FINAL REPORT:
ICE ACCRETION ALGORITHM DEVELOPMENT

WINTER 1998 - 1999

Prepared for

NATIONAL WEATHER SERVICE (W/OSO14x1)

July 28, 1999

by

RAYTHEON ITSS

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EXECUTIVE SUMMARY

This algorithm-development task is a continuation of work that has been in progress since 1995. (See Attachment 1: Bibliography) Previous work had established a consistent relationship between the Net Frequency Change (NFC) of the ASOS icing sensor and various measurements of ice accretion. This project was intended to verify the previously-developed quantitative relationships.

The 1998-1999 field evaluation confirmed the quantitative relationships between the ASOS icing sensor and ice accretion. The following figure illustrates the relationship for the most basic and reliable measurement of ice accretion: ice mass per unit length on a horizontal metal rod (emulating a typical high-voltage power line).

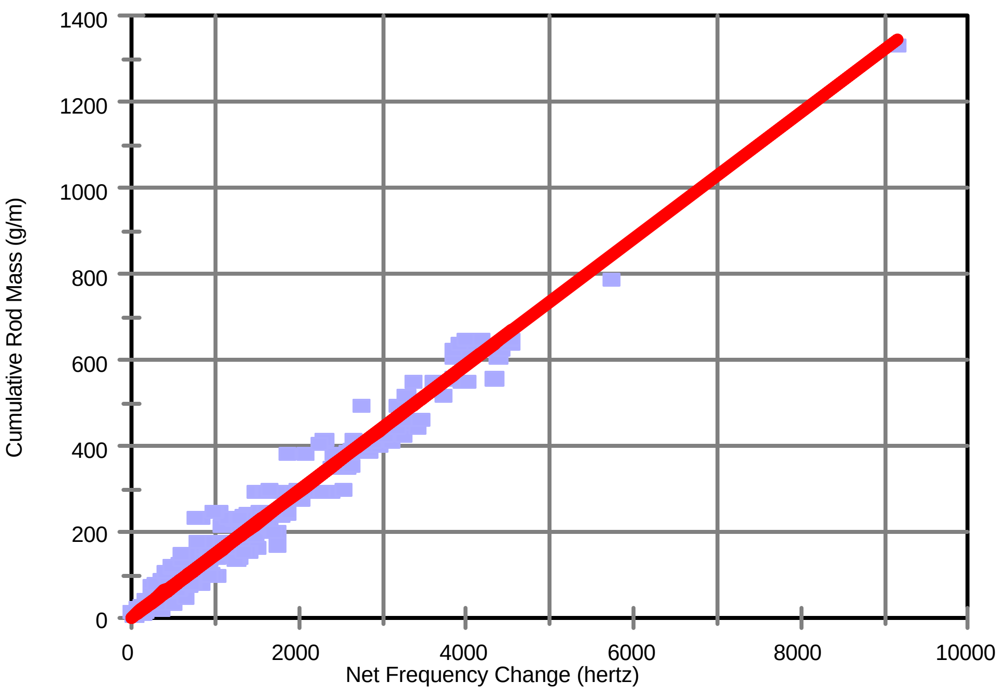

Figure EXEC -1 Cumulative Ice Mass per Unit Length on 32-mm Rod as a Function of Net Frequency Change, 1995 - 1999

The relationship is expressed as:

CUMULATIVE ICE MASS (grams per meter) = **0.15** (NFC)

The correlation coefficient for this relationship is 0.98.

Similar relationships with the ASOS NFC were confirmed between ice thickness and ice mass on a horizontal metal plate.

ICE THICKNESS (mm) = **0.004** NFC

ICE THICKNESS (in) = **0.00014** NFC

The correlation coefficient between cumulative ice thickness and NFC is 0.70.

ICE MASS PER UNIT AREA (grams per square decimeter) = **0.033** NFC

The correlation coefficient between cumulative ice mass and NFC is 0.96.

ICING RATES AND AIRCRAFT DEICING OPERATIONS:

The minute-to-minute values of calculated icing-rates from the ASOS are typically highly variable. The short-term variability in the icing-rate values makes them highly perishable, and would make icing rates meaningless for long-line transmission in METAR/SPECI reports. A real-time icing rate would normally change significantly before it could even be transmitted.

ASOS reports of ice accretion provide *certain* indications of icing *at the ASOS location* (Ramsay, 1997). While it is logical to extrapolate precipitation occurrence and rate over significant distances in stratiform precipitation typical of icing events, it is not reasonable to extrapolate estimates of ice amount or rate. The rate of accretion of ice is highly dependent on local variations in the temperature of surfaces (influenced by many factors, including ambient air temperature, long-wave radiation sources and sinks, and wind speed / direction.) Because of differences in ambient temperatures, local heat sources, and wind shielding, it is likely that the ASOS will over-estimate icing relative to actual ice amounts and rates near an airport terminal. For the same reason, it is likely that ASOS will under-estimate icing relative to the maximum possible ice amounts within a few miles of an airport, at locations with lower temperatures and greater wind exposure (e.g., at different elevations and on the windward sides of hills.)

