



The Demonstration of a Light Extinction Tomography System at the NASA Glenn Research Center's Icing Research Tunnel

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Outline



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Introduction / Motivation

Demonstration of a prototype **Light Extinction Tomography System** in the Glenn Research Center's (GRC) Icing Research Tunnel (IRT)

- Developed to provide in-situ “real-time” measurements of the IRT’s icing cloud uniformity (liquid water content) across the plane of the test section
- Very important as the icing cloud represents a primary test condition provided to test customers in the IRT
- These measurements are currently acquired through manual means during periodic calibrations of the IRT cloud conditions
 - Labor intensive and time consuming
 - Assumes cloud uniformity does not greatly vary between calibrations
- Goal: Provide the measurements in-situ and in “real-time” to minimize need for manual measurements
 - Allow facility operators to detect any changes in icing spray conditions between calibrations

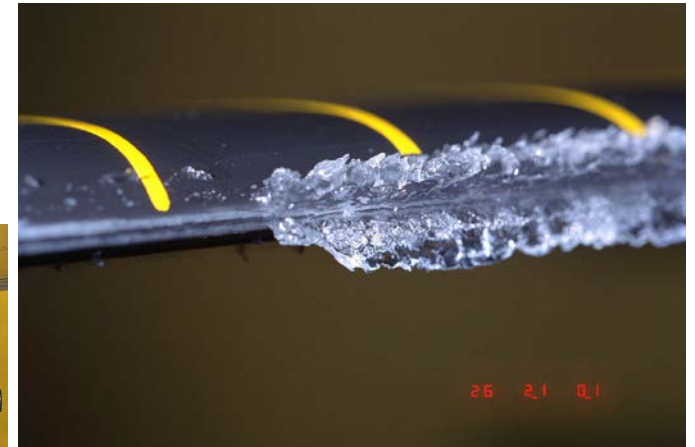


IRT - Ice accretion testing

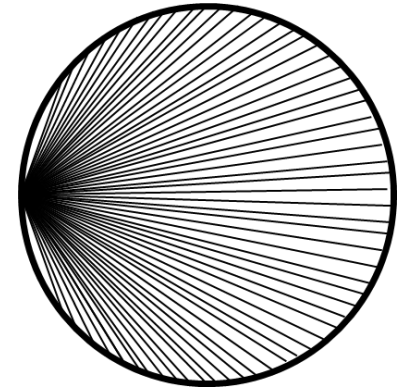
Video of an icing cloud spray



IRT – Test Section Photos, Typical Experiments



Background



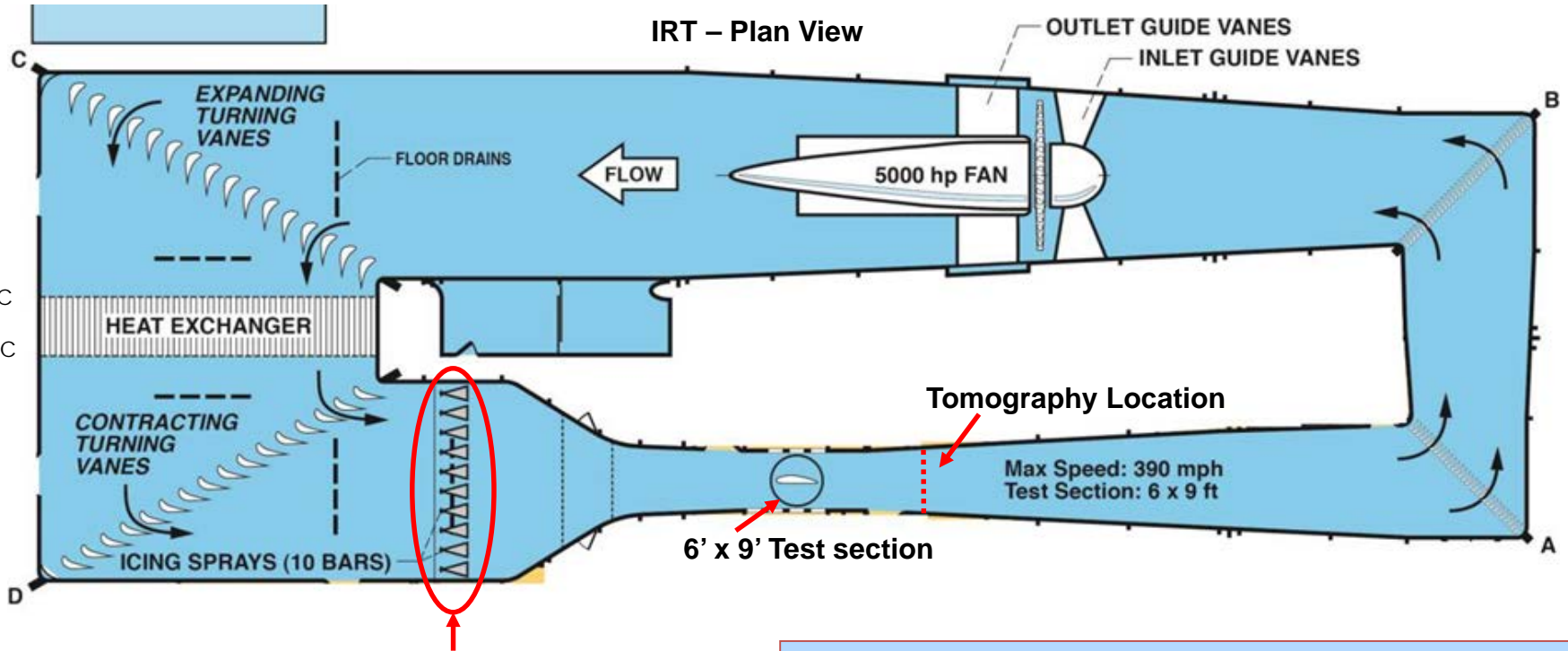
Tomography
Model Example

- Light Extinction Tomography first envisioned for use on icing clouds in the late 1990s - early 2000s by Timothy Bencic, NASA GRC¹⁻³
 - Light sources and detectors located around the periphery of a measurement plane
 - As light source “fires”, the detectors measure light extinction due to cloud/water particles in the optical path from the lasers to the detectors
 - Sequential firing of light sources located around the periphery yields data for a 2D reconstruction of the cloud using tomographic data reconstruction techniques
- Light Extinction Tomography developed and successfully implemented in the NASA GRC Propulsion Systems Laboratory (PSL) in the 2010 to 2013 timeframe⁴
 - Circular geometry, 60 sources, 120 detectors, 36” diameter → 1018 in²
 - Used to measure icing conditions for engine “ice ingestion” testing
- System studies and development began on system for the IRT in ~2015
 - Extension of concept developed for the PSL
 - Much larger square geometry 60 sources, 120 detectors, 6’ by 9’ → 7776 in²
- Prototype system completed in 2017
- ***Proof-of-Concept test successfully demonstrated in the IRT early 2018***

IRT Facility Description



IRT – Plan View



IRT Spray Bars

- 10 rows spray bars
- 55 nozzle positions, each with a Mod1 nozzle (low flow), a Standard nozzle (high flow), or a plug

