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INSTRUMENTATION FOR MEASURING ATMOSPHERIC ICING

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1. Introduction

In regions with severe climatic conditions atmospheric icing on structures is a serious problem. The general effects of icing are increased vertical loads on structures as well as increased wind drag caused by an increased area exposed to the wind, leading to a severe increase in wind load. Planning and building requires specifications of expected climatic scenarios. The process of ice build-up on the surface of an object is described as accretion. Accretion results in the different types of icing on structures. This accretion is a function of meteorological parameters such as air temperature, wind speed, cloud liquid water content, cloud droplet spectra, etc.

Atmospheric icing is traditionally classified according to three different formation processes:

1) precipitation icing:
    a. freezing rain or drizzle
    b. accumulation of wet snow
2) in-cloud icing which consists of super-cooled water droplets in a cloud or fog.
3) hoar frost/sublimation. Direct phase transition from water vapour into ice. Hoar frost is of low density and strength, and normally does not result in significant load on structures.

Ice accretion also depends on the properties of the accreting object itself, described by its shape, size, orientation relative to the wind and material, as well as the surface structure. Measurements of ice accretions must therefore be specified with respect to devices, procedures, arrangements on site, etc. The rate of accretion by dry growth onto an object by in-cloud icing is given by the equation

$$\frac{dM}{dt} = \alpha_1 \cdot q_{LWC} \cdot A \cdot v \qquad [\mathrm{Kg\ s^{-1}}] \qquad (1)$$

where q_{LWC} is the liquid water content of the air, flowing with the wind speed velocity V, towards the cross-sectional area A, of an object. The efficiency coefficient α_1 represents the collision efficiency. It is the fraction of the total number of droplets in the path of the object that actually collide with that object. Small droplets, large cross sections and low wind speeds reduce α_1.

Early results of icing on structures used in continental measurements were obtained by manual registration of ice thickness and weight of the ice accretion, or sometimes simply by visual estimates. Few observations and a high degree of uncertainty in the existing observations was not satisfactory for scientific purposes. Due to this, new techniques of measuring atmospheric icing were developed (Poots, 2000).

The early instruments were primarily cylindrical objects such as steel cylinders and horizontal wires. The scientists in the former USSR developed a system of horizontal wires (Nikforov, 1983), while the Europeans mainly used “the Grunow net” (Grunow and Tollner, 1969). The Grunow net is a tube of wire netting which was often installed on the top of precipitation gauges. It recorded water run-off from melting accreted ice. A well known method of estimating the cloud liquid water content and the median volume diameter, is by the rotating multicylinder method (Makkonen and Stallabras, 1987, Finstad et al., 1988c).

The international standard, ISO 12494, 2001, Atmospheric icing of structures, gives recommendations of standardisation of measurements for ice actions on structures. The standard device is a cylinder with the diameter of 30 mm which slowly rotates around a vertical axis. The cylinder length is 1 m, and should be placed 10 m above the surface. Among the different variables, such as density and dimension, which can be measured, the ice load is considered most important. The output from the measurement series should form the basis for extreme value analysis, ranging from a few years to several decades. Shorter time series connected to longer series of meteorological data, statistically or physically in combination with theoretical models, will provide important information. Wind measurements and detailed load recordings of reactions in all directions, vertical and horizontal, will give the basis for estimating the drag coefficient, C_D by calculation.

2. Description of the ice scale system

A system was constructed based on the requirements and specifications outlined in the introduction. The entire measurement system is shown in the block diagram in Figure 2.1. It consists of the following main components; ice scale, temperature and humidity sensor, ultrasonic anemometer, data logger, and power supply / converter units.
Each instrument is described briefly before attention is turned to the ice scale itself.