INTER-SENSOR VARIABILITY OF ICING ESTIMATES:

Data from both Johnstown and Sterling indicated that a given amount of ice may produce significantly different responses on different sensors. It is believed that the differences among sensors arise from the basic mechanical response of different probes to the same mass of ice. Raytheon ITSS will conduct a series of chamber tests at Sterling to determine if it is possible to establish sensor-specific sensitivity values. If sensor responses can be “corrected” by measuring responses to a known mass, it would be possible to assign individual sensitivity factors which would reduce the differences in response to ice accretion.

RECOMMENDATIONS:

The ASOS ice accretion algorithm should be adopted for operational use with no changes from previously-derived constants of proportionality.

> In spite of a significant range of differences (±25%) between ASOS ice-accretion estimates and *in situ* measurements, the ASOS estimates provide data which are currently not available to NWS forecasters. ASOS icing estimates are believed to be well within the natural spatial variability of ice accretion in the vicinity of an airport.

Icing rates derived from the ASOS algorithm should NOT be used in decisions or evaluations of aircraft deicing activities.

> Local variations in icing may be so large as to limit the application of ASOS data to broad-scale NWS forecasting and verification applications. Icing rates at an ASOS location may not accurately represent icing rates even at nearby locations (e.g., aircraft at airport terminals) because of significantly different temperature and wind regimes.

Contingent upon the results of a Raytheon ITSS investigation into sensor variability, the National Weather Service should consider applying sensor-specific sensitivity factors to reduce the variability in icing estimates from different sensors in identical icing environments. Implementation of the icing accretion algorithm for operational purposes should not be delayed pending the outcome of this investigation.

1.0 BACKGROUND

Observations during previous testing seasons indicated that the cumulative change in frequency of the ASOS icing sensor is strongly correlated with the total accumulation of ice on surfaces. (See Attachment 1: Bibliography.) During the winters of 1995-96, 1996-97, and 1997-98, a joint effort among the U.S. Army Corps of Engineers Cold Regions Research and Engineering Laboratory (CRREL), Hanover, N.H., the ASOS Program Office, the National Weather Service (NWS) Eastern Region, and NWS offices at Binghamton, NY, and Cleveland, OH, established a quantitative relationship between sensor frequency and ice accumulation.

The algorithm is described in a paper presented at the 1999 annual meeting of the American Meteorological Society (Ramsay, 1999).

2.0 PURPOSE

The specific question to be answered in this continuation of previous algorithm-development efforts is:

> Are modifications required for the previously-developed relationships between the ASOS icing sensor and ice mass, thickness, or accretion rate of ice on surfaces or structures?

3.0 PERFORMANCE REQUIREMENTS

Applications of ice-accretion data include: forecasting and verification of icing events; real-time management of airfield, highway, railroad, waterway, and electric-utility operations; and (once a long-term climatology has been established) the design of structures to withstand expected ice loads.

At the time this development project started, there were no documented requirements for quantitative ice-accretion information. The National Weather Service established a requirement for ice-accretion information in the ASOS Request for Change (RC) Number NWS485S(S01036), March 3, 1999, "Ice Accretion Remark Encoded in METAR/SPECI Reports."

4.0 TEST CONFIGURATION

4.1 The ASOS Icing Sensor

The Rosemount Model 872C3 Sensor was used in this development project. Within the ASOS, this instrument is known as a “Freezing Rain” sensor; however, because this development project is intended to extend the capabilities beyond freezing rain, this sensor will be referred to as the ASOS Icing Sensor. The sensor detects ice accumulation by monitoring the resonant frequency (nominally 40,000 hertz) of a vibrating metal probe. The resonant frequency decreases with increasing ice accretion. Data are acquired from the sensor once each minute and are recorded in a dedicated Data Acquisition System or in the ASOS 12-hour data archive.

Figure 1 ASOS Icing Sensor

4.2 Ice Accretion Measurements

Ice mass and thickness were determined from standardized aluminum rods and an aluminum plate, mounted on a rotatable ice rack. The orientation of the rack was manually adjusted to keep the rods orthogonal to the prevailing wind direction throughout an event. Data (rod weight, plate weight and thickness) were recorded manually every hour or two hours, depending on the location. (See Section 4.3)

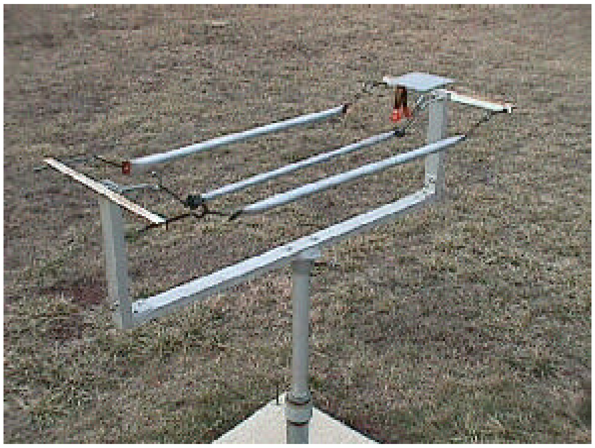

Figure 2 Ice Rack, Rods, and Plate

4.3 Test Locations and Data Collection

Tests which require dedicated (full-time) "clinical" observations were performed primarily at Sterling, Virginia, and Johnstown, Pennsylvania. At Sterling, data were obtained from three ASOS units (ST0, ST1, and ST2) and from three sensors in the Building 16 testbed. At Johnstown, data were obtained from the KJST ASOS and from six sensors in the Johnstown ASOS testbed. Testbed data were stored in ASCII data files for subsequent detailed analysis and comparison with clinical observations.

