Aircraft Icing Detection Technology

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In partnership with…

Intelligent Vision Systems, LLC

…a University of Michigan startup

Background

- **Ice accumulation on airplanes is one of the major causes of weather related accidents**
  - The "classic" icing certification envelopes (§25.1419 Ice Protection) covers at most only 99% of the icing conditions encountered during research flights conducted more than 50 years ago
  - Outside these conditions ice can accumulate rapidly and cause loss of control in minutes
  - Ice ingestion by turbines can cause severe power loss within minutes (e.g., AirBridge 747-8F)
  - In order to mitigate these problems, **Supercooled Large Drop Icing Conditions (SLD)** was added to 14 CFR 25 as §25.1420 in 2014

- Technologies originally developed for space applications can be used to **detect when an airplane is flying outside the icing certification envelopes**
  - The new technologies that we have been maturing contain only non-intrusive sensors

Basic Cloud Physics

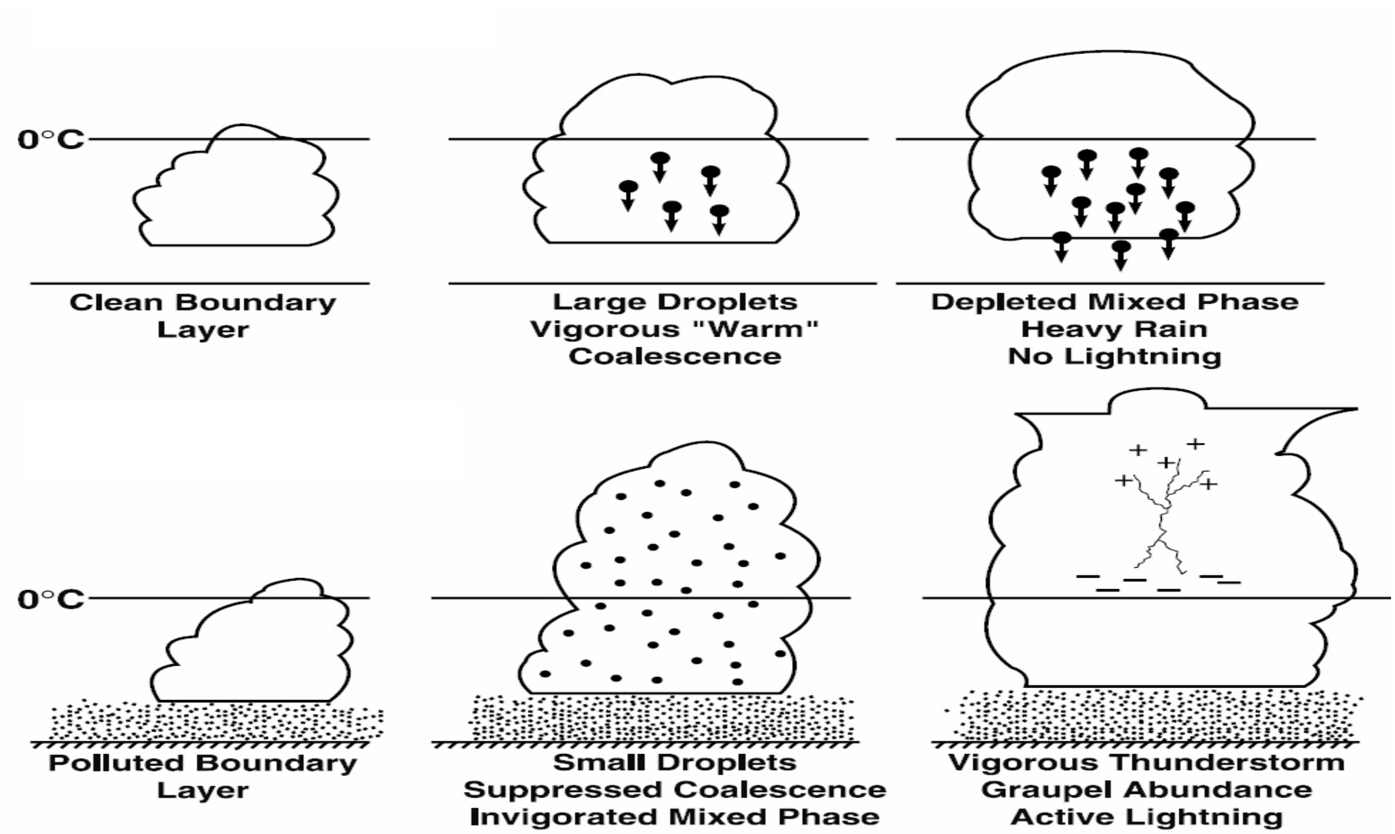
- **Condensation of pure water vapor requires supersaturation of several hundred percent**
  - Since condensation nuclei are common in the atmosphere, supersaturation (of more than 1%) is rare
  - The number of cloud condensation nuclei usually determines the number of droplets in a cloud
  - Fixing the liquid water content (LWC), clouds forming in clean air have larger droplets than clouds forming in polluted air

- **Pure liquid water can be cooled to about -40 °C without freezing**
  - Since ice nuclei are rare in the atmosphere, supercooled liquid water is ubiquitous
  - Supercooled liquid water droplets freeze when contacting a solid (contact nucleation), causing icing

Cloud Droplets:
The Aerosol Hypothesis

Maritime

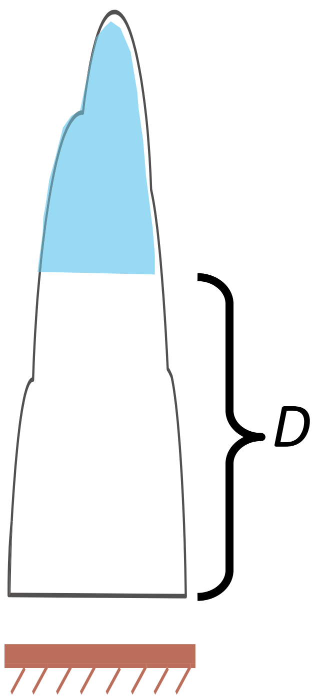
Continental



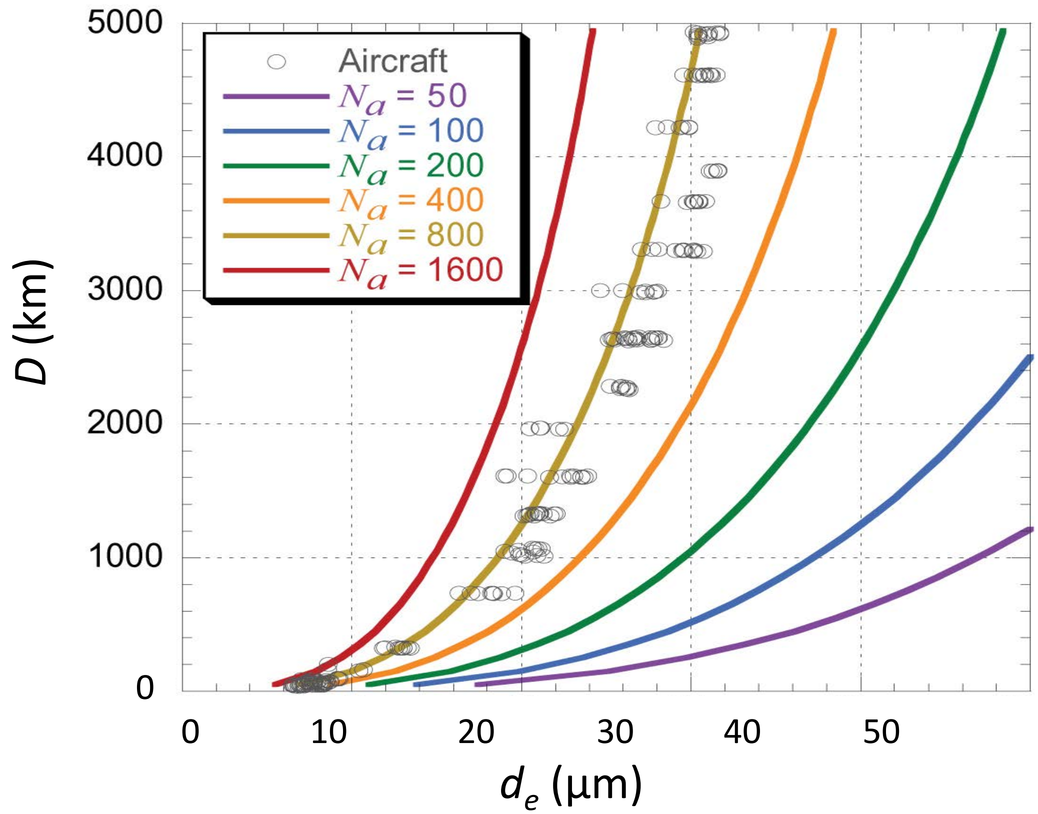
(Williams et al., 2002)

Cloud Droplet Radius Profile: A Function of the Number of Activated Aerosols (N_a)

Only ice crystals are found at temperatures lower than -40 °C



Rosenfeld et al., 2012



Certification

- **Ice Protection Systems (IPS) are designed to mitigate problems when an airplane is exposed to icing conditions likely to be encountered during operation**

- **The design and test of icing protection systems involves consideration of**
  - The meteorological conditions of 14 CFR part 25, Appendices C and O
  - The operational conditions which would affect the accumulation of ice on protected and unprotected surfaces of an airplane and its power system(s)
  - The ability of an airplane to either **detect-and-exit SLD icing conditions safely, or operate safely in them** was added to 14 CFR part 25 in 2014

- **Impingement rate is a function of droplet size and concentration**
  - A Mean Effective Diameter (MED) of 20 µm is usually used to determine the water catch rate and an MED of 40-50 µm to determine the impingement limits (AC 20-73)
  - New certification requirements are described in 14 CFR part 25 and AC 25-28

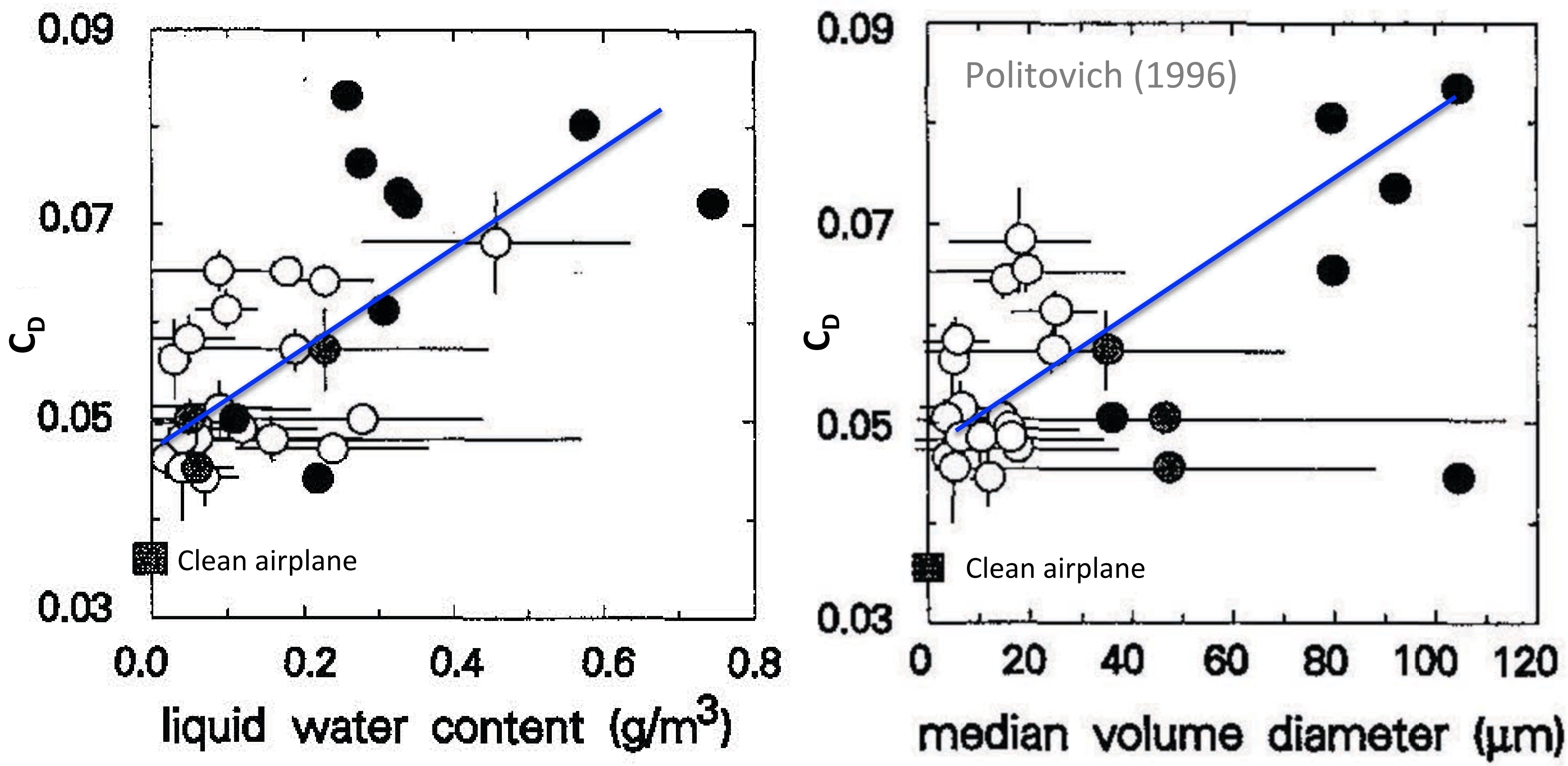
Today's Situation

- **Icing continues to be a challenge**
  - **Statistically, the "classic" icing certification envelopes (14 CFR part 25, Appendix C) do not cover the conditions encountered in at least 1 of each 100 icing encounters**
  - Icing decreases C_D, decreases C_L and can cause loss of control
  - Automatic flight control systems can mask the effects of ice accumulation
  - Early detection of ice accumulation is critical to flight safely—even for airplanes equipped with current icing protection systems

- **Icing conditions can be detected immediately with new technologies**
  - In flight, in the airspace around an airplane (including ice crystals)
  - Before takeoff, in the airframe, below snow accumulated after deicing

- **Immediate detection can**
  - Alert pilots **when flying in conditions outside the icing certification envelopes**
  - Comply with new requirements of 14 CFR part 25

The Real World Conditions



Original Icing Intensity Scale

Supercooled LWC (g/m^3)	Icing Intensity
0-0.1	Trace
0.1-0.6	Light
0.6-1.2	Moderate
> 1.2	Severe or Heavy

Lewis (1951)

Based on statics from measurements in Mt. Washington (Richard K. Jeck, 2001)

Rosemount Icing Intensity Scale

Supercooled LWC (g/m^3)0	Icing Intensity
0-0.25	Level 1 (Trace)
0.25-0.5	Level 2 (Light)
0.5-1.0	Level 3 (Moderate)
1-2	Level 4 (Heavy)

Jeck (2001)

Rosemount Model 871FN/512AG Icing Rate System, Product Data Sheet 2517 (1998)

Ice Accretion Rate

- **Depends critically on the value of three parameters**
  - **Cloud Liquid Water Content (LWC), droplet diameter, and temperature (Jones and Lewis, 1949)**
- **For a specific supercooled LWC, cloud droplet size distribution, and outside air temperature (OAT)**
  - Different airfoils have different accretion rates
  - The accretion rates depend on airspeed, geometry, altitude and angle of attack
- **Numerical models**
  - Such as LEWICE are usually used to calculate accretion rates (Wright, 1995)
  - Are used to calculate the amount of ice accumulated in a given time interval

