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I, Biswarup Deb, hereby submit this original work as part of the requirements for the degree of Master of Science in Electrical Engineering.

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Committee member: Douglas Nims, Ph.D.

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CONTINUED WEATHER MONITORING SYSTEM FOR THE VETERANS’ GLASS CITY SKYWAY

A Thesis submitted to the Division of Research and Advanced Studies of the University of Cincinnati

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE (M.S.)

in the Department of Electrical Engineering of the College of Engineering and Applied Sciences 2014

By

BISWARUP DEB

B.TECH, WEST BENGAL UNIVERSITY OF TECHNOLOGY, INDIA, 2010

Committee Chair: Arthur J. Helmicki, Ph.D
Abstract

The Veterans’ Glass City Skyway (VGCS) is a large cable-stayed bridge with a single pylon. The stays have stainless steel sheathing. It is in Toledo, Ohio and owned and managed by the Ohio Department of Transportation (ODOT). The stainless steel sheath was chosen as it provides aesthetic and life cycle cost advantages over other materials. During certain wintry weather conditions, ice accumulates on the Veterans’ Glass City Skyway stays, up to thickness of 19mm (¾ inch) - 75mm. When the stays warm up, ice sheds and may fall up to two hundred and fifty feet on to the roadway. The ice pieces can be whisked across many traffic lanes on the bridge deck. This causes difficulty for the traveling public and may cause potential traffic accidents. ODOT closed the lanes due to ice accumulation on the bridge four times in the seven years the VGCS has been open. There are no existing ice anti/deicing technologies that are realistic for solving the problem. Therefore, an intelligent automated monitoring system (referred to as the dashboard) was developed. The first generation of the dashboard, developed in phase I of the project, used regional weather information to assist ODOT in managing icing events. This supplemented the visual and manual approach previously used. The VGCS has local weather conditions that influence icing and the original dashboard algorithm had deficiencies. To further assist ODOT in monitoring icing events, thesis presents a revision to the dashboard that addresses the microclimate on the bridge and improves the monitoring algorithm.

To address the microclimate on the VGCS a local weather station was built on the bridge. This weather station includes stay mounted thermistors, a dielectric wetness sensor, a solar radiation sensor, ice an detector and a tipping bucket rain gage. This thesis describes the function of the new sensors, rigorous laboratory experiments conducted to validate their performance, the sensor calibration, installation on the bridge and their performance monitored during their first year of service.

To be useful to the bridge operators, the new local data and the regional weather data were tied together in an improved dashboard. Critical parameters to help determine ice accretion and shedding, such as solar radiation, type of wetness, thickness of ice were now included in modular algorithms that combine the data from multiple sensors into a weighted an icing accretion and shedding assessments. Incorporating the new data in this manner increased the speed, redundancy and accuracy of the algorithm. A new module has been added in the algorithm to test the functioning of all the remote weather station. The data logger programs were revised to provide better data control. With active control overscheduling data collection, thresholds and sampling rates can be tuned as required. Additionally, the local sensor system data can be sampled and recorded in seconds, if required. During the winter of 2013-2014, several minor icing events occurred. The new sensors and improved algorithm successfully helped identify ice accumulation which would not have been previously detected. Recommendations for continued improvement of the dashboard are presented. This work is a significant advancement in helping ODOT manage icing events at the VGCS in the long-term.
I take this opportunity to articulate my heartfelt gratitude to the few individuals involved with the automated ice monitoring project at Veterans’ Glass City Skyway: who were associated with the Ohio Department of Transportation, University of Cincinnati, and the University of Toledo. Without their help this report would not have been possible.

Firstly I would like to express my sincere thanks to Dr. Arthur Helmicki, my advisor and Dr. Victor Hunt, my co-advisor for their extensive and all-encompassing support with the thesis. I attribute a lot of my research success to the knowledge and design of the professors which helped me address the intricacies of my thesis.

I thank Dr. Douglas Nims from University of Toledo for providing guidance in the project and taking the time to review my thesis. I would also like to thank ODOT District 2 individuals involved on this project who made it possible for the ice monitoring project to take place through financial and personal aide.

I am thankful to engineers at Campbell Scientific & Geokon Inc. for their support with the sensors. I thank Charles Ryerson from CRREL, U. S Army Corps of Engineers, for his valued inputs towards solving the problem statement.

I thank Jason Kumpf, graduate student for assisting me in field experiments and providing technical assistance for the project. Finally, I thank my family and friends for their moral support and encouragement towards reaching my goals.
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Chapter 1: Introduction

1.1 Veterans’ Glass City Skyway Bridge: An Introduction

The Veterans' Glass City Skyway (formerly known as the Maumee River Crossing) is currently the largest single project ever undertaken by the Ohio Department of Transportation (ODOT). Citizens in northwest Ohio have been continuously working with ODOT since April of 1999, when the design of this landmark project began.

The Ohio Department of Transportation (ODOT), in cooperation with Toledo Metropolitan Area Council of Governments (TMACOG) and the communities of northwest Ohio, designed and constructed a new cable-stayed bridge structure and its accompanying roadway approaches. The project is a major architectural, engineering and transportation asset for northwest Ohio.\(^1\)

The construction cost of the new cable-stayed bridge portion of the project is $220 million. The new crossing has three lanes of traffic in each direction on Interstate-280 over the Maumee River, extending from I-75 on the north end to Navarre Avenue (SR 2) on the south end. The surface of the roadway reaches about 130 feet high near the center of the river. The stainless steel sheathing on the bridge stays provides life cycle expense benefits as well as aesthetics over other materials.

In the past years during winter the bridge suffered from icing problems, where under certain weather conditions, ice formed on the stays. Falling ice chunks or particles is hazardous for the traffic traveling underneath. The choice of using stainless steel for stay sheathing contributed largely to the ice accretion issue. In such situations during the previous winters, ODOT shut down lanes in each direction until all the ice is melted / removed and the road was safe for transportation again. The weather conditions contributing to icing is little nebulous and hence are not be entirely reliable. The goal has been to find a solution that should not affect the aesthetics of the bridge and is non-destructive in nature. Hence, during Phase I of the project in 2011, the University Of Cincinnati Infrastructure Institute (UCII) along with teams from University of Toledo, NASA and CRREL aimed at comprehending the microclimate of the bridge, analyzing ice accretion and shedding causes, and modeled an automated weather monitoring system for mitigating the icing problem at Veterans' Glass City Skyway.
1.2 Icing History

Although the concept of icing on bridges stays is relatively new, various incidents of falling snow and ice of stays, cables or hangers were found in the literature or through correspondence with other bridge managers and researchers. Some of the bridges where such incidents have taken place before include Veterans’ Glass City Skyway, Incheon Bridge, Great Belt Bridge, Uddevalla Bridge, Severn and Second Severn Crossing, Charles River Bridge, Alex Fraser Bridge, Øresund Bridge and Port Mann Bridge. In most instances the problems on these bridges were related to falling ice rather than snow. Falling snow was reported on Port Mann and Severn Bridges. Unfortunately, no measures were taken to restrict traffic under these conditions in the Port Mann and Charles River Bridges. Due to the accidents and vehicle damage on other the bridges, extensive research has been carried out and remedial measures attempted.

Uddevalla Bridge, Uddevalla, Sweden
There were 19 damages reported at this bridge between 2000 and 20004 due to falling ice and snow. Among various initial tests, electric pulse technology for ice removal was used on the bridge. Though some of the tests were effective, it has not been implemented due to its complexity and power demands. This technology would also be inefficient to remove wet snow accumulations. They have implemented an ice monitoring system on the bridge to alert authorities to conditions requiring closure of the bridge due to falling ice. 9

Incheon Bridge, Incheon, South Korea
Due to the winter climate at the bridge, special procedures were implemented for closure in case of snow and ice conditions. Robots have been developed and arranged to remove accretions of snow from the stay. 3

Øresund Bridge, Copenhagen, Sweden / Malmo, Denmark
This 7.8 km long bridge has been closed 5 times in 9 years due to ice shedding. 4
Severn and Second Severn Crossing Bridges, Aust, England / Chepstow, Wales
During February and December, 2009, the Second Severn Bridge was closed due to inclement weather. In the first case, on February 6th three vehicles were struck by falling ice, thereby damaging windshields. Severn Crossing was also closed the same time. After some research, an ice accretion warning system was introduced to indicate when ice formation is likely. Their criteria for monitoring are:
- Temperature between -1.5 and +1.5 deg C,
- Wind speed over 8 m/sec; and
- Relative humidity over 95%.
The ice events on the crossings have occurred at temperatures of +0.5 to +1.5 deg C, with wind speeds between 10 to 15.5 m/sec and with mixtures of snow and rain. These conditions were found to cause rain, sleet or snow. Once accretions are formed, these tend to remain in place until there is a rise in temperature. This can also be triggered by the appearance of the sun warming the bridge even when the air temperature remains below zero. To implement an effective weather forecasting and warning procedure therefore, the temperature on the bridge must also be monitored. The bridge manager stated that he was not aware of any successful methods of dealing with ice, other than to close to traffic, although on one occasion, the downdraft from a close flying helicopter did assist in clearing the ice once it had started to fall.5

Great Belt Bridge, Zeland / Funen, Denmark
During the period of 2004-2007 this suspension bridge has been closed 12 hours per year due to falling snow & ice.4

Charles River Bridge, Boston, USA
In 2005, the bridge was temporarily closed due to problems of falling ice & snow. Ice shedding was reported again in 2010 and in 2012.6

Alex Fraser Bridge, Richmond / New Westminster, Canada
On the Alex Fraser Bridge, falling ice & snow from the tower H-frames and stay cables have caused harmful impacts on the traffic. Several instances of vehicle damage were reported in 2005, 2007, 2008 and as recent as December 2012. De-icing product was applied on the H-frames on January 4, 6, and 11, February 25, and December 9, 2011, as well as on January 14, 16, and 18, February 28, and December 19, 2012.5

Port Mann Bridge, Vancouver, Canada
In December 2012, large chunks of snow fell from the bridge cables, damaging about 350 vehicles on the span linking Coquitlam and Surrey. Many more incidents were reported later in winter. Now the B.C. government says engineers have found a few possible solutions to the problem, including a custom-designed cable sweeper and ice-repellent coatings to prevent ice buildup. The sweeper would fit around the outside the cable. In addition, engineers had also identified a de-icing solution that could be applied to the bridge cables as a further preventative measure. Similar to de-icing applications on aircraft, the solution would be sprayed onto the
bridge cables. The product, which is also used to de-ice ships, forms a barrier that prevents the formation of ice. However, all these de-icing techniques are still part of research and the BC government is trying to implement an ice monitoring system akin to that at Veterans’ Glass City Skyway.

Fig.2. Icing event at Port Mann Bridge, Canada

In most of the above cases, however, no practical solutions were found to prevent the accretions until recently, like at Port Mann where chains are being used to slide down the accumulated snow/ice with gravity. Most of these bridges are closed when these events occur until the snow or ice is cleared by natural warming conditions. Monitoring systems and procedures have been developed and deployed for these bridges as aid to operators in determining events requiring bridge closure. The meteorological conditions that were identified as most important are ambient temperatures (around freezing) and high humidity combined with moderate winds, all in the presence of snow. Accretions of snow fall after when the temperature of the cables increases above freezing. This may happen several hours after the accumulation has actually occurred.

Veterans’ Glass City Skyway
There are various kinds of icing conditions, including precipitation icing (those occurring on bridges and cable transmission lines) and in-cloud icing (those forming on aircrafts). Due to its adverse effects, icing can be a serious hazard to public safety as well as money. One of the best examples is the situation at the Veteran’s Glass City Skyway Bridge at Toledo, Ohio. At VGCS, during the previous few winters, ice formed on the stay cables. Ice accumulations can be up to 0.75” thick and the ice takes the cylindrical shape of the stay sheath. The stays shed the ice when they get warmer and if shedding occurs the ice can be whirled all over the bridge. The huge
chunks of ice shedding require lane closures and could present possible threats to the moving vehicles. This sort of event will be referred to as ‘icing event’ and can be chiefly divided into two stages:

A. Ice accumulation – Ice accretion phenomenon on the stays of the bridge.
B. Ice shedding – Ice cracking and falling phenomenon

Four icing events of these kinds have been reported to have occurred on the VGCS Bridge during period between Dec 2007 and Jan 2009 based on Kathleen Jones's research work at the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL). The table below provides a list of those the ice events dates and the reasons behind ice accumulation and ice shedding.¹⁰

<table>
<thead>
<tr>
<th>Icing Event Dates</th>
<th>Ice Accumulation Causes</th>
<th>Ice Shedding Causes</th>
</tr>
</thead>
<tbody>
<tr>
<td>December 2007</td>
<td>Freezing Rain &amp; Fog</td>
<td>Temperature above 32F</td>
</tr>
<tr>
<td>March 2008</td>
<td>Snow, Rain &amp; Fog</td>
<td>Sun with Temperature above 32F</td>
</tr>
<tr>
<td>December 2008</td>
<td>Snow &amp; Fog; Freezing Rain &amp; Fog</td>
<td>No shedding reported</td>
</tr>
<tr>
<td>January 2009</td>
<td>Freezing Rain &amp; Fog</td>
<td>Gusty winds, temperature above 32F</td>
</tr>
</tbody>
</table>

UCII Monitoring System Implemented

| February 2011    | Freezing Rain           | Solar Radiation, temperature above 32F |

No icing events occurred in winter 2011-2012

<table>
<thead>
<tr>
<th>26 February 2013</th>
<th>Snow</th>
<th>No shedding</th>
</tr>
</thead>
</table>

Between December 2012 and April 2013, there were few other instances of minor accumulation which didn’t qualify to trigger the ice shedding alarm.

| 9th December 2013 | Freezing Rain, Snow     | No shedding |

Table1. Past Icing Events Summary

In past events, the precipitation has been sometimes described as a wintery mix: snow, sleet, ice pellets, or rain. In the March 2008 event, according to the Toledo Blade there were various reasons contributing including lightning, thunder, sleet, snow, rain, and freezing rain (Blade March 29, 2008 cited in Jones 2010). Sometimes, instead of a discrete event, there could be series of precipitation events.

The following photographs are a good representation of ice accumulation and shedding from the stay cables in the Veterans’ Glass City Skyway bridge. These are from December 11, 2007.
Fig.3. Ice hanging on stay\textsuperscript{33}

Fig.4. Ice fallen from the stays\textsuperscript{33}
February 26, 2013 Icing

On February 26, 2013 the dashboard started reporting Y1 every hour since 12 noon. At 3:30pm, the ice accumulation on stays was reported. The thickness of ice ranged up to 1/4 inch. After talking to Dr. Doug Nims (personal communication) this was reported on UCII website:

“Based on observations at the site, ice had been found (primarily on the eastern sides of the sheaths and pylon). Accumulations of up to 0.25 inch have been measured.” – Dr. Arthur J Helmicki.

At 7 pm the dashboard hit R1 and the report said “Further observations show ice still present, but greatly reduced. Temps up. Steady rain.” – Dr. Arthur J Helmicki

These photos were taken during the event:

(photo credits: research team from University of Toledo)

Fig.5. North-bound (left) and South-bound stays

Further report from Toledo informed us that at 10:00pm the ambient temperature rose up above freezing. The stays and pylon became clear off ice. There was water running rapidly down underside of stays. Some loose slush fell off the pylon. Thickness was less than ¼”. Ice did not shed. It melted and ran off. The same behavior was observed on the full-scale mock-up by University of Toledo research group.

This winter (December 2013 - March 2014), which has been riddled with low temperatures and frequent snow showers seemed to have lot of potential to see some icing events. However, only a few instances were reported in December when our dashboard reported ice accumulation. However, when verified with visual inspection, hazardous accumulation was not confirmed. We had quite a significant ice accumulation incident on December 9, 2013. At 2:10 am there was: “Thin layer of ice on all cables. Temp of cables were 24-27 F. Air Temp was 31F. Light freezing rain and light snow was observed.” – Matt Harvey (ODOT)
Accumulation was minimal between January and March. There was no report of shedding this year.

1.3 Previous Research / Literature Review

Icing in bridges is a relatively new problem, but different icing models have been developed in the past few decades based on different mathematical and statistical methods. Here are a few examples of previous research done on the issues of ice formation and suggested remedies. As discussed before, one of the most significant causes for ice accumulation at VGCS is freezing rain.

Freezing precipitation, defined by the American Meteorological Society's Glossary of Meteorology as freezing rain, freezing drizzle, and freezing fog (Glickman, 2000), can have a devastating effect on many industries, including transportation, energy, agriculture, and commerce.

One of the most thorough reviews of freezing precipitation studies was performed by Cortinas and Bernstein where they conducted a comprehensive analysis of freezing rain, freezing drizzle, and ice pellets. They used data from surface observations across North America. This study provides additional information about the temporal characteristics of the distribution. Another one of the most significant reviews of freezing precipitation research can be found in a U.S. Army report (Bennett, 1959). Bennett hypothesized how freezing rain in the US occurs east of the Rocky Mountains primarily between November and March extending from northwestern Texas all the way up northeast to New England. Bennett estimated that once every three years in this "glaze belt" most areas will experience storms with ice accumulations between 0.64 and 1.27 cm.

Another significant study was based on statistical analysis of meteorological data for icing and ice shedding on overhead power-line conductors (Savadjiev and Farzaneh, 2004). The data studied were recorded during the 57 icing events (1659 hr), which took place between February 1998 and January 2000 at the Mont Bélair icing test site in Quebec, Canada. They tried to establish shape and statistical parameters of the transfer functions representing the correlations between hourly icing rate and the variations of the various meteorological variables like ambient temperature, hourly number of ice-rate meter signals, wind speed and direction, and freezing precipitation rate.

They considered diverse stages of the ice formation process such as in-cloud icing and freezing precipitation icing. Savadjiev and Farzaneh obtained a set of fitting regression curves as the statistical base for creating an empirical probabilistic icing, and ice shedding model for studying and forecasting atmospheric-icing loads on overhead power-line conductors.

In the US, ice pellets and freezing precipitation occur mostly from November through March (Robbins and Cortinas, 1996) and are usually short lived (Cortinas et al. 2000). The National
Climatic Data Center (NCDC) provided surface observations made hourly for the United States and Canada during the period 1976-90.

