ice have contrasting electrical properties in-terms of both charge transport efficiency and charge transport mechanics. In brine, the differential movement of the abundant free salt ions constitutes an electrical current, while conduction in ice is facilitated by imperfections in the crystalline lattice.These defects propagate through the structure by reorientation of molecules and reordering of bonds, a phenomenon known as protonic conduction. Pure ice is a poor electrical conductor because the defect concentration is low, while any brine included in the ice has a high conductivity. Electrical methods can be performed on the ice in-situ and they offer the possibility of automated sea ice monitoring.The measurement of ice thickness using coplanar capacitance sensors based on the different permittivities of sea ice and water. The basic principle of this apparatus centers on the capacitance end effects of the capacitance sensor.



(a) (b)

Figure 1: Electric field model of a multi-electrode capacitance

(a) The basic working principle of the coplanar capacitance sensor
1-- electric field between the electrode plates .2,4-- exciting electrode plate .3--receiving electrode plates
(b) illustrates the field distribution in the layers of the underlying medium.

Figure. 1(a) illustrates the basic working principle of the coplanar capacitance sensor. The apparatus is composed of exciting and receiving electrode plates. The plates are isolated by grounded shield layers. The electric field variation between the exciting and receiving electrode plates depends on the ice thickness and so the latter may be measured indirectly. In 1969, Noltingk first proposed a high-precision measurement system based on the end effects of coplanar capacitance. In addition, he implemented the design structures of two sensors, namely, a giant coplanar capacitance sensor and an annular coplanar capacitance sensor. The two sensors both utilized the capacitance end effect to measure micro-distances. In 1976, Noltingk, Nye and Turner presented a mathematical analysis of the coplanar capacitance sensor for polar plates that are rectangular in structure. In 1993, Luo and Chen mathematically analyzed the annular coplanar capacitance sensor and established the corresponding mathematical model. In more recent years, coplanar capacitance sensors have been widely used for material thickness measurement（J.Graham,2000 ） moisture or humidity measurement, etc. Sundara-Rajan et al. used coplanar capacitance to determine the moisture content in paper. A. S. Zyuzin et al. adopted coplanar capacitance to detect the moisture content in food, such as biscuits, etc. TianMing Chen employed coplanar capacitance to perform nondestructive inspection of multi-layer structures. Nassr also used coplanar capacitance to inspect the moisture content of a medium with complex structure.

Figure. 1(b) shows the electric field distribution produced in the media layers beneath the sensor. Since the electric field strength decays exponentially with the thickness of the measured medium, the permittivity of the medium closer to the fixed electrode surfaces has a larger impact on the capacitance between the coplanar electrodes. In the cross-section shown in Fig. 1(b), a coplanar sensor is created by two electrodes of width s spaced 2g apart on two substrate layers of heights h1 and h2 (from the upper surface) and dielectric permittivities ε_r, respectively. In the analysis, the electrode strips are assumed to have zero thickness and infinite conductivity. Also, the strip length l is larger than the width (l > s) to avoid end effects. The capacitance between the two electrodes due to the substrate layers is given in closed form as

$$C = \varepsilon_0 \varepsilon_r \frac{K(k_0^{'})}{K(k_0)}, \qquad (1)$$

where K(k) is the complete integral function, ε0 is the vacuum permittivity (F m–1), and k_0 and $k_0^{'}$ are functions of s and g. They are given by

$$k_0 = \frac{g}{s+g}, \quad \text{and} \quad k_0^{'} = \sqrt{1-k_0^2}.$$

It can be seen from Eq. (1) that the variation in the capacitance of the coplanar electrodes shows a certain functional relationship with the permittivity of the medium close to the electrode. Since water, ice, and air present different permittivities at a certain environmental temperature, a plurality of electrodes can be installed in parallel in the same plane to constitute a coplanar multi-electrode capacitance sensor. Such a sensor can then be installed vertically in the ice and the water under the ice. Since the media contacting the electrodes are ice, water, or air, the capacitances between each electrode and adjacent electrodes are different. Thus the vertical measurement of ice thickness can be realized.

