Vibrating-Wire, Supercooled Liquid Water Content Sensor Calibration and Characterization Progress

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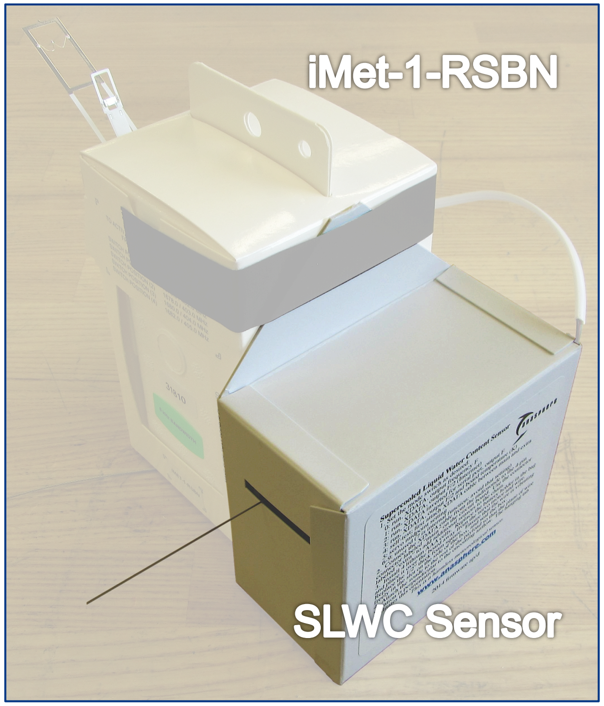
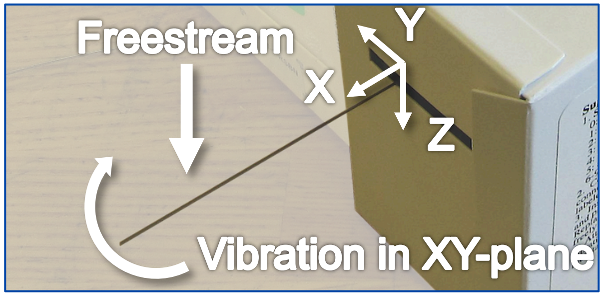
Background

- Inflight icing of aircraft remains a hazard to the aviation community.
- Providing operators with real-time information of atmospheric icing conditions is a means to reduce hazard by operationally minimizing exposure.
- NASA has been developing icing remote sensing technology to provide the necessary information, but the technology requires validation through in-situ measurements.
- NASA funded Anasphere, Inc., through the SBIR program, to develop and calibrate weather balloon-borne, supercooled liquid water content (SLWC) sensors.
- NASA conducted a field campaign at the NASA Glenn Research Center (GRC) in Cleveland, OH during winter 2015 to develop a validation database using the Anasphere SLWC sensors.
- Significant effort has been made to calibrate and characterize these sensors including facility development and experimental testing.
- Progress has also been made to understand an unexpected behavior observed in the SLWC sensor data from the winter 2015 campaign.

SLWC Sensor Description

- The weather balloon instrument package used during the field campaign included the iMet-1-RSBN Radiosonde and the vibrating-wire, SLWC Sensor.
- The measurement principle behind the SLWC sensor is that ice accretion along the wire leads to a decrease in the natural frequency of the wire.
- Vertical profiles of SLWC can be derived from the time history of the measured wire vibration frequency and the ascent speed.
- The 0.6 mm steel wire is periodically "plucked" using a servomotor with a magnet attached to a short support.
- A thin film piezoelectric sensor, sandwiched between a silicon rubber structure, measures the wire vibration frequency.
- An Anasphere, Inc. proprietary signal processing method is used to determine the natural frequency every 3 seconds.



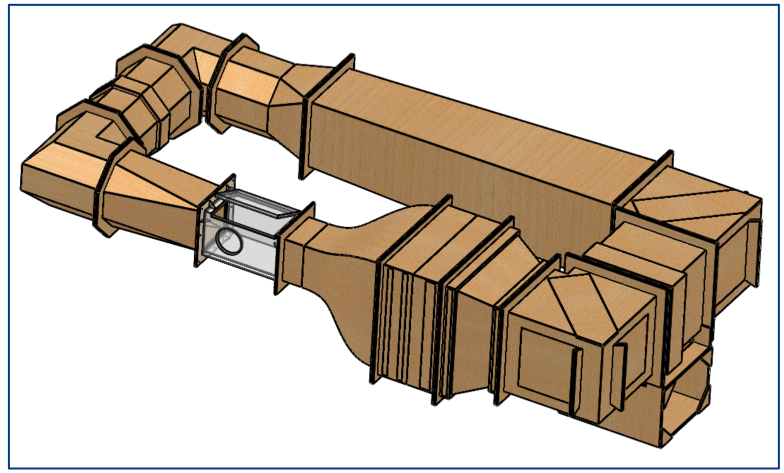


Instrument Package – SLWC Sensor highlighted in images

Calibration:

