# IN-SITU AUTOMATIC OBSERVATIONS OF ICE THICKNESS OF SEAS

## Yinke Dou[1)], Xiaomin Chang[2)]

*1) College of Electrical and Power Engineering, Taiyuan University of Technology, Taiyuan, 030024, China (✉ douyinke@sina.com)*
*2) Institute of Measuring and Controlling, Taiyuan University of Technology, Taiyuan, 030024, China*

**Abstract**

Ice thickness is one of the most critical physical indicators in the ice science and engineering. It is therefore very necessary to develop in-situ automatic observation technologies of ice thickness. This paper proposes the principle of three new technologies of in-situ automatic observations of sea ice thickness and provides the findings of laboratory applications. The results show that the in-situ observation accuracy of the monitor apparatus based on the Magnetostrictive Delay Line (MDL) principle can reach ±2 mm, which has solved the "bottleneck" problem of restricting the fine development of a sea ice thermodynamic model, and the resistance accuracy of monitor apparatus with temperature gradient can reach the centimeter level and research the ice and snow substance balance by automatically measuring the glacier surface ice and snow change. The measurement accuracy of the capacitive sensor for ice thickness can also reach ±4 mm and the capacitive sensor is of the potential for automatic monitoring the water level under the ice and the ice formation and development process in water. Such three new technologies can meet different needs of fixed-point ice thickness observation and realize the simultaneous measurement in order to accurately judge the ice thickness.

Keywords: ice thickness, observation, MDL, resistance, capacitive induction.

## 1. Introduction

Freezing is a universal natural phenomenon in the polar regions and sub-polar regions and the sea ice of the polar region plays an important role in the global climate system and is also the indicator of global climate changes. Sea ice thickness is the most basic and important parameter of describing the sea ice status [Perovich et al., 1997]. The acquisition of prototype data for sea ice thickness changes helps to improve our understanding of the interactive mechanism of air – ice – sea [Perovich, et al., 2003]. Sea ice with different degrees will be generated in every winter in the sub-polar regions such as China's Bohai Sea, Baltic Sea, etc. and the sea ice exerts an important impact on the shipping and oil/gas production. The river ice in high altitude regions in winter and spring usually caused the destruction of bridges and hydraulic structures. The reservoir freezing plays a critical role in the safety management of dams and water intake works. Ice thickness is one of key indicators of calculating the action force of sea ice, river ice and reservoir ice on marine works or hydraulic structures [Laxon, et al. 2003; Tamura, et al. 2007].

Ice thickness has been considered one of the physical indicators of sea ice or freshwater ice that are the most difficult to be monitored [Laxon, et al.,2003]. The direct measurement of boreholes is the most reliable monitoring means of measuring the ice thickness, but it is difficult to meet the needs of ice science and ice engineering research due to its low effectiveness. At present, a variety of automatic observation technologies for ice thickness have been developed in the world, including satellite remote-sensing [Tamura, et al., 2007], radar detecting [Holt, et al., 2009], combination of electromagnetic induction technology and laser ranging technology [Haas, 1998], shipboard or moored sonar [Rothrock, et al. 1999;

Strass, 1998], etc., of which, the satellite remote sensing, shipboard or airborne radar detector, electromagnetic induction and laser ranging devices, ship-based sonar, etc., have realized the detection of sea ice thickness of middle size and large size. The wide application of these detecting devices has enabled people to master the distribution situation of sea ice thickness in a large range and its inter-annual variation [Hass, et al., 2009]. The application of moored up-looking sonar has realized the automatic monitoring of in-situ ice thickness change process [Strass, 1998], and its observation accuracy is however sensitive to the observation environment and ice physical properties. The field practices show that its typical accuracy is only 20 cm and its relative accuracy is 11.5%, which is difficult to meet the needs of ice science and ice engineering research, and moreover, this technology cannot nowadays be applied to the measurement of ice thickness in shallow water areas, in other words, such technology is not applicable in the shallow water areas such as river ice, reservoir ice, Bohai Sea, etc. Therefore, it is very necessary to develop the efficient new technologies of in-situ sea ice thickness automatic observation.