Largest Icing Tunnel in the US
 6 ft. x 9 ft. Test Section
 Calibrated Speed Range: 50 to 325 knots

- Used to study the effects of icing on aero vehicles, wings, surfaces and structures
- Data for customer's aircraft icing certification
- Ice protection systems development
- Icing prediction/code validation

IRT Cloud Calibration

Currently use an ice accretion based method of making icing cloud uniformity measurements

- 6' by 6' grid physically bolted in the test section.
- Mesh elements are 6" by 6", 2" deep with a flat 1/8" face for ice accretion
- Facility is operated and the grid is exposed to an icing spray for a given period of time. Ice is accreted on the exposed face of the grid.
- Facility is shut down, a technician enters the test section and uses calipers to measure the ice thickness at ~156 points on the grid
- Process is repeated for every spray condition to be calibrated
 - Tunnel airspeed, temperature, cloud water content, cloud water droplet size, nozzle spray pattern, nozzle pressure, etc.

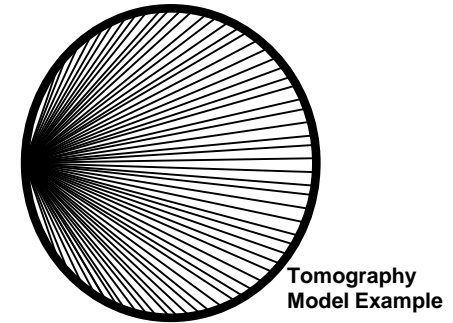


Technician measuring the thickness of ice accreted on the Grid.

- A check calibration is performed every 6 months, a full calibration is performed every ~5 years (ARP5905 recommended practice)

Light Extinction Tomography - Theory

- Tomography reconstruction is the recovery of a quantity from a collection of line integrals of that quantity along the optical path from the source to the detector
- For this application the relevant quantity is liquid water content (LWC)
- Extinction of a light beam passing through an icing spray will be proportional to the line integral of liquid water content along the path of that ray
- For the particle sizes and expected path lengths in the IRT, a single scattering model was applied²
- This data collection model is defined as:



$$-\ln\left(\frac{I}{I_0}\right) = \int_{l_i} \mu(x) ds$$

I_0 , Intensity of the light source, acquired while spray is not present

I , Intensity of measured on the detector while spray is present

$\mu(x)$, Attenuation coefficient for the spray

l_i , Optical path from source to detector

s , Length along optical path l_i

Light Extinction Tomography - Theory



- Methodology

- Data sets are measured for a collection of lines, with each line corresponding to a source-detector pair
- From the measured data the line integral of $\mu(x)$ along the optical path from source to detector is computed
- Tomographic reconstruction algorithm is then used to obtain the attenuation coefficient, $\mu(x)$, from the line integrals
- The attenuation coefficient is proportional to the liquid water content (LWC)

