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Ultrasonic Method for Monitoring Environmental Risks Associated with Precipitation

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This paper presents a solution that utilises ultrasonic technology to allow monitoring snow layer thickness or water level based on measurement from air. It describes the principle of operation of a measurement device using three methods of compensating for changing external factors affecting appliance's precision. Block diagram of the device is also provided. In order to verify the proposed solutions, the research team tested the device in laboratory and operating conditions. The results obtained this way make it possible to select a configuration of device operation depending on the required measurement precision and limitations associated with installing the system for actual operation.

Keywords: ultrasonic methods, snow layer, monitoring of environmental risk.

1. Introduction

Ultrasonic technology has many practical applications in science and technology. It can, for instance, be used for monitoring precipitation amounts (e.g. rain, snow). Measuring snow layer thickness is especially important as excessive load can compromise the structural integrity of e.g. flat roofs. Water level measurements are associated with assessing flood hazards. Among many methods that can be used to perform such measurements, those utilising ultrasonic transducers operating in air environment are especially interesting. They are based on the phenomenon of reflection of ultrasonic waves from the air-snow surface or air-water surface boundary. If the ultrasonic wave travel time along transducer-impedance discontinuity path is measured, it is possible to determine the changes in snow or water level.

2. Physical parameters of snow and ice

Solid and liquid precipitation forms at altitudes at which water vapour becomes saturated. Crystal nuclei are formed around freezing nuclei. This results in the formation of water layer with droplets or snowflakes if sublimation or coagulation processes are involved. After the snowflakes fall, they become snow cover the specific properties of which depend on internal and external factors (mostly temperature and humidity, cf. Gudra, 2005). The character of snow cover changes continuously as a result of physical processes occurring both inside and on its surface. Density is the most important snow parameter for risk assessment. Actual automatic monitoring of snow density is very difficult. It is, however, possible to measure snow layer depth using the ultrasonic method. Acoustic impedance of snow is related to snow density which means that it is possible to determine the latter parameter based on reflection coefficient measurement at air-snow layer surface boundary.

Ice is formed in the process of water freezing; water has maximum density at 4°C and further cooling results in decreasing density. During freezing, the density of water decreases by about 10%. As in the case of snow cover, there are various types of ice. Its density, however, is similar in all cases.

Snow cover measurements which are a part of standard meteorological observation, are performed everyday by weather stations. Automation of measurement of snow layer parameters with the use of ultrasound allows more detailed and frequent observations of changes which can help assess risks in advance.

Non-contact monitoring of water level in rivers and water basins can be performed in a similar fashion as in the case of snow layer depth measurement.

3. Methods of compensating for parameters affecting measurement precision

In order to perform precise measurement of snow layer thickness or water level for the purposes of monitoring changes occurring in time, it is necessary to compensate for external factors affecting value c – velocity of sound propagation in a given medium (temperature, humidity, pressure, wind, etc.). Depending on the required measurement precision, it is possible to use three methods of compensation (Gudra *et al.*, 2011):

- temperature compensation (Canali *et al.*, 1982);
- parametric compensation with the use of a reflector (Chande *et al.*, 1984);
- parametric compensation with the use of two measurement probes.

Figure 1 shows measurement principles with one of the above mentioned compensation methods utilised.

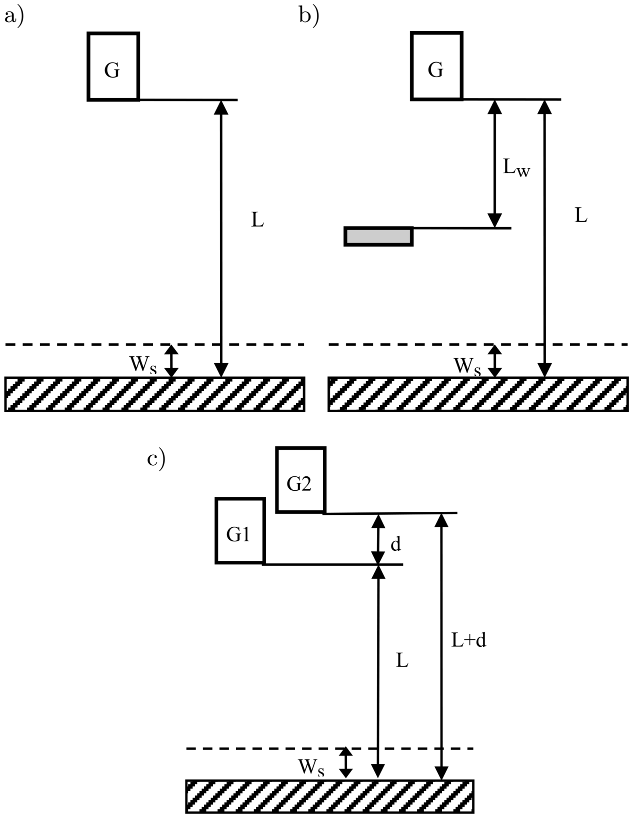

Fig. 1. Methods of compensating for external factors affecting measurement precision: a) a system with temperature compensation; b) a system with parametric compensation with the use of a reflector; c) a system with parametric compensation with the use of two probes.

In the system with temperature compensation, the device measures t_1 – ultrasonic wave travel time from the measurement probe G to the measured surface and back, as well as ambient temperature T_c. Snow layer depth W_s can then be determined using the following formula:

$$W_s = L - \frac{t_1 \cdot c}{2}, \tag{1}$$

where L is the reference distance (no snow layer) and c is the sound velocity equal to $c = 331.5(1 + T_c/273.15)^{1/2}$ m/s.

In the system with a reflector, the device measures t_1 – the ultrasonic wave travel time from probe G to the reflector and back and t_2 – the ultrasonic wave travel time from probe G to the measured surface and back. Snow layer depth W_s can then be determined using the following formula:

$$W_s = L - L_w \frac{t_2}{t_1}, \tag{2}$$

where L is the reference distance (no snow/ice layer) and L_w is the distance of the measurement probe from the reflector.

In the system with two measurement probes, the probes are located at a different altitude in relation to the measured surface (assuming uniform snow surface below the probes) and the distance between the probes is known and is d. The device measures two times of flight: t_1 – the ultrasonic wave travel time from probe G_1 to the measured surface and back and t_2 – the ultrasonic wave travel time from probe G_2 to the measured surface and back. Snow layer depth is determined using the following formula:

$$W_s = L - d\frac{t_2}{t_2 - t_1}, \tag{3}$$

where L is the reference distance (no snow/ice layer) measured for probe G_2.