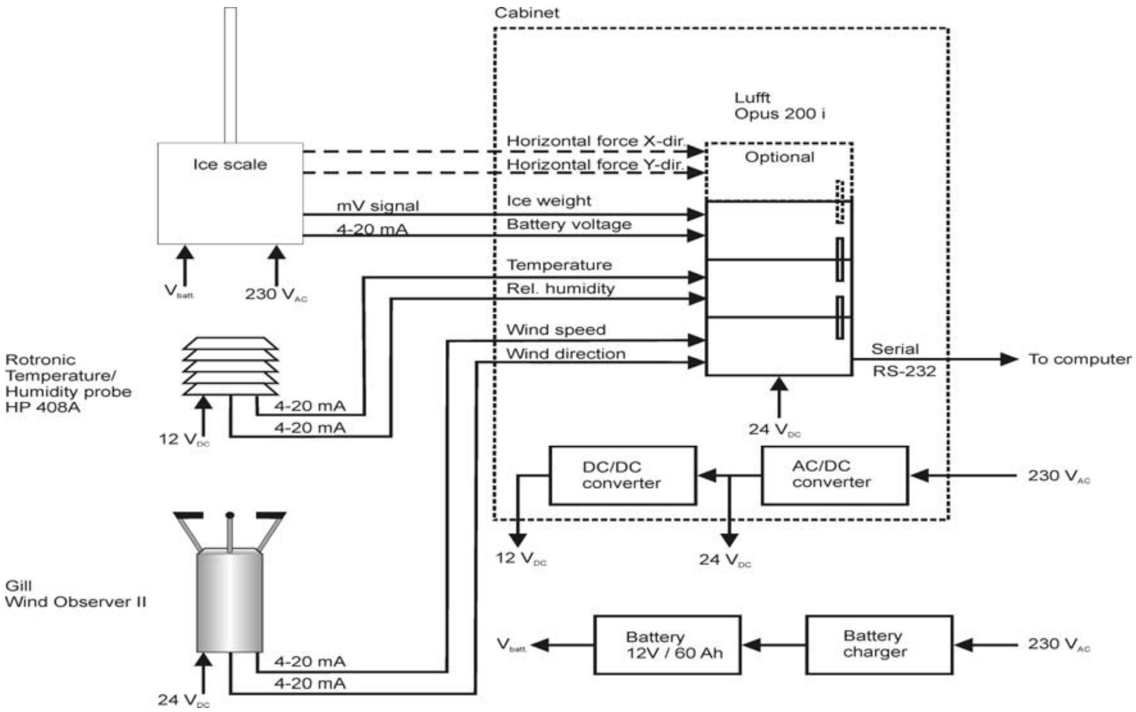

Figure 2.1 Block diagram of the ice scale system.

Table 2.1 Measurement ranges and accuracies of the sensors in the ice scale system.

Parameter	**Range**	**Accuracy**
Temperature	-40 to 60°C	0.3 °C at 23 °C
Relative humidity	0 to 100 % RH	1.5 % at 23 °C
Wind speed	0 to 70 m/s	2 % at 12 m/s
Wind direction	0 to 360 degrees	2 % for WS<25m/S 4 % for 25m/s<WS<60m/s
Battery voltage	0 to 15 V	
Ice weight	0 to 100 kg	
Horizontal force, x-direction	0 to 980 N	
Horizontal force, y-direction	0 to 980 N	

Temperature and humidity sensor

The Rotronic MP408A sensor is a combined platinum PT100 temperature sensor and a capacitive relative humidity sensor. It is housed within a radiation screen to minimize the error due to solar heating. The sensors are calibrated to output a current 4 to 20 mA proportional to the measuring ranges. See Table 2.1.

Ultrasonic anemometer

The Gill Instruments Wind Observer II is an ultrasonic anemometer (Gill Instruments, 2000). The instrument is designed to measure horizontal wind speed along two fixed orthogonal axes by transmitting and receiving sonic signals. Sampling is done every 25 mins, each axis being sampled sequentially. The analogue output is updated every 1 s, based on an average of 39 measurements. Wind speed and direction is calculated based on the two wind vector data.

In order to prevent icing on the wind sensor, there are heating elements inside the probes. The effect of the heating element is 72 Watt. These proved to be insufficient in preventing icing under extreme conditions in the areas where the ice scale system was used. Additional heating elements of 90 Watt were attached externally to the sensor housing, with the same result.

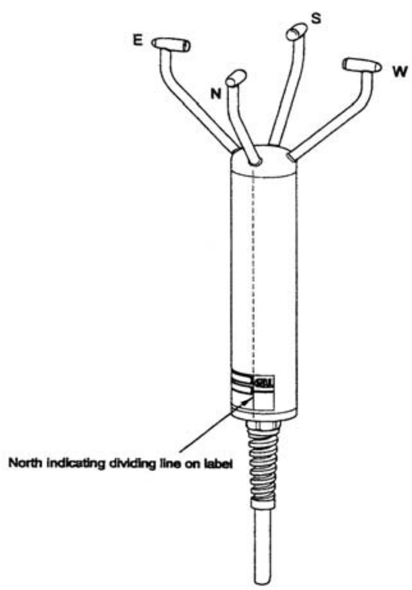

Figure 2.2 Gill wind sensor.

Data logger

The data logging system consists of 3, optional 4, Opus 200i loggers produced by Lufft (Lufft Opus, 2000). The Opus 200i is a universal 2-channel data logger. Each input channel can be configured for either resistance, current, voltage, or frequency input. Several loggers may be connected in series via a CAN-bus to facilitate additional input channels. For an ice scale system, either 3 or 4 Opus 200is are required depending on horizontal forces are measured or not.

Each input can operate an actor output channel configured as either a switch or current loop signal. This feature is currently not used for the ice scale system, but could in the future be used to control a de-icer when a certain weight is reached.

The data logger sampling interval can be set individually for each input channel, but the periods are limited to 0.1 s, 1 s, 10 s, 30 s, and 60 s.
Storage intervals are also individually selectable, but limited to 0.1 s, 1 s, 10 s, 30 s, and 1 minute to 1440 minutes. Stored values can be either average, minimum, or maximum values, or any combination.
Data is stored in the internal memory which has a capacity of 30000 values for each logger.

Programming and data retrieval is accomplished via a computer with a program called SmartControl 1.0 connected to the data logger serial connector. By connecting a modem to the serial connector remote data download is possible via either telephone line or GSM mobile net.

The configuration of the Opus data loggers for the ice scale system is outlined in Table 2.2.

Table 2.2 Configuration of the Opus 200i data loggers in the ice scale system.

