6.6 AN ALGORITHM DERIVING SNOWFALL FROM AN ENSEMBLE OF SONIC RANGING SNOW DEPTH SENSORS

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1. INTRODUCTION

Because of the desire to save money, as well as the need to take measurements in remote locations and difficult terrain, ultrasonic snow depth ranging sensors (USDS) have traditionally been one of the most popular methods for taking automated snowfall (SF) measurements in lieu of manual observations. These sensors have been used extensively with regards to avalanche forecasting (Ferguson et al. 1990), and for snow removal operations triggered by exceeding specified snow-depth thresholds (Gray and Male 1981). These sensors have also be used to quality control automatic recording gauge measurements by providing additional details on the type, amount, and timing of precipitation (Goodison et al. 1988).

While this technology is not the only in-situ method currently used to measure SF (weighing snow gauges, pulse light source detectors, hotplate total precipitation gauge, laser snow gauge, and infrared triangulation sensors are other commonly used technologies all of which have advantages and disadvantages of using in comparison to USDS technology), USDS have the advantage of being "relatively" cheaper to install, easier to maintain, safer to use, and use less power in comparison to some of the other technologies. Technologies which measure snowfall rates using the principle of optical attenuation have been shown to be misleading in many instances due to the wide variety of snow crystal types (Rasmussen et al. 1999). Meanwhile, technologies which calculate total precipitation, and not SF, are not always able to correctly identify the phase of the precipitation it measured.

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The operating principle behind using USDS is that they take snow on ground readings as a point-oriented distance to target measurement. The USDS chosen by Environment Canada (EC) is the Campbell Scientific Sonic Ranging Sensor (SR50; CSD 2003). The SR50 consists of a transmitter/receiver which emits/receives a 50 kHz ultrasonic pulse. The time it takes for the pulse to return to the receiver (after reflecting off a targeted surface) divided by two gives the distance to the target in metres. The more snow there is on the ground beneath the sensor, the less time it takes for the sound to return the receiver. Subtracting this number from a fixed reference point creates a "Snow on Ground" (SOG) measurement. The change in SOG levels over time gives, in theory, a SF measurement.

Because SF measurements are constructed from the derivation of SOG measurements over time, other meteorological phenomena; such as melting, settling, and redistribution of snow; can influence the ability to derive a SF statistic. Additionally, the snow surface structure (low density snow) can cause problems with the SR50's ability to report snow depth (Goodison et al. 1984). Problems have also been identified with the ultrasonic pulse being attenuated owing to intense snowfall or low density snowfall events, thus resulting in less reliable return signals (Brazenec and Doesken 2005).

It is because of these concerns that EC has been working on an algorithm to improve upon the derivation of automated SF measurements (Fischer and Durocher 2006; hereafter referred to as FD06). The idea behind their work was that by using an ensemble of three SR50's, as well as a Geonor Total Precipitation Gauge with single Alter-shield, a more accurate SF measurement is produced if there is a consensus amongst the instruments that SF occurred (increase in Snow on Ground levels under the three SR50 sensors, and Precipitation in the case of the Geonor). The reason for using two different types of sensors is that both the SR50 and Geonor were not developed to measure actual SF. From this point forward the algorithm used will be denoted as S3-1 (i.e. three SR50's and one Geonor sensor algorithm).

The objective of this study is to continue the evaluation of the S3-1 algorithm which was first introduced in FD06. The new case studies are from St. John's, Newfoundland. St John's is located on the Avalon Peninsula, a site which experiences strong winter storms, as well as warm and cold spells which should greatly influence SOG measurements. Because of St. John's vicinity to the Atlantic Ocean, the area experiences heavy snowfall events (often blowing snow occurs simultaneously), as well as heavy rain and mixed precipitation events. Frequent periods of freezing rain and freezing drizzle are also common.

The authors of this paper strongly recognize the triple configuration precipitation algorithm developed by NOAA's National Climatic Data Center for the Geonor Weighing Precipitation Gauge (Baker et al. 2005). The SF algorithm which will be presented in this paper is an adaptation of this algorithm. The SF value presented in this paper will be compared to the "measured 24 hour SF totals" (MSF) owing to the fact the manual observations of SF were measured at this time frequency.

2. TEST DATA SETS

Raw data was collected from three SR50's and a Geonor at St. John's International Airport Newfoundland, Canada (CYYT) from 06 UTC 23 January 2006 to 06 UTC 1 April 2006. The ground surface of the test-site slopped downwards towards the north, so any SR50 readings made were somewhat comprised by this fact. The uneven ground surface also made it more likely that drifting snow would become an issue for this experimental data set.

The SR50's were attached onto posts approximately 2 metres high off the ground. The posts were connected onto a trestle oriented in the northeast-southwest direction. The first SR50 sensor (hereafter referred to SR50a), faced northwest and was placed 7 metres to the northeast of the other two sensors. The remaining two of SR50's (hereafter referred to as SR50b and SR50c, respectively) were oriented 180 degrees apart from each other at the southwest end of the trestle, and faced southeast and northwest respectively. The concrete posts on which the trestle was mounted also comprised somewhat this experiment, because snow could occasionally pile up near the posts.

The SR50's were configured to detect three target echoes and send serial ASCII messages with distances and quality numbers. Sensors were polled once a minute and output data was recorded in daily files with a time stamp. Any missing return signals or data of low quality were replaced by the value recorded by that SR50 one minute earlier. The data was then filtered to retain values for the last 4 minutes of each quarter hour (each quarter hour ended at zero, fifteen, thirty, and forty-five minutes, respectively). The four minutes of each quarter hour were then checked between each other to see how many of the SOG values were within 2.5 cm of each other. All the target echoes which met these criteria where then were averaged to produce an averaged quarter-hour SOG value. In cases where none of the four SOG measurements were within 2.5 cm of each other, the SOG value constructed 15 minutes earlier was used.