The coplanar multi-electrode capacitance ice thickness measurement is based on the model in Figure1. Through the contact made with different media (such as ice and water) the exciting metal electrode is affected and the electric field around the metal electrode is changed. The capacitance of the metal electrode is thereby altered. It is assumed that C3 is the capacitance composed by one single capacitance electrode plate (A in the diagram) and its adjacent grounding electrode plates. The air's permittivity is ε_0, ε_r is the dielectric coefficient of the medium, and A is the electrode plate area. When ε_r fluctuates, the capacitances C1, C2, and C3 are changed. Since the three capacitances are in parallel in the circuit, the total variation of the capacitance Cx can be found from Cx = C1 + C2 + C3. In the equivalent circuit shown in Figure 2, the voltage at point A is proportional to 1/Cx. The voltage detected at point B is first transformed into a direct current (DC) through the internal detector and low-pass filter of the device. Then the DC signal is processed by the external microcontroller bearing an analog to digital (A/D) converter. For example, a single chip microcomputer (SCM) can be used. The microcontroller is capable of treating multiple signals and can thus achieve the goal of the measurement.

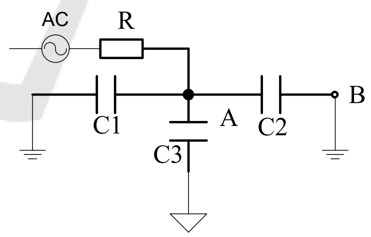


Figure 2: The equivalent circuit for medium measurement using the capacitance of one coplanar electrode.

The principle underlying ice thickness measurement using a coplanar multi-electrode capacitance sensor and corresponding system is shown in Figure 3. Considering the requirements for the actual measurement of sea ice, the ice thickness sensor is designed to be a plurality of electrodes. More than 100 electrodes are used, which are uniformly arranged in the same plane (each electrode measures 1 cm). The detection principle is as follows. The control instrument of the SCM sends control signals to the sensor to open its multi-switch. Thus, the sinusoidal signal of first measurement circuit unit is connected with the first electrode at the top of the sensor, while the other electrodes are connected to earth. Then , the sinusoidal signal flows back to sine power supply to generate a ground electrode signal by the divider resistance, the capacitance formed by the metal electrode and the rest of the electrodes around, and the capacitance formed by the electrode and the medium.

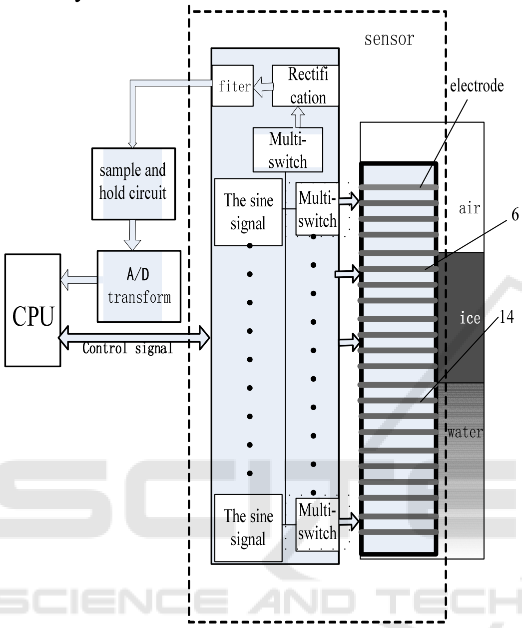


Figure 3: A schematic diagram illustrating the principle of the measurement system

Afterwards, the ground electrode signal sends voltage on the electrode to the A/D input port of the SCM after transferring the voltage into a DC signal by rectification, and filtering circuit in sequence. The SCM collects and saves these voltage signals. Then the SCM releases a control signal to get connected with the second electrode from the top. The voltage on the second electrode is measured, and so on. Since the permittivities of air, water, and ice are different at particular environmental temperatures, the capacitances between each electrode and its adjacent electrodes are different. The difference in capacitance is expressed as a variation in the voltage. Therefore, a set of voltage data is obtained by measuring, in order, the voltages on each of the electrodes using the SCM. According to the voltage jumps on the electrodes, it can be judged which electrode is surrounded by ice, which is surrounded by water, and which is surrounded by air. In this way, the ice thickness can be determined. The SCM collects data at fixed times separated by a certain time interval. Finally, it periodically sends the data acquired to a computer terminal by wireless transmission.

