A Combined Sensor Method for Detecting Frost Formation

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1. Introduction

Frost accretion on aircraft surfaces is a potential hazard because frost buildup can reduce wing performance. Currently, pilots have to manually check aircraft for frost and deice if frost is present. Anti-icing fluids are often applied if frost is expected to form overnight. Since frost is not associated with any type of observable precipitation, can't be observed by radar or satellite, and isn't reported by ASOS/AWOS or in the METARS, it can be a difficult phenomenon to detect in an automated way. In order to address this problem, a study was undertaken to determine the feasibility of developing an automated algorithm for frost detection using a suite of various instrumentation.

2. Methodology

One of the principle instruments used in this study was a Decagon Leaf Wetness Sensor (LWS) shown in figure 1. The LWS is sensitive enough to detect miniscule amounts of water or ice buildup on its surface. It estimates the surface wetness by measuring the dielectric constant (also known as the relative permittivity) of the sensing surface. The dielectric constant is the extent to which a material concentrates an electrical flux. The LWS used in this study has an average dielectric constant of 258 mV. As water or ice builds up on the surface of the sensor, the measured dielectric constant increases.

Figure 1 – Decagon Leaf Wetness Sensor

In addition to the LWS, data from a B.F. Goodrich Ice Detector was used. Previous research has shown that the Goodrich Ice Detector used by Automated Surface Observation System (ASOS) for detecting freezing rain has some capability of detecting heavier accumulations of frost (Ryerson and Ramsay 2007, Ryerson 1994). This sensor uses a rod that vibrates at 40,000 Hz. As ice accretes on the rod, the frequency decreases. If a heavy enough frost occurs, a decrease in frequency will

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** Corresponding author address: Scott Landolt, National Center for Atmospheric Research, 3450 Mitchell Lane, Boulder, CO 80301; email: landolt@ucar.edu* be observed. The combination of the Goodrich ice detector, temperature and relative humidity sensors, sky cover measurements, and LWS voltage were the basis for exploring an initial automated frost detection algorithm. Data from these sensors were collected during the 2008 - 2009 winter season at the National Center for Atmospheric Research (NCAR) Marshall Field Site just south of Boulder, Colorado.

Figure 2 – ASOS B.F. Goodrich Ice Detector Sensor.

Since there was no visual confirmation of frost formation during the 2008 – 2009 winter season, frost was inferred using the criteria established in Table 1. Dew point depressions of less than 6ºC were used to ensure near saturation conditions at the surface. No instrumentation was available to determine frost point temperature and depression; dew point temperature and depression were used as a substitute. Wind speeds were measured at two meters above ground level and a wind speed threshold of 4.5 meters per second was used to ensure turbulent mixing of the atmosphere wasn't preventing the formation of frost. Precipitation gauge data was analyzed to ensure no precipitation was occurring. Local METAR reports were evaluated for ceiling heights to confirm that no low clouds were present that may inhibit radiational cooling. Several cases were identified from this criteria and a case study from February 27, 2009 is presented here as an example for which all the conditions in Table 1 were met.

Instrument	Criteria
Leaf Wetness Sensor	Greater than 5mV
Dew Point Depression	Less than 6ºC
Wind Speed	< 4.5 m/s
METAR Ceiling	CLR or FEW
Precipitation Gauge/METAR	No precipitation reported during LWS increase

Table 1: Criteria used to determine frost cases

3. 2008 - 2009 Data analysis

The LWS showed skill in detecting frost when periods of voltage increases correlated well with low dew point depressions (Figure 3). Sensor voltage began increasing at 0500 UTC, which correlates well to the dew point depression dropping below 6ºC. Similarly in Figure 4, while wind speeds were briefly above the 4.5 m/s threshold when the LWS began showing an increase in voltage, they quickly dropped below the threshold and remained there for the duration of the event.