Because the speed of sound is dependent on the density of air (primarily as a function of temperature), the distance to target measurements have to be corrected by the following equation:

$$CDT = RDT*(T_{KELVIN}/273.15)^{0.5}, \quad (1)$$

where CDT = Corrected Distance to Target Reading in metres
RDT = Raw Distance to Target Reading in metres
T_{KELVIN} = Air Temperature in Kelvin

The Geonor Total Precipitation Gauge was sited approximately 28 metres to the southwest of the SR50 array. It had one transducer, and an Alter-Shield. The instrument took readings every five seconds of the weight of liquid water captured by the instrument (change of liquid water over time yields a "precipitation" statistic). Each measured reading was inserted into the following recursive equation (a low-pass filter):

$F(X_i) = W^*X_i + F(X_{i-1})^*(1-W),$ (2)

where F is the value of the Geonor at any given X_i and is denoted by $F(X_i)$

X_i is the current output value of the Geonor

W is the weighting function which in this case is 10 percent (0.1)

Using this equation ensures that anomalous readings are filtered out, and that no missing values in the time series would be recorded.

Finally, daily 24 hour MSF at 06 UTC, and hourly aviation Metars taken by a NAV CANADA contract weather observer were recorded. The 24 hour MSF, which is defined as the "True Value" in this study, will be compared to the SF values outputted by the algorithm in order to validate the algorithm's "goodness". It should be noted that the SF measurements taken by the observer at a different part of the airport compound, so the answers may be comprised by this fact.

3. DESCRIPTION OF THE SNOWFALL ALGORITHM

There are two main parameters upon which the S3-1 algorithm will be dependent on. The first parameter must deal with the aforementioned problem that changes in SOG levels may not be because of SF. The second parameter sets a time limit over which changes in SOG levels beneath each SR50 sensor are compared.

Once the parameters have been defined, a detailed description of the S3-1 algorithm will be presented. Please refer to FD06 for a similar flowchart of this algorithm.

3.1 *Threshold Snowfall Parameter*

To deal with the issue that SOG levels can be caused by factors other than SF, a "snowfall threshold" (ST) value of 1.0 cm is introduced (the accuracy of the SR50 is ±1.0 cm). The purpose of the ST is to set a minimum value where changes in SOG must occur beneath each SR50 sensor before deciding that SF possibly occurred beneath that sensor. At time step zero, SOG values for the three SR50 sensors (a, b, and c), and the measured weight of water collected by the Geonor are put into place-holder reference levels. For each subsequent time step (every 15 minutes), new SOG measurements are recorded and then subtracted from the reference levels as denoted in equation 3.

Δ (SOG for the SRa) if (3)
(SRa – SRahold) ≥ ST or
(SRa – SRahold) ≤ ST

Δ (SOG for the SRb) if
(SRb – SRbhold) ≥ ST or
(SRb – SRbhold) ≤ ST

Δ (SOG for the SRc) if
(SRc – SRchold) ≥ ST or
(SRc – SRchold) ≤ ST

When at least 2 of the 3 SR-50's meet these criteria, the following procedure is performed. If the Δ SOG levels are negative, the three SRholds and the Geonorhold are reset to the new values measured at the last time step. The process then begins again with step 3.

Otherwise if the Δ SOG levels are positive, the three SRholds and the Geonorhold are reset to the new values measured at the last time step. A check is then done to see if the Geonor has also indicated precipitation using equation 4.

(Weight of water presently in Geonor) – Geonorhold ≥ 0.2 mm (4)

If equation 4 is not true, then the process begins again with equation 3. Otherwise, if equation 3 is true, the algorithm will assume that SF has occurred. How the SF statistic is actually calculated will be presented is subsection 3.3.

3.2 *Time Limit Parameter*

The second parameter that the S3-1 algorithm is dependent on is related to how long one holds the SOG place-holders if SF has not occurred. In theory, one can keep going forward in time subtracting every 15 minutes the new SOG measurements from the place-holders until this subtraction becomes a value greater than/less than or equal to the ST value. The problem with doing this is that it increases the uncertainty to the reasons why the Δ SOG values have occurred. Besides the aforementioned possibilities in previous sections, the Δ SOG levels could be due to a series of very-light snowfall events (thus the SF statistic produced by this algorithm would not be representative of a single, continuous SF event).

Before the algorithm computes the values denoted in step (3), the current time is subtracted from the time of the SOG placeholders (i.e.; the Time count). If this value exceeds 6 hours (i.e.; a difference of 6 hours and 15 minutes), all the SOG and Geonor placeholder values are advanced 15 minutes to the measurements recorded 6 hours earlier.

To summarize, the minimum amount of time that new SF could be indicated by the S3-1 algorithm is 15 minutes (i.e.; one time step). The maximum amount of time allowed between the current SOG reading for each sensor and its' associated reference level place-holders is 6 hours (i.e.; 24 time steps).

3.3 *The Calculation Procedure*

The procedure described in this subsection assumes that all three equations met the criteria in equation 3. In the cases where only two of the three sensors met these criteria, the procedure that will be described below is only applied to the relevant SR50 sensors. Since this is a subset of the overall procedure, all of these possible permutations will not be described in this paper.

Once the conditions set subsections 3.1 and 3.2 have been met, a question has to be asked about which Δ SOG value is the most representative of the actual SF. To answer this question a "difference in the Δ SOG" (DSG) statistic is introduced. In this statistic all the Δ SOG's are subtracted from each other, and then seen if they are less than a maximum threshold value. The equations are calculated as follows:

DSGab = ABS (Δ (SOG for the SRa) - Δ (SOG for the SRb)) ≤ 1.5 cm (5)

DSGac = ABS (Δ (SOG for the SRa) - Δ (SOG for the SRc)) ≤ 1.5 cm

DSGbc = ABS (Δ (SOG for the SRb) - Δ (SOG for the SRc)) ≤ 1.5 cm

The left-hand side (LHS) of equation 5 checks how far apart the Δ SOG values are for two SR50's. If the DSG numbers are not small, this means that one cannot be certain that other meteorological conditions, such as drifting snow, influenced the observed Δ SOG values.