The coplanar multi-electrode device and its system consist of two parts, namely, the sensor itself and its accompanying measuring instrument. The sensor mainly consists of the metal electrode sensors, multi-switches, sine signal generators, a rectifier, and a filter. Part of the circuit board of the sensor is sealed by encasing it together with the metal capacitance electrodes. The measuring instrument is composed of the SCM, the A/D conversion circuit, the data storage circuit, the GSM modem, etc. In the circuit design, the circuits generated by each sine wave generator are combined with a rectification circuit to form a circuit module. Each module contains 7 electrodes at most to avoid parasitic capacitance on the electrodes caused by wires on the circuit board that are too long. The SCM control circuit mainly controls the sensor circuits and thereby detects the ice thickness. The circuit board of the measuring instrument containing the SCM is placed on one end of the sensor. It is insulated from the electrodes by hard plastic sheets. The surface of the coplanar multi-electrode sensor is sealed using insulating materials to prevent direct contact of the capacitance electrodes with the ice and water. Using the SCM control circuit and wireless transmission module on the sensor, automatic unattended remote monitoring of the ice thickness can be achieved.

Considering that the ice thickness measurement depends mainly on the measurement and judgment of the positions of the interfaces between air and ice, and ice and water, the whole apparatus is generally chosen to be a long rod shape. A large number of experiments and comprehensive data results show that the sensing effect is optimum using 0.3 mm thick copper foil for the electrode material. Electrodes are placed every 1 cm, so that the measuring precision of the sensor is kept to the centimeter level. In the experiment reported here, copper foils measuring 6 mm and 4 mm in width and 15 cm in length are used for the metal electrodes (the thickness is 0.3 mm, as already said).

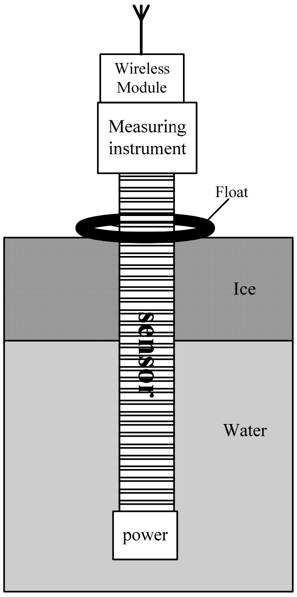


Figure 4: Installation diagram of the sensor in the ice.

Experimental results also suggest that the wider the copper foil strip is, the lower the voltage on the electrode, and the larger the capacitance of the copper strip is. With increasing space between metal electrodes, the voltage on the metal electrode gradually grows until it reaches a certain value. This phenomenon indicates that an increase in the space between electrodes can reduce the capacitance of electrodes, however, this reduction will not continue when a certain value is reached. To better seal the electrodes, we molded a thin layer of insulating epoxy resin material on the bottom of grinding apparatus of PVC material in a selected shape and volume before laying out the electrodes. Generally, the epoxy resin layer is around 2 mm thick. When the epoxy resin had completely solidified, copper foil electrodes were laid on the surface of the thin epoxy resin layer at an interval of 4 mm and 1 cm for one electrode. The installation diagram of the sensor and the corresponding measuring system for measuring ice thickness is shown in Figure 4.

3 IN SITU EXPERIMENTS

3.1 In Situ Environment

In March 15, 2016, researchers installed the two sets of apparatus into the sea ice near Zhongshan station (specific location 69°22′05.1″S, 76°21′51.3″E). The photograph on the left in Figure 5 shows the in situ installation of the two sets of measuring devices. Points A and C are the sites where the measurement devices are installed. The horizontal distance between the two sites is 20 m. The right-hand photograph in Figure 5 presents the in situ installation of the sensor at point A. At installation, the in situ snow depth was only 1 cm thick. The installation steps are indicated below.

