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Meteorologisch Instituut
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De Bilt, December 2010 – June 2011

Marijn de Haij

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KNMI, R&D Information and Observation Technology

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1 Introduction

1.1 Background

Since the automation of the meteorological observation network in the Netherlands in 2002, snow depth was not included anymore in the set of in-situ observations used for synoptic and climatological purposes. At present, the Royal Netherlands Meteorological Institute (KNMI) collects snow depth data only on a daily basis, using a network of around 325 voluntary precipitation observers. The lack of snow depth information in the international bulletins issued by KNMI has been recognized as a serious problem. The European Centre for Medium-Range Weather Forecasts (ECMWF) model, for example, relies almost exclusively on in-situ snow depth information that is routinely available via the Global Telecommunication System (GTS). Recent snowfall events in the Netherlands have demonstrated that large errors in the ECMWF 2 m temperature forecast were caused by errors in the snow analysis over Europe (ECMWF, 2010). In addition to this international need, also on a national scale there is an increasing demand for real-time and continuous snow depth information over the Netherlands, e.g. for the evaluation of weather alerts issued for heavy snowfall.

Although automated measurement techniques exist, the low frequency of occurrence and the limited depth and life time of a closed snow deck in the Netherlands form a serious obstacle in the developments towards automation. In view of the snow cover climatology calculated for the period 1961-1990 (Klein Tank, 1997), a closed snow deck occurs only 11 days a year on average. In addition, total snow depth exceeds 5, 10 and 20 cm for only 4.2, 1.5 and 0.1 days per year, respectively. A suitable snow depth sensor should therefore provide accurate measurements of the onset of snow cover and the first centimeters of snow. A recent inventory of commercially available snow depth sensors (De Haij, 2007), which were at that time all using an acoustic measurement principle, did not result in suitable candidates. The new Jenoptik SHM30 laser snow depth sensor, introduced in 2008, seems to overcome the problems that can be expected with sonic rangers under typical Dutch snow cover conditions. First reports of experiences with this sensor by National Meteorological and Hydrological Services (NMHSs) in Europe show largely positive results (e.g. Lanzinger et al., 2010a).

Supported by these positive experiences, KNMI has evaluated the Jenoptik SHM30 laser snow depth sensor in De Bilt from 16 December 2010 to 30 June 2011. The aim of this test was to get experience with the sensor in Dutch conditions and investigate whether the SHM30 is a suitable candidate for automated snow depth observations in the meteorological observation network. This report describes the results from the test and provides recommendations for further actions.

1.2 Automatic techniques for snow depth measurement

Traditionally, manual measurements of the total snow depth are made using a graduated ruler, which is pushed down through the snow layer to the ground surface. This is still common practice in the voluntary observation network of KNMI, where daily snow deck information is provided every day at 08 UTC in the period 1 October-1 May. In countries where human observers are still employed at the weather stations in the observation network, manual snow depth measurements are at best issued every hour in SYNOP reports.

During the past decade, more and more countries started to automate the snow depth measurement using acoustic distance sensors. An acoustic snow depth sensor (or: sonic ranger) measures the time interval between transmission and reception of an ultrasonic pulse. This measurement is used to determine the distance between the sensor and the surface. Examples of sensors that are widely used by NMHSs are the Campbell Scientific SR50A and Sommer USH-8. Most important drawback of the acoustic snow depth measurement technique is the dependency on air temperature, required to correct for variations of the speed of sound in air. Furthermore, data outages occur due to precipitation passing through the measurement cone. The cone normally has an angle of aperture in the order of 10 to 30**°**. The measurement uncertainty of sonic rangers is 0.5-1% of the distance, which leads under typical conditions to a measurement uncertainty for snow depth in the order of 1 cm.

Laser sensors for snow depth measurement were only introduced a few years ago and have already been under test and in operational use by various NMHSs in Europe (Lanzinger et al., 2010a; Mair et al., 2010; Zanghi, 2010). The SHM30, manufactured by Jenoptik GmbH from Jena in Germany, was the first commercially available laser snow depth sensor on the market. The sensor uses an optoelectronic distance measurement principle to achieve a specified measurement uncertainty of better than 5 mm. A promising feature is the signal strength output of the SHM30, which can possible be used to detect the first few millimeters of snow. In view of these specifications it seems that the laser technique offers interesting capabilities for countries where snow decks are generally shallow. Apart from the laser distance sensors, also other optical techniques are in use, for example in the SOLIA sensor used by Météo France for combined measurements of state of ground and snow depth (Zanghi, 2010).

An important drawback of all in-situ techniques used for the observation of snow depth is the lack of spatial representativeness. In fact, a point measurement with a limited field of view is performed by sensors, whereas an observer is also able to average multiple measurements in uneven snow cover and provide information about the state of the snow deck, i.e. whether it is closed or broken. In spite of this disadvantage, automated snow depth measurement techniques offer more objective results which can be made available continuously and in near real-time. This is in contrast with observations reported by a human observer at synoptic stations, where the measurement interval is generally one hour or in some cases even six hours.

1.3 Requirements

According to WMO guidelines (WMO, 2008), snow depth is defined as the total depth of snow on the ground at the time of observation. The snow depth should be measured and reported over a range of 0-25 m with a resolution of 1 cm. The required measurement uncertainty is 1 cm for depths ≤ 20 cm and 5% above 20 cm. It should be noted that no clear definition exists of the area for which the measurement should be representative.

As for the international exchange of snow depth data, the total snow depth parameter is included in BUFR descriptor 0 13 013, which provides the reporting of the measurement in m with a 0.01 m resolution. Provision is made to report so-called "little snow depth", indicating values smaller than 0.5 cm (value set to -0.01) or non-continuous snow cover (value set to -0.02). Meta data related to the snow depth measurement are issued through BUFR descriptor 0 02 177. At present only manual, acoustic and video camera techniques can be chosen. Recently it has been proposed to include also code figures for laser sensors and other optical snow detectors, as well as for the description of the target surface, like ground/grass, gravel or white PVC.

2 Field test setup

2.1 Test site De Bilt

The Jenoptik SHM30 sensor was installed at the test site (Figure 1) near the KNMI premises in De Bilt (52º 06’N 05º 11’E) on 16 December 2010. The sensor was mounted on a mast pole at a height of 2 m above grass and pointing in east-south-easterly direction (105**°**). The inclination angle was 20° off vertical. Using an angle between 10 and 30° is recommended by the manufacturer to prevent icicles and droplets from affecting the measurement surface. A small area below the sensor was marked by cordon tape to prevent people from walking on the target surface. As the SHM30 performs a distance measurement, it is of crucial importance that the snow deck probed by the sensor remains untouched.

The snow depth sensor was closely collocated with the automatic weather station for test purposes in De Bilt (06261), at which a variety of meteorological variables is reported that can be used in the evaluation of new sensors. Amongst these variables are for example the precipitation type and accumulation observed by a Vaisala FD12P present weather sensor. Furthermore, three disdrometer sensors that are evaluated for possible improvement of automated precipitation type discrimination (De Haij et al., 2010) were present in a field setup very close to the snow depth sensor. This setup included a Thies Laser Precipitation Monitor, an Ott Parsivel and a Lufft Radar Rain Sensor (R2S), installed at 1.5 to 2 m above the surface and providing precipitation intensity and type every minute. The distance between the Parsivel and the SHM30 sensor (cf. Figure 1) was approximately 5 m.

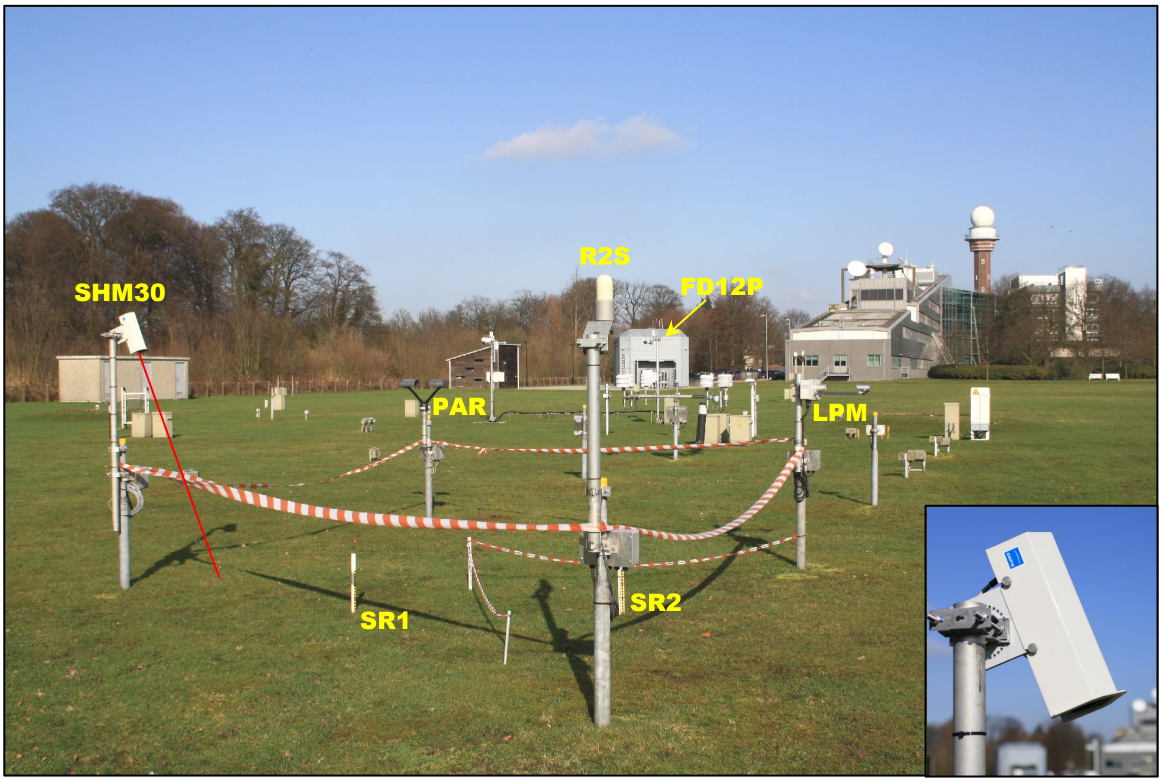

Figure 1. The KNMI test site in De Bilt, with the secured area for snow depth measurements in the foreground. Indicated are the position of the Jenoptik SHM30, Ott PARsivel, Thies LPM, Lufft R2S, two graduated snow rulers (SR1 and SR2) and the Vaisala FD12P in the background. The inset shows the SHM30 sensor.

To obtain a reliable reference observation for snow depth during the field test, several additional measurements were collected. Firstly, two snow rulers (indicated by 'SR1' and 'SR2' in Figure 1) were erected close to the measurement spot of the SHM30 sensor. The snow depth could be visually inferred from these rulers by using automatically generated snapshots from an AXIS214 PTZ network camera, installed approximately 10 m from the snow depth test area. Secondly, observations from a voluntary observer close to the test site were used. Thirdly, a number of incidental manual readings were made at the test site itself with a standard KNMI snow ruler.

No maintenance was performed on the SHM30 sensor during the field test. The conditions of the test site only changed due to regular cutting of the grass, performed every 2-3 weeks during the growing season. Monitoring of the field test took place in near real-time; quicklooks of the sensor measurements were produced, providing e.g. the actual snow depth, signal strength and disdrometer precipitation type and accumulation. Moreover, 10-minute camera images of the test site and the two snow rulers were presented.

2.2 *Jenoptik SHM30 sensor*

The SHM30 snow depth sensor (Jenoptik, 2010) uses an optoelectronic measurement principle to perform an accurate distance measurement. The sensor contains a laser diode emitting eye-safe visible light at 650 nm. Reflected light is received and compared with the signal from a reference diode. A microprocessor calculates the phase shift and the distance to the target. Figure 2 shows a schematic representation of the measurement principle. Every 0.16 s a measurement with a single frequency is performed. Five modulation frequencies are used and measurements are averaged to obtain a more accurate measurement on critical targets, like snow. The SHM30 allows probing distances up to 15 m with a resolution of 1 mm. The measurement accuracy for the snow depth measurement is specified at better than 5 mm.