By introducing a maximum threshold value (1.5 cm on the right-hand side (RHS) of equation 5) for which the equations in equation 5 must meet, one introduces a check to ensure that the Δ SOG levels were primarily due to SF. The value of 1.5 cm was chosen because the precision of an observation taken by the SR50 is ±1.0 cm. Subtracting two SR50 observations from each other results in a number with an error value slightly greater than ±1.4 cm (this number was rounded up to 1.5). A DSG number greater than the absolute value of 1.5 cm means that the two Δ SOG levels are statistically different from each other. In contrast, a DSG number less than this value means that the SF answers produced by the two SR50 sensors are statistically similar to each other.

There are four possible outcomes represents of equation 5 which are as follows:

<u>Outcome # 1</u>

DSGab, DSGac and DSGbc are all ≤ 1.5cm. In this case all three sensors give a possible SF answer. Therefore all three Δ SOG values averaged.

SF = Average of (SRa – SRahold), (SRb – SRbhold), and (SRc – SRchold)

<u>Outcome # 2</u>

Two of three DSG's are ≤ 1.5cm (take DSGab and DSGac as an example). In this case the Δ SOG that occurred beneath the SRa sensor is within 1.5cm of both the SRb and SRc sensors. However the Δ SOG that occurred beneath the SRb and SRc are different by more than 1.5cm. Therefore in this case only the SRa instrument is used to calculate SF.

SF = (SRa – SRahold)

<u>Outcome # 3</u>

Only one of the three DSG's has a value ≤ 1.5cm (in this example take DSGab).

In this case the Δ SOG that occurred beneath the SRa and SRb sensors are within 1.5cm of each other. The Δ SOG that occurred beneath the SRc sensor is different by than 1.5cm to both the SRa and SRb sensors. Therefore only the Δ SOG values for the SRa and SRb sensors are averaged in this case.

SF = Average of (SRa – SRahold)
and (SRb – SRbhold)

Outcome # 4

In this case all three DSG's have values > 1.5 cm. This means that underneath all three sensors, large Δ SOG values occurred that were not within 1.5 cm of each other. Situations like this are most likely to occur when heavy SF, such as lake-effect, occurs. Therefore, another test is needed to calculate a SF statistic. To deal with this possible scenario, a normalization parameter (NP) is introduced, as is calculated as follows:

NPab = (DSGab) / (Δ (SOG for the SRa) + Δ (SOG for the SRb)) ≤ 0.35 (6)

NPac = (DSGac) / (Δ (SOG for the SRa) + Δ (SOG for the SRc)) ≤ 0.35

NPbc = (DSGbc) / (Δ (SOG for the SRb) + Δ (SOG for the SRc)) ≤ 0.35

In equation 6, the LHS of the equations represents the "difference of SF" (DSG) in the numerator divided by the "total magnitude of snowfall" in the denominator. The RHS of equation 6 checks to see if the LHS is ≤ to 35 percent (denoted by 0.35) of the total magnitude of SF which occurred underneath both sensors.

The procedure then continues exactly as before (this time using equation 6) when the four possible outcomes of equation 5 were considered. If this time Outcome #4 is reached, a SF value of zero cm is given. Once a SF statistic has been produced, the procedure begins again with subsections 4.1 and 4.2.

Although the statistics presented in this paper will be for 24 hour SF totals, the S3-1 algorithm was developed to automatically output an answer every 6 hours (i.e., at 00, 06, 12, and 18 UTC).

4. CASE STUDIES

4.1 *Overview Of The Figures*

When examining the SR50 SOG and Geonor curves displayed in all of the subsequent figures, one needs to look at their derivatives and not instantaneous values. The starting points for the three SR50 curves were arbitrarily set (the Geonor curve was set to zero) for easier visual examination. A positive derivative (either Δ SOG values underneath each SR50 sensor over time; or Δ in measured weight of water captured by the Geonor over time) indicates periods were SF might have occurred.

The Weather Indicator (WxInd) curve is a function which is either zero or a positive value such as one or three. At each time step where no weather is occurring (i.e.; clear skies), the function is given a value of zero. Otherwise, if precipitation is occurring (i.e.; SF, freezing rain, etc) then a value greater than zero is indicated.

The measured snowfall (MSF) curve is outputted each day at 06 UTC. Its value is set to zero at every other time step. This function represents the 24 hour MSF totals taken by the NAV CANADA contract observer at St. John's International Airport.

The wind speed curve (WndSpd; on figures which they are displayed) represents a fifteen minute average of ten metre winds in knots. Higher wind speeds are, obviously, often associated with drifting and blowing snow events. Additionally when relevant, the temperatures will be denoted by the Temp function.

Finally, the S3-1 curve is a step function where each step represents the value of the SF statistic calculated by the algorithm. Segments of the curves where the slope is zero represent no SF observed. Obviously there will be a delay between the actual start of a SF event and the S3-1 algorithm outputting a SF statistic.