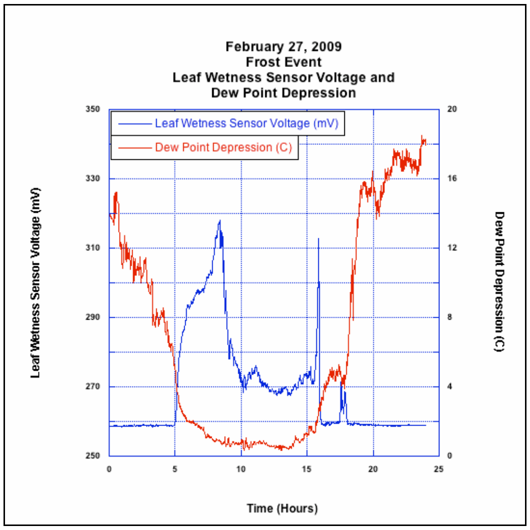

Figure 3 – Leaf wetness sensor voltage and dew point depression for February 27, 2009.

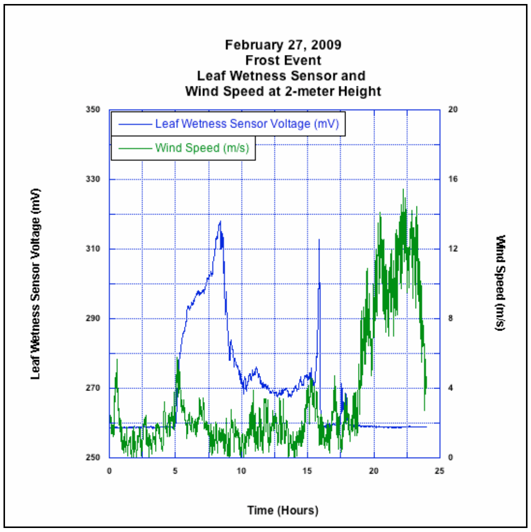

Figure 4 – Leaf Wetness Sensor voltage and wind speed for February 27, 2009.

The Goodrich Ice Detector did not show any frequency decreases during the February 27th event and precipitation gauges showed no accumulations (not shown). METAR observations showed high visibilities and ceilings from the surrounding ASOS (Table 2). Sky cover from the surrounding ASOS showed clear to few clouds indicating that cloud cover should not have inhibited radiational cooling (Table 2).

ID	TIME	VIS	CEIL	COV
KAPA	0753	10		CLR
KBKF	0755	25	120	FEW
KDEN	0753	10	110	FEW
KGXY	0755	10	110	SCT
KFNL	0755	10	110	SCT

Table 2 – METAR observations of visibility, ceiling and cloud cover for 27 February, 2009 around 0800 UTC.

4. 2009 - 2010 Data analysis

With the 2008 – 2009 winter dataset showing some skill at detecting frost, additional equipment was deployed for the 2009 – 2010 winter season. This included a webcam capable of taking pictures every five minutes, as well as black and silver plates angled at ten degrees to simulate an aircraft wing (Figure 5). A mass balance was placed under the silver plate to weigh the mass of the frost accreted on the plate and data was collected every few seconds. Finally, a ceilometer was added to the site to ensure clear sky conditions during frost events. A case study from December 31, 2009 is presented here based on data from the new equipment.

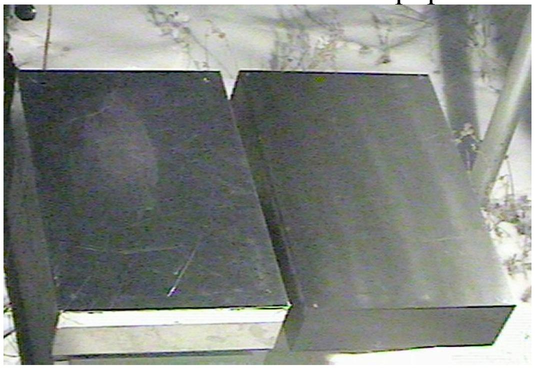

Figure 5 – Silver (left) and black (right) frost plates as deployed at the Marshall Field Site.

As with the February 27, 2009 event, the voltage from the LWS was compared to the dew point depression and the 2-meter height wind speed (Figures 6 and 7). LWS measurements were already above the 258mV baseline. Dew point depressions were lower than the 6^{o}C threshold and wind speeds were well below the 4.5 m/s threshold throughout the first 13 hours of the day.