Figure 2 shows block diagram of the measurement device for all compensation methods. According to the measurement principles presented in Fig. 1, temperature measurement is not required in systems with parametric compensation and only one probe is sufficient in systems with a reflector.

Figure 2b shows the structure of a measurement ultrasonic probe. The probe consists of a piezoelectric ultrasonic transducer intended to work in air environment at the frequency of $f = 50$ kHz (ATK 50, Airmar, USA) and all the electronic systems necessary for the measurement device operation (Banasiak *et al.*, 2009; Bednarek *et al.*, 2010). A parabolic acoustic horn is used to guarantee a required ultrasonic beam shape (width at -3 dB below 20°). Theoretical measurement range of snow layer thickness is 10 m.

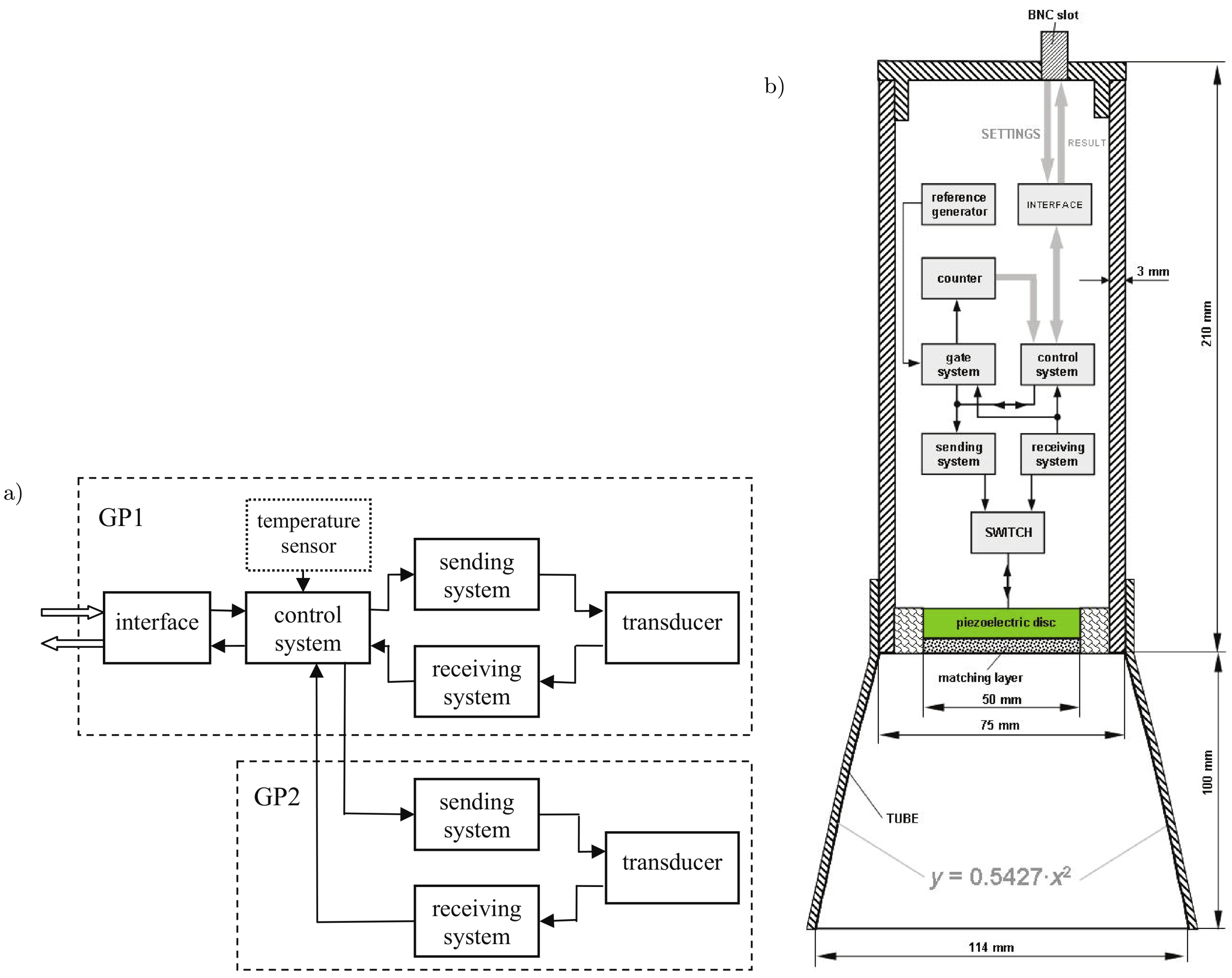

Fig. 2. Diagram of the measurement device.

4. Measurements

The developed measurement device was tested in various operating configurations and measurement conditions (also during snow precipitation). All the measurements were intended to check whether the device operates properly and the obtained results are consistent as well as to determine uncertainty of distance measurement (snow layer depth measurement). Table 1 shows the results of analysis of the measuring inaccuracy for individual measurement methods.

Using the exact differential method to analyse measurement inaccuracy shows that total measurement uncertainty includes components related to device configuration and direct error components related to the actual measurement. The values related to measuring instrument configuration are a result of measurement geometry; their effect can be minimised through calibration.

As the device is intended to work in harsh conditions (low temperatures, humidity, icing), it had to be properly tested. Initial measurements were performed

Table 1. Analytical relations for snow layer thickness and measurement uncertainty with various measurement methods.