This paper will introduce three new technologies of in-situ ice thickness observation and show the findings of its in-situ or laboratory application studies. The practices have proved that these technologies have their own advantages, and can meet the different needs of fixed-point ice thickness observation.

## 2. Ice Thickness Monitor Apparatus Based on the MDL Principle

### 2.1. Measurement Principles

The displacement detection technology realized based on the Magnetostrictive Delay Line (MDL) principle can realize the multi-position and high-precision displacement measurement [Karagiannis, et al., 2003] and is widely applied to the fields of piston position measurement, fluid level measurement, arena, etc [Hristoforou, et al., 2002; Hristoforou, 2006]. Based on the MDL principle, we have developed a new ice thickness monitor apparatus in combination with the environment applicability.
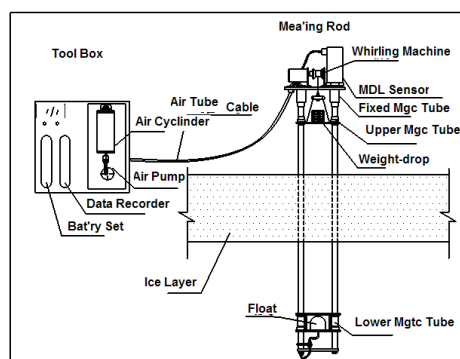


Fig. 1. Configuration sketch of the sea ice thickness monitor apparatus based on MDL.

As shown in Fig. 1, the ice thickness monitor apparatus is composed of an instrument box and a measuring rod. The instrument box and the measuring rod are connected via the airway and cables, of which, the airway is used to connect the air cylinder with the airbag in the magnetic tube mechanism, and the cables are used to connect the electrical parts of fluid level sensor and winch motor. There is a fixed magnetic tube and two moveable magnetic tubes on the measuring rod. The measuring process of the monitor apparatus is realized mainly by controlling the motion of the two moveable magnetic tubes. During the measurement, the lower magnetic tube moves downward under the action of hammer gravity and is placed onto the ice/snow surface; the motion of the lower magnetic tube is controlled via the pneumatic

mode. The airbag in the lower magnetic tube is connected with the air cylinder via the airway and when the air cylinder is driven by the reducer motor to compress the air, the airbag inflates and the resultant force of buoyancy and gravity will float the lower magnetic tube to be contacted with the underside of the ice. At this moment, the MDL sensor is used to detect the distance between the fixed magnetic tube and the upper magnetic tube and the distance between the fixed magnetic tube and the lower magnetic tube. Compared to the initial values, the position of current ice/snow surface and ice underside is obtained. The measured result is recorded in the data recorder. After completing the measurement, in order to prevent the snow from covering the upper magnetic tube, the lower magnetic tube is frozen in the ice underside and the upper magnetic tube moves upward under the action of the traction force of the winch and releases the pressure of the air cylinder to retract the airbag and then the lower magnetic tube goes down. The resolution of this product is ±0.1 mm, with the design accuracy of ±1.0 mm and operating ambient temperature of -55~50°C.

## 2.2. Field Application Examples of Apparatus

The apparatus is applied to the in-situ measurement of fixed ice thickness of Zhongshan Station in the 22nd Chinese National Antarctic Research Expedition. The apparatus installation was carried out on the sea ice surface in Neila Bay near China's Zhongshan Station in South Pole on March 27, 2006. The water depth at the installation location of the apparatus is about 9 m and the sea ice thickness is 25 cm when the apparatus is installed, the preset detecting length for upper magnetic tube is 75 cm and the preset detecting length for lower magnetic tube is 225 cm. The apparatus was put into operation on March 30, with a measurement interval of 180 min and even 120 min for some days. During the operation process, the apparatus has experienced the test of heavy weather such as polar night, low temperature, gale, snowstorm, and the tidal flood and ebb time, as well as the underside biological interference. The field conditions during the experiment of the apparatus are summarized in Table 1.