Additional data were gathered at:

- NWS offices at Binghamton, NY, and Cleveland, OH, and Taunton, MA
- U.S. Army Corps of Engineers Cold Regions Research and Engineering Laboratory, Hanover, NH
- Mount Washington Observatory, NH

Detailed surface observations were made by Raytheon ITSS and NOAA/NWS observers at Sterling and Johnstown; NWS staff at Binghamton and Cleveland; U.S. Army meteorologists at Hanover or Lebanon, NH; and NWS-certified observers at Mount Washington.

Ice racks, rods, plates, and scales were provided by the CRREL for use at Sterling, VA; Johnstown, PA; WSFO Binghamton, NY; WSFO Cleveland, OH; Hanover or Lebanon, NH (CRREL); and Mount Washington, NH. Hourly observations were made at Sterling and Johnstown, and 2-hour observations were made at other locations because their primary responsibilities did not permit more frequent observations.

An operational evaluation of the ice-accretion algorithm was performed at the NWS Forecast Office at Taunton, MA. Sensor data were downloaded during icing events and were processed through a spreadsheet which generated estimates of ice thickness. NWS staff at Taunton compared ASOS icing estimates with spotter reports, and evaluated the utility of ASOS reports to their forecasting / verification process.

5.0 METHODOLOGY AND RESULTS

5.1 Relationships Between Ice Amount and Sensor Data

The response of the ASOS icing sensor to ice accretion is measured by summing all frequency drops (from a nominal value of 40,000 hertz) over the course of an icing event. The summation of frequency drops is referred to as the "Net Frequency Change" (NFC).

Analysis of the 1995-1998 ice accretion data resulted in the following estimates of ice mass and ice thickness:

Ice mass (g/m on a 32-mm diameter rod) = **0.15** (NFC) (1)

Ice thickness (inches on a horizontal aluminum plate) = **0.00015** (NFC) (2)

Ice mass (g/dm^2 on a horizontal aluminum plate) = **0.033** (NFC) (3)

5.2 1998-1999 Observations / Data Acquisition

In 1998-1999, staff at all test locations were prepared to make routine measurements of ice mass and ice thickness on standardized rods and plates and to record precipitation type and intensity. Raytheon ITSS collected one-minute frequency data from ASOS icing sensors at Sterling and Johnstown, and also routinely downloaded frequency data from the Sterling, Johnstown, Binghamton, and Cleveland ASOS units. Staff at the CRREL and the Mount Washington Observatory provided sensor frequency data and icing measurements by transferring data files to Raytheon at Sterling via the Internet.

During the course of the field evaluation, situations developed that precluded analysis of all data: conditions at Mount Washington were occasionally so severe as to preclude any measurements at all; there were *no* observations made under glaze icing conditions. In late December 1998, Raytheon ITSS identified a software problem in ASOS firmware Version 2.50; this problem with control of deicing cycles invalidated icing data from any ASOS with V 2.50, including Cleveland, Binghamton, and the three ASOS units at Sterling, Virginia. Icing reports from Cleveland, Binghamton, and the Sterling ASOS sensors were, therefore, not included in the analysis.

Data collection was performed successfully at Sterling and Johnstown, and provided over 250 additional values of ice mass and thickness. These data were combined with previous data sets to produce the results presented below.

Observers at Sterling and Johnstown recorded icing data on the form shown in Attachment 2. Data include:

ice mass on *one* of the two 32-mm diameter, one-meter-long rods (the second 32-mm rod was held in reserve in the case the primary rod was damaged); the 25-mm rod used in previous years was not used in 1998-1999 because the 32-mm diameter has been proposed by the International Electro-Technical Commission as a standard for ice-measuring rods);

ice mass on the aluminum plate;

ice thickness on the aluminum plate;

icing type (glaze, rime, or frost); and

the presence of icicles on the aluminum rods.

5.3 Algorithm for Ice Mass, Thickness, and Accretion Rate

Hourly measurements of ice mass and thickness were compared to the raw (frequency) data from the ASOS icing sensor, with the intent of confirming or refining the 1995-1998 relationship between ice accretion and Net Frequency Change.

Observations of sensor data and ice mass from 1995 through 1999 indicate that the relationship is linear, of the form

ICE MASS or THICKNESS = (PROPORTIONALITY FACTOR) (NFC)

5.3.1 Ice Mass Per Unit Length

The success of the ice-accretion algorithm was measured by the correlation between the algorithm-derived ice mass and the measured ice mass per unit length on an aluminum rod. “Cumulative” values referred to in this section indicate the event-total mass or thickness determined at the time of measurement. “Hourly” values indicate differences in mass or thickness over time periods between individual measurements.

Data from the 1998-1999 winter testing were combined with data from previous winters, with results for the 505 data points illustrated in Figures 3 and 4.

