National Aeronautics and Space Administration

Update on the NASA Glenn Propulsion Systems Lab Ice Crystal Cloud Characterization (2015, 2016)

Judith Van Zante, Timothy Bencic, Thomas Ratvasky

Presented by: Judy Van Zante

NASA Glenn Research Center

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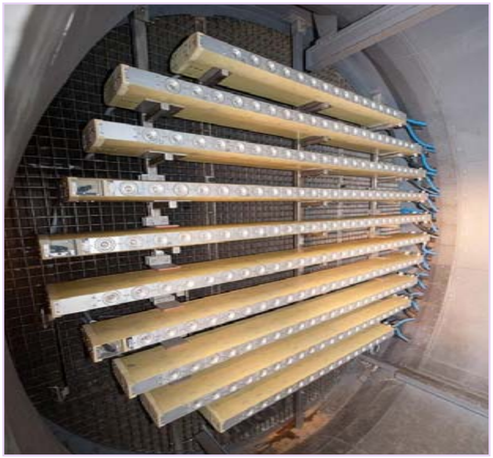
PSL Icing Session

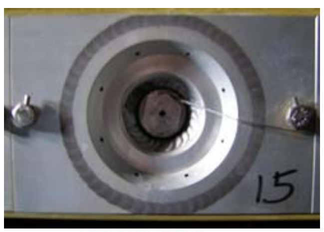
Time	Topic	Presenter
2:00 PM	Turbofan Ice Crystal Rollback Investigation and Preparations Leading to the Second, Heavily Instrumented, Ice Crystal Engine Test at NASA PSL-3 Test Facility	R. Goodwin
2:30 PM	Determination of engine recovery after an ice accretion rollback, engine performance deterioration and health monitoring using minimal instrumentation during icing testing at NASA Glenn PSL-3	D. Walker
3:00 PM	Preliminary Results from a Heavily Instrumented Engine Ice Crystal Icing Test in a Ground Based Altitude Test Facility	A. Flegel
3:30 PM	Modeling of Highly Instrumented Honeywell Turbofan Engine Tested with Ice Crystal Ingestion in the NASA PSL	J. Veres
4:00 PM	Test Point Selection for Engine Crystal Icing Test at NASA PSL-3 for focused sensitivity, peak intensity, and anti-ice evaluations	D. Dischinger
PM	NASA Glenn Propulsion Systems Lab Ice Crystal Cloud Characterization Update (2015)	J. Van Zante
5:00 PM	Aircraft engine icing instrumentation used in the NASA Glenn Propulsion Systems Laboratory	T. Bencic

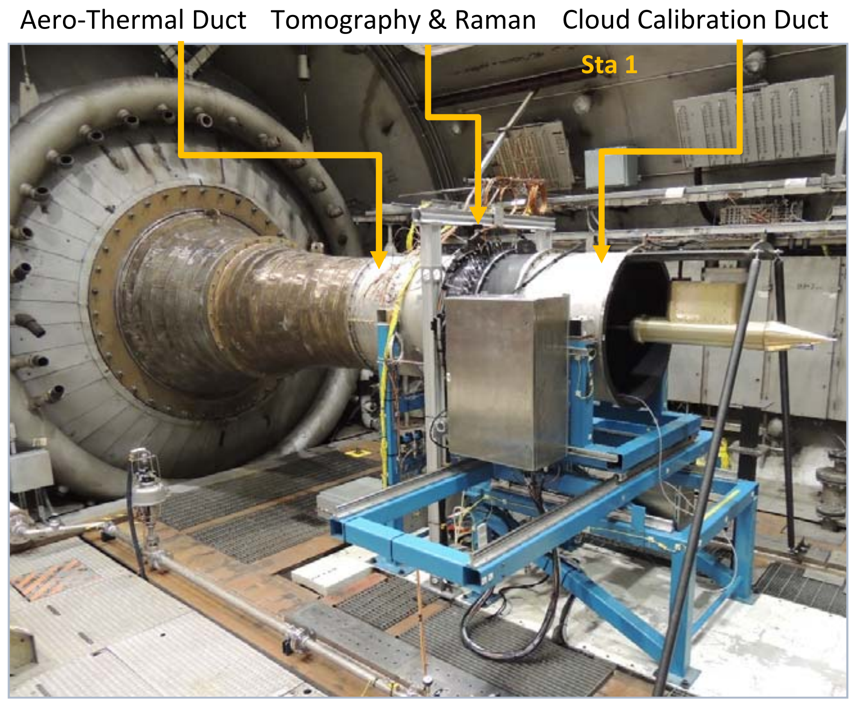
Outline

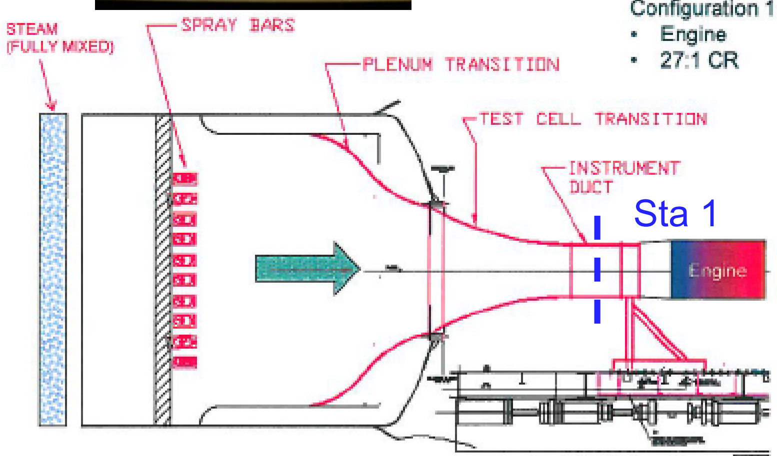
- Facility Description
- Cloud Characterization Parameter Space
- Aspects Characterized
- Conclusions

PSL Facility

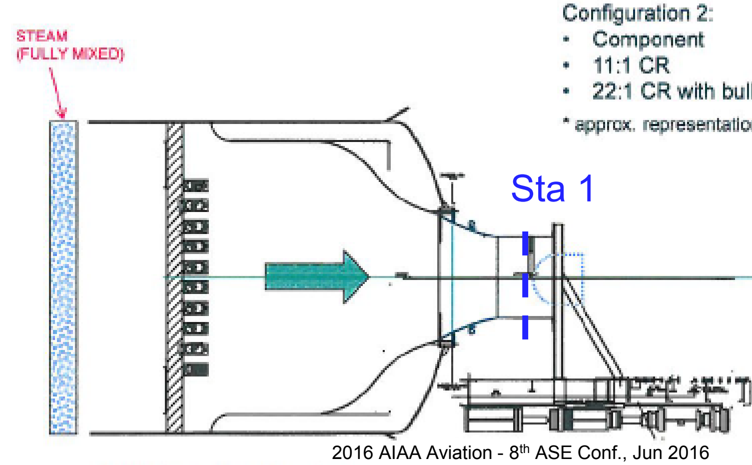








Configuration 1:
- Engine
- 27:1 CR



Configuration 2:
- Component
- 11:1 CR
- 22:1 CR with bullet nose*

* approx. representation

Modification upstream of spraybars

PSL Parameter Space

Airflow Conditions

- (Duct Geometry)
- Pressure Altitude, *P0*
- Mach, Air Mass Flow Rate, *Wa*
- Temperature, *TPL*
- Relative Humidity, *RHPL*

