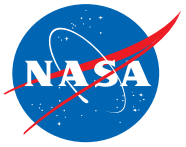


Update on the NASA Glenn PSL Ice Crystal Cloud Characterization (2016)

J. Van Zante, T. Bencic, T. Ratvasky, P. Struk

Presented by: Judy Van Zante

NASA Glenn Research Center

HAIC Forum, Toulouse, France, 2016-09.

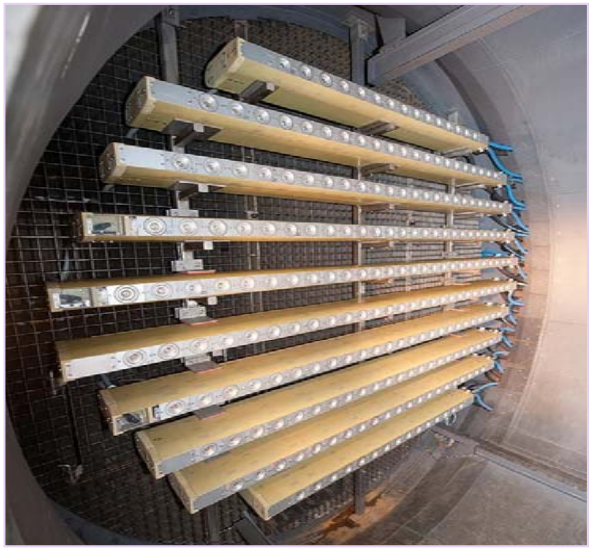
PSL Goal: to simulate the ice crystal icing physics inside the engine core flow path.

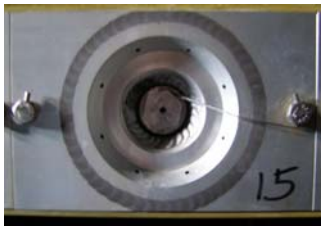
Outline

- Facility Description (very briefly)
- Cloud Characterization Parameter Space
- Aspects Characterized
- Conclusions

Ref: Van Zante, J.F., Bencic, T.J., and Ratvasky, T.P., "Update on the NASA Glenn Propulsion Systems Lab Ice Crystal Cloud Characterization (2015)", AIAA 2016-3897, AIAA Aviation Conference, AIAA, Washington, DC, 2016.

