P 3.8 DEMONSTRATION OF THE USE OF RUNWAY VISUAL RANGE (RVR) VISIBILITY SENSORS FOR ESTIMATING SNOWFALL RATES THROUGHOUT THE AIRPORT DOMAIN

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1. INTRODUCTION

Efficient management of aircraft on the airport during snowfall events requires knowledge of liquid-equivalent snowfall rates at all times over and all possible tracks of aircraft transit on the surface. A fundamental requirement is knowledge of the amount of equivalent liquid water content of snowfall that aircraft experience during their transit through frequently inhomogeneous conditions on the airport surface. This paper demonstrates the potential of using Runway Visual Range (RVR) sensors as a means of estimating snowfall rate over the entire airport domain. This is done using actual snow gauge and visibility sensor (VS) extinction coefficient (σ) data from Denver International Airport (DEN) during a snowfall event on March 15, 2000. The process includes: co-locating a snow gauge with an RVR sensor; comparing snow gauge measurements to exco measurements at this same site to determine the calibration factor for transforming values of σ to snowfall rates; using this calibration factor to compute liquid-equivalent snowfall rates at all RVR sensor locations; interpolating these snowfall rates over the entire airport domain; and then associating aircraft tracks derived from aircraft tracking systems with snowfall rates along the tracks in real time. An alternative approach is to interpolate values of σ first and then transform these into snowfall rates, using the calibration factor derived from the co-located VS and snow gauge. The resulting product should prove highly useful for ensuring safe operation of aircraft under all types of snowfall conditions and for managing deicing operations and snowfall removal, particularly at large airports with large geographical extents that utilize RVR VSs throughout much of the airport domain.

1.1 Background

METAR Data Format is the international standard for official reporting of surface weather conditions based on either human observations or automated observing systems. The official weather conditions reported in this paper are derived from Automated Surface Observing System (ASOS) METAR data recorded at DEN; the ASOS at DEN is located about 1.5 nautical miles SSE of the terminal area, between RVR sensors VS04 and VS05 near RW 17R35L. This location is shown in Fig. 1 along with the identity of VSs and the snow gauge used in this study. METAR visibilities are reported in statute miles (SM) with precipitation and obstruction to visibility designated as: SN – snow; BLSN – blowing snow; FG – fog; FZFG – freezing fog; and/or BR – mist.

An *RVR Visibility Event* is defined as any time when RVR is less than 6,500 ft (US) or 1,600 m (international). The most common causes are fog and snow. In the US, the 3 categories of RVR are: Cat I for 2,400 ≤ RVR ≤ 6,500 ft; Cat II for 1,200 ≤ RVR < 2,400 ft; and Cat III for RVR < 1,200 ft

RVR values reported to controllers are computed products that depend on measurements of σ obtained from visibility sensors (VS) on active runways, runway light settings and background luminance. The fundamental atmospheric parameter of interest for snowfall rate inferences is σ. Only in daytime conditions does this parameter relate directly to the RVR values, that is, Koschmeider's Law applies and yields

$$V = 9842.5\ \sigma^{-1} \qquad (1)$$

where V is the visibility in ft and σ is in km^{-1}. This corresponds to ranges of about 1.5 - 4.1 km^{-1} for Cat I conditions; 4.1 - 8.2 km^{-1} for Cat II; and over 8.2 km^{-1} for Cat III.

All times are given either in Greenwich Mean Standard Time (GMT) or in minutes relative to a specified starting time.

The snow gauge and VSs recorded measurements concurrently from 1750-2359 GMT during the March 15, 2000 snow event. The measurements were recorded once a minute. The snow gauge was a Geonor T-200B Precipitation Gauge, operated independently by the National Center for Atmospheric Research (NCAR). The data were made available by Dr. Roy Rasmussen. The VSs were part of the RVR System operated by the Federal Aviation Administration (FAA) in support of airport operations at DEN.

Table 1 identifies the VS designations and their respective runway configurations. Note that two of the runways are designated Category III runways with VSs sited near Touchdown (TD), Midpoint (MP) and Rollout (RO) locations. Four other runways are Category II runways with VSs located at each end of the runway. As noted previously, the corresponding map of the runways is shown in Fig. 1. The snow gauge is located about 500 m W of VS12. The ASOS site is also identified, since its data are used for generating the METAR reports used here to identify weather conditions.