	Single-probe measurement	Two-probe measurement	Single-probe measurement with a reflector
Snow layer	$W_s = L - \dfrac{2 \cdot c}{t}$	$W_s = L - d\dfrac{t_1}{t_2 - t_1}$	$W_s = L - L_w\dfrac{t_2}{t_1}$
Measurement inaccuracy	$\Delta W_s = \Delta L + \left\lvert \dfrac{2 \cdot c}{t^2} \right\rvert \Delta t$	$\Delta W_s = \Delta L + \dfrac{t_1}{t_2 - t_1}\Delta d + \dfrac{d}{(t_2 - t_1)^2}\Delta t_1 + \dfrac{dt_1}{(t_2 - t_1)^2}\Delta t_2$	$\Delta W_s = \Delta L + \dfrac{t_2}{t_1}\Delta L_w + \dfrac{L_w}{t_1}\Delta t_2 + L_w\dfrac{t_2}{t_1^2}\Delta t_1$

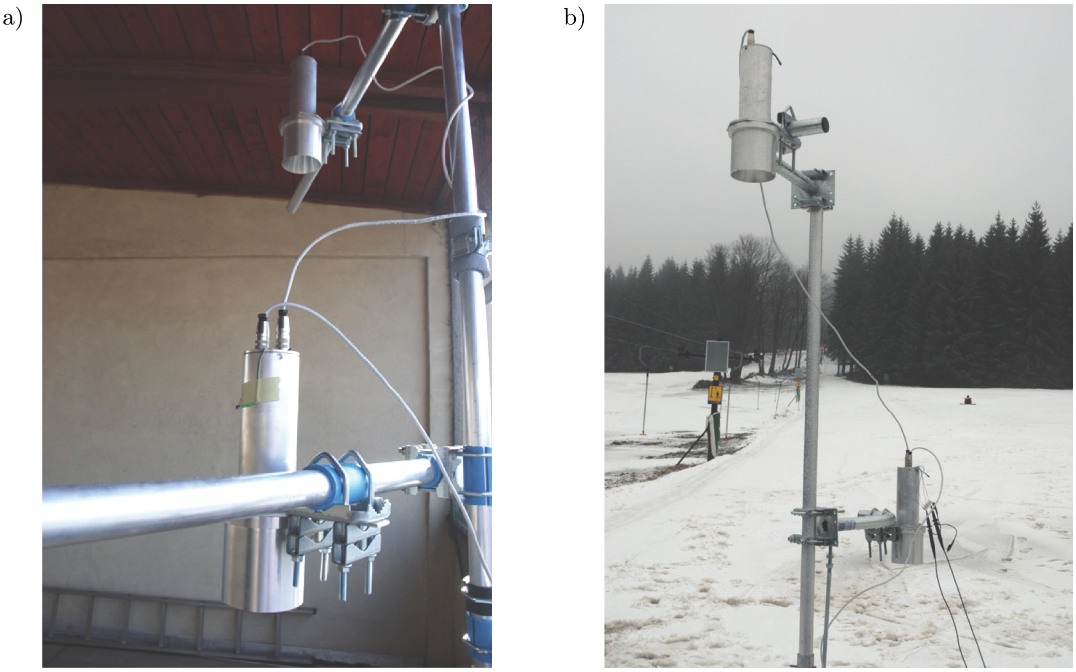

Fig. 3. Probe configuration during measurement: a) in laboratory conditions; b) in operating conditions.

on the roof of building C-5 of the Wrocław University of Technology where the measurement instrument was mounted. A view of the appliance is shown in Fig. 3a. With the presented configuration it is possible to study the effect of weather conditions on the operation of the device for methods I and II. During the measurements, the team observed result consistency and studied the effect a given compensation method has on result spread. As there was no snow, the device was tested in the above described study arrangement using mineral wool with appropriate parameters to simulate snow (Iwase *et al.*, 2001).

According to recommendations related to snow layer measurements presented by Ryan *et al.* (2007), such a measurement should be performed periodically with a 5 minute interval. To test result repeatability, the distance was measured 4 times for each channel. This allowed the team to discard measured values with gross error and average the results.

Measurements in operating conditions were performed in Czarna Góra ski resort. Device mount is shown in Fig. 3b.

5. Measurement results

Measurements performed at the measurement position provided results that can be further analysed. As the device is characterised by fractional result inconsistency which is manifested as drastic result differences inside a single measurement series, the team used a simple calibration algorithm that made it possible to discard such results. In the algorithm, a certain level of calibration is assumed for a given channel (base level with no snow), and then the measured values are compared to previous results in accordance with the following relation:

$$x_n = \begin{cases} x_n & \text{for} \quad x_n \geq k \cdot x_{n-1}\,, \\ x_{n-1} & \text{for} \quad x_n < k \cdot x_{n-1}\,, \end{cases} \tag{4}$$

where k is a coefficient from $0-1$ range that discriminates dynamic properties of measurement result changes (snow cover increase). Values of k close to one describe a situation in which even very small changes in the measurement interval will be discarded by principle as an error result. It is important to note that this policy is justified because snow cover is not likely to change significantly between 5 minute intervals. Initial device tests included laboratory measurements the purpose of which was to determine device precision and result repeatability. Examples of laboratory measurement results were presented as time series diagrams and bar charts shown in Fig. 4 and Fig. 5.

Figure 6 shows the result of a measurement in configuration III which can also be treated as two independent measurement results in configuration I. The measurement was performed outdoors without temperature compensation, as it is clearly visible in the chart. If temperature compensation is applied according to relation dependence (1), it is possible to achieve the result visible in Fig. 7. Analysis of the chart suggests that distance measurement results are not correlated with temperature, which in turn decreases the mean value spread. It can however be observed that both histories are to some extent correlated as a result of environmental conditions other than tempera-