Icing Certification Envelope

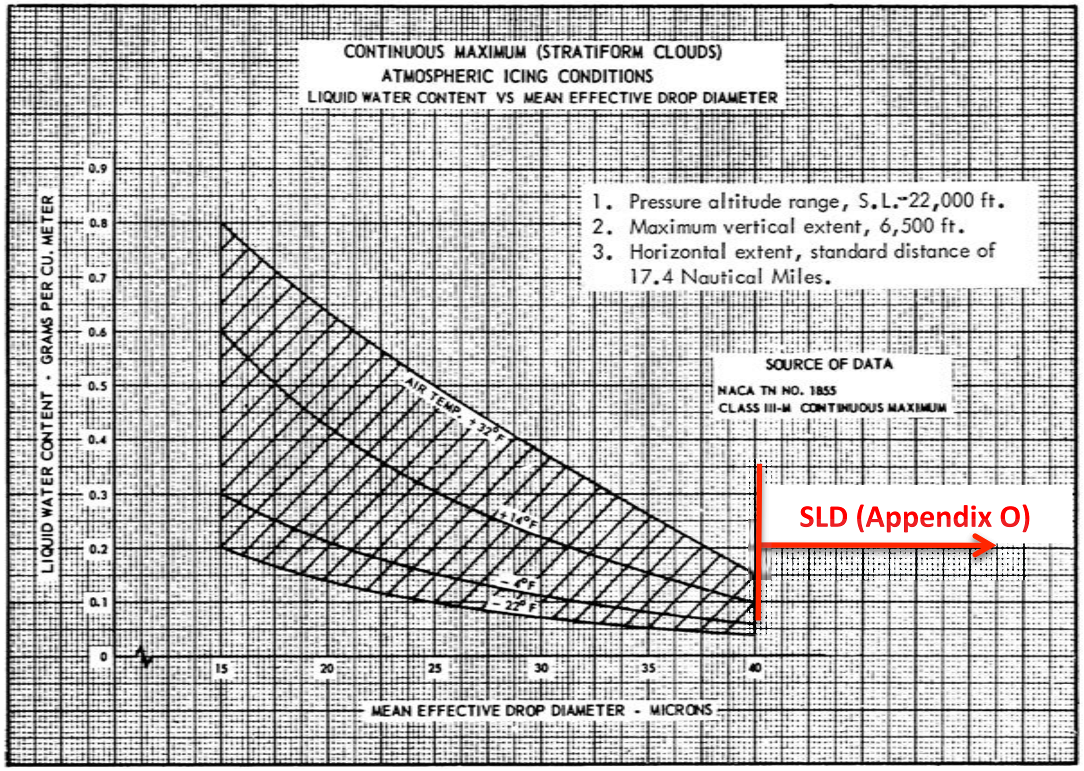
- **Specified in Appendices C and O of 14 CFR part 25**
  - Appendix C is based on data collected during 252 icing encounters by research airplanes in the 1940s (Lewis and Bergrum, 1952)
    - **Continuous maximum conditions** represent icing conditions in stratiform clouds (important for the design of thermal ice protection systems for large airplanes)
    - **Intermittent maximum conditions** represent icing conditions in convective clouds (important for the design of engine ice protection)
  - **Appendix O is based on more recent data.** It includes SLD, freezing drizzle, and freezing rain

- **The Appendix C and O icing envelopes contain the three most important parameters for the design of airplanes ice protection systems**
  - Appendix C represents the probable maximum (99%) value of cloud liquid water content (LWC) and droplet size expected in **random icing encounters of "standard" extent**
  - Appendix O represents less likely but more hazardous SLD encounters

Continuous Maximum Envelope

14 CFR part 25 Appendix C

Typically extending horizontally 17.4 nm.

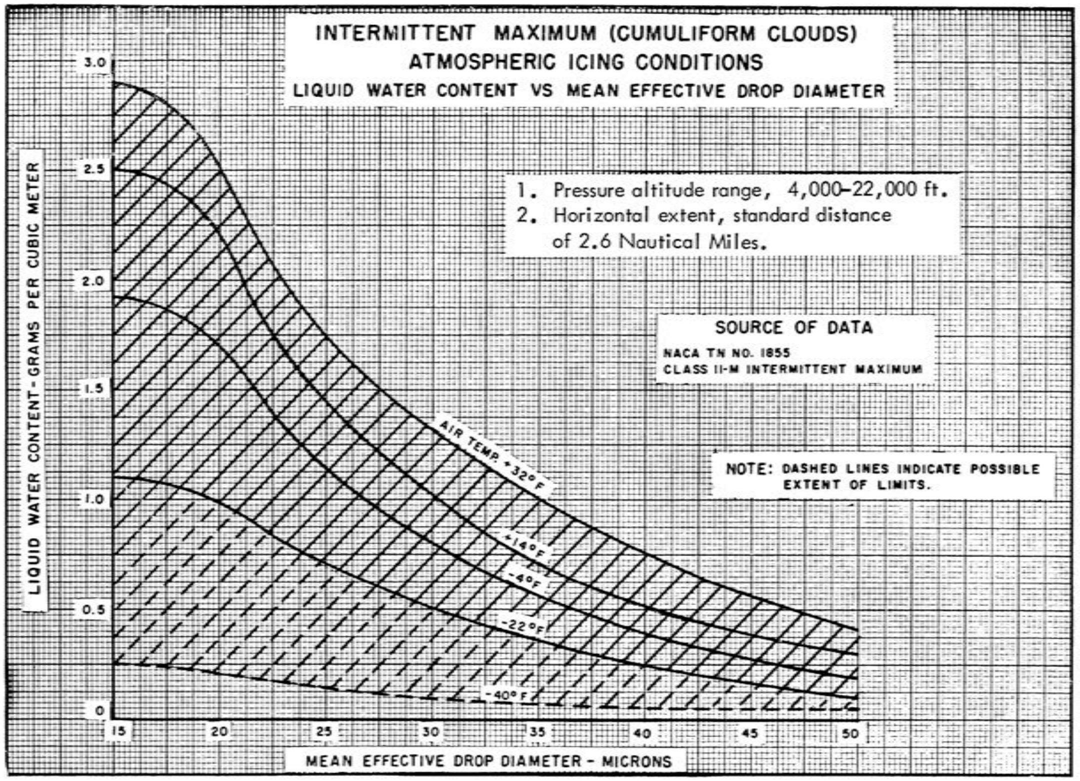


The probability of group of values of liquid water content (LWC) associated simultaneously with air temperature (T), and droplet diameter (d) within specific ranges being exceeded.

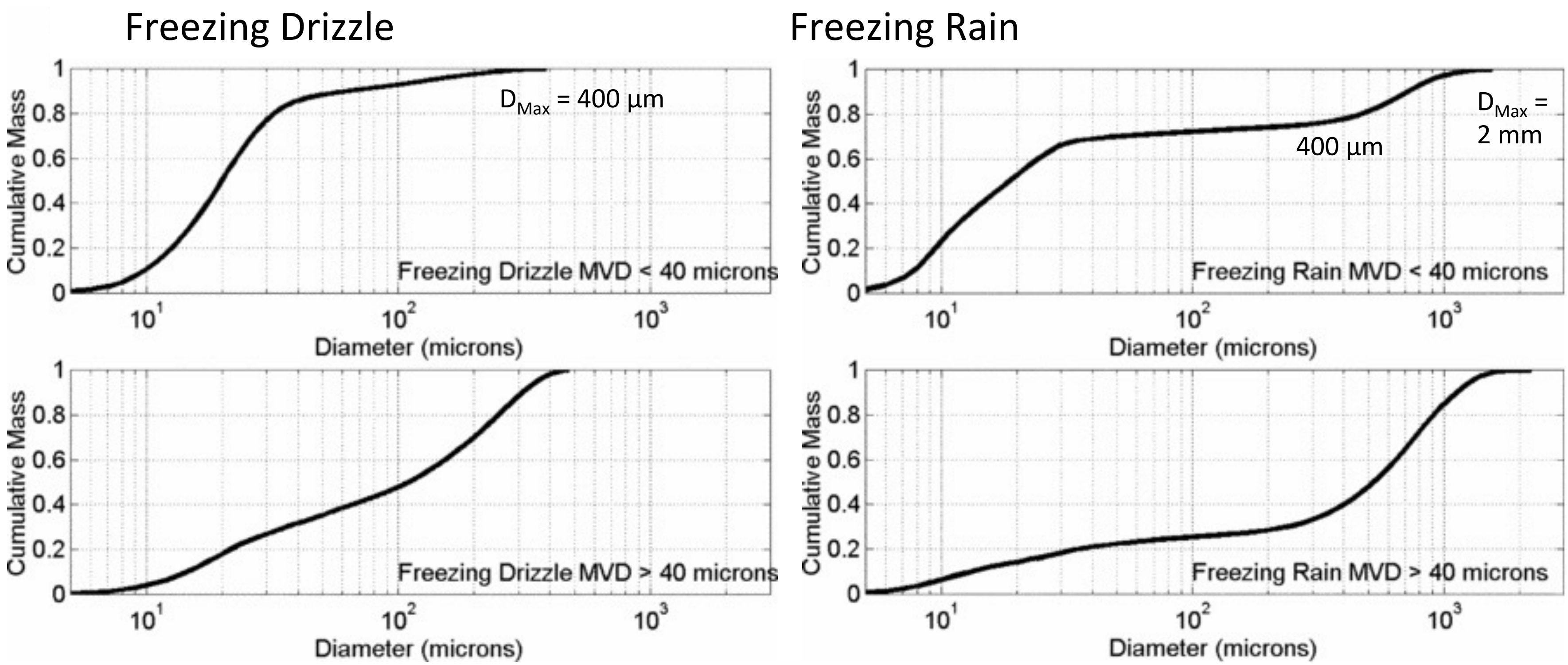
Intermittent Maximum Envelope

14 CFR part 25 Appendix C

Typically extending horizontally 2.6 nm.

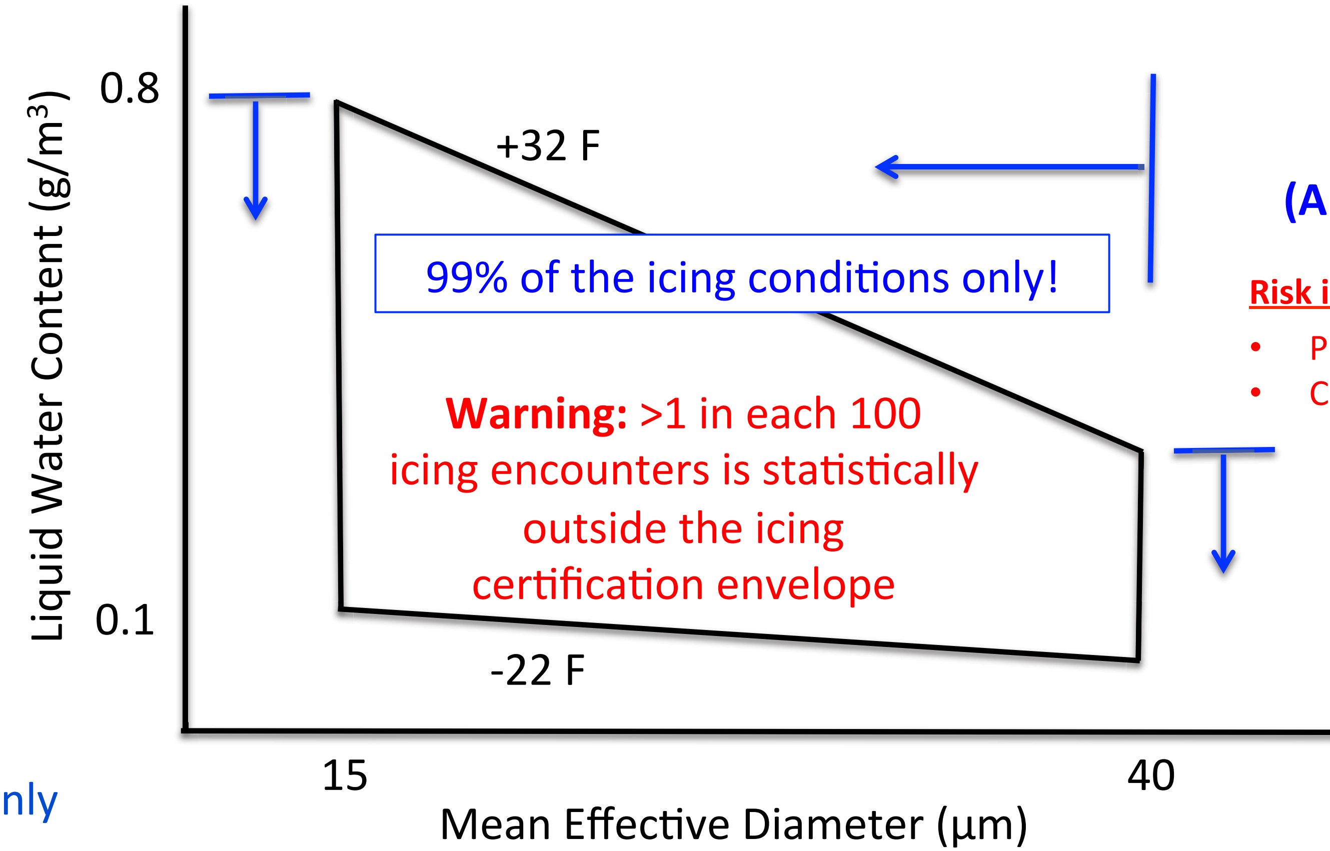


14 CFR Part 25 Appendix O



Appendix C Certification Envelope

Stratiform Clouds (Continuous Max)



SLD (Appendix O)

Risk is 2-D Quantity

- Probability
- Consequence

45 min only

Summary

- **Icing is a serious problem even for airplanes certified to fly in it**
  - Statistically more than **1 in 100 icing encounters are outside the "classic" (14 CFR part 25, Appendix C) icing certification envelope**
  - Hot air systems may not fully evaporate all impinging water drops, resulting in runback ice
  - **Tapping air from the engine to anti-ice systems reduces the available thrust**
  - Automation systems can mask effects of ice accumulation and lead to stalls

- **Immediate detection can**
  - Alert pilots **when conditions outside the icing certification envelope are encountered**
  - Help pilots mitigate the negative effects of automation

- **The technology discussed next can alert pilots**
  - Immediately after an airplane encounter conditions outside the icing certification envelope
  - **Can reliably detect ice crystals**
  - **Increase fuel efficiency and range by decreasing the use of bleed air**

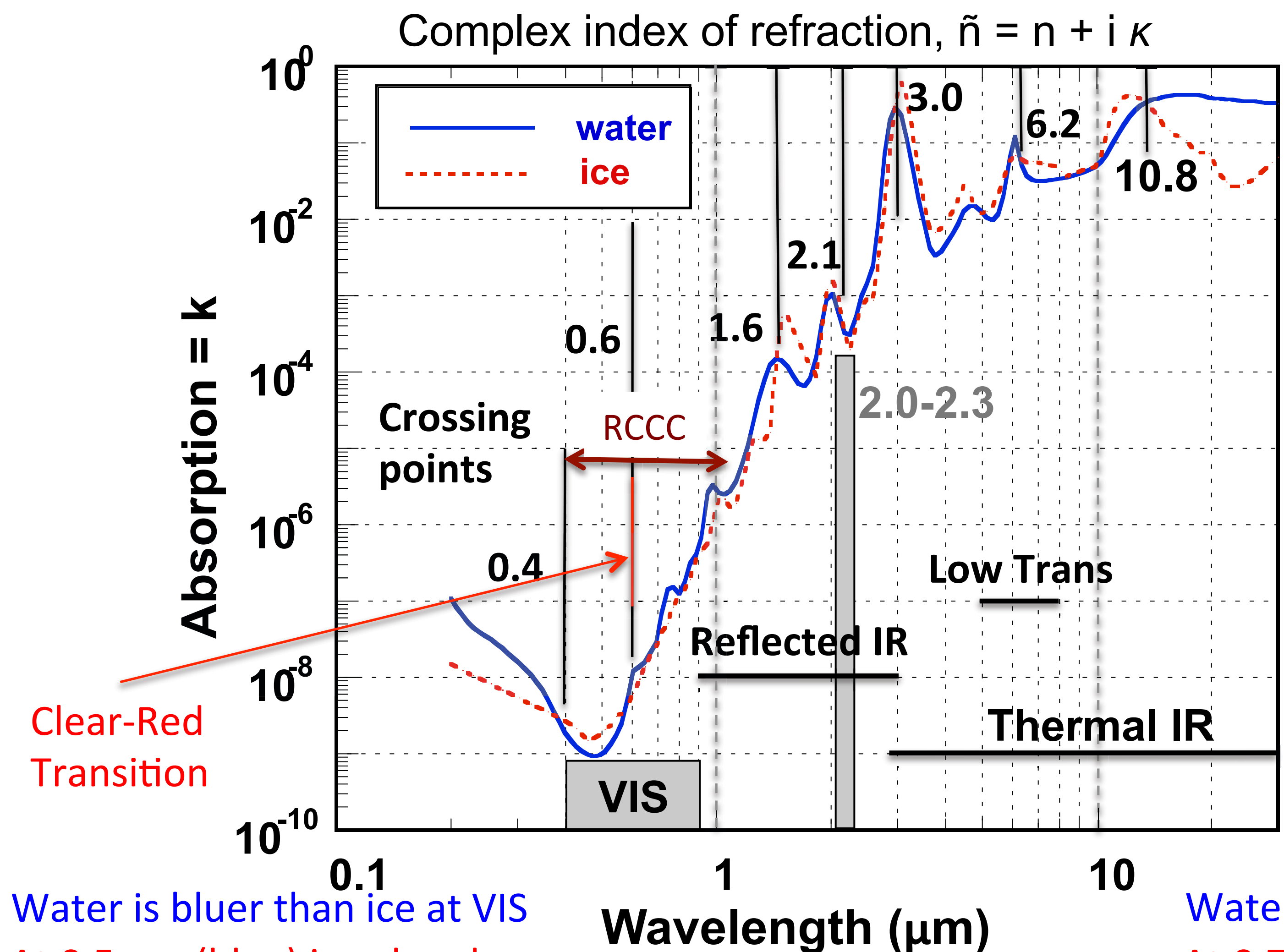
A Sample of Current Technologies


LET

Dassault Avoids Existing Ice Detection Probes

Our Approach to Icing Detection

Absorption Spectra of Water Substance



The 2.05-2.30 µm band is ideal because it is in a water vapor window region **illuminated** by solar radiation. Moreover, water and ice are **strongly absorbing** in this band which is located in the **reflected portion** of the IR spectrum.