Parameter	**Input**	**Sampling int.**	**Storage int.**	**Storage option**
Temperature	current 4 to 20 mA	1 s	10 min	mean
Relative humidity	current 4 to 20 mA	1 s	10 min	mean
Wind speed	current 4 to 20 mA	1 s	10 min	mean
Wind direction	current 4 to 20 mA	1 s	10 min	mean
Battery voltage	current 4 to 20 mA	1 s	10 min	mean & max
Ice weight	voltage 0 to 20 mV	1 s	10 min	mean & max
Horizontal force, x-direction	voltage -40 to 40 mV	1 s	10 min	mean & max
Horizontal force, y-direction	voltage - 40 to 40 mV	1 s	10 min	mean & max

Power supply and converter units

The ice scale system is designed for operation from mains power supply. Several units have a power consumption that makes battery operation difficult. Heating of the wind sensor is especially power consuming. The power converters are included to ensure that the different units are supplied with adequate voltages.

3. The ice scale

The construction of the ice scale is based on the recommendations from ISO 12494. The ice scale consists of a vertical steel rod with a length of one meter exposed to atmospheric icing (figure 3.1).

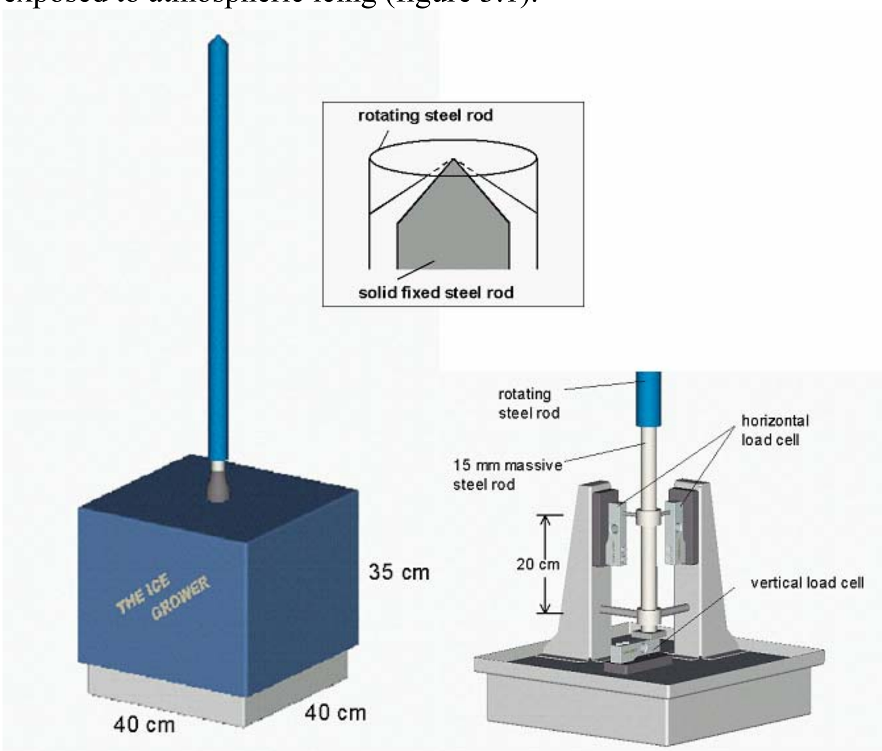

Figure 3.1 Ice scale

Three load cells, Global Weighing Technologies type MP41/12C3, are placed inside the box to record all reactions on the steel rod. One load cell is located on the floor of the box, recording the vertical load. Two load cells are placed perpendicular to each other on the walls of the box, recording horizontal load and load direction. The solid fixed steel rod which stands on the vertical load cell has a total length of 1.35 m and a diameter of 15 mm. The rod can freely be displaced in the vertical direction, but is fastened to the wall to prevent displacements in the horizontal directions. The horizontal load cells are placed 20 cm up the shaft of the solid steel rod. This rod passes through the top of the box through a 30 mm diameter hole. The rod is formed with a sharp pointed top. For the recording of ice loads on a stationary construction, a non rotating cylinder should be used for reference measurements according to the ISO 12494 standard.

For standard reference measurements, a 30 mm diameter hollow steel rod is fed over the outside of the solid rod. Within in the top of the hollow rod is a cone enclosure which allows the rod to rotate smoothly, see Figure 3.1. Further a cylindrical enclosure at the bottom of the rotating rod prevents horizontal displacement. During episodes of icing the rod rotates due to the mechanical forces of ice and wind action. Free rotation means the rod will turn until minimum drag is achieved. The angle where minimum drag is achieved therefore experiences an increase in wind drag around it. Several field observations of icing on the cylinder confirm this theory, showing a cylindrical ice accretion on the cylinder (figure 3.2).

Testing the vertical load (ice weight)

To test the vertical load cell a mechanical collar was constructed. This was attached to the lower part of the vertical steel rod. One or more high precision calibrated loads were placed on this collar to load the vertical load cell, see Figure 3.3. The testing was performed in an indoor laboratory at a temperature of approximately 21 °C.
Output from the load cell is a function of applied load and the supply voltage to the load cell. The load cell was therefore powered by a laboratory power supply (Iso-Tech model IPS 2303DD) at several different voltages. Output from the load cell was measured by a digital voltmeter (Keithley 196 system DMM).

Figure 3.2. Ice scale with rotating 30 mm cylinder after icing incident at 1800 m a.s.l. at Mt. Gaustatoppen, 0925hrs April 2, 2003.