Facility Development

- Anasphere, Inc. developed a low speed icing tunnel for calibration testing of the SLWC sensors.
- The facility is a closed circuit, fan driven, icing tunnel with a 30 cm by 30 cm test section.
- Steady airspeeds around 5 m/s are achieved in the test section
  - The nominal ascent rate of the winter 2015 weather balloons is 5 m/s.
- The tunnel is insulated and the heat exchanger is capable of cooling to subfreezing temperatures between -15 °C and -10 °C.
- A single Spraying Systems Co. 1/4J-SS air-atomizing nozzle is used to create the supercooled cloud.
  - Air and water pressure are controlled independently.
  - Water supply is chilled to ensure supercooling

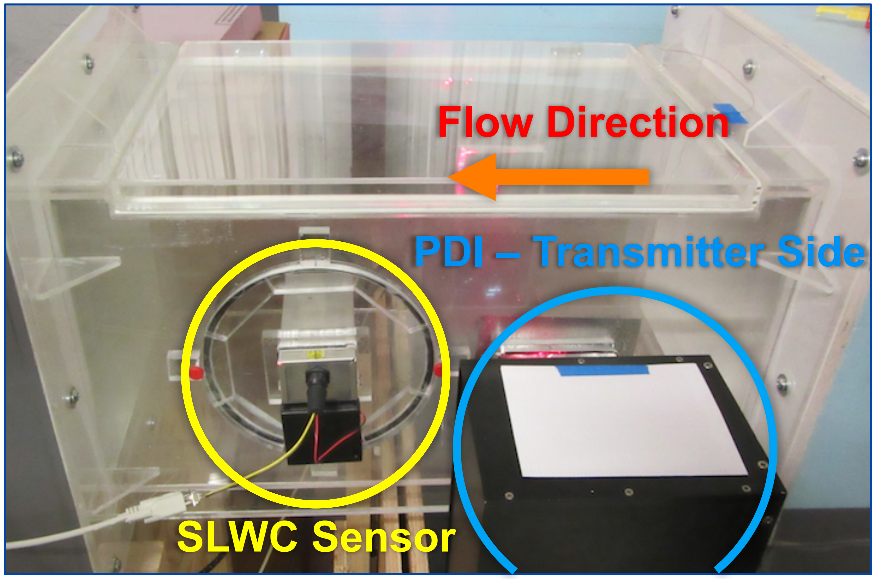


Anasphere, Inc. Low Speed Icing Tunnel

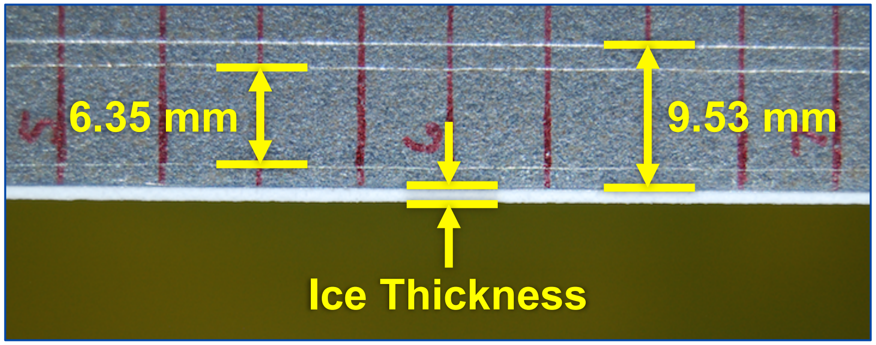
Calibration:

Tunnel Testing

- Testing was carried out in two separate phases
  - 1st Phase: SLWC Sensor and PDI
  - 2nd Phase: Icing Blade
- The SLWC Sensor frequency data and drop size and speed distributions were acquired during the 1st Phase.
  - Vibration plane of SLWC Sensor was orthogonal to the flow direction
  - PDI was non-intrusive and situated upstream of the SLWC Sensor housing
- Independent measurements of SLWC were acquired using an icing blade during the 2nd Phase.
  - Blade used due to concerns about hotwire instrument operability, data fidelity and heat load on the facility
  - 0.64 mm thick blade
  - Spray times were varied to obtain approximately 0.6 mm thick ice accretion