$$-\ln\left(\frac{I}{I_0}\right) = \int_{l_i} \mu(x) ds$$

I_0 , Intensity of the light source, acquired while spray is not present

I , Intensity of measured on the detector while spray is present

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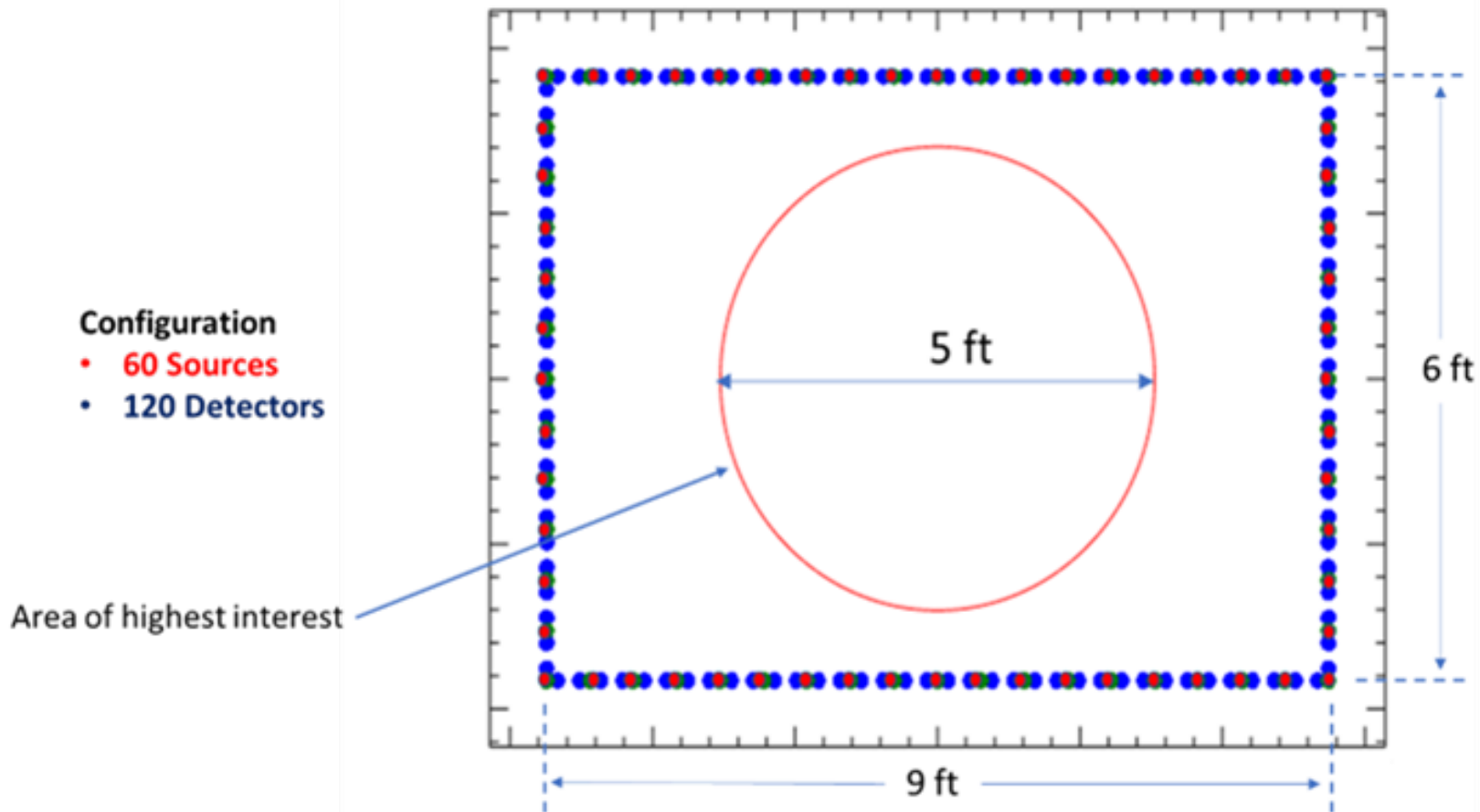
L_i , Optical path from source to detector

S , Length along optical path l_i

- Measurement model is similar but distinct from those used in medical and structural computed tomography (CT)

- Rectangular geometry creates irregular line sampling, not applicable to standard circular CT application (regular line sampling).
- IRT used a variant of the linear fit algorithm that was proposed by Izen, Bencic³ and used for the PSL application⁴
- The acquired spray measurements are fit to a linear combination of image basis elements
- Due to the expected smoothness of the cloud, Gaussian blobs are used instead of pixel basis elements used in medical CT.....This better represent the cloud shapes

Light Extinction Tomography – IRT Configuration



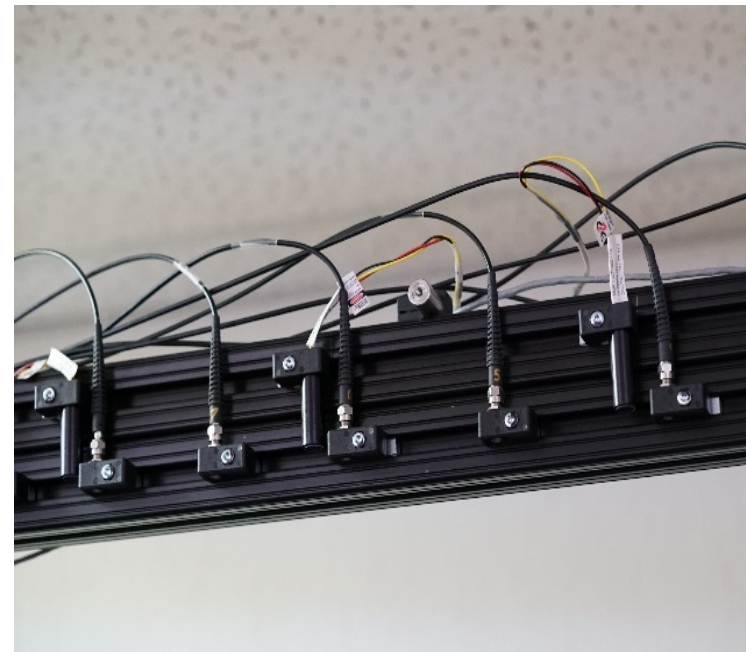
Spaced at equiangular distances around the periphery of the measurement plane

- Light detectors spaced every 3°
- Light sources spaced every 6°

Light Extinction Tomography – IRT Configuration



Prototype system setup in the lab



Laser diodes and light detectors

- 80/20 rails used for 6' by 9' system frame
- 658nm laser diodes with sheet generating optics used for the 60 light sources
- Fiber optically coupled detection elements with flashed opal input diffusers mounted at the fiber entrance were used for the 120 detectors.
 - Allowed coupling of laser light into fiber detectors at very wide angles, +/- 85°
 - Optical filter installed to only allow laser light from the sources