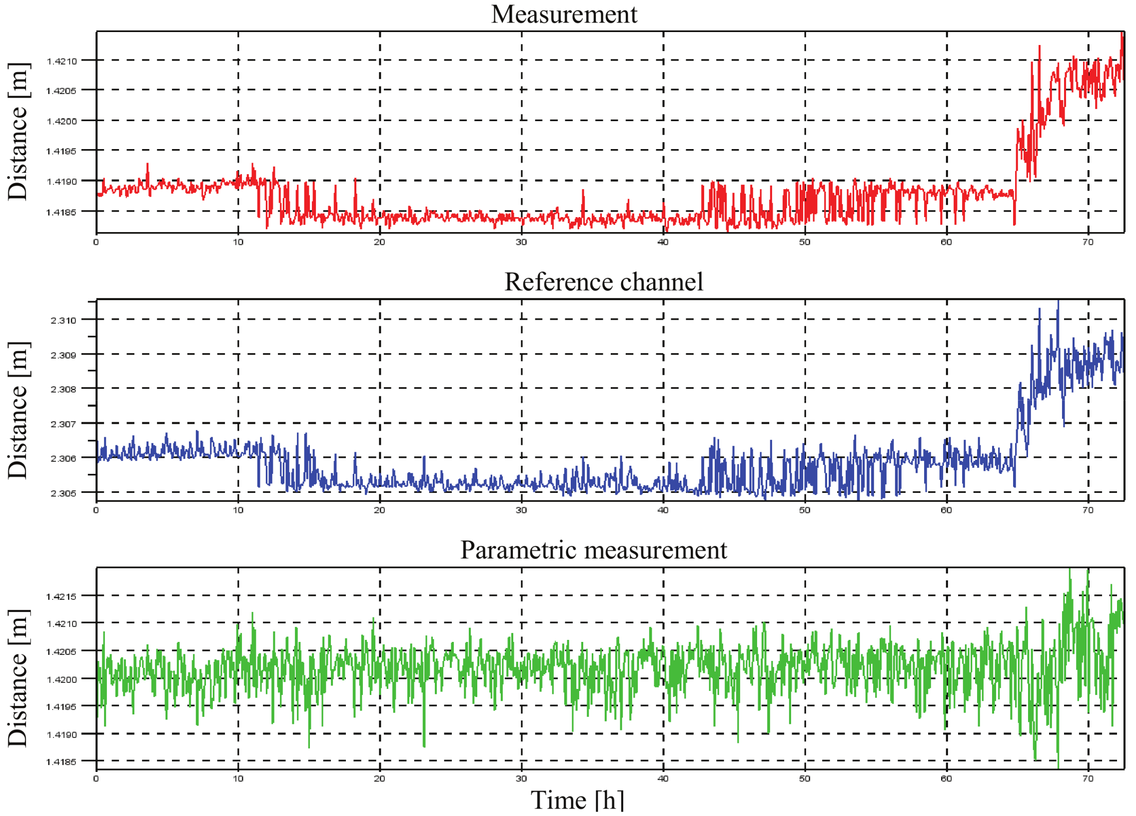

Fig. 4. Device laboratory tests – results for distance measurement in configuration III with temperature compensation. Parametric measurement calculated for distance $d = 0.888$ m.

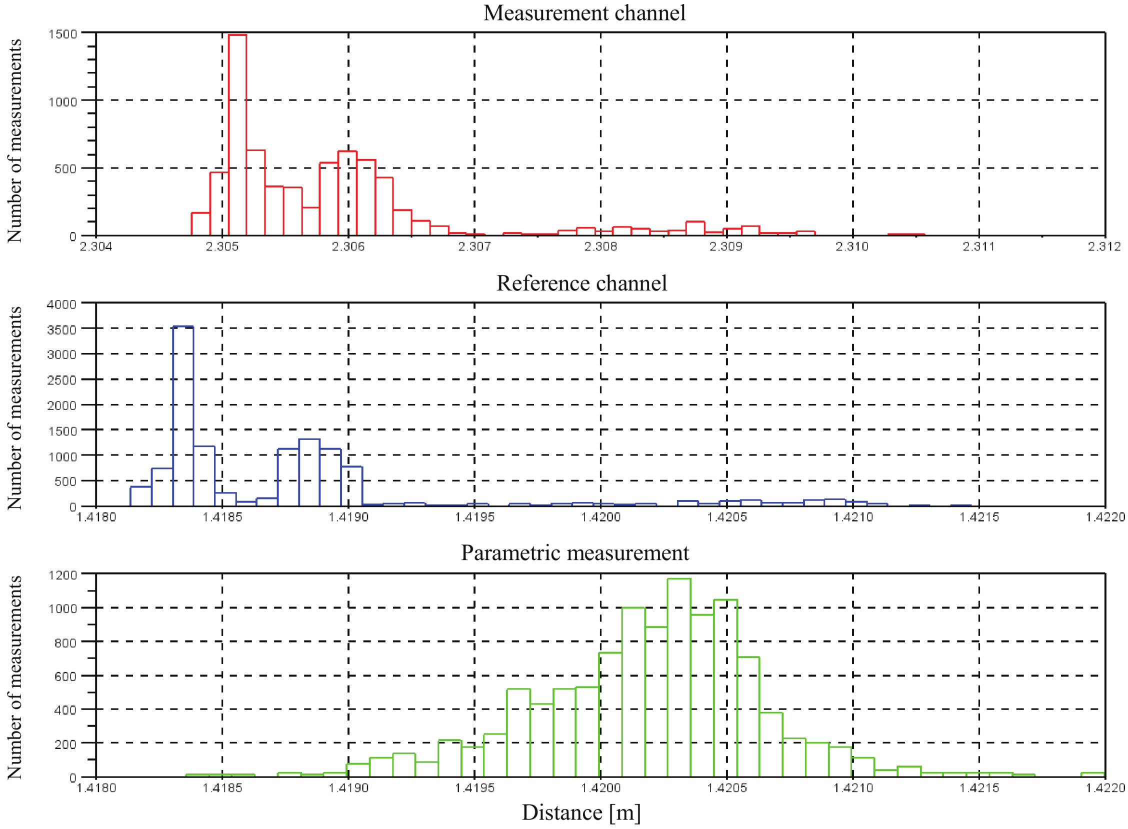

Fig. 5. Device laboratory tests – histograms of measurement results in configuration III with temperature compensation. Parametric measurement calculated for distance $d = 0.888$ m.

