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Optical Precipitation Gauge

– Determination of Precipitation Type and Intensity by Ligth Attenuation Technique –

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There exists a great need for automatic precipitation gauges for effective road maintenance during the winter period. These gauges should be inexpensive, not require mains supply, need little attendance, give information about presence of precipitation and determine type (snow, rain or sleet) while there is no need for high accuracy of the precipitation intensity. Light attenuation precipitation sensors (optical gauges) fulfil several of these requirements and are used in the Swedish National Road Administration Road Weather System. The optical gauges measure the time it takes for particles of snow *etc.* to pass (attenuate) a light beam and relate this time to precipitation type and intensity. The rain precipitation mass is approximately proportional to the accumulated attenuation time. To investigate whether or not optical gauges could also be used for solid precipitation, the precipitation mass for snow, rain and sleet was measured with a reference gauge and compared to the attenuation time. The passage time of individual hydrometeorologic particles (snow, rain and sleet) was compared with precipitation type and wind speed. Air temperature could be used as a rough guide to distinguish three precipitation categories for the following temperatures: rain (>+2 °C), sleet (0 to +2 °C) and snow ($\leq$ 0 °C). At low wind speeds (< 3 m/s) the passage time of individual particles could be used to distinguish between rain and snow. The accumulated attenuation time for the same precipitation mass was approximately 25 and 5 times greater for snow and sleet respectively compared to rain. With the attenuation time for the snow-fall corrected for wind influence the quotient between the attenuation time for snow and rain is decreased from approximately 25 to approximately 12 times.

Introduction

Many countries are building Present Weather Systems to automate the winter road maintenance. The intention with these systems is to reduce the cost of snow and ice removal, improve the trafficability and increase safety (see *e.g.* Axelsson 1992; Boselly 1992; and Pilli-Sihvola *et al.* 1992). One of the most important parameters to measure is the winter precipitation. To replace the need for human observations of the water-equivalent precipitation a network of precipitation gauges has to be rather dense and hence the gauges have to be rather inexpensive. The gauges should be possible to locate without mains supply, so they should be battery powered. Besides they should be insensitive to splash and dirt and not need to be emptied. Information about the type of precipitation is also needed since this is one of the factors used to determine if it is necessary to start snow removal or de-icing activities. The beginning and ending of a precipitation event is also important information to road users to improve the traffic safety. For winter road maintenance there is no need for great accuracy of the precipitation mass but the gauges will have to be located along the roads and hence in wind exposed locations.

For most types of precipitation gauges the major problem with solid precipitation is a great under-catch a high wind speeds due to distortion of the wind field around the precipitation gauge (see *e.g.* Carlsson and Svensson 1984). To minimize this error many different kinds of shields have been constructed (*e.g.* Tabler *et al.* 1990, Huovila *et al.* 1988) and empirical relationships relating the true catch to the gauge catch and the wind speed are also presented (see *e.g.* Tabler *et al.* 1990, Førland and Aune 1985). Most of the recording gauges (those that consist of a container disturbing the wind field) also suffer from the wind-induced under-catch but for recording gauges other errors also emerge.

There are essentially six types of recording precipitation measurement methods: The tipping bucket gauge, the heated siphon gauge, the weighing gauge, the radar and the satellite image methods and the optical gauges. The tipping bucket gauge (Hansson *et al.* 1983) and the heated siphon gauge (Sevruk 1983) give too little solid precipitation. The weighing type gives roughly the same monthly totals as non-recording gauges but the daily totals may vary considerably when the precipitation is sticky (Goodison and Metcalfe 1988; Bakkehøi *et al.* 1985). During the latest years radar (*e.g.* Duvernoy *et al.* 1992) and satellite images (*e.g.* Karlsson and Liljas 1990) have come into use for instant information about the extension of the precipitation area and the intensity. The radar and satellite image methods are not yet so developed that they can substitute standard methods. The optical gauges are claimed to be able to determine both the type of precipitation and the intensity of the precipitation. There are some tests of their ability to determine the type of precipitation (*e.g.* van der Meulen 1992; Gaumet and Salomon 1992) but their ability to determine the precipitation intensity seems as yet to have been little tested. Preliminary tests of an optical gauge indicated that rain precipitation intensity was a fairly linear function of light attenuation time (Millgård 1992, personal commucation) but one test of optical gauges with snow precipitation reported by Stepek *et al.* (1992) gave very inconsistent results.