4.2 *Light Snowfall Case Study*

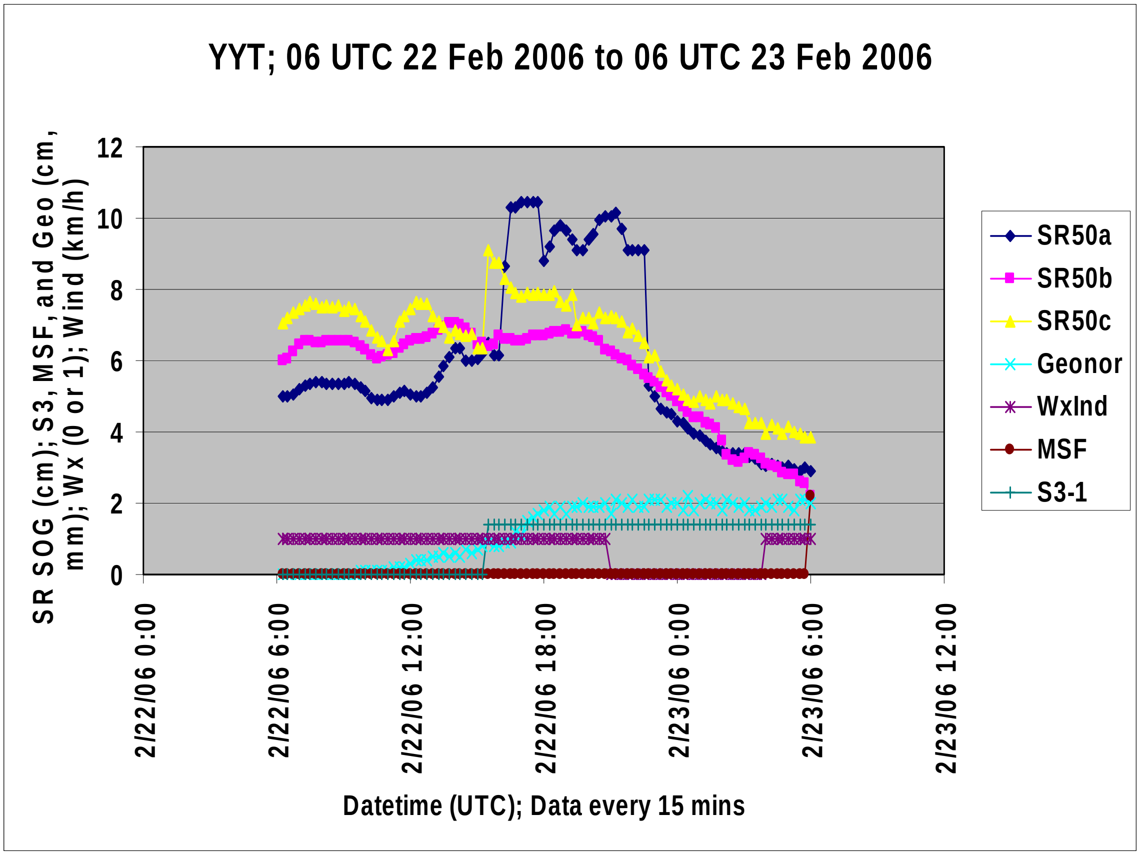

Figure 1. SR50 SOG measurements, accumulative Geonor and S3-1 algorithm functions, Aviation Metar Weather Indicator (WxInd; zero = no snow or one = snow), and daily 06 UTC 24 hour measured snowfall (MSF) at St. John's International Airport (CYYT), Newfoundland, Canada for 22 February 2006.

For the first case study (Fig. 1) a passing low pressure system was responsible for the weather observed at St. John's airport on 22 February 2006. Two separate periods of SF (as indicated by the break shown by the WxInd curve) fell. The first period of SF occurred with an easterly, onshore flow (winds increasing from 3 to 15 knots) slowly backing to north as the low pressure system passed near St. John's. A break in the precipitation began near 21 UTC on February 22nd. Snow showers began to fall over the test site in the strong southwesterly flow (winds near 25 knots) behind the passing cold front near 03 UTC on February 23rd. The temperatures remained relatively stable throughout the day ranging from -3° C to -7° C.

Observing the behaviour of the three SR50 curves, all slightly oscillate up and down throughout the time series. This is indicative of SF (when it occurred as indicated by the WxInd); as well as settling and drifting of the snow pack. The drifting is most obvious in the later part of the day as all the SOG levels under all three SR50 sensors fell as the winds increased in strength.

SF was indicated by the S3-1 algorithm when the SR50a and SR50c sensors (both facing towards the northwest) indicated an increase of SOG levels near 16 UTC on the 22nd (a 1.4 cm SF statistic versus the 2.2 cm MSF taken by the NAV CANADA weather observer). The fact that it was the northwest facing sensors that indicated SF proves that, in this case, the SF "statistic" was somewhat influenced by snow drift, and the directional orientation of the sensors. These two points illustrates some limitations of using sonic ranging sensors to derive SF. However, that fact that two out of the three sensors indicated a rise in SOG levels illustrates an example where using a consensus of snow depth sensors gives an advantage over using just one sensor.