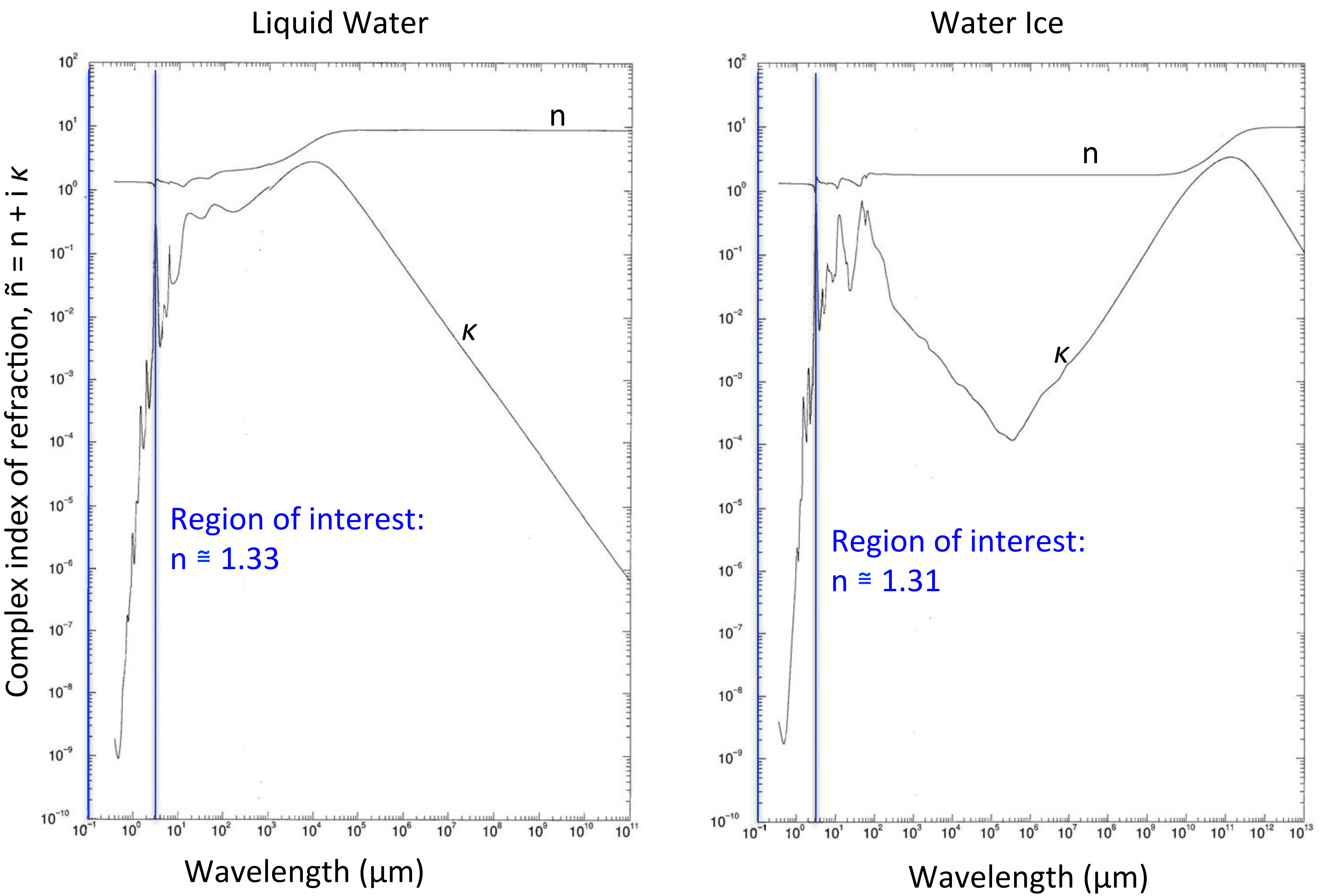
Water is bluer than ice at VIS

At 0.5 µm (blue) ice absorbs twice as much radiation as water.

Water is less red than ice at VIS

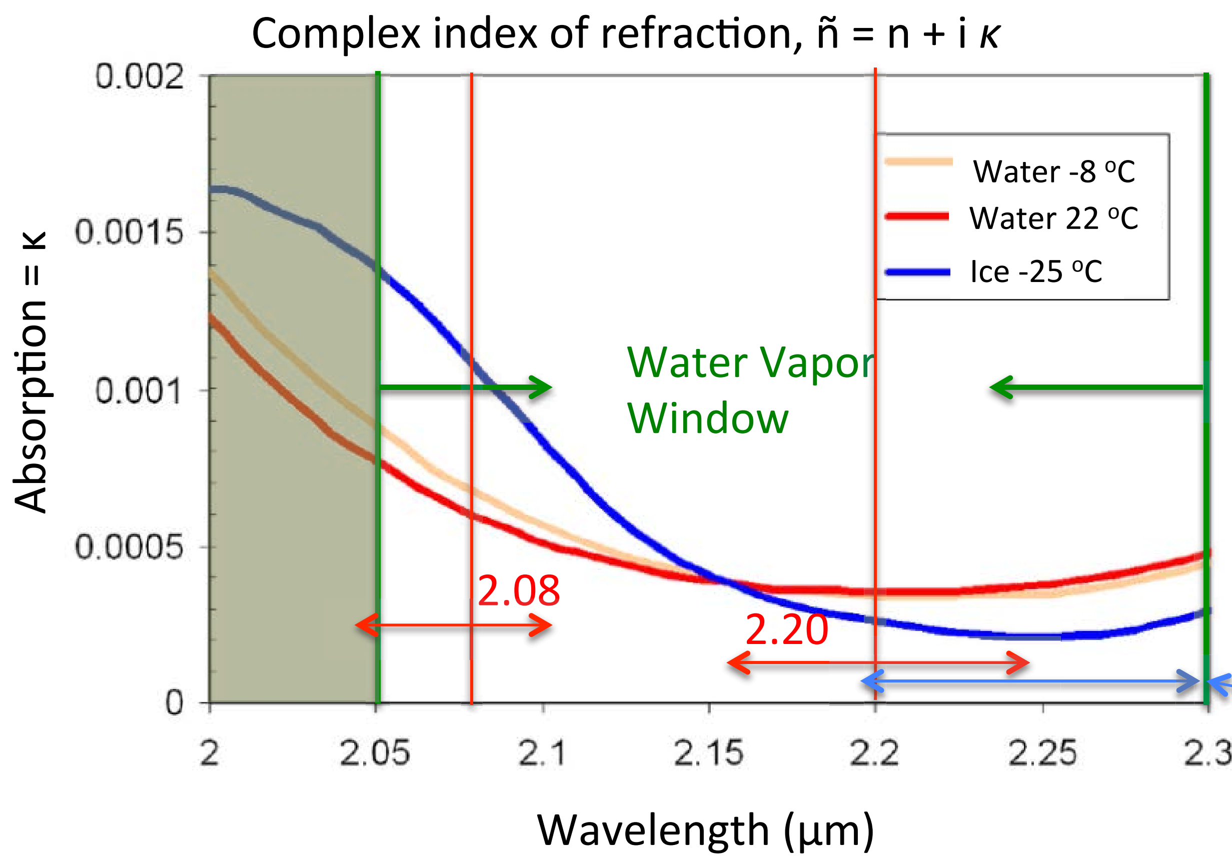
At 0.7 µm (red) water absorbs more radiation than ice.


Sea Ice & Water
Water is bluer than ice



Gauthier, 1996

The 2.05-2.30 µm Band



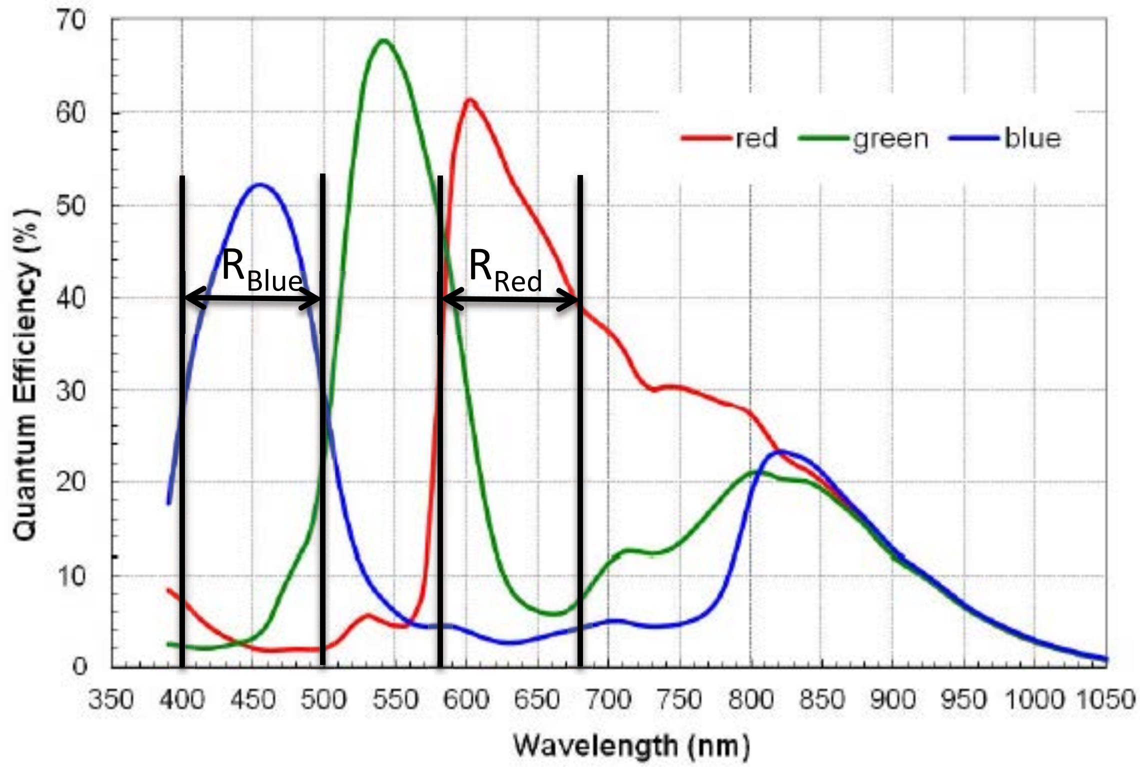
$n = c/v_{ph}$
where v_{ph}
phase speed

κ = absorption

Possible for
increasing
the signal

$\varepsilon = \varepsilon_R + i\,\varepsilon_i$ where $\varepsilon_R = n^2 - \kappa^2$ and $\varepsilon_i = 2\,n\,\kappa$

Typical Visible Camera Specs



The spectral bandwidth of the Red and Blue bands is about 100 nm.
The QE is about 40% or 0.4.

Theoretical Transmittance Ratios

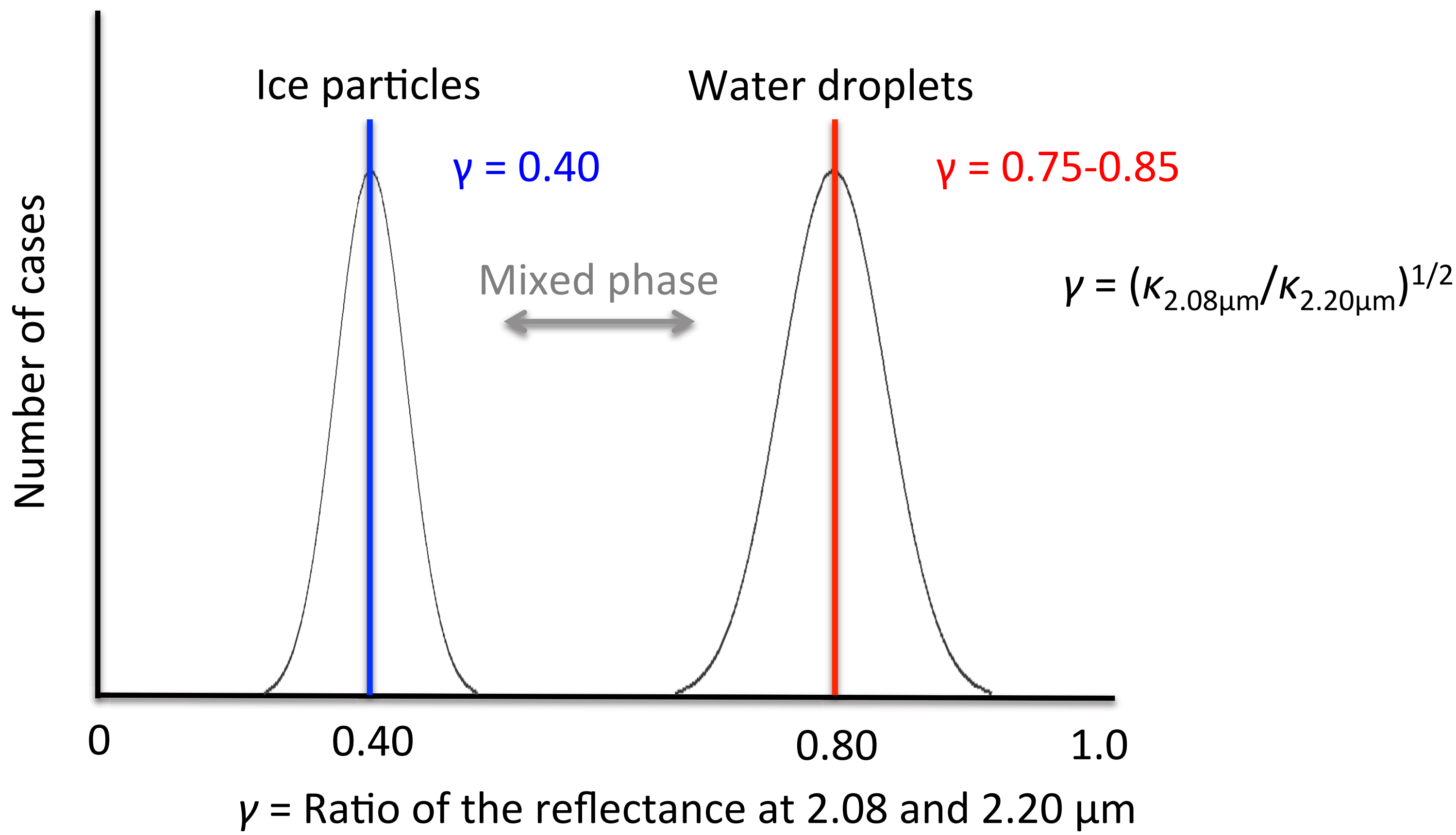
Crossover Point	$(I_{Red}/I_{Blue})_{Water}$	$(I_{Red}/I_{Blue})_{Ice}$	Comment
0.6 µm	0.83 (1 m)	0.95 (1 m)	Water is bluer than ice
1.6 µm	0.50 (1 mm)	0.05 (1 mm)	Water is redder than ice
2.15 µm	0.08 (1 mm)	0.008 (1 mm)	Water is redder than ice

$$\frac{I_{\mathrm{Red}}(z)}{I_{Blue}(z)} = \frac{\exp(-\frac{4\pi\kappa_{\mathrm{Red}}z}{\lambda_{\mathrm{Red}0}})}{\exp(-\frac{4\pi\kappa_{Blue}z}{\lambda_{Blue0}})} = \exp\left(4\pi(\frac{\kappa_{Blue}}{\lambda_{Blue0}} - \frac{\kappa_{\mathrm{Red}}}{\lambda_{\mathrm{Red}0}})z\right)$$

I = transmitted signal, z = path length.

