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

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AIAA Aviation 2019
Dallas, TX
June 17-21, 2019

AIAA-2019-3130641

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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

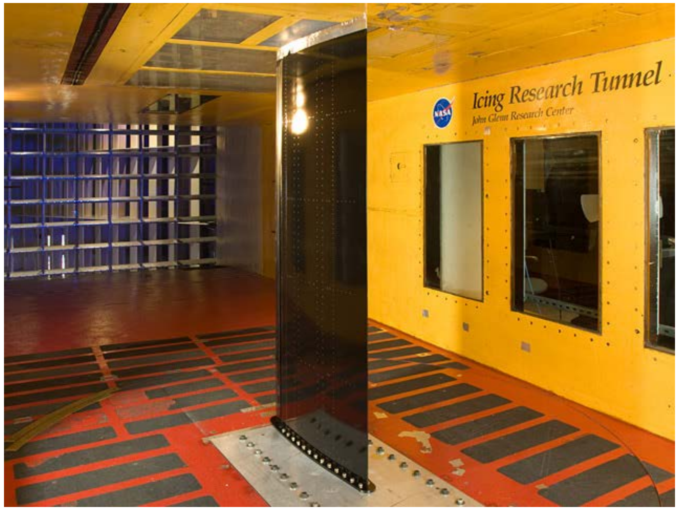
- These measurements are currently acquired through manual means during periodic calibrations of the IRT cloud conditions
    - Labor intensive and time consuming
    - Assumes cloud uniformity does not greatly vary between calibrations

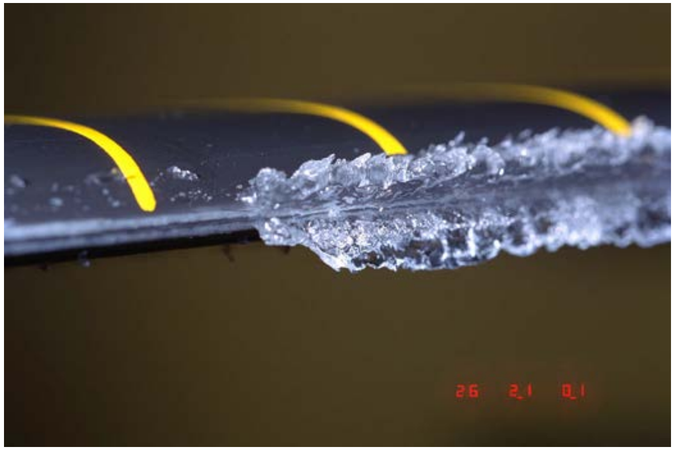
- Goal: Provide the measurements in-situ and in "real-time" to minimize need for manual measurements
    - Allow facility operators to detect any changes in icing spray conditions between calibrations

IRT - Ice accretion testing

Video of an icing cloud spray

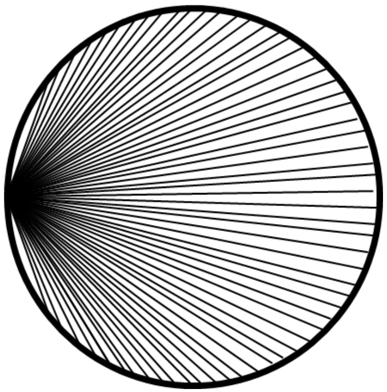
IRT – Test Section Photos, Typical Experiments





Background

- Light Extinction Tomography first envisioned for use on icing clouds in the late 1990s - early 2000s by Timothy Bencic, NASA GRC[1-3]
  - 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