PSL is Isentropic & Adiabatic

Spray Conditions

- Nozzle Type & #: Mod1, Std
- Water Pressure, *Pwat*
- Air Pressure, *Pair*
- Air/Water Temp, *Tair, Twat*
- Water Source: City, DI
- Spraybar Cooling Air and Pressure

Physics of the Process:

- Liquid water issues from the spraybars.
- Water particles immediately start to evaporate.
- Particles start to chill/freeze as they travel through the plenum and into the contraction.
- The vapor …

Setting Conditions

Customer Provides

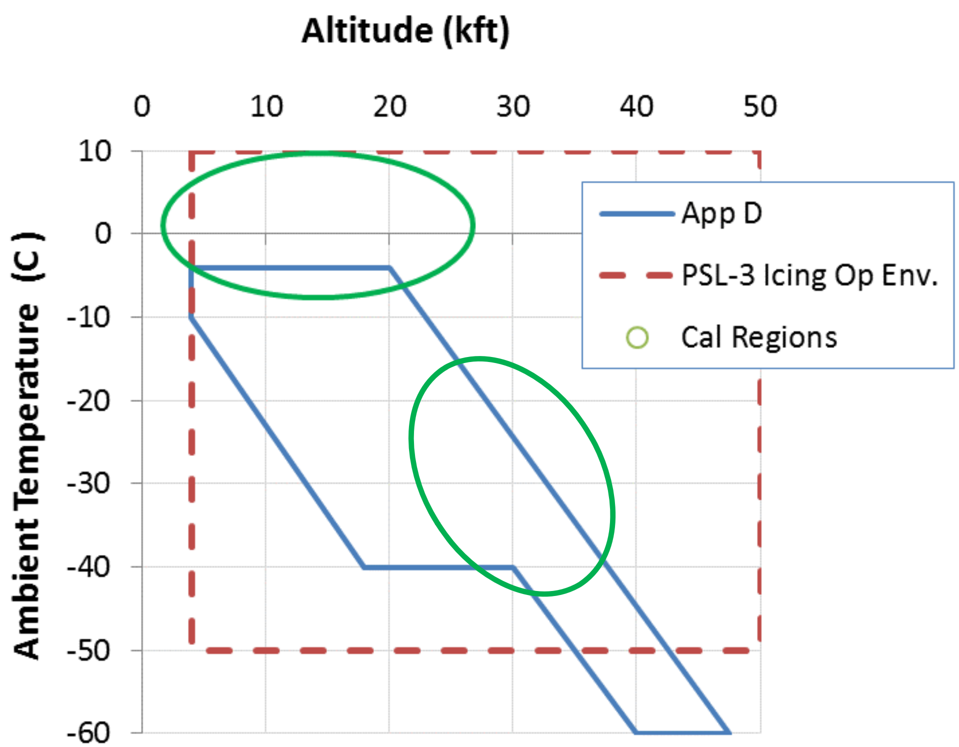
Ranges at Plane of Interest (inlet to Fan or Booster):

- Ps, static pressure
- Ts, static temperature
- Mach
- Altitude
- TWC, Total Water Content
- MVD (Particle Size)

NASA Actions

- Calculate Wa to set Facility Conditions
- Characterize Spray Conditions
- Phase of particles at Sta 1 primarily a function of wet bulb Temp, Twb. New model to predict (T. Bartkus).

PSL Cloud Characterization Envelops



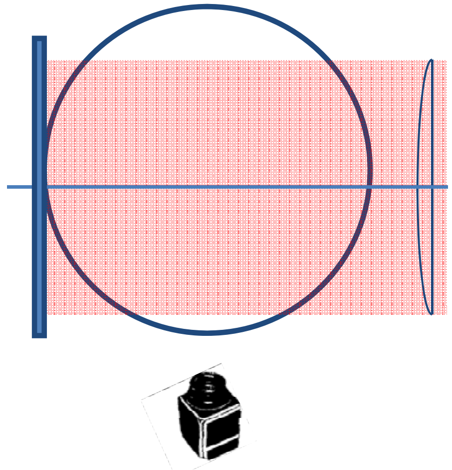
Two regions of conditions simulated

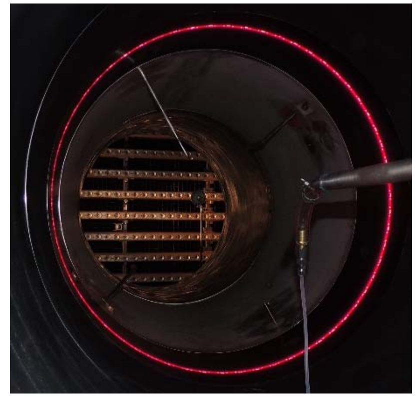
- Engine Fan Face
  (Honeywell Engine Tests LF01 & LF11)
- Aft of Fan / Inside Booster
  (Fundamental Ice Crystal Icing Study, Struk et. al)

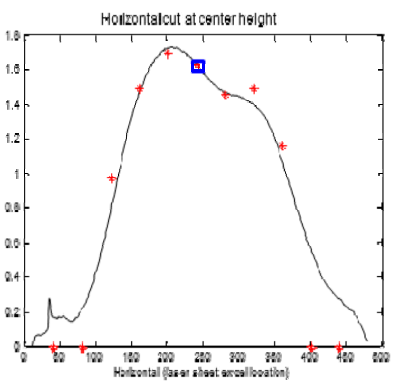
PSL Cloud Characterization Process

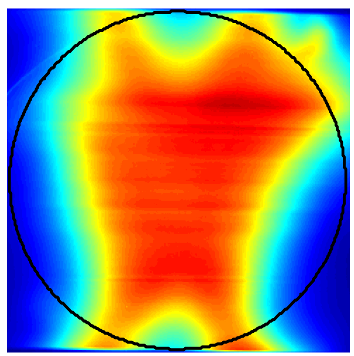
- Cloud Uniformity
- Total Water Content
  - Measurements in Center
  - Bulk average in Cross-Section
- Particle Size
- Particle Phase and Temperature - *T. Bencic will cover next talk*.