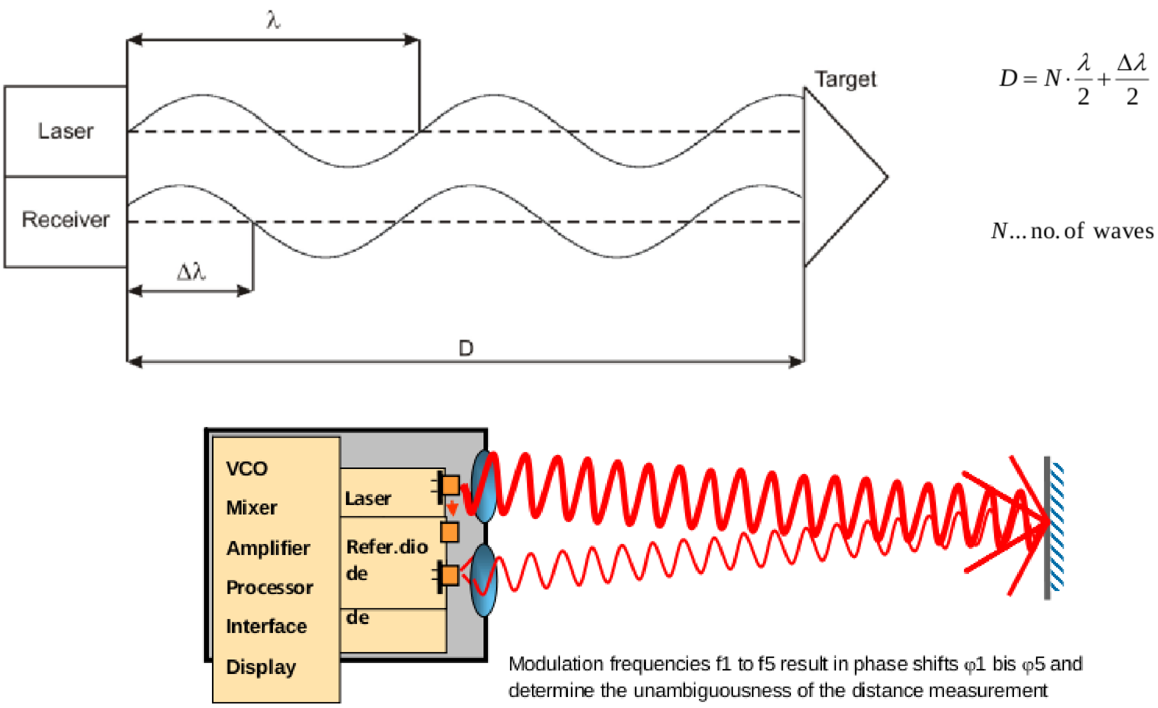

Figure 2. Illustration of the measurement principle used by the Jenoptik SHM30 laser snow depth sensor (Wille, 2011).

Divergence of the SHM30 laser beam amounts to 0.6 mrad, which implies that the beam diameter is 2-3 mm in size at 2 m distance. The light source in the SHM30 is classified as a Class 2 laser product. This means that it is safe only because the blink reflex of the human eye will limit the exposure to no more than 0.25 seconds.

Table 1. Specifications of the Jenoptik SHM30 sensor.

Laser		**Electrical**	
Laser class	650 nm laser diode, visible, laser class 2	Power consumption	0.5-1 W (w/o heating) <12 W (with heating)
Output power	< 1 mW	Power supply	15-24 VDC
Laser divergence	0.6 mrad	**Operating**	
Snow depth		Temperature range	-40 - +50°C
Range	0-15 m (0-50 ft)	Humidity range	0-100%
Measuring accuracy (95% statistical spread)	< ±5 mm	Heating activity	<0 °C, configurable
Time for measurement	6 s	**Dimensions/weight**	
Reporting interval	10-600 s, configurable	Dimensions	303x130x234 mm
Measured value resolution	1 mm	Weight	2.5kg (sensor) 0.7kg (mounting clamp)

The longest possible averaging interval of 6 seconds (ST25 setting) is used for snow depth measurement. This way, unwanted signals due to e.g. hits on falling snow particles will be filtered out. It is important to note that the general assumption of this distance measurement technique is that each change of the measured distance is attributed to an increase or decrease of the snow depth. Hence also leaves, animals or other objects obstructing the laser beam generate positive snow depth values. Optionally the SHM30 offers an online validation possibility of the snow depth measurement by means of the command *XM*. This validation is based on the maximum allowed difference between two consecutive measurements. However, this option was not used during the test because it might suppress the sensor output under difficult conditions.

The SHM30 sensor used during the field test operated under firmware version 9.04. It was delivered together with a test report of final inspection performed by the manufacturer (cf. Appendix A). An overview of most relevant technical specifications of the sensor is given in Table 1.

Data acquisition and processing

The RS422 output of the SHM30 was connected to a MOXA NPort 5650 serial device server which enabled serial communication with the sensor from within the KNMI LAN. The LabView acquisition tool “Read SHM30” (Figure 3) was deployed to perform the measurement sequence described below.

- The sensor is initialized to perform a snow depth measurement with 6 second averaging time (*XT10, ST25*) in polled mode (*SRN*).
- The measurement is started by the command *XM*.
- After 8 seconds, the output of the sensor is acquired (*XW*) and stored together with the time stamp of the acquisition PC.
- Each data telegram contains snow depth, signal strength, internal temperature, error code and a check byte.
- After the snow depth measurement, the sensor is initialized in short averaging time mode by the commands *XT10*, *ST01* and *SRN*.
- The measurement is started again by *XM*.
- After 3 seconds, the output of the sensor is acquired (*XW*) and stored in a separate file, together with the time stamp.
- The ST01 measurements are repeated until 10 readings have been taken.
- After 10 measurements, the acquisition tool turns to “Idle” state and waits for a new minute to begin.

Figure 3. Snapshot of the acquisition tool in use during the field test.

Note that the measurements based on an averaging time of 6 seconds (XT10 ST25) are used throughout this report as the automatic snow depth measurement by the SHM30 sensor. The 1-second (XT10 ST01) measurements were additionally stored to study its capabilities for drifting snow detection.

Before the start of the field test, the distance offset (*SO* = -1.94014 m) and inclination angle (*SP* = 20°) were stored in the sensor settings. The distance offset was determined from a zero measurement above grass just after installation, whereas the inclination angle was simply adopted from the punched disk attached to the sensor (cf. Figure 1 inset). This disk has a resolution of 10°. Furthermore the default heating settings of the sensor were not changed. Hence the heating turned on automatically when the sensor temperature was below 3°C and turned off above 12°C.

Explanation of the data telegram
The 6-second (XT10 ST25) 1-second (XT10 ST01) data telegrams acquired from the sensor were stored separately in daily files. Below an example of the data records in these files is shown, together with a description of the individual elements. The error code reported by the sensor provides information on the status of the hardware and communications and on the quality of the signal/measurement (Jenoptik, 2010). An error code '00' means no warnings or errors.

```
20101219 06:24:09 XT10 ST25  >000.179 011.548  +4 00
|        |        |    |      |       |        |  |
date
         UTC time
                  XT setting
                       ST setting
                              snow depth (m)
                                      signal strength
                                               sensor temperature
                                                  error code
```

2.3 *AXIS 214PTZ camera (CAMERA)*

An AXIS 214 high performance color camera with pan, tilt and zoom (PTZ) functionality was installed at the test site in De Bilt in November 2010. The system can be accessed over the web from anywhere within the KNMI network and offers the opportunity to monitor the test site and some specific predefined locations remotely. The camera provides MPEG4 video steam or JPEG images with a resolution up to 704x576 pixels during day and night. It is mounted on a secured 2.5 m high mast located approximately 10 m from the laser snow depth sensor. Two examples of images acquired from the AXIS camera are presented in Figure 4.

Figure 4. Camera images of the snow depth testing area (left) and snow ruler SR2 (right) on 25 December at 10:00 UTC.

Images from the camera system were captured every minute between 2 and 22 December 2010. As from 22 December 2010, an automatic script produced three dedicated images of the snow depth test area on a 10-minute resolution. One overall image of the whole test area was stored together with close-ups of snow rulers SR1 and SR2 (cf. Figure 1). Both rulers consisted of white PVC pipes on which a yellow and black scale was fitted. This scale provided enough contrast to read the actual snow depth from the camera images, even under difficult circumstances. The range was 0-30 cm with a 1 cm resolution. An independent data validation specialist of KNMI evaluated 3-hourly images of snow ruler SR1 afterwards to construct time series of snow depth for the test period (Olminkhof, 2011). In this process, the SHM30 data were not consulted. The measurements inferred from the AXIS 214 images will be referred to from here as “CAMERA”.

2.4 Voluntary precipitation observer (OBS550)

KNMI operates a network of approximately 325 voluntary precipitation observers in the Netherlands. They provide manual readings of daily precipitation accumulation year-round by telephone. The measurements are automatically recorded by a voice response system. In case a snow deck is present, also the total depth of the snow deck measured with a graduated ruler is reported (cf. Figure 5). In accordance with WMO recommendations (WMO, 2008), multiple readings at the observation station are averaged to obtain a representative value. The resolution of the snow depth report is 1 cm. Coding conventions in use at KNMI also allow reports of a closed snow deck < 1 cm (code 997), a broken snow deck (code 998) and mounds of snow (code 999).

Snow deck information from the voluntary observer in De Bilt (station number N550, location 52º 06’N 05º 11’E) was used in this study as one of the data sources for intercomparison with the SHM30 sensor. The manual measurements were conducted near a farm located ±200 m south of the KNMI test site. Hereafter these measurements will be referred to as “OBS550”. Note that the special codes 997, 998 and 999 were not taken into account, because it was not possible to compare them with the snow depth measurement performed by SHM30.

2.5 Snow ruler measurements (RULER)

In addition to the camera images and the voluntary observer data, several manual measurements of snow depth were incidentally made at the test site using the standard KNMI snow ruler (cf. Figure 5) that is also used by the observers. These measurements were taken by the author or by the meteorologist on duty out of office hours. They will be indicated in this report as "RULER". Only a limited number of 14 snow depth measurements were conducted between 17 December 2010 and 3 January 2011. During five events a number of five readings close to the sensor location were performed to obtain information about the spatial homogeneity of the snow deck. In those cases the average of the individual readings was used for comparison with the sensor.

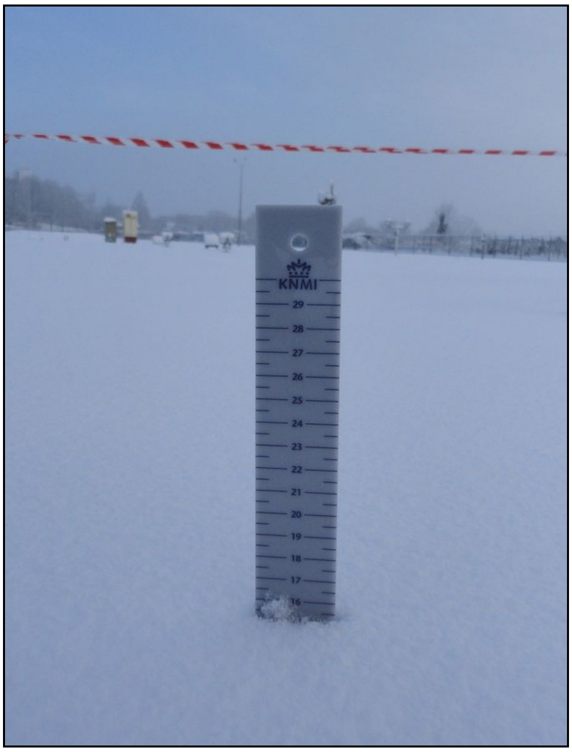

Figure 5. The graduated snow ruler used by the voluntary precipitation observers in the Netherlands. The range of the ruler is 0-30 cm with a resolution of 0.5 cm.

3 Results

3.1 General numbers

The six-month evaluation period of the SHM30 snow depth sensor at the test site started in early winter 2010-2011. From 16 December 2010 to 30 June 2011, 282903 1-minute data telegrams were acquired from the sensor. Overall the SHM30 performed very well; it did not show any malfunctioning nor did it require maintenance. Even during periods with heavy precipitation or insects no data outages occurred. Only five data records on 3 April contained an error code E15, indicating that the signal was too weak to perform a good measurement. The reason for these errors is unclear.