Light Extinction Tomography – IRT Configuration



Line scan camera to fiber interface



Area scan camera to fiber interface

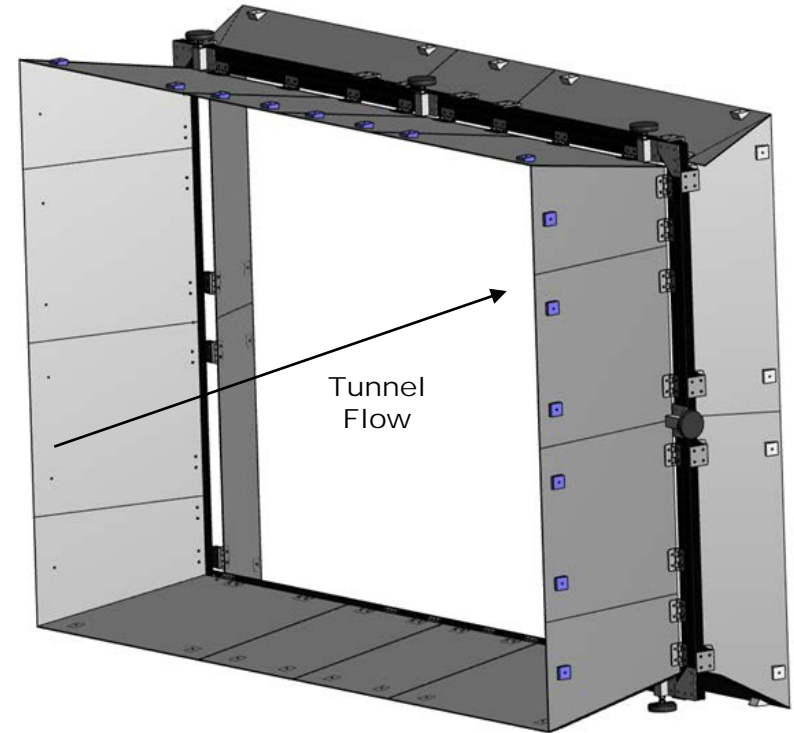
- The fiber detectors were directly coupled to a CCD camera in order to achieve simultaneous sampling of all 120 light detector channels
- Two camera configurations were evaluated during demonstration:
 - Line scan camera with 12 bit depth
 - ✓ Area scan camera with 16 bit depth
- Custom timing and triggering circuitry built in-house to pulse the laser diodes and control the data acquisition

Light Extinction Tomography – Facility Installation



CAD model of facility installation

- Prototype lab system constructed of off-the shelf rail hardware was used for this initial proof-of-concept test
- The system was installed where it would fit into the facility
 - ~91 inches downstream from end of the test section in the facility's diffuser
- Leveling feet used to align the system's frame and mount to the tunnel walls
- Aluminum fairing panels were designed, fabricated and installed to guide the flow through tomography frame and protect source & detector cabling.
- Acrylic panels were installed along the periphery of the rig's measurement plane to protect the optics from water and ice



Light Extinction Tomography – Facility Installation



Frame mounted to tunnel walls (forward looking aft)



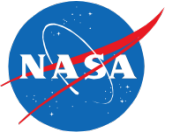
Forward fairing installed, routing of detector and source cabling on aft side (aft looking forward)

Installation Compromises

- Location, diffuser vs test section
- Convergent-divergent flow area around tomography system
- Equipment box located in diffuser



Final system installation (forward looking aft)

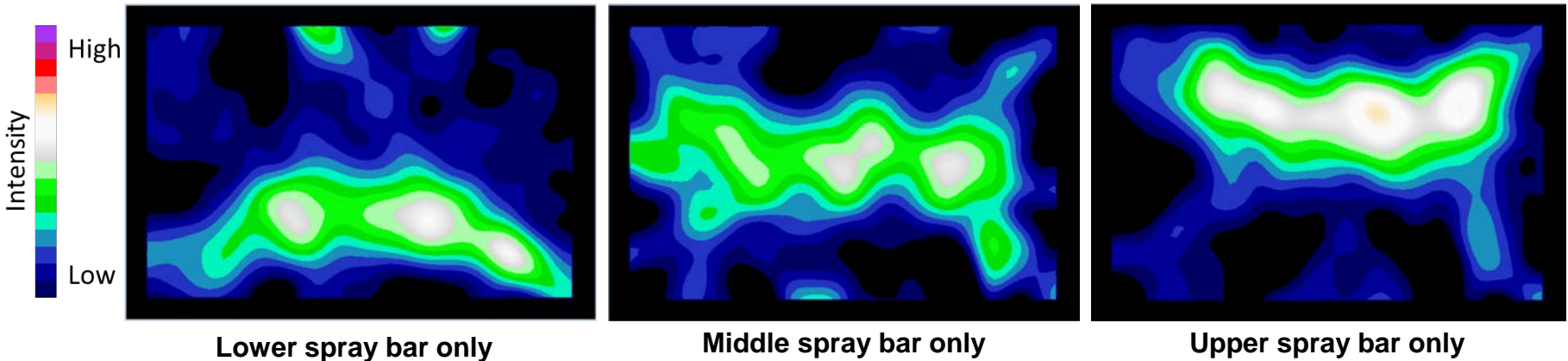


Demonstration Test Plan and Execution

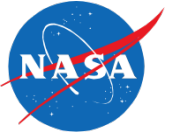
Four (4) main categories of test conditions

- Distortion Checks
 - Baseline Grid Sprays
 - Sensitivity Checks
 - Tomographic Exercises
- ✓ Data successfully acquired for 79 spray conditions over a three day period

Results / Analysis – Distortion Checks



- Involved operating a specific row or column of spray bars to see if tomography system correctly measured and tracked the cloud location
- Location of spray bar that was being operated showed up in expected location
- Similar patterns also observed when specific columns of spray bars were operated
- ✓ **Light Extinction Tomography System was correctly tracking the cloud's position in the two-dimensional measurement plane**