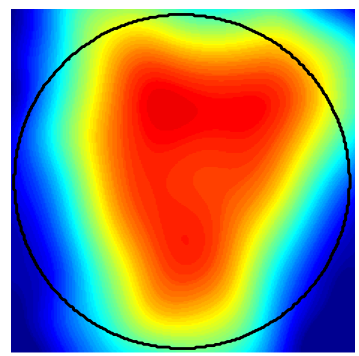
Cloud Uniformity











Grid

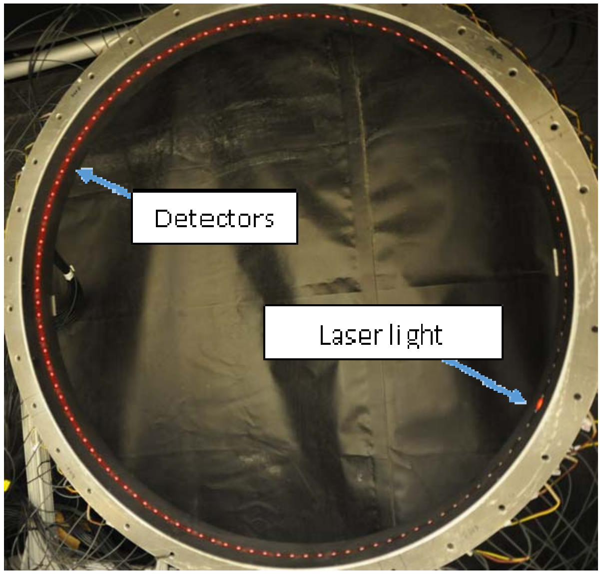
Laser Sheet

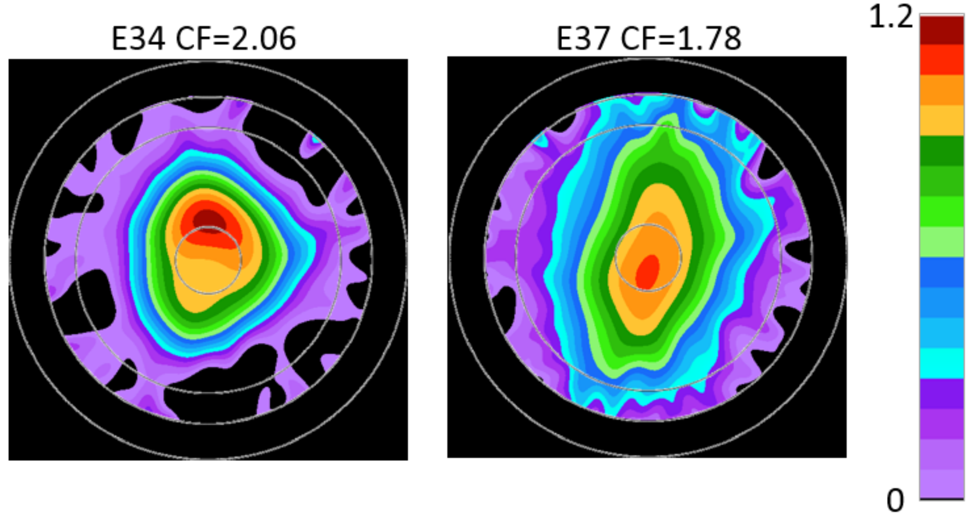
Tomography

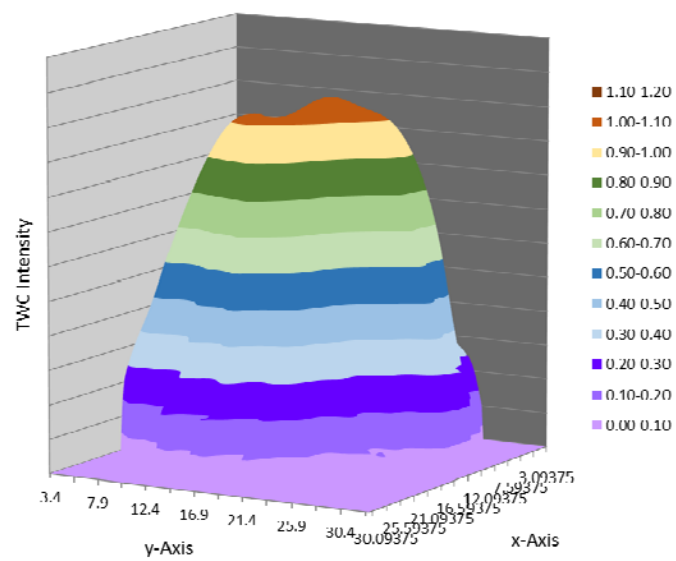
AIAA's
2014 Van Zante &
2015 Bencic et.al:
Good agreement between these three methods.

Tomography is the diagnostic of choice.

Tomography – near real-time monitoring





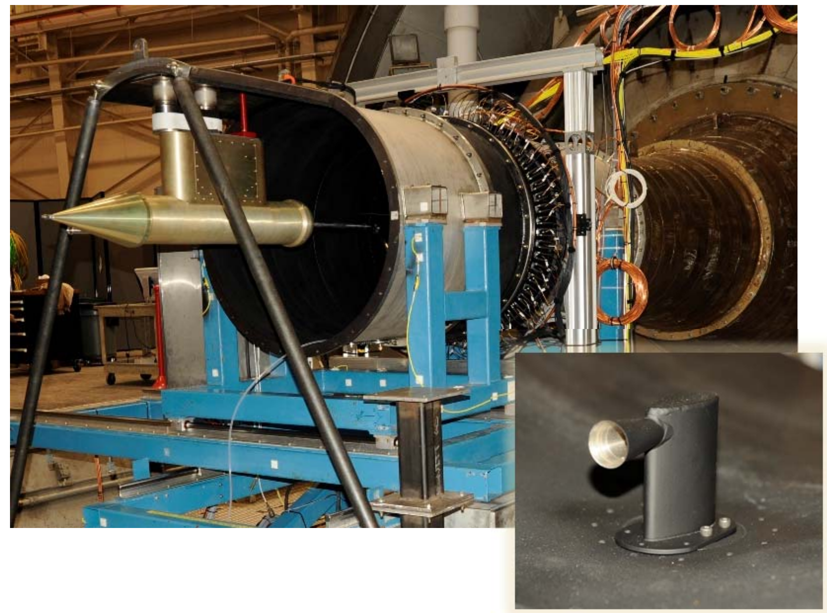


Procedure:

- Measure light extinction with cloud OFF (baseline)
- Measure light extinction with cloud ON (extinction due to size and number of particles)
- Intensity Ratio, I_{ij}, output at every 'pixel' (i, j)
- Calculate avg Intensity Ratio over 1x1-in Center, I_{00}
- Calculate Concentration Factor, CF, $I_{00}/\sum I_{ij}$

Total Water Content: Measurements

SEA, Inc.