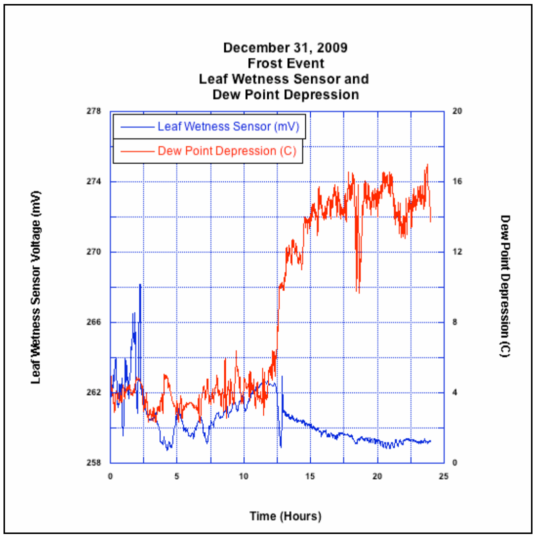

Figure 6 - Leaf wetness sensor voltage and dew point depression for December 31, 2009.

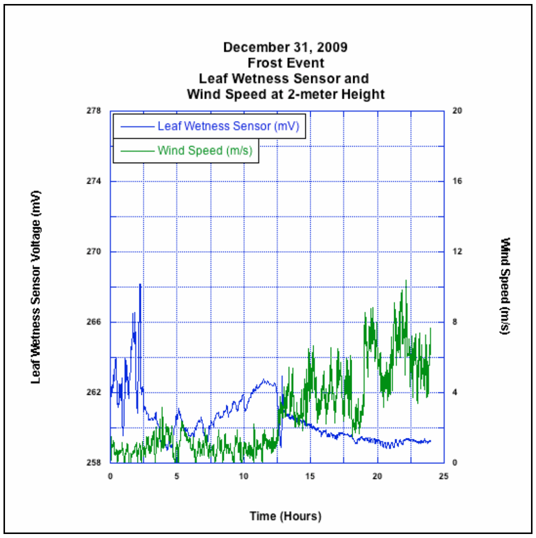

Figure 7 – Leaf Wetness Sensor voltage and wind speed for December 31, 2009.

The webcam images starting from the beginning of the day (0000 UTC) show a buildup of frost on the black frost plate (Figures 8B – 8H).

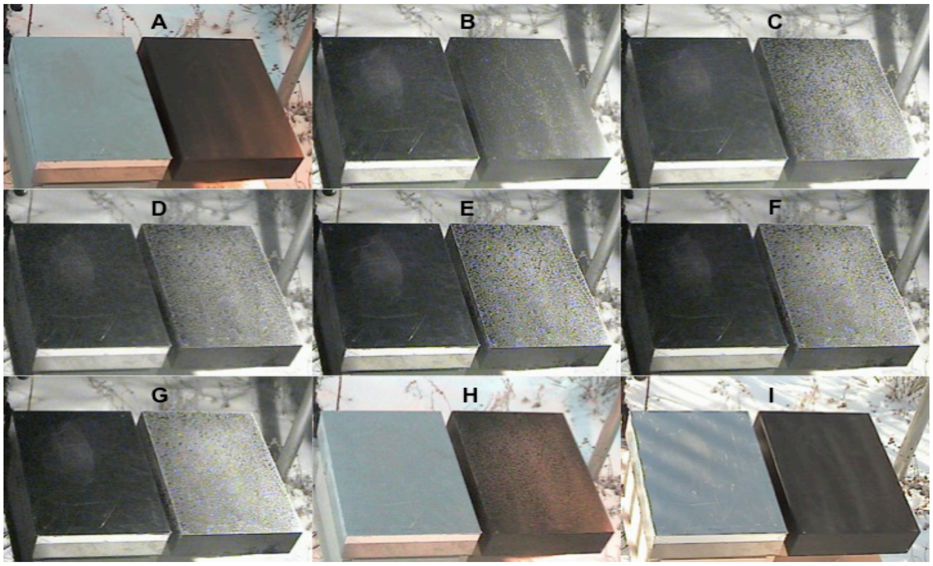

Figure 8 – Webcam images taken every two hours starting at 0000 UTC on December 31, 2009.