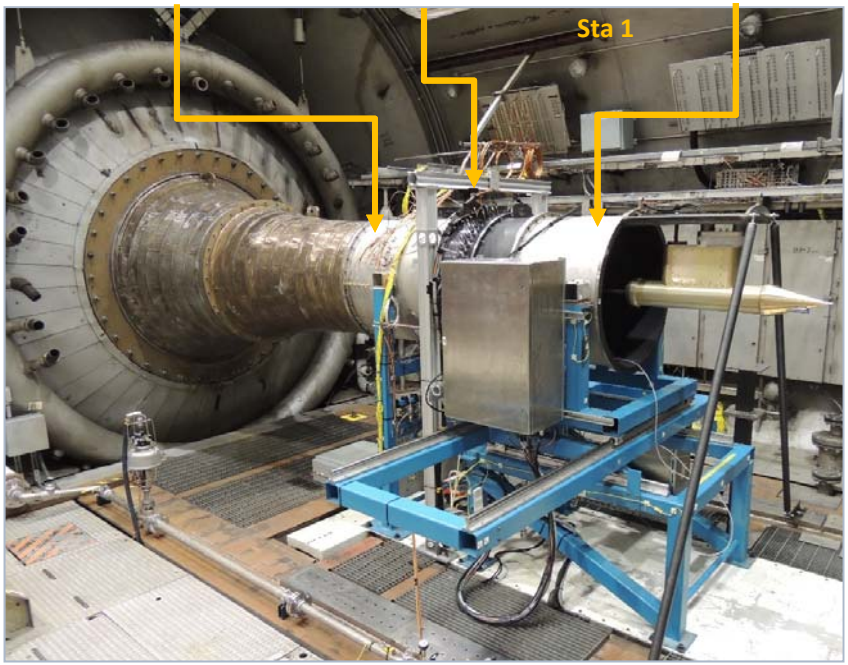
PSL Facility

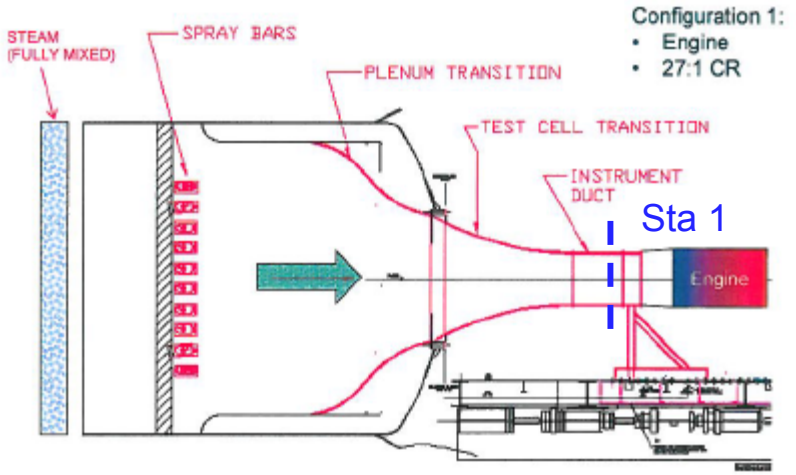




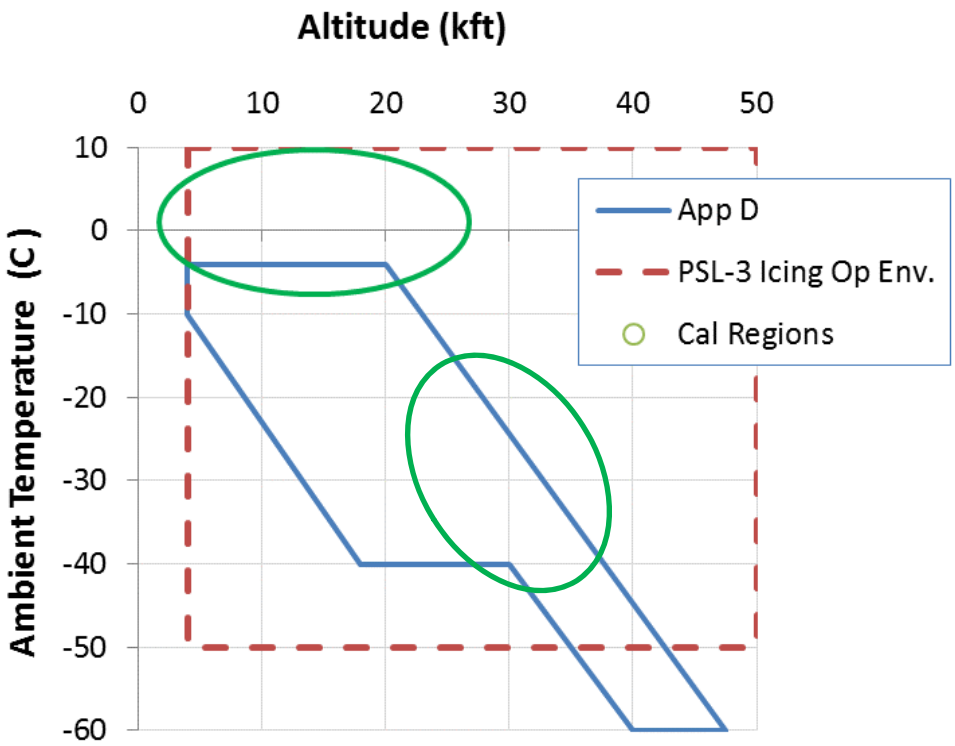
Crystals from spray nozzle freeze-out

Aero-Thermal Duct Tomography & Raman Cloud Calibration Duct





PSL Cloud Characterization Envelopes



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 Parameter Space

Airflow Conditions

- (Duct Geometry)
- Pressure Altitude, *P0*
- Temperature, *TPL*
- Mach, Air Mass Flow Rate, *Wa*
- 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 Temp 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 …