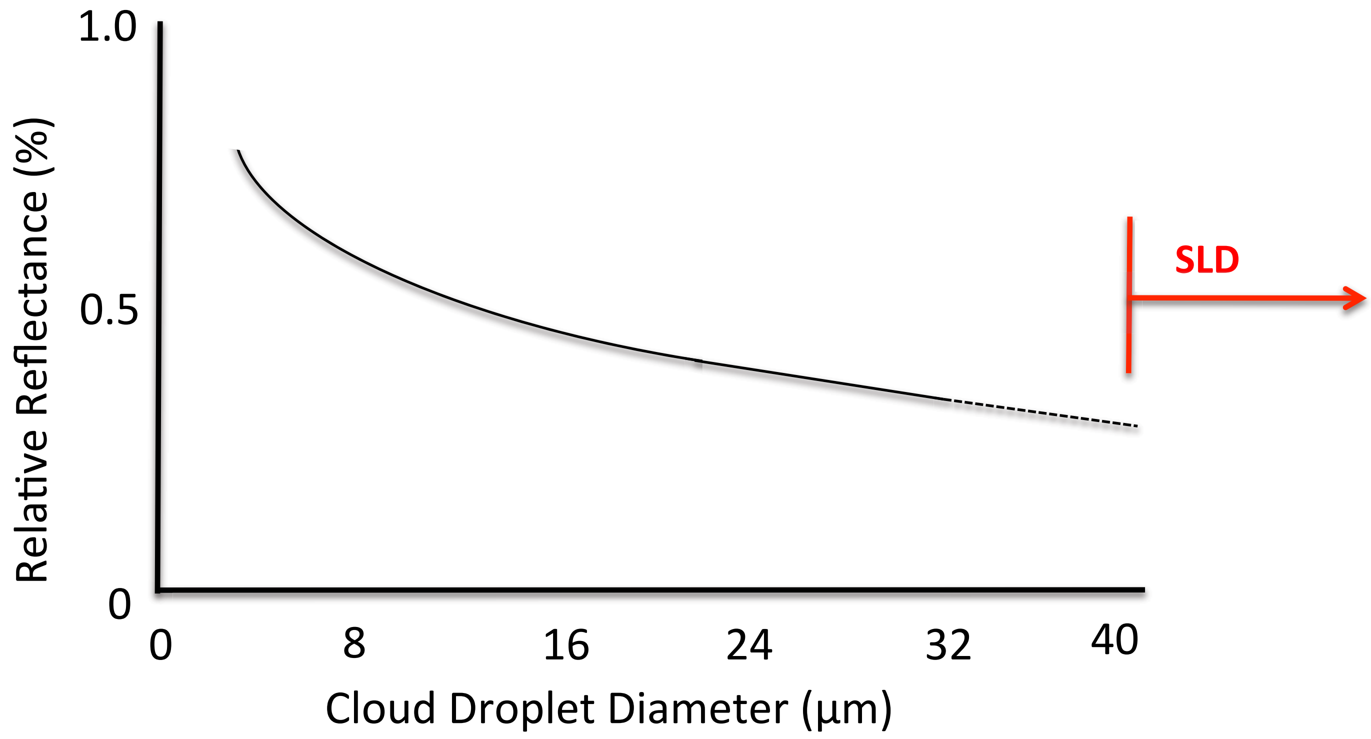
At 0.6 µm and 1.6 µm, increases in the light-path-length increases the redness because around these crossover points absorption increases with wavelength. At around 2 µm, the opposite behavior is observed because absorption decreases with wavelength.

Ratio of Reflectance Measurements and Absorption Coefficients



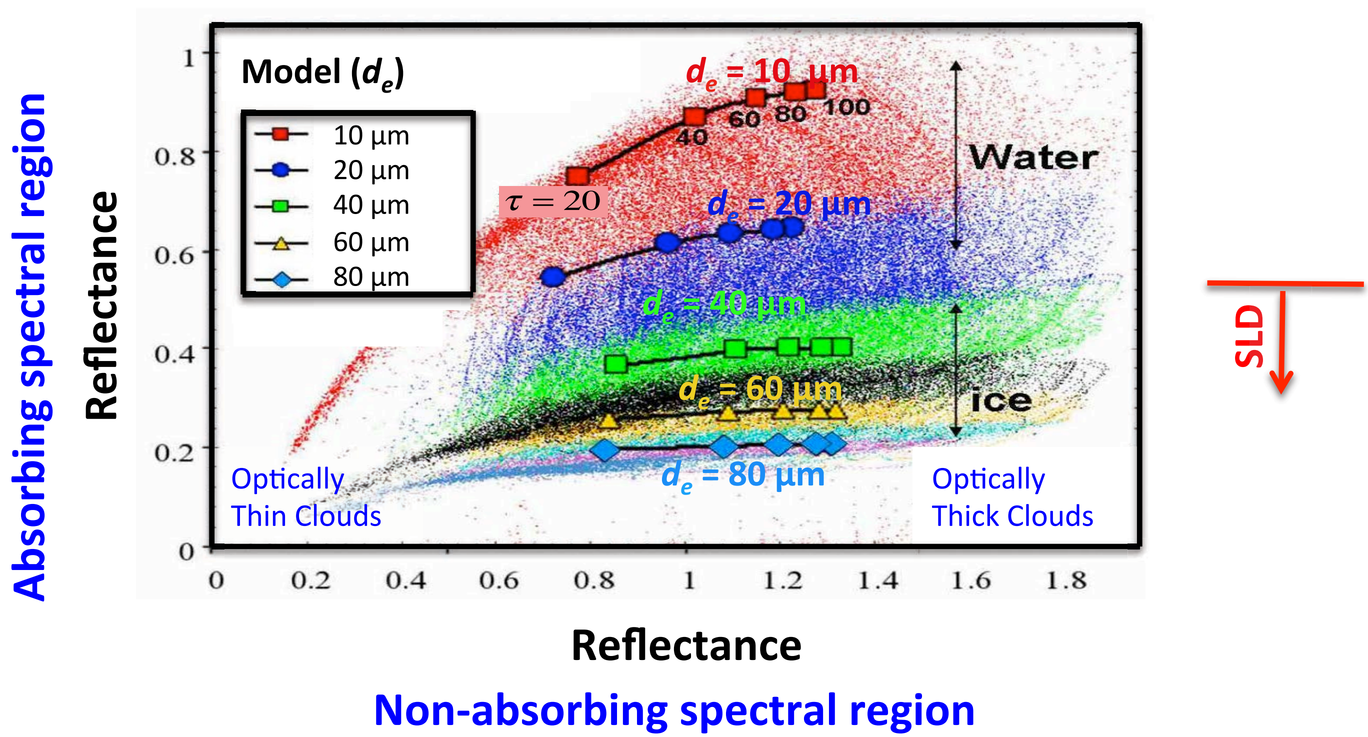
Supercooled Large Droplets (SLD)

A hazard for any airplane... can be measured optically

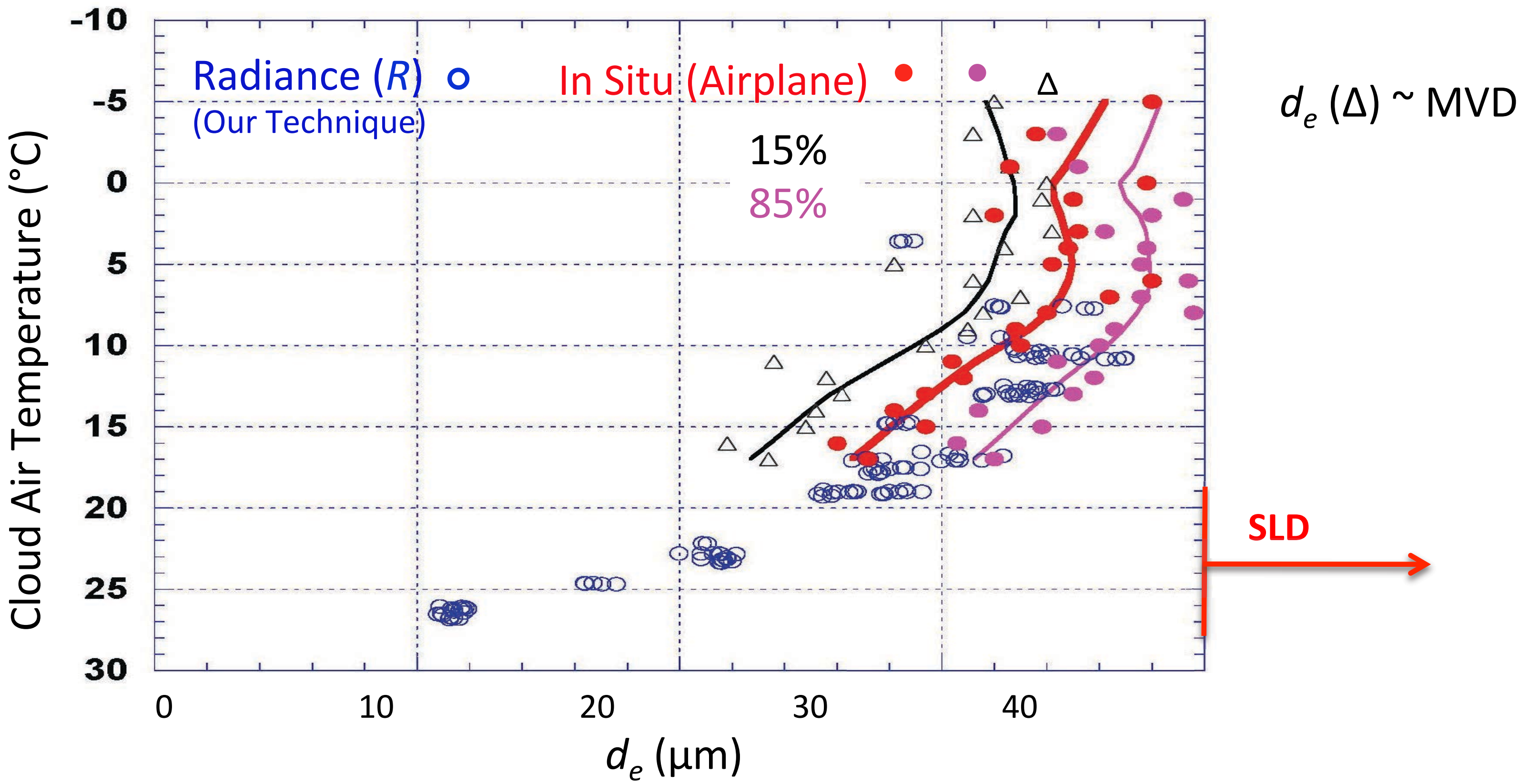


Supercooled Large Droplets (SLD)

A more sophisticated model



Droplets Size Retrieval

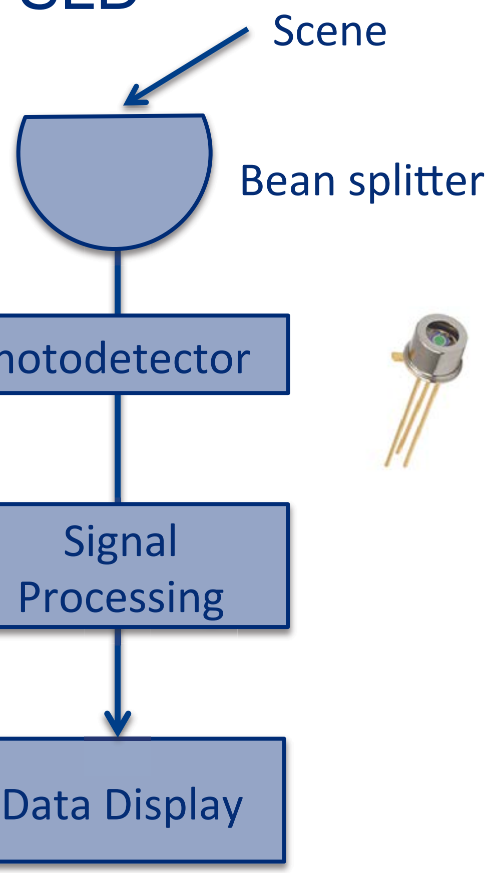


After Rosenlfeld et al. (2012)

The Simplest Implementation

For detecting supercooled water and SLD

Sources: Steve Parsons/PA

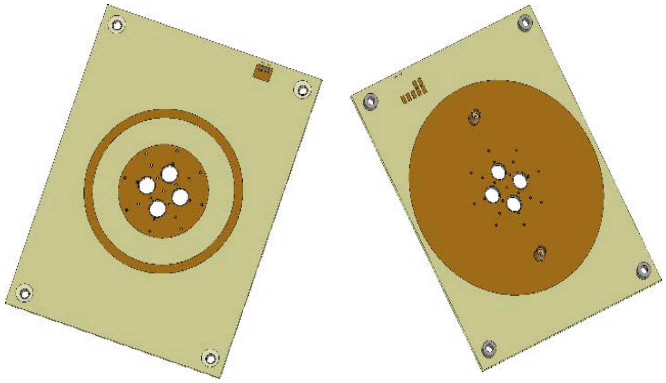


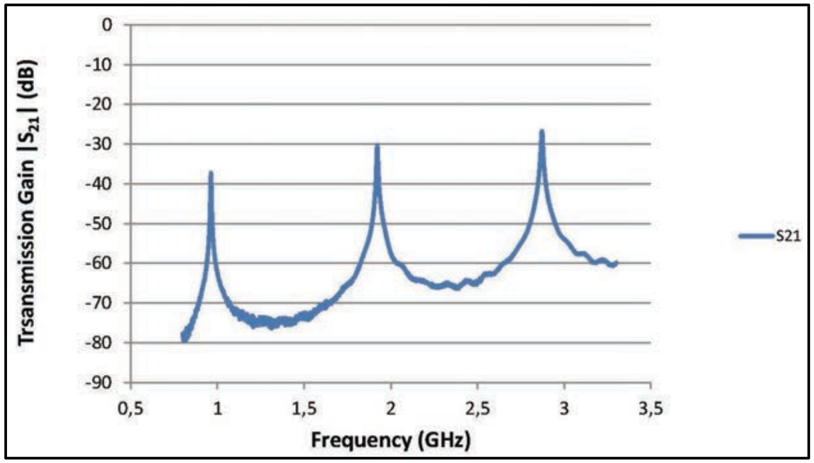
Supporting Technique: Ring Resonator

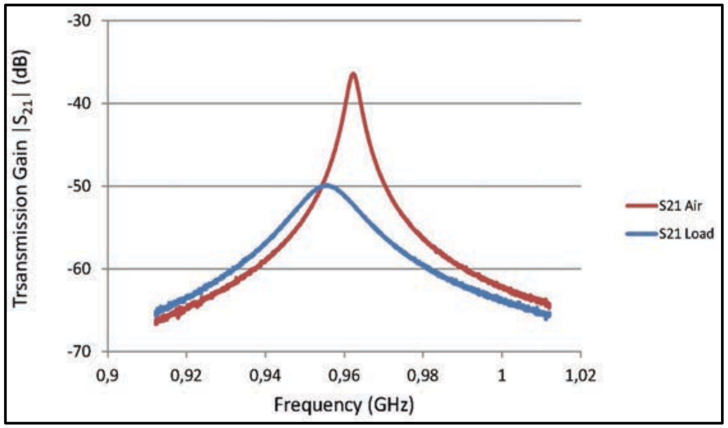
Capable of Measuring Liquid Water Content

Detects Ice Accumulation… where it matters!