Figure 5: *In situ* installation pictures.

A wooden strip fixed 8 cm below the top of the sensor was used as a float. A hole was drilled in the ice's surface using a hand-cranking ice driller. Then, the ice thickness around the ice hole was manually measured using a tape measure and the ice suspension height was determined using a ruler. The rod-shaped sensor was vertically inserted into this ice hole until the float was stuck on the ice surface. Then the ice hole was filled using ice flakes or snow to keep the apparatus vertical. After the power supply was switched on, the apparatus started to work. Finally, a few holes were drilled in the ice surface. The storage battery sealed using insulating material was fixed using wooden rods and ropes to prevent the wind blowing it away. The initial number of electrodes of the measurement sensor exposed to the air at site A was 8, that is, the top sensor is 8 cm from the ice surface in site A. The top sensor at site C was 10 cm from the ice surface initially.

Table 1: The *in situ* conditions of the measurement device.

Item	Site A	Site C
Initial snow thickness (cm)	0.2	0.2
Initial ice thickness (cm)	26	27
Initial ice suspension (cm)	4	5
Lowest temperature (°C)	–33.8	
Highest	0.1	

temperature (°C)	
Maximum snowfall (cm)	48
Maximum wind speed (m/s)	40.7

From March 16, 2016 to August 31, 2016, the lowest and highest temperatures of the sea area at the two devices were –33.8°C and 0.1°C, respectively, according to in situ detection. During the monitoring period, the monitored sea area experienced many periods of snowfall, and the highest snow thickness was 31 cm. The sensor became completely covered by snow, but in a short period of time most of the snow was blown away by wind. The maximum wind speed in the detection area was 40.7 m/s during this period. Table 1 describes the field environment of the detected sea area during the monitoring period.

3.2 Experimental Results

From March 16 to August 31 in 2016, the southern region of Australia was in autumn and winter and Antarctica was in winter. Throughout this time period, the two measurement devices worked normally on the sea ice near Zhongshan Station for a total of 168 days. Measurement was conducted 3 times a day. Thus, 504 groups of data were obtained from each measurement device. In the experiment, the Iridium Satellite system's remote data delivering service was employed for a week of the experiment. The rest of the data was collected directly by field researchers who read the SD memory cards in the apparatuses at fixed time points.

By preliminarily analyzing the data acquired, it was found that the maximum daily growth in ice thickness was 3 cm. We employed the data collected at 0:00 every day and obtained 168 sets of data. The ice thickness and daily temperature variation curves in the detected sea area acquired by the two measurement devices over the 168 days are shown in Figure 6. In this figure, the ice thickness variation at sites A and C are basically consistent. The ice thickness data detected at the two sites from June to July are very close. In the two periods with rapid growth (April 20–May 15 and in August), the ice thicknesses show larger differences. From March 16 (when the two sets of measurement devices were installed) to March 28, ice thickness grew from 0 cm to around 30 cm. (Since the sensors were initially installed in ice holes with diameters of 10 cm drilled by the ice driller, the ice thickness grew from 0 cm. To March 28, the ice thickness in the hole that the measurement devices were installed in had been consistent with the surrounding ice thickness.

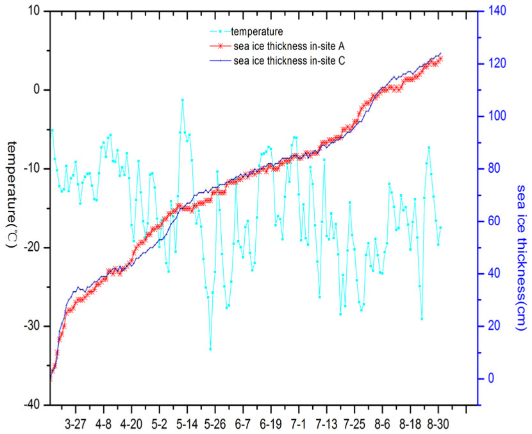


Figure 6: The ice thickness variation at sites A and C and the daily mean temperature curve.