Table 1. The field conditions during experiment.

| Minimum temperature | Minimum monthly mean temperature | Extreme wind speed | Gale | Humidity Range | Minimum Pressure | Snow | Snowstorm | Polar night time | Maximum daily tidal range |
|---|---|---|---|---|---|---|---|---|---|
| -30.2 °C | -18.6 °C | 25.9 m s$^{-1}$ | 93d | 19~92 % | 923.7 hPa | 52 d | 11 d | 58 d | 1.82 m |

Ended by September 21, 1460 groups of data are acquisitioned during the observation. According to the field observation, the measuring data variation of ice/snow surface in this region will not be more than 20 cm and the growth rate of sea ice underside will not exceed 3 cm d$^{-1}$. For this reason, when the difference between measuring data of ice/snow surface and measuring the mean value on that day is more than 20 cm and the difference between measuring data of ice underside and measuring the mean value on that day is more than 3 cm, it shall be considered as a singular value. Apart from the singular value, there are 1368 valid data of ice underside position and 1352 valid data of ice/snow surface position, so the working efficiency of the lower magnetic tube is 93.7% and the working efficiency of the upper magnetic tube is 92.6%. It is thus clear that the apparatus still keeps a high testing

stability even in a bad field environment. The singular value is however resulting from the mechanical failure of the apparatus, such as the breakage of steel wires connected to the upper magnetic tube and the winch in the snowstorm weather, failure of free movement for the upper magnetic tube mechanism due to snow's coverage on the measuring rod, failure of the lower magnetic tube to rise to ice underside due to the disturbance by an unknown object on ice underside, etc., and these mechanical failures can however be discovered and disposed on the site and the singular value caused hereof can also be identified and removed, which will not disturb the data analysis.

In order to verify the validity of the measured data of the apparatus, 24 drill-hole ice thickness measurements in all were carried out in a radius of 2 m around the apparatus at different sea ice growth stages, the measurement accuracy of drill-hole ice thickness is ±5 mm and the comparison of drill-hole measurement results and apparatus measurement results at the same time is detailed in Fig. 2. By comparing the drill-hole and apparatus-measured results of ice thickness at different sea ice growth stages, we find that their average deviation is 1.5±1.0 cm, and considering that the drill-hole measuring accuracy is ±5 mm and there are natural ups and downs on the ice underside and the ice surface, we thereby think that the observation result of the apparatus is valid.
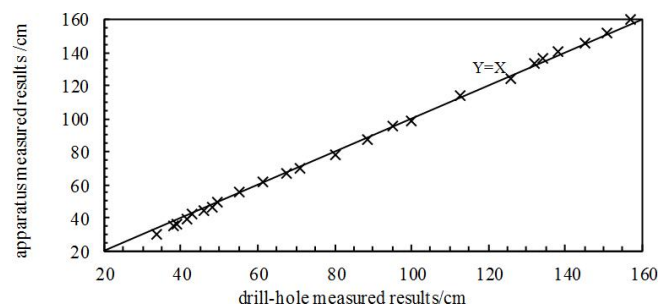


Fig. 2. Sea ice thickness record derived from drill-hole and the apparatus during experiment.

However, because the designed measuring accuracy of the apparatus is ±1.0 mm and the drill-hole measuring accuracy is ±5 mm, which are not at the same level, and there are the natural ups and downs on the ice underside and the ice surface, we cannot obtain the field measuring accuracy of the apparatus by comparing the drill-hole measured results and apparatus-measured results at the same time. In order to analyze the field measuring accuracy of the apparatus, it is necessary to firstly suppose that the sea ice daily growth rate is defined and linear fitting is applied to daily measured results, respectively, and then the difference of the fitting value and the actually observed value is calculated. The positive and negative differences are analyzed respectively to calculate their own mean value and standard deviation; the sum of absolute mean value and standard deviation is taken as the fluctuation value; the maximum fluctuation value of positive and negative conditions is taken as the fluctuation value of testing results of the apparatus. Upon the calculation, the maximum positive/negative fluctuation values measured by the apparatus are all 2.0 mm, which seem to be the field measuring accuracy of the apparatus. Therefore, regardless of the apparatus resolution of ±0.1 mm and the designed measuring accuracy of ±1.0 mm, certain fluctuation is still existing for the measurement in the in-situ practice due to the bad and complicated field conditions and the measuring accuracy cannot reach the designed value. The measuring accuracy ±2.0 mm of field practices has however basically met the needs of analyzing the subtle process of ice thickness changes and verifying numerical model simulation result of high-precision sea ices, and the field practices have proved that the apparatus can reach the designed intended purpose evaluated from the angle of either testing stability or testing accuracy.