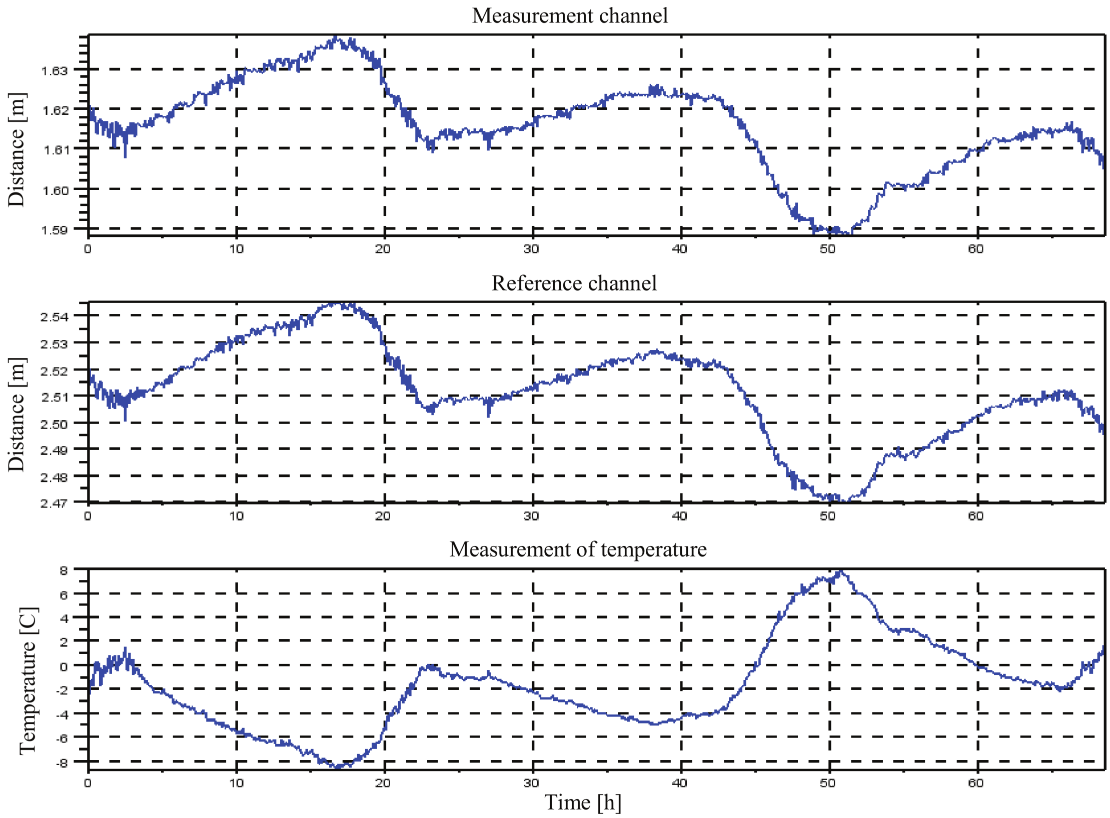

Fig. 6. Distance measurement using two probes without temperature compensation.

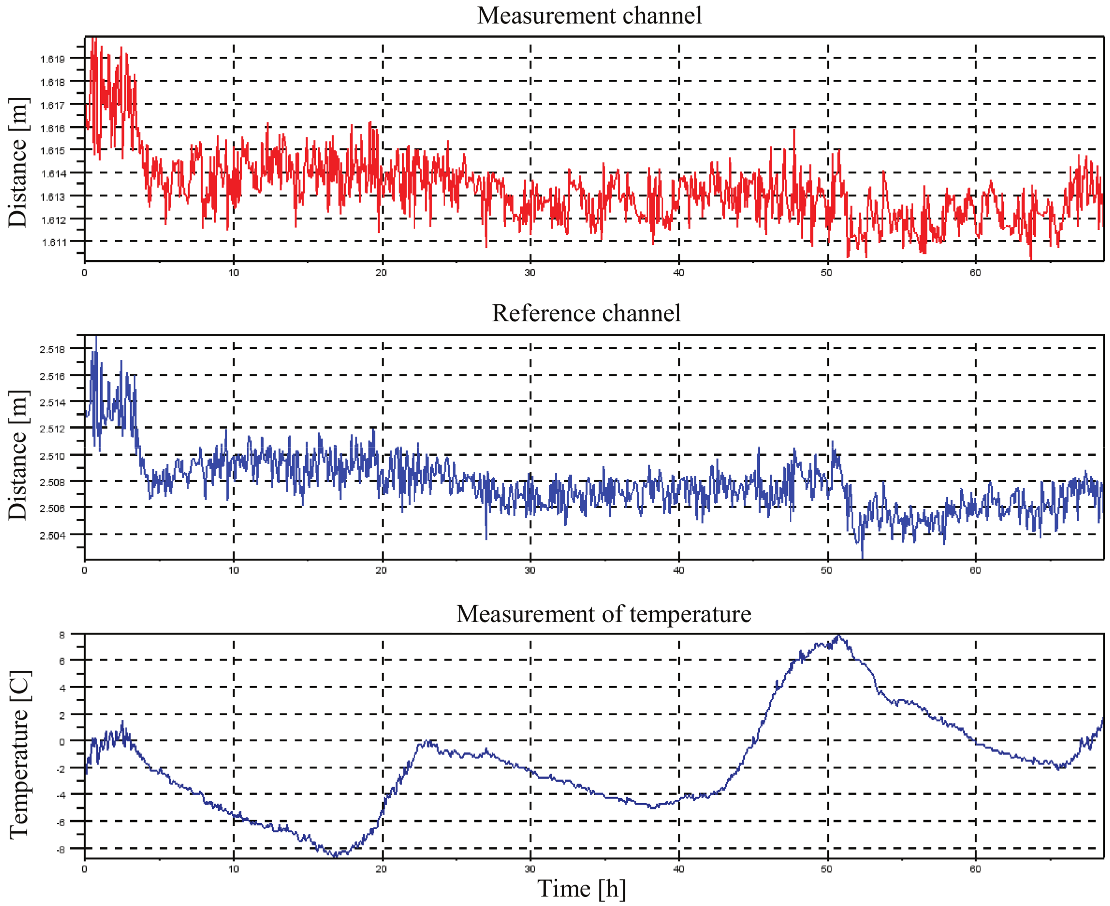

Fig. 7. Distance measurement using two probes with temperature compensation.