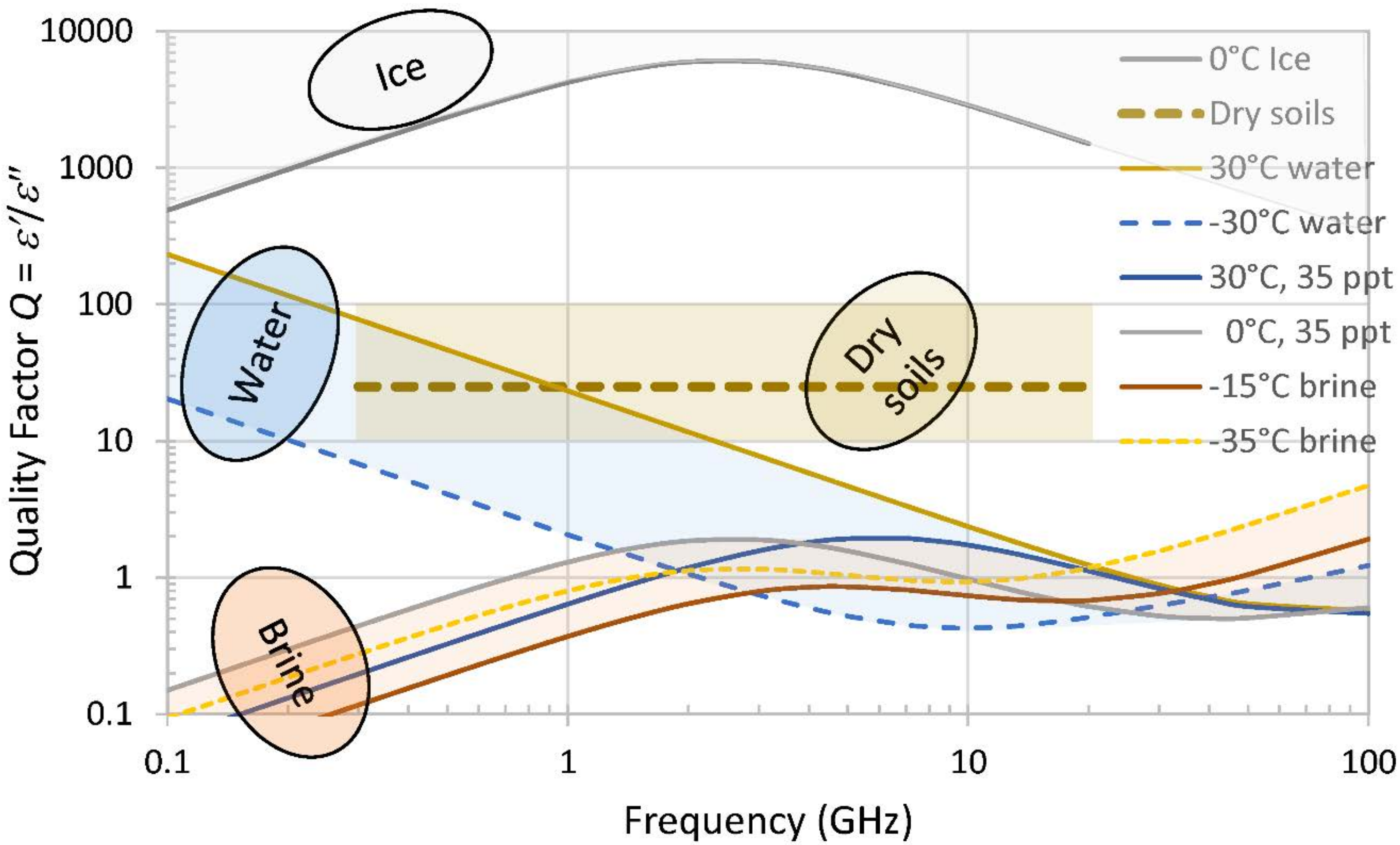
…On the airframe, anywhere that is required
with a non-intrusive sensor