Several measurements at each load and supply voltage were done to minimize errors. The average values are presented in Table 3.1. Figures in the left column are the weights of the free weights used. The steel rod, cylinder, collar, and hinges are partly measured and partly calculated to a total weight of 7.07 kg.

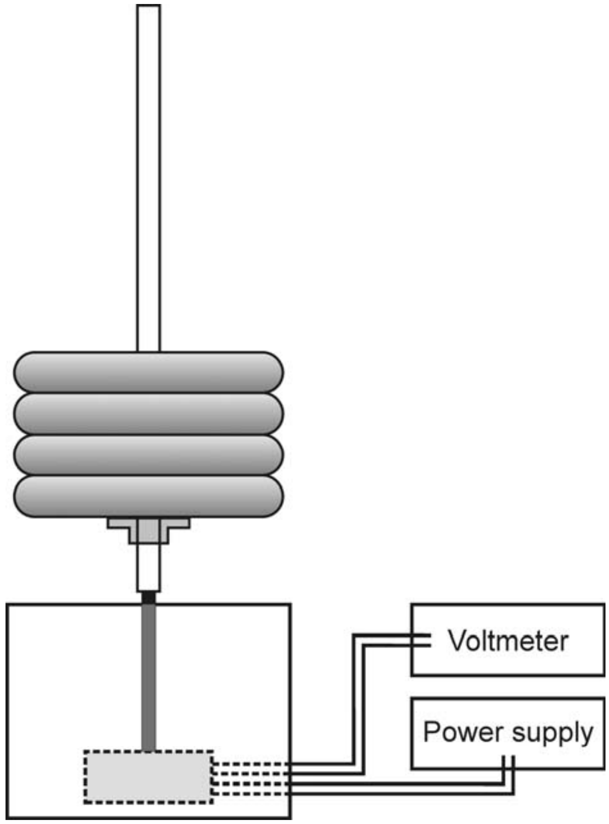

Figure 3.3 Testing the Ice scale, vertical load.

Table 3.1 Measured output signal [mV] as function of load for different supply voltages.

Weight [kg]	**V_S = 12.00 V**	**V_S = 13.00 V**	**V_S = 14.00 V**	**V_S = 15.00 V**
0	0.1831	0.1935	0.2005	0.2103
Rod, cyl., collar	1.9100	2.0521	2.2031	2.3655
10 kg	4.3597	4.6988	5.0412	5.4326
15 kg	5.5850	6.0174	6.4793	6.9648
25 kg	8.0398	8.6642	9.3246	10.0326
40 kg	11.7160	12.6642	13.5816	14.6153
50 kg	14.1686	15.3205	16.4278	17.6651
60 kg	16.6180	17.9597	19.2746	20.7231
75 kg	20.2898	21.9388	23.5116	25.2929
90 kg	23.9279	25.8960	27.7359	29.8818
100 kg	26.3676	28.5188	30.5346	32.8369

Conducting a linear regression of the measured data results in the coefficients for four lines. One line for each supply voltage. These lines were used to estimate the mass of the rod, cylinder, collar, and hinges. The results were 7.10, 7.03, 7.15, and 7.16 kg respectively, giving an average of 7.11 kg while the measured weight was 7.07 kg. Figure 3.4 shows a plot of the measurements, while Figure 3.5 shows the measurements deviation from the straight line.

From these results we can calculate the calibration coefficient (named Rated Output in the data sheet) for each measurement. These are summarized in Table 3.2. Average coefficient is 2.0358 [mV/V] with a standard deviation of 0.0052.

Table 3.2 Calibration coefficients [mV/V] calculated for different loads and supply voltages

Weight [kg]	**V_S = 12.00 V**	**V_S = 13.00 V**	**V_S = 14.00 V**	**V_S = 15.00 V**
10 kg	2.0390	2.0302	2.0256	2.0396
15 kg	2.0397	2.0299	2.0321	2.0403
25 kg	2.0415	2.0318	2.0322	2.0418
40 kg	2.0418	2.0380	2.0306	2.0402
50 kg	2.0422	2.0389	2.0310	2.0390
60 kg	2.0420	2.0376	2.0314	2.0389
75 kg	2.0416	2.0382	2.0288	2.0375
90 kg	2.0385	2.0368	2.0262	2.0378
100 kg	2.0380	2.0350	2.0236	2.0315
Average	2.0405	2.0352	2.0291	2.0385
Standard dev.	0.0017	0.0036	0.0032	0.0029

The operating range of the load cell is 0 to 100 kg. However, the mass of the rod, cylinder and collar is 7.07 kg, which means that values of more than 93 kg, as shown in figure 3.5, are outside the specified range of the load cell. In the laboratory all tests within the specified range had a maximum error of ± 0.125 kg.