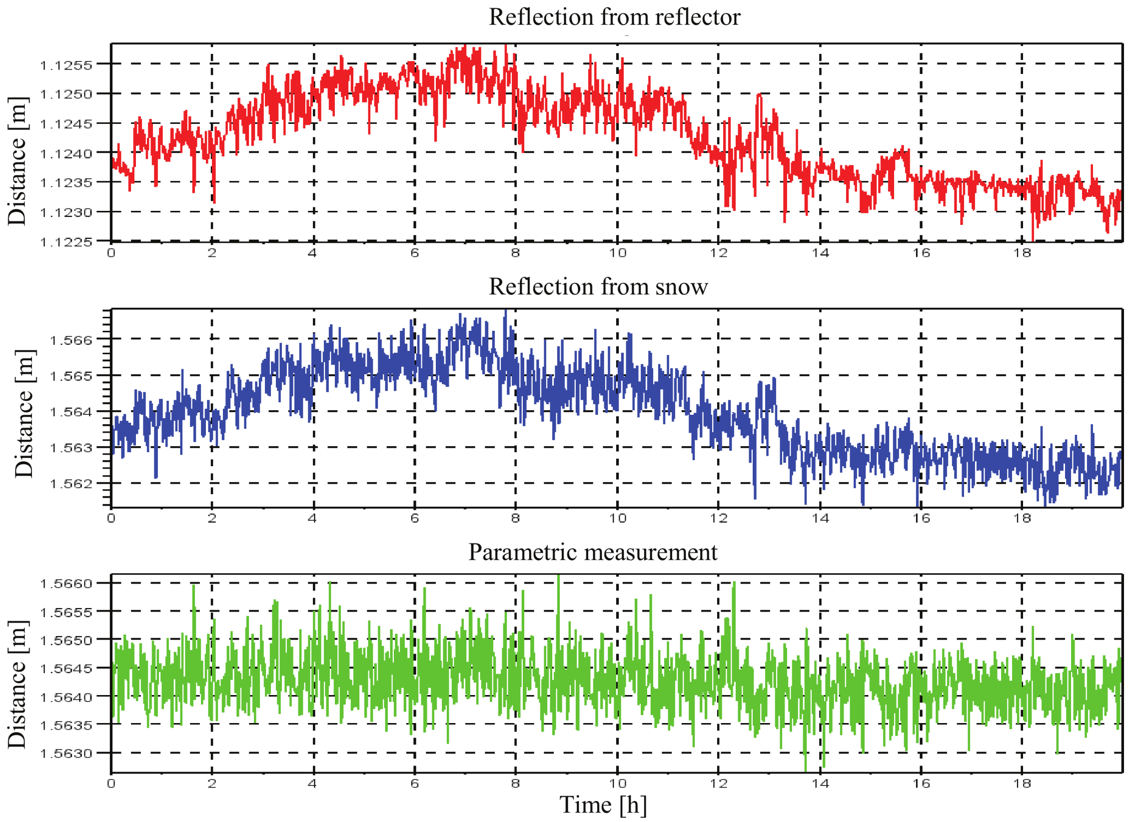

Fig. 8. Measured distance values for a measurement with parametric compensation and the use of a reflector.

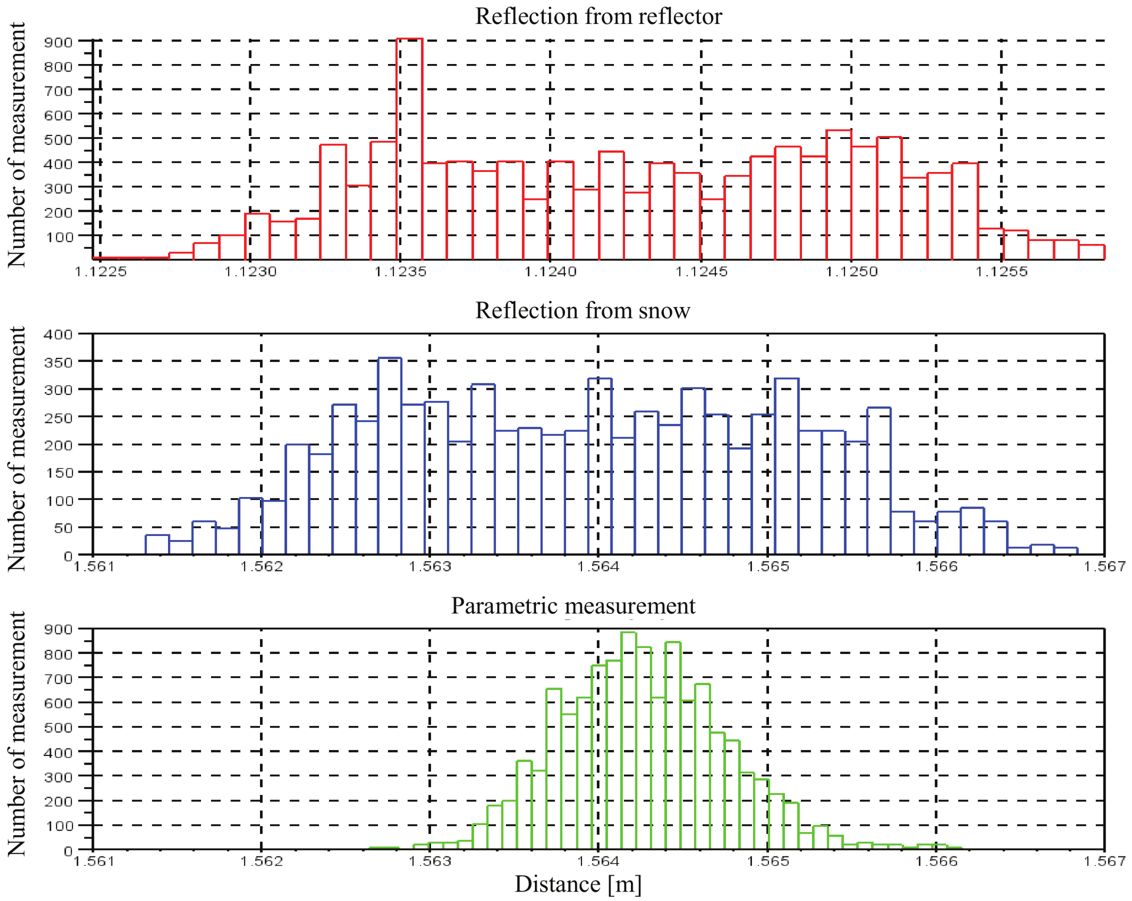

Fig. 9. Histograms for a parametric measurement with the use of a reflector and simulated snow layer.