4.3 *Heavy Snowfall Case Study # 1*

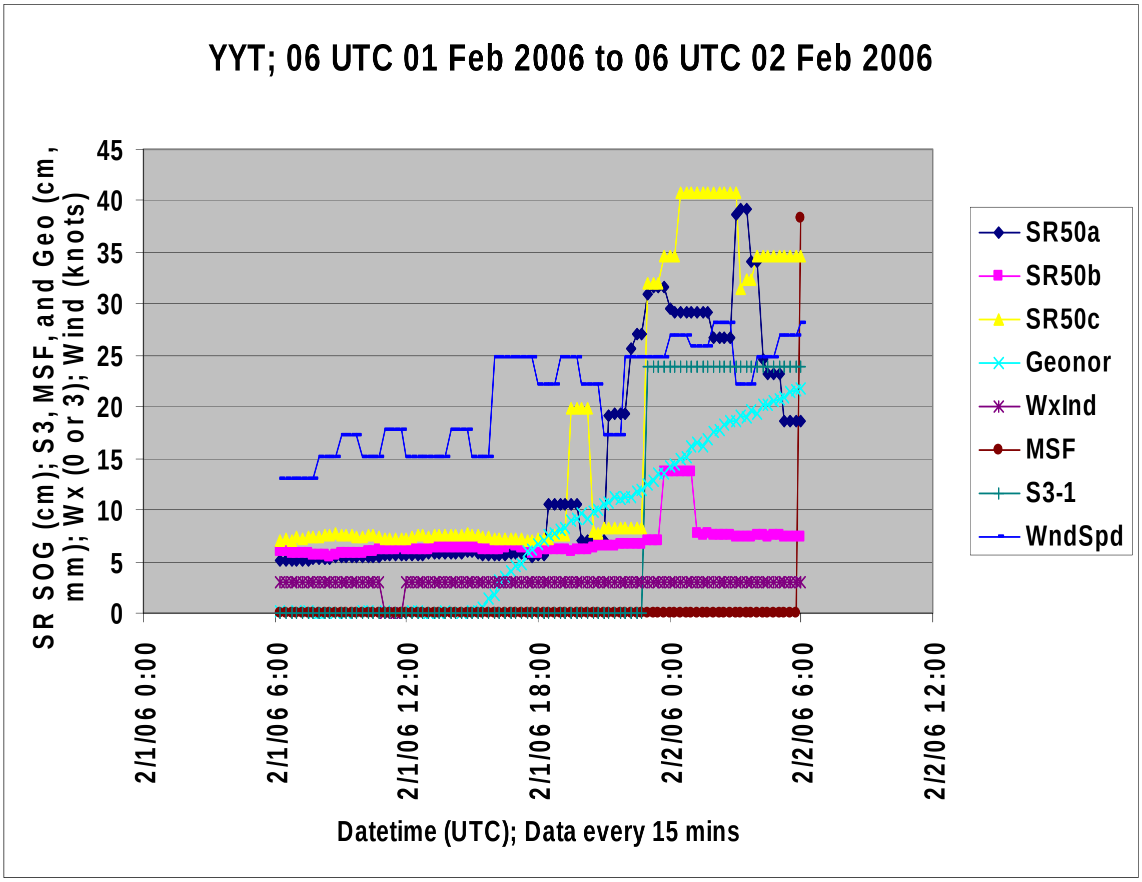

Figure 2. SR50 SOG and 10 metre Wind Speed measurements, accumulative Geonor and S3-1 algorithm functions, Aviation Metar Weather Indicator (WxInd; zero = no snow or three = snow), and daily 06 UTC 24 hour measured snowfall (MSF) at St. John's International Airport (CYYT), Newfoundland, Canada for 1 February 2006.

For the second case study (Fig. 2) snow and blowing snow affected the test site throughout the day of 1 February 2006 resulting in a heavy snowfall event (note the 21.8 mm captured by the Geonor and the official MSF value of 38.4 cm). Temperatures remained below freezing beginning at -4° C and rising to -0.6° C near the end of the day.

All three SR50 SOG curves shown in this figure were strongly filtered by the procedure described in section 2 (note the numerous periods where the slopes of curves are zero indicating that the SOG value from fifteen minutes earlier was used). This was due to the fact that very strong easterly winds, which slowly backed to the northeast by the end of the day, affected the test site. This obviously affected the minutely SOG levels beneath each of the SR50 sensors, as well as resulted in target echo returns of poor quality.

As in the first case study, the northwestward facing SR50a and SR50c sensors where more influenced by drifting snow; as well as better capturing the actual SF which fell. The SOG levels for the southeastward facing SR50b sensor (except for the snow drift between 00 and 01 UTC on Feb. 2nd) only rose by 1 cm over the 24 hour period.

A single S3-1 SF step of 23.9 cm was produced by the algorithm at 23 UTC on Feb 1st. Once again, having only a single SF step is a function of the 4 minute averaging describe in section 2. This can be seen by proved by examining the S3-1 algorithm function in Fig. 3 below.

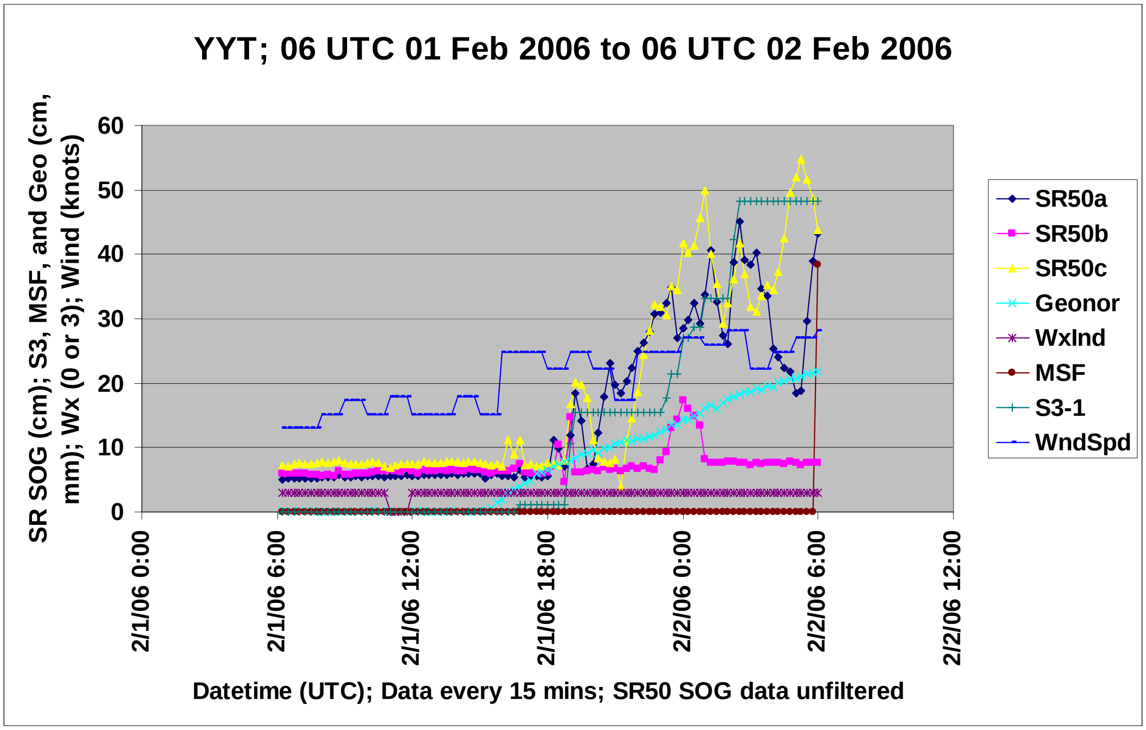

Figure 3. Same as Fig. 2 except in this case the SR50 SOG values are unfiltered

Fig. 3 is for the exact same case as Fig. 2, but in this case the SOG values for each quarter hour did not have the 4 minute filter applied to it. In other words, the SR50 values were not filtered for bad quality numbers and were not compared with the three previous minutes in the time series.

There are results two interesting facts of note to compare between the two figures. First, see how the SR50 time series (especially the SR50a and SR50c sensors) oscillate more than in the unfiltered case study. This results in S3-1 algorithm producing more than one SF statistic over the 24 hour period. Second note how the final 24 hour SF value produced by the S3-1 algorithm function is different than using the filtered SR50 time series (48.2 cm for Fig. 3 versus 23.9 cm for Fig. 2). This illustrates an important point of how making a simple change in how the SR50 data is inputted into the S3-1 algorithm can result in a different SF answer. It is impossible to develop an algorithm which will give a "better" answer in every case. Comparison statistics will be given in Section 4.