In this experiment, the data collected after March 28 is used in the calculation of sea ice growth rate. That is to say, the sea ice thickness measured by the two sets of devices from March 16 to March 28 cannot reflect the natural growth condition of sea ice at the detection sites. Thus, the natural growth rate of the sea ice is calculated when the sea ice thickness at the detection sites agreed with that due to natural growth on March 28. The calculation formula for the sea ice growth rate is where H_i is the ice thickness, ti is the measurement time, and ti+1 is the next measurement time .

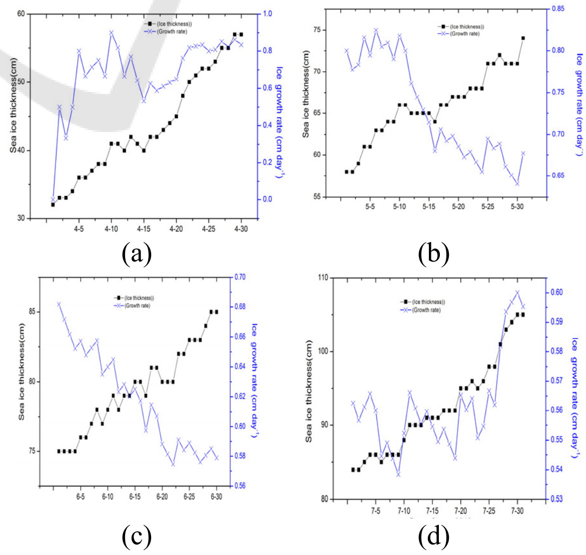


Figure 7: Graphs showing the variation in sea ice thickness and ice growth rate.

According to this formula, the daily mean growth rates of the sea ice at sites A and C of the detection area are 0.618 cm day–1 and 0.498 cm day–1, respectively. The maximum sea ice thickness growth rate at site A is observed on April to May 13, with a value of 0.83 cm day–1, as shown in Figure 7(a) and 7(b). The minimum sea ice thickness growth rate at site A is found on June 25 to July 25, with a value of 0.54cm day–1, as shown in Figure 7(c) and 7(d).

3.3 Precision Analysis

While monitoring the sea ice, the sea ice thicknesses at sites A and C were also measured manually using the hole-drilling method. Providing the weather permitted, these measurements were carried out once a day. Figure 8(a) and 8(b) show the sea ice thickness variation at sites A and C, respectively, as detected by the measurement device and manually. It can be seen from Fig. 9 that the device measurement results are all smaller than those obtained by manual hole-drilling at both sites A and C. That is, there is a certain difference between the sea ice thickness results as measured by the two measuring devices and by the manual hole-drilling method. This is attributed to the fact that the skeleton ice (flocculent ice) on the contacting part of the sea ice and sea water has a certain thickness. In a manual hole-drilling measurement, the sea ice thickness is measured using a tape. Thus, the thickness of the skeleton ice is included in it. However, with the device measurements, skeleton ice is recognized as sea water by the capacitance sensing electrodes due to its larger water content. Therefore, the sea ice thickness measured by the device is smaller than that obtained by the manual hole-drilling method. The difference is relatively large during March 28 to April 20. The maximum value of the difference at site A reaches 9 cm. By in situ inspection, we conclude that this was because the ice in the ice hole in which the device was installed in did not become frozen to the same thickness as the surrounding ice. The minimum difference value is 1 cm. The maximum and minimum difference values at site C are 5 cm and 1 cm, respectively. The difference tends to be a stable 1–2 cm after April 20. Therefore, the device measurement data and manual hole-drilling measurement data from April 20 to April 30 are used for analysis. The deviation D in the device measurement can be calculated according to the following formula

$$D = \frac{e_{zm} - d_{zm}}{d_{zm}} \times 100\% \qquad (2)$$

where, e_{zm} is the mean ice thickness measured by the device in the ten days, and d_{zm} is the mean sea ice thickness obtained by the manual hole-drilling measurement. By calculation, it is found that this formula is consistent with the work of Kovacs et al. in 1996 and Haas et al. in 1997.The relative deviation of apparatus is thus –3.5%.