Few reports of freezing precipitation and ice pellets with a surface temperature greater than 32°F were obtained after closer analysis of the data. It was observed that when a freezing rain event ends with a shift in precipitation type, it is mostly rainfall at daytime but it is evenly dispersed among various precipitation types, including snow, at night. Another important study regarding effect of freezing rainfall, ice formation, its thickness on cylindrical substances like transmission lines, branches, wire fences etc. was performed (Jones, 1996). Her report used hourly measurements of the weather conditions, including precipitation rate, air temperature, dew-point temperature, wind speed, atmospheric pressure and solar radiation, can be used with an ice accretion model to hind-cast the amount of ice accreted in past freezing-rain storms. It describes two models to calculate freezing-rain ice loads on horizontal cylinders from weather data. One model is very simple and requires only the information that freezing rain is occurring along with the concurrent precipitation rate and wind speed. The more detailed model requires as additional information the air temperature, dew-point temperature, and solar radiation flux, as well as the diameter of the wire on which ice is accreting.

A comparison of the two models using the historical weather data at Des Moines indicates that the simple flux model is conservative, as expected, but generally agrees well with the detailed heat-balance model. Jones suggested that as freezing-rain events occur at CRREL, measurements of accreted ice on horizontal rods will be compared with the models’ predictions. This field data can be used to fine-tune the heat-balance model. Parameters that may have a significant effect on the calculated ice load and may need to be adjusted, include a) the threshold for incorporating all of the runoff water in the proto icicle, and b) the projected area of the ice accretion that is assumed to intercept the precipitation flux. The good agreement between the heat-balance model and the simple flux model indicates that the modeled ice thicknesses can be easily extrapolated so that consistent ice thicknesses can be used in the design of structural elements with different cross sections. It also shows that weather data can be used to determine conservative, but apparently realistic, ice loads using back-of-the-envelope calculations.

There were rigorous research done on the various icing sensors and their utility and accuracy for weather monitoring. An aviation routine/special weather report (METAR/ SPECI) remark was developed (Ryerson and Ramsey, 2006) that would report quantitative ice thickness at over 650 locations during ice storms using new algorithms developed for the Automated Surface Observing System (ASOS). These ASOS sites have received the Goodrich Sensor Systems (formerly Rosemount) 872C3 icing sensor, providing the system with the ability to report freezing rain but with no capability to provide quantitative reports of ice accretion. The ASOS is currently programmed to report icing events only when they are associated with freezing rain. However, the ASOS icing sensor is also known to detect ice accretion from freezing drizzle, wind-driven mist that freezes on elevated objects, freezing fog, and hoarfrost.
Here Ryerson and Ramsey studied one serious problem about freezing rain that is how to measure the amount accumulated. Glaze ice accretions vary significantly not only over short geographic distances, but also with the shape and orientation of structures on which the ice gather, the thermal properties of those structures, and small-scale local variations in wind speed and direction. Above all, it is difficult to measure ice amount, even on structures as simple as tree limbs or wires.

Freezing rain occasionally creates nearly uniform ice cylinders around objects such as twigs and grass blades (Ackley and Itagaki, 1974), it more often is influenced by wind, thermal conditions, and rainfall rate, allowing water to flow before freezing, creating icicles and other non-uniform shapes.

Although Ryerson and Ramsey recognized that ice accumulation varies significantly with location because of spatial variations in meteorological and topographical conditions and the specific thermal characteristics of the accretion surface, they suggested that the ASOS ice-detection system based on Goodrich vibrating probe ice detector will now provide a consistent baseline of ice-amount information.

Tipping buckets are one of the most commonly used devices for precipitation measurement. Several studies were done regarding the performance of rain tipping buckets. The most basic argument against their accuracy was they do not measure rain rate; they provide only a rough estimate of the quantity of water accumulated in one minute by counting the number of tips. A new algorithm was proposed to extract rain rate from data gathered with modern rain gauges (D'Amico et al. 2013), and test its performance against an extensive database collected over a period of eight years. This study was used as a backdrop to model our rainfall amounts to rates.
The accuracy of rain bucket is worse at the high rain rates. Several studies recommended a dynamic calibration to account for the nonlinear behavior of the gauge, especially at the high rain rates. The water from the rainfall that falls into the funnel cone does not fall straight to the cone's outlet directly but water flows like a cyclone around the cone, especially at high rain rate. From the top view of funnel, when the cyclone water rotates itself, follow the circumference of a cone and flow through the outlet (Lelomphaisarl, 2012). A small obstruction was implemented. According to his research a new tipping bucket with obstacle sheet modified gives the better accuracy than the original one.

![Graph](image)

**Fig.7.** Percentage error of ordinary (non-modified) Rain Gage compare to the modified one

For subtle changes in precipitation, however, dielectric wetness sensors have been effective. Recently few tests were made on the LWS-L Leaf Wetness Sensor as well. These sensors are based on dielectric; as water has higher dielectric than ice, it can be used not only for wetness check, but potentially to determine type of precipitation. Andy Reehorst at Icing Branch, NASA Glenn Research Center ran the Decagon Leaf Wetness Sensor on his building’s roof for a month. He observed some cases where the temperature crossed the 0°C line and the resulting water phase change has an impact on the leaf wetness sensor’s measurements. In the figure below we can see his comparison of the leaf wetness sensor output (Volts, scale on left), the air temp (National Weather Station (NWS) hourly measurements and a probe at the LWS height (about 3 feet above roof), temp scale on right side), humidity (from NWS and his roof sensor, scale on left), NWS precipitation (on right scale), and a binary (precipitation/no precipitation) Kemo rain sensor.

“To me, this data points out the need for having temp measurements co-located with the leaf wetness sensor. But the LWS does seem quite sensitive to precipitation (particularly above freezing) and does a good job in showing persistent moisture.” (Andy Reehorst, 2012)
As elaborated before, solar radiation has been a cause for ice shedding. Different types of solar radiation sensors have been used over the years by climatologists. One common approach has been to have two sensors, one measuring radiation from the whole sky -global irradiance, the other measuring the whole sky apart from the sun -diffuse irradiance. Another method pertains using an array of pyranometers, with different fixed orientations, hence different views of the sun and sky. The known position of the sun combined with the sensor orientation is used to solve for values of global and diffuse from the differing sensor outputs.

Another well-established meteorological parameter is sunshine duration, measured using the Campbell-Stokes recorder. This uses a glass sphere to focus the direct solar beam onto a recording chart, causing a burn, which indicates the duration of bright sunshine.

When Delta-T Devices, UK brought the Sunshine Sensor BF3 to the market, a BF3 sensor was installed on the roof of a six-story building in the Merchiston Campus of Napier University, Edinburgh from February 22–July 3, 2001 to evaluate the performance of this new device. Horizontal global and diffuse irradiance data were collected from the BF3. (Wood et al. 2003)
According to their observations, the BF3 provides a reliable straightforward measurement of global and diffuse irradiation, without needing polar alignment or regular adjustment. It also provides a measure of sunshine hours that is within the WMO accuracy requirements, and is significantly more accurate than the Campbell-Stokes recorder.
1.4 Existing System

Various anti-icing and de-icing methods were researched and observed, but so far no method proved to be practical, cost-effective or implementable at VGCS. In 2011, UCII created a dashboard based on observations made by the university team and research done previously. The intermediate solution chosen was rather a model based on likelihood of icing incidents than an anti-icing or de-icing system. There were different factors that were considered while trying to implement an effective system at VGCS like installation cost, maintenance, non-destructive nature etc.

The existing dashboard has the following features (Agrawal, S., 2011):
- It only collects and interprets remote data from local weather stations, hence there is no expense incurred due to instrumentation or installation.
- Since the dashboard algorithm doesn't require physical sensors and built based on thorough study of icing causes and patterns, it require little maintenance.
- The dashboard uses very flexible solution and can be adjusted as per needs of the user.

The dashboard from phase I can be best described through this process flow diagram:

Fig.10. Dashboard process flow diagram

Precisely, criteria for ice accumulation, ice persistence and ice shedding were taken from observations made by ice experts and implemented in the dashboard algorithm. Following this,
reliable weather sources were chosen, and data parsed from these weather websites and used for decision making. Ice accumulation and shedding checks are made based on last hour’s data. There are eight states or levels in the ice event stage depending upon the extremity of the predicted icing. A user interface was built on UCII website for the client’s perusal.

“Ice accumulation on the bridge stay sheaths is a slow process and is difficult to infer if there are not accurate sensor measurements of it available on the bridge. The ability to measure precipitation rate, the temperature on the sheath, and solar radiation on the sheath or the bridge, should improve the speed and performance in making critical decisions concerning the safety of the traveling public.” (Kumpf et al. 2011)

1.5 Modified System (Phase II): Objectives & Implementation

There is no debate about the fact that ice shedding from the stays of the VGCS could pose a potential risk to safety of commuters. There is also economic loss due to damages to vehicles and delays due to lane closures. In the past few years, the existing system has been able to capture icing events only to a satisfactory level of promptness and reliability. As the Veteran’s Glass City Skyway has unique stays with stainless steel sheaths and local weather that contributes to the icing problem, need arose for establishing a more accurate microclimate station. It is not easy to monitor the presence of ice and its thickness on the sheaths without appropriate ice sensors, thus the most basic step towards improving the existing dashboard algorithm was the inclusion of new sensors on the bridge and their data into the algorithm.

Some of the major upgrades that have been implemented or proposed during Phase II of the automated ice monitoring system are:

i. Increasing robustness of the algorithm (Monitor of the monitor) – New module added in the algorithm to test the functioning of all the remote weather stations. This can be viewed through a new table in dashboard main panel which reports station status

ii. Alternate data source (Local Sensors) – To increase the speed, redundancy and accuracy of the algorithm we installed different icing sensors such as stay thermistors, ice detector, dielectric leaf wetness sensor, rain tipping gage, solar sensor etc. on the bridge location itself

iii. Added parameters – There are various parameters critical to decide ice events that the existing system had been requiring, such as solar radiation, type of wetness, ice thickness etc. Some of the new sensors have been providing data for the same.

iv. Active control – As we have active control over our data logger programs scheduling data collection, we can now change different thresholds, sampling rates etc. as per our requirements

v. Expediency – Ice events, particularly shedding, can happen very fast. Hence it is important to have a faster reporting system. The sampling speed of sensors is at 10 minutes now, and can be made faster, if required.

The next chapter details the data sources and methods that have been used to collect and process the meteorological information.
Chapters 3, 4 are about the different new sensors that have been installed at VGCS.

Chapter 5, 6 describe the proposed ice accumulation and shedding algorithm.

Chapter 7 details the weather monitor website.

Chapter 8 is about the ground reality seen past winter.

Chapter 9 concludes this thesis.
Chapter 2: Weather Data

Most of the criteria being used in the existing algorithm are based on research by K.F. Jones who performed a rigorous analysis of the icing events that occurred in Toledo, and found some of the common properties that were consistent during each of the ice events. ¹

2.1 Ice Events Criteria: After further review of additional publications, it was again observed that from previous research conducted by Bennett¹⁷, Jones¹⁰, Cortinas¹⁸,¹⁹, the following factors can be selected as important compelling criteria for ice accumulation or shedding.

Criteria that could likely cause Ice Accumulation are:

1. Freezing Rain/Rain: Precipitation with air temperature below 32F.
2. Freezing Fog: Fog with air temperature below 32F.
3. Wet Snow: Snow with air temperature above 32F.

Similarly, Criteria that would likely cause Ice Fall are:

1. Warm Air: Air Temperature above 32F.

2.2 Data Sources: There are various data sources used to obtain data for determining the local weather at the Veteran’s Glass City Skyway Bridge. Some of them are parsed from weather websites from nearby weather stations while the rest are collected from sensors that have been put up at VGCS for better reliability. These can be summarized as below:

a. Road Weather Information System (RWIS): A Road Weather Information System (RWIS) comprises automatic weather stations (technically referred to as Environmental Sensor Stations (ESS)) in the field, a communication system for data transfer, and central systems to collect field data from numerous ESSs. These stations measure atmospheric, pavement and/or water level conditions. RWIS data are used by road operators and maintainers to support decision making. Most RWIS provide data for air temperature, dew point, surface temperature, relative humidity, wind speed and direction, and precipitation type.
There are four RWIS stations used in the present dashboard algorithm:

1. 142-I-280 @ VGCS (ID 582016) – This is the local RWIS station at the bridge site.
2. 140-IR 475 @ US 23 Split (ID 582013) – This station is 6.4 miles away from the bridge location.
3. 141-IR 75 @ SLM 4.9 475 Split (ID 582014) – It is 11.2 miles away from VGCS.
4. 150-I-280 @ Libbey Road (ID 582024) – This is 10.2 miles off the bridge.

b. **Meteorological Terminal Aviation Routine (METAR):** A METAR weather report is mostly used by pilots in fulfillment of a part of a pre-flight weather briefing, and by meteorologists, who use aggregated METAR information to facilitate weather forecasting. Most METAR system provides information about temperature, dew point, wind speed, wind direction, cloud cover, visibility, pressure, precipitation amount etc.

There are two METAR stations at the local airports:-
1. Toledo Express Airport (KTOL) – It is 12.2 miles away from VGCS
2. Toledo Metcalf Airport (KTDZ) – It is 10.3 miles away from VGCS

c. **Local Stations:** There are five new types of sensors that were installed on the bridge this year: stay thermistor, leaf wetness sensor, solar radiation sensor, rain tipping bucket and ice detector that have been set up at the tower built on the bridge. These sensors, in various combinations (according to the parameters set by research done by icing experts) can contribute to the ice decision algorithm.

Unlike the RWIS & METAR stations where each of the six stations contribute to both ice accumulation and shedding decisions, our new sensors are used appropriately in the proposed algorithm to generate alarm conditions as some of these sensors collect data pertaining to only ice accumulation or shedding. The local stations, hence, can be classified into two station types:

**Accumulation Determining Stations**

1. Accu_Local1: - Stay Thermistor & Dielectric Wetness Sensor
2. Accu_Local2: - Stay Thermistor & Rain Tipping Bucket
3. Accu_Local3: - Ice Detection Sensor
The ice detector comprises of a single station alone for being able to generate ice presence and thickness information directly.

**Shedding Determining Stations**

1. Fall_Local1 :- Stay Thermistor
2. Fall_Local2 :- Sunshine Sensor

Details of each of these sensors are described in the next two chapters. In chapters 5 and 6, proposed algorithm of how these local stations can be implemented in the algorithm has been elaborated as well.

**2.3 Data Collection and Storage**

The data is collected from the various stations or various sensors to be precise at different time intervals according to the requirement of the algorithm. Once the relevant weather data from RWIS and METAR measurements is identified, we need to collect them in the local database. Similarly, data from all the local ice sensors are also collected.

![Fig.11. UCII Monitoring System Overview](image)

Since METAR records are updated on an hourly basis, the automated program runs hourly too for data mining. METAR data for KTOL & KTDZ are collected from the following websites:

**KTOL** : [http://www.wunderground.com/q/zmw:43542.4.99999](http://www.wunderground.com/q/zmw:43542.4.99999)
KTDZ:  [http://www.wunderground.com/q/zmw:43465.4.99999](http://www.wunderground.com/q/zmw:43465.4.99999)

RWIS measurements are updated every 10-minute, the automated program runs every 10 minute for the data collection. RWIS data for the four weather stations are collected from the following websites:


In case of the stay thermistors, ice detection sensor, solar radiation sensor, rain tipping bucket and dielectric leaf wetness sensor, the data is collected every 10 minutes.

Data collection: The processing program used in the backend is written in the language Python. The program is shown in Appendix.

Data storage: MySQL database is used in the UCII server for collection of data. The tables in the database used in data storage are listed below:

(a) METAR: Store METAR data.
(b) RWISatmos: Store RWIS atmospheric measurements.
(c) GlassSkyway: Store data from the stay thermistors and vibrating wire gages.
(d) VGCS_SolarSensor: Store data from the sunshine sensor.
(e) VGCS_LeafSensor: Store data from the dielectric leaf wetness sensor.
(f) VGCS_RainBucket: Store data from the rain tipping bucket.
(g) VGCS_IceDetector: Store data from the ice detection sensor.

Relevant fields in the tables:

Table (a) METAR: The fields in this table are as follows:

“unixtime” – Time of record (in UNIX time)
“Temperature” – Atmospheric temperature reading (in °F)
“Events” – Precipitation type/Sky cover in detail
“Conditions” – Precipitation type/Sky cover in detail
“Airport” – Airport at Toledo or Metcalf

Other fields recorded in this table, but not directly applied in the algorithm. They are: “Dewpoint”, “Humidity”, “Pressure”, “Visibility”, “wind_dir”, “wind_speed”, “gust_speed”, and “precipitation”.

20
Table (b) RWIS Atmospheric Measurements: The fields in this table are as follows:

- “unixtime” – Time of the record (in Unix time)
- “Sysid” – System-id 1 for the RWIS station.
- “Rpuid” – System-id 2 for the station.
- “ApAir_T” – Atmospheric temperature (in deg F)
- “Pc_Type” – Precipitation Type (1 – Rain, 2 – Snow, etc.)

Other fields recorded in this table, that are not directly applied in the algorithm are:

Table (c) GlassSkyway: The fields in this table are as follows:

- “DateTime” – Time of the record (in DateTime)
- “unixtime” – Time of the record (in Unix time)
- “Battery_Voltage” – Battery voltage of the data logger
- “Panel_Temp” – Panel temperature of the data logger
- “7X20TUO” – Stay temperature for Upper Outer thermistor at Stay 20
- “7X20TUS” – Stay temperature for Upper Sheath thermistor at Stay 20
- “7X20TWS” – Stay temperature for West Outer thermistor at Stay 20
- “7X20TLS” – Stay temperature for Lower Sheath thermistor at Stay 20
- “7X20TEO” – Stay temperature for East Outer thermistor at Stay 20
- “7X20TES” – Stay temperature for East Sheath thermistor at Stay 20
- “8X08TUO” – Stay temperature for Upper Outer thermistor at Stay 8
- “8X08TUS” – Stay temperature for Upper Sheath thermistor at Stay 8
- “8X08TWS” – Stay temperature for West Outer thermistor at Stay 8
- “8X08TLS” – Stay temperature for Lower Sheath thermistor at Stay 8
- “8X08TEO” – Stay temperature for East Outer thermistor at Stay 8
- “8X08TES” – Stay temperature for East Sheath thermistor at Stay 8

There are other fields recorded in this table, which are not used in the algorithm. These are the vibrating wire strain gages.