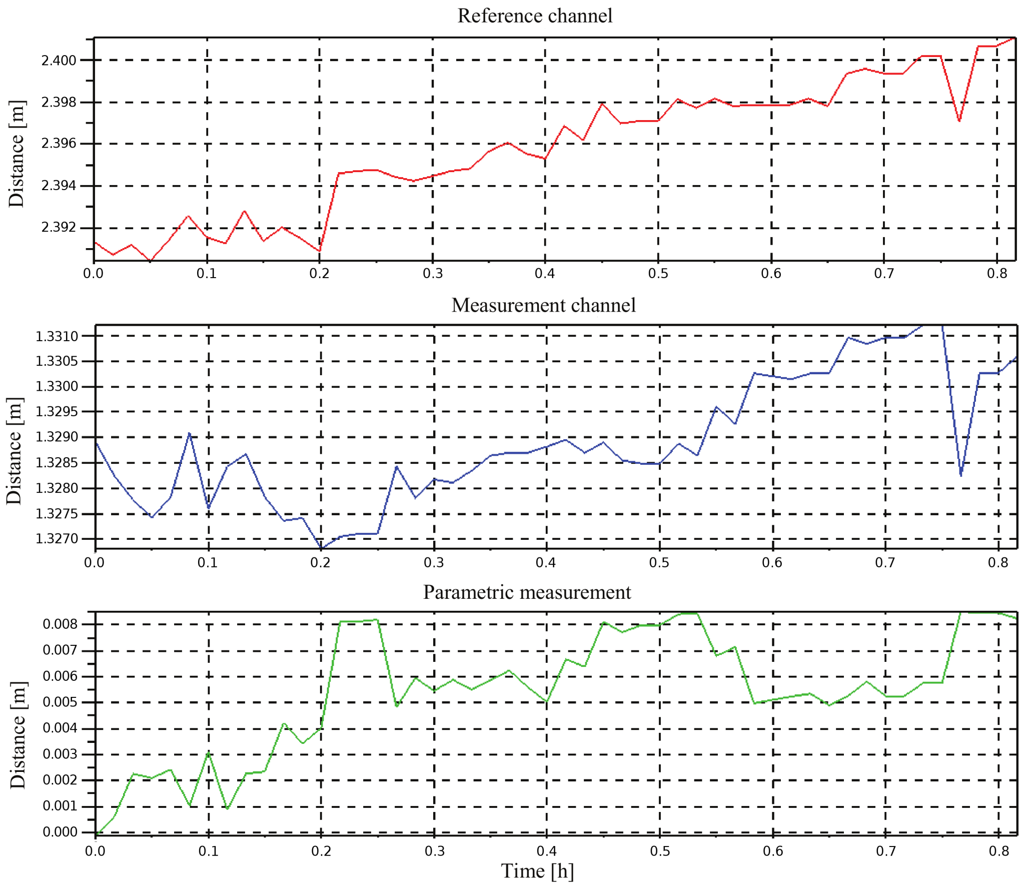

Fig. 10. Parametric measurement of snow layer (configuration III) in actual operating conditions. The lower figure shows snow cover thickness.

ture. The effect of humidity and pressure can be corrected using parametric compensation. Fiures 8 and 9 show measured distances and their corresponding histograms (visualising spread of mean value obtained from measurement results) for a measurement with parametric compensation and the use of a reflector (copper rod with the diameter of $D = 5$ mm was used as the reflector). The parametric measurement histogram is the most compact which should be interpreted as an evidence of low measurement uncertainty. Figure 10 shows an example parametric measurement of snow layer in configuration III in actual operating conditions.

Currently, the measurement device's accuracy is being verified in extreme conditions during 34th Polar Scientific Expedition to Spitsbergen organised by the Department of Polar Research of the Institute of Geophysics of the Polish Academy of Sciences in Warsaw. The snow layer thickness measuring instrument operates only in sub-zero temperature conditions. Harsh weather conditions (low temperature, wind) make it possible to verify the selected measurement methods.

Figure 11 shows the measurement instrument mounted on a mast near the Polish Polar Station and operated with temperature compensation.

Fig. 11. Ultrasonic instrument measuring snow layer thickness mounted on a meteo mast during research on Spitsbergen.

Figure 12 shows distance measurement results (related to snow layer thickness) in a system with temperature compensation, and Fig. 13 shows measurement results separately for snow layer thickness and temperature without temperature compensation (no precipitation).

The presented relations clearly show that temperature alteration results in distance measurement errors. The characteristics of the histories of both values (distance and temperature) are very similar. It is not possible to obtain a valid distance measurement without compensating for temperature changes. Resolution of measurement in the laboratory condition is 0.2%, whereas resolution in outdoor condition is approximately 1%. The uncertainty of thickness measurement is comparable with other commercial devices using temperature compensation (e.g. SR 50, USH). By applying methods with parametric compensation with the use of a reflector or two measurement probes, the measurement uncertainty is reduced.

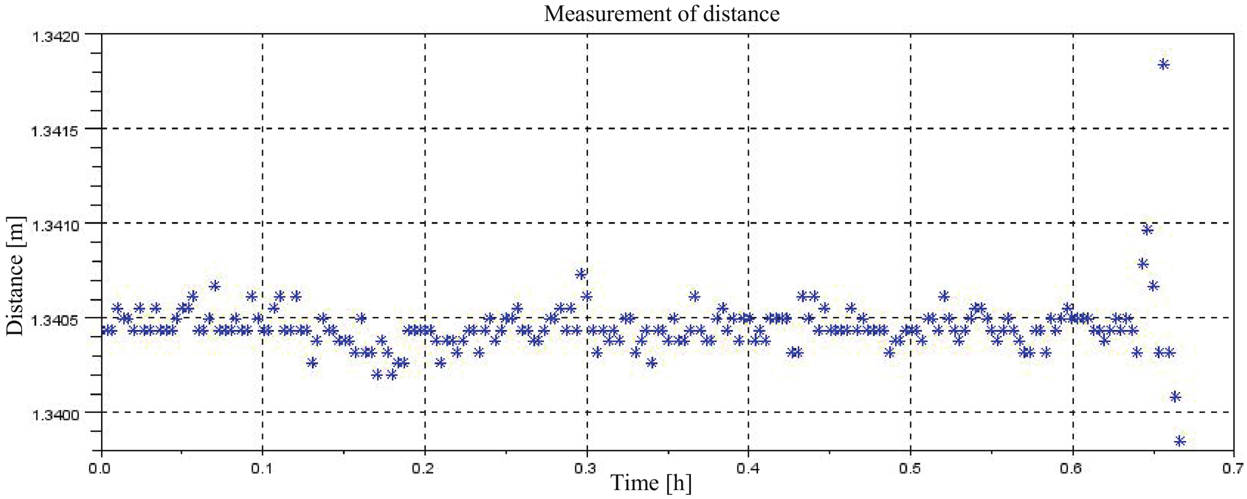

Fig. 12. Measured distance values for a measurement with one probe and temperature compensation.