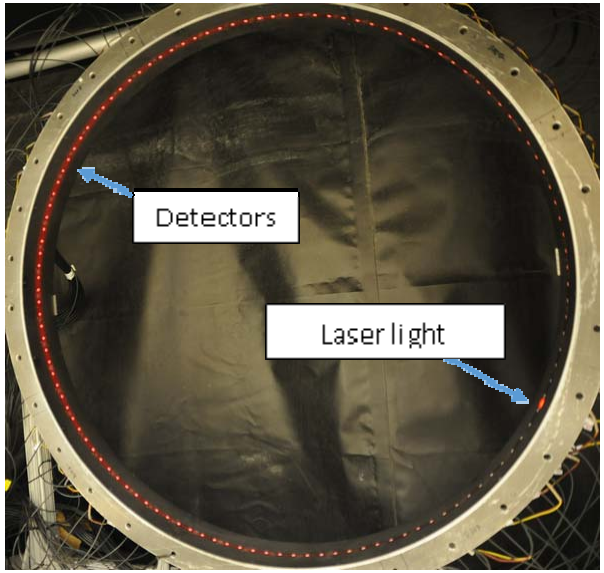
PSL Cloud Characterization Elements

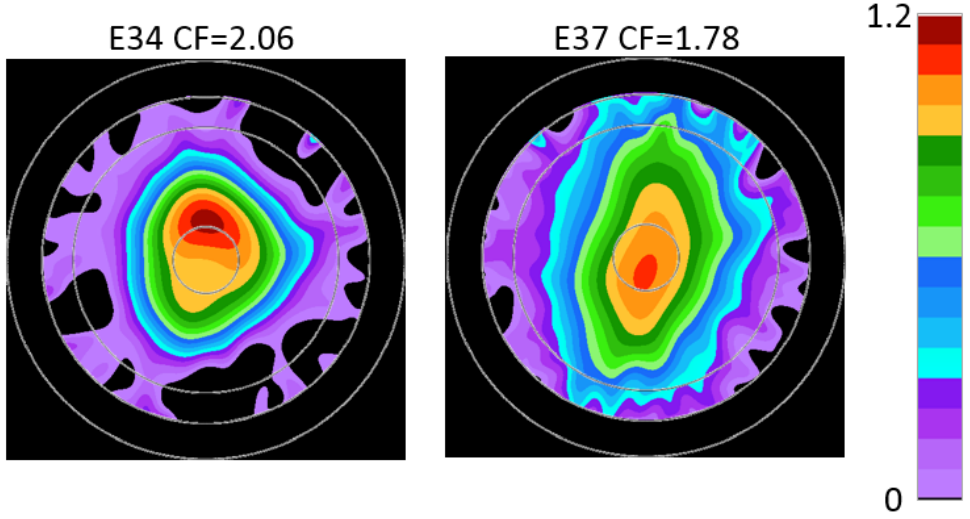
- Cloud Uniformity
- Total Water Content
  - Measurements in Center
  - Bulk average in Cross-Section
- Particle Size
- Particle Phase and Temperature

Also investigating

- Water vapor radial profile
- Temperature radial profile

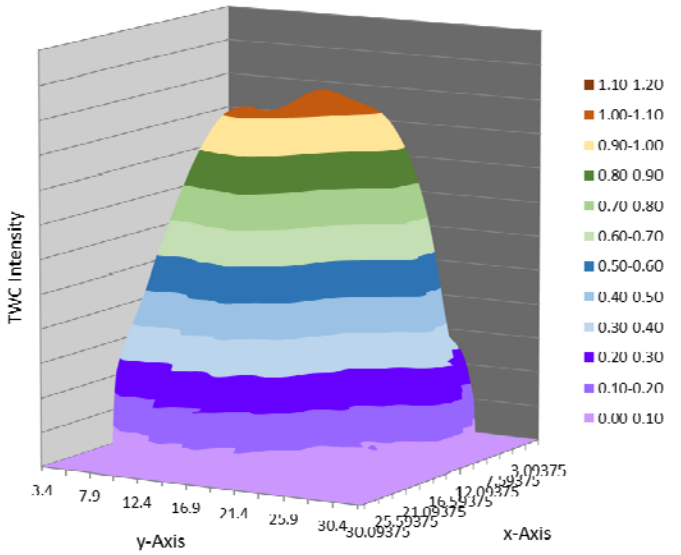
Tomography – near real-time monitoring





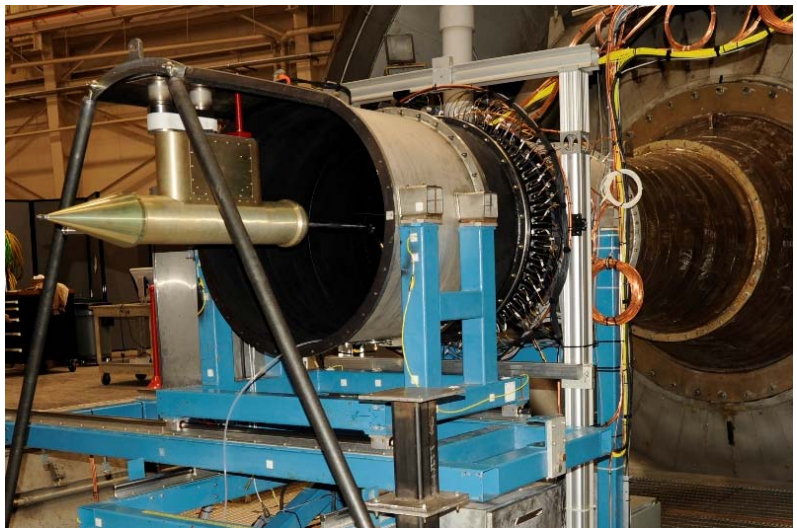
Procedure:

- 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}

TWC Measurement Notes

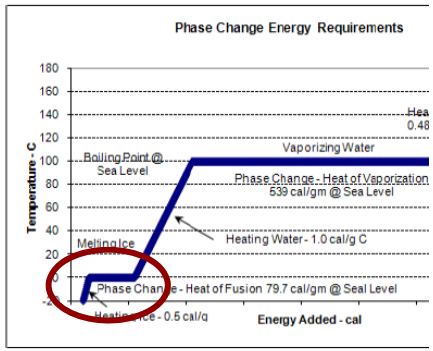
IKP2 (Standard):

- Importance of accurate background RH measurement

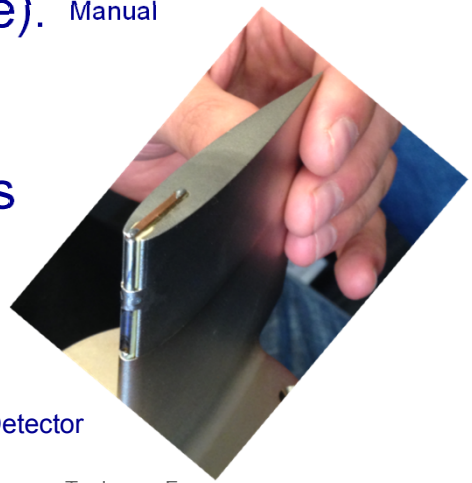
Heated Elements:

- Correct for Collection (Collision) Efficiency.
  No account for particle bouncing, splashing.
- Minimize flow angularity into MW head.
- Calculate both TWC (100% liquid) and iWC (100% ice).

  iWC / TWC ~ 0.88
- Particle Phase indicated by MW. Future investigations with SEA's Ice Crystal Detector.