Interestingly, frost buildup was not noticeable on the silver plate; which is the plate on the mass balance. An analysis of the data from the balance for the first 12 hours of the day clearly shows a gradual increase in weight for the first 4 hours. This is in agreement with Figures 8A – 8C where frost can be seen depositing on the black plate. The accumulation leveled off and then started to increase again around 0800 UTC. Examination of the webcam images shows the black plate becoming increasingly whiter during the time period of 0800 to 1200 UTC (Figures 8E – 8G). After 1200 UTC, the sun comes up and frost begins to disappear (Figures 8H – 8I). This is consistent with the decrease in mass seen on the balance during this time period. It should be noted the noise in the data is due to the increase in wind speeds causing wind loading on the silver plate.

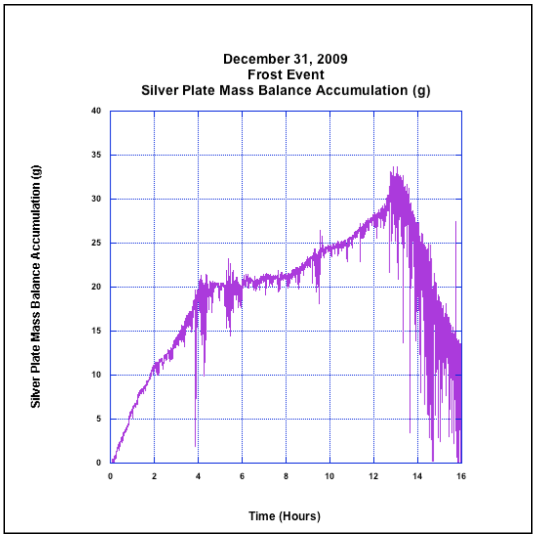

Figure 9 – The silver frost plate balance mass (g) for December 31, 2009.

Comparing the mass balance data to the LWS, it can be seen that the LWS sensor was always measuring higher than it's baseline of 258mV. Various increases in the voltage can be seen during time periods where the mass balance was showing increases in accumulation, and the LWS shows a steady decrease consistent with the balance measurements once the sun rises. Examination of ceilometer data, and precipitation gauge data (not shown) confirm that skies were clear and no precipitation was falling during this time period.

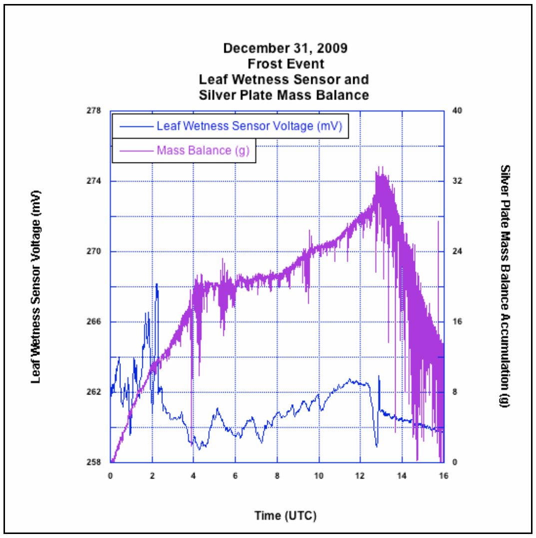

Figure 10 – Leaf wetness sensor voltage and silver plate mass balance data for December 31, 2009.

5. Results

The combination of data from the various instruments described in this paper show skill in detecting actively forming frost, though more frost events need to be analyzed to confirm this result. While it is impractical to use mass balances and web cameras in operational systems, using these data to verify frost events may lead to the incorporation of a leaf wetness sensor into surface stations (such as ASOS) to automatically detect frost formation.

In addition to the skill shown in the instruments, the indications of frost buildup on the silver plate without any visual indications on the webcam show the need for an automated algorithm to detect active frost formation and alert pilots and ground de-icing personnel to this hazard.

6. Acknowledgements

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7.. References

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