An overview of the 1-minute snow depth and signal strength measured by the SHM30 during the entire period of testing is presented in Figure 6. Already during the first month, snow depth values up to 18.8 cm were measured at the test site. This peak value was observed during a period of 15 days with a persistent snow deck that fully covered the surface between 16 December and 1 January and is discussed in more detail in Section 3.2. After New Year, the snow deck completely disappeared. Only one short snowfall event occurred some weeks later; on 23 February a maximum snow depth of 0.7 cm was observed by the SHM30. The lifetime of the snow deck was only 5 hours in that case.

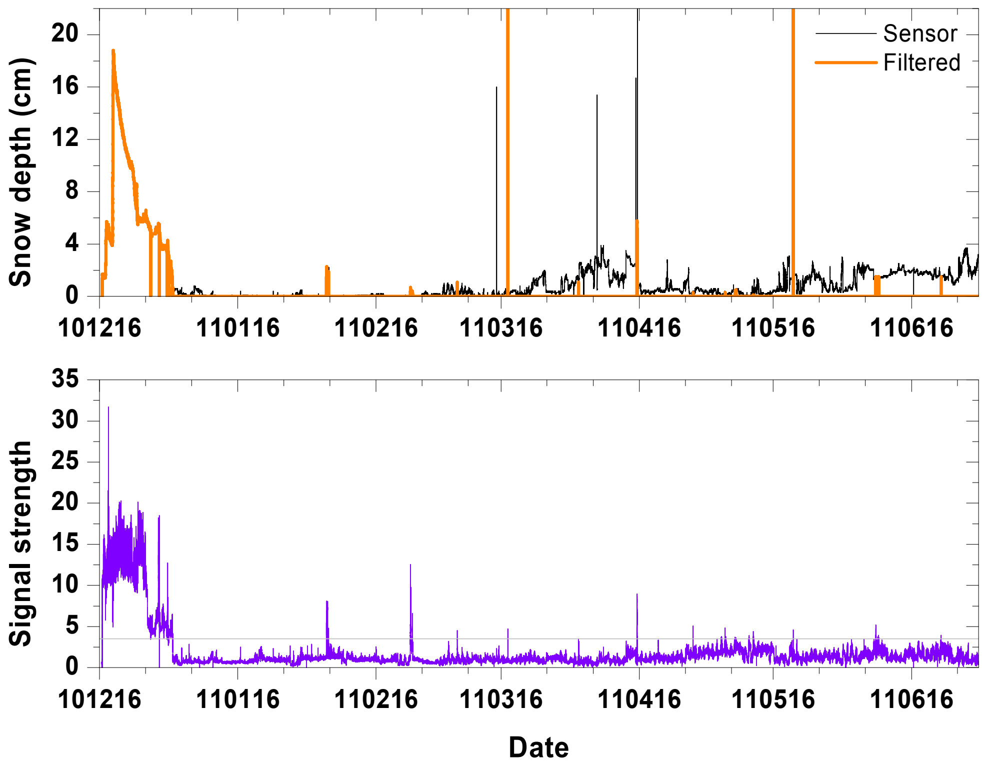

Figure 6. Snow depth (top) and signal strength (bottom) measurements by the SHM30 as a function of time between 16 December 13:00 and 1 July 00:00 UTC. The filtered snow depth is equal to the sensor snow depth only if the signal strength exceeds the threshold value of 3.5.

A broad spectrum of signal strength values is observed over the period of testing. As the light intensity reflected by the surface is stronger when the ground is covered with a layer of snow, highest values are observed during the first three weeks of the test. The grey line in the lower panel of the figure represents a signal value of 3.5, which is likely to be an appropriate threshold to distinguish between snow and grass. The filtered snow depth presented by the orange line depicts the measurement using this simple filtering criterion. After the winter period just a few peaks are observed where the signal strength is higher than 3.5 and hence a filtered value is reported. The contribution of these false alarms will be discussed in more detail in Section 3.4. The gradual increase of the sensor snow depth up to 3-4 cm starting in March is caused by the start of the growing season, leading to higher grass at the test site. It appears that the surface conditions play significant role in the signal strength output of the SHM30 sensor (cf. Section 3.5).

3.2 Comparison with manual observations

The major snow deck event at the end of 2010 provides sufficient data for a mutual comparison with the reference measurements collected during the field test. The top panel of Figure 7 shows the snow depth measurements reported by SHM30, CAMERA, OBS550 and RULER as a function of time for the period 16 December 2010-6 January 2011.

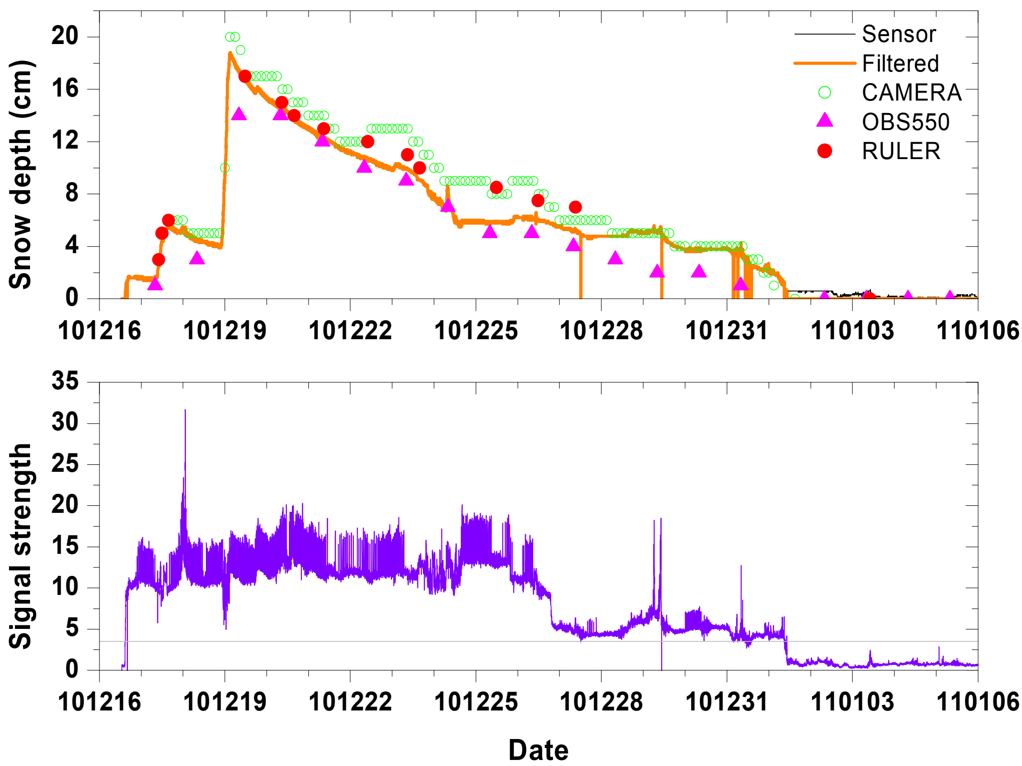

Figure 7. Automated and manual snow depth observations (top) and SHM30 signal strength (bottom) as a function of time between 16 December 2010 and 6 January 2011. An explanation of the manual snow depth observations is given in Sections 2.3-2.5.

The results show a good overall agreement when the evolution of this snow deck is considered. Snow depth values reported by both the automated and the manual methods follow each other closely. They increase as a result of snowfall events observed at the test site on 16 December (snow depth ±1.5 cm), 17 December (±6 cm), 18 December (±10 cm) and 19 December (±19 cm). It can be clearly observed in the figure that melting and compaction of the snow deck reduces the observed snow depth by 1 to 3 cm per day. Finally the snow cover disappears on 1 January. Starting 23 December, the agreement between the SHM30 sensor and manual methods becomes worse; the sensor value is 2-3 cm lower than the camera and ruler estimates. The cause of these larger differences is not clear, but it could be related in some way to the horizontal redistribution of snow on the ground due to strong winds at the test site in this period. On 24 December, 10 meter wind gusts up to 13 m/s were measured. Another interesting point to note is the sudden drop of the signal strength parameter from values around 10 to values around 5 on 26 December. This transition was observed during a drizzle/rain event at snow depth values of 5.7-6.0 cm. Although it is expected to be caused by a change in the surface conditions, the camera images do not give a satisfactory explanation. Nevertheless, signal strength records remain for the most part just above the threshold value.

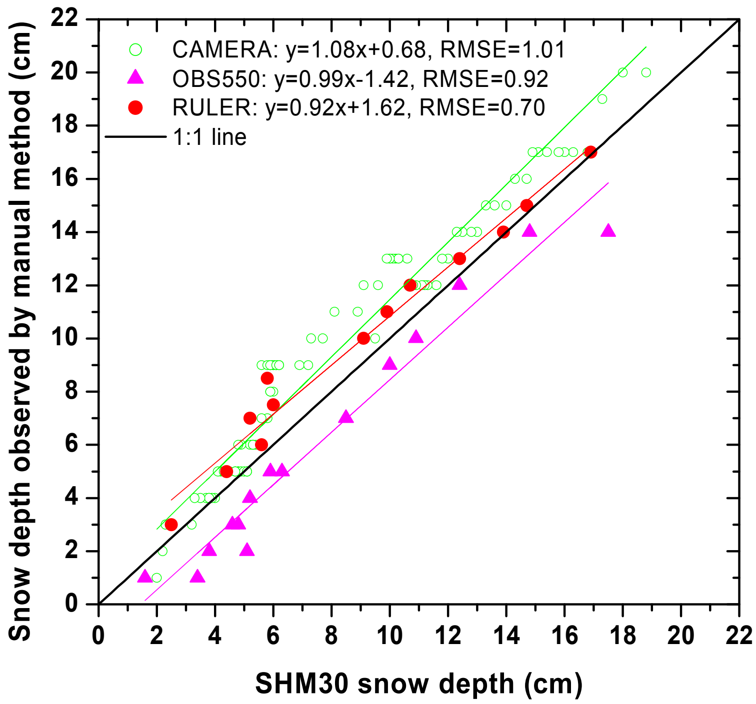

Figure 8. Scatter plot of coinciding SHM30 snow depth values with snow depth measured by the three manual methods: CAMERA (green, N=117), OBS550 (magenta, N=15) and RULER (red, N=13). The lines show the results of the linear fits and the Root Mean Squared Error (RMSE).

All coinciding manual and automated snow depth measurements are visualized together in the scatter plot in Figure 8. Three linear least squares fits have been conducted to quantify the agreement between the SHM30 and the reference methods. It should be noted that the number of measurements differs strongly from method to method due to timing aspects. The 117 snow depth values retrieved with the camera result in a linear fit $y = ax + b$ with coefficients a = 1.08 ± 0.02 and b = 0.68 ± 0.19 cm (RMSE=1.01 cm; R^2=0.95). In this fit the SHM30 snow depth is represented by x. For the voluntary observer and the ruler measurements, the coefficients obtained are a = 0.99 ± 0.05 and b = -1.42 ± 0.48 cm (RMSE=0.92 cm; R^2=0.96) and a = 0.92 ± 0.04 and b = 1.62 ± 0.45 cm (RMSE=0.70 cm; R^2=0.97), respectively. These values indicate generally a good agreement of the SHM30 measurements with all three manual methods used. Because the limited number of data points obtained during only one snow cover period, it was found not useful to analyze the snow depth differences in time or as function of snow depth itself. To conclude this subsection, Table 2 shows a few statistical results of the comparison with the manual readings. From left to right the first four columns list the average, minimum and maximum snow depth and the maximum difference in snow depth for all coinciding data points. Additionally the last two columns contain the average of the differences (bias) and the average of the absolute differences (precision) between the SHM30 and the manual methods. These numbers can be used as an indication of the measurement uncertainty. Depending on the reference used, this value amounts to 0.9-1.5 cm. Although <ΔSD> and <|ΔSD|> are equal in magnitude, a bias correction does not make sense.

Table 2. Statistics of the comparison between SHM30 and manual snow depth (SD) values. All values are given in cm.