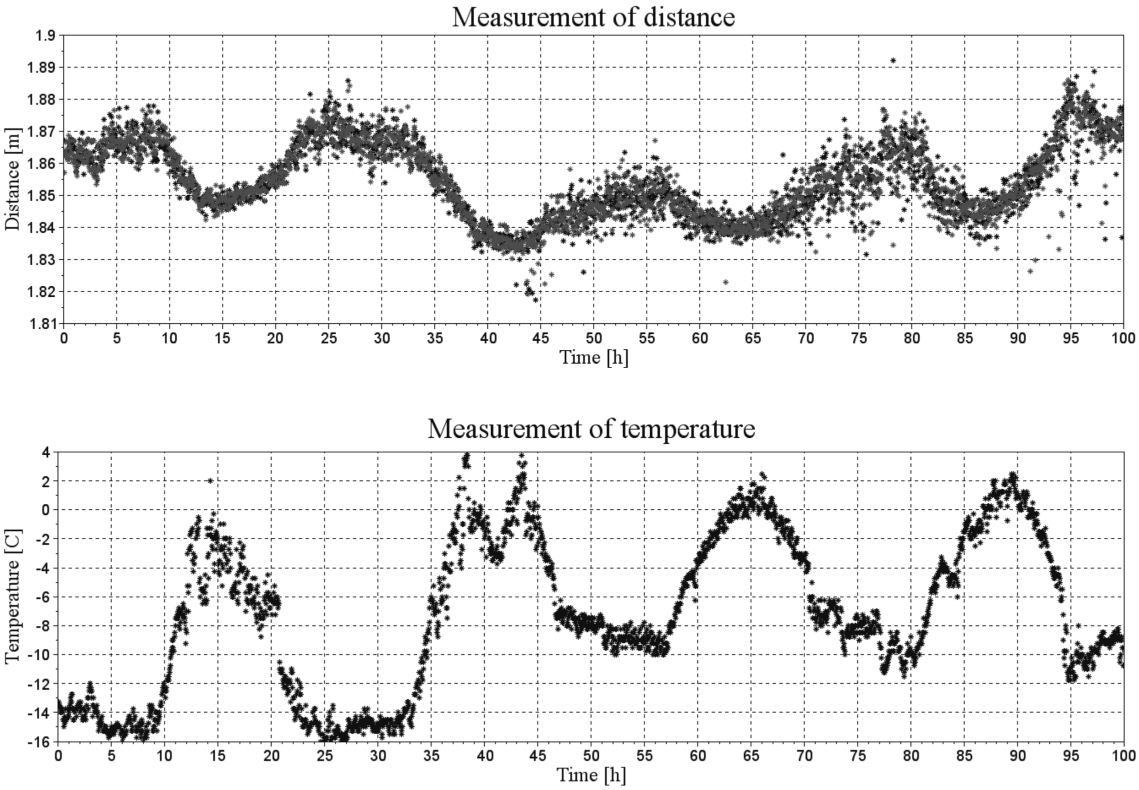

Fig. 13. Measurement results: a) for distance without temperature compensation; b) temperature.

6. Prospects for using signal reflected from a snow layer for assessment of the density of various snow types

Figure 14 shows the dependence of pressure coefficient of reflection from snow surface for the studied snow density values presented in Table 2. It is easy to notice that the coefficient value increases linearly with increasing snow density. In order to visualise the linearity better, a trend line was added to the chart. Minor deviations of the obtained results in relation to the trend line can be caused by measurement errors. They are unavoidable in case of snow – a very unstable medium.

Table 2. Coefficient of reflection of the surface of snow with various density values (Gudra, Najwer, 2011).

Snow density [kg/m^3]	Pressure reflection coefficient
120	20.30%
124	20.60%
132	22.19%
170	25.77%
232	31.58%
325	37.24%
495	53.29%
591	63.19%
696	70.24%

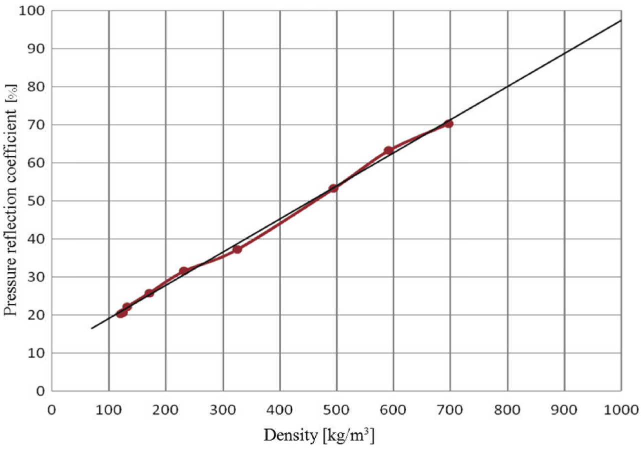

Fig. 14. The relation of the coefficient of reflection from the surface of snow to snow density (Gudra, Najwer, 2011).

Detailed analysis of the direction of trend line increase shows that for 1000 kg/m^3 density (which is close to water density at 4°C), the value of the pressure reflection coefficient would be 97%. Theoretical pressure reflection coefficient R' on the boundary between two media is described by the following relation:

$$R' = \frac{1-m}{1+m}, \qquad (5)$$

where $m = (\rho_1 c_1)/(\rho_2 c_2)$ is the ratio of acoustic impedances of the two media, air and snow.

Acoustic impedance of air is 429 kg/(m^2·s), of water – 1.48·10^6 kg/(m^2·s) (Szczeniowski, 1967). The value of the theoretical pressure reflection coefficient calculated with formula (5) is 99.94%. Comparison of the obtained values suggests that the measurement results are biased with little error. Precise measurements of reflection coefficient can be used to assess the density of various snow types (Gudra, Najwer, 2011).

7. Conclusions

The developed device can operate in three different modes, depending on required precision and mounting conditions. It should be noted that the results were obtained for a prototypical set of devices which can be further optimised. The choice of interface for the device includes RS-422 with MODBUS/ASCII protocol or standard RS-232 port operating in ASCII mode. It is also possible to use more sophisticated methods of result interpretation in order to reduce measurement uncertainty. Such calculations can be performed by a sensor network control centre.

The developed measurement device can almost immediately be used for measuring distances in air (e.g. to measure water level in rivers and other water basins).

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