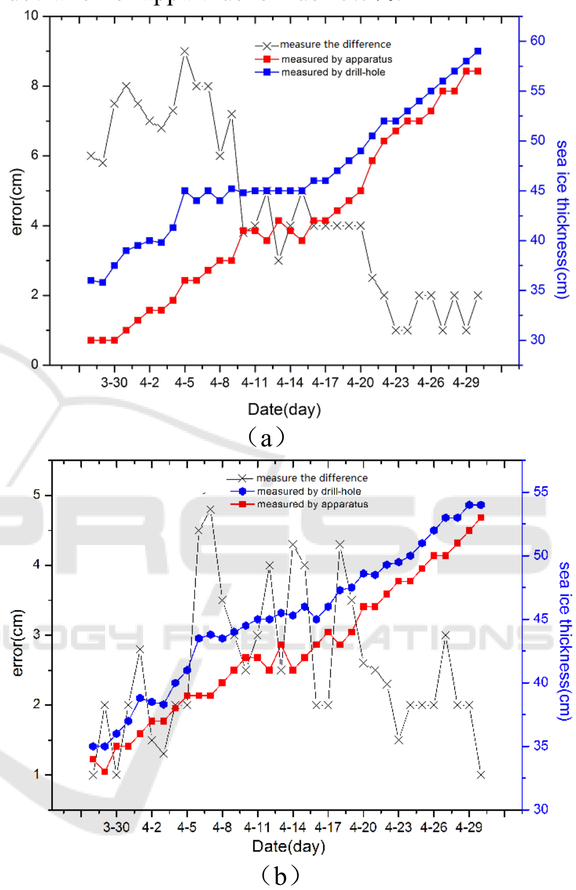


Figure 8: Comparison of the data obtained using the measurement device and by manual hole-drilling at (a) site A, and (b) site C.

4 PROBLEMS AND DISCUSSION

The sensor proposed in this study was applied to detect the sea ice thickness near Zhongshan Station. However, the sensor is only 1.4 m long, while the sea ice thickness in the detection area can reach up to 1.5 m (maximum depth). Moreover, the two sensors were exposed above the sea surface by 8 and 10 cm. This means that their under-ice measurement lengths were 1.32 m and 1.30 m, respectively. Therefore, when the sea ice thickness exceeds 1.30 m, the two sensors cannot be used to accurately measure the sea ice thickness. Thus, the experiment was terminated when the sea ice thickness exceeded 1.25 m (at the end of August). In addition, during the 6 months of the application, the snowfall thickness on the sea ice surface was more than 10 cm on May 27 and July 3. Thus the data between the air and ice snow surface, and snow surface and ice surface cannot be correctly judged by the sensors.

This study proposes a new apparatus for measuring ice thickness that uses capacitance. According to the different dielectric properties of air, ice, and water, this apparatus determines the air layer, ice layer, and under-ice water layer thicknesses using a layered measurement method and coplanar multi-electrode capacitance sensor. Moreover, it can also be applied to automatic real-time monitoring of sea ice thickness in polar regions and, by extension, to automatic monitoring of river ice thickness in rivers (or reservoirs) in winter.