	<SD>	**SD_{min}**	**SD_{max}**	**ΔSD_{max}**	**<ΔSD>**	**<|ΔSD|>**
CAMERA vs SHM30 (N=117)						
CAMERA	8.8	1	20	-	-	-
SHM30	7.5	2.0	18.8	-3.4	-1.3	1.3
OBS550 vs SHM30 (N=15)						
OBS550	6.1	1	14	-	-	-
SHM30	7.7	1.6	17.5	+3.5	+1.5	1.5
RULER vs SHM30 (N=13)						
RULER	9.9	3	17	-	-	-
SHM30	9.0	2.5	16.9	-2.7	-0.9	0.9

It should be noted that the representativeness of the snow depth measurement is not the same for all methods considered in this comparison. Inhomogeneities in the snow cover can only be accounted for by the RULER and OBS550 methods, as they usually contain multiple measurements that are averaged. The SHM30 and CAMERA methods perform purely a point measurement and are therefore not able to capture possible unevenness. To illustrate this point, during the five events where the snow ruler measurement (RULER) consisted of five individual readings at the test site, the difference between the minimum and maximum value was in the range 0.5-4.5 cm (not shown). Compared to these numbers the differences in Table 2 are relatively low.

3.3 Case studies

This subsection describes six days of the field test in more detail to illustrate the behavior of the SHM30 sensor under different circumstances. They are:

- 16 December 2010: From 0 to 1.5 cm on the first day
- 19 December 2010: Heavy snowfall resulting in a 19 cm snow deck
- 24 December 2010: Drifting snow event
- 1 January 2011: The end of a closed snow deck
- 23 February 2011: Light snowfall event
- 7 May 2011: False alarms in spring

16 December 2010: From 0 to 1.5 cm on the first day

The SHM30 sensor was installed at the test site in De Bilt on 16 December 2010 just before 13:00 UT. By accident this was just in time to take into account the start of a period with significant snowfall causing a closed snow deck until the beginning of 2011. The transition from liquid to solid precipitation between 14 and 15 UTC leading to the onset of this snow deck can be nicely observed in the bottom panel of Figure 9. It shows the 1-minute precipitation type reported by five present weather sensors in De Bilt, together with the precipitation accumulation observed on this day in the legend. The top panel contains the SHM30 measurements of snow depth (raw and filtered) and signal strength. Note the good snow depth measurements during precipitation.

According to the Thies optical disdrometer (LPM), which is the most sensitive present weather sensor at the test site, first snowfall occurred at 14:27 UTC. Subsequently the SHM30 laser sensor measured the first increase in snow depth of 0.2 cm already at 14:47. The corresponding signal strength value was 1.6. At 14:53, the first event was observed where the snow depth measurement passed the threshold signal strength (0.3 cm and signal strength 3.7). The first centimeter was exceeded at 15:19 (1.1 cm and signal strength 9.5). To illustrate the changes at the test site, two camera images before (13:00) and after (15:00) this snowfall event are presented in Figure 10. Around 20 UTC the snowfall ended and the snow depth reported by the SHM30 stabilized at 1.6-1.7 cm. Note that over the whole day the signal strength increases from values around 0.5 above natural grass to 10 above the closed snow deck. Again this emphasizes the ability to use the SHM30 signal strength for validation of the automated snow depth observation.

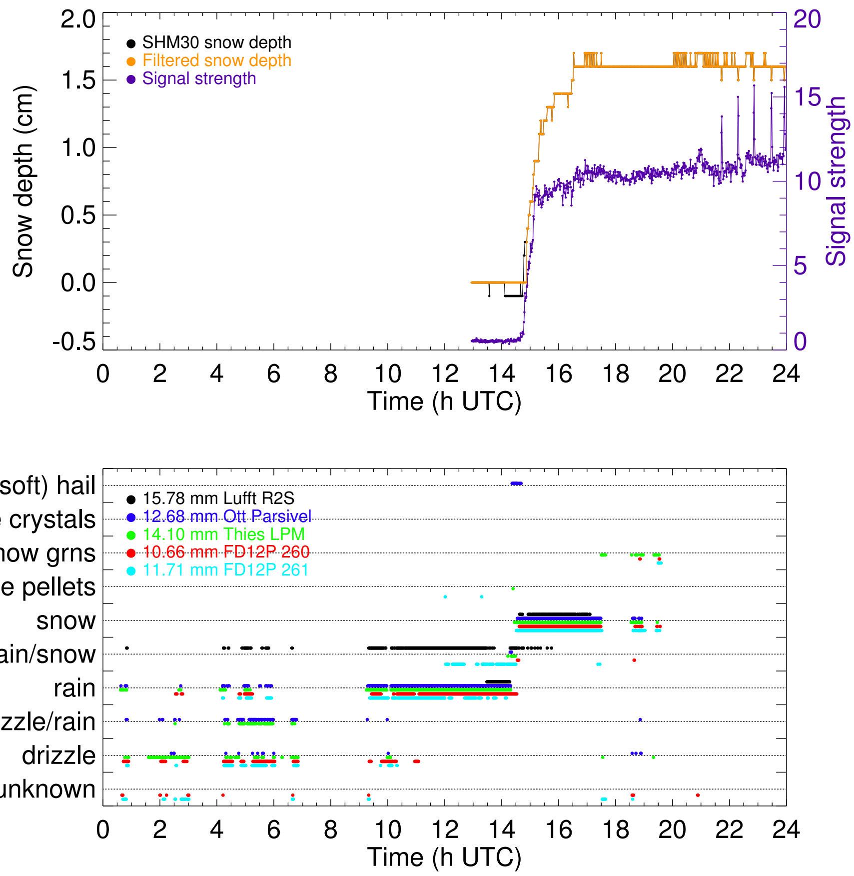

Figure 9. Time series of SHM30 snow depth and signal strength (top) and precipitation type (bottom) observed by present weather sensors at the test site on 16 December 2010. The daily (liquid equivalent) accumulation of precipitation reported by each of the PW sensors is indicated in the legend.

A remarkable feature in the top panel of Figure 9 is the spikes observed in signal strength during the late evening. This is a known issue of the sensor, caused by its heating operation. This introduces significant fluctuations in the sensor temperature (not shown), which on its turn generates spikes in the reported signal strength. Nevertheless the snow depth measurement is only slightly affected; deviations from the stable value in the order of ±1 mm are observed in the evening. The heating of the SHM30 in De Bilt was operated based on the default values of the parameters *HO* (heating on) below 3°C and *HF* (heating off) above 12°C.

Figure 10. Camera images of the snow depth test area in De Bilt on 16 December 13:00 (left) and 15:00 UTC (right).

19 December 2010: Heavy snowfall resulting in a 19 cm snow deck
A heavy snowfall event on 18 and 19 December significantly affected the snow deck at the test site and caused an increase of the snow depth towards a maximum value of 18.8 cm. This value was reached at 02:56 UTC. Snow depth data and precipitation type observed for 19 December is presented in Figure 11.

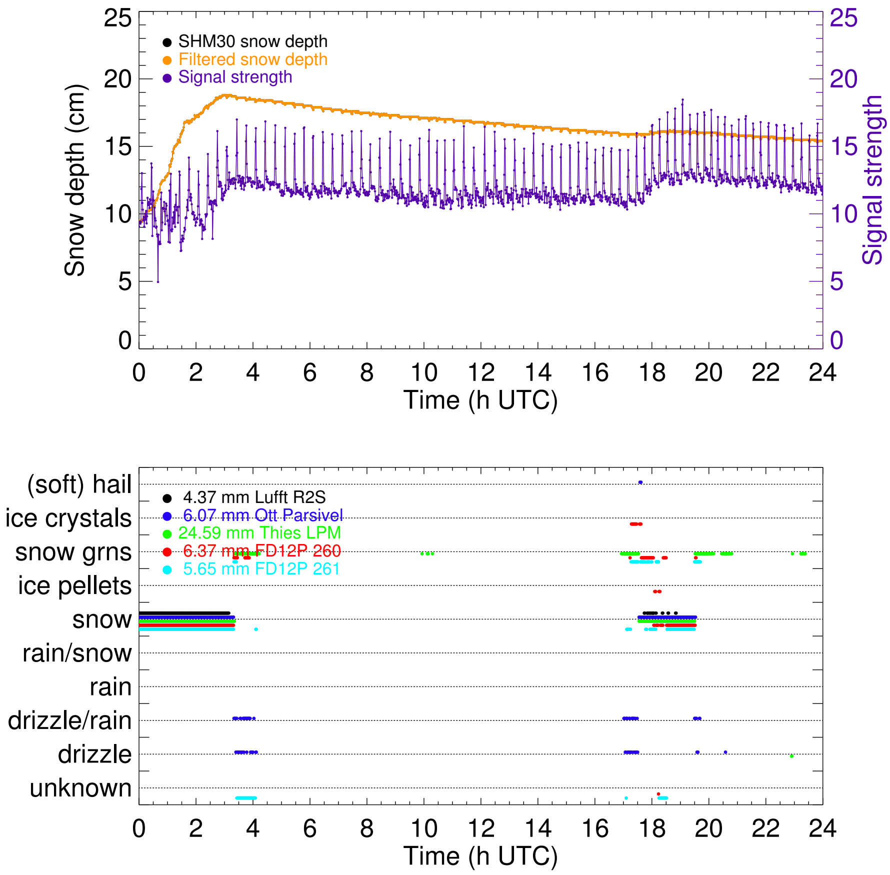

Figure 11. Similar to Figure 9, but for 19 December 2010.

The occurrence of heavy snowfall stopped according to the LPM sensor at 03:02 and continued with intensities below 1 mm/h (03:03-03:11) and even below 0.1 mm/h (03:12-04:12). In the late afternoon a second period with light snow was observed, but this had only minor effect on snow depth. Values measured by the SHM30 increased only by 4-5 mm between 17 and 19 UTC. An increase in signal strength can be observed due to this event as well, indicating the presence of fresh snow on the ground. In contrast with these sources for growth of the snow deck, a decline can be observed due to compaction. This leads to a snow depth of 15.4 cm measured at the end of the day.

Because the air temperature on the 19th was constantly below 0°C, again the activation of the sensor heating caused large fluctuations in sensor temperature (not shown). Consequently, spikes in signal strength are observed just after the sensor temperature increases above 3°C, leading to a sudden increase of the signal strength by 4-5 lasting for one to two minutes. The coinciding decrease in the snow depth measurement, which was also observed on 16 December, is very small and amounts to 1-2 mm. Figure 12 gives an illustration of the changes in snow cover conditions at the test site between 18 and 19 December.

Interpretation of these images to derive snow depth time series is not trivial. The right-hand image shows an unwanted pile-up of snow at one side of the ruler, which is most likely the side from which the wind originated. This complicates an accurate reading of the ruler. Beside pile-up effects the poor quality of nighttime images is an important issue in using this kind of information.

Figure 12. Camera images of snow ruler SR2 on 18 December 13:35 (left) and 19 December 09:30 UTC (right). Note the pile-up of snow along the ruler, discussed in the text, in the right-hand image.

24 December 2010: Drifting snow event

High winds gusting up to 13 m/s were observed in De Bilt on 24 December 2010. Figure 13 shows the snow depth, signal strength and precipitation type observations on this day. Both the filtered snow depth and the signal strength demonstrate much stronger fluctuations than observed normally above closed snow cover. This can be observed for example between 7 and 8 UTC, where snow depth increases roughly by 2 cm without any precipitation falling. At the same time, the signal strength also increases. Obviously, these changes are caused by a redistribution of snow on the ground due to horizontal movement by wind.

Considering the (false) precipitation detections by the Thies LPM and Lufft R2S in the bottom panel, the vertical range over which the drifting snow was present can be estimated at minimum at 1.5 to 2 m above the surface. After 16 UTC the disdrometers stop reporting precipitation. At the same time the cessation of the snowdrift event can be observed as well from the stabilization of the snow depth and signal strength. The event could unfortunately not be observed on the still images from the AXIS camera. Note that the 1-second (ST01) measuring mode of the SHM30 needs to be analyzed further to assess its capabilities for drifting snow detection.