Registration of snow precipitation obviously is a difficult task. Since the optical gauges fulfil several of the requirements above (they are battery powered, need little maintenance and are fairly inexpensive *etc.*) and as the Swedish National Road Administration is now building a Road Weather Information Systems with optical gauges it is important to investigate how these work with snow precipitation.

The aim of this study was therefore to investigate the suitability of a light attenuation sensor for measurement of precipitation of different phases. The accumulated sum of attenuation time was compared to the water equivalent of snow, sleet and rain measured in a conventional way. Air temperature was used to distinguish different precipitation categories and the correlation between measured precipitation mass and accumulated attenuation time was established for the different categories. An attempt to correct for the effect of wind on the attenuation time for the snow events was also made. Finally the passage time of individual hydrometeorological particles at different wind speeds was tested to distinguish different precipitation categories.

Measurements

The Optical Gauge

The precipitation sensor (TELUB AB, Sweden) consisted of two pairs of transmitter-receivers (light-diode and photo-detector) arranged at 90° angle to form a horizontal cross of light-beams (Fig 1a.). The receivers reacted to short decreases in the light-intensity (caused by snow flakes or raindrops) of the beam. As long as the receiver noticed a decrease of the light intensity it sent pulses to the sensor-output. The number of pulses was proportional to the time the object (the snowflake or the raindrop) was blocking the beam. If the beam was blocked longer than 0.1 s a blocking signal was sent to the sensor-output but the blocking was released when the photo-detector received light pulses again. The sensor was equipped with an automatic amplifying-module to compensate the dimming of the optics due to dirt and for variations in daylight intensity, but the receivers were positioned (paying attention to cardinal points) so they didn't receive direct sunlight. The transmitters and the receivers were equipped with cups to decrease the possibility of precipitation hitting the optics. A thermostatically controlled heating of the transmitters and the receivers prevented clogging of snow and ice. The optical precipitation sensor was connected to a measurement and control unit (Campbell CR10, Campbell Scientific LTD, England) that registered the accumulated sum of

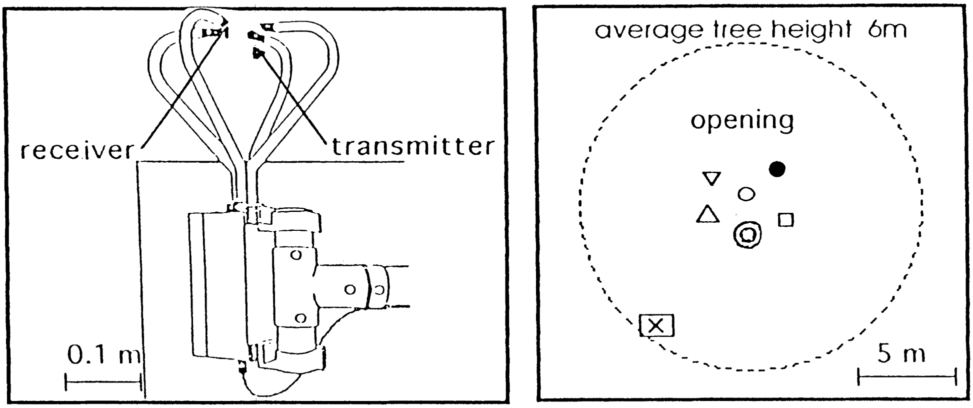


Fig. 1. a) TELUB optical precipitation gauge. b) Measurement site: □ ground based precipitation tray, ∇ SMHI gauge, • optical sensor, △ temperature sensor, ◎ wind sensor, ☒ location of control and measurement unit ---- border to forest.

light attenuation time during a measurement interval (0.5 hours) and also registered the time of each individual particle beam passage.

The Measurement Plot

A sheltered place in an opening of a sparse forest in Luleå (65°37″N, 20°09″E), in northern Sweden was chosen for the test. The place was chosen following the recommendations of Tabler *et al.* (1990) for a reference gauge to minimize the wind disturbance of the reference gauge. The optical gauge, a standard SMHI precipitation gauge with a wind shield and a ground-based precipitation tray was placed at the site together with wind-speed and a temperature sensors located at 2 m height (see Fig. 1b). The measurements during 1992 started on February 18 and continued until June 21 and were complemented with some rain events during August 3 to 17.