SEA, Inc. WCM-2000 User's Manual



Ice Crystal Detector

Bulk Total Water Content: Calculated

TWC_Wf: Simple calculation assuming uniform distribution over entire duct based on measurands

- Water Flow Rate (*Wf*)
- Air Mass Flow Rate
- Sta 1 Static Pressure and Temperature

TWC_Wf_BL: Add a cloud boundary layer thickness

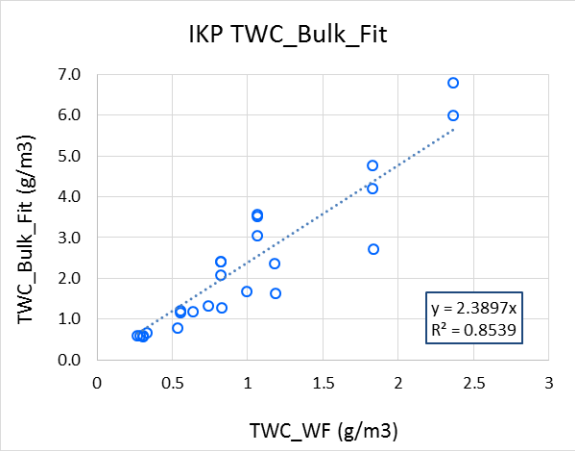
TWC_Wf is the *basis function* for TWC measurements

Bulk Total Water Content: Measured

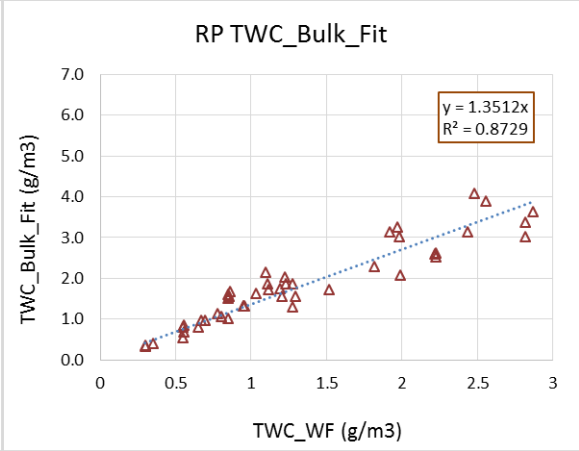
- Combine Measured TWC_{00} and Tomography CF.

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

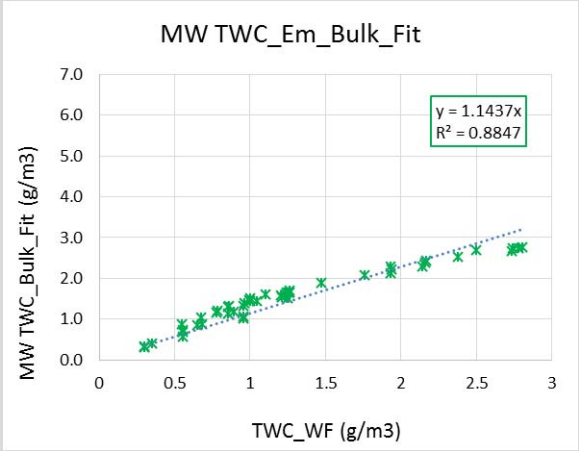
- Created a CF curve fit based upon Pair and TWC_Wf, TWC_Bulk_Fit