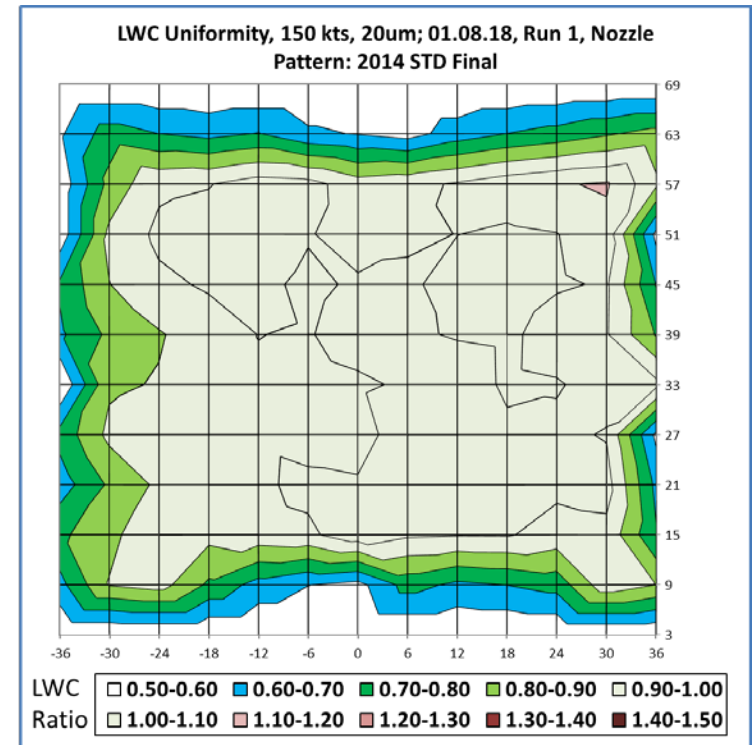
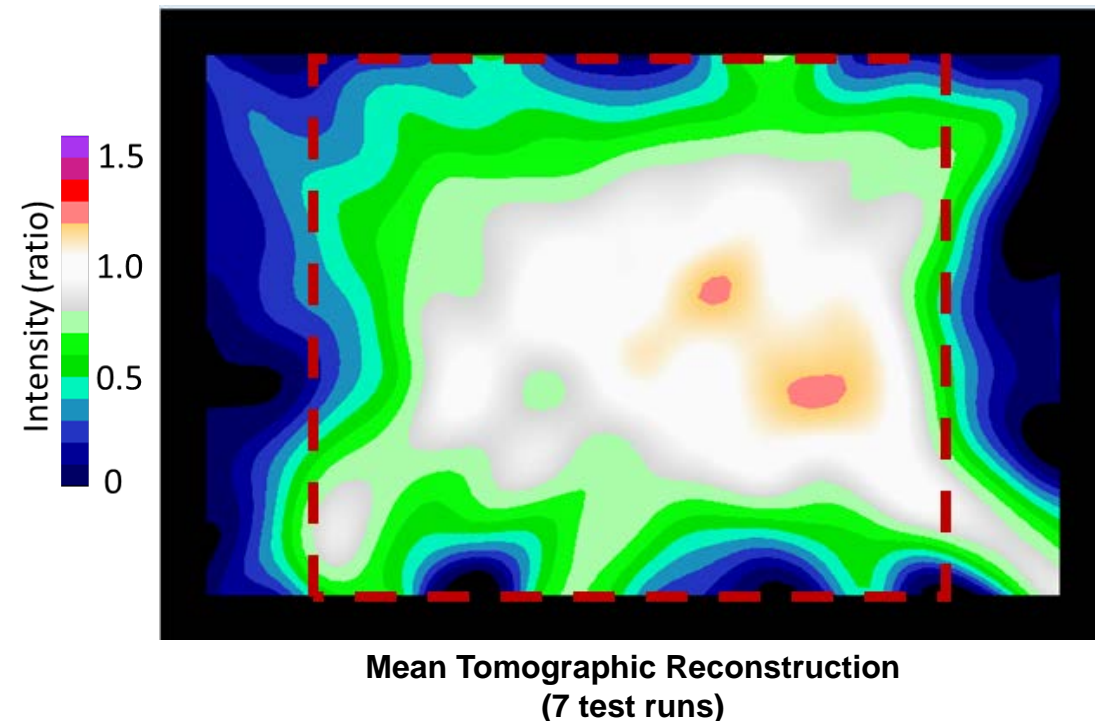
Results / Analysis – Baseline Grid Sprays

- **Two Baseline Grid Spray test conditions were used for this portion of testing**
 - Standard (MVD* = 21.4 μm , LWC** = 1.39 g/m^3)
 - Mod1 (MVD = 21.5 μm , LWC = 0.70 g/m^3)
- Main purpose was to compare to existing LWC uniformity plots derived from previous calibrations
- Conditions were repeated seven (7) times each as a means of assessing measurement variability
- Only the results from the Standard Baseline Grid Spray comparison will be shown in this presentation.

* Mean Volumetric Diameter (MVD)