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Table 1. DEN Visibility Sensor Designations.	
RUNWAY	**VS**
17L35R	VS01, VS02 and VS03
17R35L	VS04, VS05 and VS06
16-34	VS10, VS11 and VS12
7-25	VS13 and VS14
8-26	VS15 and VS16
There are no VS07, VS08 or VS09 at DEN	

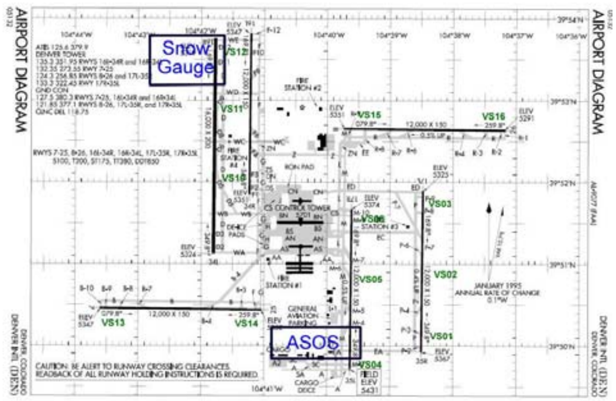

Fig. 1. Runway map of DEN and Locations of RVR visibility sensors, the snow gauge and the ASOS.

2. PREVIOUS RELATED STUDIES

Rasmussen et al. (1999) explored the use of visibility data to estimate liquid-equivalent snowfall rates. Their experimental, empirical and theoretical results clearly showed that the relationship between visibility and snowfall rate can be highly dependent on the type of snowfall, which can also be quite variable and different for different events as well as within events. In a related study that examined meteorological conditions associated with five icing-related aircraft accidents, Rasmussen et al. (2000) concluded that liquid-equivalent snowfall rates, as opposed to visibility, were more reliable for assessing aircraft icing conditions. They concluded that visibility-based assessments of snowfall conditions can be misleading to pilots and ground crews for assessing icing conditions. Nevertheless, Seliga et al. (2004) found very good general correlation between nearly co-located measurements of snowfall rates and σ. Thus, visibility measurements do relate to snowfall intensities, but the relationship is not fixed and needs to be tracked in order to be useful for inferring reliable quantitative snowfall estimates. This result is explored further in this paper, based on the hypothesis that measurements of σ can be transformed into liquid-equivalent estimates of snowfall rates on a continuous basis over the domain of the airport environment when the latter are based on real-time calibration of σ to snowfall rates at one or more instrumented, co-located sites. The applicability of this calibration procedure assumes that at any given time the type of snowfall is basically the same throughout the airport domain.

3. SNOWFALL AND EXTINCTION COEFFICIENT

The snow gauge data are shown in Fig. 2. Examination of the 1-min snowfall rate data shows a high degree of temporal variability that is most likely representative of a natural noisiness in the snow gauge data that is not useful for the application. The latter premise is tested by comparing the original 1-min data with 5-min running averages that are also shown in the figure. The data sets show that 5-min averages are both representative and provide very good time resolution of the snowfall rate inherent variability present in the data. Extinction coefficient data (not shown) also exhibited a high degree of variability with 1-min sampling, thereby indicating consistency with the snowfall data. Accordingly, 5-min running averages of snowfall rates and extinction coefficients are considered preferred over 1-min averages.

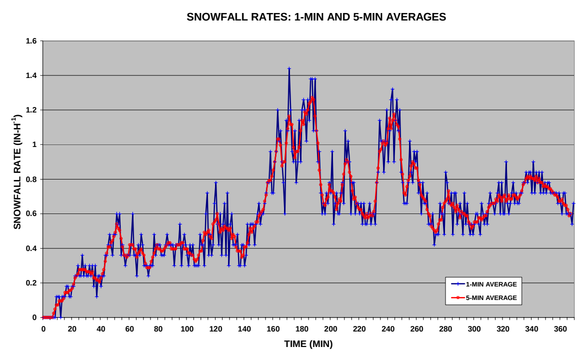

Fig. 2. Comparison of snowfall rate data at 1-min and 5-min sampling periods, showing the inherent noisiness of the former and the representativeness of the latter.