IKP



RP



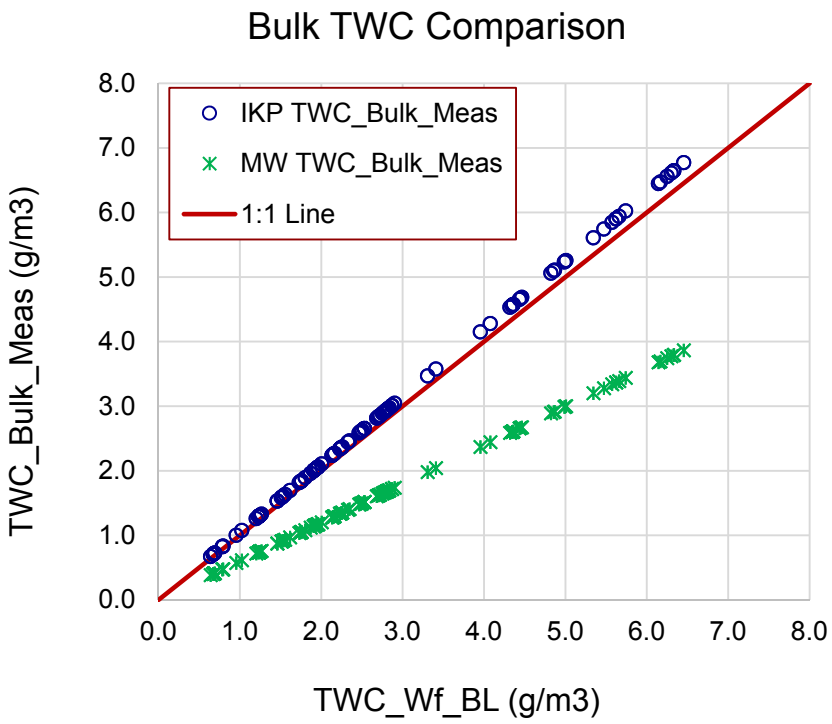
MW

TWC Bulk Comparison

IKP + Tomography ≈ Water Flow + Boundary Layer

Bulk TWC — Bulk TWC

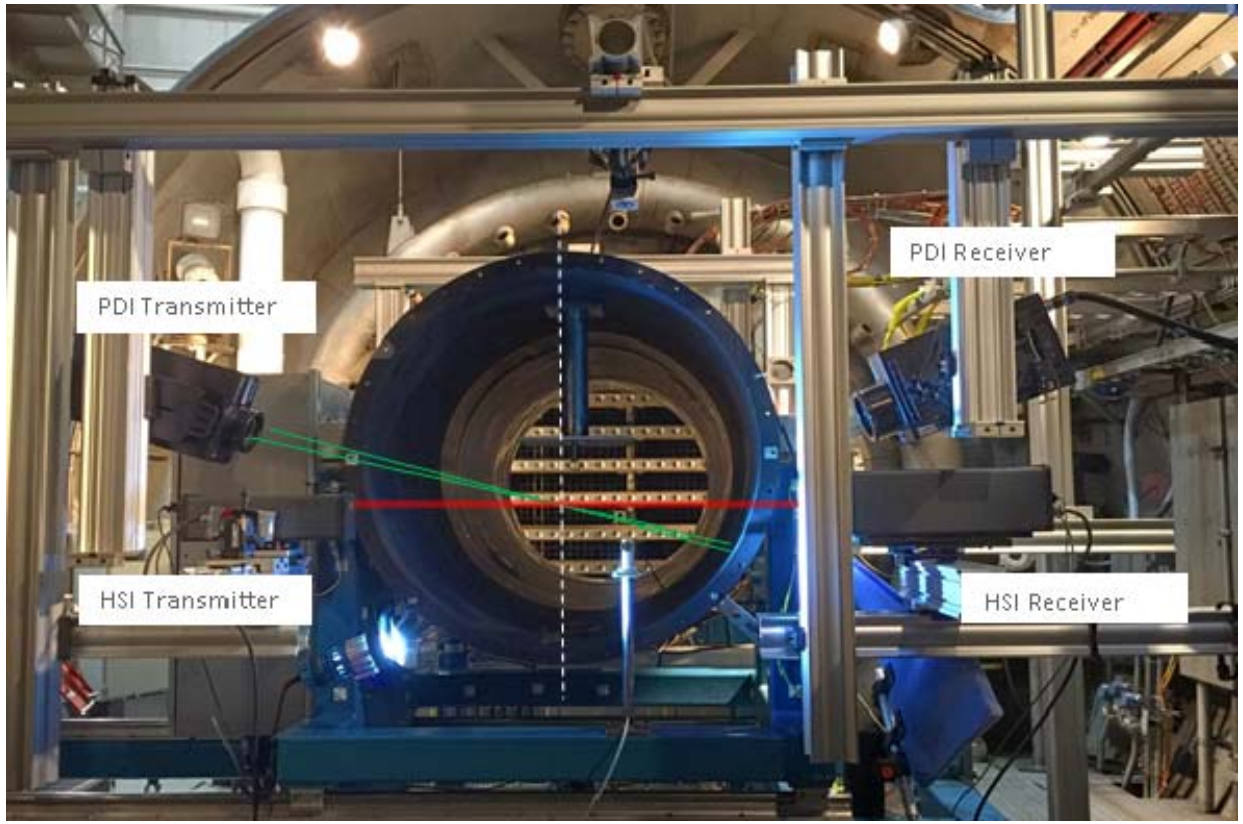
TWC_Bulk_Meas — TWC_Wf_BL



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

Particle Size Measurements

Artium, Inc.



Phase Doppler Interferometer
PDI

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

High Speed Imager
HSI

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

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 Size Measurements (liquid)

DMT, Inc.