** Liquid Water Content (LWC)

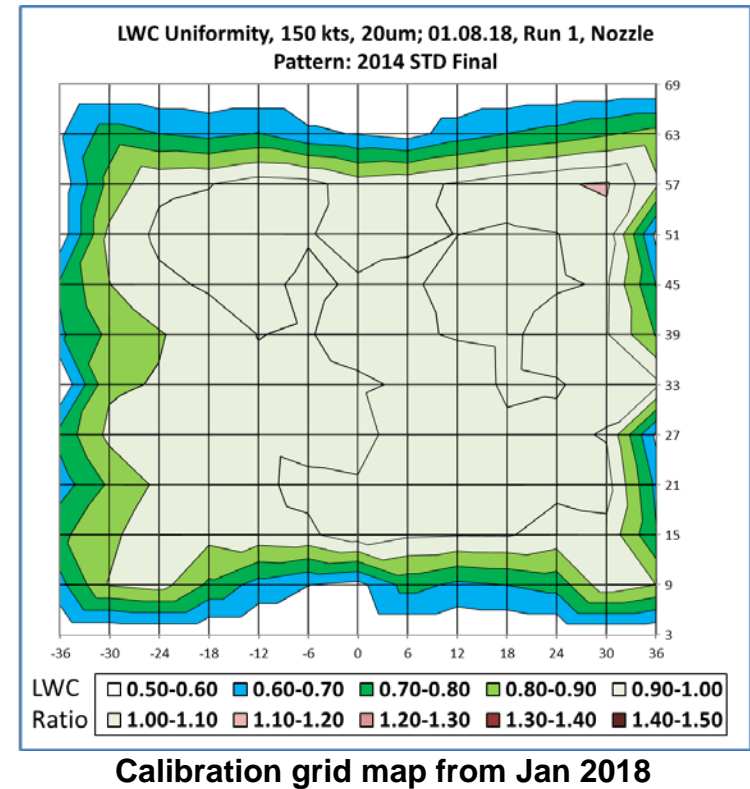
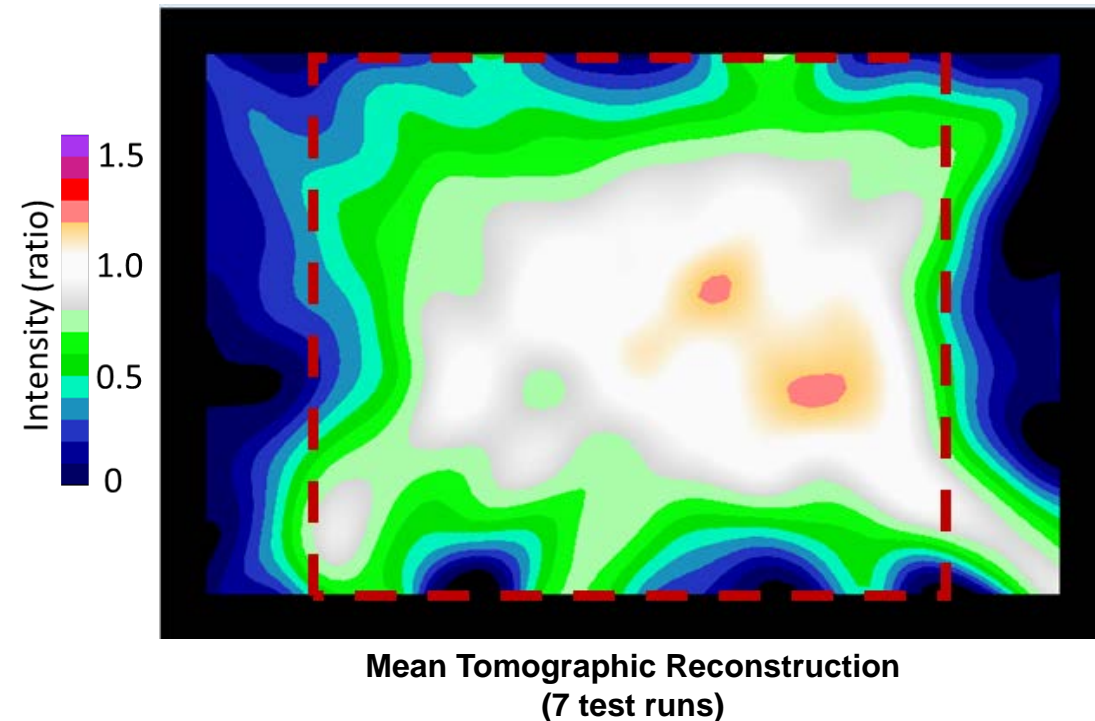
Results / Analysis – Standard Baseline Grid Spray



Calibration grid map from Jan 2018

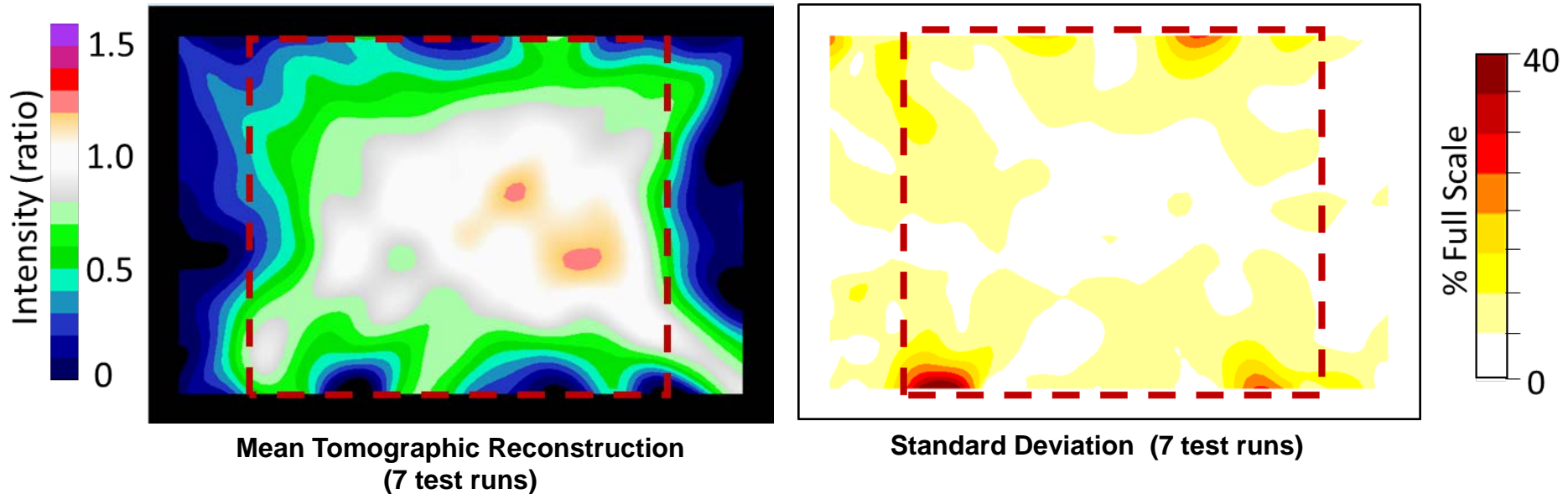
- LWC uniformity plots have similar shape and follow same trends
- Each plot has uniformity ratio values that range between 0.90 to 1.10 in the center core section of the tunnel flow
- The tomographic results does trend towards lower ratio values around edge of the core flow regime
- Also shows two high spots, ratios =~1.2, not shown in the calibration map

Results / Analysis – Standard Baseline Grid Spray



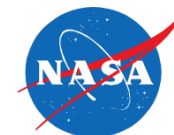
- Possible reasons for differences
 - Differences in measurement location (test section vs diffuser)
 - Flow effects associated with the prototype system's installation in the diffuser