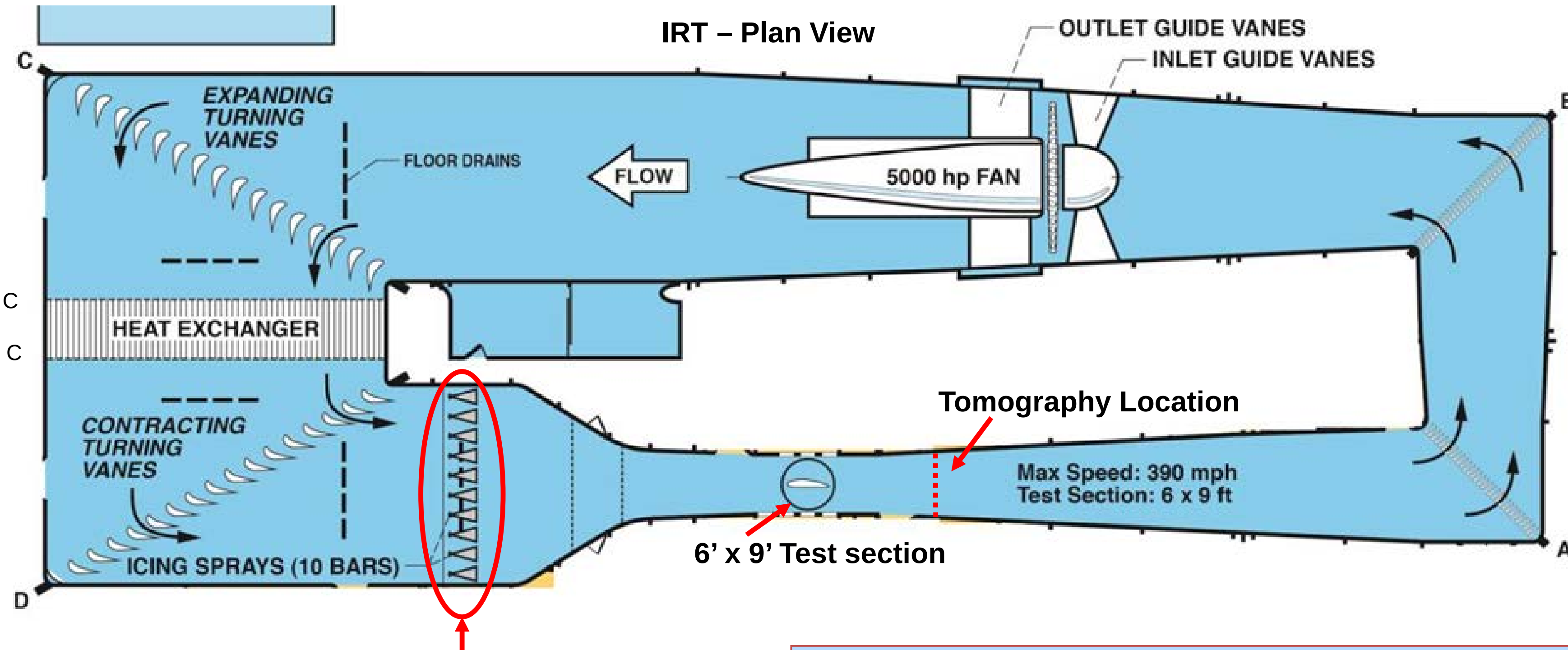
Tomography Model Example

- Light Extinction Tomography developed and successfully implemented in the NASA GRC Propulsion Systems Laboratory (PSL) in the 2010 to 2013 timeframe[4]
  - Circular geometry, 60 sources, 120 detectors, 36" diameter ➔ 1018 in^2
  - 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 in^2

- Prototype system completed in 2017
- ***Proof-of-Concept test successfully demonstrated in the IRT early 2018***

IRT Facility Description



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

IRT Spray Bars

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

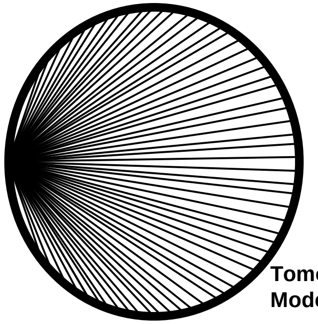
- 6’ by 6’ grid physically bolted in the test section.
- Mesh elements are 6” by 6”, 2” deep with a flat 1/8” face for ice accretion
- Facility is operated and the grid is exposed to an icing spray for a given period of time. Ice is accreted on the exposed face of the grid.
- Facility is shut down, a 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)



Tomography Model Example

- 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 applied[2]
- 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