Multi-Wire (MW)

Robust Probe (RP)

Iso-Kinetic Probe (IKP2)

All measurements at Duct Center, TWC_{00}

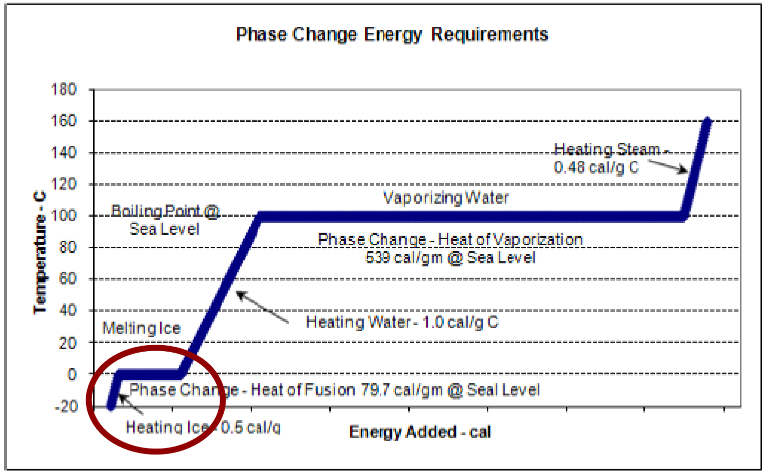
MW and RP Notes

- Meas. power to evap. impinging water
- Minimize flow angularity into MW head
- Correct for Collection (Collision) Efficiency, MW only. Effects of particle bouncing, splashing not accounted for.
- Track default TWC (100% liquid)
- Added iWC (100% ice crystal)

$$TWC = \frac{K * P_{wet}}{\left[C_{liq}\left(T_{evap} - T_{amb}\right) + L_{evap}\right] * VTAS * L * W}$$

$$iWC = \frac{K * Pe_{wet}}{\left[C_{ice}(T_0 - T_{amb}) + L_{fus} + C_{liq}\left(T_{evap} - T_{amb}\right) + L_{evap}\right] * VTAS * L * W}$$

- iWC / TWC ~ 0.88

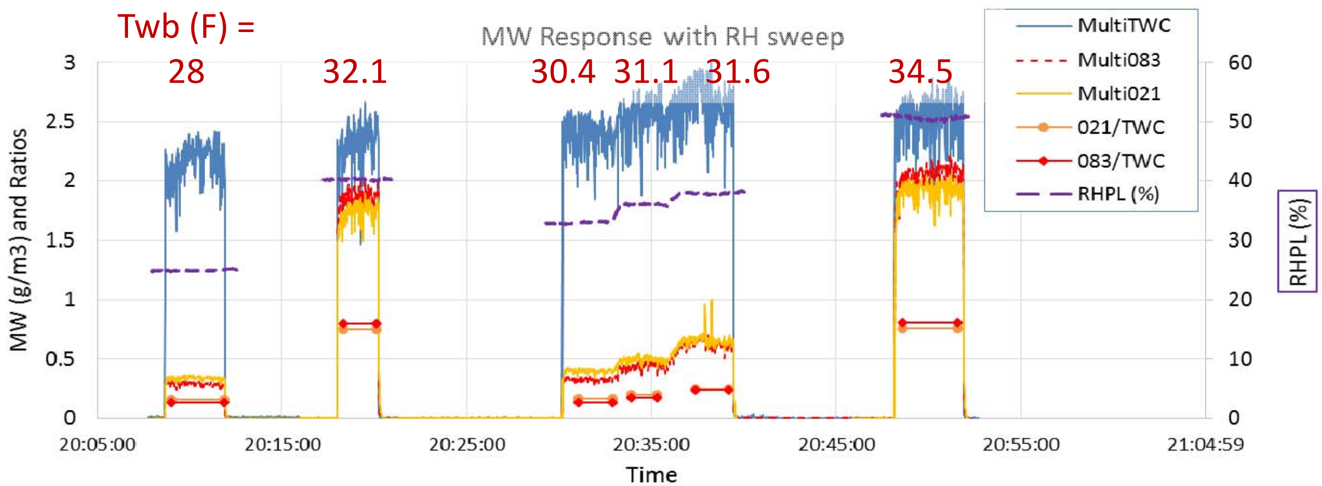


SEA, Inc. WCM-2000 User's Manual

IKP Notes

- Iso-kinetically ingests air and cloud particles (no gain or loss of mass)
- Evaporates all cloud particles, regardless of phase; measures total water vapor
- Independent measure of background water vapor is subtracted so that only Ice + Liquid phases are calculated.
- At PSL, several sources of water vapor measurements at Sta 1. Largest correction applied.
- At PSL, a radial profile of water vapor was observed (Fundamental Ice Crystal Icing Study, P. Struk, 3/2016)

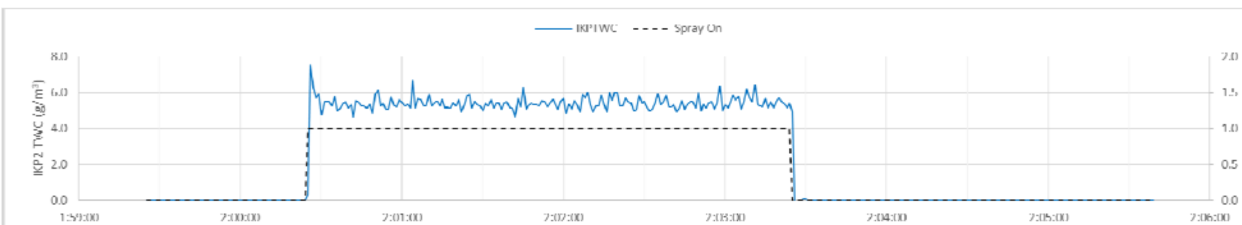
Sample TWC time traces



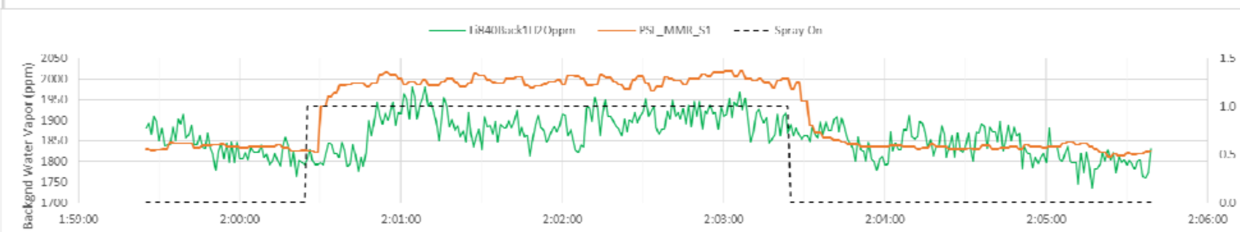
MW

RHPL Sweep

& Melt Ratio



IKP2



RHS1

Total Water Content: Bulk_Water Flow

Simple Calculation based on injected Water Flow Rate, *Wf*, Air Mass Flow Rate, *Wa*, and Sta 1 statics. Constant *C* includes density of water. Assume uniform distribution across Sta 1 Duct.