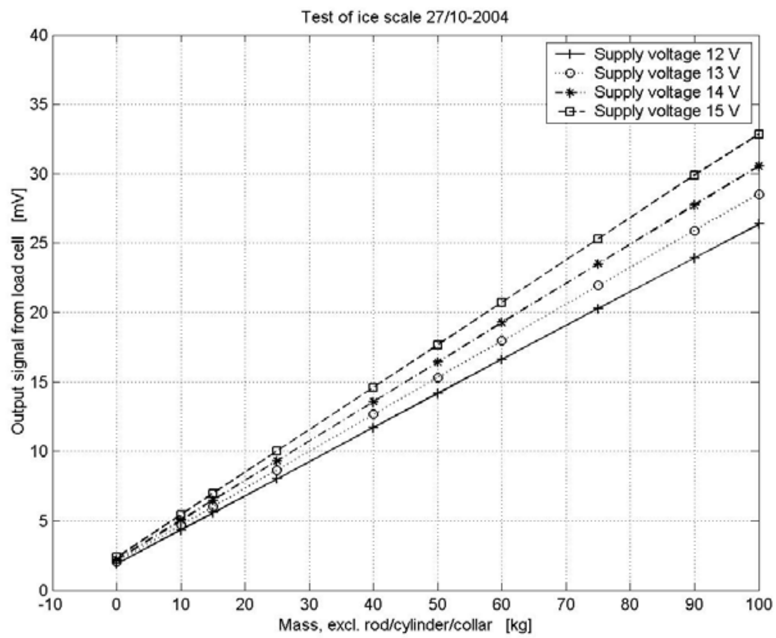

Figure 3.4 Measured output signal as a function of applied load (exclusive rod, cylinder, and collar) for different supply voltages.

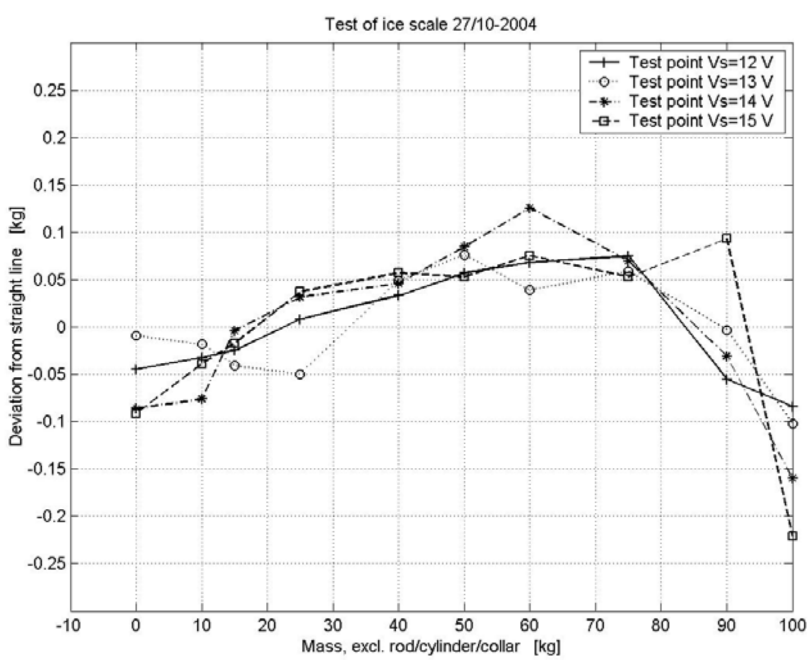

Figure 3.5 Test values deviation from linear fit.

To verify this, data from Brosviksåta between March 9 and June 6, 2004 was examined. In this period, the ice scale was fitted with a fixed cylinder of diameter 14 cm. The total mass of the rod, cylinder etc was measured to be 19.5 kg.

Within this period, data was extracted when the air temperature was above 2.0 °C. This was done to ensure that there was no ice on the ice scale. The mean output from the ice scale was calculated to be 19.509 kg with a standard deviation of 0.027 kg. Maximum output from these data was 19.584 kg and minimum output was 19.391 kg. The extracted data set consisted of 5572 10 minutes average values.

Testing the horizontal forces

Testing of the horizontal forces was done according to Figure 3.6, and as described below.

A rope was fastened to the massive steel rod at four different heights. The rope was led via a low friction wheel at a right angle to a free hanging load with a mass of 10 kg. The load was connected at different heights along the rod and the rope was, at all times, ensured to be perpendicular to the rod. It was thereby possible to simulate different horizontal forces to the load cell. Rotating the ice weight allowed all four axes to be tested (x-direction, y-direction, press and strain).

Applied force to the horizontal load cells was calculated by mechanical momentum equations. Output signal from the load cell and supply voltage was recorded. It was noted that for the horizontal forces there was a substantial hysteresis in the output signal. This was most likely caused by the mechanical construction of the ice scale and bending of the rod. Based on these observations, it was decided that two recordings would be made for each applied force. One from increasing loads and one from decreasing loads. This was supposed to be an indication of the 'worst case' values, giving a value of the uncertainty of the measurement of the horizontal forces. Refer to Table 3.3 for measured data. Note that the distance indicated in the left column is from the top of the rod.