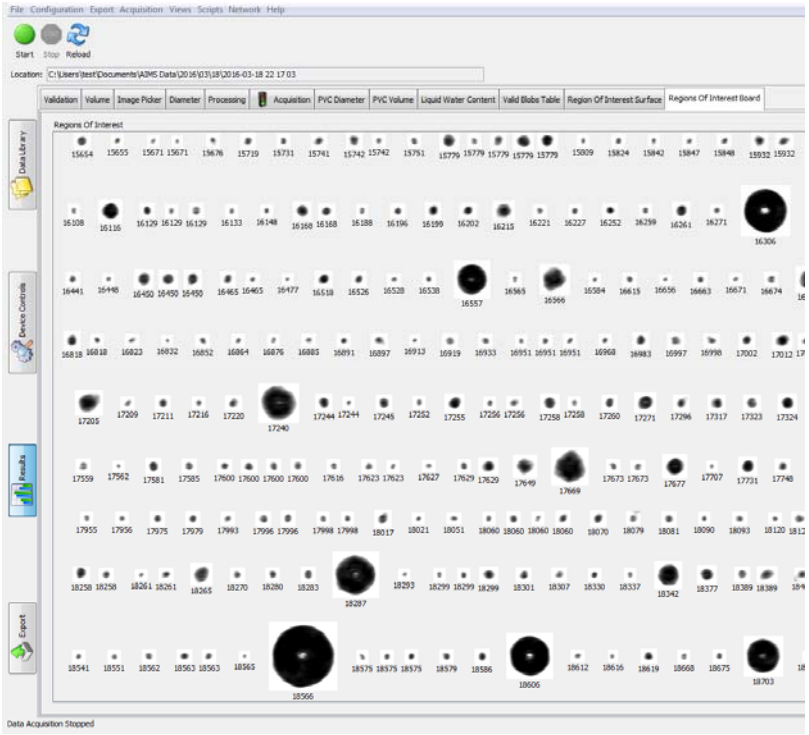
Cloud Droplet Probe
(CDP)

Cloud Imaging Probe
(CIP-GS)

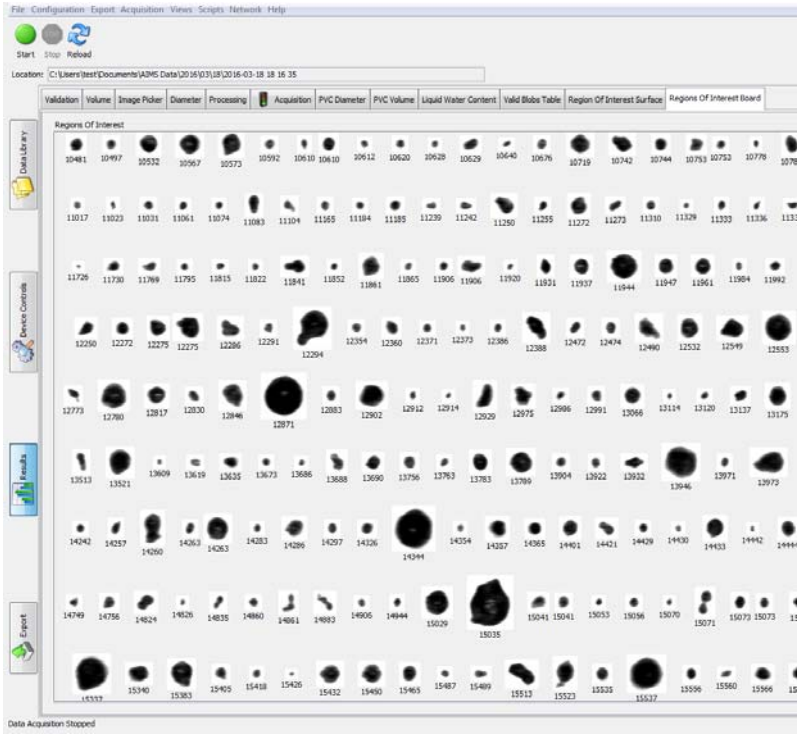
All measurements at Duct Center.
Future ability to shift off-center