$$Wf\ (gal/min) = \#Noz * Cfn * \sqrt{(DeltaP)}$$

$$TWC\_Wf\ (g/m^3) = C * Wf * Ps1 / (Wa * Ts1)$$

If add a cloud Displacement or Boundary Layer thickness δ

$$TWC\_Wf\_BL\ (g/m^3) = C * Wf * Ps1 / (Wa * ((R-\delta)/R))^2 * Ts1)$$

TWC_Wf is the *basis function* for TWC measurements

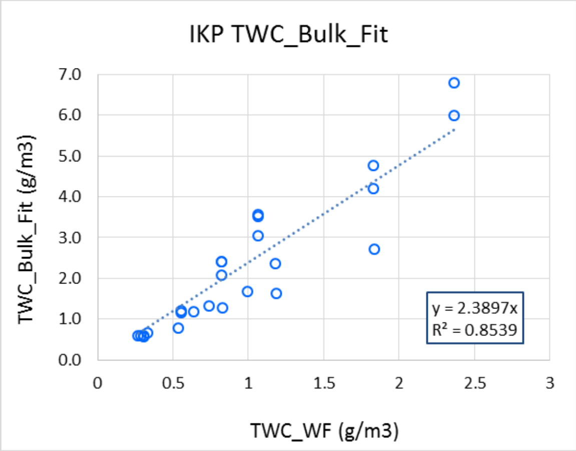
TWC_Wf_BL was recommended for LF01 and LF11 Tests

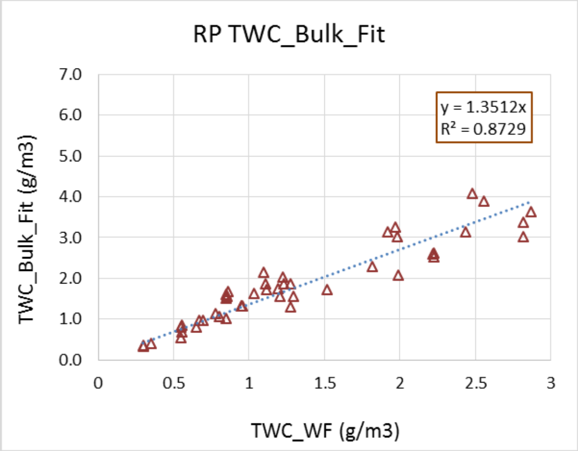
Total Water Content: Bulk_Meas

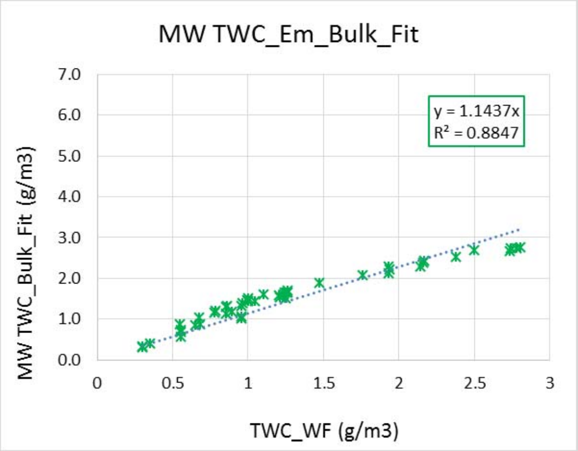
- Combine Measured TWC_{00} and Tomography CF.

$$TWC\_Bulk\_Meas\ (g/m^3) = \sum (I_{ij} * (TWC_{00}/I_{00}) * A_{ij}) / \sum A_{ij}$$