Results / Analysis – Standard Baseline Grid Spray

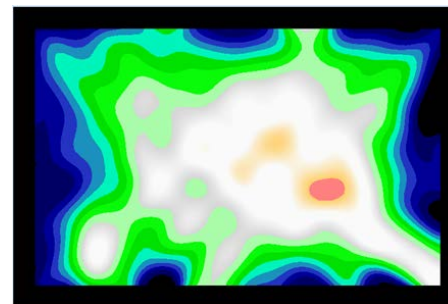


- 0 to 10% variation from reading-to-reading shown in the standard deviation plot in the center region of the core flow
- This is within reason and within what was expected
- ✓ Overall, regardless of slight differences observed from the calibration maps, the measurements matched the overall shape of the uniformity plots and ratios generated by the manually measured grid.
- ✓ Showed that the system has potential to make the desired cloud uniformity measurements in the IRT

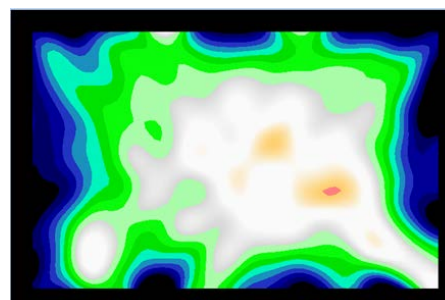
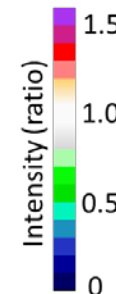
Results / Analysis – Sensitivity Checks



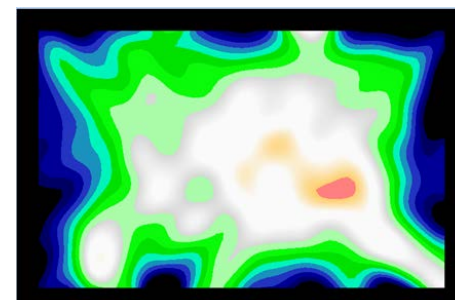
- Operated spray bars at known calibrated conditions
 - Varied MVD and LWC to determine if system could detect any changes in cloud uniformity
- Results of Mod1 spray shown
- Varying MVD from 15um to 41um
 - No major change observed in cloud uniformity
 - ✓ **Consistent with previous manual grid measurements**
- Large drop sizes cases, 266um to 460um
 - Noticeable shrinkage of cloud uniformity, less uniform
 - Large drops tend towards center of test section, decreased nozzle pressure results in less mixing
 - ✓ **Consistent with previous manual grid measurements**
- ✓ **Intensity does vary as $f(x)$ of LWC**



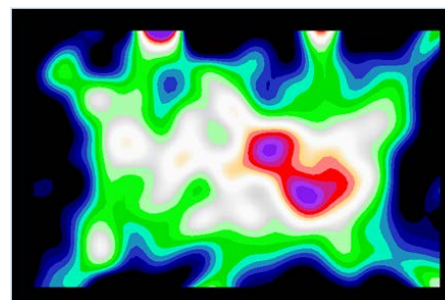
Mod1 Baseline, MVD=21.5 μm , LWC=0.70 g/m³



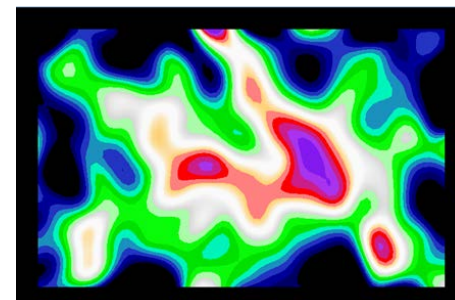
Mod1, MVD=15.3 μm , LWC=0.43 g/m³



Mod1, MVD=40.9 μm , LWC=1.19 g/m³



Mod1, MVD=266 μm , LWC=0.92 g/m³

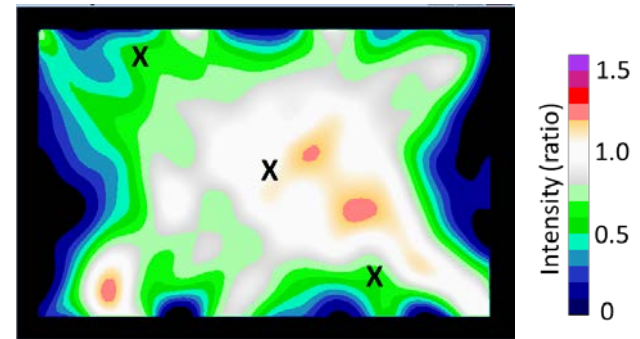


Mod1, MVD=460 μm , LWC=1.26 g/m³

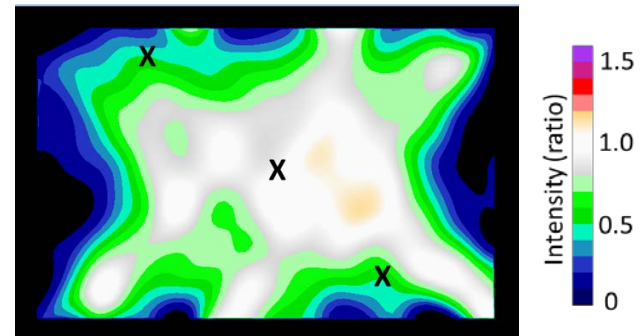
Results / Analysis – Tomographic Exercises