**3. Resistance Ice Thickness Monitor Apparatus with Temperature Gradient**

*3.1. Measurement Principle*

Electrical conductivity is one of the important physical properties of ice and water [Zhu, et al., 2010]. Natural water containing conductive ions (such as: rain, river water, groundwater, tap water, etc.) is electrically conductive at room temperature. A large number of experiments show that the resistance value of water will be gradually increased with the temperature reduction, with its resistance value in the range of tens to hundreds of kΩ, and the resistance value changes in the range of several MΩ to hundreds MΩ after reaching the frozen state. Of course, the ice resistance change not only relate to salt water, but also has a direct relationship with temperature [Golden, et al., 2009]. Ice has weak electricity characteristics and is considered as a weak conductor with larger resistance value and the air is treated as an insulator [Petrenko and Maeno 1987; Petrenko and Ryzhkin, 1984]. A kind of resistance ice thickness monitor apparatus with temperature gradient is designed according to the different conductive characteristics of the air/ice/water and the principle of the monitor apparatus is shown in Fig. 3. The monitor apparatus is composed of two parts, namely, an ice thickness sensor and an intelligent data processor. The ice thickness sensor refers to that the metal contact (touch dot) pairs are evenly set up on the surface of the rod PVC tube with a diameter of 10 cm, with one pair every 1 cm, which is used to measure the resistance of the ice/water and air. Accordingly, a temperature probe is provided evenly every 1 cm near each pair of metal contacts. The temperature probe uses the digital temperature sensor DS18B20, with a measuring accuracy of 0.5ºC.
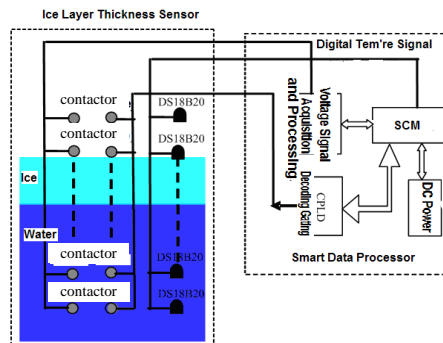


Fig. 3. The principle sketch of the sea ice thickness monitor apparatus based on resistance measurement.

The intelligent data processor is composed of a micro-controller unit (MCU), decoding grated part of CPLD**,** and a voltage-signal acquisitioning and processing unit. Its detecting principle is as follows: the temperature acquisitioning signals are transmitted under the control of the commands of the MCU, and the corresponding temperature sensors are selected to conduct the temperature conversion, and then the digital temperature signals are transmitted to the MCU for processing and storage. After acquisitioning all temperature sensors, the MCU will select or grate various contacts in turn via the CPLD decoding grading circuit, and the voltage signals are returned to the return-line point via ice, ice-water mixture or water, and through the return-line point, the voltage signals are transmitted by the analog switches to A/D switching circuit for analog-digital conversion, and then the digital signals are transmitted to the MCU for processing and storage. According to the different temperature values at various contactors and the different voltage signals returned due to the different random equivalent resistances of voltage signals through ice, ice-water mixture or water, the horizontal positions of various contacts can be determined in or out of the ice, water or air. According to the different positions of metal contacts in the ice, water or air, the ice thickness can be judged.

The temperatures of air, ice and water are different from each other, so, the temperature probe provided every 1 cm can conduct the secondary correction to the data measured by the resistance sensor of ice thickness.