- Created a CF curve fit based upon Pair and TWC_Wf, TWC_Bulk_Fit

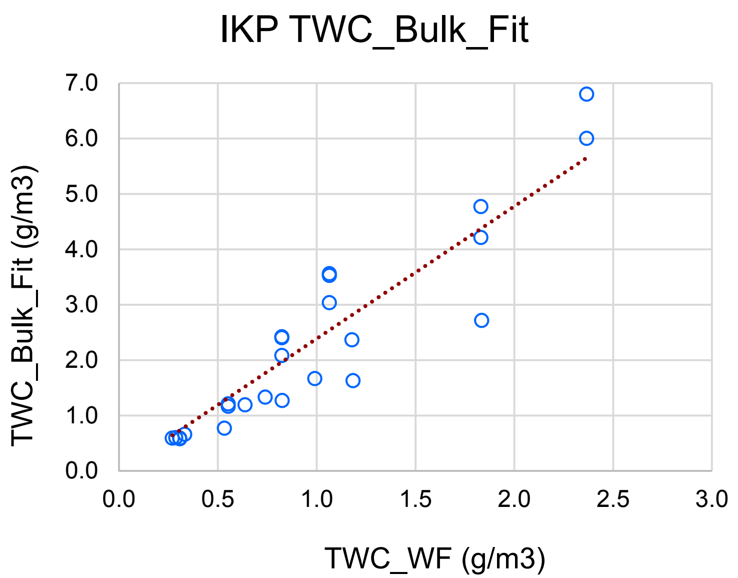


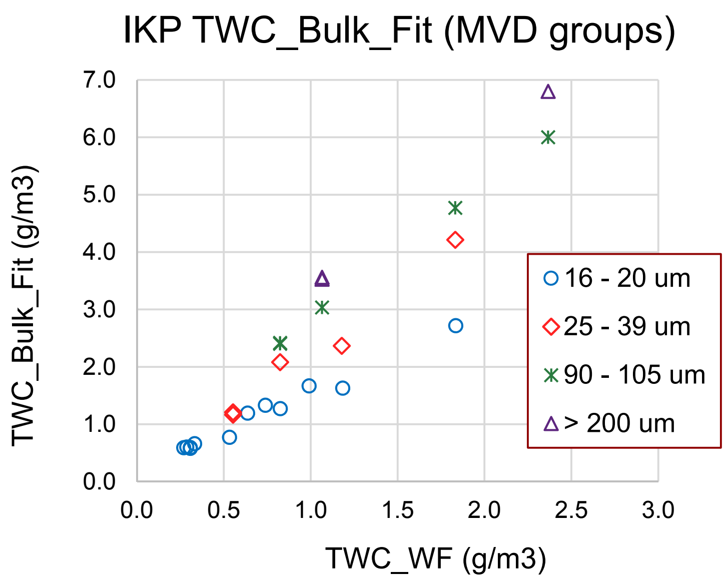




TWC & radial distribution of particle size

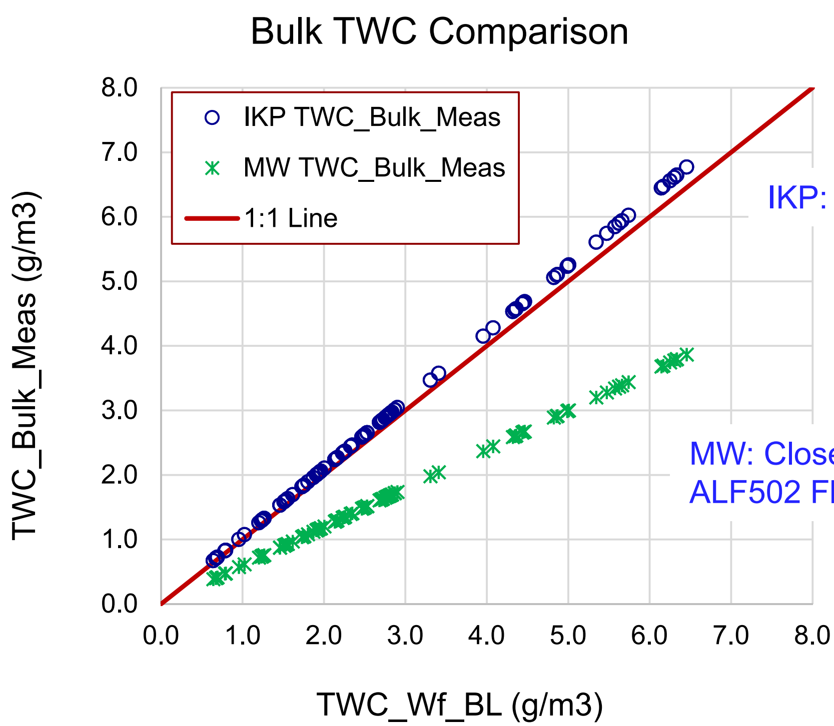
- Scatter in data due to radial MVD effect. CFD predicts larger particles concentrated at center, while smaller particles more uniformly distributed.
- This radial MVD profile is *not* currently incorporated into the tomography intensity ratios.





TWC Bulk Comparison

IKP + Tomography ≈ Water Flow + Boundary Layer
Bulk TWC Bulk TWC
TWC_Bulk_Meas TWC_Wf_BL



Used in LF01 and LF11

With the same boundary layer thickness assumption, and same basis formulation, TWC_Wf

IKP: Closer to “true” TWC

MW: Closest link to 1998 ALF502 Flight Campaign

Particle Size: Measurements

DMT, Inc.

Cloud Droplet Probe

(CDP)

Refracted + Diffracted Light

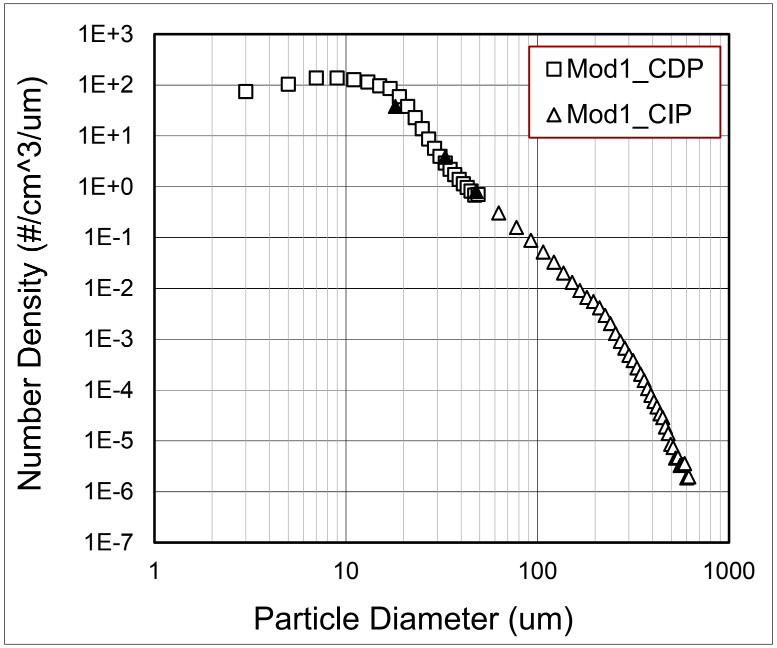
Cloud Imaging Probe

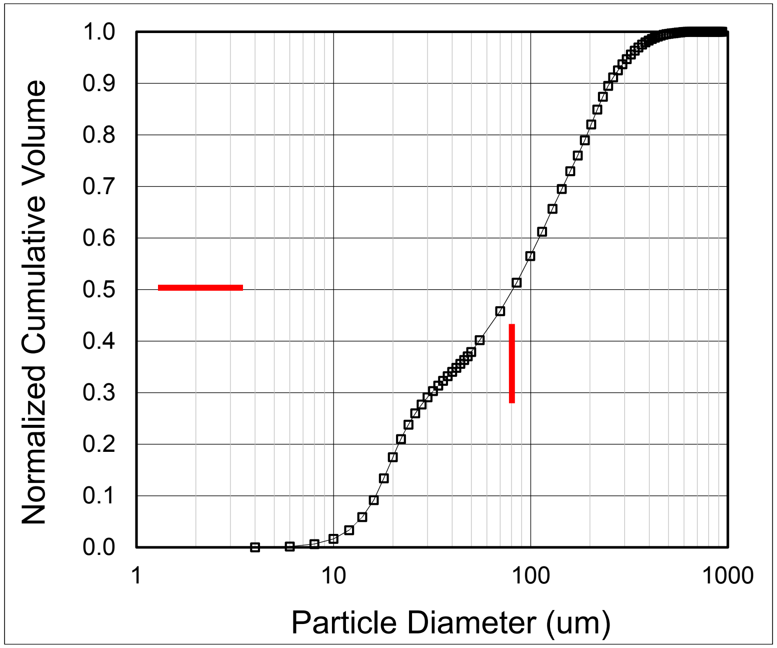
(CIP-GS)