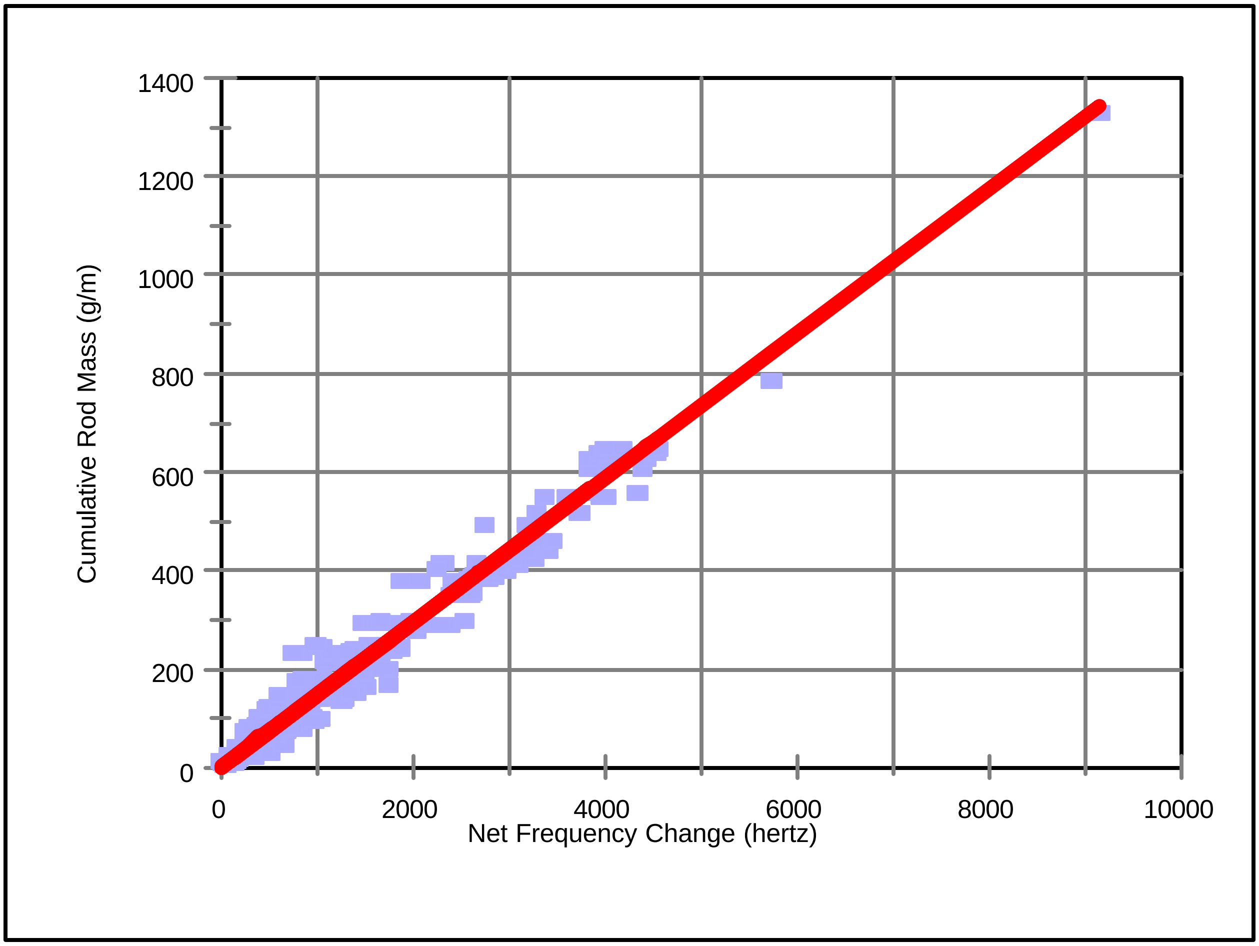

Figure 3 Cumulative Ice Mass per Unit Length on 32-mm Rod as a Function of Net Frequency Change, 1995 - 1999

The relationship between the *cumulative* ice mass per unit length during an event and the Net Frequency Change (NFC) is:

ICE MASS (g/m) = **0.15** NFC

The correlation coefficient between cumulative ice mass and NFC is 0.98.