Table (d) VGCS_SolarSensor: The fields in this table are as follows:

- “DateTime” – Time of the record (in DateTime)
- “RecNum” – Record number of dataset collected
- “Battery_Voltage” – Battery voltage of the data logger
- “Panel_Temp” – Panel temperature of the data logger
- “Global_Rad” – Global radiation in watt/m²
- “Diffuse_Rad” – Diffused radiation in watt/m²
- “SunStatus” – Binary 0 or 1 for sunshine status
Table (e) VGCS_IceDetector: The fields in this table are as follows:

“DateTime” – Time of the record (in DateTime)
“RecNum” - Record number of dataset collected
“Battery_Voltage” – Battery voltage of the data logger
“Panel_Temp”- Panel temperature of the data logger
“Frequency” – Frequency of ice detector probe vibration in Hz
“Ice” – Thickness of ice on probe in inches
“Ice_mm” - Thickness of ice on probe converted to millimeter
“HeatTime” – Record of duration when heater was last activated
Table (f) VGCS_LeafSensor: The fields in this table are as follows:

“DateTime” – Time of the record (in DateTime)
“RecNum” - Record number of dataset collected
“Battery_Voltage” – Battery voltage of the data logger
“Panel_Temp” – Panel temperature of the data logger
“LWS_mV” – Dielectric measured in millivolts
“Conditions” – Wet or dry conditions estimated from dielectric recorded
Fig. 14. MySQL table for Leaf Wetness Sensor data

Table (g) VGCS_RainBucket: The fields in this table are as follows:

“DateTime” – Time of the record (in DateTime)
“RecNum” - Record number of dataset collected
“Battery_Voltage” – Battery voltage of the data logger
“Panel_Temp”- Panel temperature of the data logger
“Rainfall_Tot” – Precipitation recorded in inches/hour
There is also a view (MySQL routine) that has been created that collects useful data from the tables of all the icing sensors and puts them in a single table. This view is basically used for easier plotting functions.

**Table/View (h) VGCSIcing_AllSensors:** The fields in this table are as follows:

- **“DateTime”** – Time of the record (in DateTime)
- **“Ice”** – Thickness of ice on probe in inches on ice detector
- **“LeafWetness”** – Dielectric measured in millivolts by leaf wetness sensor
- **“Conditions”** – Wet or dry conditions estimated from dielectric recorded by leaf wetness sensor
- **“Rain”** – Precipitation recorded in inches/hour by rain bucket
- **“Global_Rad”** – Global radiation in watt/m² measured by sunshine sensor
- **“Diffuse_Rad”** – Diffused radiation in watt/m² measured by sunshine sensor
- **“SunStatus”** – Binary 0 or 1 for sunshine status as determined from sunshine sensor
Fig. 16. MySQL view for customized data of all ice sensors
Chapter 3: New Ice Sensors & Initial Experiments

3.1 Geokon Thermistor 3800-2-2

Geokon provides the model 3800 thermistors which are basically designed to measure temperatures in rock, soil and concrete dams. The sensors behave as resistors with high negative temperature coefficient of resistance. The beads are made from a mixture of metal oxide encased in epoxy or glass. The thermistors were customized to be encapsulated in a very small stainless steel housing to maintain uniformity in surface characteristics in terms of deploying them on the stainless steel stay sheath. The cable is forty feet long to be able to run down the length of the tower without splicing. The model 3800-2-2 was chosen for its superior accuracy.

3.1.0 Laboratory experiment on temperature measurement using Geokon Thermistors 3800-2-2.

Objective: To measure room and freezing temperature using Geokon Thermistor Probes (Model 3800-2-2), estimate their accuracy and precision using different methods.

Apparatus: Geokon Thermistors 3800-2-2 (16), Campbell Scientific CR10X Datalogger (1), Geokon VW DSP Interface (1), Campbell Scientific Relay Multiplexer AM416 (1), Geokon Readout Box GK 404 (1), Standard Thermometer (1), Serial to USB Interface (1), Dell Latitude E6510 Laptop (1), Canary Systems Multillogger Software.

Experimental Setup:

Introduction

An instrument commonly used to measure surface temperature on a long term basis is a thermistor. In our experiment we chose thermistor probes manufactured by Geokon Inc. which are known for their small size, robustness and high degree of stability with a long lifespan. They have a wide operating range of measuring temperature from -50°C to 70°C. These thermistors are made from metal oxides encased in epoxy, supplied inside a stainless steel housing already potted on the end of a cable.11

Fig.17. Geokon 3800-2-2 Thermistor

Fig.18. Naked Thermistor Bead (photo credits, John Flynn, Geokon Inc.)
Operating Principle

Thermistors are semiconductors behaving as resistors with a high negative temperature coefficient of resistance. The cable effects are not significant due to high change in resistance. They give non-linear output represented by the **Steinhart-Hart log equation**:

\[
T = \frac{1}{[A + B \ln R + C (\ln R)^3]} - 273.2
\]

where \( T \) = Temperature in \(^{\circ}C\), \( \ln R \) = Natural logarithm of thermal resistance, coefficients \( A = 1.4051 \times 10^{-3} \), \( B = 2.369 \times 10^{-4} \), \( C = 1.019 \times 10^{-7} \).

\( A \), \( B \), and \( C \) are the Steinhart-Hart coefficients which vary depending on the type and model of thermistor and the temperature range of interest. Steinhart and Hart performed 100 different relationships between resistance and temperature using two to five fitted constants. A multiple regression program was run to test the relationship, and of the few reasonably good fits the above equation was consistently the best.

An extensive examination of calibration functions has yielded this function suitable for calibration curves for precision thermistor temperature measurements. This equation is often used to derive precise temperature using a thermistor since it provides a closer approximation to actual temperature than simpler equations, and is useful over the entire working temperature range of the sensor.

It is recommended to workers making precision measurements as its properties have been examined for a variety of data and a variety of thermistors. The coefficients used for the equation above is the same used by Geokon Inc. and Canary Systems Multilogger software for temperature measurement using the vibrating wire gages.
Experiment

The experiment was carried out on two tiers. For all of these, the Geokon thermistors were wired to the temperature (higher) channels of a Campbell Scientific AM416 Relay Multiplexer which was then connected to a Geokon Vibrating Wire Digital Signal Processor (VW DSP) and finally recorded (and programmed) using a Campbell CR10X Datalogger. A laptop was used to send program and collect data using the Multilogger software from Canary Systems.

Fig. 19. Geokon handheld meter used for auxiliary measurements

Fig. 20. Canary Systems Multilogger Software to send program and collect data
The experiments can be elucidated as follows:

i. **Test for accuracy:** The first setup was used to test eight thermistors all measured by Multilogger’s built-in settings for Geokon VWGs at room temperature to check for consistency and accuracy. The factory standards hail the thermistors to have an accuracy of +/- 0.2 °C. The thermistors were connected to the first eight channels of the multiplexer and read for a few hours.

**Observation**

It was seen that all of the thermistors maintain a similar trend and record similar temperature over a small or extended time period. The largest deviations are around 0.4 °C. We could conclude that the factory specification of their accuracy is dependable.

![Geokon Thermistors Temperature Measurement Trend](image_url)

**Fig. 21.** Measurement trend of eight thermistors

ii. **Test for precision at freezing temperature:** Our primary objective to use the thermistors is to measure the stay-sheath temperature on bridges during freezing conditions. Thus, our second test was conducted to observe the precision of the
temperature measured by the thermistor probes as recorded by a.) CR10X datalogger, b). Geokon GK404 hand-held meter directly, versus that c). measured by a standard thermometer. This test required four thermistors which were taped together and immersed in a cup of tap water and then put in the freezer and kept overnight.

- Fig. 22. Thermistors kept in freezer
- Fig. 23. Thermistors immersed in water
- Fig. 24. Readings simultaneously noted by handheld GK 404
- Fig. 25. Standard thermometer immersed in setup to record temperature
Observation

It was observed that the temperatures measured by all the four thermistors were in agreement and that they accurately measured temperature even at sub-zero temperature. All the thermistors were chosen individually and read by the hand-held GK 404 readout box. The temperature of the frozen water was also measured by the analog thermometer immersed in it. It was seen that the readings registered by the data logger were identical to those read by the hand-held meter and quite similar to those recorded by the standard thermometer. However, inside the freezer the water did not freeze at freezing point at few instances.

<table>
<thead>
<tr>
<th>Measurement Type</th>
<th>Time (in min)</th>
<th>Temperature (in °C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geokon Thermistor (read by Data logger)</td>
<td>0</td>
<td>8.5</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>7.8</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>7.2</td>
</tr>
<tr>
<td>Geokon Thermistors (read by hand-held box)</td>
<td>0</td>
<td>8.4</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>7.6</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>7.1</td>
</tr>
<tr>
<td>Standard Thermometer</td>
<td>0</td>
<td>8.7 (47.5 °F)</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>8.1 (46.5 °F)</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>7.3 (45 °F)</td>
</tr>
</tbody>
</table>

Table2. Comparison of readings taken by all 3 methods

Note: The readings noted by standard analog thermometer are subject to resolution issues due to error of the eye⁵.

Fig.26. Thermistor characteristics at freezing
Conclusion: The Geokon thermistors chosen for measuring stay-sheath surface and stay-sheath & ice interface temperature seem to be a reliable choice for surface temperature measurement over a broad temperature range. They follow the manufacturer’s specifications with respect to accuracy and seem to be a convenient choice in terms of cost, ease of mounting and robustness. They seem to be fairly precise in recording the surface temperature at freezing temperature as well.

3.1.1 Installation of Geokon Thermistors 3800-2-2 at Veteran’s Glass City Skyway on Stays 8 & 20

![Diagram of Gage Locations at Veteran’s Glass City Skyway](image)

Fig.27. Side view of Gage Locations at Veteran’s Glass City Skyway

- MUX locations at 2704, 2741, 2806 and 2828.
- New thermistor locations on Stay 20 (Span 7) and Stay 8 (Span 28).

Mounting: There are four existing multiplexer locations (White NEMA boxes) at Span 27 Segment 04 (2704), Span 27 Segment 41 (2741), Span 28 Segment 06 (2806) and Span 28 Segment 28 (2828).

On March 6th 2012, a team from University of Cincinnati Infrastructure Institute reached Toledo to mount six Geokon Thermistors on Stay 20 and six on Stay 8.

Customized mounts were made by the team at University of Toledo to appropriately fit the sheath facing and outer facing thermistors in a block fabricated to hold well on the sheath surface. This can be seen from the photo below (photo credits – research team, University of Toledo):
The thermistors in the mount assembly were set in different positions on the stays and a metal plate band clamp was used to hold the mounts in place. The pictures in the bottom show the installation procedure vividly (photo credits – research team, University of Toledo).

Fig.28. Custom thermistor mount fabricated for installing on stay surface

Fig.29. Thermistors placed on east side of stay side of stay  

Fig.30. Thermistors placed on upper
Fig. 31. Far view of thermistor installation on stay
The six thermistors were mounted all around the circumference of the stay sheath in clock arms of 12 (upper), 3 (east), 6 (lower) and 9 (west). While there is one thermistor each on the west and lower sides touching the stay sheath surface, there are two thermistors placed on each of the Upper and East side one touching the stay surface and the other facing Outward. The following table describes the gage nomenclature:

<table>
<thead>
<tr>
<th>Gage Name</th>
<th>MUX/Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>7X20TUO</td>
<td>MUX5/Ch1</td>
</tr>
<tr>
<td>7X20TUS</td>
<td>MUX5/Ch2</td>
</tr>
<tr>
<td>7X20TW5</td>
<td>MUX5/Ch3</td>
</tr>
<tr>
<td>7X20TLS</td>
<td>MUX5/Ch4</td>
</tr>
<tr>
<td>7X20TEO</td>
<td>MUX5/Ch5</td>
</tr>
<tr>
<td>7X20TES</td>
<td>MUX5/Ch6</td>
</tr>
<tr>
<td>8X08TUO</td>
<td>MUX6/Ch1</td>
</tr>
<tr>
<td>8X08TUS</td>
<td>MUX6/Ch2</td>
</tr>
<tr>
<td>8X08TW5</td>
<td>MUX6/Ch3</td>
</tr>
<tr>
<td>8X08TLS</td>
<td>MUX6/Ch4</td>
</tr>
<tr>
<td>8X08TEO</td>
<td>MUX6/Ch5</td>
</tr>
<tr>
<td>8X08TES</td>
<td>MUX6/Ch6</td>
</tr>
</tbody>
</table>

Table3. New Stay Thermistors List
Fig. 33. Stay sheath cross section showing thermistor positions

Each of these set of six thermistors were connected to a new multiplexer that was installed inside the existing white NEMA enclosures. Thermistors on Stay 20 were wired to a new 416 Relay Multiplexer which was screwed to the backplane inside the NEMA box at location 2741. Similarly thermistors on Stay 8 were wired to a new AM16/32B Multiplexer which was screwed to the backplane inside the NEMA box at location 2828. The figure gives the wiring diagram used for this upgrade.

**Initial Observations:** We started collecting temperature data to MySQL database from the twelve stay thermistors at Veteran’s Glass City Skyway using Campbell Scientific’s Loggernet software on March 6th 2012, 1:00 PM. This data was compared to temperature data collected from the vibrating wire gage embedded segment thermistors, panel temperature of Campbell Scientific datalogger CR10X inside the cabinet, air temperature data from local **Road Weather Information System** (RWIS) station (142-I-280) at VGCS and **Meteorological Terminal Aviation Routine** (METAR) data from two local airports: Toledo Express Airport (KTOL) and Metcalf Field Airport (KTDZ) for a period of 16 days from March 6 till March 22, 2012.
Initial inspection of the thermistors (16 days):

![Fig. 34. Stay 20 Thermistors Temperature Trend](image1)

![Fig. 35. Stay 8 Thermistors Temperature Trend](image2)

Table 4. Sky Cover and Precipitation during the period

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Sky Cover</td>
<td>0.5</td>
<td>0.1</td>
<td>0.8</td>
<td>0.2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.7</td>
<td>0</td>
<td>0.3</td>
<td>0.3</td>
<td>0.2</td>
<td>0.4</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Precipitaion (inch es)</td>
<td>0</td>
<td>0</td>
<td>0.22</td>
<td>Trace</td>
<td>0</td>
<td>0</td>
<td>1.12</td>
<td>0.11</td>
<td>0</td>
<td>0.81</td>
<td>Trace</td>
<td>0</td>
<td>Trace</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
After inspecting the temperature trend during the 16 day period it was observed that all the sources measured temperature in unison at night. Solar radiation during the daytime would cause sufficient spread in the temperature recorded depending upon the location of the thermistors. Table 4 shows the sky cover (0=clear, 1=cloudy) and precipitation(inches) from National Weather Service data.

Some of the general observations gathered were:

- Upper stay thermistors record much higher temperature than Lower stay thermistors.
- RWIS & METAR data show similar temperature trends. METAR data seem to have higher maximums and lower minimums. They both lag w.r.t. temperature of up to 3hrs or 20 F when compared to the stay thermistors.
- Embedded VWG segment thermistors have significantly lower maximum and higher minimum.

In order to gain deeper insight into the temperature characteristics of the individual thermistors we decided to choose few example days and have a magnified view of their trends. March 15 and March 16 seemed to appear to represent more days in the bracket and hence chosen for the purpose. The weather data for those days were obtained from the National Weather Service which included the sunrise, sunset, maximum and minimum temperatures, sky cover and precipitation in inches.

Initial Inspection on an example day (March 15)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Time(EST)</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sunrise</td>
<td>6:46 AM</td>
<td></td>
</tr>
<tr>
<td>Sunset</td>
<td>6:42 PM</td>
<td></td>
</tr>
<tr>
<td>Maximum Temperature</td>
<td>5:43 PM</td>
<td>78 F</td>
</tr>
<tr>
<td>Minimum Temperature</td>
<td>4:29 AM</td>
<td>58 F</td>
</tr>
<tr>
<td>Average Sky Cover</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>Precipitation</td>
<td>0.81 inches</td>
<td></td>
</tr>
</tbody>
</table>

Table 5. Weather Report on March 15
Fig. 36. Stay 20 Example Day Temperature Characteristics

The magnified view of these example days’ 24 hour characteristics provided the hourly response of each thermistor in detail. These were the general observations:

- At night, all sources seemed to converge w.r.t their temperature recording.
- It could be observed that in the early morning with sunrise, the East thermistors showed the steepest and most sudden rise in temperature.
- They were followed by the Upper thermistors more towards the noon.
- During the afternoon till late evening, the West side thermistors were the warmest.

Initial Inspection on a cold day (Freezing event):

Fig. 37. Characteristics for Stay 20 thermistors on March 9 & 10 (Freezing event day)
Since the installation of the thermistors, we did not have any icing (ice accumulation or shedding) event on the bridge in the past two winters. However, there was an occasion where the temperature was low enough and suitable for such an icing event had there been some kind of precipitation simultaneously. We term this event as “possible freezing event” that occurred between March 9th evening around and March 10th morning.

On March 9, 2012 the temperature measured by the stay thermistors fell under 32 F around 7:30 pm and remained under through March 10 night till the morning when the temperature rose above 32 F with sunrise at 6:55 am. As usual, the stay thermistors and the local RWIS station recorded similar temperature all night. However, after sunrise the East stay thermistors showed significant rise in temperature compared to other thermistors and crossed melting point (32 F) around 8:15 am. On the contrary, the local RWIS temperature read melting point three hours later at around 11:15 am. There were times where it consistently had a delta of about 20 F with the warmest thermistors. Incidentally, it was also noticed that the thermistors showed such fast and overwhelming rise in temperature (around 11 F in 30 minutes) that the current sampling rate of 30 minutes failed to track critical points.

On May 17, 2013 a trip was made again to the Veteran’s Glass City Skyway bridge, where the system was upgraded from CR10X data logger to CR1000, using CRBasic program instead of Canary Multilogger for data collection, and the sampling time was lowered to 10 minutes. This trip will be discussed in details later in Chapter 4.
3.2 LWS-L Dielectric Leaf Wetness Sensor

Leaf Wetness sensors have been developed to estimate by inference the wetness of nearby leaves. The LWS-L measures the leaf surface wetness by measuring the dielectric constant of the sensor’s upper surface. The sensor is able to detect miniscule amounts of water or ice.

![Leaf Wetness Sensor functional diagram](image)

**Fig.38. Leaf Wetness Sensor functional diagram**

3.2.0 Laboratory experiment on measurement of output voltage using LWS-L Leaf Wetness Sensor.

**Aim:** To measure output voltage of the leaf wetness sensor for a fixed excitation and determine appropriate threshold for wetness conditions.

**Apparatus:** LWS-L Dielectric Wetness Sensor (1), Campbell Scientific Datalogger CR1000 (1), Serial to USB Interface (1), PC, Loggernet Software.