Shadowing

All measurements at Duct Center.
Future ability to shift off-center

CDP + CIP Particle Size Distributions

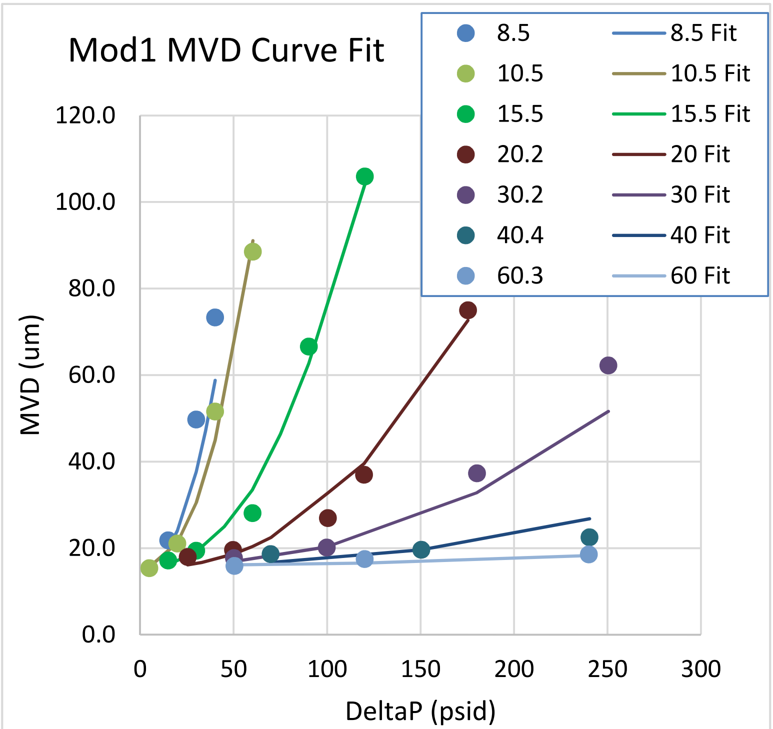


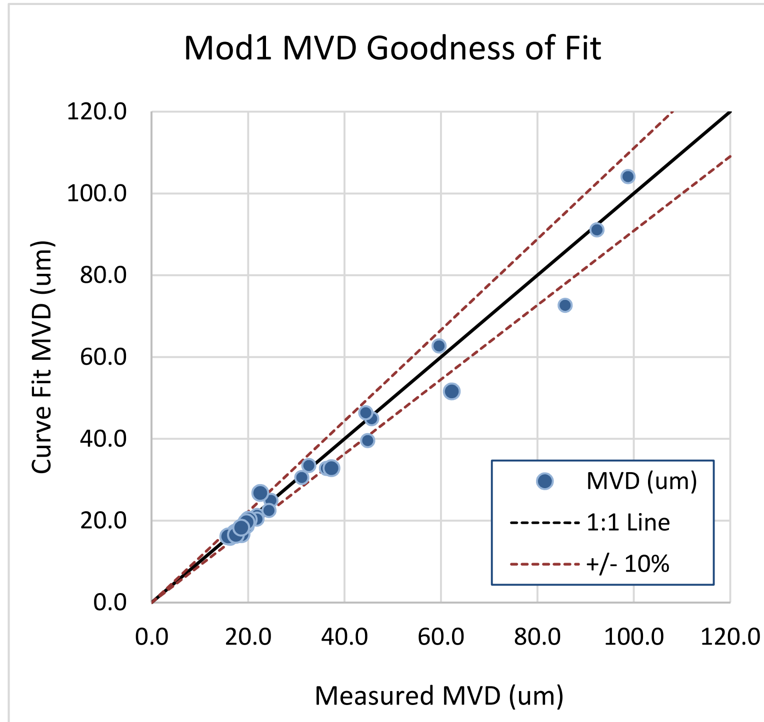


Sample PSD: For the CDP survey, Tair, Twat & TPL were 'warm'. For the CIP survey, Tair, Twat & TPL were at test conditions, 'cold'. Same Alt, Mach and RHPL.

Pair = 20 psid, DeltaP = 175 psid; MVD = 80 um

Mod-1 MVD Curve Fit

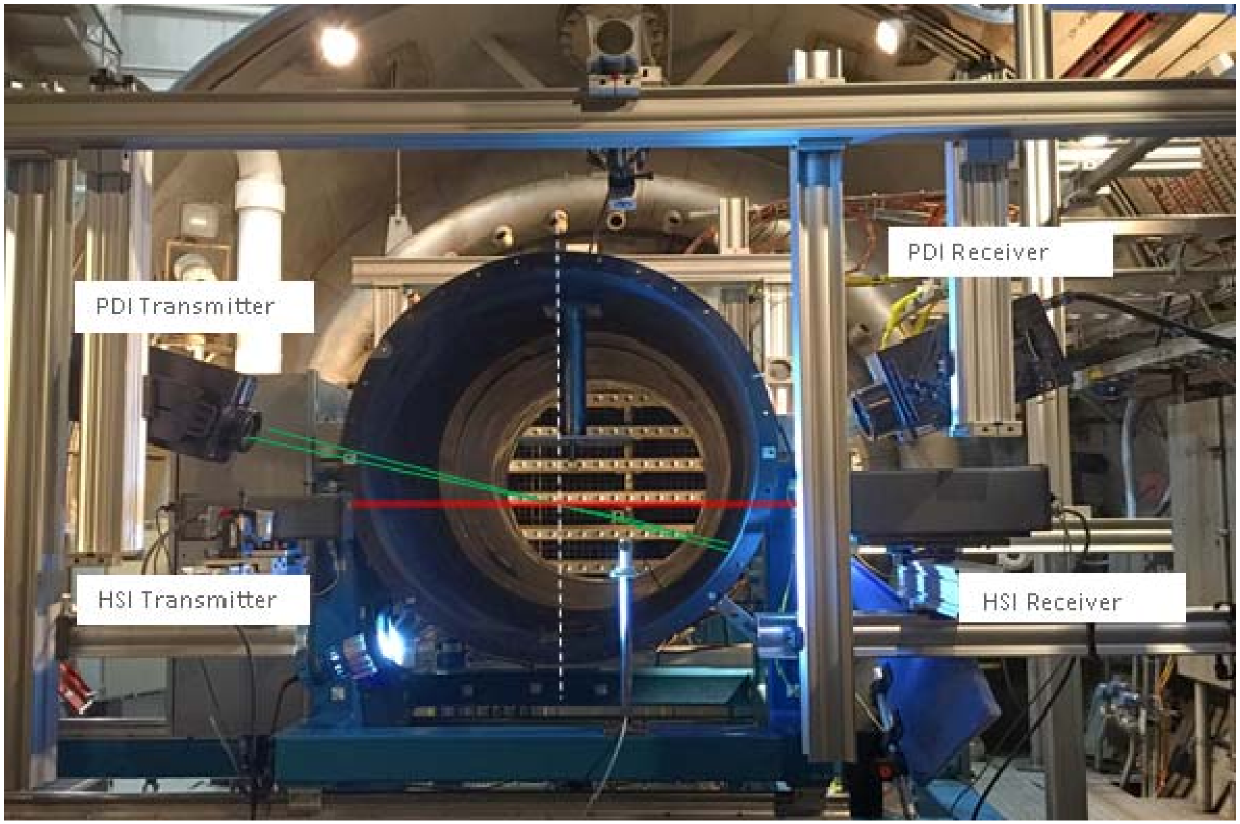




For LF11 MVD sweeps: Given a Pair line, increase DeltaP. This "guarantees" an increase in MVD, even if exact values are not known.

Additional PSD Measurements

Artium, Inc.