4.4 *Freezing Rain/Freezing Drizzle Case Study*

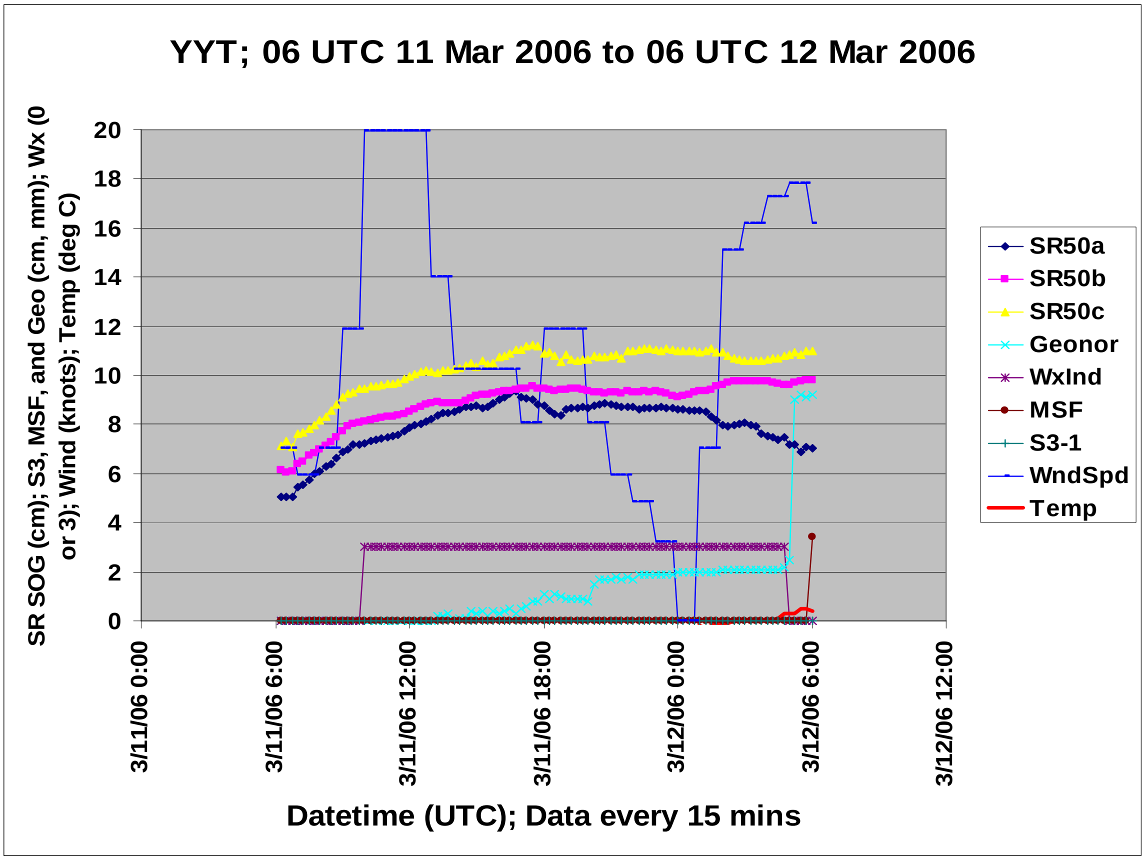

Figure 4. Same as Fig. 2 for 11 March 2006 with addition of temperature (Temp) values in ° C.

For the third case study (Fig. 4) freezing rain, freezing drizzle, ice pellets, and freezing fog was recorded by the NAV CANADA weather observer throughout the day of 11 March 2006. During this period the winds backed from the south to southeast, and temperatures remained below the freezing point. Around 01 UTC on Mar 2nd, the winds veered to the west, temperatures rose above 0° C (note the Temp function), and the weather conditions changed over to drizzle and fog.

Examining the SR50 functions from 06 to 18 UTC on Mar 11th, one can see that the SOG levels rose under all three sensors. This is yet another case of snow drift (remembering the aforementioned meteorological conditions in the previous paragraph, as well as noting the strong winds indicated the WndSpd function). Because the Geonor function did not record much precipitation accumulation, this is a case where the S3-1 algorithm successfully worked. However, this case does illustrate the need to better identify times when drifting/blowing snow occurs, as well as the need to identify the phase of the precipitation which is falling. Even though the algorithm worked in this case, under a similar scenario a false SF statistic could be produced if the Geonor had captured more precipitation.

A final point of interest is to examine the Geonor time series near 00 UTC on March 12th. The total "new" precipitation recorded by this instrument jumped from 2.5 mm to 9.0 mm in one 15 time step. This occurrence was correlated with the temperature rising above 0° C. It is obvious that the water which froze on the instrument melted and fell into the instrument. This is another example of how an increase in liquid precipitation amounts could have resulted in the S3-1 algorithm producing a false SF statistic.