1st Phase Testing Setup



Icing Blade with ice accretion from 2nd Phase

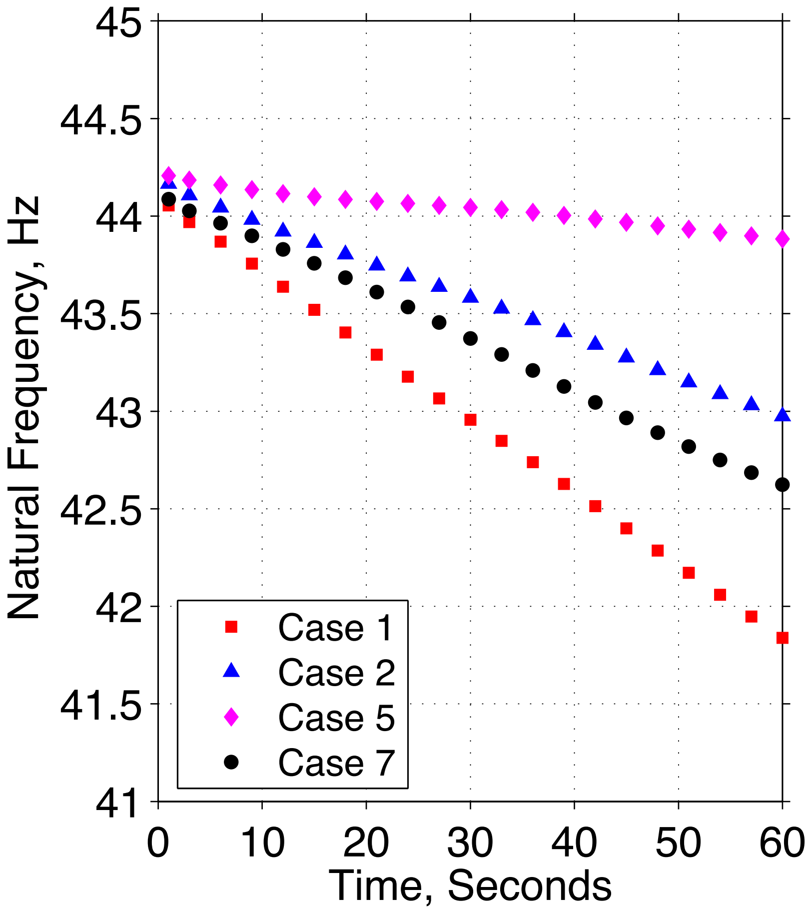
Calibration:

Data Reduction – SLWC Sensor

- ***SLWC*** is calculated using the frequency profile
  - The time derivative of the frequency, ***df/dt***, is the driving term
  - The terms ***f***, f_0, ***ε***, ***D*** and ***u*** are the frequency, clean-wire natural frequency, collection efficiency, wire diameter and ascent speed, respectively
  - The term ***b*** is a coefficient related to the physical characteristics of the wire

$$SLWC = \frac{2bf_0^2}{\varepsilon D u f^3}\frac{df}{dt}$$ [1]

- The trends for all case are linear and all have R^2 values greater than 0.996.
  - Trends were used instead of typical generalized central differencing method that have been used for atmospheric soundings.



Select SLWC Sensor Frequency Data from 1st Phase Testing

[1] Hill, G. E., "Analysis of Supercooled Liquid Water Measurements Using Microwave Radiometer and Vibrating Wire Devices," Journal of Atmospheric and Oceanic Technology, Vol. 11, 1994, pp. 1242-1252.

Calibration:

Data Reduction – Icing Blade

- ***SLWC*** is calculated using the blade equation (Ref. 2)

2

$$SLWC = \frac{\rho S}{\varepsilon u t}$$

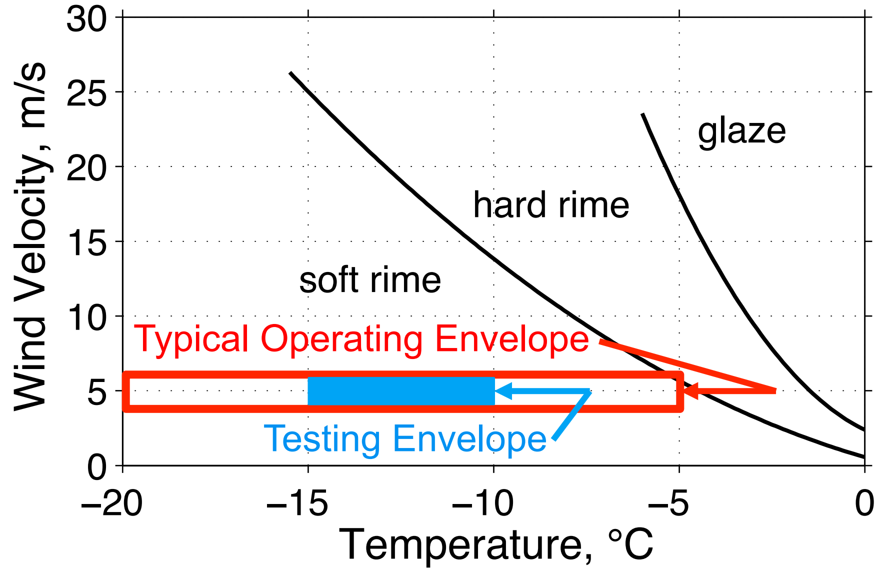
  – The terms ***ρ***, ***S***, ***ε***, ***u*** and ***t*** are the ice density, the ice accretion thickness, collection efficiency, flow speed and time, respectively

- ***ρ*** is calculated using the Macklin empirical equation (Ref. 3)

3

$$\rho = 110\left(-5\times10^{5}\,\frac{d_{v0.5}u}{T_s}\right)^{0.76}$$

  – The terms $\boldsymbol{d_{v0.5}}$ and $\boldsymbol{T_s}$ are the MVD and surface temperature, respectively
  – Soft rime was observed during testing
  – Soft rime ice densities range from 200 to 600 kg/m[3]