### 3.2. Experiment Application Examples of the Apparatus

A large number of low-temperature laboratory ice thickness measurement experiments have been carried out by the resistance ice thickness monitor apparatus with temperature gradient since it was developed successfully in 2007. The measurement experiment of Yellow River Ice Thickness was carried out from December 2009 to March 2010.
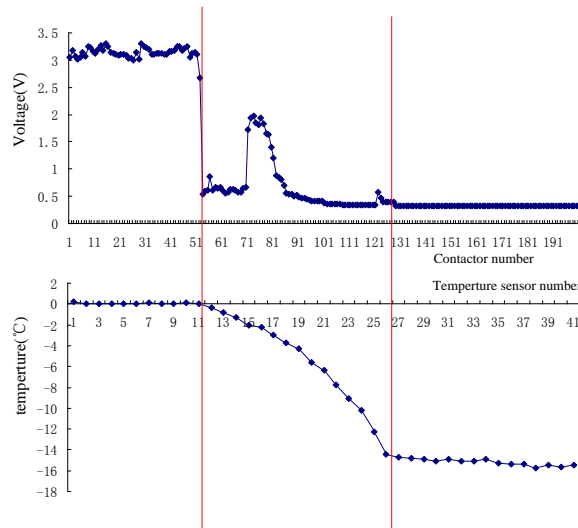


Fig. 4. The variations of pressure profile measured by the sea ice thickness monitor apparatus based on resistance measurement.

When the river ice thickness has reached 40 cm, a measuring point is selected on the river ice surface and the ice hole is drilled and the rod sensor is vertically mounted into the ice hole. The experiment was started on January 22 and ended on March 28 and the ice thickness has finally increased to 83 cm. During the experiment, the ice hole is manually drilled on the ice surface 3 m away from the measuring contactors at a regular time every day to manually measure the actual ice thickness. Fig. 5 offers measuring data by the resistance ice thickness monitor apparatus with a temperature gradient. The two small diagrams in Fig. 4 represent the voltage value of 300 metal contacts and the temperature value of 65 temperature probes, respectively. From the following figures, we can learn that the sub-voltage of the air over the ice is between 0.3-04 V, but there is a big abnormal sub-voltage in the range of 4 cm over the air/ice interface and the abnormal sub-voltage is even bigger than the sub-voltage of the ice. Such a phenomenon is quite popular among the measured results of all groups and all sensors and it is not an exception prior to freezing, with the reasons as follows: there is higher humidity of water surface prior to the freezing and after the freezing, the moisture of this region generates the frost to increase the electric conductive characteristics of such air. Such a phenomenon becomes more obvious when the ambient temperature is higher. The sub-voltage of the ice is among 0.5-1 V and there is a bigger sub-voltage difference in the ice, which is not as stable as that of the air and the water and is related to the vertical difference composed of every phase composition in the ice. The sub-voltage of the water body within 5 cm under the ice underside increases rapidly. Although such water body does not form an ice layer of fixed structure, it is found via the sink side observation window that the flocculent ice crystals have formed, which weakens the electric conductivity of such water body, and below which the

sub-voltage becomes more stable, between 3-3.5 V. The ice thickness is 73 cm during the measurement (the difference of contactor No. 140 and contactor No. 67, namely, 73 cm). It can be seen simultaneously that the water temperature is kept at 0ºC and the ice temperature decreases gradually (from water layer to ice layer) and the air temperature is between -16 – -12ºC. It is basically identical to the voltage interface measured from the water layer, ice layer and air layer.
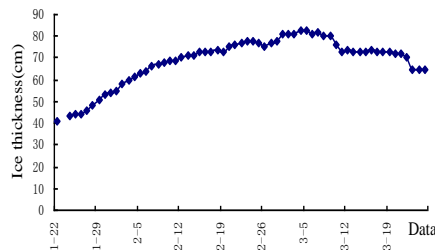


Fig. 5. Variation data of Yellow River ice thickness from January 22, 2010 to March 28 measured by resistance ice thickness monitor apparatus.

Fig. 5 shows the daily ice thickness variation data curves recorded from January 22, 2010 to March 28, 2010, one of which is the ice thickness data measured by the ice thickness monitor apparatus with temperature gradient and another curve is the ice thickness data measured by manual measuring sensor  3 m away from the monitor contactor. From the two curves we can learn that the ice thickness measured manually is basically identical to the data measured by the apparatus, with a maximum error of 2 cm. We can also learn from the figure that the daily growth rate of ice layer at the growth stage is less than 3 cm/d.