For this application, it is necessary to project past observations to future times from the latest measurements out to the next observation (1-min after the latest observation). Various levels of sophistication could be applied to this very near-term nowcasting task. However, it was found that good representation of snowfall rate (or σ) is realizable with a simple nowcasting model that gives greatest weight to two most recent 1-min data samples. The calibration procedure at the co-located site(s) uses 5-min running averages of the parameters. Transformation of extinction coefficient into values of snowfall rate depends on this calibration factor in accordance with the 1-min forward nowcasted values of σ' given by

$$\sigma' = (\sigma_o + \sigma_{-1} + 0.5^* \sigma_{-2})/2.5 \qquad (2)$$

where σ_o is the current 5-min running average measurement; σ_{-1} is the previous 1-min measurement; and σ_{-2} is the 1-min previous measurement observed 2-min prior to the current time sample. A sample comparison between the actual 5-min running averages and nowcasted values of snowfall rates is given in Fig. 3. The results are considered quite good and acceptable to the application without any further analysis.

It is also noted that the 500 m separation between sensors produced a time difference between the measurements; this difference is attributed to storm advection. During the first phase of the storm, this difference required accounting for a delay of ~13-min between the snowfall measurements and the values of σ obtained with VS12.

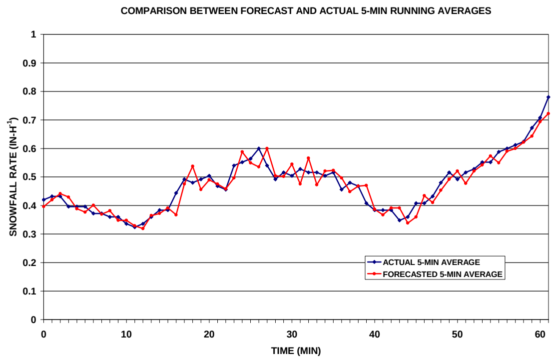

Fig. 3. Illustration of the projected values of 5-min average snowfall rates compared with actual values applicable to the same 1-min time period.

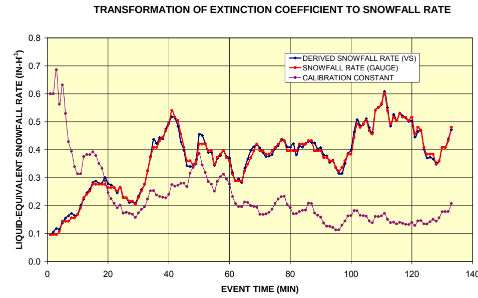

Fig. 4. Results of applying the calibration process to values of σ', showing values of the calibration constant and snow gauge data applicable to the same 1-min time periods.

3. SPATIAL RESOLUTION

An appropriate spatial resolution of the airport domain was selected as being 15 m separation between pixels. This is compatible with a speed of around 30 mph that yields a 1-pixel transit in around 1-s. Also, Airport Surface Detection Equipment (ASDE) systems have update surveillance rates of ~1-s. For the purpose of illustration in this paper, smoothed values of σ', derived from Eq. 2 at each VS, were then interpolated over the runway area with this resolution. (NOTE: VS14 was excluded from the interpolations due to failed operation.) The interpolated values of σ' could then be extracted for different tracks that aircraft might make while taxiing from a gate to deicing stations and takeoff points at the airport. The snowfall rates are found by applying the appropriate, time-dependent calibration factor to these tracks of σ'. The result of the process for determining the calibration factor and applying it to the co-located visibility sensor is illustrated in Fig. 4; the plots show the calibration factor, the snow gauge 5-min running averages and the σ'-derived values. Note that the calibration factor differs considerably over the 2+ hrs of the data, ranging from ~0.6 in the beginning of the event record to ~0.2 near the end. This result is compatible with those of Rasmussen et al. (1999) who reported the relationship to vary up to around a factor of ten.