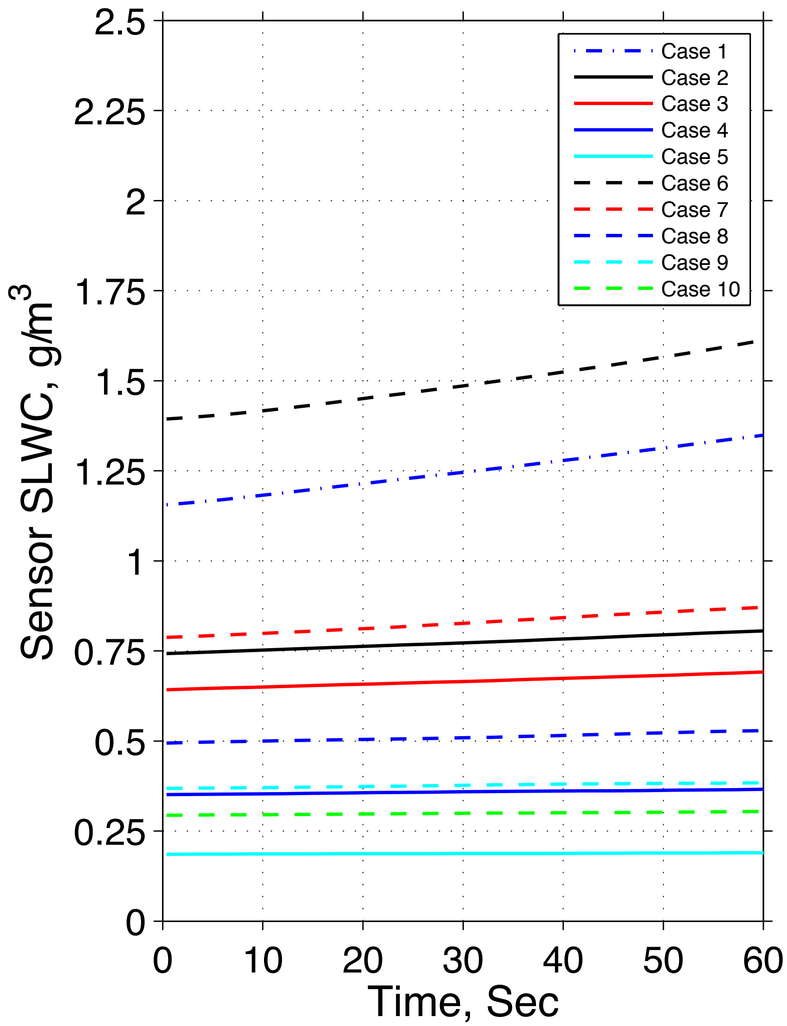
Ice accretion formation regimes with the testing and the typical operating envelopes highlighted

[2] Ide, R. F. and Sheldon, D. W., “2006 Icing Cloud Calibration of the NASA Glenn Icing Research Tunnel,” NASA/TM-2008-215177, 2008.
[3] Macklin, W. C., “The Density and Structure of Ice Formed by Accretion,” Quarterly Journal of the Royal Meteorological Society, Vol. 88, 1962, pp. 30-50.

Calibration:

Results (1 of 2)

- The calculated SLWC profiles rise to varying degrees, between 3% and 17%.
- This effect may be due to general form of the SLWC equation.
  - f^3 in the denominator, where f is a decreasing term with increasing ice accretion.
- Other effects such as cloud recirculation may also be contributing factors, but were not investigated in this work.
- The linearity of the frequency profiles suggest test section SLWC remained constant.



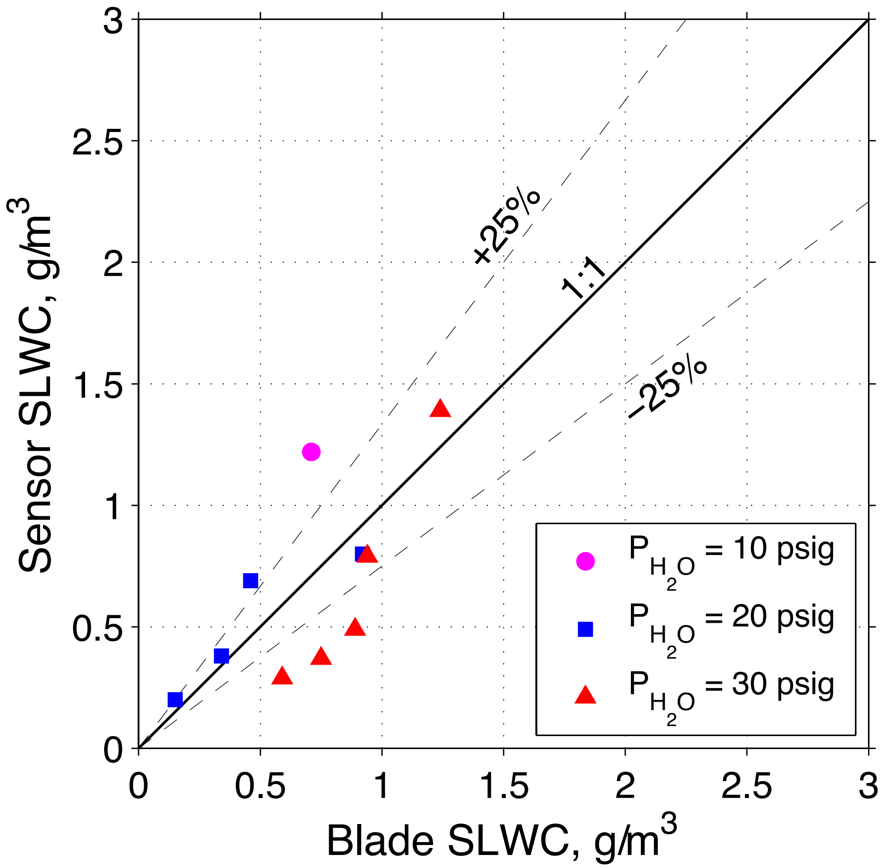
Gradual increase in calculated SLWC

Calibration:

Results (2 of 2)

Sensor and Blade SLWC Comparison Table

Case	Sensor	Blade	P_{H2O}	Marker
---	g/m^3	g/m^3	psig	---
1	1.15	0.71	10	
2	0.74	0.92	20	
3	0.64	0.46		
4	0.35	0.34		
5	0.19	0.15		
6	1.39	1.24	30	
7	0.79	0.94		
8	0.49	0.89		
9	0.37	0.75		
10	0.29	0.59		

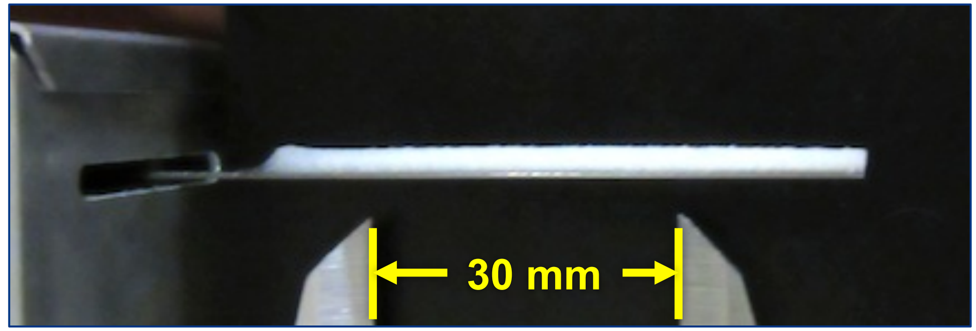


Sensor and Blade SLWC Comparison Plot

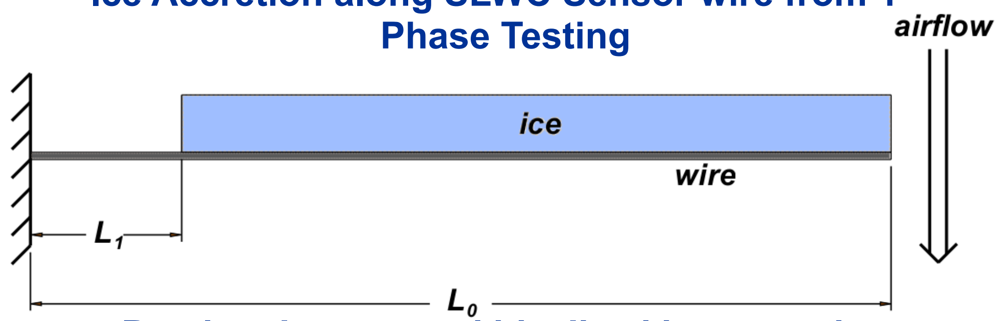
- The correlation between the two measurements is promising, agreeing to well within ±25% in several cases.

Ice Accretion Analysis:

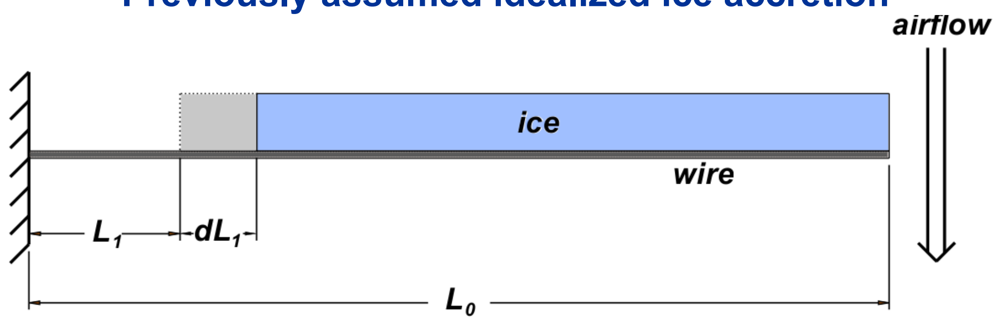
- Images of the ice accretion on the SLWC Sensor were taken during testing.
- A ‘shadow zone’ exists which has not be previously documented.
- The length of the wire with no ice accretion, L_1, increased by approximately 11%.
- Effect on the calculated ***SLWC*** was found to be negligible.
  - Increased ***SLWC*** in all cases by 0.75%
  - Parametrically, ***SLWC*** increases less than a few percent for L_1 values approaching 50% of L_0