**Experimental Setup**

**Operating principle:** The LWS-L measures the dielectric constant of a zone approximately 1cm above the upper surface of the sensor. The dielectric constant of water and ice are much higher than air, so the measured dielectric constant is strongly dependent on the presence of moisture or frost on the sensor surface. The sensor sends a millivolt signal proportional to the dielectric measurement of the zone, which in turn is dependent on the presence of moisture or frost on its surface.\(^6\)
**Experiment**: The leaf wetness sensor was connected to the CR1000 datalogger and provided switched excitation voltage of 2.5mV. The program was written in Campbell's CRBasic Editor where output voltage was set to be recorded with a scan rate of once per minute. The leaf sensor was exposed to different kind of wetness conditions and the output was recorded accordingly.

There were basically three experiments: 1. Amount of wetness test, 2. Impurity test and 3. Freezing conditions test.

![Experimental setup of datalogger CR1000 with LWS-L Leaf Wetness Sensor](image)

**Wetness Test**: Various kinds of experiments were conducted on the leaf sensor to emulate real life conditions of drizzle, light rain, heavy rainfall and freezing rain and the outputs noted accordingly.

<table>
<thead>
<tr>
<th>Time</th>
<th>Experiment</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>11:30 am</td>
<td>Dry Leaf Surface</td>
<td>262 mV</td>
</tr>
<tr>
<td>11:35 am</td>
<td>Light Sprinkle</td>
<td>335 mV</td>
</tr>
<tr>
<td>11:57 am</td>
<td>Medium Sprinkle</td>
<td>515 mV</td>
</tr>
<tr>
<td>12:06 pm</td>
<td>Heavy Sprinkle</td>
<td>597 mV</td>
</tr>
<tr>
<td>1:16 pm</td>
<td>Light Sprinkle</td>
<td>380 mV</td>
</tr>
<tr>
<td>2:50 pm</td>
<td>Soaked Napkin on surface</td>
<td>710 mV</td>
</tr>
<tr>
<td>2:57 pm</td>
<td>Partially immersed in water</td>
<td>746 mV</td>
</tr>
<tr>
<td>3:21 pm</td>
<td>Water level increased</td>
<td>759 mV</td>
</tr>
</tbody>
</table>

![Droplets of water sprinkled on leaf](image)

**Table6. Wetness Test**
Table 7. Impurity Test

<table>
<thead>
<tr>
<th>Time</th>
<th>Experiment</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>11:00 am</td>
<td>Immersed in cup of water</td>
<td>788 mV</td>
</tr>
<tr>
<td>11:05 am</td>
<td>Salt added to water</td>
<td>1030 mV</td>
</tr>
<tr>
<td>2:05 am</td>
<td>Dry napkin on surface</td>
<td>264 mV</td>
</tr>
</tbody>
</table>

The following plots demonstrate the characteristics of the leaf wetness sensor for the wetness amount experiment and the freezing conditions experiment respectively.

Fig. 41. LWS-L partially immersed in cup of water

Fig. 42. LWS-L immersed in cup left to freeze

Table 8. Freezer Test

<table>
<thead>
<tr>
<th>Time</th>
<th>Experiment</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>3:45 pm</td>
<td>Dry leaf kept in freezer</td>
<td>262 mV</td>
</tr>
<tr>
<td>4:40 pm-10:30 am</td>
<td>Immersed in cup of water (inside freezer)</td>
<td>298-300 mV</td>
</tr>
</tbody>
</table>

The following plots demonstrate the characteristics of the leaf wetness sensor for the wetness amount experiment and the freezing conditions experiment respectively.
Fig. 43. LWS wetness test

Fig. 44. LWS Freezing temperature test
**Observations:**

The different experiments yielded a handful of results. These can be explained as follows-

**Dry Leaf Output:** Unlike said in manual, it has been verified through Decagon rep and the experiments that the leaf gives an output around **250-260 mV** when dry.

**Wetness Threshold:** As a few droplets of water or a lot of frost catapults an output above **300 mV**, it can be safe to consider this threshold.

**Scan Rate:** As the leaf gives output w.r.t the quantity of wetness present on it during sampling, higher the sampling rate, the better. Scan rate of **1 min** was used for the experiment. However, the sampling rate to be implemented into the algorithm was set at 10 minutes during field installation.

**Leaf Angle:** The leaf surface is hydrophobic. It holds a bit of wetness for a few minutes while most drains off and the rest evaporates. Keeping it **horizontal** helps capture precipitation better unless the scan rate is lowered to a few seconds.

**Dust & Impurities:** With the salt test, it was observed that the presence of impurities on the leaf surface **raises the output** significantly. It doesn’t however affect much during dry conditions.
3.3 Sunshine Sensor BF5

The Sunshine Sensor BF5 is mostly used for meteorological “Global”, “Direct” and “Diffuse” solar radiation and sunshine duration measurements. The BF5 may be installed at any latitude and at any polar angle i.e. relative to North. It consists of an array of seven photodiodes encapsulated in a hemispherical dome with a shaded pattern. The following diagrams show its construction:

![Sunshine Sensor BF5 diagram]

Fig.45. Sunshine Sensor BF5 (side view) and detailed construction

3.3.0 Laboratory experiment on measurement of solar radiation using Sunshine Sensor BF5.

**Aim:** To measure solar radiation energy using sunshine sensor and determine appropriate threshold for sunshine status conditions.

**Apparatus:** Delta-T Devices Sunshine Sensor BF5(1), Campbell Scientific Datalogger CR1000 (1), Serial to USB Interface (1), PC, Loggernet Software.

**Experiment:** The sunshine sensor was connected to the CR1000 datalogger and provided voltage of 5V from the datalogger power supply. The program was written in Campbell's CRBasic Editor where the total radiation and diffuse content of the radiation were meant to be recorded every 15 mins and the output was calibrated in terms of Energy (Watt/m²). The photos below depict how the sensor was exposed on an open deck (photo credits- Dr. Arthur Helmicki, University of Cincinnati Infrastructure Institute)
Operating Principle: Uses array of 7 photodiodes with unique computer generated shading pattern to measure incident solar radiation in a way that: 24
- at least one photodiode is fully exposed to solar radiation beam
- at least one completely shaded
- both receive equal amount of diffuse sunlight from rest of sky hemisphere.

A microprocessor calculates:

i. Total (Global) and
ii. Diffuse components of the radiation and
iii. Sunshine Status

World Meteorological Organization (WMO) specified 120W/m² as the threshold for Sunshine Status. Feature doesn't work with CR1000 datalogger, so it was programmed manually according to manufacturer's formula: \( \frac{\text{Total}}{\text{Diffuse}} > 1.25 \) and \( \text{Total} > 25 \text{ Watt/m}^2 \).

Observation:
The direct and hence total radiation has a giant leap right after sunrise. It falls during sunset. Sky cover (presence of passing clouds) causes drop in the solar radiation significantly. Sunshine Status is a binary 1 when global radiation is above 120W/m2 all day from an hour after sunrise and before sunset. During sunrise and sunset the direct beam is negligible, so most of the global radiation comprises of diffuse components. These results were compared to the daily weather report from weather.com as shown in the table below and were found to be pretty consistent with each other.
Fig. 47. Solar radiation characteristics over an extended period of 16 days

**NOTE:**

i. There was shadow provided by canopy to the east and west of the deck which contributes to the low cut of the plot during mornings and evenings.

ii. The backyard was lit for dog walking, which attributes to the small peak observed during late afternoons.

After the general observation, two typical example days were chosen to get a magnified view of the daily characteristic of the solar sensor with respect to different times of the day. One was partly cloudy, another was mostly sunny and clear.
June 23, 2012 had scattered clouds and hence was chosen as a typical partly cloudy day. As expected, it was seen the solar radiation to rise quickly soon after sunrise and fall after sunset. Clouds would cause significant drop in solar radiation during the day.

![Example Day (Partly Cloudy) Solar Radiation Characteristics - June 23](image)

**Fig. 48.** A typical partly cloudy day chosen to see the daily solar radiation characteristics.

June 26, 2012 was a very bright and sunny day according to weather station data. So this day was chosen as an example day for solar radiation characteristics for clear conditions. As expected most of the day had very high and consistent solar radiation, peaking around noon to close to
1000 Watt/m².

Fig.49. A typical clear sunny day taken as example to see the daily solar radiation characteristics.
3.4 Met One Rain Tipping Bucket

**Introduction:** The Met One Rain or Heated Snow Gage is a dual chambered tipping bucket. Rain is metered into a collection funnel on top of the bucket. There is a mercury switch inside the bucket which tips for each 0.01 inch precipitation collected. It has adjustable feet to ensure proper mounting with bracket CM240. There is a primary screen on the funnel that prevents debris from clogging. The cable length is forty feet and has Santoprene rubber cable jacket for better resistance to UV degradation and moisture. The rain collected is discharged through the rain gage base. There is a thermostat based heater inside that can melt snow into water before measurement.

![Fig.50. Rain Tipping Bucket (from top left clockwise) distant view, top view and inside view](image)
3.4.0 Laboratory experiment on measurement of precipitation using Met One Rain Tipping Bucket

**Aim:** To measure precipitation amount using Met One Rain Tipping Bucket and determine appropriate sampling rates and threshold for conditions.

**Apparatus:** MetOne Rain Tipping Bucket (1), 100 mL Gessler Buret (1), Campbell Scientific Datalogger CR1000 (1), Serial to USB Interface (1), PC, Loggernet Software.

**Experiment:**

**Operating Principle:** Collects rainfall in the 12 inch collection funnel and meters the rain into tipping bucket. Snowfall captured in collection funnel and melted by thermostatically controlled heating element. For every 0.01 inches of rain/snow-water eq., the tipping bucket assembly tips due to gravity and activates a mercury reed switch. A momentary contact closure for each increment of rainfall is recorded by datalogger pulse channel. Water drains out base of the gage after tipping.25

The tipping quantity is determined by the equivalent volume of liquid collected in a given surface area.

**Met One Conversion Factor:**

\[
\text{Tip to in }^3: \text{Catch orifice area } (\pi d^2 / 4) \times \text{increment in inches} = 113.04 \times 0.01 \text{ in}^3 = 18.52 \text{ ml}
\]

**Experimental Setup:** The rain tipping gage was connected to the CR1000 datalogger and provided excitation signal of 5V from the data logger power supply. The program was written in Campbell's CRBasic Editor where the pulse (signal return) was counted every second to record every time the bucket tips without missed detection.

The data was totaled every i. 5 minutes and ii. 30 minutes to determine the amount of precipitation during the period.
**Experiment 1: Sampling Rate (5 minute)**

<table>
<thead>
<tr>
<th>Record</th>
<th>Volume of water poured (ml)*</th>
<th>Precipitation recorded (inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>45</td>
<td>0.02</td>
</tr>
<tr>
<td>3</td>
<td>45</td>
<td>0.02</td>
</tr>
<tr>
<td>4</td>
<td>20</td>
<td>0.01</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>8</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>9</td>
<td>80</td>
<td>0.04</td>
</tr>
<tr>
<td>10</td>
<td>60</td>
<td>0.03</td>
</tr>
</tbody>
</table>

Full Data shown in graph.

**Experiment 2: Sampling Rate (30 minute)**

<table>
<thead>
<tr>
<th>Record</th>
<th>Volume of water poured (ml)*</th>
<th>Precipitation recorded (inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>40</td>
<td>0.02</td>
</tr>
<tr>
<td>2</td>
<td>200</td>
<td>0.1</td>
</tr>
<tr>
<td>3</td>
<td>300</td>
<td>0.16</td>
</tr>
</tbody>
</table>

Table 9. Rain Bucket lab experiment

Fig. 51. Rain Bucket lab experiment  
Fig. 52. Gessler Buret
Observation:

It has been observed that the device follows the factory calibration standards where each tip = 18.53 ml of water. During the first few readings the quantity of liquid let in is marginally more than that tipped out, because of adhesion where some water sticks to the funnel. The result obtained is fairly consistent irrespective of fast/continuous or slow/intermittent passage of water into the bucket using the buret. One tip can be considered a threshold check for precipitation in the algorithm as each tip equals to 18.53 ml of water.

Fig.53. Rain Bucket accuracy experiment (actual vs tipping volume)
3.5 Goodrich Ice Detector

The 0872F1 Goodrich Ice Detector detects ice accumulation on an ultrasonic axially vibrating tube and communicates the associated frequency changes through an RS-232 or digital current loop data link. The 0872F1 is mounted on a pole and is designed to operate continuously in an outdoor environment.

The 0872F1 consists of four functional assemblies: a Main circuit card assembly (CCA), an Output Interface CCA, a Filter assembly, and a Strut and Probe assembly.

![Diagram of Goodrich Ice Detector](image)

Fig. 54. The Goodrich Ice Detector (external and functional diagrams)

3.5.0 Laboratory experiment on measurement of ice presence/thickness using Goodrich Ice Detector 0872F1

**Aim:** To measure ice thickness using Goodrich Ice Detector and determine appropriate sampling rates and de-icing threshold.

**Apparatus:** 0872F1 Ice Detector (1), MicroCare Anti-Stat Spray(1), Sliding Calipers (1), Campbell Scientific Datalogger CR1000 (1), Serial to USB Interface (1), PC, LoggerNet Software.
Experiment:

**Operation Principle:** The Goodrich Ice Detector 0872F1 measures precipitation transitions between solid and liquid states. It consists of a sensing element that is exposed to the environment. Ice builds up on this element when it is exposed to icing conditions causing change in its mass. This mass change causes a shift in vibration frequency in an ultrasonic axially vibrating tube. The associated frequency changes are communicated through data link. Ice Thickness is calculated as (manufacturer-specified linear relationship):  

\[
\text{Ice Thickness} = -0.00015 \times \text{Frequency} + 6 \text{ (in inches)}
\]

**Experimental Setup:** The ice detector was connected to the CR1000 datalogger and provided signal of 115V from the mains power supply. The program was written in Campbell's CRBasic Editor where the frequency of the probe was recorded every minute. The data was recorded every 1 minute to determine the corresponding amount of ice thickness.
Observation: The device follows the factory calibration based on the specified linear relationship between change in frequency and corresponding change in ice thickness. The threshold to trigger de-icing cycle was set at 0.04 inches and it proved to be able to de-ice the probe completely during the heating time. The de-icing cycle lasts longer (as the probe remains warm) than the heat-time and keeps the probe frost-free for a couple minutes.

The sampling rate chosen was 1 minute and it proved to be quite effective in determining presence of ice. An experiment was run using sliding calipers to measure ice thickness. This was done in order to manually determine the relationship between thickness of ice forming on probe and that measured by sensor, but it wasn't effective due to quick ice melting of thin layer of ice. Fig 58 shows the frequency recorded and converted to ice thickness by the ice detector CRBasic program.
The thickness (diameter) of the probe was measured using sliding calipers with and without the ice coating. The results obtained were erratic as: The ice melted too fast at room temperature and the calipers couldn't fit onto the ice layer without shaving it.
Initial results:

The chief motivation behind lab experimentation of the different sensors was to find a meaningful conversion of the parameters recorded by the different sensors into comprehensive values, and also to test and calibrate them, if necessary.

The following table is a summary report of the behavior of the new icing sensors.

<table>
<thead>
<tr>
<th>Sensors</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stay Thermistors</td>
<td>All stay thermistors measure temperature in unison at night. Solar radiation (daytime) causes sufficient spread in temperature recorded depending upon thermistor location. RWIS air temperature can have a delta of about 20 F during sunrise.</td>
</tr>
<tr>
<td>Ice Detector</td>
<td>The vibration frequency decreases with increased mass of ice on sensor probe. Correctly determines ice thickness as verified with calipers.</td>
</tr>
<tr>
<td>Solar Sensor</td>
<td>The direct and hence total radiation has a giant leap right after sunrise. It falls during sunset. Sky cover (presence of passing clouds) causes drop in the solar radiation significantly. Sunshine Status is usually above 120W/m2 (WMO threshold) all day from an hour after sunrise and before sunset.</td>
</tr>
<tr>
<td>Rain Bucket</td>
<td>The device follows the factory calibration standards where each tip = 18.53 ml of water or 0.01 inch of rainfall.</td>
</tr>
<tr>
<td>Leaf Wetness</td>
<td>The leaf gives an output around 260-270 mV when dry. It gives output ~ 300 mV when it is frosted and higher when there is rainfall or snow.</td>
</tr>
</tbody>
</table>

Table 11. Icing Sensors Initial Observations
Chapter 4: Field Trips & Sensor Installation

There were two field trips made to Toledo to firstly test the sensors out in the field during February 2013 and then again in May, to finally install them on the bridge.

4.1 Field Experiment Trips

On February 16 and February 20, it was expected of temperatures to go down to the freezing point at Toledo and hence a trip was set up to expose the sensors to a possible icing environment for a more practical test before actual installation. The leaf wetness sensor, ice detector and stay thermistors were used in this field test.

The team from University of Toledo set up stay sheath specimens and exposed them to freezing temperatures. A garden hose sprinkler and Windex bottles were used to simulate rain.

<table>
<thead>
<tr>
<th>Time</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feb 15 5 pm - 6 pm</td>
<td>Set up ice detector, leaf wetness sensor, Sunshine sensor and thermistors. Set up CR1000 white boxes.</td>
</tr>
<tr>
<td>Feb 16 4 am</td>
<td>Programmed CR1000s. UT team set up their spraying equipment.</td>
</tr>
<tr>
<td>Feb 16 4:58 am</td>
<td>Started collecting data.</td>
</tr>
<tr>
<td>Feb 16 5 am – 6:45 am</td>
<td>Water sprayed at random intervals. Photos captured and results noted.</td>
</tr>
<tr>
<td>Feb 16 6:45 am – 8:30 am</td>
<td>Sensors observed, photos taken. Left site at 8:30 am.</td>
</tr>
<tr>
<td>Feb 16 8:30 am – 4:10 pm</td>
<td>Data collected without physical observation. Started packing at 4 pm.</td>
</tr>
<tr>
<td>Feb 16 4:40 pm</td>
<td>Left site for UC.</td>
</tr>
</tbody>
</table>

Table12. Event History (February 16, 2013)

The UCII team reached Toledo on February 15th evening and set up the sensors and the data acquisition system for the next morning. The team from University of Toledo had already set up a specimen stay sheath identical to those on the bridge on a concrete pad.

Geokon thermistors, same model as those already installed on the VGCS stays were clamped on the stay sheath. Similarly the leaf wetness sensor was also zip-tied on top of the specimen. The ice detector was set up right beside the specimen stay to be exposed to similar simulated weather conditions.
The photos below show the initial set up of the sensors on the experiment pad at Toledo, just a few miles away from the Veteran’s Glass City Skyway bridge (photo credits – Jason Kumpf, University of Cincinnati Infrastructure Institute).