4. WEATHER CONDITIONS

The official METAR reports indicated SN- from 1646 through 1914, intensifying to SN from 1953 through 2353. (Note: the 0-min time in Fig. 2 is at 1750.) A high accumulation (SNINCR) report of 1 in-h^{-1} was issued at 2353. The winds blew generally from the north during the event with speeds ranging from 9-14 kt. Visibilities decreased from 7 SM at 1653 to 0.25 SM by 1905 and remained at 0.25 SM the rest of the day. Temperatures were at 2^{o} C at 1653 and decreased to 0^{o} C at 1914 and further to –1^{o} C at 2053 and remained at –1^{o} C the rest of the day. Dew points were at 0^{o} or –1^{o} C during the event until dropping to –2^{o} at 2353. Mist was recorded from 1730-1914, and then fog at 1953 and freezing fog from 2053 on. The reported changing conditions of mist, fog and freezing fog were important in that they may explain the variable calibration constant shown in Fig. 4.

5. INTERPOLATED EXTINCTION COEFFICIENTS

Figs. 5, 6 and 7 are three examples that illustrate interpolated values of σ' over the airport during the snowfall event. Multiplication of these results by the applicable calibration constant would give liquid-equivalent snowfall rates. Fig. 5 is representative of a relatively uniform portion of the event with small variability over most of the airport; MOR visibility is ~ 1-km over much of the airport. Fig. 6 shows σ' at a time when MOR visibility is around a factor of two higher over most of the airport than those in Fig. 5; this time also indicates least visibility near the touchdown areas of RW 35R and 34L. Fig. 7 shows a time when MOR visibility is highly inhomogeneous and low over much of the airport; RW 17R35L is particularly affected with MOR visibility being ~0.8-km over most of its runway extent. The combination of these sample extrapolated images of σ' demonstrate that visibility, and snowfall rate, can vary greatly over an airport. Similar high degrees of variability were also demonstrated previously at other airports by Seliga et al. (2001, 2004) and Hazen et al. (2002, 2003).

6. PARAMETER EXTRACTION

In order to determine the amount of snowfall that has fallen on an aircraft, data have to be continuously extracted from the sequence of interpolated results at aircraft locations along their tracks over the airport surface. The process requires extracting snowfall rates along these tracks from the time-dependent maps or images of σ' as aircraft proceed from gates to deicing to takeoff positions on the airport surface. This entire procedure is not illustrated here. Instead, the extrapolated values of σ' are shown versus time at the ASOS site in Fig. 8. A second example extrapolation shows plots of σ' and liquid-equivalent snowfall rates along a sample aircraft track at times corresponding to the values of σ' in Figs. 5, 6, and 7. Both types of results illustrate how parameters can be extracted from the interpolated data, either at single points on the surface or along designated tracks.

The example track is the mostly black trace shown in Figs. 5, 6 and 7. It consists of a departure starting from Gate A33 at the terminal; the aircraft then travels west to the deicing area, from which it proceeds north along another taxiway until it reaches an east-west crossing taxiway that is just north of the control tower; it then goes east to another taxiway that enables it to transit diagonally SSE to the taxiway that is to the left, parallel and adjacent to RW 17L35R. The track proceeds south to the end of RW 35R where the aircraft can then enter the takeoff position. All told, the distance of this track is ~8-km. With plane taxiing speeds ranging between around 3 to 15 m-s^{-1}, the transit time for the plane from gate to takeoff position along this track, excluding time for deicing, would by around 12-15 min. Essentially, it would be readily possible to associate snowfall rates continually along this or any other track aircraft make while transiting the surface of the airport.