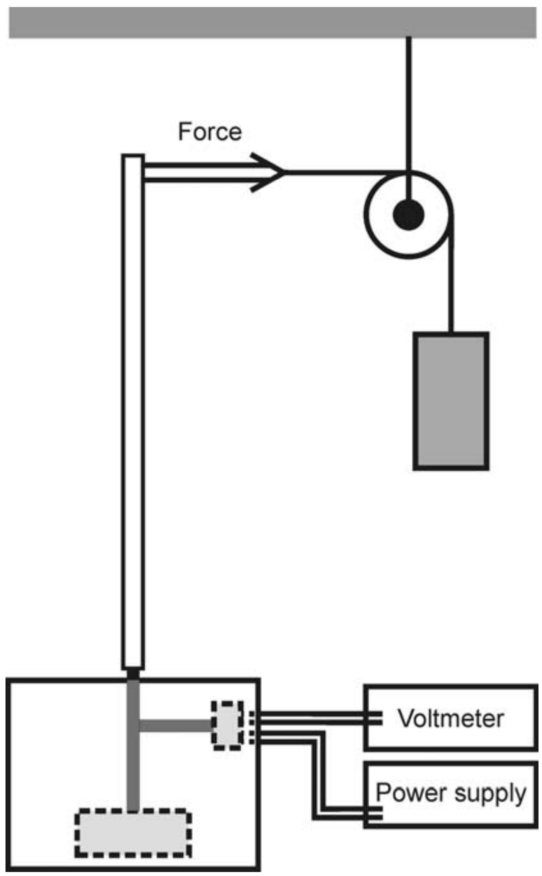

Figure 3.6 Testing the Ice scale, horizontal forces.

Table 3.3 Measured output signal [mV] as a function of applied force. Supply voltage is 12V.

Distance from top [cm]	**X-dir.**				**Y-dir.**			
	Press, incr.	**Press, decreas.**	**Strain, incr.**	**Strain, decreas.**	**Press, incr.**	**Press, dcreas.**	**Strain, Incr.**	**Strain, dcreas.**
100	3.57	3.77	3.50	3.63	3.45	3.75	3.52	3.76
75	6.29	6.76	6.22	6.51	6.33	6.80	6.26	6.68
50	9.11	9.67	9.02	9.67	9.20	9.91	9.15	9.70
25	11.96	12.58	11.79	12.69	12.13	12.52	11.97	12.56

For the x-direction, the data is plotted in Figure 3.7. Four lines in the plot indicate the data listed in Table 3.3. The fifth line is a linear fit of all these data. The deviation of the measured data with respect to the linear fit is plotted in Figure 3.8. The deviation is recalculated to force/gravity. Corresponding data for the y-direction is plotted in figure 3.9 and 3.10. In just the same way as for the vertical load cells, these data can then be used to calculate the calibration coefficients (RO) for the horizontal load cells. This is indicated in Table 3.4. Average RO for the x-direction is 1.951 [mV/V], standard deviation is 0.063. For the y-direction corresponding values are 1.961 [mV/V] and 0.068.

Table 3.4 Calibration coefficients [mV/V] calculated for different loads.

Distance from top [cm]	**X-dir.**				**Y-dir.**			
	Press, incr.	**Press, decreas.**	**Strain, incr.**	**Strain, decreas.**	**Press, incr.**	**Press, dcreas.**	**Strain, Incr.**	**Strain, dcreas.**
100	1.894	1.987	1.863	2.005	1.916	1.978	1.891	1.984
75	1.942	2.002	1.867	2.002	1.905	2.052	1.894	2.008
50	1.889	2.030	1.868	1.955	1.901	2.042	1.880	2.006
25	1.951	2.060	1.913	1.984	1.885	2.049	1.923	2.055

All these tests were conducted in an indoor laboratory at room temperature around 21 °C. The supply voltage was 12.0 V.
Tests with different supply voltages (12.0 V, 13.0 V, 14.0 V, and 15.0 V) for applied force at one height and different angles (x- and y-direction) showed that the error from variable voltage was negligible.

From Figures 3.8 and 3.10, it can be seen that the deviation in the data for the horizontal force is one order of magnitude greater than that of the vertical load. As the three load cells are of the same type, the deviation is believed to be due to the mechanical construction of the ice scale and the bending of the rod.

According to the datasheet, the load cells are temperature compensated in the range -10 to +40 °C. No facilities were available to test this.

To be able to compensate for varying supply voltage, a voltmeter was included inside the box of the ice scale. Output from this voltmeter was a current 4 to 20 mA, representing a voltage 0 to 15 V. This current was logged by the logging system, thus allowing voltage variations to be compensated for.

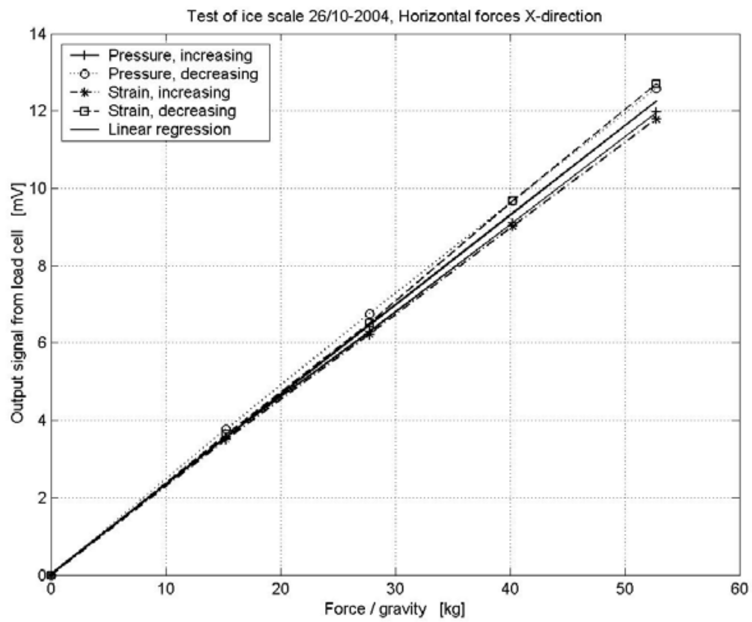

Figure 3.7 Measured output signal from x-direction horizontal load cell for different forces.