Fig. 60a. Stay specimens set in different angles

Fig. 60b. Data-logging system set up

Fig. 61. Sunshine Sensor set up

Fig. 62. Ice Detector placed right beside stay

Fig. 63. Stay thermistors zip-tied on sheath

Fig. 64. Leaf Wetness Sensor taped on top of stay specimen
The different sensors came up with interesting results. The ice detector measured ice accurately on its probe. The following photos explain its condition at different times on February 16.
Photos depict formation of ice layer on the leaf wetness sensor surface at different times of the morning on February 16 (photo credits – Jason Kumpf, University of Cincinnati Infrastructure Institute)
It was observed that with each spraying event, the temperature of the sheath rose up. This was because the stored water temperature was above the air/stay temperature which were below freezing. Shortly after each spraying, the water froze on the stay and the 0872f1 probe. Initially the deicing threshold was kept low at 0.02 inches of ice, so heating cycle was triggered early. Later it was reprogrammed to 0.15 inches.

As the stored water was warmer, most of it drained/trickled down the ice detector probe before instantaneously freezing. The sun came out at 7:28 am, the temperature recorded by the thermistor rose, and the accumulated ice started melting.

![Ice Detector Characteristics - Toledo (Feb16)](image)

*Fig. 68. Ice Detector Characteristics (Toledo experiments on February 16)*
Much similarly, there were three thermistors placed strategically touching the sheath and facing outwards and their behavior were noted. All the thermistors recorded higher temperature with each event of spraying. This was because the stored water was warmer than the stay temperature. As the water raised the stay temperature, the sheath facing thermistors recorded elevated temperatures.

Fig. 69. Characteristics of stay thermistors (Toledo experiments on February 16)
During the spraying experiments, water froze on the leaf wetness sensor as well. As a result there was a constant dielectric of about 310 mV when a layer of ice was on its surface.

Later, with sunrise, the characteristics of the leaf wetness sensor were compared to that of the radiation results obtained from sunshine sensor. It could be seen that with each peak (stronger sunshine), the dielectric also showed higher peaks due to melting of ice.

![Leaf Wetness Characteristics (Feb 16 - Toledo)](image-url)

Fig. 70. Leaf Wetness Sensor ice melting characteristics
A second trip was made to Toledo on February 20th for another set of tests. The day was carefully chosen as the temperature was supposed to go under freezing point and was considered optimum for icing experiments. On February 20 afternoon, a team from UC went to Toledo and set up the sensors and data acquisition system. The data loggers were programmed, and the spraying equipments were set up. Around 9 pm, the spraying experiments were started.

<table>
<thead>
<tr>
<th>Time</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feb 20 7:30 pm</td>
<td>Set up ice detector, leaf wetness sensor, sunshine sensor and thermistors. Set up CR1000 &amp; white boxes.</td>
</tr>
<tr>
<td>Feb 20 8:30 – 9:00 pm</td>
<td>Programmed CR1000s. UT team set up their garden hose spraying equipment.</td>
</tr>
<tr>
<td>Feb 20 9:10 pm</td>
<td>Started collecting data. Garden hose spraying started at 9:13 pm. Water direction changed at 9:19 pm.</td>
</tr>
<tr>
<td>Feb 20 10:20 pm</td>
<td>Left site. UT team stopped hose around 11:00 pm.</td>
</tr>
<tr>
<td>Feb 21 4:00 am</td>
<td>Back to site, more photos taken. Ice detector de-iced.</td>
</tr>
<tr>
<td>Feb 21 5:37 – 5:50 am</td>
<td>Ice detector programmed and deployed. Leaf sensor experiment using bug spray.</td>
</tr>
<tr>
<td>Feb 21 6:03 am</td>
<td>Garden hose restarted spraying. Close observations done to check icing/de-icing characteristics of ice detector. Spraying stopped at 6:34 am.</td>
</tr>
<tr>
<td>Feb 21 7:12 – 8:40 am</td>
<td>Ice detector disconnected. Other sensors disconnected by 8:40 am as shedding chances were lean due to sky cover.</td>
</tr>
</tbody>
</table>

Table13. Toledo event summary (February 20-21)
These photos below are a good exhibit of the icing experiments setup at Toledo on February 20 – 21 (photo credits – Jason Kumpf, University of Cincinnati Infrastructure Institute)

Fig.71. Ice detector set up
Fig.72. LWS-LS with different slants
Fig.73. Top & side thermistors
Fig.74. Garage heater for heating
Fig.75. Heating set up by UT crew
Fig.76. First garden hose
These photos demonstrate the spraying experiments:

Fig.77. Garden Hose mount on ladder (left) & hand held (right) for experiment on ice detector & leaf sensors.

Below are photos taken of the ice detector during its ice accumulation & de-icing.
Quite similar to February 16th experiments there were three thermistors placed strategically touching the sheath and facing outwards and their behavior were noted. All the thermistors recorded higher temperature with each event of spraying. This was because the stored water was warmer than the stay temperature.

As the water raised the stay temperature, the sheath facing thermistors recorded elevated temperatures.

![Thermistors Characteristics (Toledo Feb 20 - 21)](image_url)

Fig.79. Stay thermistor characteristics (Toledo experiments February 20 – 21)
There were two dielectric leaf wetness sensors that were placed on the stay at different slants. Due to the warm water being sprayed on them, they captured high dielectric in the beginning. As the water froze on the leaves, they reported dielectric around 310 mV. They were left overnight covered with thick layer of ice.

Next morning, both sensors were manually deiced and exposed to water sprinkler again. They showed similar characteristics, except the tilted leaf wetness sensor drained off its water faster and hence showed lower dielectric.

![Leaf Wetness Sensors Overview (Toledo - Feb 20-21)](image-url)

Fig.80. Leaf Wetness Sensor Characteristics (Toledo experiments February 20 – 21)
Initially smaller bug spray bottles were used for testing ice accumulation on the ice detector probe. It was observed that with each little spraying event, the ice detector recorded proportional increase in thickness of ice on its probe. Shortly after spraying was started using garden hose, the water froze on the stay and on the 0872F1 probe. Initially the deicing threshold was kept low at 0.06 inches of ice, so heating cycle was triggered early. Later it was reprogrammed to 0.15 inches.

During ice accumulation on the probe, a set of calipers were used to manually determine the ice thickness and get an estimate of the ice detector characteristics. It was noted that the human errors aside, the calipers gave accurate readings.

Fig. 81. Ice Detector characteristics (Toledo experiments February 20 – 21)
4.2 VGCS Ice Sensors Bridge Installation trip (May 16-17, 2013)

On 15\textsuperscript{th} of May, 2013 a team from University of Cincinnati Infrastructure Institute made a trip to Toledo in order to install all the ice sensors on the bridge. Contractors from U.S Utilities had finished building a standard 45 GSR meteorological tower by the stay 19 location.

![Weather Tower Drawing](image)

Fig. 82. Weather Tower Drawing

The tower was built 30 feet in height with solid round legs and solid bracings. A cabinet was built at its base to house the data loggers for the ice sensors.

![Tower mounted near stay 19](image)

Fig. 83. Tower mounted near stay 19 (left) and initial plan by UT research team for tower mounting
On 16th May morning, the URT gathered at Veteran’s Glass City Skyway to mount all the sensors on the tower. Horizontal cross-arms were fixed on to the tower at different heights to support the sensors. The UCII crew was divided into three groups to:

a) set up the data loggers inside the tower cabinet,

b) ride a bucket truck and mount the sensors at different elevations, and

c) upgrade the data acquisition system with new hardware and new sampling rate.

<table>
<thead>
<tr>
<th>Crew Position</th>
<th>Duties</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Tower Cabinet</td>
<td>• Set up white backplanes on shelves.</td>
</tr>
<tr>
<td></td>
<td>• Receive cables from conduit.</td>
</tr>
<tr>
<td></td>
<td>• Connect cables from each sensor to CR1000 and push new program.</td>
</tr>
<tr>
<td></td>
<td>• Reprogram with appropriate sampling rate.</td>
</tr>
<tr>
<td></td>
<td>• Set up IP address for each data logger.</td>
</tr>
<tr>
<td>2. On the tower (each sensor location)</td>
<td>• Connect vertical cross-arm to tower.</td>
</tr>
<tr>
<td></td>
<td>• Install the gage on the arm.</td>
</tr>
<tr>
<td></td>
<td>• Let the cable down through the conduit.</td>
</tr>
<tr>
<td></td>
<td>• Repeat for all sensors.</td>
</tr>
<tr>
<td>3. Old/Main cabinet location</td>
<td>• Upgrade system to CR1000.</td>
</tr>
<tr>
<td></td>
<td>• Reprogram with new scan rate.</td>
</tr>
<tr>
<td></td>
<td>• Set p new IP configuration.</td>
</tr>
</tbody>
</table>

Table14. Summary of VGCS Sensor Installation Trip
MOUNTING TECHNIQUES

Different techniques were used to mount the sensors on the tower at different elevation. The ice detector was at the topmost level, followed by solar radiation sensor, rain tipping bucket and leaf wetness sensor.

**Leaf Wetness Sensor:** The leaf wetness sensor was placed laterally on the cross arm and firmly attached to it using zip-ties.

**Rain Tipping Bucket:** The rain bucket was screwed on to a leveling bracket which sat on a vertical pipe. This pipe was mounted on the cross arm using cross-over T joints with OD 1.9” for 1.5 IPS cross arms.

**Sunshine Sensor:** The sunshine sensor was screwed to a horizontal plate with holes drilled at its corner to insert U-bolt and and firmly attach it to the cross-arm.

**Ice Detector:** A plate was attached to the body of the ice detector which was tied to stainless steel band clamps circling a 1.5 IPS pipe. This pipe was again mounted on the cross arm using cross-over T joints with OD 1.9” for 1.5 IPS cross arms. (*photo credits – Jason Kumpf, University of Cincinnati Infrastructure Institute*)

Fig.84. Leaf Wetness Sensor zip-tied to cross-arm
Fig. 85. Rain Bucket mounted on cross-arm using leveling bracket

Fig. 86. Sunshine Sensor attached to cross-arm with steel U-bolts
Fig. 87. Ice Detector mounted using steel worm band-clamps

Fig. 88. Sensor cables run down conduit

Fig. 89. CR1000 Datalogger setup inside tower cabinet
IP Configuration

All the new data loggers had to be mapped to the IP addresses provided by ODOT IT personnel.

Existing DL (Strain Gages, Stay Thermistors) – 10.102.90.236: port 6783
DL1 (Ice Detector) – 10.102.90.237: port 6783
DL2 (Leaf Wetness Sensor) – 10.102.90.238: port 6783
DL3 (Sunshine Sensor) – 10.102.90.239: port 6783
DL4 (Rain Bucket) – 10.102.90.240: port 6783

All pointed to the same external IP 156.63.133.93

Note: DL = Data Logger

---

Datalogger Memory Life

It was pertinent to check the remaining memory life of the CR1000 data loggers in case of communication failure.

Ice Detector: 653 days
Leaf Wetness Sensor: 502 days
Sunshine Sensor: 726 days
Rain Bucket: 1005 days

---

Weather Station Deployed !!!

After the sensors were physically installed, and all firmware configurations settled, UCII started collecting local weather data at the bridge from May 17, 2013, real time.
Chapter 5: Ice Accumulation Algorithm

5.1 Stations Chosen:
In Chapters 1 & 2, we already discussed the parameters considered for developing our algorithm. After careful review, there were weather stations which were chosen to be incorporated in the dashboard algorithm depending upon various factors, such as proximity, reliability, number of relevant weather parameters. Depending upon these features the following stations were selected:

a. Road Weather Information System (RWIS): There are four RWIS stations:
   1. 142-I-280
   2. 140-IR 475 @ US 23 Split
   3. 141-IR 75 @ SLM 4.9 475 Split
   4. 150-I-280 @ Libbey Road

b. Meteorological Terminal Aviation Routine (METAR): There are two METAR stations at the local airports:
   1. Toledo Express Airport (KTOL)
   2. Toledo Metcalf Airport (KTDZ).

c. Local Stations: There are two local stations having five new sensors that contribute to the accumulation conditions and hence the algorithm:

   Accumulation Determining Stations
   1. Accu_Local1: Stay Thermistor & Dielectric Wetness Sensor
   2. Accu_Local2: Stay Thermistor & Rain Tipping Bucket
   3. Accu_Local3: Ice Detection Sensor

   The ice detector comprises of a single station alone for simplicity of the algorithm because of its superior reliability.

5.2 Data Update Time: An important factor to consider in the ice determination algorithm is that each of the weather stations has a distinct data update time. The RWIS stations update data about 4-6 times an hour, while the METAR stations do it once or twice.
The new UCII sensors have a sampling rate of 10 minutes.

5.3 Station Individual Weights: According to the importance of each station, they had been assigned weights for their contribution towards triggering an alarm. The closest weather station (RWIS 142-I-280) has, thus a weight of 0.3. Similarly, both
the airports report additional data and also have a weight of 0.3 each. The other three RWIS stations each have a weight of 0.1. The new Accu_Local 1,2,3 stations based on local icing sensors on the bridge are designed to have a weight of 0.3 as well in the algorithm.

5.4 Threshold Weights: Various simulations had been previously done to obtain a fitting threshold for triggering ice accumulation. The threshold was set at 0.3 so that either of the two METAR airports or the local RWIS station could trigger ice accumulation alert alone. The other three distant RWIS stations can only do the same, when in unison. Each of the new local stations included in the proposed algorithm can also trigger this threshold by itself.

5.5 Ice Accumulation Algorithm: We have discussed the ice accumulation conditions before. Sensors in any environment can occasionally misread the actual measurement. So for each of the eight weather stations (including four RWIS, two METAR, and new local stations Accu_Local1, Accu_Local2, Accu_Local3), we evaluate all the records for the last hour. Only if certain % of the total records from the last hour meets any of the ice accumulation criteria, then the station has satisfied the icing criteria for the last hour and is given a Boolean value 1.

However, if this condition is not satisfied by a weather station, the respective station is provided a Boolean value 0. At this point the proposed percentage of satisfying records is 50% for local sensors, and 80% for the RWIS / METAR stations. This is then used to find the conditions favorable to ice accumulation by multiplying the Boolean value of each weather station (0 for not met, 1 for met) with the station weight and summing each result.

If the total weight calculated, as above, is greater than a set threshold (0.3), we consider that icing conditions has met for the last hour.
In the existing algorithm, there have been separate functions used for each station. Hence there is a function for the four RWIS stations, one for the two METAR stations.

Similarly, three new functions have been introduced for the new UCII sensors. This kind of modularity helps upgrade the existing algorithm independently without affecting it.

The table in the next page describes the modularity of the modified ice accumulation algorithm.
The flowchart below is a representation of the ice accumulation algorithm proposed and later implemented in phase II. So far we have been using test thresholds for each of the new sensors. The proposed threshold of ice thickness by ice detector is 0.15 after which melting cycle starts. The threshold for leaf wetness sensor is 300 mV and for rain bucket is a rate of 0.1 inches/hr. These thresholds are subject to training in the real world and with more icing events and data analysis, we can settle with a more and more appropriate threshold for each of the new sensors’ icing criterion.

### Ice Accumulation Check Stations

<table>
<thead>
<tr>
<th>Function Name</th>
<th>Type</th>
<th>Measurement Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. RWIS</td>
<td>Web(4 Locations)</td>
<td>Precipitation: Rain, Snow Temperature: Air Temp.</td>
</tr>
<tr>
<td>2. METAR</td>
<td>Web(2 Locations)</td>
<td>Precipitation: Rain, Snow (various types) Temperature: Air Temp.</td>
</tr>
<tr>
<td>3. LocalStation1</td>
<td>Stay Thermistors, Leaf Wetness Sensor</td>
<td>Precipitation: Dielectric Constant (mV) to wetness check conversion Temperature: Stay Temp.</td>
</tr>
<tr>
<td>4. LocalStation2</td>
<td>Stay Thermistors, Rain Bucket</td>
<td>Precipitation: Water collected (inches) Temperature: Stay Temp.</td>
</tr>
<tr>
<td>5. LocalStation3</td>
<td>Ice Detection Sensor</td>
<td>Ice Presence check directly.</td>
</tr>
</tbody>
</table>

Modular: 3 new independent station functions for ice accumulation criteria.

Table 15. Ice Accumulation Station Functions
5.6 State Transitions: The determination of possible ice conditions (‘yes’=1 or ‘no’ = 0) happens each data collection cycle as already stated. However, historically it has been noted that persistent ice accumulation over hours led to ice shedding. To determine if ice event conditions persist and to what extent required the development of a set of states and corresponding conditions for transition between states.\(^1\)
Different states used in the Ice accumulation process are:
C: ‘Green’–No Ice present
Y1: ‘Yellow 1’–Icing possible
Y2: ‘Yellow 2’–Icing likely
Y3: ‘Yellow 3’–Icing highly likely
A: ‘Orange’–Ice confirmed

The state transitions can be best represented pictorially. Already established (Agrawal, 2011), the state transition decisions were modified and updated very minutely with observation. Here are the updated ice accumulation transition states:

State Transition from ‘Clear’ (Green)

State Transitions possible from Yellow 1

Fig.94a. State Transition from Clear

Fig.94b. State Transitions from Y1
State Transitions from Yellow 2

Fig. 9c. State Transitions from Y2

State Transitions from Yellow 3

Fig. 9d. State Transitions from Y3

MAIL STATUS:
Email to Tier2 list if no response obtained.
Once at Alert, the ice shedding algorithm gets initiated, to see if there is possibility of ice falling from the stays. If not, it remains at this state, unless there is a report after visual verification.

This algorithm and corresponding transition states have been described in details in the next chapter.
Chapter 6: Ice Shedding Algorithm

6.1 Stations Chosen: As we already discussed the parameters considered for developing our algorithm. After careful review, there were weather stations which were chosen to be incorporated in the dashboard algorithm depending upon various factors, such as proximity, reliability, number of relevant weather parameters. Depending upon these features the following stations were selected:

a. Road Weather Information System (RWIS): There are four RWIS stations as discussed in chapter 5 section 5.1

b. Meteorological Terminal Aviation Routine (METAR): There are two METAR stations as discussed previously in chapter 5 section 5.1

c. Local Stations: There are two local stations having five sensors that contribute to the accumulation conditions and hence the algorithm:

    Shedding Determining Stations

    1. Fall_Local1: Stay Thermistor
    2. Fall_Local2: Sunshine Sensor

6.2 Data Update Time: An important factor to consider in the ice determination algorithm is that each of the weather stations has a distinct data update time. The RWIS stations update data about 4-6 times an hour, while the METAR stations do it once or twice.