4.5 *Heavy Snowfall Case Study #2*

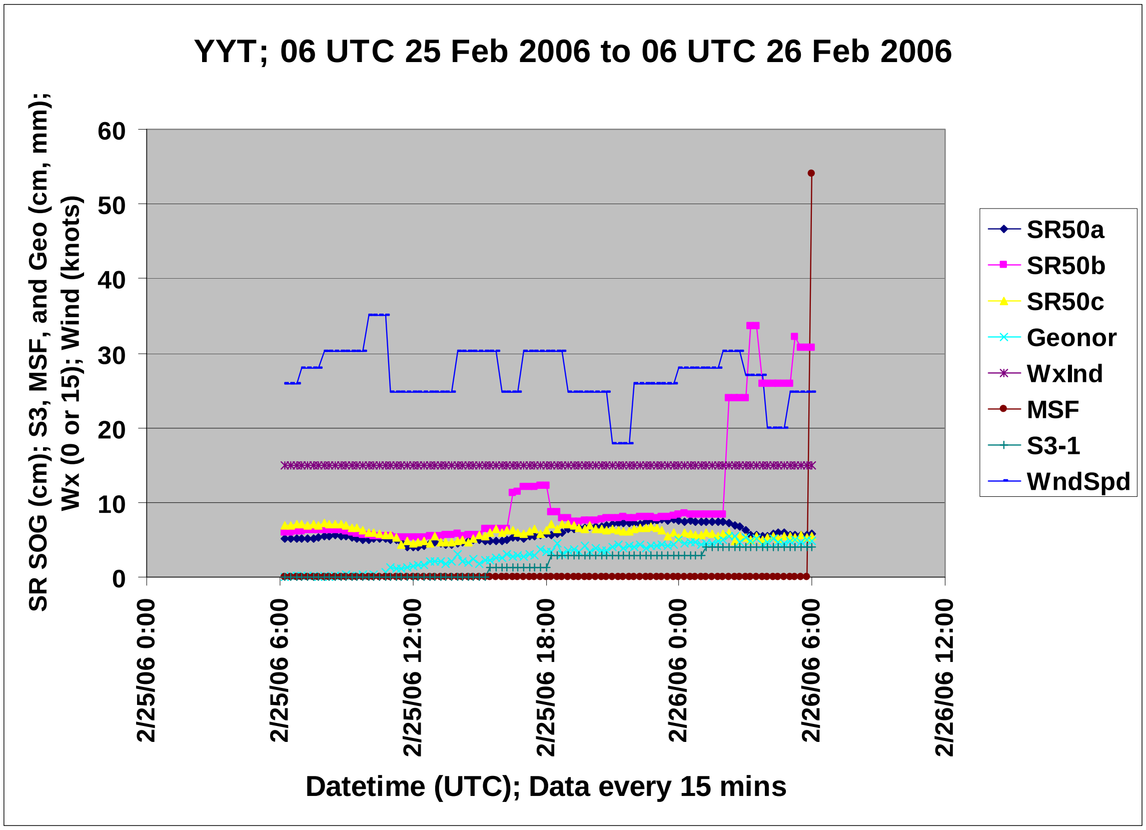

Figure 5. Same as Fig. 2 for 25 February 2006 except *Aviation Metar Weather Indicator (WxInd; zero = no snow or fifteen = snow).*

For the fourth case study (Fig. 5) snow and blowing snow (at times heavy) was recorded by the NAV CANADA weather observer throughout the day of 25 February 2006. During this period very strong winds backed from northwest to west, and temperatures remained below freezing ranging from -5.7° C to 1.6° C.

Examining the SR50 functions, one can see that very little new snow was able to accumulate under the northwestward facing SR50a and SR50c sensors. Only under the more wind-shielded southeastward facing SR50b sensor did approximately 25 cm of new snow accumulate (remember that the SR50 time series was filtered so the sudden 16 cm step observed at near 2 UTC on the 26th is artifact of that filtering). This example once again illustrates a major problem of using sonic ranging sensors to derive SF from the differential of SOG measurements (i.e.; drifting snow caused by strong winds makes it difficult to measure new SF). In this case the S3-1 algorithm produced at 4.0 cm 24 hour SF statistic in comparison the 54 cm measured by the NAV CANADA weather observer.

The problem of drifting snow influencing SOG levels beneath the SR50 sensors becomes further obvious if one examines Fig. 6.

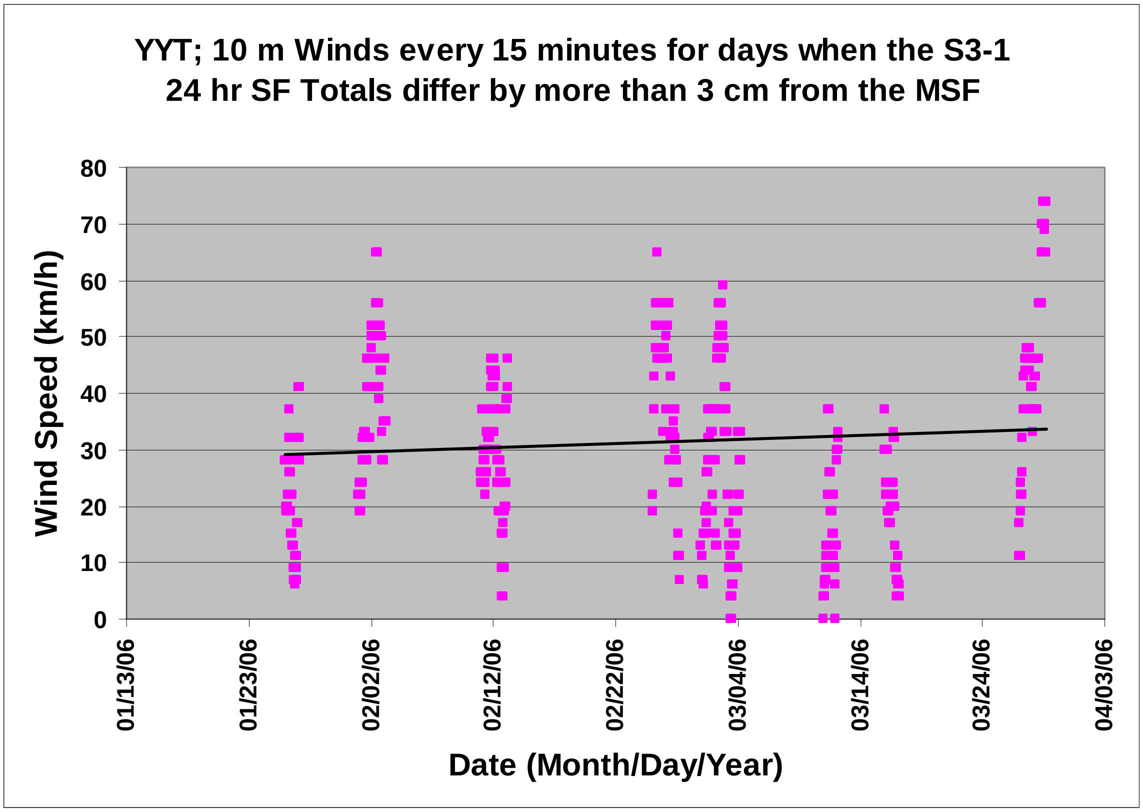

Figure 6. Ten metre winds every 15 minutes for the days when the 24 hr SF values produced by the S3-1 algorithm differ from the official 24 hr MSF value by more than 3 cm. A trend line was added to the figure to identify average wind speed over the 22 days comprising the data set.