The ground-based tray consisted of a 0.36 m^2 white painted tray with sharp 0.05 m edges placed horizontally on the ground. The reference precipitation (the SMHI-gauge and the tray) was emptied manually at intervals varying from 1 to 24 hours. The temperature measurements were made with a ventilated and shielded platinum resistance thermometer (Prt) probe (YA-100-Hygrometer, Rotronic Instrument Corporation, Switzerland) and the wind speed was measured with a Young Model 12002 3-cup anemometer (R. M. Young Company, U.S.A.) with a threshold velocity of 0.5 m/s. The temperature and the wind were recorded with the measurement and control unit and 0.5-hour averages of the parameters were stored.

Theory

Temperature as Category Divider

With a roughly linear relationship between rain precipitation amount and accumulated attenuation time the same relation was assumed for snow and sleet but with different k-values for the three categories. The precipitation amount was calculated according to

$$P = t\,k(\text{precipitation form})$$

where P was the precipitation (mm), t was the accumulated attenuation time (s), k(precipitation form) was a constant depending on the type of precipitation (mm/s).

There exists statistical correlation between air temperature and form of precipitation. The findings of Rohrer (1989) from Switzerland were used to divide the precipitation into rain, sleet and snow. Rohrer concludes that snowfall events at temperatures T above +2°C or rainfall events below 0°C are all of low intensities. Precipitation categories were thus assumed depending on the temperature

a) T greater than +2°C, only rain
b) T between 0 to +2°C, mixed snow and rain, *i. e.* sleet
c) T less than 0°C, snow only.

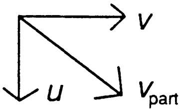
The measured attenuation time (the passage time) should be corrected for wind since the passage time for a particle is influenced by the wind velocity. The passage time in calm air t_{calm} for a particle with the radius r is

$$t_{\text{calm}} = \frac{2r}{u}$$

where u is the fall velocity.

The passage time t_{wind} for a particle influenced by the wind velocity v is

$$t_{\text{wind}} = \frac{2r}{v_{\text{part}}} \quad \text{with } v_{\text{part}} = \sqrt{(v^2+u^2)}$$



The passage time in still air t_{calm} can thus be calculated from the wind influenced passage time t_{wind} using the correction factor f if the fall velocity u is known

$$t_{\text{calm}} = t_{\text{wind}} f \text{ with } f = \sqrt{(\frac{v}{u})^2 + 1}$$

Since snow is lighter than sleet and rain the influence of wind should be greatest for the snow events. The average snow fall velocity 0.75 m/s (see Fig. 2) reported by Mellor (1966) and Rosinski *et al.* (1983) was used for the calculations.

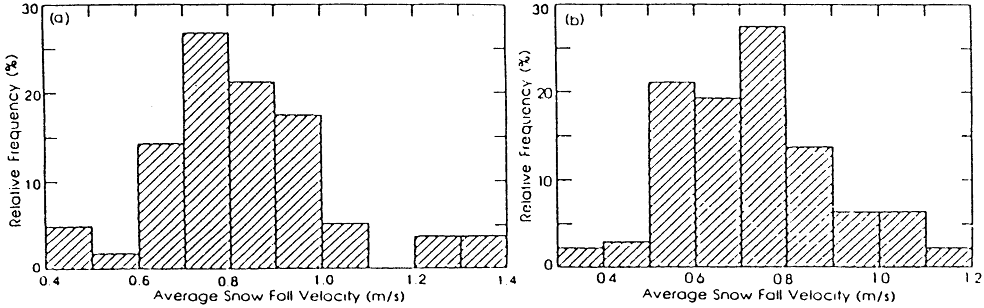


Fig. 2. Histogram of average snow fall velocity. a) Mellor 1966. b) Rosinski *et al.* (1983) – from Koh *et al.* (1988).