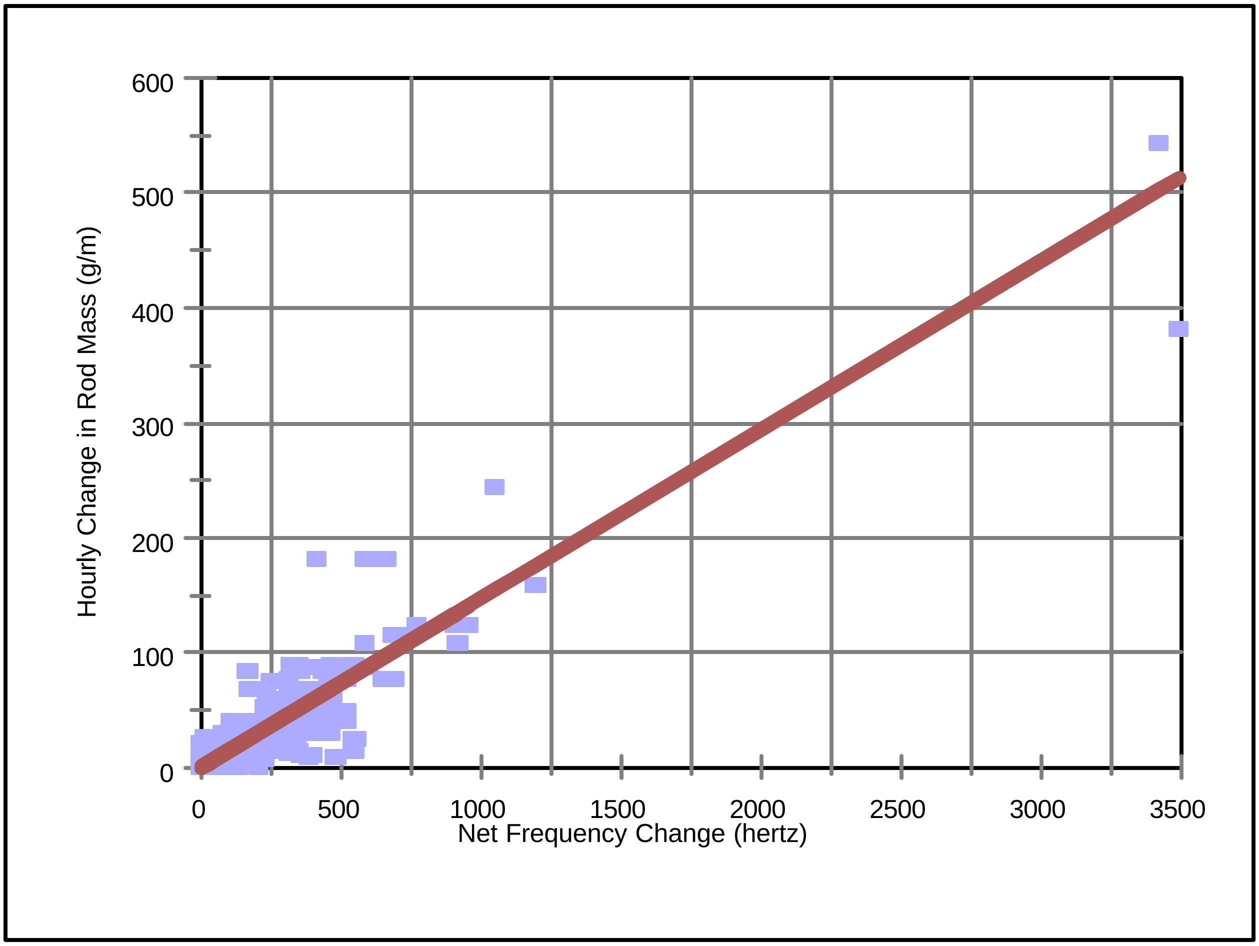

Figure 4 Hourly Ice Mass per Unit Length on 32-mm Rod as a Function of Net Frequency Change, 1995 - 1999

The relationship between the *hourly* measurements of ice mass per unit length during an event and the Net Frequency Change (NFC) is:

ICE MASS (g/m) = 0.14 NFC

The correlation coefficient between hourly ice mass per unit length and NFC is 0.90.

5.3.2 Ice Thickness

The success of the ice-accretion algorithm was measured by the correlation between the algorithm-derived ice thickness and the ice thickness measured on a horizontal aluminum plate.

Ice thickness measurements on a small horizontal surface suffer from two primary deficiencies:

> 1) The horizontal surface can collect icing from snow and ice pellets, in addition to icing from freezing rain and freezing drizzle. Ice pellets, in particular, require the observer to select a representative location on the rough surface to make a thickness measurement. Additionally, liquid precipitation can pool on the surface, and can freeze many minutes after being collected. Both of these effects can add "noise" to the thickness measurements by adding ice thickness which is not truly contributed by freezing rain or freezing drizzle.
>
> 2) A far more significant problem with the horizontal plate is the *effective area of the collection surface* that is presented to the precipitation. If the precipitation is falling vertically, the plate used in this field evaluation presents an effective collection area of 420 square centimeters. If, however, the fall direction is not perfectly vertical, the effective collection area is reduced by the cosine of the fall angle. If the precipitation particles are falling at a 45 degree angle, the effective collection area is reduced by 30%, to a value of about 300 square centimeters. If the particles fall at an angle of 60 degrees off the vertical, the effective collection area would be reduced by half, to a value of about 210 square centimeters. Given the wind speeds during a typical icing event (usually 4 to 10 knots), and the common occurrence of light precipitation or freezing drizzle, it is probable that the *effective* collection area presented to the precipitation was often less than the 420 square centimeters. It is, therefore, expected that thickness measurements from the horizontal metal plate would probably *under-estimate* icing on the ground.

Data from the winter testing were combined with data from previous winters, with results for 395 data points illustrated in Figure 5.