As can be seen in this figure, the average wind strength for these 22 days was around 30 km/h. Improvement of the S3-1 algorithm to deal with cases of snow drift under high wind conditions will be done in a future generation of the model.

5. ALGORITHM VERIFICATION STATISTICS

5.1 *Overview Of The Statistics*

The S3-1 algorithm will be run three times with different permutations in order to identify how well the various components of the algorithm work. The first model run will be performed using the procedure described in section 2. The second model run will test to see how not using the four minute filter affects the final statistics. In other words, only take the SOG measurements at zero, 15, 30, and 45, and rerun the algorithm program. The third model run will only use the SR50a sensor in order to see if a consensus approach gives statistically a better answer. The algorithm program from the second model run was modified so that a SF event was identified if the SOG levels beneath the SR50a passed the 1.0 cm ST, and if the Geonor also indicated that at least 0.2 mm of precipitation had fallen.

We propose to characterize the "goodness" of the S3-1 algorithm for all the model runs by calculating the average of the absolute value of differences (i.e.; the "Error") between 24 hour MSF (by a human observer) and 24 hour SF statistics produced by the S3-1 algorithm. In other words, how close are the algorithm derived 24 hour SF values to the measurements taken by a human observer? This approach is a better method of calculating the variance than using the least squares method. The reason for this is that taking the square of a small number produces a number of a much smaller value (i.e.; causes distortion). The main reason why this approach is not used frequently in data analysis is because the absolute value function is not differentiable at zero.

To further identify the “goodness” of the algorithm, the dataset will be subdivided into three classes. These classes will see how well the algorithms perform over all days comprising the data set (ALL N class), days were SF ≥ 0.2 cm occurred (SF class), and days where no precipitation of any type fell (NO SF class). Days where trace SF occurred were included in the NO SF class. The magnitude of cases comprising the SF class ranged from 0.2 cm to 54.0 cm.

Another statistic which shall be used to validate the algorithm is to take the percent difference between the daily SF measurements taken by a human observer (summed over the entire data set) versus the sum of SF measurements calculated by the S3-1 algorithm. Percent difference is a simple, traditional measure of strength of relationship between what is defined as the “True Value” versus the “Observed Value”.

5.2 *Analysis Of The Statistics*

ALGORITHM S3-1	CLASS	∑|MSF-S3| /N	% DIFF BET. S3 AND MSF FOR ALL N	DAYS (N)
4 minute Filter used	ALL N	3.58	70.14	67
	SF	5.21	71.91	45
	NO SF	0.24		22
4 minute Filter not used	ALL N	6.62	29.91	67
	SF	9.62	26.44	45
	NO SF	0.47		22
SR50a only 4 minute Filter not used	ALL N	96.09	2125.3	67
	SF	128.67	1906.89	45
	NO SF	29.44		22

Table 1. Average of the Absolute Value of Difference Statistics between 06 UTC daily measured snowfall (MSF) and S3-1 algorithm (four minute filter used, four minute filter not used, and SR50a sensor only), and Percent Difference over the entire data set between Total MSF and Total SF calculated by the S3-1 algorithm (same three permutations as before). The Class column comprise these statistics for of all days in the data set (ALL N), days that snowfall ≥ 0.2 cm fell (SF), and days with no measurable precipitation of any kind (NO SF).

To interpret the results of Table 1, one compares the numbers down a column. The smaller the number, the closer the average value produced by the S3-1 algorithm is to SF values measured by a human observer. A value of zero means, in theory, a perfect score.

When examining the results of the Absolute Value of Difference column, it is obvious that statistically the best results, no matter the class, are obtained when the four minute filter was used. This suggests that filtering the SR50 SOG values helps to minimize false reports of SF when the SOG values fluctuate wildly from minute to minute, or the signal returns are of poorer quality. However, if one compares the Percent Difference column, it would suggest that statistically one obtains a better answer if the four minute filter was not used. The case study presented in section 4.2 (a SF statistic of 23.9 cm for the filtered case versus 48.2 cm for the unfiltered case and 38.4 cm taken by the human observer) gave an example when using filtered SR50 SOG data also filtered new SF measurements (even when the 4 minute filter uses a relatively large number of 2.5 cm as a threshold value). Other case studies (not shown) proved that averaging the SR50 data may result in the S3-1 algorithm missing light SF events. It also tends to underestimate SF values when SF occurs.

Of the three algorithm model runs, the statistics for the SR50a only version was by far the worst. This proves that using a consensus of three sonic ranging sensors to derive a SF statistic from SOG measurements gives a better answer than just using one sensor.

6. CONCLUSIONS

There are five definitive conclusions that can be drawn from the results of this study. First, using a triple configuration of SR50 Ultrasonic Ranging Sensors to produce a consensus snowfall statistic yields a more precise answer than using just one SR50. Second, when deriving snowfall from the differential of "Snow on Ground" measurements, averaged data helps to minimize false reports of snowfall caused by snow drift or poor return signals. Third, averaging the SR50 data during periods of snowfall can have the effect of filtering out actual snowfall, and thus result in a less accurate total snowfall measurement. Fourth, better diagnosis of snow drift will be needed to further minimize snowfall measurement errors. Fifth, the orientation of the SR50 sensors (the compass direction the sensors are facing) can result in differing "Snow on Ground" measurements.

This study has introduced and statistically qualified an algorithm which tries to incorporate the points identified in the previous paragraph. While this algorithm has shown promise, more work will have to be done to minimize the average difference between the magnitudes of snowfall produced by the algorithm and measured snowfall by a human observer. More data from other sites with different snowfall climatologies will have to be collected and analyzed to ensure that the results presented in this study are not an artifact of geographic location. Finally, more analysis will be needed to deal with the aforementioned problem of snow drift, as well as the measurement of very light snowfall events.

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