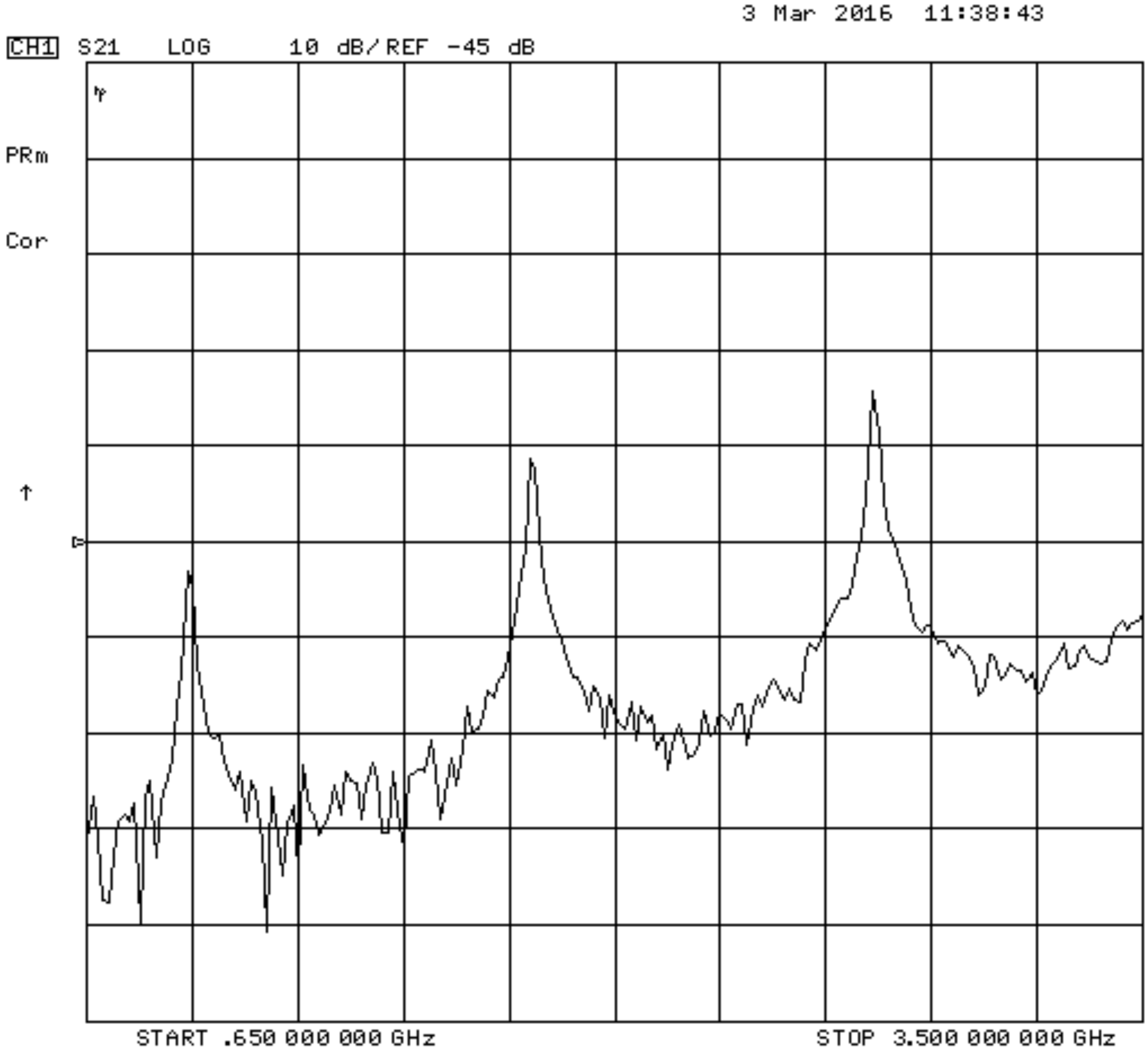


Theoretical Quality Factor

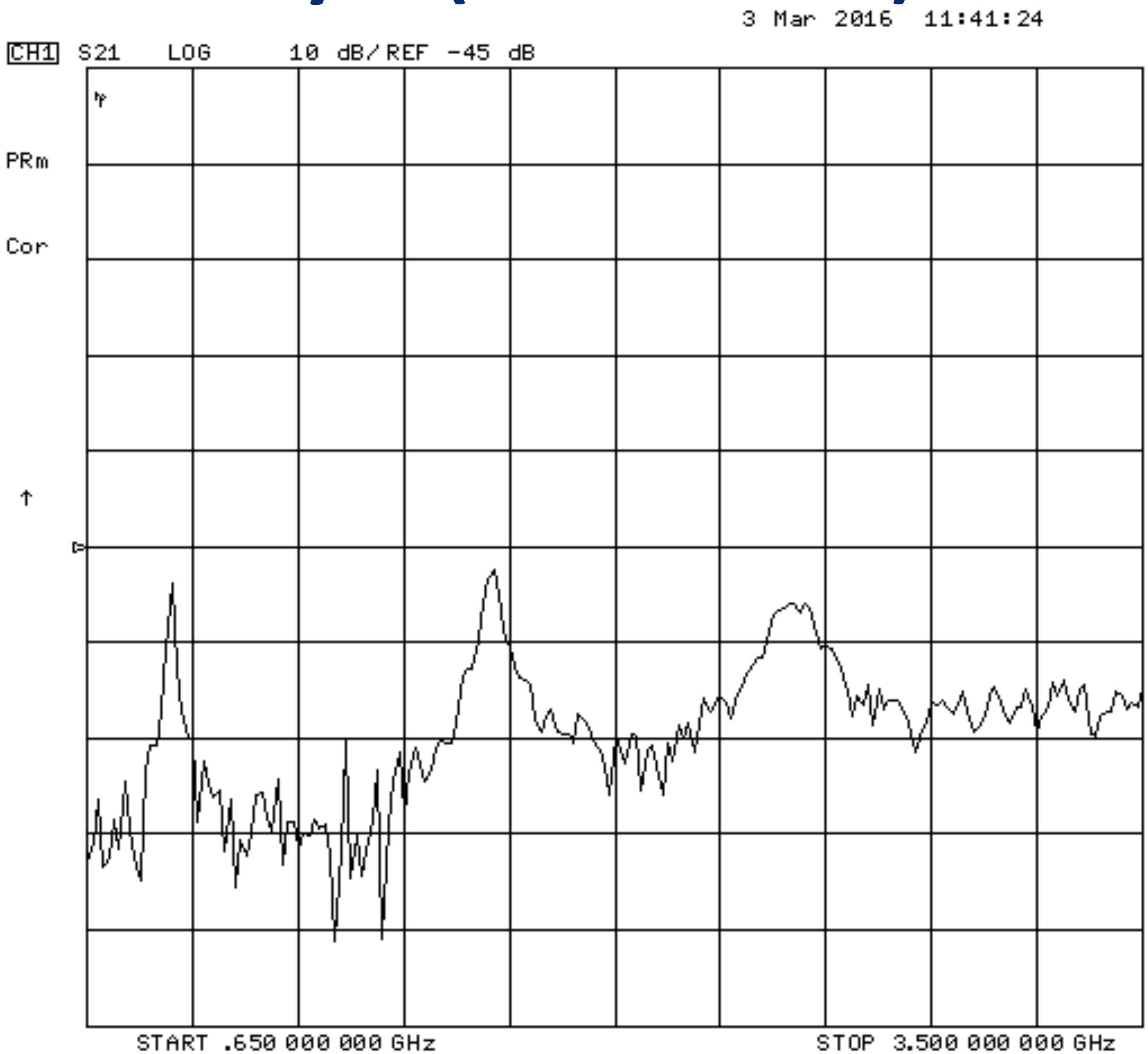


A Few Results

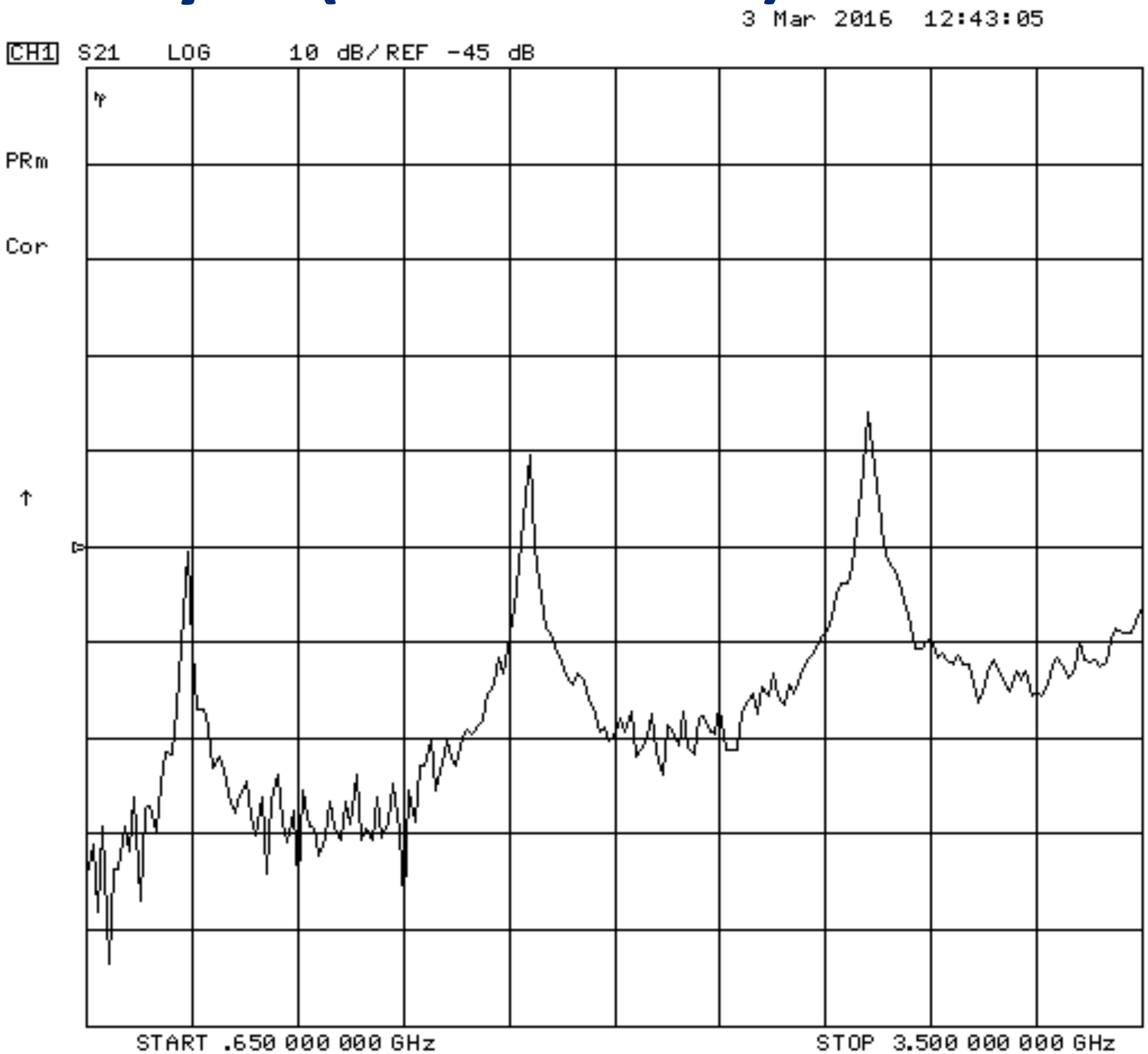
Unloaded: Air Only



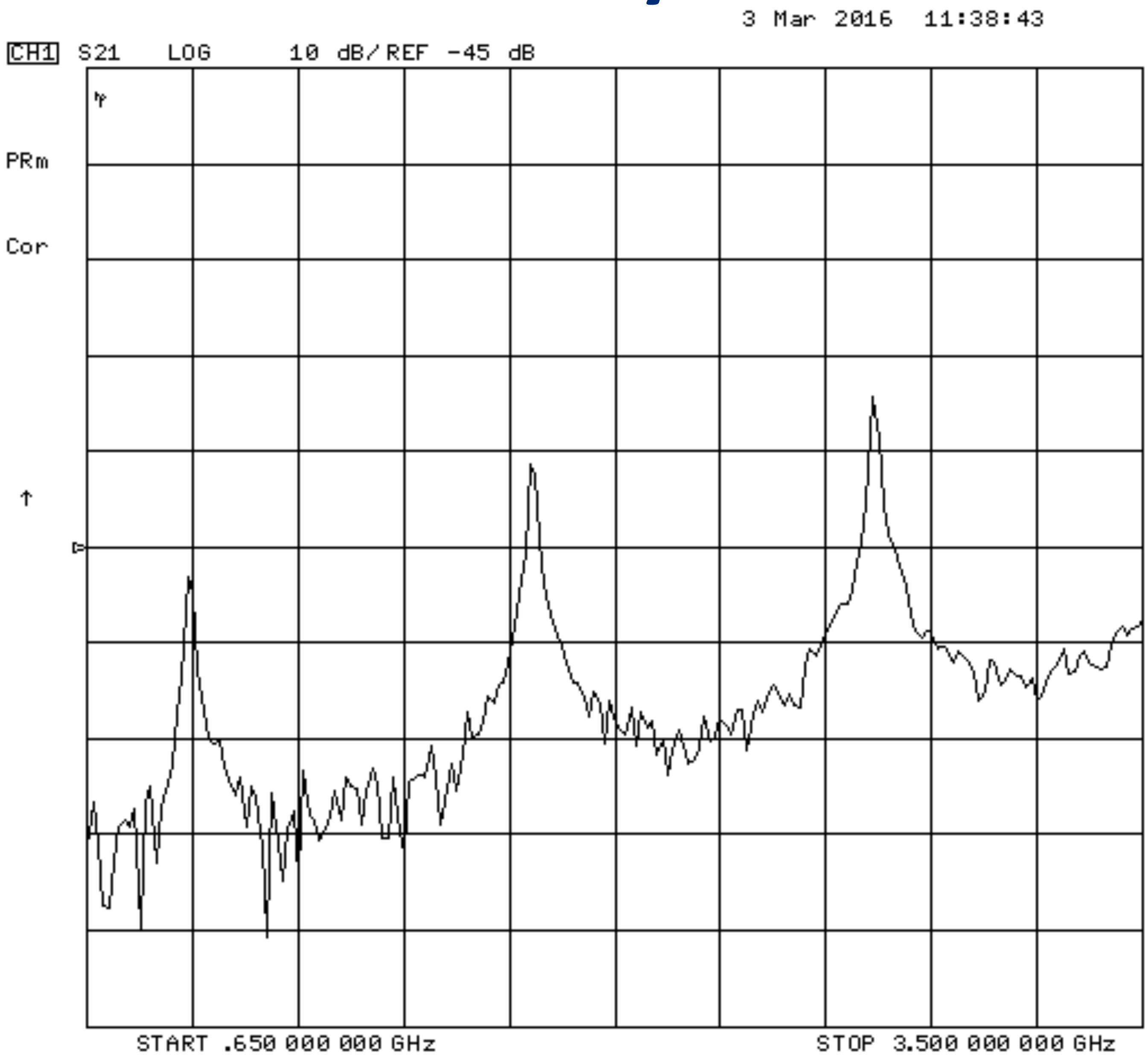
Water Layer (2 mm thick)



Ice Layer (2 mm thick)

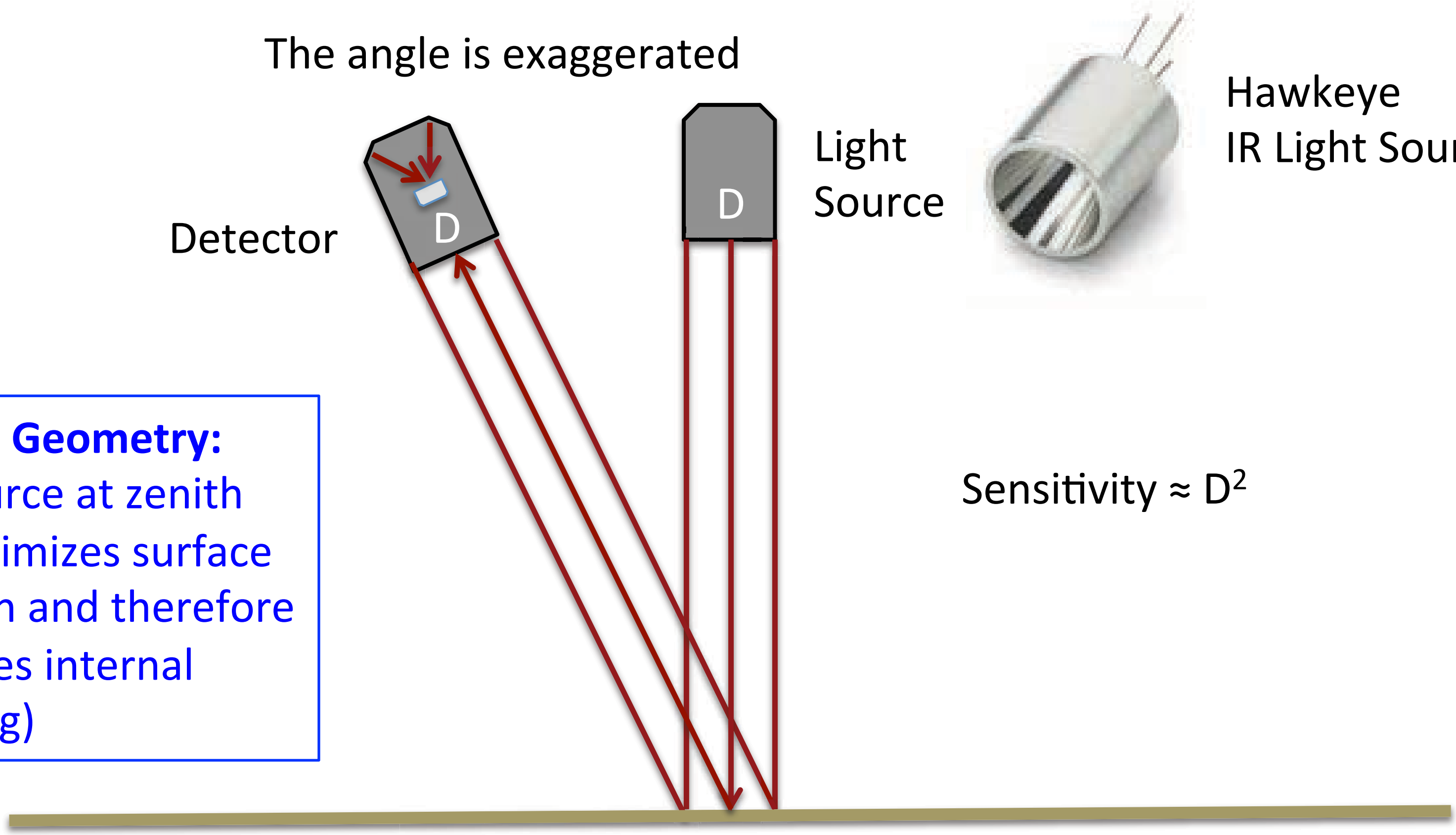


Unloaded: Air Only



Detector & Light Source Geometry

The angle is exaggerated

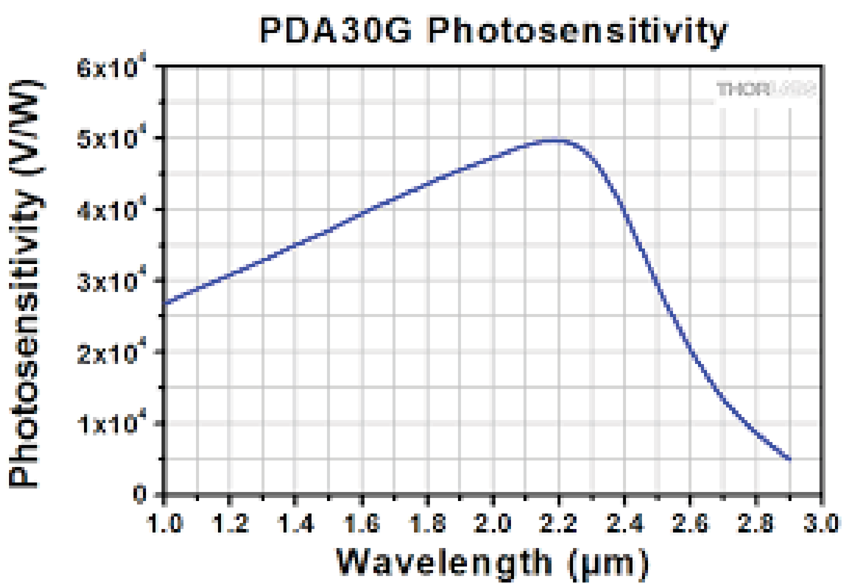


Sensitivity ≈ D^2

The Best Geometry:
Light source at zenith (this minimizes surface reflection and therefore maximizes internal scattering)

A Good Performing Detector

- The PbS Photodetector (PDA30G) sensor



Halogen Automotive Light Source

Brand CEC Industries
Energy Used 70 Watts
Volts 24
Base PK22s
Bulb Shape T-3 1/4
Candle Power 146
Bulb Finish Clear
Bulb Technology Halogen
Average Rated Life (hr) 150
Class and Filament C-6
Length (in) 1.65
Diameter (in) 0.45

Hawkeye Light Source

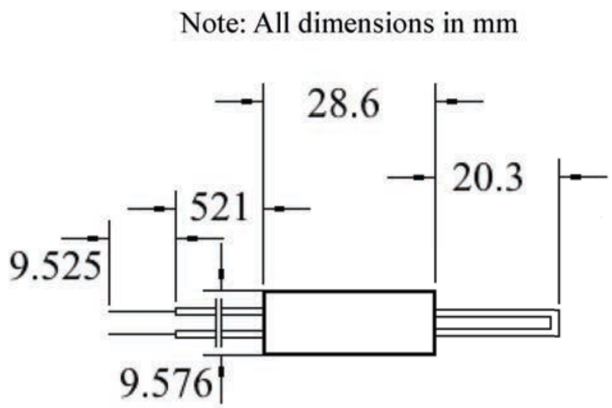
Recommended (Maximum) Operating Parameters

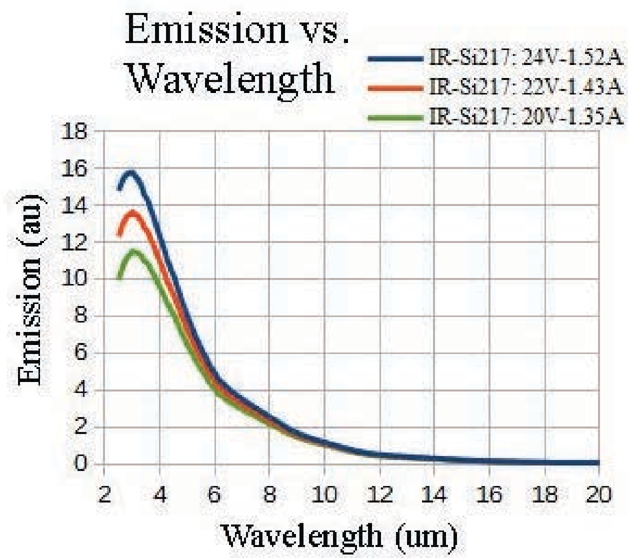
Voltage, V	24	(28)
Temperature °C	1385	(1500)
Current, A	1.5	(1.77)
Power, W	37	(49.56)

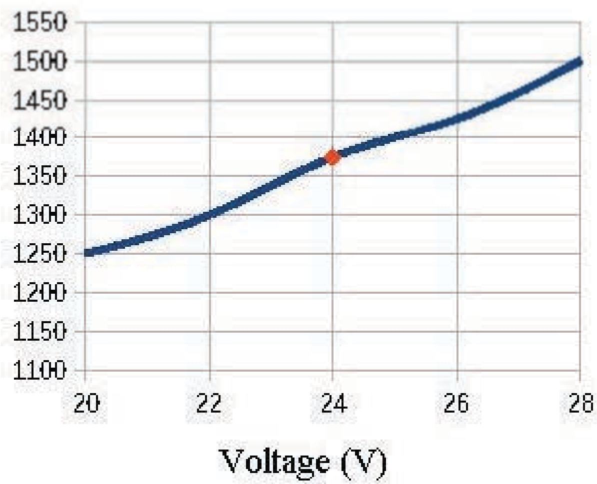
Properties at Recommended Parameters

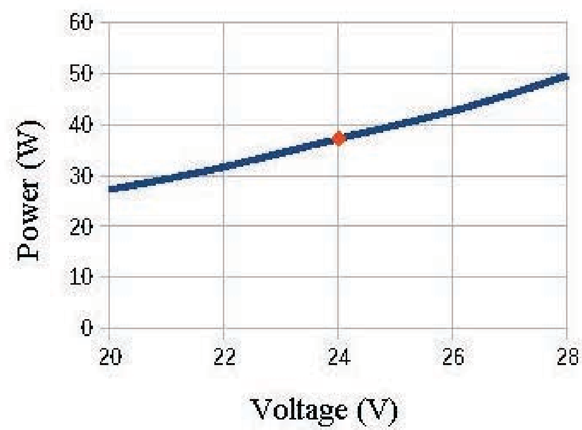
Life	5,000+ Hours
Emissivity, %	80
Active Area (mm)	6 (W) X 4.4 (L)
Material	Silicon Carbide

IR-Si series emitters can be paired with elliptical or parabolic reflectors for a significantly more efficient collimation of energy. Windows are also available for specific transmitting ranges.