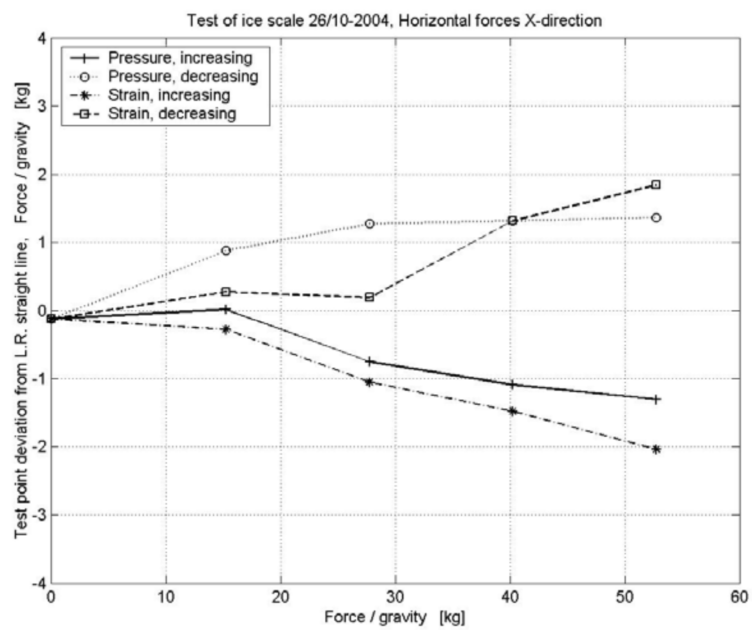

Figure 3.8 Deviation from linear fit.

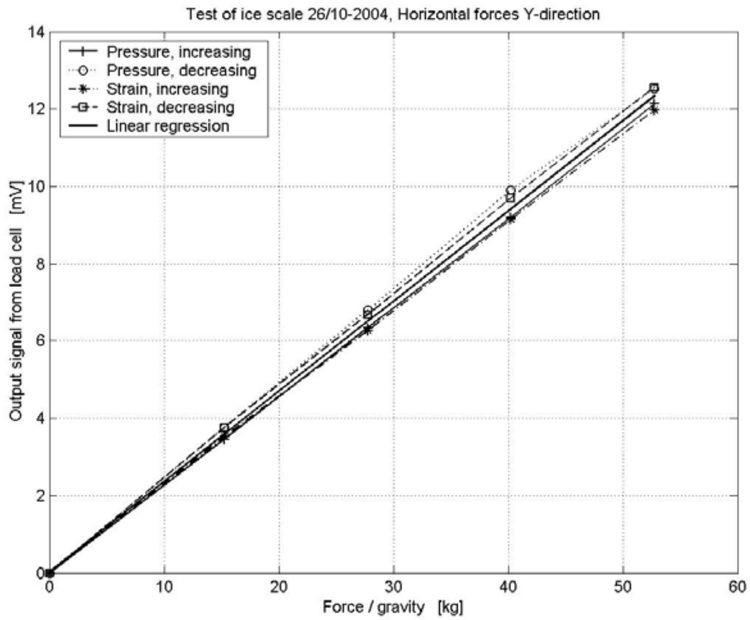

Figure 3.9 Measured output signal from y-direction horizontal load cell for different forces.

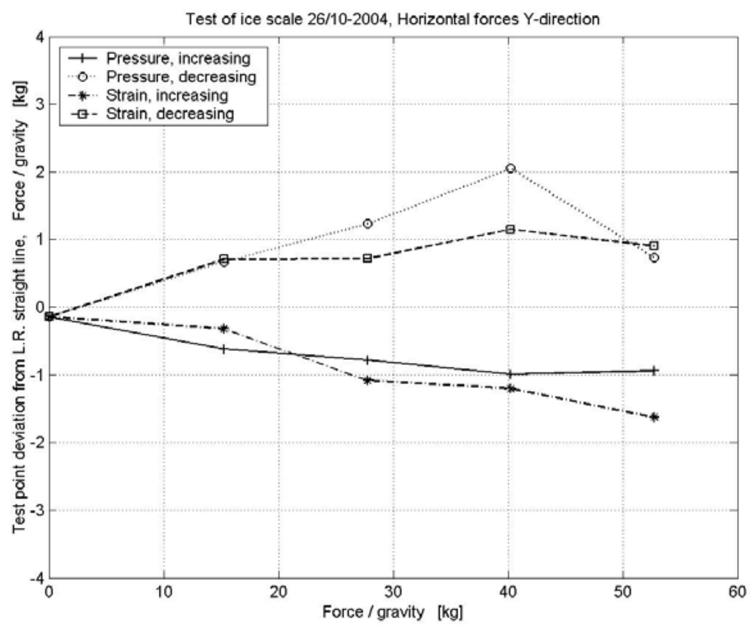

Figure 3.10 Deviation from linear fit.