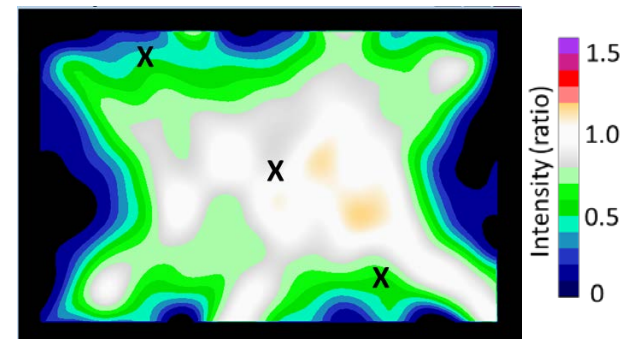
- Purpose was to see if tomography system could detect changes due to anomalies in the spray bar system
- Simulated “anomalies”
 - Used a high number density (ND) “Standard” spray
 - MVD=15.4 μm , LWC=1.52 g/m^3
 - Turned three (3) Standard nozzles off
 - Upper LH corner, Center, Lower RH corner
 - Kept three (3) standard off, turned on three (3) “Mod1” nozzles
 - Similar locations as previous case



#1-High ND Standard-nozzle spray



#2-Three Standard nozzles off



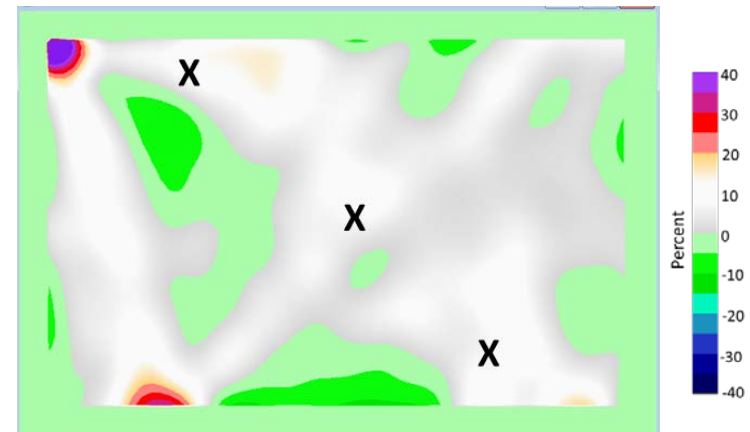
#3-Three Standard nozzles off,
three Mod1 nozzles on

Results / Analysis – Tomographic Exercises

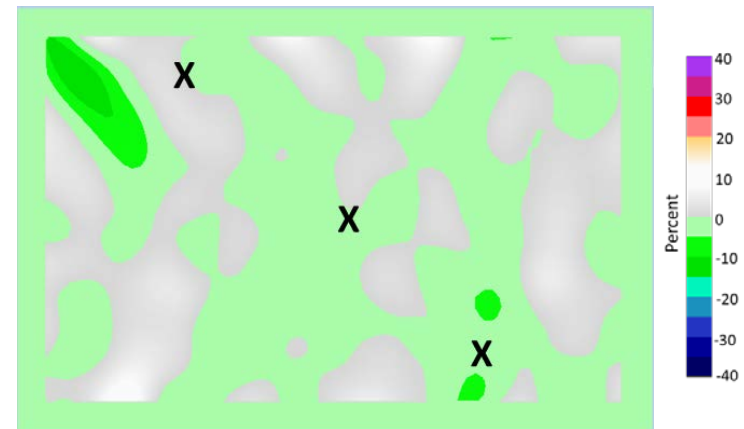


- Image subtraction used for the analysis
- Results are inconclusive
 - No real pattern that relates to disturbances that were expected by the Standard nozzles being turned off and the Mod1 nozzles being turned on
 - Differences in both cases show a +/- 10% variation across the core section of the cloud flow which is with-in previous observed reading variability
 - System appears not to have needed sensitivity to detect these “small” changes
 - May be due to the system being installed down in the diffuser giving the flow more time to mix, minimizing the expected holes where the nozzles are located
 - May be due to effects associated with the temporary installation

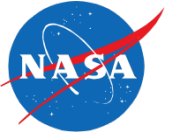
! Will investigate improving system sensitivity for future implementation



#1-High ND Standard-nozzle spray
minus
#2-Three Standard nozzles off



#2-Three Standard nozzles off
minus
#3-Three Standard nozzles off, three Mod1 nozzles on



Conclusion

- A prototype light extinction tomography system was installed and successfully demonstrated in the NASA Glenn Research Center's Icing Research Tunnel
 - Was able to track icing cloud location
 - Was able to measure/assess cloud shape and uniformity with results comparable to manually made measurements acquired using the calibration grid
 - ➔ Technique is viable and has potential for future implementation in to the IRT
 - Prototype system was shown to be limited in the sensitivity needed to detect failures on a single valve level
 - ➔ This is solvable and may have had more to do with the prototype system hardware and temporary installation rather than limitations of the technique itself.
- This was the first attempt of using Light Extinction Tomography on a square geometry of this large scale
- The results acquired in this proof-of-concept demonstration test will serve as the basis for further improvement and long term installation of a light extinction tomography system in the Icing Research Tunnel

Acknowledgements



- **We would like to thank the NASA Aerosciences Evaluation and Test Capability (AETC) Portfolio's Test Technology Subproject for supporting this effort**
- Trevor John from NASA GRC for the machining and build-up of the tomography system hardware
- The IRT Facility Manager, Engineers and Technicians for their dedication and hard work in supporting this demonstration test



-
- **Questions?**

References



¹Bencic, T. J., “Development of Advanced Optical Instrumentation for Use in the NASA Glenn Icing Research Tunnel,” AIAA-2001-0396, 2001

²Lock, J., “Mapping the Position-Dependence of the Liquid Water Content in the NASA Glenn Icing Research Tunnel Using Light Scattering Tomography,” NASA Grant NAG3-2232, 2000

³Izen, S. H. and Bencic, T. J., “Application of the Radon Transform to Calibration of the NASA-Glenn Icing Research Wind Tunnel,” Contemporary Mathematics, Vol. 278, pp. 147-166, 2001

⁴Bencic, T., Fagan, A., Van Zante, J., Kirkegaard, J., Rohler, D., Izen, S., “*Advanced Optical Diagnostics for Ice Crystal Cloud Measurements in the NASA Glenn Propulsion Systems Laboratory*,” 5th AIAA Atmospheric and Space Environments Conference, San Diego, CA. June 24-27, 2013