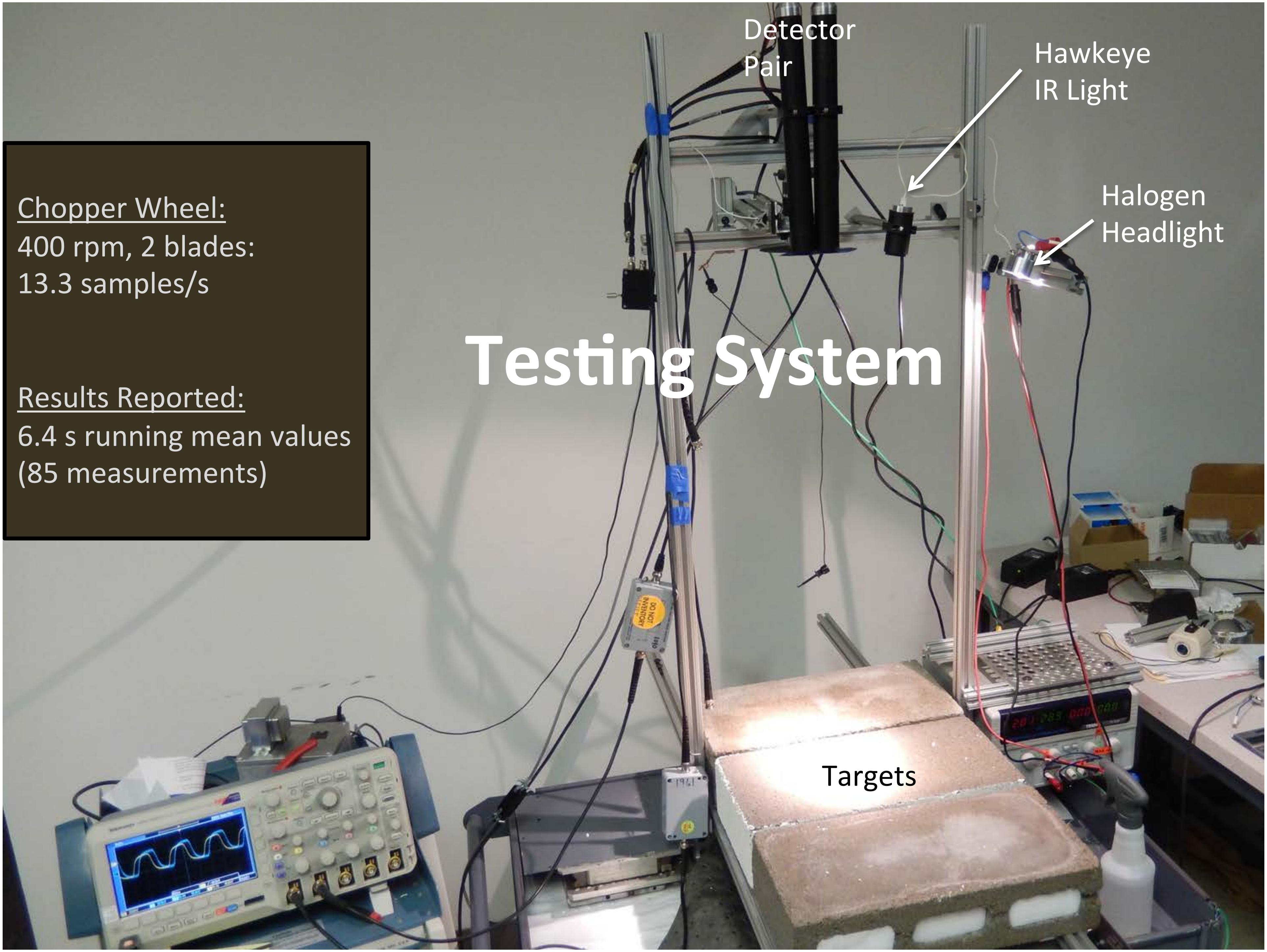




Testing System

Chopper Wheel:
400 rpm, 2 blades:
13.3 samples/s

Results Reported:
6.4 s running mean values
(85 measurements)



A Few Results

PbS Detector Signal (V)
Halogen Bulb: LumenFlow Reflector

10 V, 1.57 A Placed about 30° from the vertical

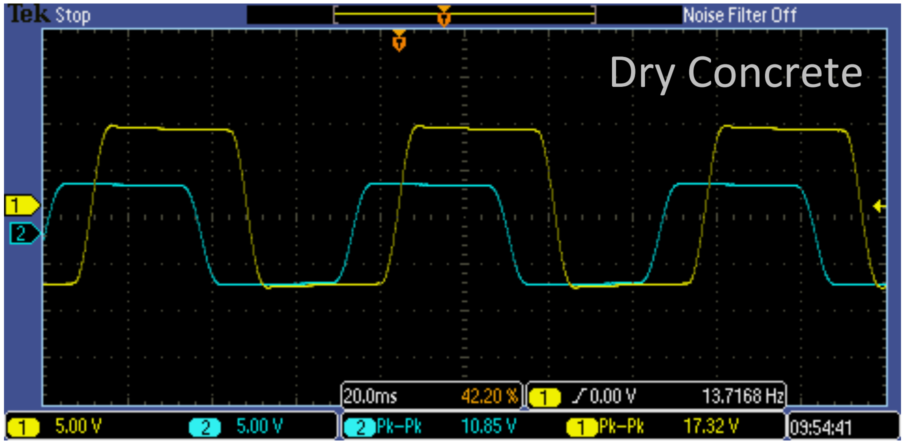
06/19/15

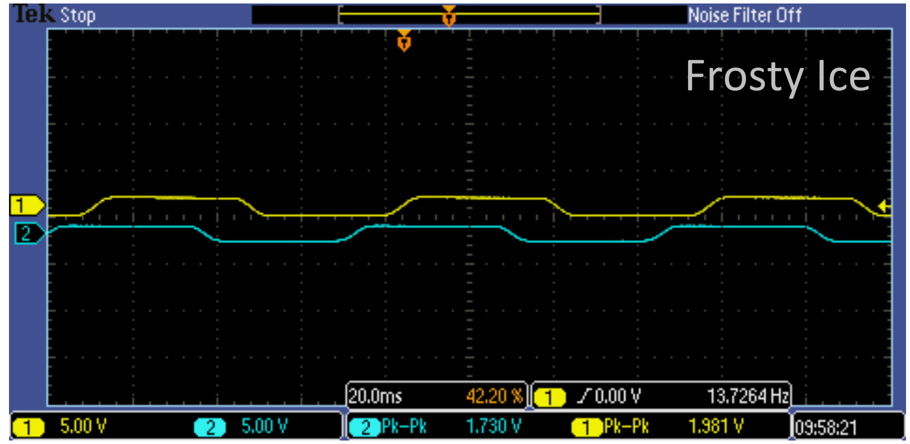
	1. Blue (V)	2. Maize (V)	R_1/R_2
Dry	10.85	17.32	0.63
Wet	5.972	9.700	0.62
Water	2.167	3.543	0.61
Frosty Concrete	1.730	1.981	0.87
Black Ice –Smooth	1.349	1.202	1.12

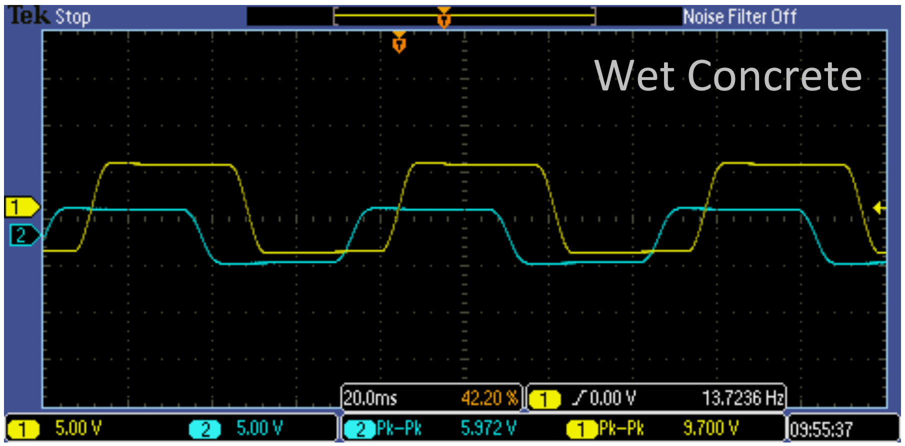
400 rpm
1.2 m from target

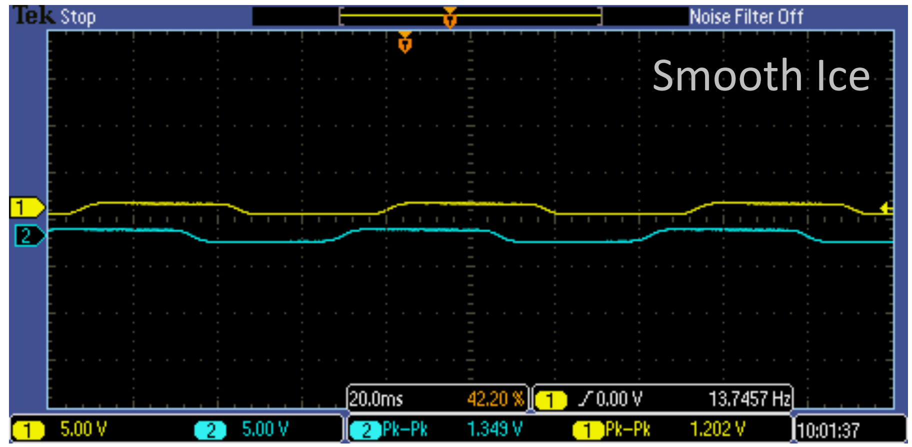
1. Blue Channel = 0.624 μm
2. Maize Channel = 0.450 μm

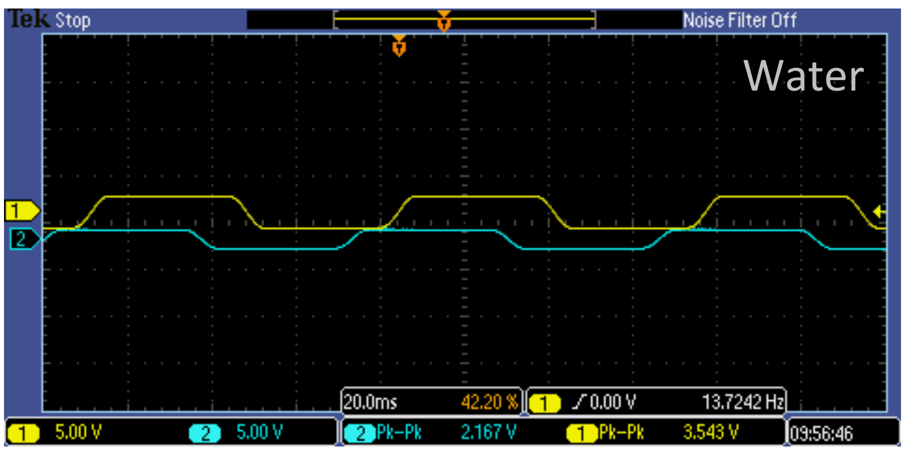
As expected water is bluer than ice.


Tek Stop
Noise Filter Off
Dry Concrete
20.0ms 42.20 %
1 0.00 V 13.7168 Hz
1 5.00 V
2 5.00 V
2 Pk-Pk 10.85 V
1 Pk-Pk 17.32 V
09:54:41


Tek Stop
Noise Filter Off
Frosty Ice
20.0ms 42.20 %
1 0.00 V 13.7264 Hz
1 5.00 V
2 5.00 V
2 Pk-Pk 1.730 V
1 Pk-Pk 1.981 V
09:58:21


Tek Stop
Noise Filter Off
Wet Concrete
20.0ms 42.20 %
1 0.00 V 13.7236 Hz
1 5.00 V
2 5.00 V
2 Pk-Pk 5.972 V
1 Pk-Pk 9.700 V
09:55:37


Tek Stop
Noise Filter Off
Smooth Ice
20.0ms 42.20 %
1 0.00 V 13.7457 Hz
1 5.00 V
2 5.00 V
2 Pk-Pk 1.349 V
1 Pk-Pk 1.202 V
10:01:37


Tek Stop
Noise Filter Off
Water
20.0ms 42.20 %
1 0.00 V 13.7242 Hz
1 5.00 V
2 5.00 V
2 Pk-Pk 2.167 V
1 Pk-Pk 3.543 V
09:56:46

PbS Detector Signal (V)
Halogen Bulb: LumenFlow Reflector

19 V, 2.23 A Placed about 30° from the vertical

06/19/15

	1. Blue (V)	2. Maize (V)	R_1/R_2
Dry	Sat	Sat	---
Wet	14.26	21.28	0.67
Water	5.045	6.991	0.72
Frosty Concrete	4.952	5.176	0.96
Black Ice –Smooth	2.957	2.398	1.23

400 rpm
1.2 m from target

1. Blue Channel = 0.624 µm
2. Maize Channel = 0.450 µm

As expected water is bluer than ice.

PbS Detector Signal (V)
Hawkeye IR Light: Si-217-p-1

24 V, 1.30 A Placed about 10° from the vertical

06/19/15

	1. Blue (V)	2. Maize (V)	R_1/R_2
Dry	3.599	5.816	0.61
Wet	1.850	3.071	0.60
Water	0.710	0.797	0.89
Water Drying	1.925	3.032	0.64
Frosty Concrete	0.645	0.705	0.91
Black Ice –Smooth	0.319	0.248	1.29

400 rpm
1.2 m from target

1. Blue Channel = 0.624 µm
2. Maize Channel = 0.450 µm

As expected water is bluer than ice.

PbS Detector Signal (V)
Halogen Bulb: LumenFlow Reflector

24 V, 2.53 A   Placed about 30° from the vertical

06/19/15

	1. Blue (V)	2. Maize (V)	R_1/R_2
Dry	3.965	5.916	0.67
Wet	2.365	3.326	0.71
Water	0.896	0.562	1.59
Frosty Concrete	0.527	0.640	0.82

400 rpm
1.2 m from target

1. Blue Channel = 1.705 µm
2. Maize Channel = 1.535 µm

As expected water is redder than ice at around 1.6 µm.

PbS Detector Signal (V)
Hawkeye IR Light: Si-217-p-1

Measurements made on June 22, 2015

24 V, 1.23 A   Placed about 10° from the vertical

06/22/15

	1. Blue (V)	2. Maize (V)	R_1/R_2
Dry	0.454	0.269	0.59
Wet	0.252	0.162	0.64
Water	0.174	0.564	3.24
Frosty Concrete	0.116	0.103	0.89
Black Ice –Smooth	0.409	0.238	1.72

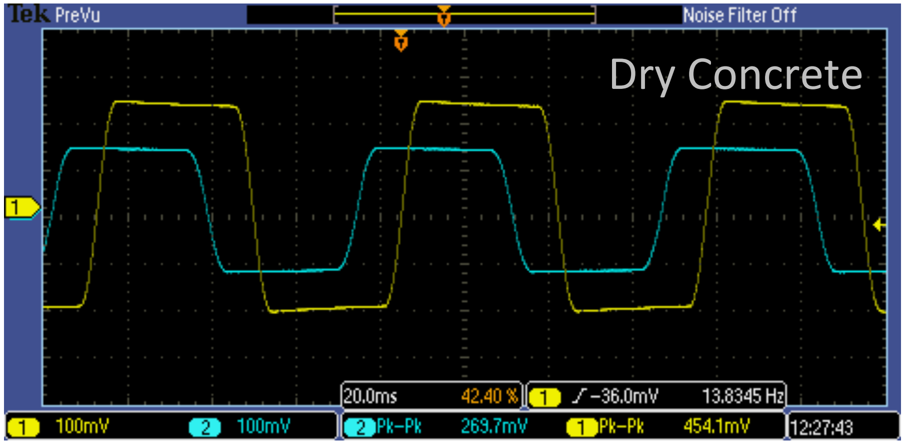
The 2 μm band is the best for detecting water.

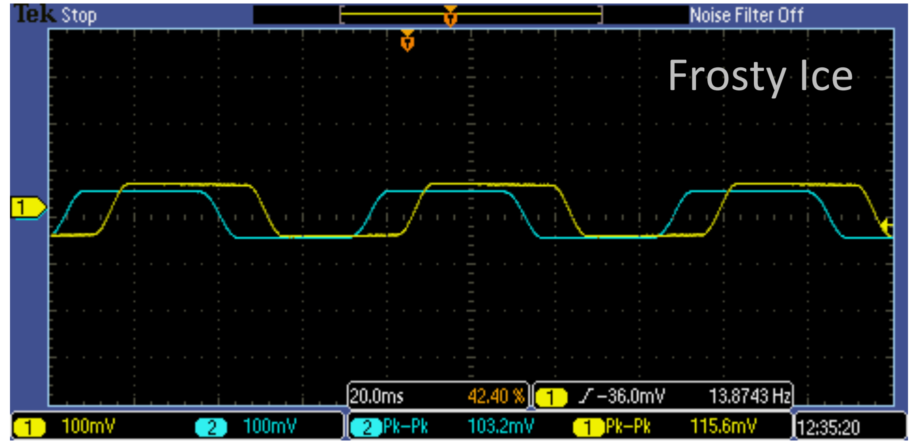
400 rpm
1.2 m from target

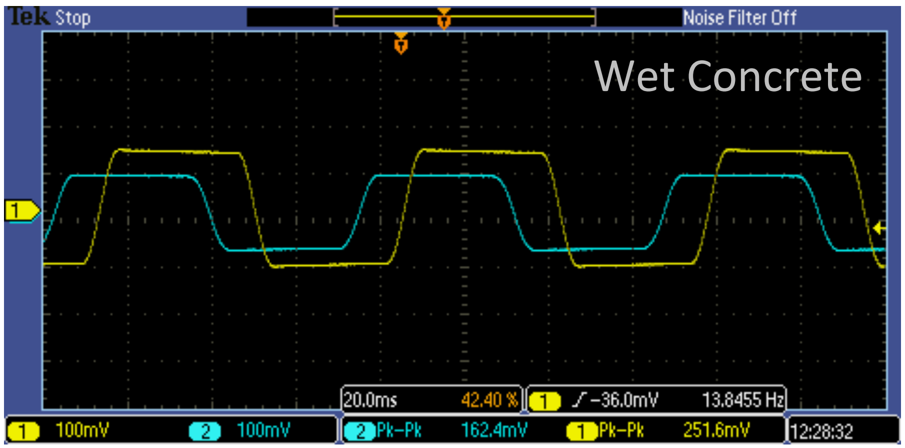
1. Blue Channel = 2.200 μm
2. Maize Channel = 2.090 μm

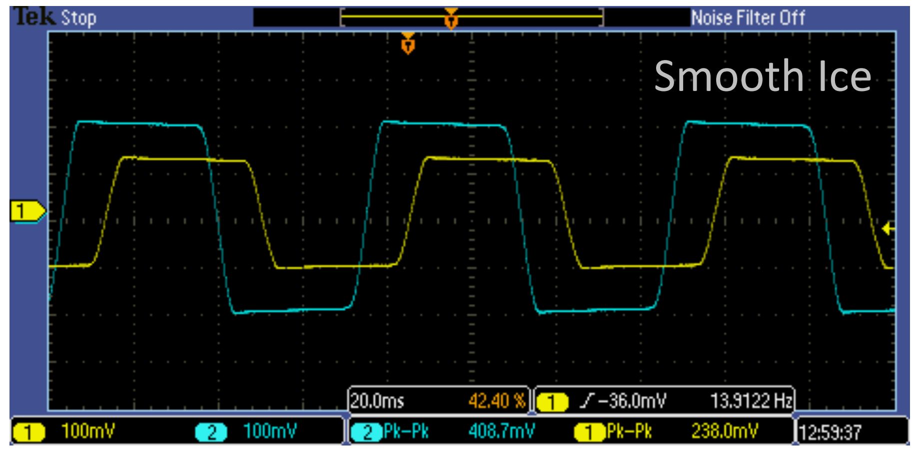
As expected around 2 μm water is redder than ice.