Sample HSI Images

Liquid

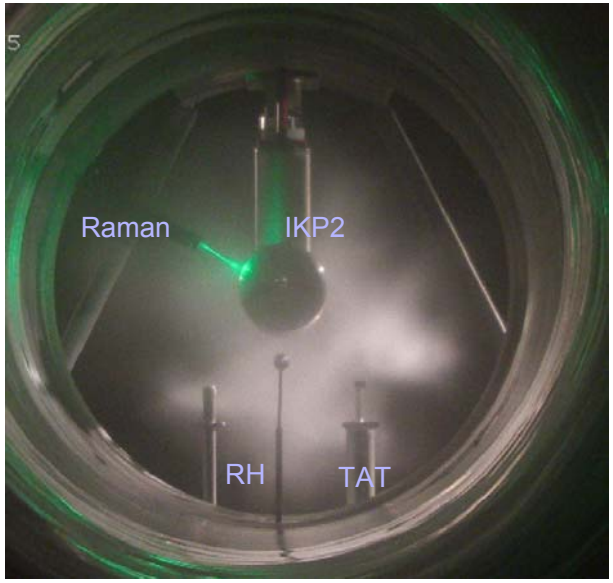


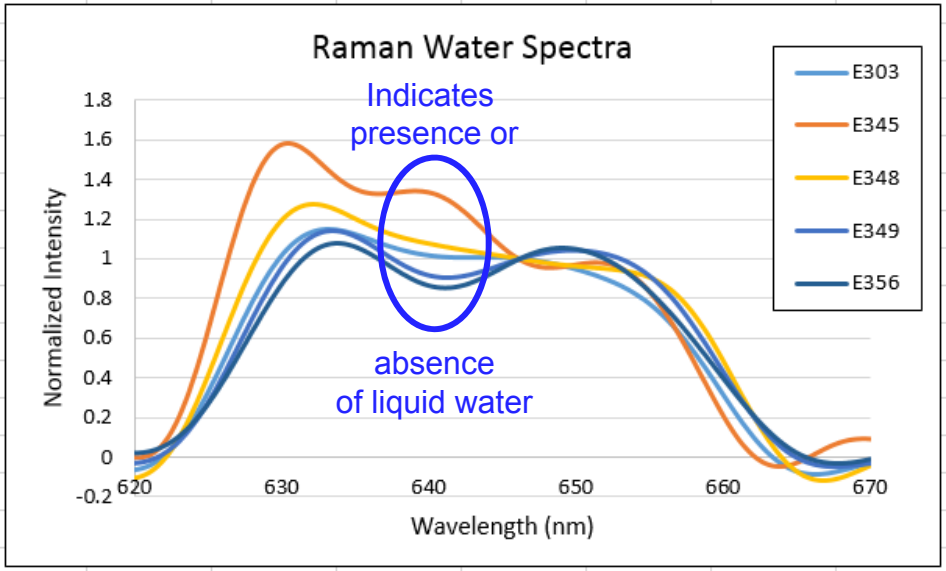
Crystal



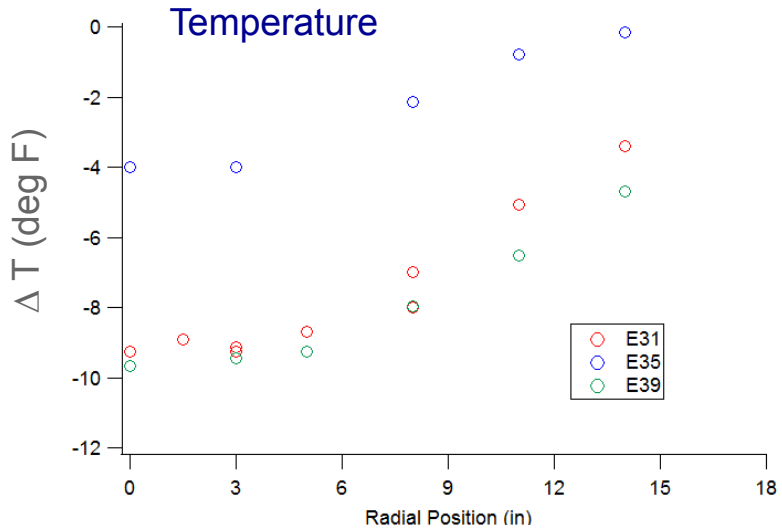
Particle Phase & Temperature Meas.

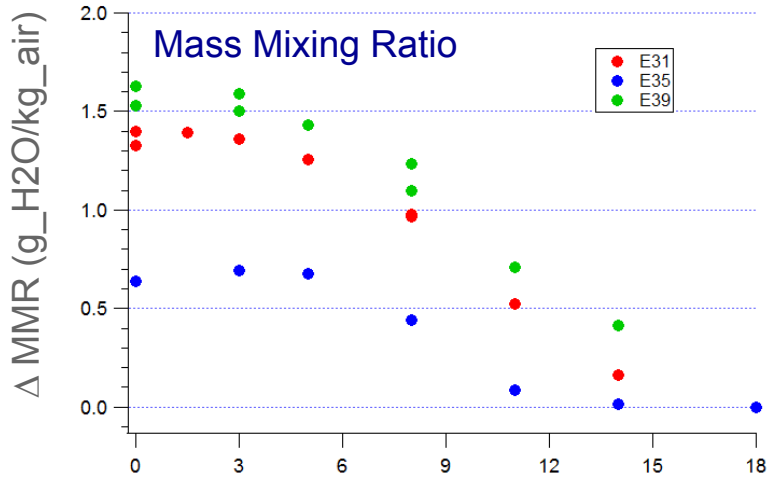
- “Point” measurement at beam waist
- Benchtop success and some success in PSL, with particles moving at 0.5 Mach
- Development continues





Radial Temperature & Humidity Profiles at Station 1 Change, Δ = (Station 1 – Plenum⁺) with Cloud On