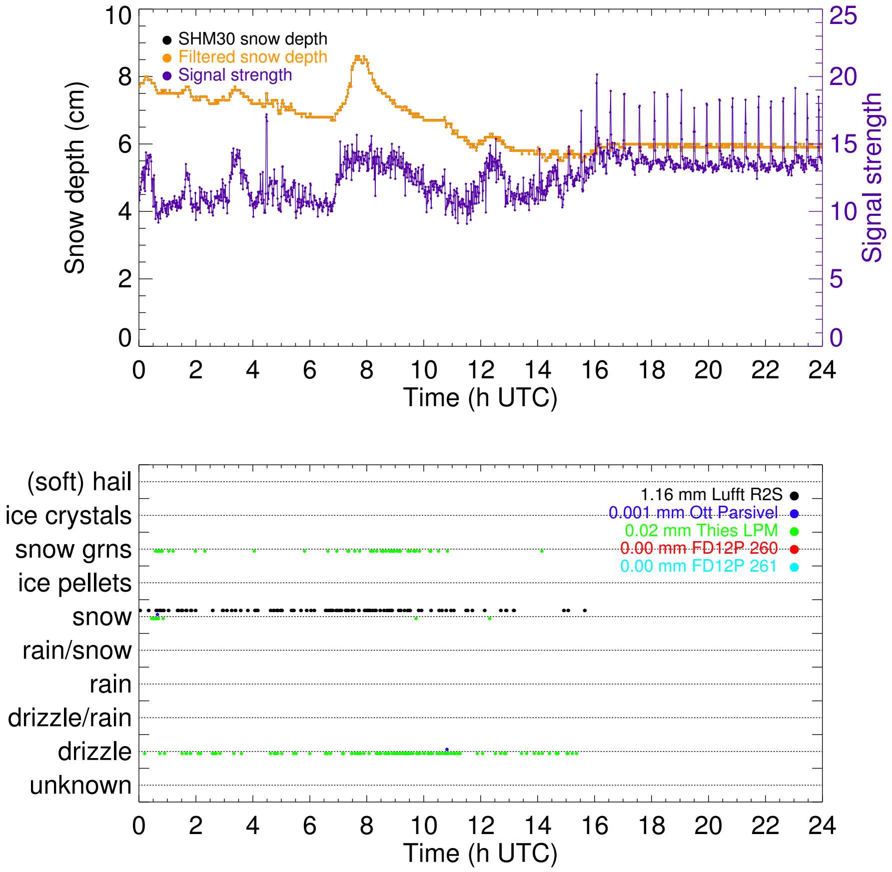

Figure 13. Similar to Figure 9, but for 24 December 2010. The precipitation records in the lower panel are caused by drifting snow.

1 January 2011: The end of a closed snow deck

The closed snow deck that resided at the test site for about 15 days disappeared on 1 January. This can be concluded from the measurements presented in the upper panel of Figure 15. Under the influence of compaction, melt and liquid precipitation, the last millimeters of snow under the SHM30 sensor location were observed between 9 and 10 UTC. The increased transparency of the declining snow layer immediately resulted in signal strength values below the threshold value of 3.5. The first measurement below this threshold was made at 08:58, at a sensor snow depth of 1.0 cm. About 40 minutes later, at 09:35, the snow depth started to stabilize at 0.4-0.5 cm.

Figure 14. Camera images of the snow depth testing area on 1 January at 08:00 (left) and 11:00 UTC (right).

Although the value does not return to zero, the signal strength and the camera images (Figure 14) around that time confirm that the snow cover has indeed disappeared. A broken snow deck is still present, but the measurement spot at ±75 cm from the mast pole of the SHM30 probes the grass again.

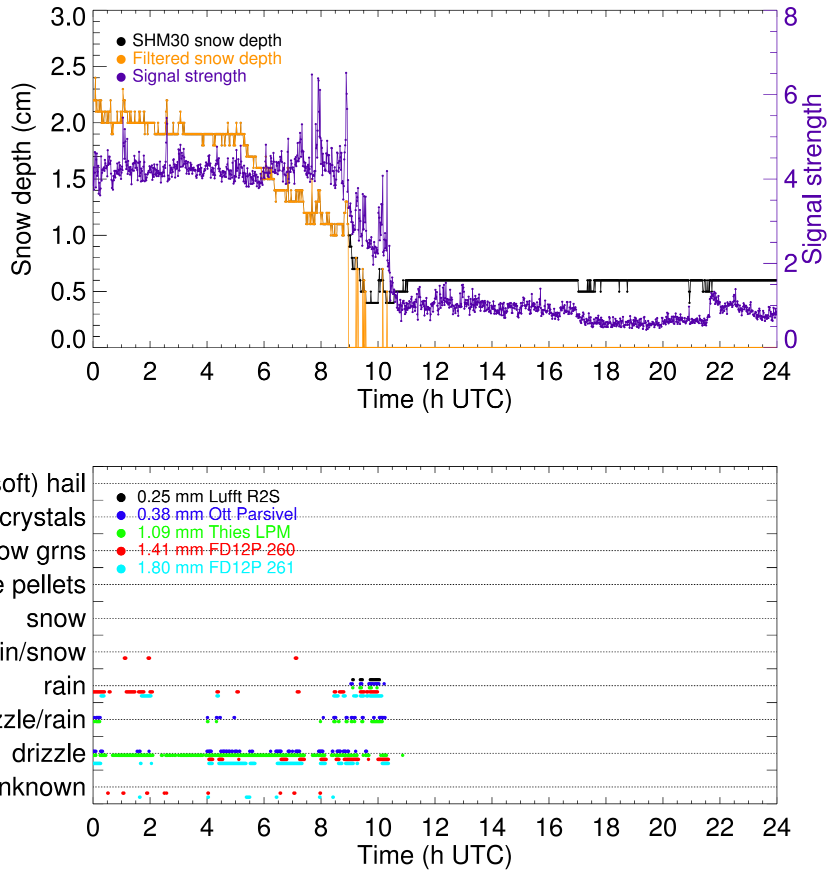

Figure 15. Similar to Figure 9, but for 1 January 2011.

23 February 2011: Light snowfall event

Seven weeks after the first snow cover episode at the test site had come to an end, another snowfall event was observed. This event on 23 February caused a slight but measurable increase in snow depth between 16 and 19 UTC. Figure 16 depicts the SHM30 measurements and the precipitation types observed on this day. The Thies optical disdrometer (LPM) reported the first snowfall at 15:42 UTC. The first 0.2 cm of snow depth increase was observed at 16:34 (signal strength 3.0), whereas the first positive value of filtered snow depth was observed 12 minutes later, at 16:46 (0.2 cm and signal strength 4.0).

Just like the case on 16 December the first (validated) snow depth output of the SHM30 sensor is observed roughly one hour after the onset of the snowfall. This time interval will of course depend on the evolution of the snowfall intensity in time. In this case the first 2 mm of snow deck was measured after 0.14 mm of (liquid equivalent) snow accumulation reported by the FD12P. Subsequently, the first 5 mm of snow depth by the SHM30 was reported after 0.25 mm of precipitation accumulation. This relation will be further explored in Section 3.6.

Furthermore, it should be noted that the snow depth measured above grass, just before the snowfall, obtained a value -0.1 cm. This low value gives confidence in the fact that the offset that was configured in the sensor during installation, is still a suitable approximation of the zero level at the time of this event in February.

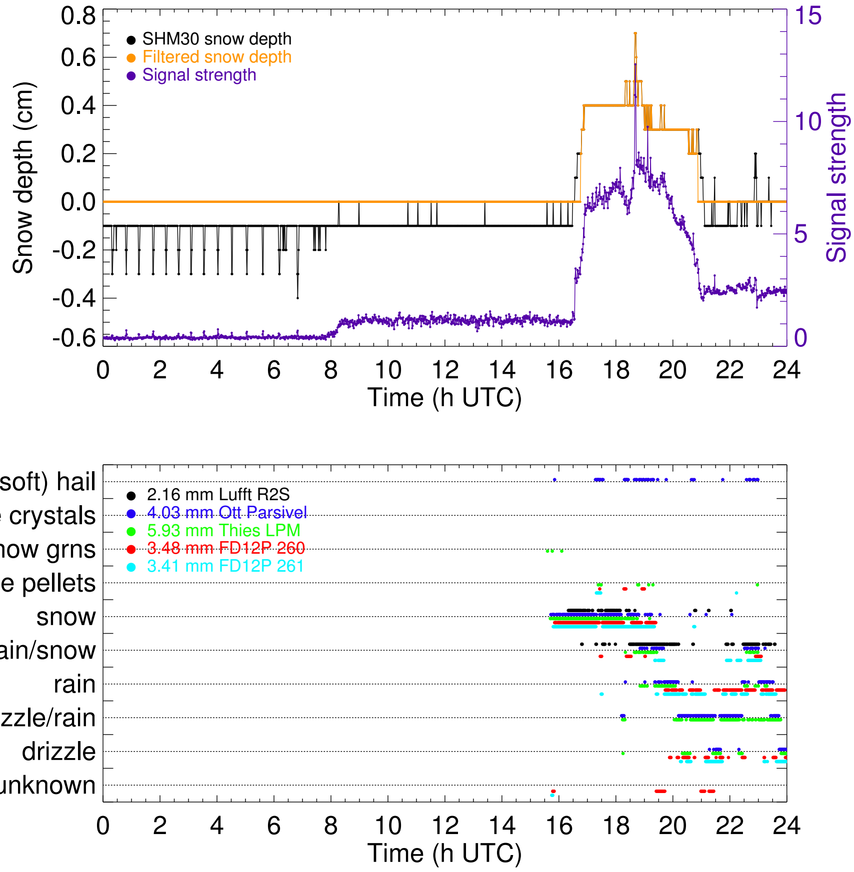

Figure 16. Similar to Figure 9, but for 23 February 2011.

7 May 2011: False alarms in spring

In Figure 6 it was already observed that some spikes of filtered snow depth occurred after the winter had come to an end. One day where several false alarms were encountered was 7 May 2011. The bottom panel of Figure 17 confirms that no snowfall or other precipitations were observed at the test site on this day, except for one false report by the R2S sensor. In the upper panel it can be seen that the raw SHM30 snow depth obtains positive values between 0.3 and 0.5 cm, giving in this case an indication of the height of the grass at the target surface.

Although no snow cover was present, 14 records between 10:24 and 16:30 UT obtained a signal strength slightly exceeding the threshold of 3.5, causing a positive value of filtered snow depth to be reported. The signal strength reached a maximum value of 3.7 during this period. It is assumed that these higher values are induced by the increased reflectivity of withered grass, combined with the bright sunshine conditions during daytime. To illustrate this point, Figure 18 shows two camera images demonstrating the surface conditions during the afternoon of 7 May. Possibly related to the dry spring in the Netherlands in 2011, the surface conditions were far from perfect. Especially around the masts of the disdrometer test area the grass has obtained a brown/yellow color. Despite the false alarms observed in the snow depth data, it may be expected that additional validation rules for the snow depth measurement can be easily implemented. For example the air temperature can be used in such a filter; during this event the 1.5 m temperature was above 25°C (not shown). In Section 3.6 it will be shown that also precipitation data from a present weather sensor (PWS) can be used to validate the automated snow depth measurement.