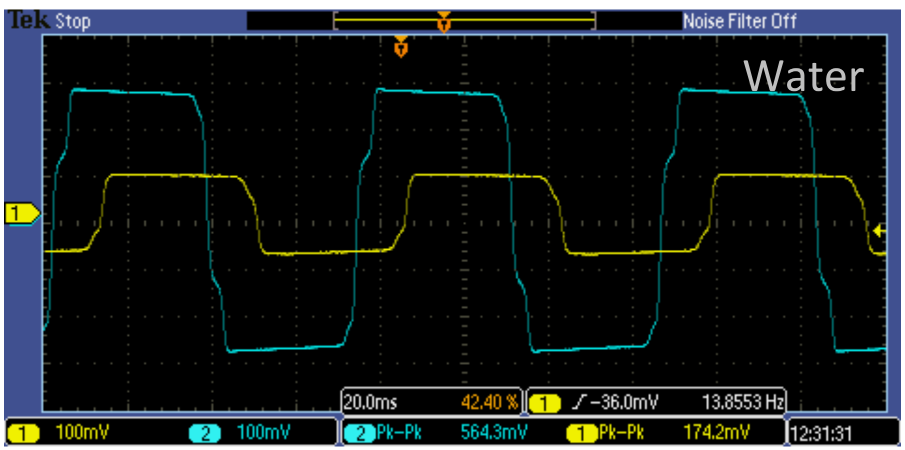
Illumination from the zenith maximizes the results.


Tek PreVu
Noise Filter Off
Dry Concrete
20.0ms 42.40 %
1 ∫ −36.0mV 13.8345 Hz
1 100mV
2 100mV
2 Pk−Pk 269.7mV
1 Pk−Pk 454.1mV
12:27:43


Tek Stop
Noise Filter Off
Frosty Ice
20.0ms 42.40 %
1 ∫ −36.0mV 13.8743 Hz
1 100mV
2 100mV
2 Pk−Pk 103.2mV
1 Pk−Pk 115.6mV
12:35:20


Tek Stop
Noise Filter Off
Wet Concrete
20.0ms 42.40 %
1 ∫ −36.0mV 13.8455 Hz
1 100mV
2 100mV
2 Pk−Pk 162.4mV
1 Pk−Pk 251.6mV
12:28:32


Tek Stop
Noise Filter Off
Smooth Ice
20.0ms 42.40 %
1 ∫ −36.0mV 13.9122 Hz
1 100mV
2 100mV
2 Pk−Pk 408.7mV
1 Pk−Pk 238.0mV
12:59:37


Tek Stop
Noise Filter Off
Water
20.0ms 42.40 %
1 ∫ −36.0mV 13.8553 Hz
1 100mV
2 100mV
2 Pk−Pk 564.3mV
1 Pk−Pk 174.2mV
12:31:31

Ice Detection on Airplane Surfaces

PbS Detector Signal (V)
Halogen Bulb: LumenFlow Reflector

White Polyurethane

7.2 V, 1.32 A   Placed about 30° from the vertical

06/22/15

	1. Blue (V)	2. Maize (V)	R_1/R_2
Dry	22.35	22.48	0.99
Wet	14.04	22.31	0.63
Icy	12.35	18.95	0.65

400 rpm
1.2 m from target

1. Blue Channel = 0.624 µm
2. Maize Channel = 0.450 µm

Water is expected to be bluer than ice.

Measurements made on June 22, 2015

PbS Detector Signal (V)
Halogen Bulb: LumenFlow Reflector

24 V, 2.54 A   Placed about 30° from the vertical

06/22/15

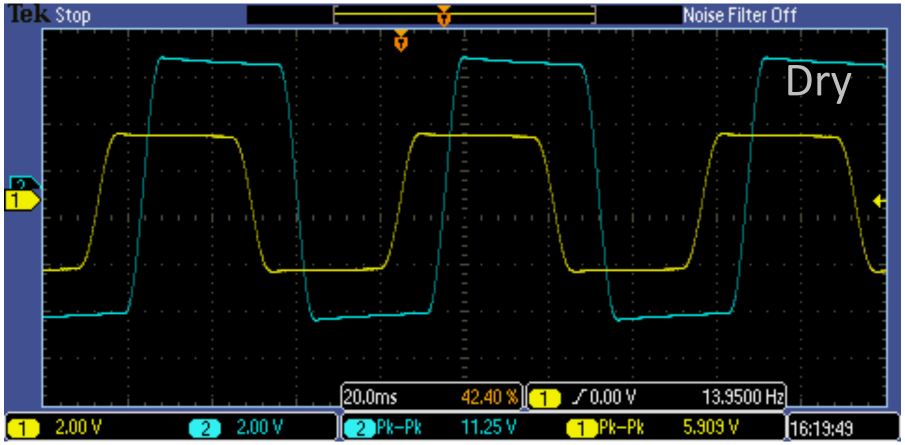
	1. Blue (V)	2. Maize (V)	R_1/R_2
Dry	11.250	5.909	1.90
Wet	5.058	2.852	1.77
Icy	2.307	3.331	0.69

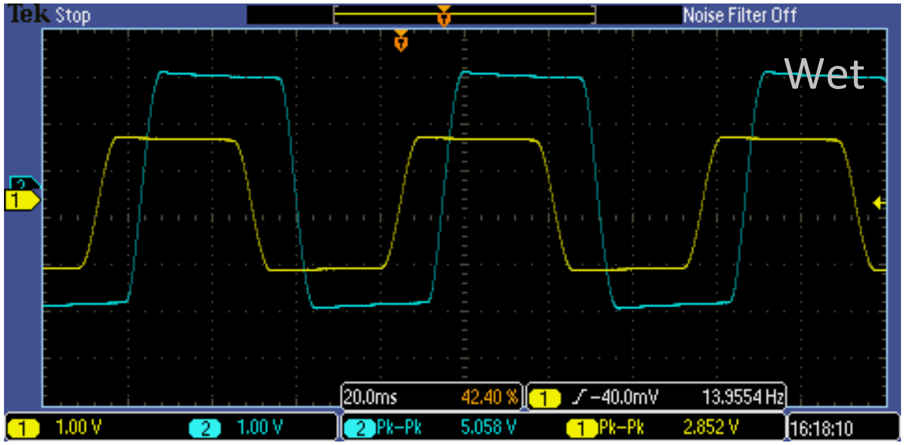
400 rpm
1.2 m from target

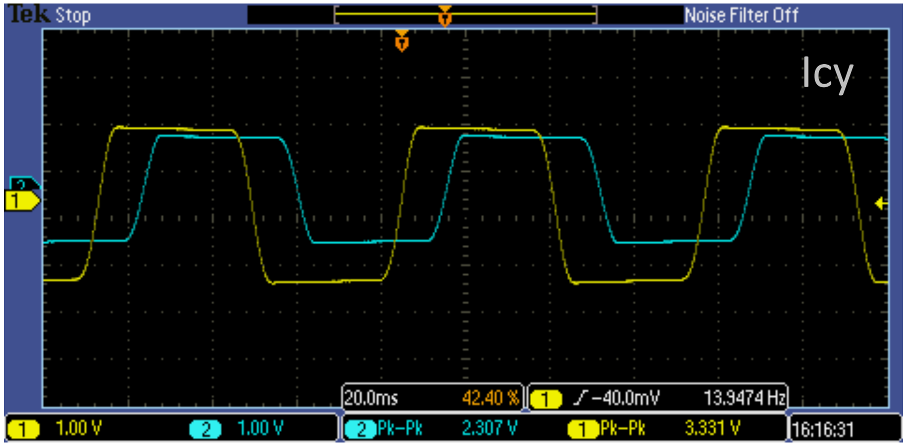
1. Blue Channel = 2.200 µm
2. Maize Channel = 2.090 µm

Measurements made on June 22, 2015

As expected water is redder than ice around 2 µm.


Tek Stop
Noise Filter Off
Dry
20.0ms 42.40 %
1 0.00 V 13.9500 Hz
1 2.00 V
2 2.00 V
2 Pk-Pk 11.25 V
1 Pk-Pk 5.909 V
16:19:49


Tek Stop
Noise Filter Off
Wet
20.0ms 42.40 %
1 −40.0mV 13.9554 Hz
1 1.00 V
2 1.00 V
2 Pk-Pk 5.058 V
1 Pk-Pk 2.852 V
16:18:10


Tek Stop
Noise Filter Off
Icy
20.0ms 42.40 %
1 −40.0mV 13.9474 Hz
1 1.00 V
2 1.00 V
2 Pk-Pk 2.307 V
1 Pk-Pk 3.331 V
16:16:31

2M Thermopile Signal (mV)
Halogen Bulb: LumenFlow Reflector

White Polyurethane

28.9 V, 2.81 A   Placed about 30° from the vertical

06/22/15

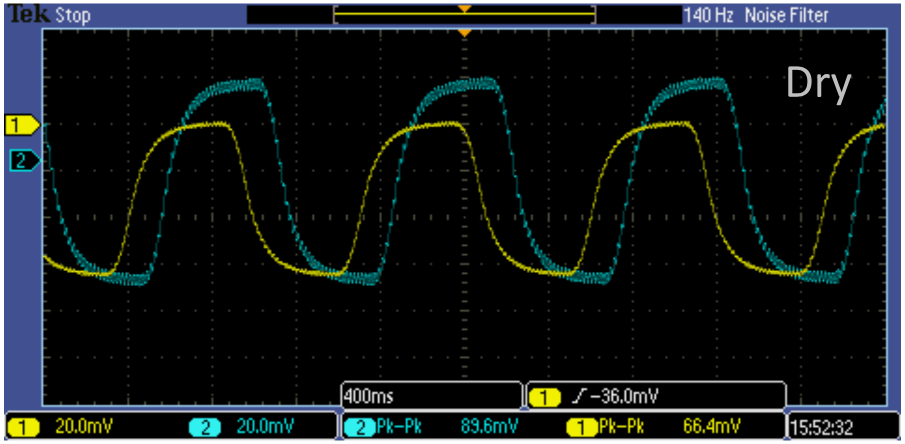
	1. Blue (mV)	2. Maize (mV)	R_1/R_2
Dry	89.6	66.4	1.35
Wet	58.4	49.6	1.18
Icy	16.8	30.4	0.55

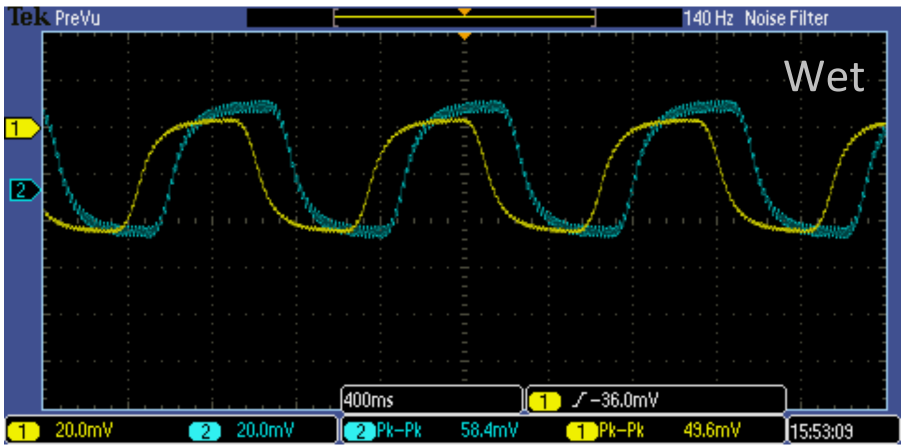
400 rpm
1.2 m from target

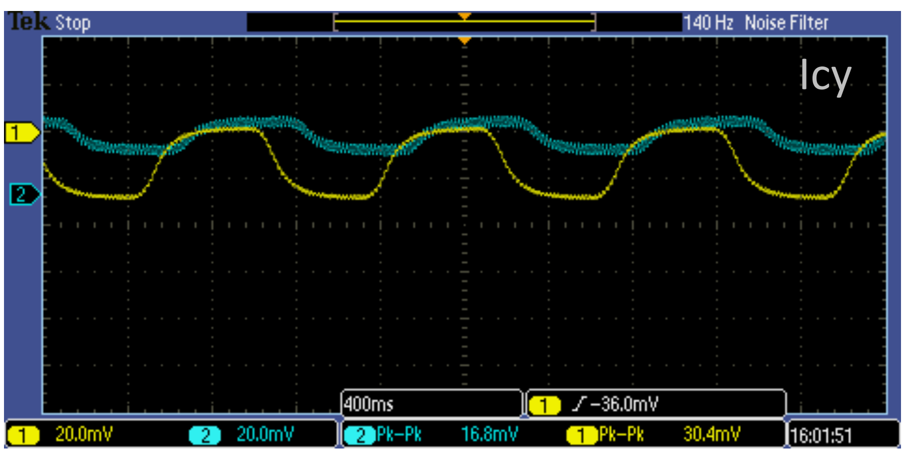
1. Blue Channel = 2.200 µm
2. Maize Channel = 2.090 µm

As expected, around 2 µm water is redder than ice.

Measurements made on June 22, 2015


Tek Stop
140 Hz Noise Filter
Dry
400ms
1 -36.0mV
1 20.0mV
2 20.0mV
2 Pk-Pk 89.6mV
1 Pk-Pk 66.4mV
15:52:32


Tek PreVu
140 Hz Noise Filter
Wet
400ms
1 -36.0mV
1 20.0mV
2 20.0mV
2 Pk-Pk 58.4mV
1 Pk-Pk 49.6mV
15:53:09


Tek Stop
140 Hz Noise Filter
Icy
400ms
1 -36.0mV
1 20.0mV
2 20.0mV
2 Pk-Pk 16.8mV
1 Pk-Pk 30.4mV
16:01:51

Concluding Remarks

- **The new technologies that we have been maturing**
  - Have the potential to detect if an airplane is flying within the icing certification envelops
  - Comply with regulations (14 CFR part 25, Appendices C and O)
  - Could lead to reducing in fuel consumption
  - Could increase thrust available during critical flight phases

- **Immediate icing detection can**
  - Alert pilots **when conditions outside the icing certification envelope are encountered**
  - Help pilots mitigate the negative effects of automation

- **What is the best way to work together?**
  - On technology maturation
  - On prototype development (legacy companies have expressed interest in the technology)

Thanks!