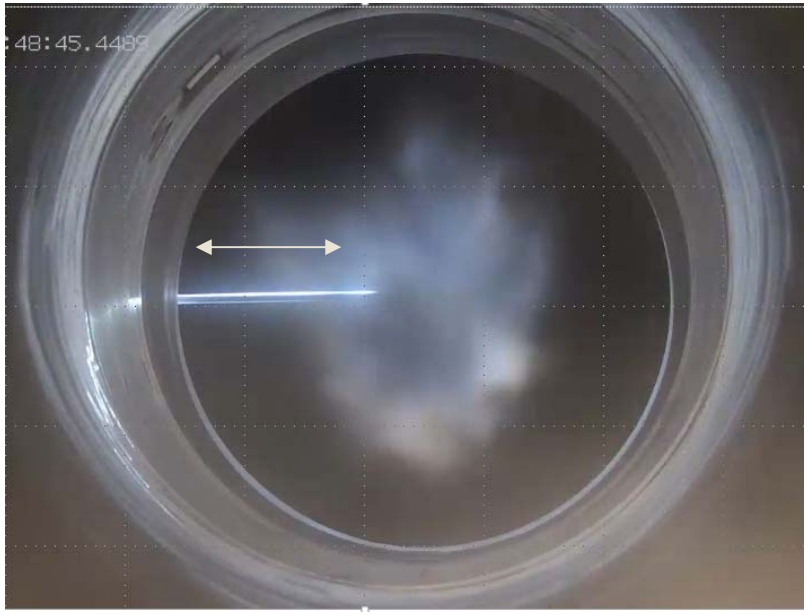




Preliminary Data

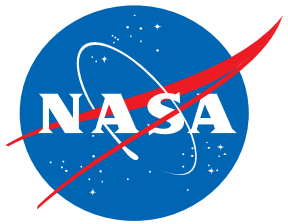
Test #	31	35	39
T0 (°F)	50	50	50
P0 (psia)	6.5	12.6	6.5
Mach	0.25	0.40	0.26
TWCi (g/m3)	2	2	8.5
MVDi (μm)	15	50	35

Translating Temperature and Humidity Probe



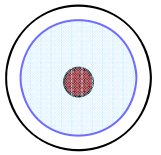
Conclusions & Future Work

- Cloud Cal Space is 12-parameters with complex interactions
- TWC Measurements
  - Best measured with IKP2.
  - Bulk Measured (IKP + tomography) matches Bulk Calculated.
- PSD Measurements (least confidence)
  - HSI for ice crystals, but misses smallest particles (< 9 um).
  - Investigate off-center measurements.
- Particle Phase and Temperature Measurements
  - Phase indicated with MW. Ice Crystal Detector in future?
  - Progress on measuring with Raman / Fluorescence spectra.
- Investigate and document Cloud On radial RH and Temperature profiles

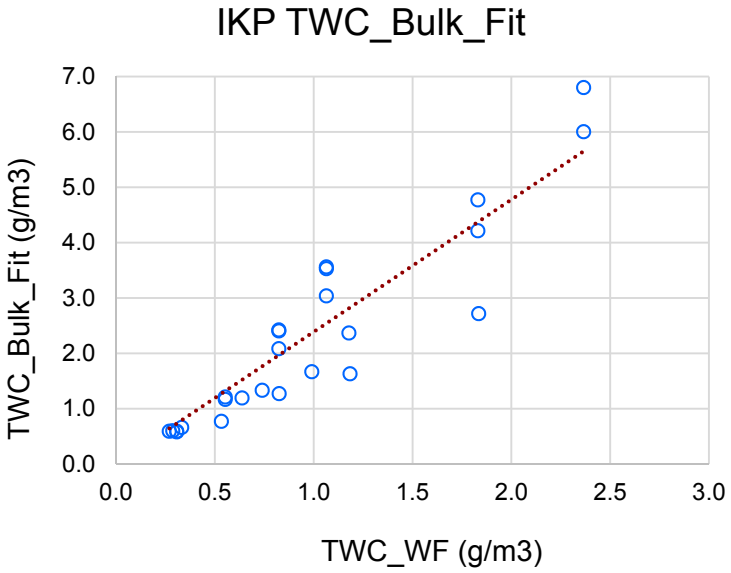

NASA

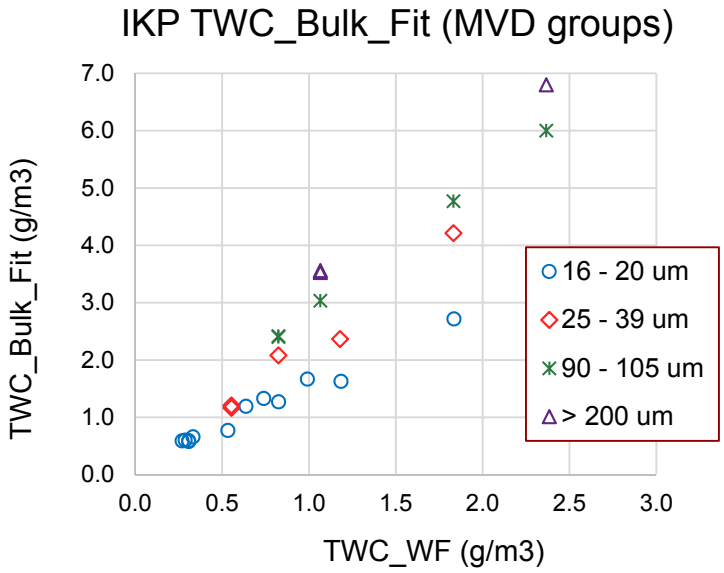
TWC & radial distribution of particle size

- 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.



Distribution of
20 um
100 um





Particle Phase and Temperature

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