Passage Time as Category Divider

Rain particles should have shorter passage times than snow particles due to the smaller size and the higher density of the rain particles. This is confirmed by the recognition matrix for precipitation (HSS 1987) giving the velocities and the particle sizes for different hydrometeorologic particles. To investigate if the passage time of the individual particles could be used as an indicator to distinguish different types of precipitation (rain and snow) the attenuation of individual particles was also registered and compared to the type of precipitation.

Result

The reference gauges, the SMHI-gauge and the ground-based tray gave roughly the same results. The average differences was less than 5% so only the SMHI-gauge was used for the comparisons with the optical gauge. The calculations of snow-water equivalent were made for half-hour period but the comparisons with the reference could only be made for longer periods since the reference was emptied manually with times varying from 1 to 24 hours.

Temperature as Category Divider

The attenuation time (without wind correction) plotted *versus* the reference precipitation in Fig. 3 for the three temperature categories shows great scatter but the values fall around three different lines. The rain values fall along a line with a steep slope (much precipitation for each attenuation time unit) and the snow values fall along a line with float slope (little precipitation for each attenuation time unit) and the sleet values scatter around a line somewhere in between.

The slope of the lines – the *k*-value – (forcing the line through origo) was determined for each temperature group. The *k*-values for the snow, sleet, rain categories became 0.016, 0.82 and 3.69 mm/s, respectively. The *k*-value thus varied

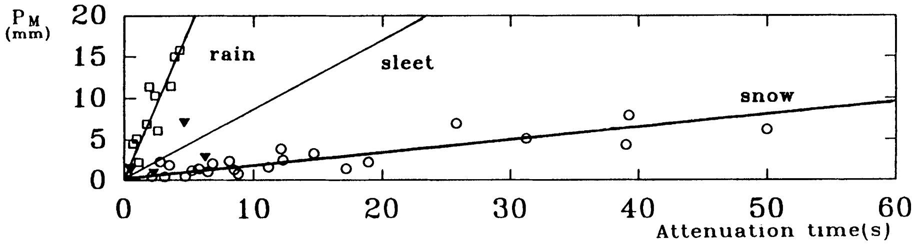


Fig. 3. Attenuation time plotted *versus* measured precipitation. □: rain, $+2 < T$ (°C), ▽: sleet, $0 < T \leq +2$ (°C), o: snow, $T \leq 0$ (°C). T is average temperature during the snowfall event, all temperatures are given the same weight without consideration to the amount of precipitation falling during each interval.

with a factor of approximately 5, the k-value of sleet was approximately 5 times as great as the k-value of rain and the k-value of snow was approximately 5 times as great as the k-value for sleet. Since the scatter was rather great and there were few observations within each group (especially the sleet group) approximate values of the k-values were used according to

$$k(\text{snow}) = 0.16 \text{ mm/s}; \quad k(\text{sleet}) = 5 * k(\text{snow}); \quad k(\text{rain}) = 25 * k(\text{snow})$$

The calculated precipitation with approximate k-values and no wind correction determined for each half-hour period in Fig. 4 shows a rather large scatter with a

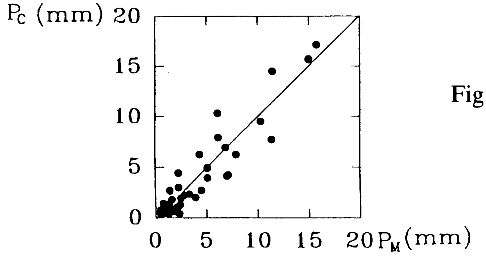


Fig. 4. Calculated precipitation values P_C using k-values $k(\text{snow}) = 0.16$ mm/s; $k(\text{sleet}) = 5 * k(\text{snow})$; $k(\text{rain}) = 25 * k(\text{snow})$ plotted versus measured precipitation values P_M. No wind correction.