Ice Accretion along SLWC Sensor wire from 1st Phase Testing



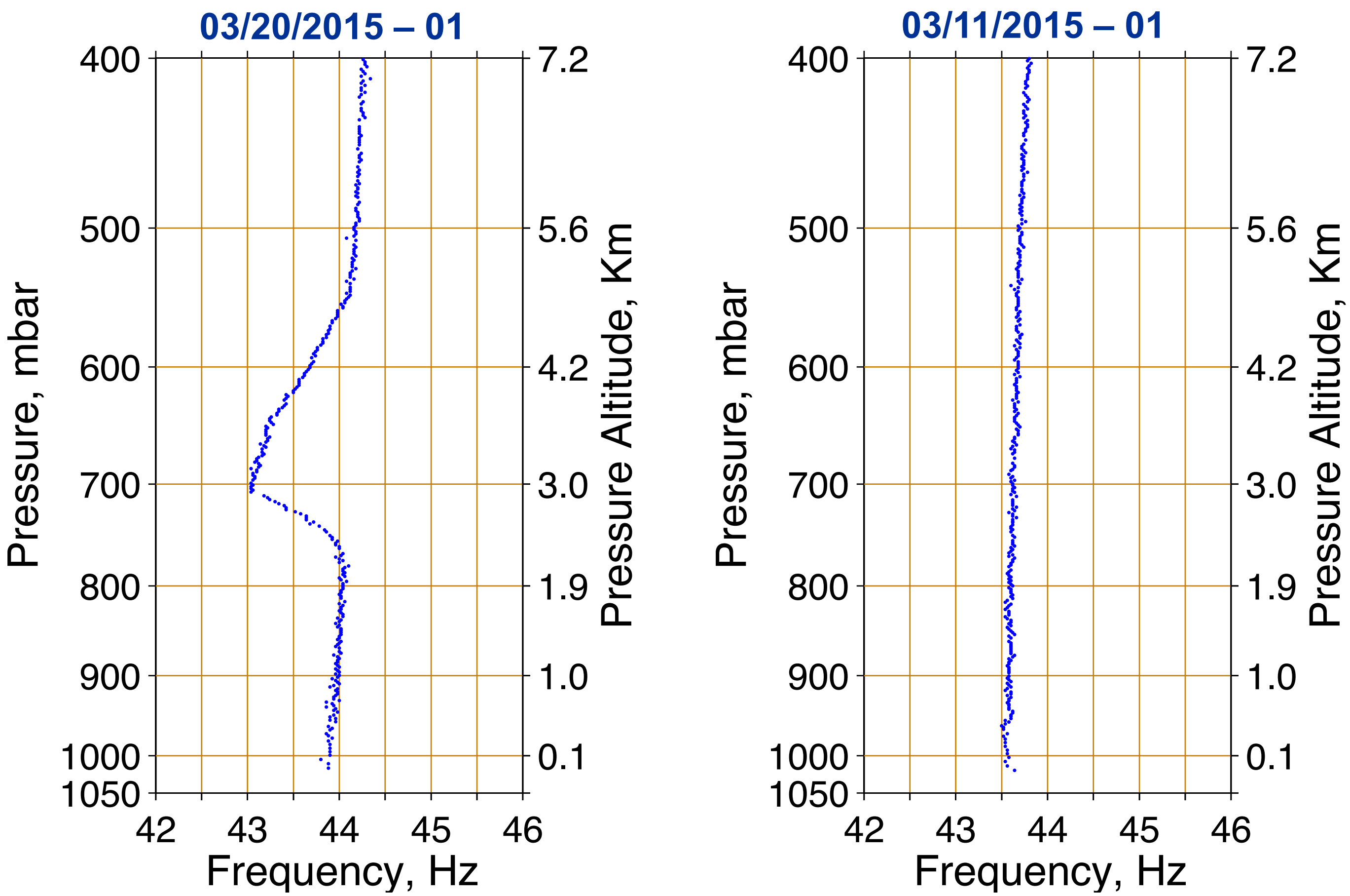
Previously assumed idealized ice accretion



Current assumed idealized ice accretion highlighting shadow zone

Sensor Data Drift:

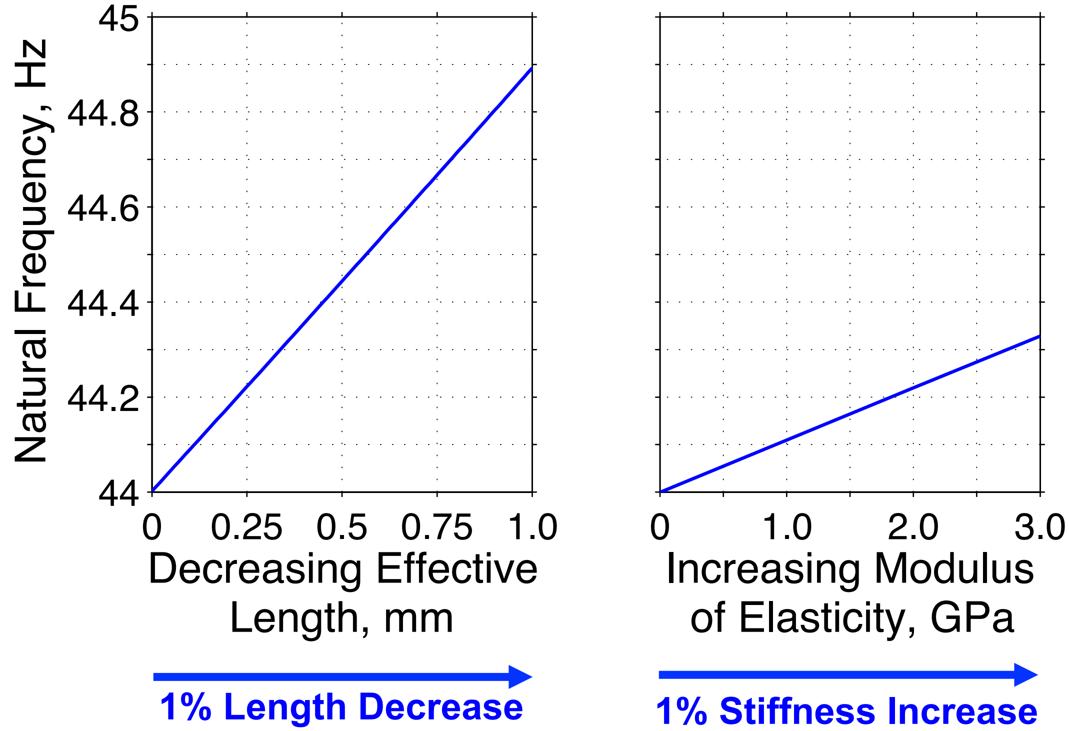
Data Analysis (1 of 2)



- The gradual increase, or drift, in the frequency profiles is observable.
- The drift is linear when plotted on a logarithmic pressure scale, and does not appear to be affected by the presence of icing conditions.

Sensor Data Drift:

Data Analysis (2 of 2)



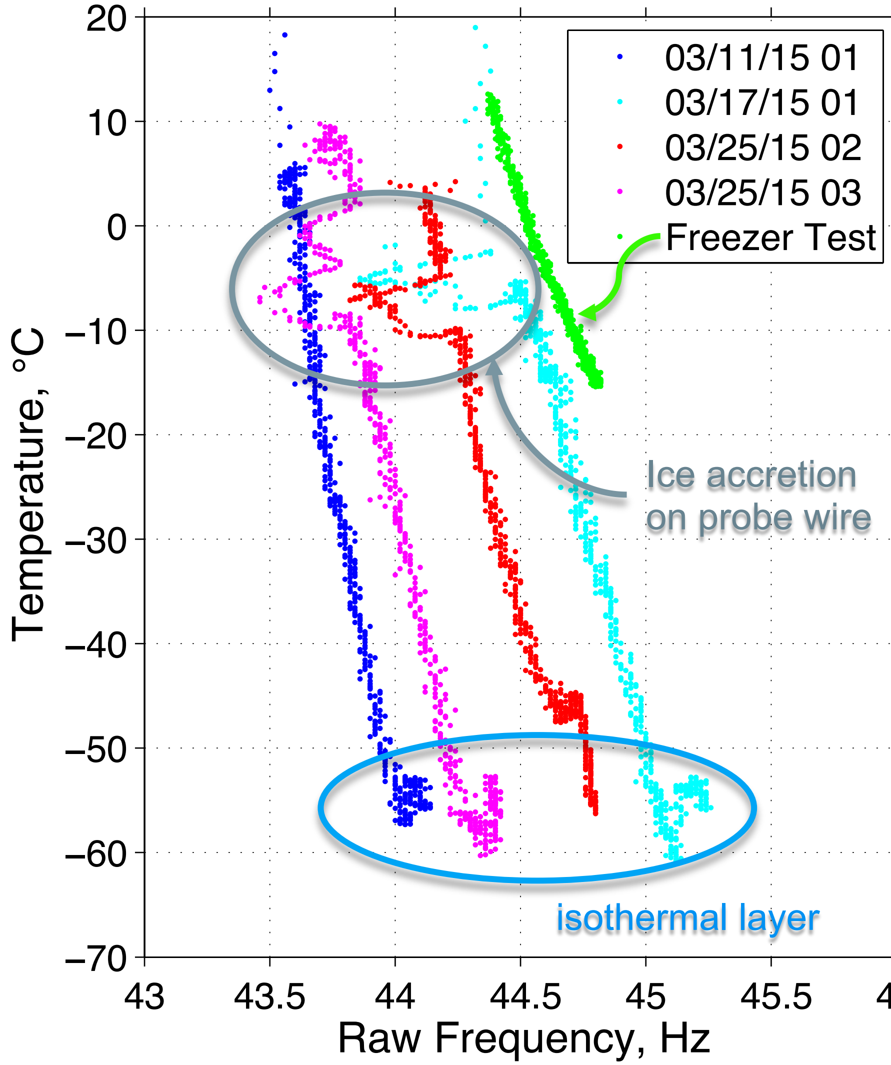
Relative Comparison of Thermal Effects

- The primary suspect sources include:
  - Increased modulus of elasticity of the silicone rubber clamping structure, reducing the effective length of the wire by decreasing the clamp's structural pliability.
  - Increasing modulus of elasticity of the steel wire, thus stiffening the wire.