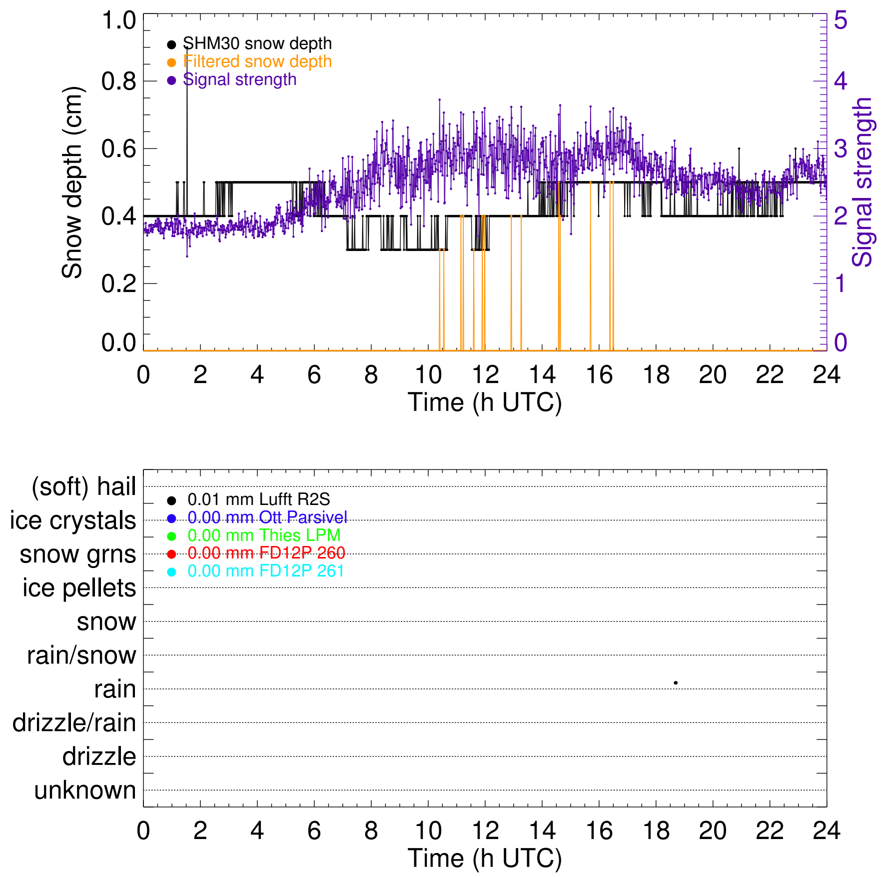

Figure 17. Similar to Figure 9, but for 7 May 2011.

Figure 18. Camera images of the snow depth testing area (left) and a close-up of the grass (right) at the test site on 7 May at 14:30 UTC.

3.4 False alarm analysis

The SHM30 laser sensor determines the snow depth from a distance measurement between the sensor and the target surface. Hence also natural grass, or objects like rabbits or birds residing on the ground below the sensor may lead to changes in the observed snow depth. In this section an attempt is made to quantify the false alarms during the field test and describe the performance of the SHM30 in commonly used skill scores. In view of the snow depth climatology in the Netherlands (cf. Section 1.1) it should be noted that false alarms are one of the major concerns in the automation of this type of observation. Following the case studies in Section 3.3 a filtering procedure based on the SHM30 signal strength is likely the way to go to avoid false reports of snow cover.

The histogram in Figure 19 shows the occurrence distribution of the snow depth for a selected period without snow cover at the test site, i.e. 1 March-30 June 2011. The total number of 1-minute measurements performed by the SHM30 sensor in this period is 174240. Note that 15 April was excluded from the data, because some experiments were conducted on that day to investigate the effect of different target surfaces (see Section 3.5). As already mentioned in the discussion on Figure 6, especially during the spring months the natural grass at the test site causes reduced distances between the sensor and the surface, which results on its turn in positive snow depth values up to 4 cm. The orange bars in Figure 19 denote those events where sensor measurements were qualified as valid by the signal strength filter. In fact, this was the case for 82 measurements (=82 minutes), which are considered from here as false alarms.

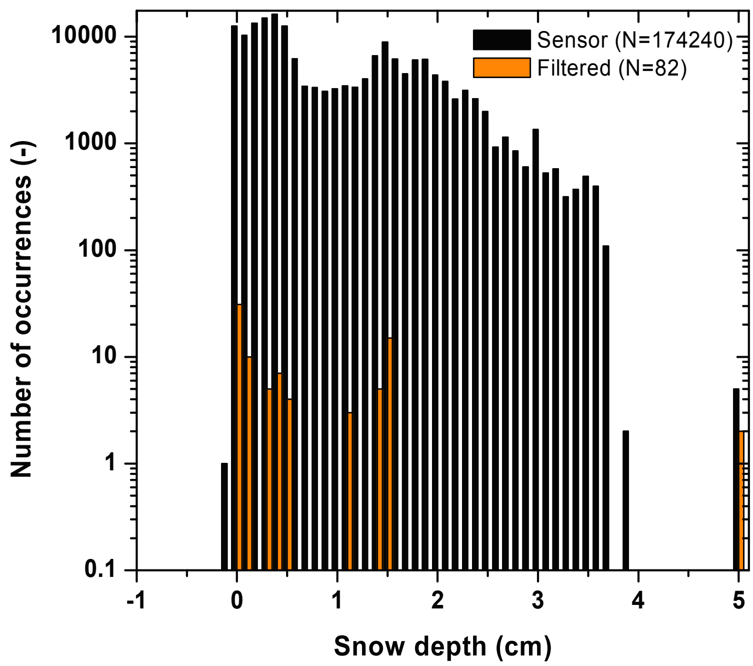

Figure 19. Occurrence distribution of snow depth measurements by the SHM30 during a period with no snow cover (1 March-30 June). Shown are all snow depth measurements (black) and the selection of records where the signal strength exceeds 3.5 (orange). Bin size is 0.1 cm.

The bin at 5 cm contains all cases where snow depth above the grass was equal to or larger than 5 cm. Only 2 out of the 5 cases in this bin passed the filter. The corresponding snow depth in these cases was 108.8 cm (17 March 12:09) and 128.6 cm (20 May 11:13). After consultation of the images from the AXIS camera at the test site these measurements were attributed to KNMI employees giving a guided tour and blocking the laser beam of the SHM30 sensor. The signal strength observed during these events was 4.7 and 4.6, respectively. Because the signal strength for the other three sensor values above 5 cm was below 3.5, they did not pass the filter.

Another way to look at the snow cover vs. signal strength relation is presented in Figure 20, which depicts the occurrence distributions of the signal strength for the same period without snow cover (1 March-30 June, N=174240) and for a period with confirmed snow cover (16-31 December, N=22147). As expected the values above snow are generally higher than above grass. For signal strength values between 2.5 and 5.5 an intermediate area can be observed where both periods have contributions. The amount of cases included in this area is 5735, which is roughly 3% of the total number of data points in the two periods together. Going from a threshold of 2.5 to higher values, the number of false alarms will decrease at the cost of a higher number of misses. Beside this intermediate area a bimodal pattern can be observed in the histogram of the snow cover data, related to the sudden decrease in the signal strength output on 26 December (cf. Figure 7).

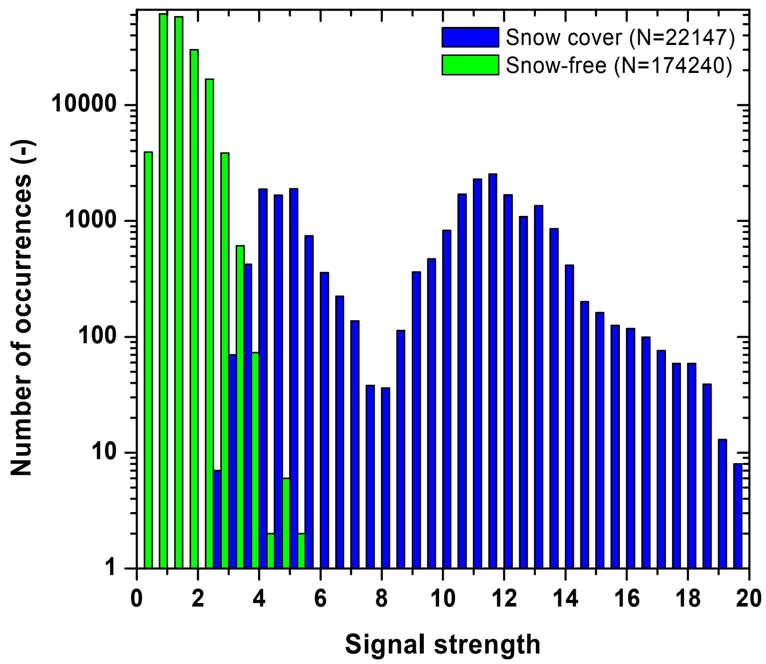

Figure 20. Occurrence distribution of the signal strength measured by the SHM30 during a period with snow cover (16-31 December, in blue) and without snow cover (1 March-30 June, green). Bin size is 0.5.

The performance of categorical measurements can be expressed in verification scores like the Probability Of Detection (POD), False Alarm Rate (FAR) and Critical Success Index (CSI). Considering the SHM30-filter combination as a detector (yes/no) of snow cover, these scores can be used to analyze the performance of the filter used. Moreover it can be used to explore whether the threshold value is adequately chosen.

A 2x2 contingency matrix for the results of each combination of "yes/no" events is shown in Table 3. Each event can be classified in one of the four cells in the matrix, corresponding to one of these situations:

a: both the reference and the sensor report the event (correct hit)
b: the reference reports the event, but the sensor does not (missed event)
c: the sensor reports the event, but the reference does not (false alarm)
d: both the reference and the sensor do not report the event (corr. rejection)

The numbers of entries in the 2x2 contingency matrix are used to determine the following verification scores (Kok, 2000):

Probability of Detection (POD) = 100% * a/(a+b)
The POD is a measure for the proportion of observations by the reference that is correctly reported by the sensor.
False Alarm Ratio (FAR) = 100% * c/(c+d)
The FAR is a measure for the proportion of observations by the sensor that is not correct according to the reference.
Critical Success Index (CSI) = 100% * a/(a+b+c)
The CSI indicates the overall performance of the sensor with respect to the reference, based on a combination of POD and FAR.

Table 3. Illustration of a 2x2 contingency matrix.

		SHM30 and backscatter signal filter	
		Yes	**No**
Reference	**Yes**	**a** : correct hits	**b** : missed events
	No	**c** : false alarms	**d** : correct rejections

Table 4. Skill scores of the validation filter for different threshold values. See text for an explanation of the variables included.

threshold	a	b	c	d	POD	FAR	CSI
2.0	22147	0	21211	153029	100%	12.2%	51.1%
2.5	22147	0	4522	169718	100%	2.6%	83.0%
3.0	22140	7	691	173549	100%	0.4%	96.9%
3.5	**22070**	**77**	**82**	**174158**	**99.7%**	**0.0%**	**99.3%**
4.0	21647	500	10	174230	97.7%	0.0%	97.7%
4.5	19773	2374	8	174232	89.3%	0.0%	89.2%
5.0	18106	4041	2	174238	81.8%	0.0%	81.7%

In order to find the optimum value for this sensor, the threshold used in the signal strength filter was varied in the range 2.0-5.0. Table 4 lists the resulting parameters in accordance with the naming conventions introduced above. Results for *a* and *b* were obtained from the first dataset (16-31 December) where the reference confirms the presence of a snow deck, whereas the results in columns *c* and *d* were calculated from the second dataset (1 March-30 June) which is representative of the snow-free situation. During the period with snow cover only 77 events occurred where the validation filter corrected the measured snow depth to zero because the signal strength was too low. On the other hand, the sensor-filter combination resulted in a false alarm during only 82 minutes of the snow free period.

The threshold value of 3.5 was introduced as a first guess to discriminate between snow-covered and snow-free situations. Obviously, it follows from this table that the chosen value is very appropriate to be used with this specific sensor. The combination of misses and false alarms encountered during the two selected periods leads to the following scores: POD=99.7%, FAR=0.0% and CSI=99.3%. Note that a CSI score of 100% indicates a perfect performance. Variation of the threshold value clearly deteriorates the score and hence the performance of the SHM30-filter combination. However, because the signal is not calibrated at all and varies together with the signal values measured against black and white surfaces (cf. Appendix A), it is expected that the value needed for adequate filtering varies from sensor to sensor. This is in agreement with the experiences reported by DWD and ZAMG (Lanzinger, 2011; Mair, 2011).

3.5 The effect of different surface properties

The test site in De Bilt is maintained regularly and has ideal conditions for snow depth measurements over short cut, natural grass of good quality. As this may not be the case at all automatic weather stations in the KNMI observation network, a small experiment has been conducted to explore the effects of different soil types and vegetation on the SHM30 signal strength parameter. A similar experiment has been performed by Lanzinger et al. (2009).

Figure 21 shows an overview of the target surfaces and lists the averages in snow depth and signal strength obtained during measurements over grass, dry sand, wet sand, pebble stones, dry ground and wet ground on 15 April between 10:30 and 13:30. Following this order of appearance, carton boxes with the materials were put in the sensor laser beam for 30 minutes while the normal measurement sequence as described in Section 2.2 continued. Figure 22 shows the 1-minute sensor output during this test as a function of time. Firstly it should be noted that the low variability in the 30 measurements above sand and ground give good confidence in the stability of the measurement. During the four periods where these soil types were used the standard deviation is within 1 mm. The high variability between the 1-minute measurements above the pebble stones was caused by a reshuffling of the box with stones during the measurement interval.