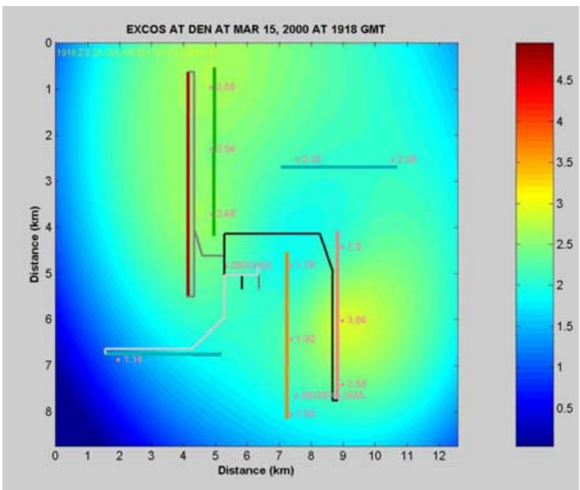

Fig. 5. Interpolated values of extinction coefficient during a time when MOR visibility (and snowfall rate) was ~ 1-km and relatively uniform over most of the airport domain.

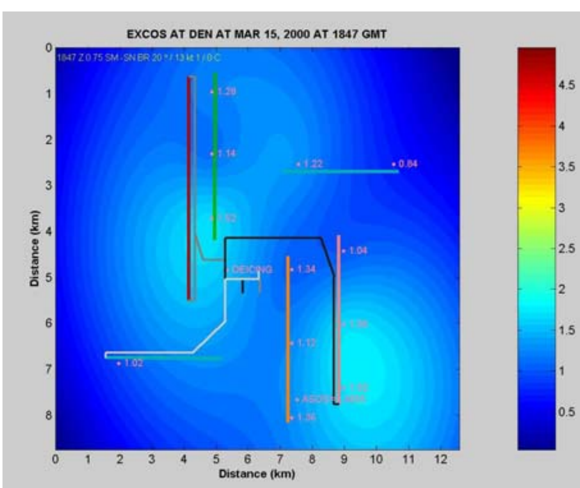

Fig. 6. Interpolated values of extinction coefficient during a time when MOR visibility (and snowfall rate) was $\gtrsim$ 1.7-km over the airport, being least near the touchdown areas of RW 35R and RW 34L.

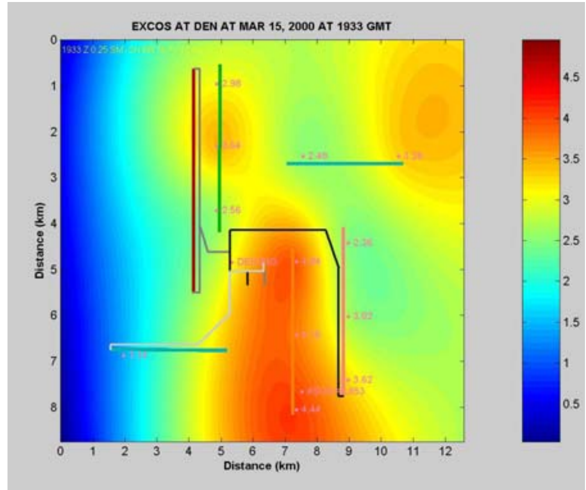

Fig. 7. Interpolated values of extinction coefficient during a time when MOR visibility (and snowfall rate) was highly variable, exhibiting a minimum MOR of ~0.7-km over nearly all of RW 18L35R.

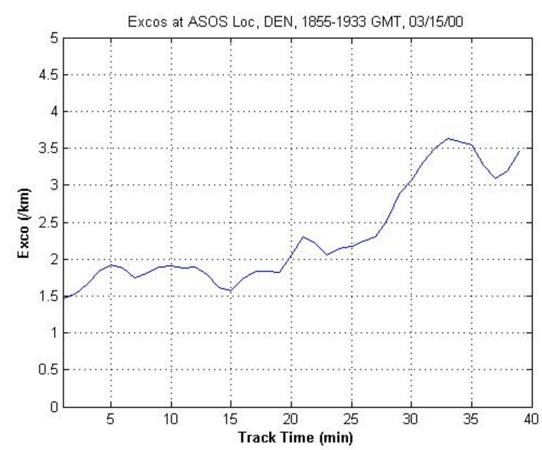

Fig. 8. Example of extracted values of extinction coefficient (readily transformable into liquid-equivalent snowfall rates) at the DEN ASOS location.