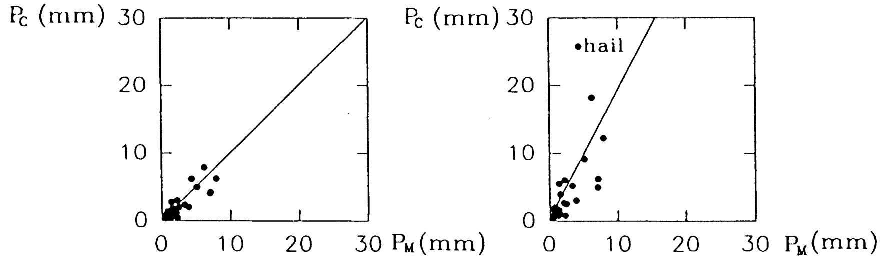


Fig. 5. Correlation between calculated solid precipitation P_C and measured precipitation values P_M using $k(\text{snow}) = 0.16$ mm/s. a) Without correction factor. b) With wind correction assuming fall velocity $u = 0.75$ m/s.

correlation r^2 of 0.87 between the calculated and the measured precipitation values.

The introduction of the wind correction factor f when calculating the snow precipitation showed that the k-factor for the snow events should be lowered from 25 to a value approximately half that value (see Fig. 5). The correlation between the calculated and the measured values did not improve by introducing the correction factor and a hail event P_C = 26 mm deviates from the other values.

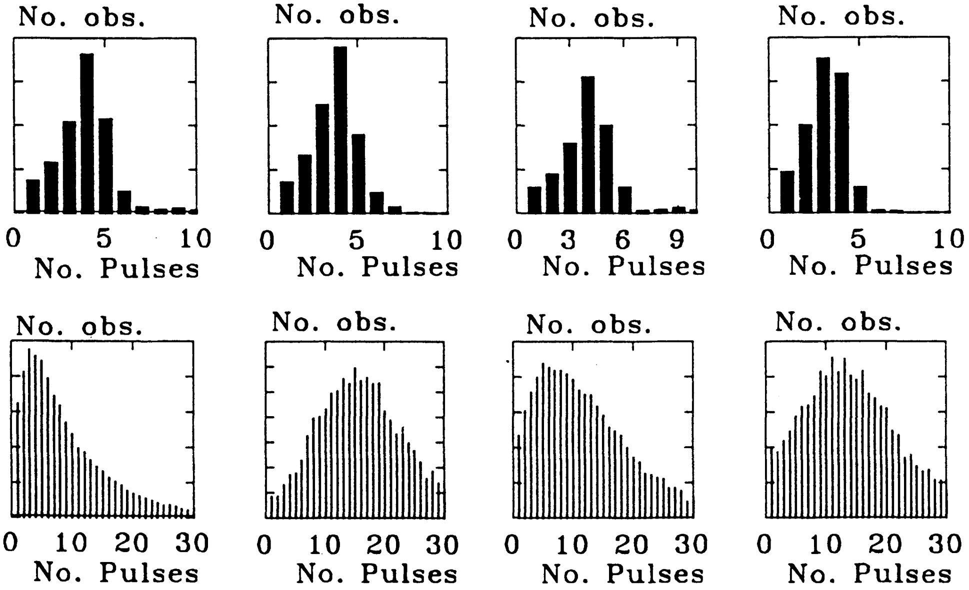


Fig. 6. Distributions of particle passage times for four different a) rain and b) snow events. No. obs. = number of observations, No. Pulses = number of pulses, one pulse = 120 μs, M = median passage time.

Passage Time as Category Divider

The distribution of particle passage time for some measured rain events (Fig. 6a) shows that almost all rain events have a median particle passage time M of 4 pulses $\approx$ 0.5 m/s.

The distribution of particle passage time for some snow events (Fig. 6b) showed greater dispersion. The median value of particle passage time varied between 4 and 17 pulses. The number of rain, snow and sleet events for different median particle passage times M plotted in Fig. 7 (the temperature categories used earlier in this article were used for determination of precipitation type) showed that all rain passage times were shorter than five pulses (= 0.6 m/s) and that all but one snow event had longer passage times than five pulses. The sleet events had medium pulses varying from 3 to 8 pulses.

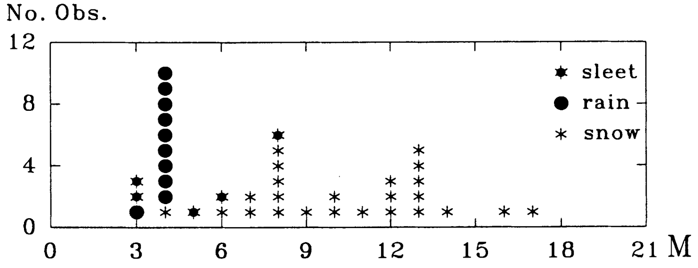


Fig. 7. Number of precipitation events of different categories plotted against median particle passage time M (1 pulse = 120 μs).