Sensor Data Drift:

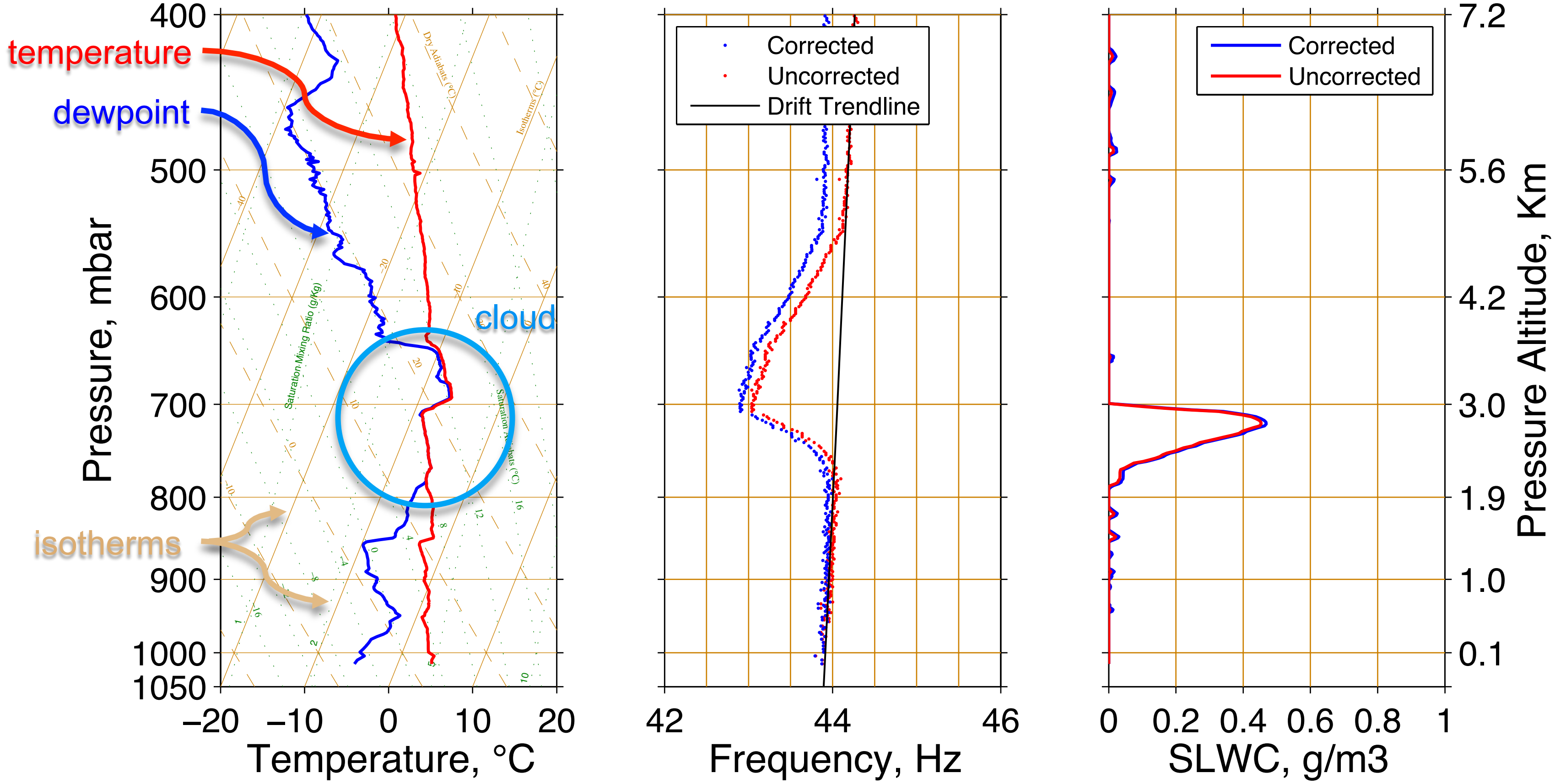
Laboratory Testing and Analysis

- A SLWC sensor was tested in a controlled laboratory environment to better understand this behavior.
  - A thin thermocouple used to measure the temperature of the silicone rubber square.
  - The sensor was placed in a freezer with a controllable temperature, and the thermocouple temperature and vibration frequency were recorded over a period of 30 minutes.
- The data clustering near -60 °C for some cases is due to the weather balloons reaching the isothermal layer near the tropopause.
- The trends for the balloon soundings and the laboratory test are similar indicating the effect is thermal.



Sensor Data Drift:

Correcting Data



- The data was corrected by fitting a trend and removing the difference between the trend and clean wire natural frequency
- The maximum SLWC only increases marginally, approximately 3%, but the integrated liquid water, ILW, increases by 20% for this case.

Summary and Conclusions

- Significant progress has been made calibrating and characterizing vibrating-wire sensors —the goal of this work.
- Preliminary results are promising, based on the agreement between the sensor and blade.
- An expanded calibration database is needed.
- The gradual increase in SLWC without corresponding decrease in frequency suggests that the equations may need to be modified to handle larger mass formations.
- The extent of ‘shadow zone’ was identified and shown to have negligible effect on results.
- Possible causes for the frequency drift in the winter 2015 campaign data were investigated.
- A method to correct winter 2015 campaign data was developed and presented.

Questions?