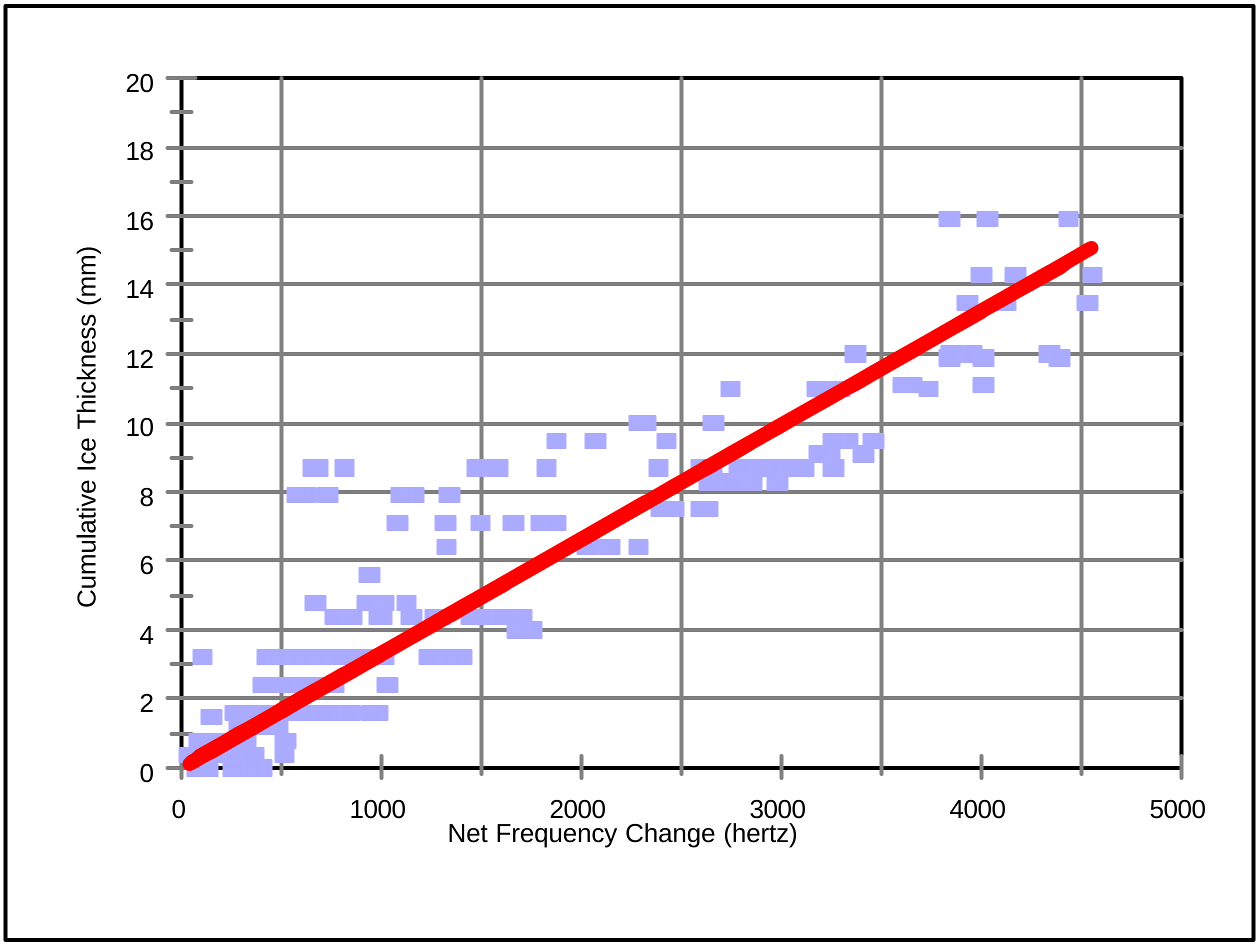

Figure 5 Cumulative Ice Thickness as a Function of Net Frequency Change, 1995 - 1999

The relationship between the cumulative ice thickness on a horizontal aluminum plate during an event and the Net Frequency Change (NFC) is:

ICE THICKNESS (mm) = **0.004** NFC
ICE THICKNESS (in) = **0.00014** NFC

The correlation coefficient between cumulative ice thickness and NFC is 0.70.

This "new" value (0.00014 inches per hertz) is somewhat lower than the value of 0.000152 inches per hertz that is encoded in the ASOS firmware. Considering that the "new" value is expected to be somewhat LOWER than actual conditions because of the effect described above, it is *not* recommended that the ASOS firmware be changed to the new value.

5.3.3 Ice Accretion Rate and Ice Mass Per Unit Area

The basis for determining ice accretion is the time history of sensor frequency, F(t). Continuously summing the minute-to-minute decreases of frequency over the duration of the event yields the Net Frequency Change (NFC(t)), which has been found to be highly correlated with measurements of ice accretion. It should be possible to determine the instantaneous slope of NFC(t), which would represent the icing rate. A typical example of NFC(t) is shown in the following figure. The rate-of-change of the Net Frequency Change, dNFC/dt, smoothed over a 10-minute interval, is also shown.