   The new UCII sensors have a sampling rate of 10 minutes.

6.3 Station Individual Weights: According to the importance of each station, they had been assigned weights for their contribution towards triggering an alarm. The closest weather station (RWIS 142-I-280) has a weight of 0.3. Similarly, both the airports report additional data and hence also have a weight of 0.3 each. The other three RWIS stations each have a weight of 0.1. The new Fall_Local 1 & 2 stations based on UCII icing sensors on the bridge are designed to have a weight of 0.3 as well in the algorithm.

6.4 Threshold Weights: Various simulations had been previously done to obtain a fitting threshold for triggering ice shedding. The threshold was set at 0.3 so that either of the two METAR airports or the local RWIS station could trigger ice accumulation alert alone. The other three distant RWIS stations can only do the same, when in unison. Each
of the new UCII stations included in the proposed algorithm can also trigger this threshold by itself.

6.5 Ice Shedding Algorithm: We have discussed the ice shedding conditions before. Sensors in any environment can occasionally misread the actual measurement. So for each of the eight weather stations (including four RWIS, two METAR, and new UCII stations Fall_Local1, Fall_Local2), we evaluate all the records for the last hour. Only if certain % of the total records from the last hour meets any of the ice shedding criteria, then the station has satisfied the icing criteria as for the last hour and is given a Boolean value 1.

However, if this condition is not satisfied by a weather station, the respective station is provided a Boolean value 0. So far the proposed percentage is 50% for UCII sensors, and 80% for the RWIS / METAR stations. This is then used to find the conditions favorable to ice shedding by multiplying the Boolean value of each weather station (0 for not met, 1 for met) with the station weight and summing each result.

If the total weight calculated, as above, is greater than a set threshold (0.3), we consider that icing conditions has met for the last hour.
In the existing algorithm, there have been separate functions used for each station. Hence there is a function for the four RWIS stations, one for the two METAR stations.

Similarly, two new functions have been introduced for the new UCII sensors. This kind of modularity helps upgrade the existing algorithm without affecting it.

The table in the next page describes the modularity of the modified ice shedding algorithm.
### Ice Shedding Check Stations

<table>
<thead>
<tr>
<th>Function Name</th>
<th>Type</th>
<th>Measurement Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. RWIS</td>
<td>Web(4 Locations)</td>
<td>Temperature : Air Temp.</td>
</tr>
<tr>
<td>2. METAR</td>
<td>Web(2 Locations)</td>
<td>Sky Cover: Clouds/Visibility.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Temperature : Air Temp.</td>
</tr>
<tr>
<td>3. LocalStation1</td>
<td>Stay Thermistors</td>
<td>Temperature : Stay Temp.</td>
</tr>
<tr>
<td>4. LocalStation2</td>
<td>Sunshine Sensor</td>
<td>Sky Cover : Solar radiation(Watt/m²)</td>
</tr>
</tbody>
</table>

**Modular : 2 new independent station functions for ice accumulation criteria.**

Table16. Ice Fall Station Functions in algorithm

The flowchart below is a representation of the proposed ice shedding algorithm. So far we have been using test thresholds for each of the new sensors. The solar radiation threshold is set at 125 Watt/m². With more icing events and data analysis, we can settle with a more and more appropriate threshold for each of the new sensors’ icing criterion.
6.6 State Transitions: The determination of possible ice shedding conditions ("yes"=1 or "no" = 0) happens each data collection cycle as already stated. Historically, ice shedding is a much faster process can happen in a matter of few minutes to a couple hours after sufficient accumulation.

To determine if ice shedding event conditions exist and to what extent a set of states and corresponding conditions for transition between states just like ice accumulation was developed.
The different states for shedding conditions are:

A: ‘Alert’– Ice confirmed

R1: Red level 1 for ice shedding conditions met

R2: Red level 1 for ice shedding conditions met

R3: Red level 3 for ice shedding conditions met

State Transitions from Red 1:

![State Transitions from R1](image)

Fig. 97a. State Transitions from R1

State Transitions from Red 2:
Fig. 97b. State Transitions from R2

State Transitions from Red 3:

Fig. 97c. State Transitions from R3

MAIL STATUS:
Emails to Tier 1 list whether it goes to R1 or R3.
Chapter 7: Monitor Website

In the previous chapters we discussed the design and functionality of the algorithm. This chapter explains how the algorithm is implemented for front end user.

One of the primary purposes behind developing the ice monitor system was to alert the appropriate authorities about the icing potential on the stays at the bridge. The idea was to create a website that would be user friendly, informative and interactive for the clients at the Ohio Department of Transportation. The main website had several tabs:

1. Dashboard
2. Map (Weather Data by location)
3. History
4. Documentation
5. Plotting

7.1 Dashboard Main Panel

A tool was designed in the monitor website through which the algorithm results are made accessible to users. This is called the “Dashboard”. The implementation of the Python algorithm was exhibited through the dashboard was divided into few parts in order to integrate data from and manage connectivity between separate systems.

The function of the first part was to automate the collection and data mining of weather measurements of the RWIS stations and airport METAR data. These processes needed to be abiding and sturdy so that we have a reliable set of weather measurements from all the appropriate sources. This system wasn’t so much essential in the development of the next part, but for increasing system performance, reliability and robustness by local data storage. The software was finally developed to carry out the automated evaluation process and put on schedule to run once per hour. A new tab in the ice monitor web page called the dashboard was created.

The dashboard was created on a speedometer based graphical application which has several levels of warnings embedded in it. Below listed are few of the dashboard’s important features:

- Displays user-friendly speedometer style display of current icing status
- Records last 48 hours weather report conditions
- Automatically process incoming weather data and update icing status
- Generate icing alerts during ice accumulation/shedding events
- User-friendly navigation of other tabs: weather map, history, documentation & plotting

The primary dashboard panel contains the icing speedometer showing all the states including (G, Y1, Y2, Y3, O, R1, R2, and R3) which are the Green, Yellow levels 1, 2, & 3, Orange (Alert) and Red levels 1, 2 & 3. These levels express the stages of ice accumulation and shedding. The main panel also contains the reporting function for ODOT, which can be used to report icing
status after visual inspection has been made. Ice conditions of the last 48 hours are shown on the ticker on the main panel.

**Monitor of the monitor:** A new module has been added to the dashboard algorithm that determines the functional status of each remote weather station. It reports when any of the six stations has not been reporting enough data in the past one hour.

At the bottom of the main panel is the table that shows the functional status of each of the four RWIS and two METAR stations. The green symbol turns red for each station not reporting data. The main panel also includes the links to all other pages of the dashboard. Please find below a screen shot of the web site showing the main dashboard panel:

![Dashboard Main Panel](image)

**Fig.98. Dashboard Main Panel**

### 7.2 Existing Panels: Weather Map, History

Some of the existing weather panels in the monitor website that were updated were the Weather Maps and History sections.
7.2.1 Map (Weather Data by location)

The icing monitor website includes an interactive map of the weather stations. It contains pop-up balloons for each weather station where current sensor readings are shown and historical readings can be plotted on a timeline. The map also provides view of the cameras installed on the bridge. Google Maps API has been used for this application. Google Maps is a free web mapping service provided by Google, which offers street level maps for pedestrians, cars, and public transportation. It has an extendable API (Application Programming Interface) that can be used to develop custom Google Maps based applications.

The Google map on the dashboard is used as a graphical interface providing the particulars about the various weather sites being monitored for determining the icing conditions at VGCS. It also contains the location of various sites, their past/present weather conditions along with their source links. The primary features of the weather map are:

- Weather station locations
- Displaying the live cameras installed at VGCS
- Past/present weather readings
- Site information of all the stations

Initially, this weather map comprised of the few RWIS, METAR and local stations surrounding the bridge. After successful installation of the various new ice sensors on the bridge, new station have been added to the weather map comprising information about these UCII sensors and newly installed camera.
When the map tab is clicked, the Google map opens with several markers corresponding to the different stations. There are two green balloons written “A” on them. These are the two Airports namely KTOL (Toledo Express Airport) and KTDZ (Metcalf Field Airport). The RWIS stations data come from the source link: [http://www.wunderground.com](http://www.wunderground.com). On clicking this source link, the details of the weather report can be obtained as follows:
The four red balloons written “R” on them are the four RWIS stations namely Site 140-IR 475 @ US 23 Split, Site 141-IR 75 @ SLM 4.9 475 Split, Site 142-I-280 @ Veterans Glass City Skyway, and Site 150-I-280 @ Libbey Rd. The RWIS stations data come from the source link: www.BuckeyeTraffic.org. On clicking this source link, the details of the weather report can be obtained as follows:
There are two yellow balloons written “L” on it. These are the local weather stations near to the VGCS Bridge. They are: East Toledo, Oregon. These are not considered in the algorithm. The pink marker is the link to the web cameras installed on VGCS. The local station information is also obtained from the ‘weatherunderground’ website.

Another green marker with “U” written on it represents the local sensors station. In the UCII marker, on clicking any of the ice sensors provide detailed information through a 48 hour plot. Here is an example:
On clicking the leaf wetness sensor in the pop-up marker, we get the following 48 hour plot of the sensor data:

Similarly, the last 48 hour plots for the ice sensor and the rain sensor can be obtained by clicking the appropriate links in the marker.
7.2.2 History

The History section of the ice monitoring website provides many additional features that are useful for the users for analyzing past data. This section provides a detailed explanation of the historical data and reports. The history tab can be better visualized with the help of the following figure:

The following information can be obtained from the history section:
(a) List of icing events in the time range selected. User can choose two dates between which the states need to be displayed. Also clicking on any particular event will provide the particulars of the event.
(b) List of responses received: All the feedback received by the dashboard over the time is displayed here, including the names of the people who posted the comments.

Fig. 104. History Tab – Events section
(c) Summary: The summary tab provides detailed statistics of the weather conditions for all the six weather stations used in the algorithm.

![Summary Tab](image)

Fig. 105. History Tab- Summary section

7.3 Documentation

In this section all the research work for the project has been documented. This includes the following:

1. Weather Documents: Consists of various app notes and manuals of the different sensors installed on the bridge
2. Project Documents: This includes various documentation including proposals, RWIS & METAR reports etc
3. Data Files: Excel sheets of various important icing events
4. Icing Conditions Algorithm: All documents pertaining to the dashboard algorithm
5. Tower Documents: Plans and photos of the VGCS icing tower
6. Video Files: Videos catching different ice shedding incidents

The following snapshot is a representation of the Documentation tab:

![Snapshot of Documentation tab](image-url)

Fig.106. Snapshot of Documentation tab
The document section has various simple buttons for uploading and managing documents for the user.

7.4 New Sensors Plotting

An entirely new tab has been added to the dashboard monitor to reflect the characteristics of all the essential stations contributing to the algorithm. This is a plotting tab which has different sections as elaborated under. Each plotting section can be populated with the different stations/sensors it consists of. The user can select the range of the start and end date for this plotting function. Accordingly, the data for the different sensors can be obtained for the desired time range. At present the different sections in the ice monitor plotting tab are:

1. Stay Thermistors – Shows temperature data of the twelve stay thermistors installed in the bridge.

![Thermistors - Temp Plot](image)

Fig.107. Stay 20 Thermistors plot (January 1 – July 1)
2. Local Sensors – Shows data of the various new icing sensors: ice detector, leaf wetness sensor, rain tipping bucket and solar radiation sensor. There is a radio button which allows users to select the type of weather plot they wish to see among the various weather sensor options.
Fig. 109. Ice Detector plot (June 1 – July 1)

Fig. 110. Leaf Wetness Sensor plot (June 1 – July 1)
Fig. 111. Rain Tipping Bucket plot (June 1 – July 1)

Fig. 112. Sunshine Sensor plot (June 1 – July 1)
3. RWIS 142-I-280 – Shows data of the nearest RWIS station to the VGCS bridge. The temperature and dew point are the parameters that are included in the plotting function.

Fig.113. Local RWIS temperature & dew point plot (January 1 – July 1)

4. METAR from Toledo Airports – Shows the air temperature and dew point data of the two nearest METAR airport stations KTOL (Toledo Airport) and KTDZ (Metcalf Airport).

For each of the above sections, there is an export button that helps export the data for the user in an Excel file. This allows the users to plot graphs of weather data with different units or different sources together, if necessary.
Fig. 114. KTOL air temperature & dew point plot (January 1 – July 1)

Fig. 115. KTDZ air temperature & dew point plot (January 1 – July 1)
Chapter 8: Ground Truth – New Sensors

8.1 Introduction

Since the installation of the new ice sensors by University of Cincinnati Infrastructure Institute in May 2013, we have been able to obtain data for one season of winter, December 2013 – April 2014. To test the performance of the new sensors before being installed, rigorous testing methods had been implemented in the lab and in the field. Those experiments helped us understand the nature and anticipate the usefulness of the sensors when deployed in the real world. However, to establish ground truth of the actual performance of the sensors, the training data obtained in 2013-2014 winter is very important.

This winter had been quite eventful as far as wintry conditions are concerned. We have had multiple occasions where our upgraded dashboard algorithm triggered ice accumulation warnings, mostly at moderate levels of Y1 (level 1 ice accumulation), few Y2 (level 2 ice accumulation) and Y3 (level 3 ice accumulation). There has been no incidence where the dashboard warned ice shedding.

The remote weather sensors from RWIS and METAR stations had helped our ice event determination algorithm the past few winters. However, that data had various issues including time delay, inaccuracy and lack of local supervision. The new sensors – ice detector, leaf wetness sensor, solar radiation sensor, rain tipping bucket and stay thermistor have paved way to a new level of microclimate information at the Veteran’s Glass City Skyway bridge. Each of them has been obtaining different and crucial data for ice accumulation and/or ice shedding event determination.

The stay thermistors had been installed on the bridge in April 2012. However, the other sensors were installed more recently (May 2013) and were exposed to icing conditions on the bridge for the first time this past winter. The collection of ground-truth data will enable calibration of remote-sensing data for the years to come, and aid in the interpretation and analysis of the weather parameters.
The events triggered by the sensors winter 2013-2014 are enumerated in the following table:

<table>
<thead>
<tr>
<th>Date</th>
<th>Highest Dashboard Status</th>
<th>Stations/Sensors Triggered</th>
</tr>
</thead>
<tbody>
<tr>
<td>12/09/2013</td>
<td>Alert</td>
<td>KTOL, ODOT Report</td>
</tr>
<tr>
<td>12/11/2013</td>
<td>Y1</td>
<td>Stay Thermistor + Dielectric Sensor</td>
</tr>
<tr>
<td>12/12/2013</td>
<td>Y1</td>
<td>Stay Thermistor + Dielectric Sensor</td>
</tr>
<tr>
<td>12/13/2013</td>
<td>Y2</td>
<td>RWIS2016, Stay Thermistor + Dielectric Sensor</td>
</tr>
<tr>
<td>12/14/2013</td>
<td>Y3</td>
<td>Stay Thermistor + Dielectric Sensor</td>
</tr>
<tr>
<td>12/23/2013</td>
<td>Y1</td>
<td>RWIS2016</td>
</tr>
<tr>
<td>12/29/2013</td>
<td>Y1</td>
<td>KTDZ, RWIS2016</td>
</tr>
<tr>
<td>01/01/2014</td>
<td>Y1</td>
<td>Stay Thermistor + Dielectric Sensor, RWIS2016</td>
</tr>
<tr>
<td>01/04/2014</td>
<td>Y1</td>
<td>RWIS2016</td>
</tr>
<tr>
<td>01/05/2014</td>
<td>Y2</td>
<td>RWIS2016, Stay Thermistor + Dielectric Sensor, KTDZ</td>
</tr>
<tr>
<td>01/09/2014</td>
<td>Y1</td>
<td>KTDZ</td>
</tr>
<tr>
<td>01/10/2014</td>
<td>Y2</td>
<td>Stay Thermistor + Dielectric Sensor, RWIS2016</td>
</tr>
<tr>
<td>01/17/2014</td>
<td>Y1</td>
<td>RWIS2016</td>
</tr>
<tr>
<td>01/20/2014</td>
<td>Y1</td>
<td>Stay Thermistor + Dielectric Sensor, RWIS2016</td>
</tr>
<tr>
<td>02/20/2014</td>
<td>Y2</td>
<td>Stay Thermistor + Dielectric Sensor, RWIS2016</td>
</tr>
<tr>
<td>03/08/2014</td>
<td>Y1</td>
<td>Stay Thermistor + Dielectric Sensor, RWIS2016, KTDZ</td>
</tr>
<tr>
<td>03/12/2014</td>
<td>Y2</td>
<td>KTOL, KTDZ</td>
</tr>
<tr>
<td>03/29/2014</td>
<td>Y1</td>
<td>KTDZ</td>
</tr>
<tr>
<td>04/03/2014</td>
<td>Y2</td>
<td>Stay Thermistor + Dielectric Sensor, Stay Thermistor + Rain Bucket, KTDZ, Ice Detector</td>
</tr>
<tr>
<td>04/15/2014</td>
<td>Y1</td>
<td>KTOL, Stay Thermistor + Rain Bucket</td>
</tr>
</tbody>
</table>

Table 17. Chronology of winter 2013/14 icing event triggers

*Note: The weight of the station for leaf wetness sensor + stay thermistors was reduced to 0.1 in early January, thus reducing false alarms.
8.2 Ice Events (Winter 2013/2014)

Thanks to the polar vortex/jet stream, this winter provided decent opportunities for the icing sensors to be tested out in the real world where there is dust, debris and reduced access to maintenance. There were several days where the temperature was way below freezing temperature, and there was ample precipitation.

We had multiple ice accumulation incidents; however, there were no prominent instances of ice shedding. Some of the significant days are enumerated below:

**December 9, 2013**
The first time this winter layer of ice of significance was found on the stays was on December 9. Matt Harvey, ODOT, checked the stays at 2:10 am and reported thin layer of ice on all cables. Temperature of cables was 24-27°F. The air temperature was 31°F. There was light freezing rain and light snow. Again at 10 am, he reported, “As of 9:32 a thin layer of ice in on the top 2/3 of the cables. No ice on pylon.” David Canavel, ODOT, cleared the bridge of any ice by visual inspection in the afternoon.

During December 9, 2013 there was ample precipitation at freezing temperatures as recorded by the leaf sensor. Although mostly quiet all winter, the ice detector did record up to 0.12 inches of ice on the day of the icing event. It did not trigger the dashboard, although the threshold was set at a much lower value of 0.05 inches.