Several problems arise in the application of the coplanar multi-electrode capacitance ice thickness sensor:1) Since electrodes are installed in different positions in the sensor, the influence of the adjacent electrodes on an electrode is different. This phenomenon results in different voltages being detected by two electrodes although the surrounding medium is the same. This is an inherent problem arising from the nature of the sensor. The mutual interference between electrodes can be reduced by shielding measures, etc., but cannot be completely eliminated.2) Environmental temperature has a certain influence on the capacitance presented by the coplanar electrodes. For electrodes of the same size, the lower the temperature is, the smaller is the capacitance formed by one electrode with an adjacent electrode. As the temperature in the ice layer varies from top to bottom, the capacitances of the metal electrodes at the same site are different for different parts of the ice layer. In this way, the medium around the electrode may be easily misjudged. This problem can be solved using temperature compensation, that is, the environmental temperature around the electrode is detected by setting a certain number of temperature sensors. When the temperature changes, the electrode capacitance can then be compensated using a hardware circuit.3) Power supply problems. Since the ice thickness measurement system is operated in a low temperature environment, the power consumption of the electronic components is increased. Thus, it is a requirement that the whole system must be provided with a reliable power supply. In this study, a storage battery with a relatively large capacity is employed. Moreover, it is sealed by encasing and placed in the lower part of the sensor. In this way, the storage battery can be constantly immersed in river or sea water. As river water has a temperature around 0°C and sea water temperature is around –3°C, battery power loss will not be induced by an overly-low temperature.

5 CONCLUSIONS

The coplanar multi-electrode capacitance ice thickness detecting sensor and its system is still currently in a laboratory research and field trial stage. To realize fixed-site automatic monitoring of ice thickness, the following problems need to be further studied and addressed.

First, The dielectric properties of sea ice. Sea ice has complex structural forms, e.g. pure ice form, ice-brine form, etc . Therefore, it exhibits different dielectric properties at the same temperature. This situation can induce misjudgment of the ice medium when using the capacitance electrode. Thus, a large amount of laboratory experiments are needed to measure the dielectric property of sea ice in its different forms and to establish a dielectric database of the ice's properties as a function of temperature and form. The results obtained can provide a database for accurate measurements with the capacitance electrode.

Second,The structure of the sensor. This problem is mainly concerned with the size of the coplanar electrode and the space between electrodes. It directly affects the measurement precision of the sensor. Thus, if measurement precision is required to be improved to ±3 mm, the width of the sensor's electrodes can only be 2 mm at most, and the space width can be at most 1 mm. Moreover, whether the setting is the optimal plan or not needs to be verified via simulation. That is, the optimization of the sensor structure needs to be realized by software simulation.

In conclusion, an ice thickness sensor based on coplanar multi-electrode capacitance has achieved preliminary success in a laboratory study and field experiment. After the problems above are solved, the system will be considerably improved. Using the system, it is feasible to measure the thickness of river and sea ice at fixed sites. The ice thickness data thus obtained can subsequently provide reliable data for research on the thermodynamics of the ice.

ACKNOWLEDGMENTS

We are grateful to the Chinese Arctic and Antarctic Administration for its logistic support during our experiment; to Mr. Zhao jiecheng and Mr. Han desheng,for their field-work support; to the Meteorological Office of Zhongshan Station for providing meteorological data. Three anonymous reviewers are thanked for their comments, which considerably improved this work.

REFERENCES

Meier,W., Stroeve, J., Fetterer, F.,Knowles, K.,2005. Reductions in arctic sea ice cover no longer limited to summer. Eos, Transactions of the American Geophysical Society .v86, p3-26;

Stroeve, J., Serreze, M.C., Fetterer, F., Arbetter, T., Meier,W., Maslanik, J., Knowles, K., 2005. Tracking the Arctic's shrinking ice cover; another extreme September sea ice minimum in 2004. Geophysical Research Letters 32, L04501.

Sturm, Matthew; Perovich, Donald K.; Serreze, Mark C. Meltdown in the North, October 2003, Scientific American, v289, n4, p60-67;

Perovich, Donald K.; Stroeve, Julienne C. ; Richter-Menge, Jackie,al.,et, November 2006, Snow depth and ice thickness measurements from the Beaufort and Chukchi Seas collected during the AMSR-Ice03 Campaign. Transactions on Geoscience and Remote Sensing, v 44, n11, p3009-3019;

Richter-Menge, Jacqueline; Sonntag, John G..al,.et, 2012,A first assessment of Ice Bridge Snow and Ice thickness data over arctic sea ice. IEEE Transactions on Geoscience and Remote Sensing, v50, n6, p2098-2111;