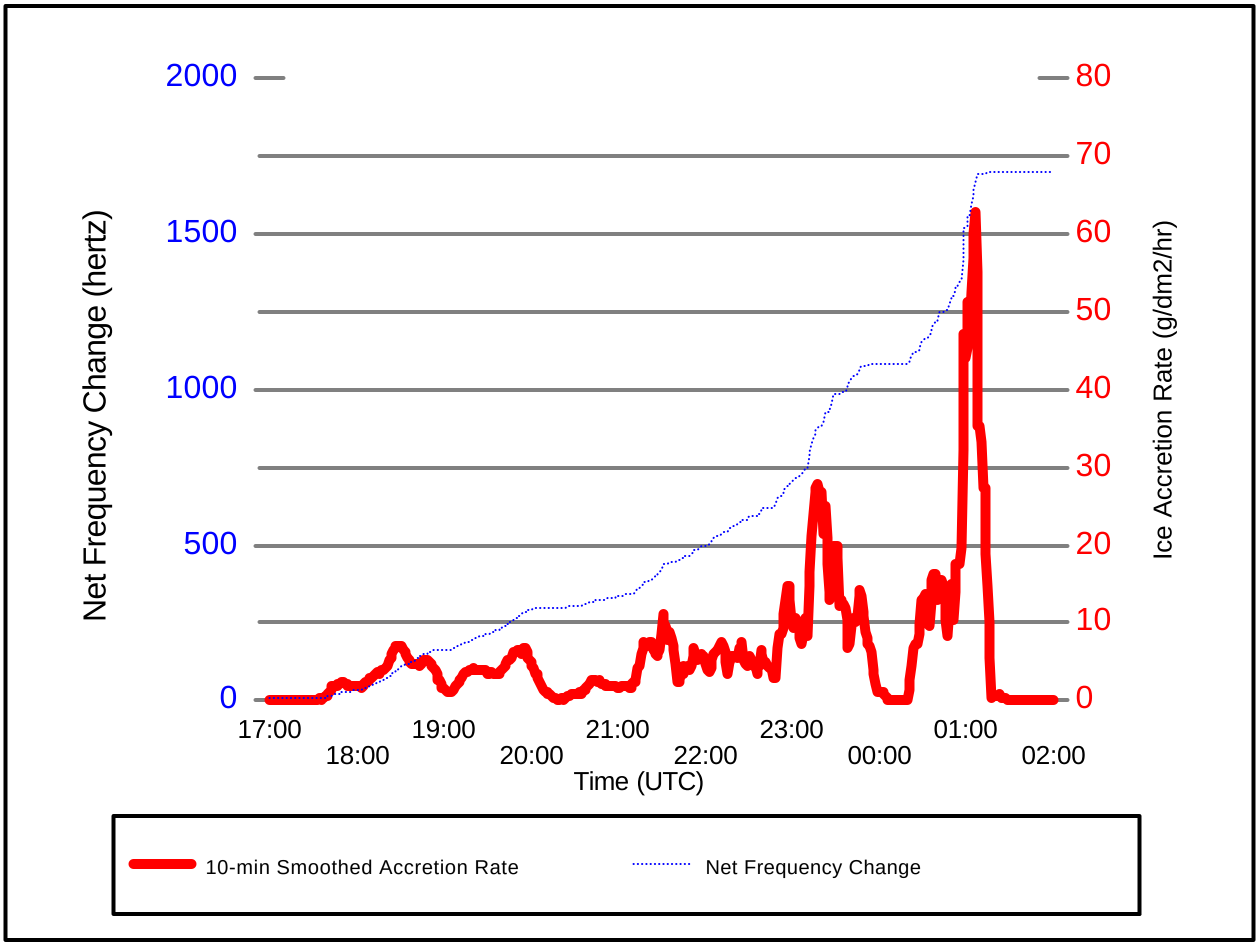

Figure 6 Net Frequency Change, NFC(t), and Smoothed Ice Accretion Rate, dNFC/dt

The relationship between the cumulative ice mass per unit area on a horizontal aluminum plate during an event and the Net Frequency Change (NFC) is:

ICE MASS PER UNIT AREA (grams per square decimeter) = **0.033** NFC

The correlation coefficient between cumulative ice mass and NFC is 0.96.

5.3.4 Applicability of ASOS Icing Estimates to Aircraft Deicing Operations

The real-time selection of aircraft deicing fluids is based on knowledge of the local icing rate. Icing rates are currently determined from the *intensity* of freezing precipitation in the METAR/SPECI reports. Two factors lead to recommendation that ASOS icing estimates should *not* be applied to real-time aircraft deicing decisions or to post-event “regulatory compliance” evaluations of deicing operations:

1) The minute-to-minute variability in NFC(t) is such that icing-rate values from the ASOS are highly variable, even when smoothed over ten- to fifteen-minute intervals. The variability in the icing-rate values makes them highly perishable, and would make icing rates meaningless for long-line transmission in METAR/SPECI reports. A real-time icing rate would normally change significantly before it could even be transmitted. Additionally, inspection of 96 icing-event case studies for 1998-1999 indicate that the calculated icing rates fall into the FAA “light-icing” category (less than or equal to 25 grams per square decimeter per hour) more than 95 percent of the time. Given the high variability in icing rates during an event, and the infrequent and short-lived occurrences of icing rates greater than the FAA definition of “light icing,” it is doubtful that real-time reports of icing rates from the ASOS would be of value to deicing operations.