Target surface	Time interval	Snow depth (cm)	Signal strength
1) (Green) grass	10:30-11:00	0.8 ± 0.13	0.8 ± 0.2
2) Dry sand	11:00-11:30	5.7 ± 0.05	6.1 ± 0.6
3) Wet sand	11:30-12:00	4.4 ± 0.04	2.3 ± 0.4
4) Pebble stones	12:00-12:30	3.6 ± 0.51	6.5 ± 1.5
5) Dry ground	12:30-13:00	5.2 ± 0.03	3.3 ± 0.4
6) Wet ground	13:00-13:30	3.7 ± 0.04	0.9 ± 0.3

Figure 21. Overview of the target surfaces probed by the SHM30 sensor. The table below the photographs lists the average and standard deviation of the snow depth and signal strength measurement over the 30-minute intervals.

More importantly to note are the large differences in signal strength obtained for the different targets. They reveal that some types generate similar or even higher signals than observed above snow cover. Dry sand (6.1 ± 0.6) and the pebble stones (6.5 ± 1.5) are abundantly above the threshold value of 3.5 used in the filter, whereas the measurements over dry ground (3.3 ± 0.4) are roughly at the same level. The values obtained for wet sand (2.3 ± 0.4) and wet ground (0.9 ± 0.3) are below the threshold.

The value for wet ground compares well to the signal strength that is typically measured above grass (0.8 ± 0.2). In view of these results it must be noted that the performance of the SHM30-filter snow cover detection largely depends on the conditions of the surface under the laser sensor. The darker the surface, the better contrast will be achieved with respect to snow cover. Some countries use a snow plate for manual and automatic snow depth measurements in order to achieve a better optical contrast when the first snow flakes settle on the surface (Lanzinger et al., 2010b). Because such a plate will affect the heat transfer through the surface and the snow deck, the material and design needs to be chosen with care.

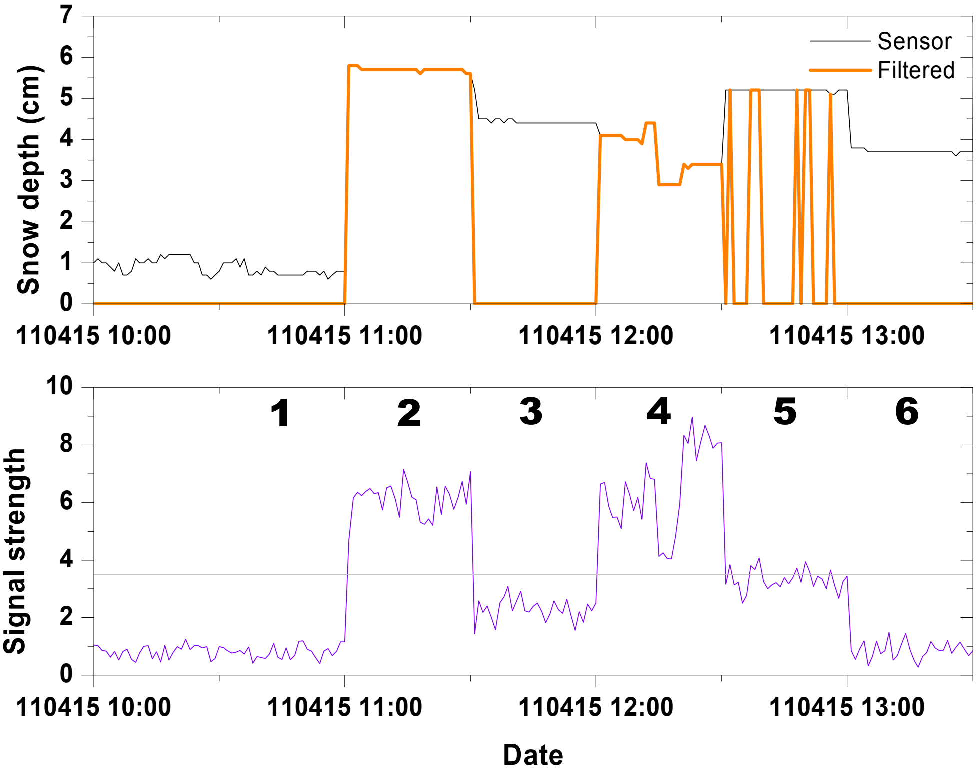

Figure 22. Snow depth (top) and signal strength (bottom) measurements as a function of time between 10:30 and 13:30 on 15 April. The numbers in the bottom panel correspond to the target surfaces introduced in Figure 21.

3.6 Relation to solid precipitation measurement by PWS

The precipitation type and accumulation output reported by present weather sensors (PWS) are a useful source of additional data in the analysis of automated snow depth readings. This was confirmed in several of the case studies discussed in Section 3.3, where changes in measured snow depth could be directly related to the onset of solid precipitation events. Consequently, it can be expected that the solid precipitation accumulation measured by a PWS can be used to make an estimate of the depth of fresh fallen snow, i.e. the increase in snow depth over a certain time interval. It is known that 1 mm of snowfall corresponds roughly to an increase in snow depth of 10 to 15 mm. In this subsection a first attempt is made to derive such a relationship. Therefore hourly values of liquid equivalent precipitation accumulation were calculated for the entire period of testing (16 December-30 June) by summing up the reported 1-minute intensities divided by 60. Sensors included in the comparison are the Vaisala FD12Ps at the operational (260) and test site (261) and the Thies LPM and Ott Parsivel optical disdrometers at the test site. In order to take into account snow only, intensities were filtered on the occurrence of solid precipitation using the present weather code. Solely those events where the sensors reported snow, snow grains, ice pellets or hail were included. For the SHM30 sensor the hourly increase in snow depth was calculated as the difference in filtered snow depth between hh:59 and hh:00 (if positive). Note that the KNMI rain gauge is not included in this analysis, because this sensor needs some time to melt solid precipitation before it actually measures an intensity. The use of direct (optical) measurements of solid precipitation is more appropriate in this case.

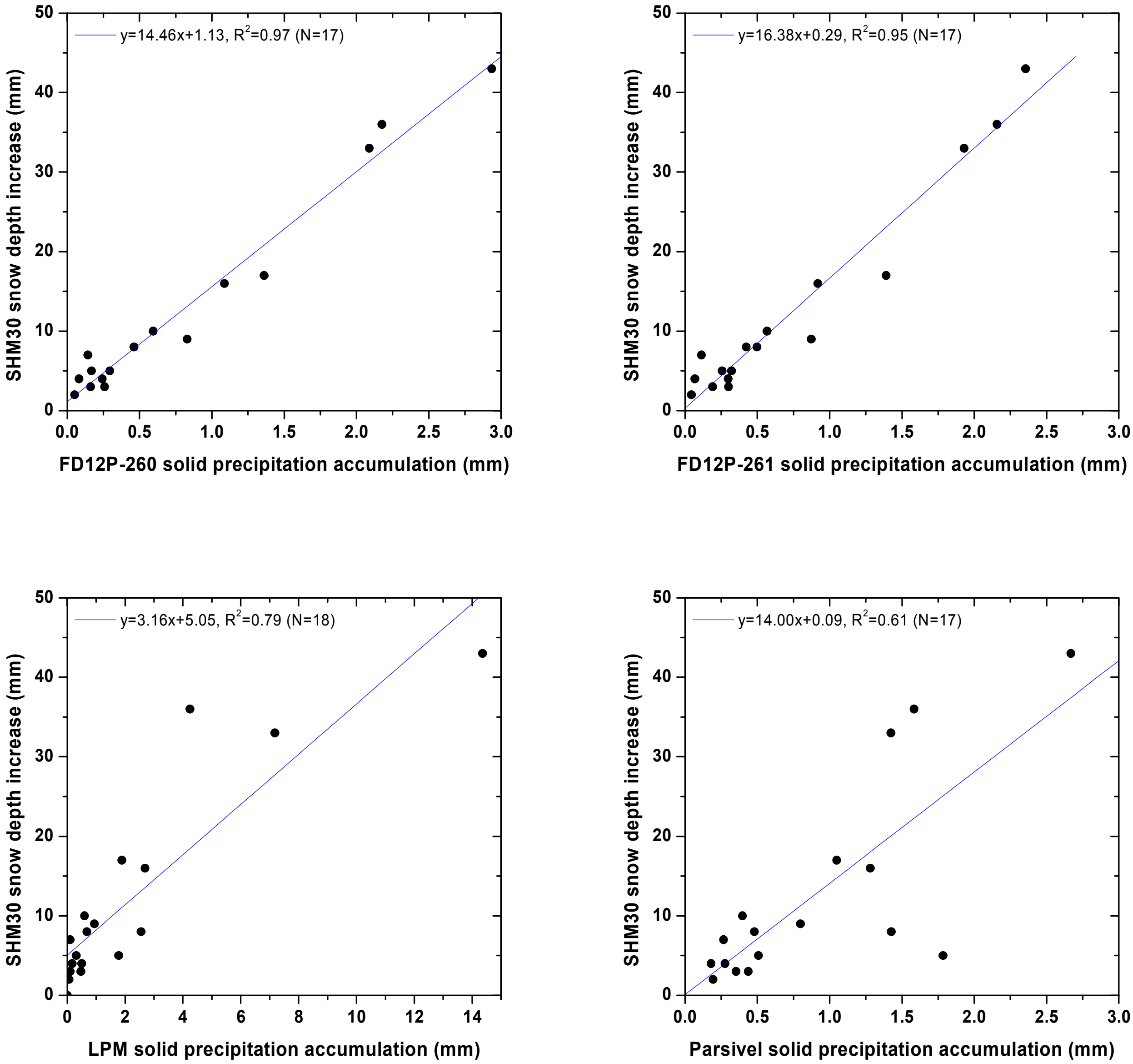

Figure 23. Scatter plots of hourly (liquid equivalent) solid precipitation accumulation vs. snow depth increase measured by the SHM30 sensor and filter. Shown are the results for the two FD12Ps (top panels) and the Thies LPM (bottom left) and Ott Parsivel (bottom right) optical disdrometers.

Figure 23 shows the scatter plots where the hourly values are mutually compared. All PW sensors use default calibration factors to determine the liquid water content of solid precipitation. Results of the linear least squares fits are provided for each sensor in the upper left corner of the scatter plot. Note that the number of observations included (N) is slightly different for the LPM sensor. The FD12P sensors at 260 and 261 provide the best linear fits $y = ax + b$ with coefficients $a = 14.46 \pm 0.63$ and $b = 1.13 \pm 0.72$ mm (R^2=0.97) and $a = 16.38 \pm 0.96$ and $b = 0.29 \pm 1.01$ mm (R^2=0.95), respectively. As the data points are clearly more scattered for the optical disdrometers in the bottom panels, this logically results in fairly lower correlation coefficients of R^2=0.79 for the Thies LPM and R^2=0.61 for the Ott Parsivel. Looking closer at the largest hourly increase of snow depth (43 mm), it can be observed that the corresponding accumulations reported by the FD12Ps (2.9 and 2.4 mm) and the Parsivel (2.7 mm) are more or less equal, while at the same time the LPM (14.4 mm) is much higher. Obviously this is the case for more data points. The maximum snow depth increase of 43 mm was observed on 19 December between 01 and 02 UTC (cf. Figure 11).

In summary, the linear fit results obtained in Figure 23 suggest that a strong relationship exists between the solid precipitation accumulation of the FD12P and the SHM30 snow depth increase on an hourly basis. It should however be noted that only a limited number of data points is included. In case the relation proves to be valid for more sensors, it can be used as a first estimate of the depth of fresh snowfall at locations where only a PWS is installed. Results should however be interpreted with care as not all snowfall has the same density and effect on snow cover. Direct measurements of the snow depth remain inevitable to monitor total snow depth adequately because apart from snowfall, processes like melting, turbulence and compaction can decrease snow cover.