## 4. Capacitive Induction Ice Thickness Monitor Apparatus

### 4.1. Measurement Principle

It is often necessary to assign or arrange multiple monitor contactors in different locations to improve the measuring accuracy of ice growth variation with regard to the engineering sea ice survey or river ice monitoring and the survey of multi-contactor ice thickness variation will usually not need the continuous measurement with a high frequency, the technical method of setting the monitoring contactors by combining many measurement methods can be taken into consideration. For this purpose, the authors have researched and designed the capacitive induction ice thickness monitor apparatus, and its fundamental principle is capacitive induction.

The schematic map of the capacitive induction principle is detailed in Fig. 6. The signal generator generates a low-frequency sine wave with a peak value of 5 V and frequency of 10 kHz, which is loaded on the exciting electrode via resistor R, and when ice or water is close to such electrode as the different media, the strength of the electric field around such electrode is changed, which is represented that the voltage of the electrode is changed with the electrode and the capacitance composed by "virtual grounding" [Perme, 2007]. A change of the capacitance results in the change of contactor A voltage to ground, and the voltage component of contactor-A change is transmitted to the signal acquisitioning circuit after  rectification and filtering, so as to distinguish between ice or water of the medium close to such electrode.

Fig. 7 is the principle diagram of the capacitive induction ice thickness monitor apparatus, which is composed of a measuring sensor and MCU monitor apparatus. The sensor is composed of an external electric field induction measurement electrode, a multi-circuit analog switch circuit, a sine signal generator circuit, rectification/filtering circuit and a control circuit.
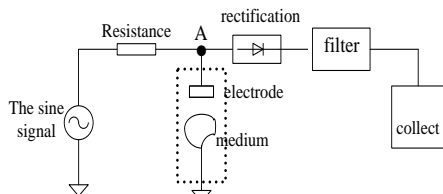
Fig. 6. Schematic map of
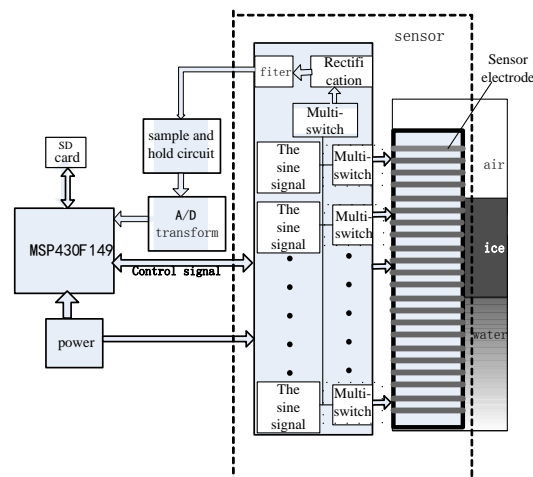capacitive induction mechanism.



Fig. 7. Principle diagram of capacitive induction ice
thickness monitor apparatus.

Each group of sine signal generator circuits and multi-circuit switch circuits is designed or integrated on the same circuit board to connect seven electrodes. According to the difference of measured ice thickness, the sensor of 1 m can be designed, namely, 100 external measurement electrodes, or the sensor of 3 m can be designed, namely 300 measurement electrodes. This sensor is also a non-planar diffused capacitive sensor, a kind of electric field-leaked sensor [Xiang and Dong, 2004; Karagiannis, et al., 2003]. The multi-circuit analog switch uses the MC33993, which is used to select the channels of each electrode under the control of the MCU so as to measure the signal voltages of different electrodes. Through the selection of channels, the voltage signal components measured from different electrodes are transmitted by the signal acquisition circuit to an MSP430MCU for storage after the A/D conversion.

## 4.2. Field Application Example of the Apparatus

The successfully developed capacitive induction ice thickness sensor was tested by the authors on the river channel of Inner Mongolia Section of the Yellow River from December 20, 2009 to February 20, 2010. The specific location is at the Toudaoguai Hydrometric Station, a hydrometric station of Yellow River, in Togtoh County of Hohhot Region.
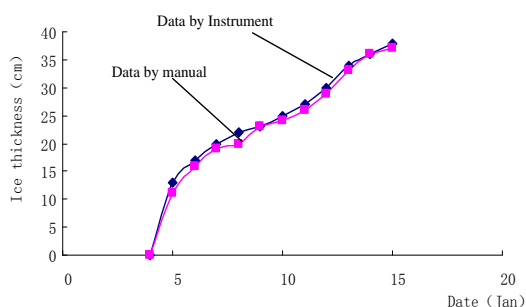