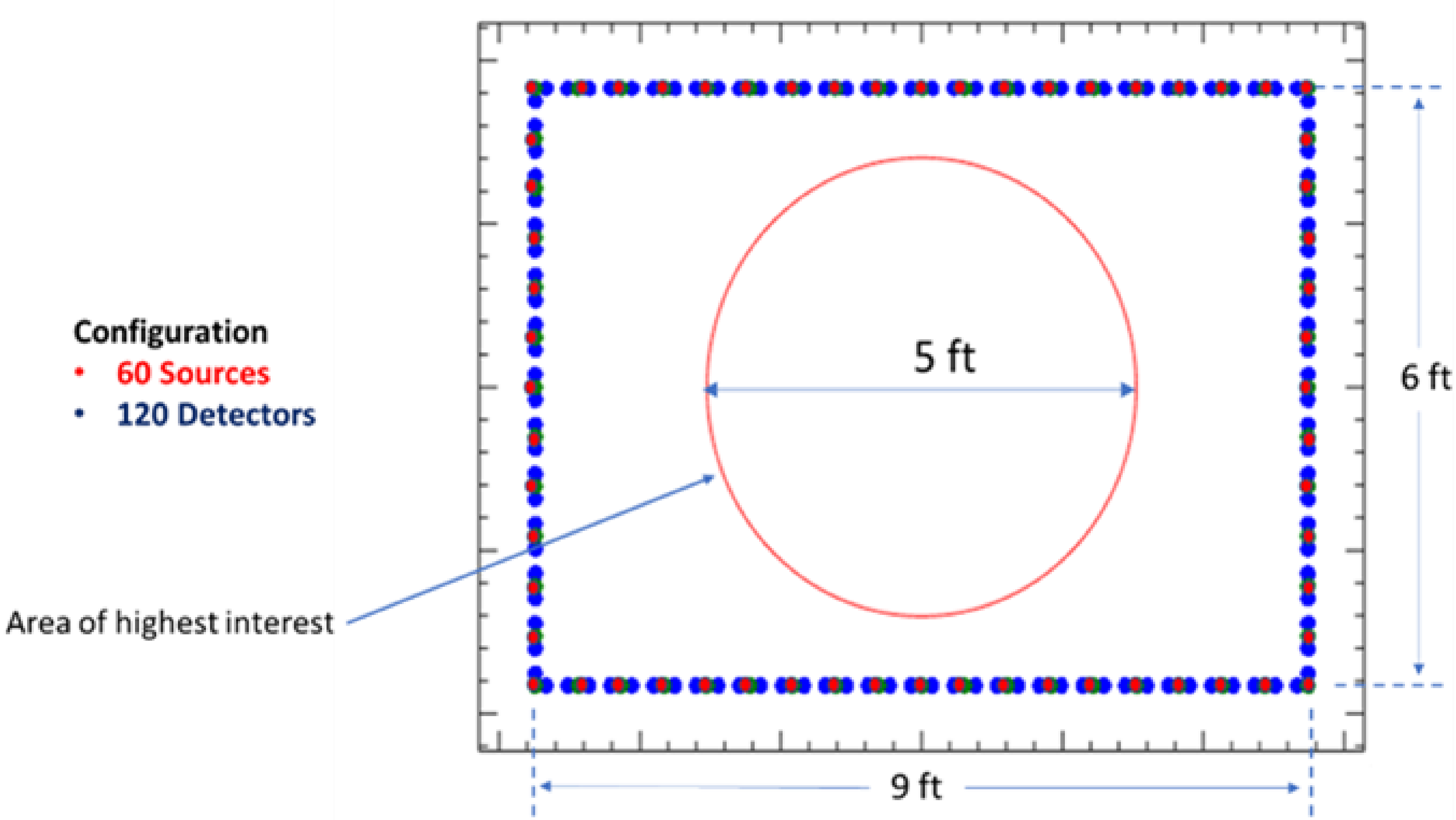
$\mu(x)$, Attenuation coefficient for the spray

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, Bencic[3] and used for the PSL application[4]
  - 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