4. Application of the Ice scale system.

An ice scale system was installed on top of a building on mount Brosviksåta (723 m) on the western coast of Norway. This was run during the 2002/2003 winter, using a 14 cm cylinder on the ice scale. The period from March 20 until March 25, 2003 was selected to illustrate the features of the ice scale system. Data from this period is plotted in Figure 4.1.

On the morning of March 20, the wind direction turned from north-east to south. This was accompanied by decreasing temperature and increasing relative humidity. From noon on March 21, ice accretion started to build up on the cylinder, reaching a maximum of 4.5 kg in the morning of March 23. The weight indicated in Figure 4.1 is the net weight of the accreted ice only. These data are further described in Drage and Hauge (2004).

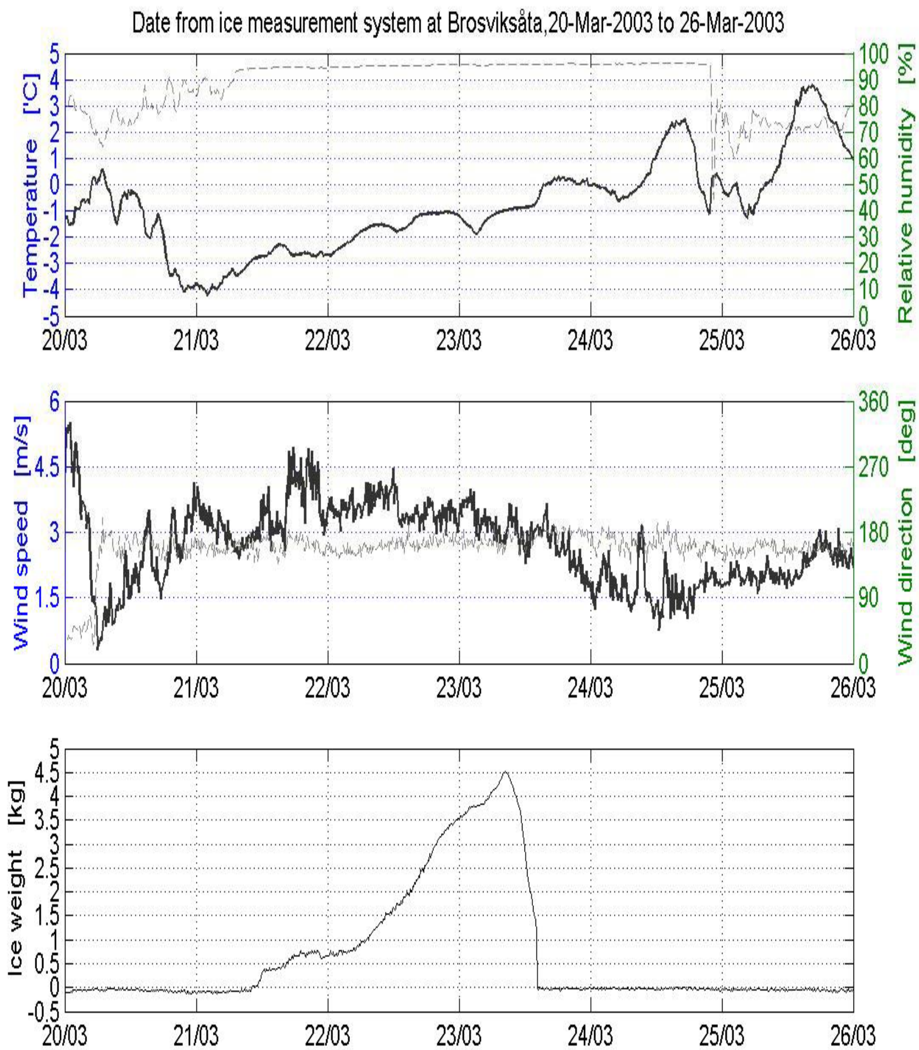

Figure 4.1 Data from Ice scale system from Brosviksåta March 20 to 26, 2003.

5. Conclusion

A total of three prototype ice scales and two complete systems have been built. They have been run for, all together, 34 months at different locations, both in mountainous regions in southern Norway and a coastal area in the north of the country. The ice scale systems have proved to provide useful and reliable data for testing and verifying icing models.

The mass of the ice scale from the field measurements, with no load, was calculated to be 19.509 kg. This showed a deviation of 0.009 kg from what was measured in the laboratory. The standard deviation, as calculated in the laboratory, was 0.027 kg.

For horizontal force tests of the ice scale indicated that ice weight can be measured with an absolute accuracy of approximately 0.125 kg.

The mean output from tests in the laboratory suggests an absolute accuracy between 20 N and 500 N for a horizontal force.

Based on these experiences, a few improvements can be suggested. The ice scale itself is quite heavy, approximately 60 kg. It should be possible to construct a box with sufficient strength and a substantially lower weight. It could be useful to add a de-icer to the ice scale. This could be controlled by the data logger and all ice should be removed when a certain weight is reached. In severe icing conditions, the de-icer attached to the wind sensors have proved inadequate. A different wind sensor or better de-icer should be considered. Choosing a data logger with more inputs would eliminate the need for three or four smaller loggers, thus simplifying the system.

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