There were some questions that arose about the disappearance of the layer of ice off the sheath, whether it could be attributed as shedding, melting, evaporation or sublimation. No chunks or fragments of ice were observed underneath the stays. However, both the leaf wetness sensor and the ice detector were impressive in the sense it seemed that plots of both the graphs (as shown below) were showing both increasing trend until about 3 am, which coincides with "snow" data both at the airports and observations by ODOT. Similarly, both sensors showed decreasing values thereafter, which coincides again with the airports not reporting "snow" and observations by ODOT on the ground.
December 13 & December 14, 2013

The rest of the month of December saw few minor accumulation events. A lot of ice accumulation alerts were triggered between December 13 and December 14, 2013. Initially it was just the local RWIS2016 sensor that reported freezing rain. This was followed by consistent simultaneous reporting of high dielectric and sub-zero temperature by the leaf wetness sensor and the stay thermistors respectively. The dashboard reported level Y3 at 4 pm on December 14. This was a significant cause for concern and called for some visual report, this being among the first events for the new ice sensors. However, Matt Harvey, ODOT reported, “Found no ice, very little snow on cables. Cable temperature at 4:47 am was 19.5-23°F. Pylon temperature was 21°F”.

January 5, 2014

There were just a few sporadic triggers on the 1st of January, but January 5th marked the first true ice event of the year 2014, as there was a lot of ice accumulation warnings from the dashboard on this day. The local RWIS2016 reported freezing rain in the previous evening, which was followed by snow as reported by the Toledo Metcalf Airport. The leaf wetness sensor also triggered higher dielectric. The dashboard stayed at Y2 for three hours.
January 10, 2014

On this day the icing alarm was triggered by the local RWIS2016 station, and the Leaf Wetness Sensor with stay thermistors. Initially freezing rain was reported by RWIS2016 which was followed by snow. The dielectric LWS reported higher dielectric. It was, in fact one of the days when it recorded about 800-900 mV dielectric which usually signifies rainfall. The rain bucket tipped twice in long intervals, and recorded lower precipitation than its threshold (set at 0.05 inches) thus failing to set its flag to true for the ice accumulation trigger. Trace of ice was measured by the ice detector as well, although that didn’t trigger the alarm. According to National Weather Service, there were 0.46 inches of precipitation and 0.6 inches of snow.

February 20, 2014

The dashboard started reporting icing conditions since 1 o’clock in the morning. This was triggered by the local RWIS sensor 582016 which reported freezing rain. At 6 am the status moved to Y2 and continued staying at Y2 for 3 more hours. The RWIS 2016 stopped reporting freezing rain activity and the status came down to Y1 at 9 am. This time both the airports signaled freezing rain conditions. The wetness sensor also reported higher dielectric.

On this day the ice detector measured 0.06 inches of ice, but interestingly, this did not trigger the dashboard although the threshold was set at 0.05 inches. However, this was not a case of missed detection as there was just this one spike above the threshold, not satisfying the condition of having enough records in one hour to set the icing flag. Instead, the ice thickness quickly fell to 0.01 inches (see figure 118). Since the heat time recorded by the sensor was zero (its de-icing threshold being set at 0.15 inches), shedding happened right on the device.
probe naturally. Wind or bridge vibrations may be a possible cause. The outer stay thermistors dwelled under 32°F longer than other thermistors possibly due to the latent heat required to melt the ice at those locations.

![Ice Detector & LWS February 20, 2014](image)

**Fig.118. Ice Detector & Leaf Wetness Sensor characteristics on February 20**

**March 12, 2014**

The March 12 ice accumulation event was mostly driven by fog in the morning. According to estimate by Dr. Nims, flecks of ice and then a slight build up on the top was expected. Until 2 pm, the snow was dry enough that it was not sticking to the sides of the VGCS or PMB specimens even though the wind was steady. With progression of time, and the temperature dropping and the snow slowing down, both the sticking efficiency and the volume of snow in the air was getting lesser.

The airports continued to report cold and fog which is what had been triggering the dashboard alerts. The ice detector didn’t show icing. The cameras appeared to be snow covered and hence were inconclusive as well.

**April 3, 2014**

The dashboard recorded its first Y1 at 11 am and Y2 at 5 pm. The ice detector continued to register no ice. The RWIS & METAR weather stations recorded air temperature staying higher than the stay temperature. Temperature of the stays dipped and precipitation continued. Precipitation was confirmed in unison by both the leaf wetness sensor and the rain tipping bucket. The airport at Toledo Metcalf also reported some freezing rain. As a result, the dashboard went up to Y2. If this continued, there was a strong possibility of reaching Y3 status.
Personal communication was made between UCII and UT researchers. According to Dr. Douglas K Nims, University of Toledo, "I spoke with Dave Kanavel. He had checked the stays about 3 pm and 3:45 pm. He observed a thin layer of ice that did not wrap around the stays (~1/32") at 3 pm and it was gone when he crossed back over at 3:45 pm. The ice extended about 30 feet up the stays. The ODOT weather service forecast is for the temperature to rise to 40°F by midnight."

Some shedding was observed as well later this day. According to Clint Mirto, student, University of Toledo, icing was occurring on VGCS. Around five feet piece of ice was reported to fall off around 4 pm.

This was another event of significance as the ice detector triggered the alarm the only time this winter. It recorded 0.16 inches of ice at 11:50 am. The deicing threshold was set at 0.15 inches and the heater melted the ice (see figure 119), but it recorded 0.13 inches of ice again at 1 pm. Interestingly, the ice shed off the probe, but not because the heater went into de-icing cycle this time (see figure 119). The ice detector recorded zero seconds of heating time which means the heater did not get turned on. The shedding of the ice on the probe can possibly be attributed to natural causes like wind or vibrations. The shedding/melting of ice on the stays around 3 pm – 4 pm can be attributed to the rising temperature of the stays above 32°F and little peaks of solar radiation (~120 Watt/m²). This was a good day for observation of the heated rain/snow gage performance. The rain bucket too tipped constantly several times during the heavy showers. According to National Weather Service, there was 1.15 inches of precipitation on April 3rd, 2014.

![Fig.119. Ice detector & Leaf wetness Sensor characteristics on April 3](image-url)
Fig. 120. Rain Tipping Bucket & Leaf Wetness Sensor characteristics on April 3

Fig. 121. Solar Radiation Sensor & Stay Thermistor 8X08TWS characteristics on April 3
April 15, 2014

April 15th has been marked as the last day of icing alert recorded this winter season. There were two alerts of Y1. This was also the second time the rain tipping bucket was the cause of an alarm. The rain bucket tipped few times between midnight and 3:20 am. The local airport at Toledo (KTOL) also set the alarm due to snow. The ice detector measured very mild accumulation after midnight. According to National Weather Service, there was 0.13 inches of precipitation on this day.

<table>
<thead>
<tr>
<th>Date</th>
<th>From</th>
<th>Icing</th>
<th>Attachment</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>2013-12-09</td>
<td>Matt Harvey</td>
<td>Yes</td>
<td>na</td>
<td>Checked at 2:10am thin layer of ice on all cables. Temp. of cables 24.27f. air temp 31f. Light freezing rain and light snow. Your gauge says no ice present. Thought you should know.</td>
</tr>
<tr>
<td>2013-12-09</td>
<td>Matt Harvey</td>
<td>Yes</td>
<td>na</td>
<td>As of 9:32 a thin layer of ice in on the top 2/3 of the cables. No ice on pylon.</td>
</tr>
<tr>
<td>2013-12-09</td>
<td>Arthur Helmicki</td>
<td>No</td>
<td>na</td>
<td>Based on a visual report from David Kanavel, there is small/no ice left on stays.</td>
</tr>
<tr>
<td>2013-12-13</td>
<td>Arthur Helmicki</td>
<td>No</td>
<td>na</td>
<td>Visual inspection in the area revealed no icing.</td>
</tr>
<tr>
<td>2013-12-14</td>
<td>Arthur Helmicki</td>
<td>No</td>
<td>na</td>
<td>Visual inspection in the area revealed no icing.</td>
</tr>
<tr>
<td>2013-12-14</td>
<td>Arthur Helmicki</td>
<td>No</td>
<td>na</td>
<td>Local reports indicated snow, but no/minimal ice on stays.</td>
</tr>
<tr>
<td>2013-12-14</td>
<td>Matt Harvey</td>
<td>No</td>
<td>na</td>
<td>Found no ice, very little snow on cables. Cable temp. at 4:47am 19.5-23. Pylon temp was 24.</td>
</tr>
</tbody>
</table>

Fig.122. Web Report Tool: Sample Icing Events and comments recorded during December 2013

8.3 Sensor Performance:

All the sensors (remote RWIS/METAR stations as well as the new local sensors) gave us useful information this past winter. There were several instances of ice accumulation alarms and we can say, it has been but a busy winter at the Veteran’s Glass City Skyway bridge.

However, in spite of the added sensors, there were cases where we had false alarms, possible missed detections of shedding, as well as loss of data during a large power outage in January 2014 (personal communication, Dr. Victor J Hunt, University of Cincinnati). It was observed that the majority of the ice accumulation events were triggered by the leaf wetness sensor and the local RWIS station at VGCS (RWIS2016). A good number of these were false alarms; the RWIS2016 sensor broke down a few times. The RWIS 2016 has had a history with its
rain sensor being stuck during freezing rain. This year RWIS 2013 and KTDZ also were down a few times, not providing data seamlessly. Similarly, the local sensors albeit more dependable, were not perfect either.

8.3.1 Dielectric wetness sensor

The dielectric leaf wetness sensor triggered alarms many times, some of which were false alarms. This has to do with the threshold being used in the algorithm mostly. As the sensor is sensitive to very low quantity of moisture, raising its threshold in the algorithm or forming a band of freezing conditions (290-310 mV) after high dielectric activity (>400 mV) can help reduce these false alarms.

However, it gave us vital triggers on events such as December 14 and February 20th when the ice detector did not measure any ice. Due to its high frequency of false alarms, the weight of the sensor station was lowered from 0.3 to 0.1 in the ice accumulation algorithm in early January following which this problem was resolved. Nevertheless, the current threshold used for the LWS leaf wetness sensor needs to be adjusted apropos to visual inspection and more training data in the future.

![Image of Leaf Wetness Sensor characteristics winter 2013/14](image-url)
8.3.2 Stay Thermistors

The stay thermistors are crucial sensors on the bridge. This is because the icing algorithm requires temperature data in addition to the precipitation data provided by sensors like leaf wetness sensor and rain tipping bucket. The stay thermistors provided valuable data for the stay temperature throughout the winter. This data was necessary as knowledge of stay temperature is more instrumental for quicker determination of icing events which the remote RWIS/METAR data do not provide.

The thermistors placed at different positions and directions gave us appropriate data of temperature of the stays. During melting conditions, it was observed that sheath thermistors got warmer sooner than the outer thermistors due to latent heat required to melt the ice (Figure 125). Here the sensor chosen 7X20TUS is the thermistor directly lying on the sheath while the sensor 7X20TUO is facing more outwards. When a stay is iced and the temperature starts to go above freezing, the ice has to melt and so at that location the temperature plateaus right at 32°F while other temperatures are going up. This can last several hours depending upon how much ice is involved and sun intensity. Heating of ice at greater depths is through conduction. If the ice temperature is below freezing, the energy absorbed by the ice raises the temperature to the freezing point followed by a phase change from ice to water as the ice absorbs more energy. This can also explain the greenhouse effect that can be seen in chapter 3, section 3.1.1.
8.3.3 Rain Tipping Bucket

The heated rain/snow tipping bucket mostly gave inaccurate results most of winter as it was devoid of regular maintenance and was down. The primary screen of the device needs to be removed during snowfall and reinstalled after snowfall to protect it from dust and debris. Removal of the screen enables the snow to reach the heated filament and melt, so that the equivalent precipitation can be measured by the tipping gage. The tipping bucket inside consists of a hinge that also needs to be calibrated from time to time so that it tips accurately without getting stuck.

The rain bucket always gave accurate data in the lab experiments, and has performed well recently on icing events of April 3\textsuperscript{rd} and April 15\textsuperscript{th}, 2014.
8.3.4 Ice Detector 0872F1

Although the most popular candidate for ice thickness determination, the ice detector hardly recorded much accumulation earlier this winter, as it is basically apt for fast ice accumulation through freezing rain rather than through slow snow accumulation as the snow slides down before freezing on its almost vertical probe. It has automated heating feature, which is crucial to its functions. We have had events where the ice on the sensor probe shed off naturally without the heater being turned on at the said threshold of 0.15 inches (February 20 & March 4 events) which may not have occurred due to automated heating.

On December 9, 2013 the algorithm had a case of missed detection although the ice detector measured 0.12 inches of ice. Since automated heating adversely affects the reading of ice thickness, more research needs to be done to use a suitable de-icing threshold and adjustment of the algorithm appropriately (for instance use cumulative ice thickness). In a few cases, the ice on the sensor probe got removed because of shedding probably due to natural causes like wind or vibration. This cases need to be investigated. Also, since the ice may disappear due to automated heating or just plain melting, ice thickness measurement should be done by measuring cumulative ice accretion on the probe. Besides measurement of ice thickness, the sensor could also prove valuable for shedding events if deicing due to automated heating and that due to natural conditions are analyzed.

New ideas were brought to the table about utilizing the sensor also for ice shedding vis-à-vis the reduction of ice on the probe. However, this brings to question the elimination of its
automated heating which may affect its accuracy in measuring ice thickness and its lifespan and hence is subject to further discussion. It is important to note that the ice thickness indicated on the ice probe may not exactly equal that found on the stay sheath as they are two very different structures with different materials, size, shape and orientation; hence, some calibration of this must be achieved using field observations during the past and future events. More icing events and a larger training set will help determine efficacy of the sensor.

Fig.127. Ice Detector characteristics winter 2013/14

8.3.5 Sunshine Sensor BF5

Because of how solar radiation can affect ice shedding even at lower temperatures, this sensor is a great potential predictor of ice shedding. The solar radiation sensor gave us excellent data of year round sunshine, and we have set its sunshine threshold for ice shedding at 120 Watt/m². However, the sensor’s effectiveness for ice shedding, its threshold and adjustment to the ice shedding algorithm can only be achieved once we have enough training data from shedding events. We are yet to receive a shedding event and decipher the threshold number of our sunshine sensor that could accurately trigger alarm for ice shedding event on stays.
8.3.6 Conclusion

The effect of the new sensors can be further internalized by observing their frequency of occurrence in the icing alarms and is explained in the graph below:

As we discussed before, the weight of the leaf wetness sensor had to be lowered due to its high frequency triggers. This problem will be ameliorated once we can settle on the most
appropriate threshold value for the sensor. The rain bucket being down most of the season also does not have a large share of the dashboard triggers. The ice detector set the alarm off only twice as it has a high threshold of 0.05 inches. Since this device is primarily being used for ice determination and not thickness in the algorithm, we could either lower its threshold (although about 0.2 inches ice or more is considered hazardous) or quickly send our warning level to Y2 (secondary alarm for accumulation).

Similarly, for ice shedding sensors – stay thermistors and solar radiation sensor, the individual sensor threshold flag was set numerous times, but we do not have any useful data for deliberation as the overall shedding conditions were not met and hence the shedding alarms were not triggered.

If we look back at table 17, there have been many events were the remote weather stations missed an event but the new icing sensors caught them and vice versa. There is no doubt that introduction of the new sensors have strengthened our dashboard algorithm by complementing & supplementing the existing remote weather stations with redundancy. The ultimate goal is to have as many sensors reporting similar icing conditions accurately and eliminate any requirement of human intervention.

Despite their minor shortcomings which can only be improved by our learning of their long term characteristics, the new sensors have provided us much more redundancy and control over our dashboard algorithm. Tuning the dashboard algorithm most accurately would depend upon these sensors’ performance and their longevity, and these can be better validated with time and a larger training set.
### 8.4 Application Tools

Various kinds of tools and software were required to develop this highly robust and resilient weather monitoring dashboard system. These can be tabulated as under:

<table>
<thead>
<tr>
<th>Class</th>
<th>Application Used</th>
<th>Intent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Back end processing</td>
<td>Python</td>
<td>Weather data parsing</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dashboard decision algorithm</td>
</tr>
<tr>
<td>Front end scripting</td>
<td>PHP/HTML/JavaScript/CSS</td>
<td>Website design</td>
</tr>
<tr>
<td>Graphs</td>
<td>JpGraph, Matplotlib</td>
<td>Weather plots</td>
</tr>
<tr>
<td></td>
<td>MS Excel</td>
<td>Extended graphical analysis</td>
</tr>
<tr>
<td>Database</td>
<td>MySQL</td>
<td>Data storage</td>
</tr>
<tr>
<td>Server</td>
<td>Loggernet, Apache</td>
<td>Data scheduling</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Web services</td>
</tr>
<tr>
<td>DAQ system</td>
<td>CRBasic</td>
<td>Programming loggers</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Collection of data</td>
</tr>
</tbody>
</table>

Table 18. Application Tools Used
Chapter 9: Conclusion & Future Work

The automated ice detection and monitoring dashboard for the Veterans’ Glass City Skyway Bridge was created during winter 2011. The basic cause towards building this system was the need of an immediate tool that could help monitor and predict the bridge microclimate and declare icing hazards as the anti-icing and de-icing methods discussed previously could not be deployed effectively. Thus icing dashboard was developed, implemented, successfully tested, and have been used by researchers and ODOT officials for the past 4 years.

This thesis pertains to the performance of the basic dashboard, the upgrades made to it and suggested recommendations based on what was learned during the first and second phases of the project but couldn’t be implemented yet. The existing ice monitoring system had given us decent response because the initial idea was to deploy a cost-effective system to monitor the local weather in a short span of time. Data was parsed from nearby RWIS and METAR stations, and used by the dashboard algorithm. It was observed that in order to get a superior monitoring system, it was pertinent having a VGCS microclimate with our own set of sensors.

Some of the basic objectives of Phase II of the automated ice monitoring system at VGCS are:

i. Increasing consistency and robustness of the algorithm

ii. Alternate data source – To increase the speed, redundancy and accuracy of the algorithm

iii. Added parameters – There are various parameters critical to decide ice events that the existing system had been requiring, such as solar radiation, type of wetness, thickness of ice etc.

iv. Active control – More control is required to adjust different functions of the weather monitoring system.

v. Expediency – Ice events, particularly shedding, can happen very fast. Hence it is important to have a faster reporting system. The sampling speed of sensors is at 10 minutes now, and can be made faster, if required.

Most of the objectives for phase II had been successfully implemented.