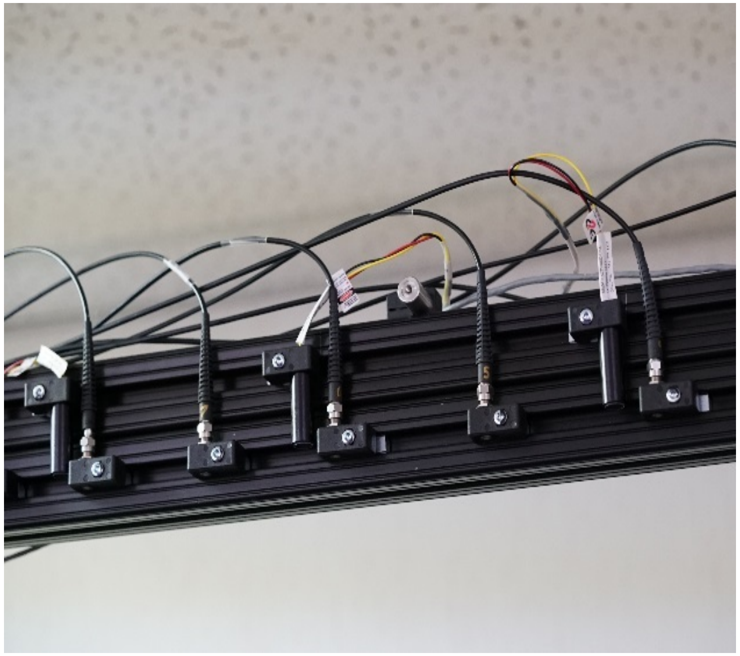


Spaced at equiangular distances around the periphery of the measurement plane

- 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

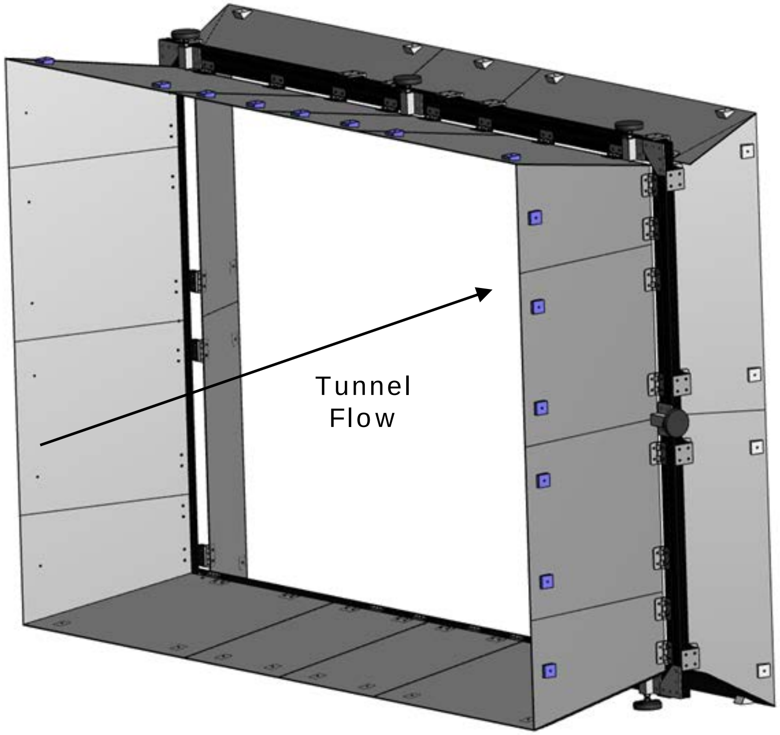
Area scan camera to fiber interface

- 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

- 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

CAD model of facility installation



- 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)

<u>Installation Compromises</u>

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

Final system installation (forward looking aft)