Considering the 10 events of snowfall onset experienced between 16 and 31 December and on 23 February, a first estimate can be obtained for the amount of solid precipitation that is required before an increase of 2, 5 or 10 mm of snow depth can be expected. Thereby the FD12P at the test site (261) is taken as reference sensor for accumulation. On average, 32 minutes after the onset of snowfall (detected by LPM), the SHM30 snow depth had increased with 2 mm. The precipitation accumulation since the onset was 0.07 ± 0.05 mm in those cases. Similarly, an increase of 5 mm (5 events) was observed on average 67 minutes and 0.25 ± 0.06 mm after the onset. Finally, an increase of 10 mm (3 events) was observed on average after 88 minutes and 0.51 ± 0.08 mm. Again the results should be interpreted with care as the number of events is very low. Moreover, the time and accumulation required are strongly dependent on the type of solid precipitation and the ambient weather conditions. Figures 9 and 16 in Section 3.3 show two cases during the onset of snowfall where the snow depth measurements are depicted together with the automated present weather observations.

4 Summary, conclusions and recommendations

4.1 Summary

A six-month evaluation of the Jenoptik SHM30 snow depth sensor was performed at the KNMI test site in De Bilt from 16 December 2010 to 30 June 2011. This sensor determines the total snow depth with a 1 mm resolution from a laser distance measurement to the ground. During the field test it was investigated if the SHM30 sensor is suitable for operational use in the national observation network of KNMI. A comparison with manual measurements inferred visually from camera images and taken with a graduated snow ruler delivered satisfactory first estimates of the uncertainty that can be expected using the SHM30. On average the difference between the laser sensor and the three manual methods was in the range -0.9 to +1.5 cm, mainly caused by local differences in the snow deck. Overall the sensor performed very well and did not bring to light any problems that are frequently encountered with more conventional acoustic measurement techniques for snow depth.

4.2 Conclusions

In view of the good results obtained with the SHM30 laser sensor during the field test, it is expected that this sensor will be able to fulfill the general requirements for snow depth measurement concerning range, resolution and uncertainty. Moreover, the sensor at the test site did not manifest any malfunctioning nor did it require maintenance. Compared to manual observations of snow depth the sensor performs well. However, the values can not easily be compared because the sensor performs a point measurement only, probing the surface at a spot of approximately 2-3 mm in size. More specifically, the following conclusions are drawn.

- The SHM30 sensor captured the evolution of the snow deck that resided at the test site in De Bilt between 16 December 2010 and 1 January 2011 well. Snow depth data showed good agreement with the onset and ending of the snow cover, fresh snowfall due to precipitation events, redistribution caused by drifting snow and the snow depth decline by 1-3 cm per day due to melting and compaction processes.
- Even during heavy precipitation events no data outages were observed and the snow depth time series were of good quality.
- SHM30 values of total snow depth were on average 1.5 cm higher than those reported by the voluntary observer in De Bilt (OBS550). A negative bias was found compared to visually inferred snow depth from camera images (-1.3 cm) and those incidentally taken with a snow ruler (-0.9 cm).
- Positive snow depth values were reported by the sensor during snow-free conditions due to obstacles and growing grass blocking the laser beam. Grass heights up to 4 cm were observed, regularly interrupted by cutting events.
- It was found essential to use the signal strength reported by the sensor to determine whether the ground is covered with snow or not. A threshold value of 3.5 provided optimal performance and was used here to remove false alarms of snow depth for the most part.
- Using the filter, only 77 misses (0.3%) and 82 false alarms (0.05%) were observed in the 1-minute snow depth data during selected periods with and without snow cover. The Critical Success Index (CSI) for snow cover detection filter amounts to 99.3%.
- The effect of surface properties on the signal strength was explored in the field. Only dry sand and pebble stones generated substantially higher signal strength values than the threshold of 3.5 used for snow cover

detection above natural grass. Hence the condition of the surface below the laser sensor should be a focus in future installations.
- A comparison of the hourly increase in filtered SHM30 snow depth and solid precipitation accumulation measured by two Vaisala FD12P weather sensors gave promising results. A linear fit with R^2=0.97 (260) and 0.95 (261) was established for two snow deck events during the field test. Worse results were obtained in the comparison with the LPM and Parsivel optical disdrometers.
- For 10 events where the onset of snowfall was observed, the average time and (liquid equivalent FD12P) accumulation needed for 2, 5 and 10 mm of snow depth increase was 32 minutes / 0.07 ± 0.05 mm, 67 minutes / 0.25 ± 0.06 mm and 88 minutes / 0.51 ± 0.08 mm, respectively.

Only some minor issues were observed during the field test and need attention:
- No automatic zero calibration is performed. Hence the predefined offset value is used continuously in the derivation of the snow depth from measured distance. The difference in 'zero level' before and after the major snow episode during the field test was approximately 0.5 cm. Before the second snow deck event the zero level above grass was -0.1 cm.
- The default heating scheme of the sensor, turning the heating fully on below a sensor temperature of 3°C (programmable) and off above 12°C, introduces sudden increases in signal strength under cold conditions. This has also minor effect on the reported snow depth in the order of -1 to -2 mm.

Although at first sight the results are satisfactory, it is important to note that the conclusions in this report are drawn from a relatively short field test of 6½ months. Moreover just one sensor was evaluated based largely on a period of 3 weeks where the test site was fully covered with snow. Before a decision on operational implementation can be made, further testing needs to be performed.

4.3 Recommendations

The Jenoptik SHM30 snow depth sensor has shown satisfactory performance during the field test in De Bilt and should therefore be considered a serious candidate for fully automated snow depth measurements for operational purposes. Although the first results obtained by colleague NMHSs (Lanzinger et al., 2010a; Mair et al., 2010; Zanghi, 2010) confirm the promising capabilities of this optical technique, it is recommended to extend the evaluation of the SHM30 at multiple locations for at least one winter period with sufficient snowfall events. Some guidelines for further testing are listed in the last paragraph of this subsection.

In view of the results from the first field test, a number of recommendations for improvement of the automated snow depth measurement by SHM30 can be made.
- The manufacturer should be requested to adapt the firmware to a version that incorporates the calibration values for black and white targets (cf. Appendix A). Only then a common threshold for the detection of snow cover can be applied. ☞ *The need for such an update has been discussed with Jenoptik and the feature will be implemented in firmware v9.05 due for release in September 2011 (Wille, 2011).*
- The spikes in signal strength caused by the sensor heating deserve special attention. Only a very limited effect on the snow depth measurement has been observed so far, but if this turns out to be more problematic, the sensor heating should be reconsidered in cooperation with the manufacturer. ☞ *Experiences in Austria (Mair, 2011) revealed that the*

default heating settings should be changed to HF=HO=2 to reduce the strong fluctuations in signal strength. KNMI will adopt these settings.

- A laboratory test should be developed to check the distance measurement and signal strength by the SHM30 sensor against hard targets.
- It was concluded that false alarms can be filtered out for the most part by using a threshold on signal strength. Nevertheless, it is recommended to explore further measures to optimize the validation practices. Some options to be considered are:
    - Step validation in the SHM30 software (using the 'XP' command)
    - Transient warning in the KNMI sensor interface SIAM
    - Validation in central database calculations, based on e.g. temperature or PWS data
    - Constraining the snow depth measurement to several months of the year (e.g. 1 October – 1 April)

In case it is decided to extend the field test, it is recommended to take into consideration the following points.

- It is recommended to conduct further testing with the Jenoptik SHM30 laser snow depth sensor at about 5 locations in the KNMI observation network. The test can be considered a pre-operational phase where the added value of the automated measurements is further evaluated.
- Special attention in the field test should be given to the general applicability of the conclusions obtained in this research. Also, finding suitable procedures for operational installation of the sensor and preparation of the target surface need be included. Test locations should be maintained normally and are preferably inspected by a local operator on request, or remotely by camera.
- Snow depth data from the sensors should be made available to KNMI users and experts to involve them closely in the introduction of this new measurement.
- It is advised not to include the SHM30 measurements yet in (inter)national meteorological bulletins issued by KNMI.
- DWD and ZAMG are introducing snow grid plates (Lanzinger et al., 2010b) of glass fibre reinforced plastic (GRP) in their network to achieve regulated zero level and contrast to snow. Further testing with such a grid plate at the test site in De Bilt is recommended. The PTZ camera at the test site should be used to monitor snow cover conditions on the plate and its direct surroundings.
- Attention should be paid in the installation at existing masts to avoid problems related to heat transfer from construction elements. More details about the installation can be found in the manual (Jenoptik, 2010).

4.4 Acknowledgements

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Appendix A Test Report for SHM30 sensor 101834

JENOPTIK

Test Report
Final Inspection

Type	LDM30.21
Serial number	101834
Order number	012840-632-26
Firmware version	9.04
Serial interface	RS422
Maximum frequency [Hz]	10

Test item	Description	Specified	Measured
1.1	Visual inspection, no foreign objects inside	OK	OK
1.2	Optical cleanliness	OK	OK
2.1	Meas. accur. XM white [mm]	± 3.0	−0.1
2.2	Signal power XM white	> 0.01	4.94
2.3	Meas. accur. XM black [mm]	± 3.0	−2.2
2.4	Signal power XM black	> 0.01	0.46
3.1	Status LED	OK	OK
3.2	Iout	OK	OK
3.3	Heating	OK	OK

Parameter set	ASXM / BR9600 / HO3 / HF12 / OF0 / RB-5 / RE5 / SA1 / SE1 / SF1 / SP0 / SRn / ST25 / XT60 / XP10

Final inspection passed:

03. DEZ. 2010 .... ESW QS 865

Date Signature Stamp

protocolversion 2.6, 101834(00).pdf, 03.12.2010 07:37:48

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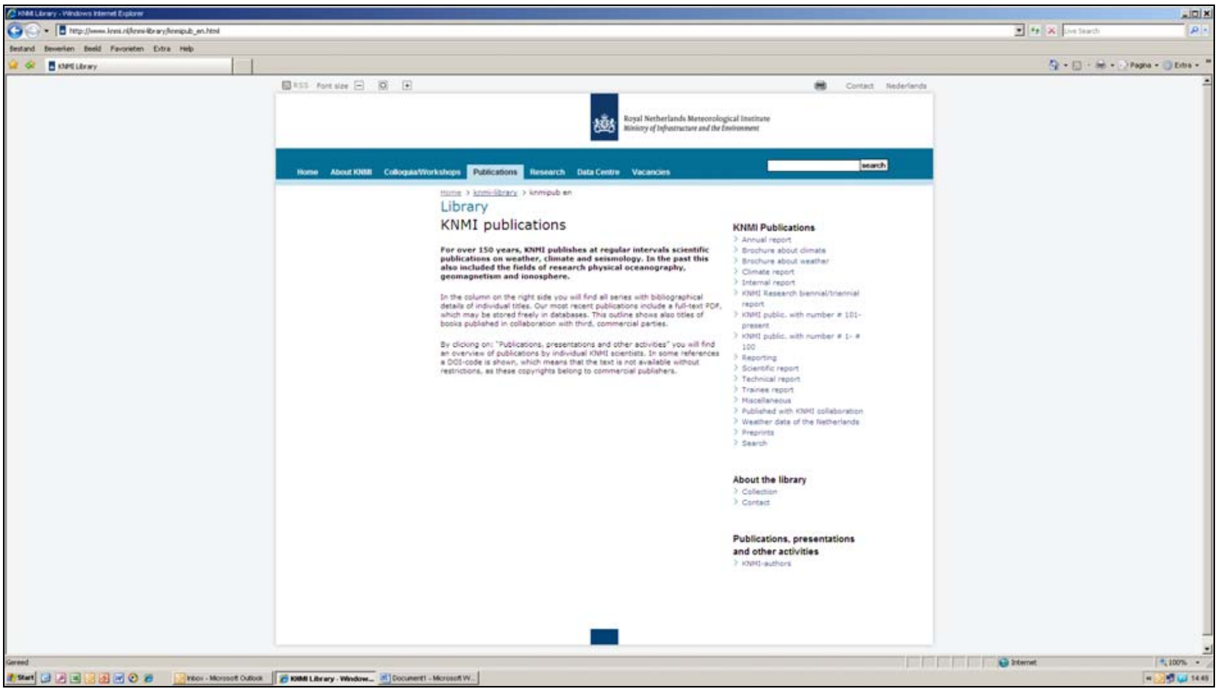

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