- New module has been added in the algorithm to test the functioning of all the remote weather station. This monitor of the monitor concept can be viewed through a new table in dashboard main panel which reports station status as green (working) or red (not working).

- To increase the speed, redundancy and accuracy of the algorithm we installed different icing sensors such as stay thermistors, ice detector, dielectric leaf wetness sensor, rain tipping gage, solar sensor on the bridge location itself.
In order to decide ice events more accurately, there are some parameters that are critical, such as solar radiation, type of wetness, thickness of ice etc. New sensors now provide us this data.

As we have active control over our data logger programs scheduling data collection, we can now change different thresholds, sampling rates etc. as per our requirements.

As we required a much faster system to catch quick ice shedding incidents, our local sensor system can now collect data in seconds, if required.

As a result of having research collaboration with the University of Toledo, and a full-scale mockup test by the joint research team, we came to understand the following:

At this point passive ice prevention is not practical as the anti-icing coatings used did not seem to work very well. Deicing fluids did not seem adequate either. Heating experiments were more promising. Overall, it seems using local ice monitoring system is still the most effective tool for ice monitoring/prevention. Due to the success of this system, it only makes sense to develop the system better using new sensors and upgrade the dashboard algorithm after rigorous data analysis. All of the newly installed sensors have been providing us data, seamlessly, real-time.

The stay thermistors have been quite effective in measuring local stay temperature. The leaf wetness sensor has proved to be very sensitive for minute amount of precipitation, and can differentiate between rain and ice. It gave many false alarms, however, and its threshold needs to be calibrated. The rain tipping bucket has been successful in recording the amount of rainfall in the past few months of its deployment. However, its breaking down during the winter is cause of alarm and teaches us that it requires more regular maintenance. The solar radiation sensor has given identical results as the other solar radiation reports from nearest stations. The ice detector measured ice thickness accurately in the mock-up tests. It gave decent results on the bridge as well. However sufficient calibration is required to translate the ice thickness on the probe to the thickness on the stay sheath. All these sensors have been deployed on the bridge for only one winter, and their performance, longevity and reliability still needs to be validated. This winter taught us a good lesson that time to time calibration of the sensors and tuning of the weights and thresholds in the dashboard algorithm is required until we have enough training set and let the system be entirely automated.

As already pointed out in Chapter 7 and 8, what still needs to be verified, is the consistency and reliability of all these sensors with time. Their success can inspire lesser human intervention and more safety to the traffic. Alternatively, their failure should pave way for more sturdy and reliable sensors. Most of the shortcomings of Phase I has been mitigated by introduction of the VGCS microclimate sensors; we have a faster, controlled, more robust and practical weather
station. However, we still require continual collection of data obtained by the new sensors and see their performance when appended into the algorithm. For instance, the current threshold used for the LWS leaf wetness sensor needs to be adjusted apropos to visual inspection and more training data as discussed in Chapter 8. Deeper analysis needs to be done for events like that on December 9, 2013 when the algorithm had a case of missed detection although the ice detector measured 0.12 inches of ice. All these require more learning, and a bigger training set. The ultimate success of the system is yet to be deciphered. Accounting for more parameters like horizontal visibility, atmospheric pressure and accounting for direction of weather propagation (like radar) may help make the algorithm faster in terms of prediction.

In the future, further analysis has to be done to tune to the most appropriate threshold values for each sensor. With a larger training set, and upgrading the algorithm with smarter decision making, we can make the dashboard algorithm more intelligent.


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Appendix A

I. CR1000 Program for LWS-L Dielectric Wetness Sensor

'LWS_L Basic Program

'Program Author : Biswarup Deb
'Date Created: 12 August 2012
'Date Updated: 9 May 2013

Public PTemp,batt_volt
Public LWS_mV
Public Conditions As String

DataTable (LWSData,1,-1)
Sample(1,batt_volt,IEEE4)
Sample(1,PTemp,IEEE4)
Sample(1,LWS_mV,IEEE4)
Sample(1,Conditions,String)
EndTable

'Main Program

BeginProg
Scan (10,Min,3,0)
PanelTemp(PTemp,250)
Battery(batt_volt)
BrHalf(LWS_mV,1,mV2500,1,VX1,1,2500,False,10000,.60Hz,2500,0)
If LWS_mV<275 Then
Conditions="Dry"
Else
Conditions="Wet"
EndIf
CallTable(LWSData)
NextScan
EndProg

II. CR1000 Program for Sunshine Sensor BF5

'CR1000 Series Datalogger
'Program Author: Biswarup Deb
'Date Created: 7 October 2012
'Date Updated: 9 May 2013

'Declare Public Variables

Public PTemp, batt_volt
Public Global_Rad, Diffuse_Rad
Public SunStatus As Float

'Main Program
'CR1000 Series Datalogger
'Sunshine Sensor BF5 Basic Program
DataTable (Solardata,1,-1)
Sample(1,batt_volt,IEEE4)
Sample(1,PTemp,IEEE4)
Sample(1,Global_Rad,IEEE4)
Sample(1,Diffuse_Rad,IEEE4)
Sample(1,SunStatus,IEEE4)
EndTable

BeginProg
Scan (10, Min, 0, 0)
PanelTemp (PTemp, 250)
Battery (batt_volt)
VoltDiff (Global_Rad, 1, mv5000, 1, 1, 0, _60Hz, 0.5, 0)
VoltDiff (Diffuse_Rad, 1, mv2500, 2, 1, 0, _60Hz, 0.5, 0)
If ((Global_Rad/Diffuse_Rad) > 1.25 AND (Global_Rad) > 25) Then
  SunStatus=1
Else
  SunStatus=0
EndIf
CallTable Solardata
NextScan
EndProg

III. CR1000 Program for Met One Rain Bucket

'CR1000 Series Datalogger
'Program Author: Biswarup Deb
'Declare Public Variables

Public PTemp, batt_volt
Public Rain_in
Units Rain_in=inch
Public Rainfall as float

'Main Program
'CR1000 Series Datalogger
'Rain Tipping Bucket Basic Program

DataTable (RainData,True,-1)
Sample(1,batt_volt,IEEE4)
Sample(1,PTemp,IEEE4)

DataInterval(0,10,Min,0)
Totalize(1,Rainfall,FP2,0)
EndTable

BeginProg
  Scan (1,Sec,1,0)
    PanelTemp (PTemp,250)
    Battery (batt_volt)
    PulseCount(Rain_in,1,18,2,0,.01,0) 'Black wire connect to C8
  'Change Rainfall equation acc. to sampling rate to convert from instantaneous Rain_in(inches) to Rainfall(inches/hour)
    Rainfall=(Rain_in*6)
  CallTable RainData
NextScan
EndProg

IV. CR1000 Program for Goodrich Ice Detector

'Ice Detector with CR1000 Series Datalogger
'Date Created: Sept 19, 2012
'Date Updated: May 9, 2013
'Program Author: Biswarup Deb

'Declare Public Variables

Public MainString As String * 30
Public Freq_Str As String
Public batt_volt,PTemp
Public Frequency As Float
Public CSum As String
Public Status As String
Public Ice As Float "Default units are in inches"
Public Ice_mm As Float "Ice accumulation in millimeters"
Public HeatTime As Float
Public ThresholdDisp As Float
Const Threshold = 0.15 'This icing threshold is constant. It is not used until we come up with a definite threshold.
'Note: The recommended min threshold for de-icing is 0.02 inches of ice, and the max is 0.16 inches of ice.

'Define Data Tables
DataTable (IceAcc,True,-1)
   Sample (1,batt_volt,IEEE4)
   Sample (1,PTemp,IEEE4)
   Sample (1,Frequency,IEEE4)
   Sample (1,Ice,IEEE4)
   Sample (1,Ice_mm,IEEE4)
   Sample (1,HeatTime,IEEE4)
EndTable

'Main Program
BeginProg
   SerialOpen (Com1,2400,0,0,1000)
   Scan (10,Min,0,0)
      PanelTemp(PTemp,250)
      Battery(batt_volt)
   'Clear buffer before sending commands
   SerialFlush (Com1)
   'Send serial out command to request frequency information
   SerialOut (Com1,"Z1","",0,0)
   'Send serial in command to read information form datalogger buffer.
SerialIn (MainString, Com1, 100, 0, 100)

'The following instructions are used to parse the received string.
Freq_Str = Left (MainString, 11)
Freq_Str = Right (Freq_Str, 5)
Status = Left (MainString, 6)
Status = Right (Status, 3)
CSum = Left (MainString, 13)
CSum = Right (CSum, 2)
Frequency = Freq_Str

'Formula used to convert the Frequency into Ice Thickness (inches).
Ice = -0.00015*Frequency + 6

'Convert ice accumulation from inches to millimeters
Ice_mm = Ice * 25.4

'Used to get rid of NAN, and use floating point numbers.
If Frequency = "NAN" Then Frequency = -9999
If Frequency = -9999 Then Ice = -9999
If Ice = -9999 Then Ice_mm = -9999

'Used to make sure we do not have negative Ice thicknesses in data
If Ice < 0 Then Ice = 0
If Ice_mm < 0 Then Ice_mm = 0

'Check to see ice is greater than threshold.  If so, turn on heaters
't long enough to remove any ice accumulation.
If Ice > ThresholdDisp Then
  HeatTime = 214.29 * Ice + 5.7142
  HeatTime = INT (HeatTime)

 'If the heat time is calculated higher than 45 seconds, heat for only 45 seconds.
 'NOTE: The heater time is limited to 45 seconds based on time required to melt
 'The recommended maximum allowable icing of 4mm (0.16 inches) on the sensing element.
If HeatTime > 45 Then HeatTime = 45

'Store icing event data. Calling "IceAcc" table is temperature dependant.
'CallTable IceAcc

'Heat sensing element for prescribed time calculated in "HeatTime" variable
SerialOut (Com1,"Z3"+HeatTime,"",0,100)
EndIf
CallTable IceAcc
NextScan
EndProg
Appendix B

Circuit Diagrams

1. Leaf Wetness Sensor
2. Met One Rain Tipping Bucket

Both signal cable, power cable manufacturer supplied

Numbers indicate SCB20D I/O
3. Sunshine Sensor BF5
4. Goodrich Ice Detector
5. Stay Thermistors (* Upgraded later to CR1000)
### Appendix C

**Sensor Specifications**

1. Dielectric Leaf Wetness Sensor

<table>
<thead>
<tr>
<th>Features</th>
<th>Specs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Requirements Excitation</td>
<td>2.5 VDC (2mA) to 5.0 VDC (7mA)</td>
</tr>
<tr>
<td>Output</td>
<td>10% to 50% of excitation voltage</td>
</tr>
<tr>
<td>Minimum Excitation Time</td>
<td>10 ms</td>
</tr>
<tr>
<td>Measurement Time</td>
<td>10 ms</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>-20°C to 60°C</td>
</tr>
<tr>
<td>Cable Length</td>
<td>5 m. Extension cable available.</td>
</tr>
<tr>
<td>Maximum Lead Length</td>
<td>250 feet</td>
</tr>
<tr>
<td>Probe Dimensions</td>
<td>11.2 cm x 5.8 cm x .075 cm</td>
</tr>
<tr>
<td>Interchangeability</td>
<td>Interchangeable sans painting/individual calibration.</td>
</tr>
</tbody>
</table>
2. Met One Rain Tipping Bucket

<table>
<thead>
<tr>
<th>Features</th>
<th>Specs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Requirements</td>
<td></td>
</tr>
<tr>
<td>Heater Power</td>
<td>115 VAC(50/60 Hz)-5Amp</td>
</tr>
<tr>
<td></td>
<td>Funnel : 240W</td>
</tr>
<tr>
<td></td>
<td>Base : 75W</td>
</tr>
<tr>
<td></td>
<td>Funnel &amp; Base Heater 40°F(4.4°C)</td>
</tr>
<tr>
<td>Thermostat Set Point</td>
<td></td>
</tr>
<tr>
<td>Accuracy</td>
<td>+/- 0.5% &lt; 0.5”(1.27cm)/hr rate</td>
</tr>
<tr>
<td></td>
<td>+/- 2.0% &lt; 3.0”(7.62cm)/hr rate</td>
</tr>
<tr>
<td>Resolution</td>
<td>0.01 inch(0.254mm)</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>-20°C to 50°C</td>
</tr>
<tr>
<td>Humidity</td>
<td>0 to 100%</td>
</tr>
<tr>
<td>Weight</td>
<td>12.2 pounds(5.57kg) w/ 50’ signal cable</td>
</tr>
<tr>
<td>Dimensions</td>
<td></td>
</tr>
<tr>
<td>Height:</td>
<td></td>
</tr>
<tr>
<td>Diameter(Funnel):</td>
<td>14”(35.5cm)</td>
</tr>
<tr>
<td></td>
<td>12”(30.5cm)</td>
</tr>
</tbody>
</table>
3. Sunshine Sensor BF5

<table>
<thead>
<tr>
<th>Features</th>
<th>Specs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Requirements</td>
<td>2mA (awake), &lt;30μA (asleep)</td>
</tr>
<tr>
<td>Input voltage range</td>
<td>1.4-3.6V DC, internal battery</td>
</tr>
<tr>
<td></td>
<td>5.0-15V DC, external power</td>
</tr>
<tr>
<td>Fuse Trip Point, on sunshine status signal</td>
<td>0.5A, 30V self resetting (switch closure mode)</td>
</tr>
<tr>
<td>Fuse : max voltage, current</td>
<td>24V, 1.6A (self-resetting)</td>
</tr>
<tr>
<td>Max applied voltage to sunshine status output</td>
<td>0-24V</td>
</tr>
<tr>
<td>Heater : max power, current</td>
<td>15W at 12V DC, 1.5A at 15V</td>
</tr>
<tr>
<td>Heater input voltage</td>
<td>12-15V DC</td>
</tr>
<tr>
<td>Heater output below 0°C</td>
<td>15W</td>
</tr>
<tr>
<td>Heater output above 5°C</td>
<td>2W reducing to 0W at 35°C</td>
</tr>
<tr>
<td>Range</td>
<td>0-1250Wm⁻²</td>
</tr>
<tr>
<td>Resolution</td>
<td>0.3 Wm⁻²</td>
</tr>
<tr>
<td>Overall Accuracy : Total Diffuse</td>
<td>+/-5Wm⁻² (12%)</td>
</tr>
<tr>
<td></td>
<td>+/-20Wm⁻² (15%)</td>
</tr>
<tr>
<td>Analog Output Sensitivity</td>
<td>1mV=0.5Wm⁻²</td>
</tr>
<tr>
<td>Analog Output Range</td>
<td>0-2500mV</td>
</tr>
</tbody>
</table>
Sunshine Sensor BF5 (Contd.)

<table>
<thead>
<tr>
<th>Features</th>
<th>Specs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal output &amp; power in connector</td>
<td>8 pin M12</td>
</tr>
<tr>
<td>RS232 connector</td>
<td>5 pin M12</td>
</tr>
<tr>
<td><strong>Accuracy: sunshine hours</strong></td>
<td><strong>Specs</strong></td>
</tr>
<tr>
<td>: cosine correction</td>
<td>+/- 10% (WMO definition)</td>
</tr>
<tr>
<td>: azimuth angle</td>
<td>+/- 10% of incoming radiation over 0-90° Zenith angle</td>
</tr>
<tr>
<td></td>
<td>+/- 5% over 360° rotation</td>
</tr>
<tr>
<td>Response Time</td>
<td>&lt;250ms (100ms after power up)</td>
</tr>
<tr>
<td>Spectral response</td>
<td>400-700nm</td>
</tr>
<tr>
<td>Latitude capacity</td>
<td>-90° to +90°</td>
</tr>
<tr>
<td>Temperature coefficient</td>
<td>+/- 0.15% /°C typical</td>
</tr>
<tr>
<td>Temperature range</td>
<td>-20 to +50°C, alkaline batteries / -20 to +70°C, lithium batteries</td>
</tr>
<tr>
<td>Internal battery</td>
<td>2 x 1.5V AA alkaline batteries</td>
</tr>
<tr>
<td>Cable Length</td>
<td>SP-BF/w-0S(5m), EXT/8W-xx(extension)</td>
</tr>
<tr>
<td>Weight</td>
<td>635g</td>
</tr>
<tr>
<td>Dimensions</td>
<td>120mm x 122m x 95mm</td>
</tr>
</tbody>
</table>
4. Goodrich Ice Detector 0872F1

<table>
<thead>
<tr>
<th>Features</th>
<th>Specs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Requirements</td>
<td>115 VAC, +/-10%, 60Hz</td>
</tr>
<tr>
<td>Power Consumption</td>
<td>Sensing Mode: 10W (0.087Amps)</td>
</tr>
<tr>
<td></td>
<td>De-icing Mode: 385W (3.35Amps)</td>
</tr>
<tr>
<td>Output Format</td>
<td>RS-232 or RS-232 Current Loop(2400 BAUD)</td>
</tr>
<tr>
<td>Measurement Range</td>
<td>0 - 2.5mm (0-0.10 inches) of Ice</td>
</tr>
<tr>
<td>Minimum Measurement Threshold</td>
<td>0.13mm (0.005 inches) of Ice</td>
</tr>
<tr>
<td>Resolution</td>
<td>+/- 4Hz</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>-50°C to +50°C</td>
</tr>
<tr>
<td>Humidity</td>
<td>74% RH @ 35°C to 100% RH @ 25°C</td>
</tr>
<tr>
<td>Wind</td>
<td>Steady –up to 55.5km (30 knots), Gust – up to 85.2km (46 knots)</td>
</tr>
<tr>
<td>Rain</td>
<td>76.2mm (3&quot;)/hr with 55.5km (30 knots) winds</td>
</tr>
<tr>
<td>Freezing Rain</td>
<td>Ice accretion to 25.4mm (1&quot;) with a 37km (20 knot) wind, @ 12.7mm (1/2&quot;)/hr</td>
</tr>
<tr>
<td>Ingress Protection</td>
<td>IPX4</td>
</tr>
<tr>
<td>Maximum Cable Length</td>
<td>30 meters</td>
</tr>
<tr>
<td>Weight</td>
<td>5.7kg (12.55 lbs)</td>
</tr>
<tr>
<td>Dimensions</td>
<td>Electrical Housing : 230mm X 200mm X 110 mm (L x W x D)</td>
</tr>
<tr>
<td></td>
<td>Sensing Element &amp; Heat Sink : 164mm X 173mm X110mm (L x W x D)</td>
</tr>
<tr>
<td></td>
<td>Probe : 25mm X 6mm (L x Dia.)</td>
</tr>
</tbody>
</table>