Fig. 8. Apparatus measured ice thickness variation
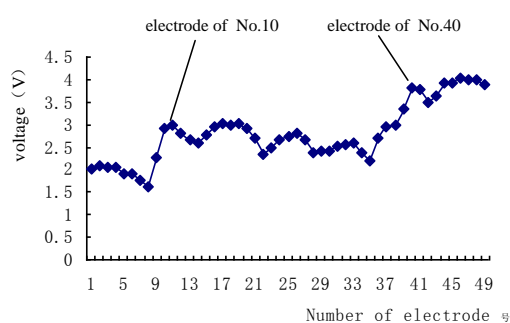data and manually measured ice thickness data.



Fig. 9. Once-sampling data of ice thickness.

Twice measurements of ice thickness were carried out by the capacitive induction ice thickness sensor and its system from December 26 to January 15. Fig. 8 is the variation curve of the apparatus measured ice thickness variation data and the actually measured ice thickness

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data in the second experiment. From the figure we can learn that the ice thickness has been 20 cm when the sensor was installed. The drill-hole installation was carried out on January 4 and the ice thickness in the hole was rapidly frozen to 13 cm on January 5. The water in the ice hole is easily frozen at a lower temperature after the thickness of the ice around the ice hole in which the ice thickness sensor is installed has reached 20 cm. the freezing speed of the ice layer becomes slow since January 6. The ice thickness has reached 38 cm by January 15 for the freezing of 11 days. From the figure we can learn that the ice thickness measured by the capacitive induction ice thickness sensor is basically identical to the actually measured ice thickness, with a maximum error of 2 cm.

The once-sampling data of the ice thickness sensor made on January 12 is shown in Fig. 9. From the figure we can learn that the curve is significantly divided into three steps. The electrodes in the step of higher voltage are located in the air, and electrodes 10-40 are in the ice, we can hereby judge that the ice thickness is 30 cm. Electrodes 1-9 are located in the water.

## 5. Conclusions

(1) The field testing accuracy of ice thickness monitor apparatus based on the MDL principle is ±2 mm and at the millimeter level, which has met the needs of automatically acquisitioning the in-situ high-precision ice thickness variation data. The field data will provide a powerful support for the sea ice thermodynamic numerical simulation with high resolution. Such technology has solved the "bottleneck" problem of restricting the fine development of a sea ice thermodynamic model [17] and the practices have proved that the newly developed apparatus can be operated reliably and steadily even in the bad observation environment in winter at the South Pole. The existing mechanical technical problems will not disturb the analysis of measured data and such problems can be overcome in the forthcoming technical improvement upon the accumulation of field experiences.

(2) The resistance ice thickness monitor apparatus is still at its exploratory research stage, but the laboratory application has embodied the detecting ability of the technology of ice thickness measurement. Such technology can be optimized in the future and is expected to replace the existing technology of using the air/ice/water vertical temperature profile to calculate the ice thickness that is applied in the ice buoy, and such technology can be applied to the measurement of glacier surface substance balance to replace the existing manual measurement method of lining pole and in addition, it can be applied to the measurement of ice thickness of rivers, reservoirs and lakes, and simultaneously the measurement of underwater level as well as the monitoring of the formation and development process of ice in water that is resulted from the cooling water at a certain depth under the water surface.

(3) The thermo-resistance ice thickness monitor apparatus is characterized by the single manufacture, low cost, convenient operation and reliable data, but it does not belong to the automated devices and its measuring accuracy is only at the centimeter level. It can however guarantee the continuous observations in multiple positions and reduce the physical labor of drill-hole measurement, and therefore such technology is applied to the local small-size hydrometric stations in North China.

The above-described three types of automatic ice thickness measuring technologies all require to be installed in a drilled ice hole when the ice thickness reaches a certain degree, to conduct the in-situ observation of ice thickness variations. Due to the low cost, these in-situ ice thickness measuring technologies can be arranged at several fixed points, so as to accomplish the large-scale in-situ observation of sea ice, river ice, polar snow and ice, and offer reliable on-site data for relevant researches and engineering sectors.

## Acknowledgements

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