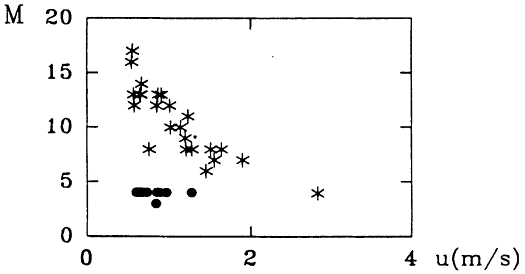


Fig. 8. Median particle passage time M plotted versus wind velocity for rain ● and snow * (1 pulse = 120 μs).

The median pulses M plotted against medium wind velocity (Fig. 8) confirm that the snow passage time becomes shorter when the wind velocity increases. The snow median passage time can be expected to approach (and even fall below) rain values at wind velocities above 2-3 m/s.

Discussion and Conclusions

At low wind speeds (< 2 m/s) it seems possible to use median particle passage time as a tool to distinguish snow from rain. Approximately 40% of the solid precipitation measured at an open site in Finland near Helsingfors falls at wind speeds (2 m level) lower than 2 m/s according to Madsen *et al.* (1990; 1993). For those 40% it should be possible to use particle passage time as a tool to distinguish precipitation type. It might be possible to distinguish snow from rain at higher wind-speeds by using some other distribution parameter than the median. This has not been tested here. For high wind-speed events temperature should be better as a tool to distinguish precipitation categories. According to Rohrer (1989) the number of snow events with high intensities at temperatures above +2°C and the number of rain events with high intensities at temperatures below 0°C is even lower if the wet bulb temperature is used instead of air temperature. The wet bulb temperature should thus be better suited than the dry air temperature for distinguishing rain from sleet and snow. The wet bulb temperature was not tested in this study due to lack of short-time reference precipitation measurements.

That the correlation between measured snow precipitation and calculated precipitation (see Figs. 5a and b) was not improved when the wind correction was introduced was a bit surprising. One explanation might be that we only had events with rather low wind speeds, since the measurement plot was located in a forest opening. Another explanation might be the high threshold velocity of the wind-speed sensor causing all wind velocities less than 0.5 m/s to be recorded as 0.5 m/s. That the hail event (Fig. 5b) gave too high a calculated precipitation when treated as snow was however to be expected, since hail has higher density than snow. Wind corrections should also be performed on rain and sleet events but the effect of these corrections should be less since those particles have higher densities and are thus less influenced by the wind. For special studies of the wind-error the gauge should be placed in a wind exposed place and the reference measurements must be made with much greater time resolution than in this study.

From this study it it not possible to see if there is any under-catch due to convection caused by the heating of the transmitters and receivers, neither is it possible to see the effect of wind from the aerodynamic design of the gauge. The under-catch due to wind should be considerably less than with the traditional bucket type of gauges, due to the aerodynamic design of the gauge. The heat required to warm the small transmitters and receivers is little so the convection error should be small. The gauge itself does not distinguish between hydrometeorological particles and other particles and reacts to airborne seeds (*e.g. Tarraxacum sp.*), but this can be done by filtering away non-hydrometeorological particles.

It seems possible to estimate the type and the amount of precipitation for different types of precipitation with an optical gauge provided the demand on accuracy is not too high. This can be done by using the particle passage time to determine type of precipitation at low wind velocities and the wet bulb temperature for higher wind speeds. The precipitation mass can be calculated by using different linear relationships between accumulated passage time for the rain, snow and sleet categories. The passage times should be corrected for wind influence first and the non-hydrometeorological particles have to be filtered away.

The company TELUB has continued to develop the gauge after this test and delivers the gauge with software calculating the precipitation intensity, the type of precipitation and filtering away of the non-hydrometeorological particles. Temperature and windspeed is accounted for when determining the precipitation. No information is given about how these corrections are made nor how the filtering is made. The gauge including software have been accepted for a test by the World Meteorological Organisation (WMO).

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