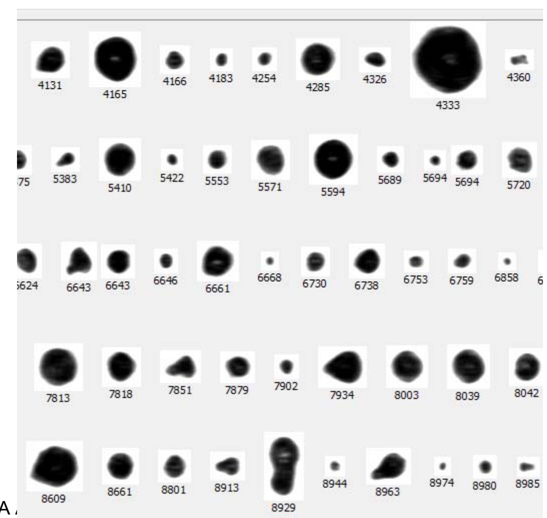


Phase Doppler Interferometer PDI

- Particle size (liquid only)
- Particle velocity
- Number density
- LWC

High Speed Imager HSI

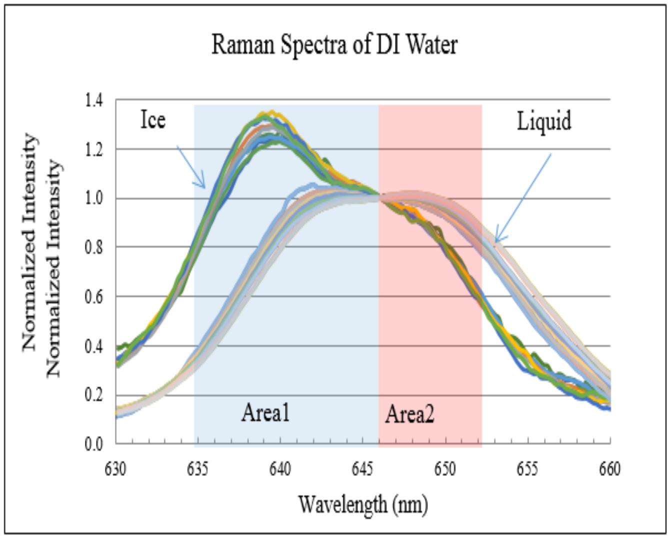
- Particle size (ice & liquid)
- Shape
- Number density
- TWC

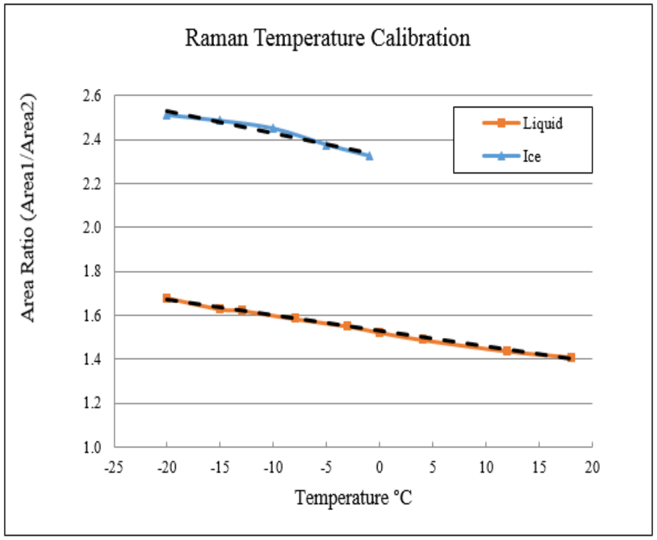


Both PDI and HSI are non-intrusive.
Have taken data in two most recent efforts
at center and off-center. Will be reported in future.

Particle Phase and Temperature

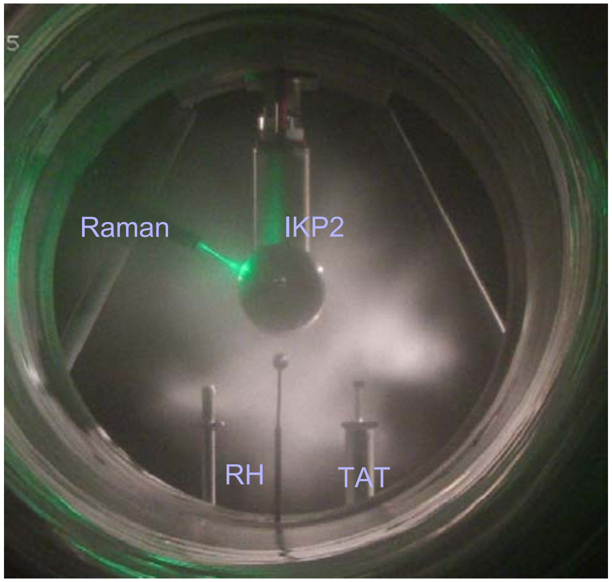
- Raman Spectra can evaluate bonded structure of water in both liquid and solid phases, as well as temperature.
- Benchtop success

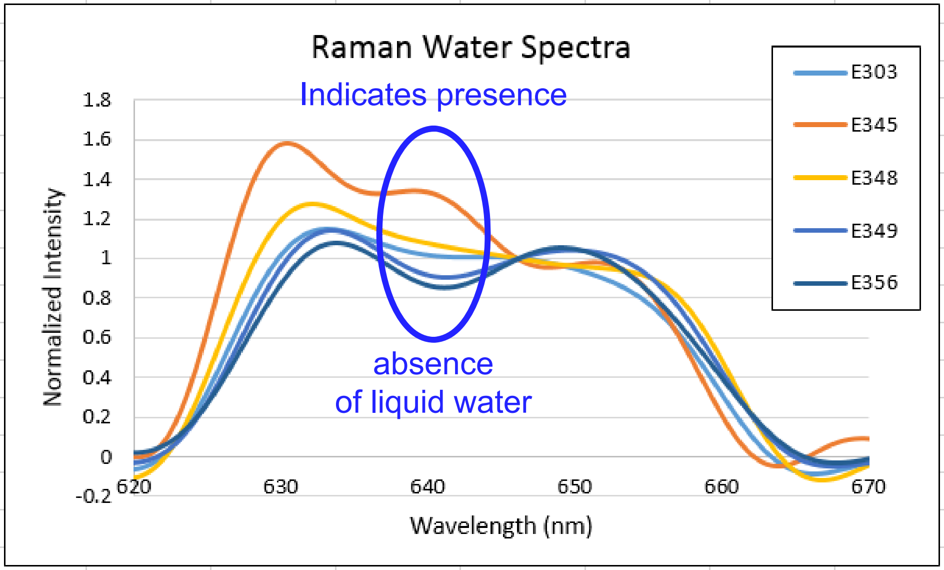




Particle Phase, Temperature - Raman

- “Point” measurement at beam waist
- Some success in PSL, with particles moving at 0.5 Mach
- Continuing development





Conclusions

- Cloud Cal Space is 12-parameters with complex interactions
- Radial variations (concentrations in center) noted in
  - TWC, total water content
  - PSD, particle size distribution
  - RH, relative humidity
- Near-independent verification of Bulk TWC measurement: IKP2 + Tomography within 5% of Water Flow with Boundary Layer
- Lowest confidence measurement is ice crystal PSD, MVD. Actively investigating alternate methods.
- Some success with measuring Particle Phase, Temp. via Raman Spectroscopy