Rothrock, D.A.; Yu, Y.; Maykut, G.A.. December 1, 1999,Thinning of the Arctic sea-ice cover, Geophysical Research Letters, v26, n23, p3469-3472;

P. Wadhams.2009,sea ice. Reference Module in Earth Systems and Environmental Sciences,p141-158;

Kovacs, Austin; Valleau, N.C.; Holladay, J.Scott ,Airborne electromagnetic sounding of sea ice thickness and sub-ice bathymetry. Oct 1987, Cold Regions Science and Technology, v14, n3, p289-311;

Haas, Christian1; Lobach, John2; al.,et, March 2009,Helicopter-borne measurements of sea ice thickness, using a small and lightweight, digital EM system, Journal of Applied Geophysics, v67,n3,p234-241;

Holladay, J.S.; Rossiter, J.R. Airborne measurement of sea ice thickness using electromagnetic induction during LIMEX 89, 1990, Proceedings of the International Offshore Mechanics and Arctic Engineering Symposium, v4, p309-315;

Ruibo lei,Zhijun,li,et al,A New Apparatus for Monitoring Sea Ice Thickness Based on the Magnetostrictive -Delay-Line Principle. April 2009, Journal of atmospheric and oceanic technology,v26 ,p818-827;

V. Petrenko and R. Whitworth, Physics of Ice ,Oxford University Press, New York, 1999.

B.E.Noltingk,A novel proximity gauge[J],Journal of scientific instruments,1969,v22(2):p356-360;

B.E.Noltingk,A.E.T.Nye,H.J.Turner,Theory and application of a proximity gauge using fringing capacitance[C],IN Proc.ACTAIMEKO,1976,p537-549;

R.C.Luo,Z.H.Chen,Modeling and implementation of innovative micro proximity sensor using micromachining technology[C],IEEE/RSJ international conference on Intelligent Robots and System Yokohama,Japan,1993:p1709-1716;

J.Graham,M.Kryzeminski,Z.Popovic,Capacitance based scanner for thickness mapping of thin dielectric films[J],Review of Scientific Instruments,2000,v71(5):p2219-2223;

K.Sundara-Rajan,L.Byrd,A.V.Mamishev, Moisture content estimation in paper pulp using fringing field impedance spectroscopy[J],IEEE Sensors Journal,2004,v4(3):p378-383;

X.Li,A.S.Zyuzin,A.V.Mamishev, Measuring moisture content in cookies using dielectric spectroscopy[J],2003 Annual Report Conference on Electrical Insulation and Dielectric Phenomena,2003:p459-462;

TianMing Chen,Nicola Bowler. analysis of concentric coplanar capacitive sensor for Nondestructive Evaluation of Muiti-layered Dielectric Structures. IEEE Transaction on dielectrics and insulation. v17,n4,August 2010:p361-382;

Arm A Nassr,Wale H Ahmed, coplanar capacitance sensors for detecting water intrusion in composite structures.Meas.Sci.Technol.19(2008).

Gevorgian S and Berg H ,2001, Line capacitance and impedance of coplanar-strip waveguides on substrates with multiple dielectric layers Proc. European Microwave Conf.(London):153-6;

Perovich, T. C. Grenfell, J. A. Richter-Menge, B. Light, W. B. Tucker III,and H. Eicken, 2003: Thin and thinner: Sea ice mass balance measurements during SHEBA. J. Geophys. Res., 108, 8050,

Kovacs, A., 1996. Sea ice: Part I. Bulk salinity versus ice floe thickness. US Army Cold Regions Research and Engineering Laboratory, CRREL Report v96,n7, 16 pp;

Haas, C., Gerland, S., Eicken, H., Miller, H., 1997. Comparison of sea-ice thickness measurements under summer and winter conditions in the Arctic using a small electromagnetic induction device. Geophysics v62 ,n3.p 749–757;

S. Buchanan, M. Ingham, and G. Gouws, October 2011.The low frequency electrical properties of sea ice. Journal of applied ohysics, v110,n7. 074908pp;