The extracted liquid-equivalent snowfall rates along the track, corresponding to the images in Figs, 5, 6 and 7 are shown in Figs. 9, 10 and 11, respectively. Note that the transformation from σ' to snowfall rate at the different times of these cases were nearly equal for Figs. 5 and 7 and differed considerably for Fig. 6; the respective calibration constants for each of the figures (0.166, 0.312, 0.163) were derived from comparison of the nearly co-located gauge and VS. Aside from demonstrating extraction of snowfall along a track, the results also illustrate that there can be a high degree of variability of snowfall rate (and σ') along aircraft tracks. Note that, for another related application, temporal integration of snowfall rates on such tracks can be used to gauge snowfall accumulations and assist airport operators more effectively plan and manage snowfall removal operations.

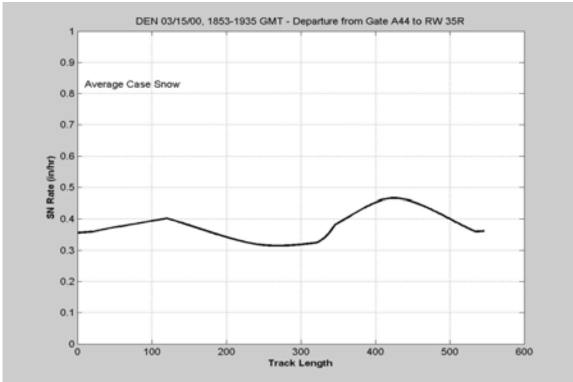

Fig. 9. The snowfall rate along the designated track at the time of the example extinction coefficient image shown in Fig. 5. The calibration constant for this transformation is 0.166.

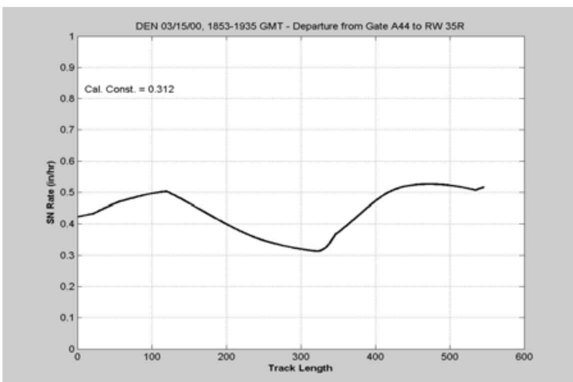

Fig. 10. The snowfall rate along the designated track at the time of the example extinction coefficient image shown in Fig. 6. The calibration constant for this transformation is 0.312.

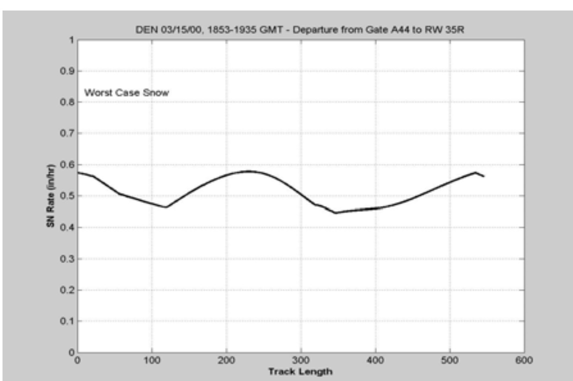

Fig.11. The snowfall rate along the designated track at the time of the example extinction coefficient image shown in Fig. 7. The calibration constant for this transformation is 0.163.

7. CONCLUSIONS

This paper demonstrated a method of estimating snowfall rates anywhere on an airport surface. The technique involves: calibration of extinction coefficient measurements obtained from RVR visibility sensors based on snowfall rate measurements at one or more co-located sites; and interpolation of extinction coefficient measurements (or transformed snowfall rates) over the airport domain. The snowfall estimates can also be enhanced through the addition of other sensors (snow gauge or extinction coefficient) as needed at any given facility. The results are expected to prove useful for estimating amounts of snowfall impacting aircraft during their surface operations, and for assisting airport maintenance personnel in managing snowfall removal operations. The concept is particularly appealing as a means for enhancing the performance capabilities of decision-making systems such as the Weather Support to Deicing Decision Making system that was designed to provide airline, airport and air traffic users with winter weather information (Rasmussen et al., 2001).

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