2) ASOS reports of ice accretion provide *certain* indications of icing *at the ASOS location* (Ramsay, 1997). While it is logical to extrapolate precipitation occurrence and rate over significant distances in stratiform precipitation typical of icing events, it is not reasonable to extrapolate estimates of ice amount or rate. The rate of accretion of ice is highly dependent on local variations in the temperature of surfaces (influenced by many factors, including ambient air temperature, long-wave radiation sources and sinks, and wind speed / direction.) ASOS icing rates, taken in an open area at an airport, do not necessarily represent conditions at near-by locations with different temperature regimes and wind exposure (e.g., aircraft parked at a terminal building.) Because of differences in ambient temperatures, local heat sources, and wind shielding, it is likely that the ASOS will over-estimate icing relative to actual ice amounts and rates near an airport terminal. For the same reason, it is likely that ASOS will under-estimate icing relative to the maximum possible ice amounts within a few miles of an airport, at locations with lower temperatures and greater wind exposure (e.g., at different elevations and on the windward sides of hills.)

5.3.5 Inter-Sensor Variability of Icing Estimates

Data from both Johnstown and Sterling indicated that a given amount of ice may produce significantly different responses on different sensors. The Icing Event Case Study for Johnstown, Pennsylvania, January 8-9, 1999, provides an example of inter-sensor variability among seven sensors exposed to the same icing environment. The extreme values of icing estimates deviated ±25% from the median value.

It is believed that the differences among sensors arise from the basic mechanical response of different probes to the same mass of ice. In June 1999, the ASOS Product Improvement Working Group approved a short investigation into the response of various sensors to a standard mass. During the summer of 1999, Raytheon ITSS will conduct a series of chamber tests at Sterling to determine if it is possible to establish sensor-specific sensitivity values. If sensor responses can be “corrected” by measuring responses to a known mass, it would be possible to assign individual sensitivity factors which would reduce the differences in response to ice accretion. Results of this investigation are scheduled to be presented in a separate report in September 1999.

Implementation of the icing accretion algorithm for operational purposes should not be delayed pending the outcome of this investigation.

5.3.6 Field Evaluation of ASOS Icing Estimates

Mr. Walter Drag, Lead Forecaster at the NWSFO Taunton, MA, volunteered to perform an operational assessment of the ASOS ice-accretion capability during the winter of 1998-1999. His final report (May 4, 1999) to the ASOS Program Office stated, in part:

> “The glaze algorithm performs well, providing reliable CONSERVATIVE information regarding ice accretion, not only for glaze but also frost and apparently freezing drizzle.
>
> “ASOS glaze data can be a valuable contributor to a host of weather related programs. Beneficiaries will include not only NWS and private sector meteorologists, but also departments of transportation, aviation interests at airports, electric utilities and possibly agricultural customers.
>
> “The data will be of considerable objective value in event assessments with subsequent update of objective glaze climatology improving our damage-WARNING thresholds. Meteorologists will eventually have a better understanding of glaze accretion during varying freezing rainfall rates.”

6.0 RECOMMENDATIONS

The ASOS ice accretion algorithm should be adopted for operational use with no changes from previously-derived constants of proportionality.

In spite of a significant range of differences (±25%) between ASOS ice-accretion estimates and *in situ* measurements, the ASOS estimates provide data which are currently not available to NWS forecasters. ASOS icing estimates are believed to be well within the natural spatial variability of ice accretion in the vicinity of an airport.

Icing rates derived from the ASOS algorithm should NOT be used in decisions or evaluations of aircraft deicing activities.

Local variations in icing may be so large as to limit the application of ASOS data to broad-scale NWS forecasting and verification applications. Icing rates at an ASOS location may not accurately represent icing rates even at nearby locations (e.g., aircraft at airport terminals) because of significantly different temperature and wind regimes.

Contingent upon the results of a Raytheon ITSS investigation into sensor variability, the National Weather Service should consider applying sensor-specific sensitivity factors to reduce the variability in icing estimates from different sensors in identical icing environments. Implementation of the icing accretion algorithm for operational purposes should not be delayed pending the outcome of this investigation.

ATTACHMENT 1: BIBLIOGRAPHY

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ATTACHMENT 2: ASOS ICING DATA FORM

ASOS ICING DATA FORM **LOCATION:** **DATE:**

TEST CONFIGURATION:

(USE UPWIND ROD FOR PRIMARY DATA COLLECTION;
KEEP DOWNWIND ROD IN RESERVE IN CASE ICE ON UPWIND ROD IS DAMAGED)

UPWIND ROD COLOR _________ **TARE WEIGHT** _________ **g**

DOWNWIND ROD COLOR _________ **TARE WEIGHT** _________ **g**

PLATE TARE WEIGHT _________ **g**

TIME (LST)	**ROD COLOR**	**ROD WEIGHT (g)**	**PLATE WEIGHT (g)**	**TOTAL THICKNESS (PLATE + ICE) (inches)**	**ICE TYPE (Glaze, Rime, Mixed, Frost)**	**ICICLES ? (Y/N + est length in cm)**