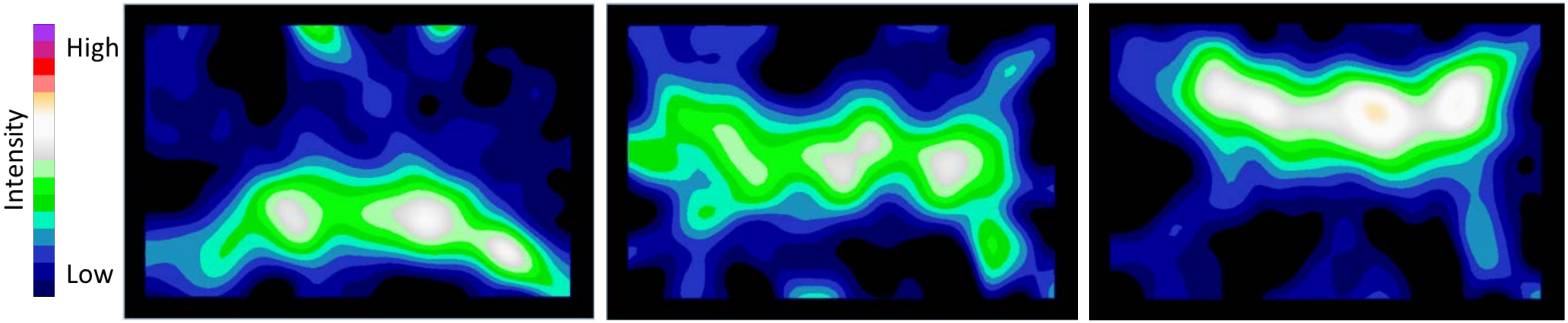
Demonstration Test Plan and Execution

<u>Four (4) main categories of test conditions</u>

- **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



Lower spray bar only **Middle spray bar only** **Upper spray bar only**

- 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 um, LWC** = 1.39 g/m^3)
  - Mod1 (MVD = 21.5 um, LWC = 0.70 g/m^3)

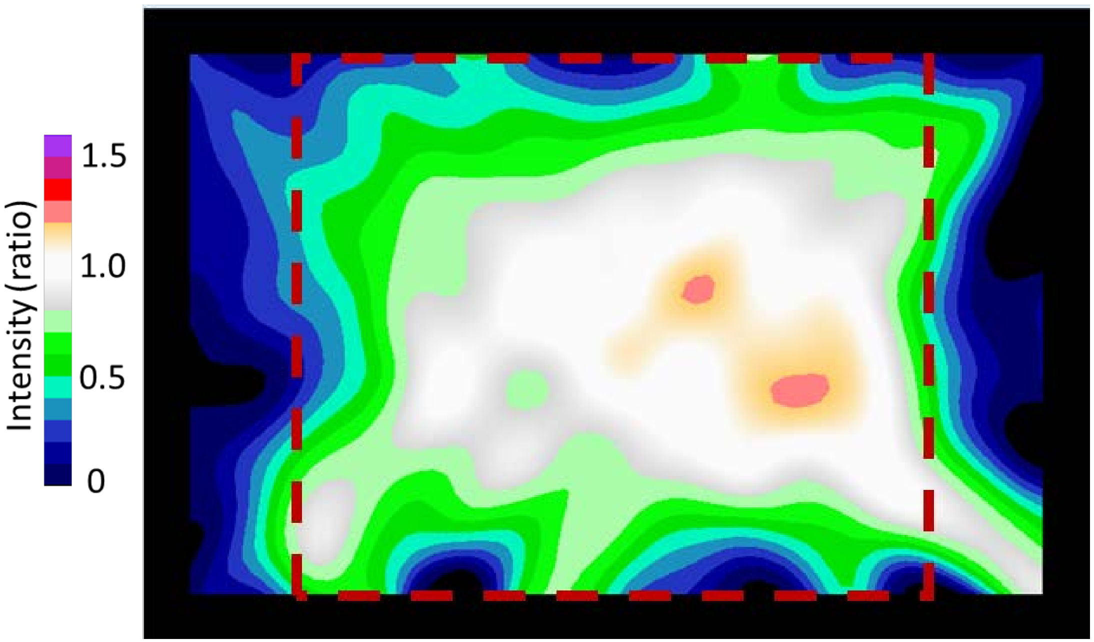
- Main purpose was to compare to existing LWC uniformity plots derived from previous calibrations

- Conditions were repeated seven (7) times each as a means of assessing measurement variability

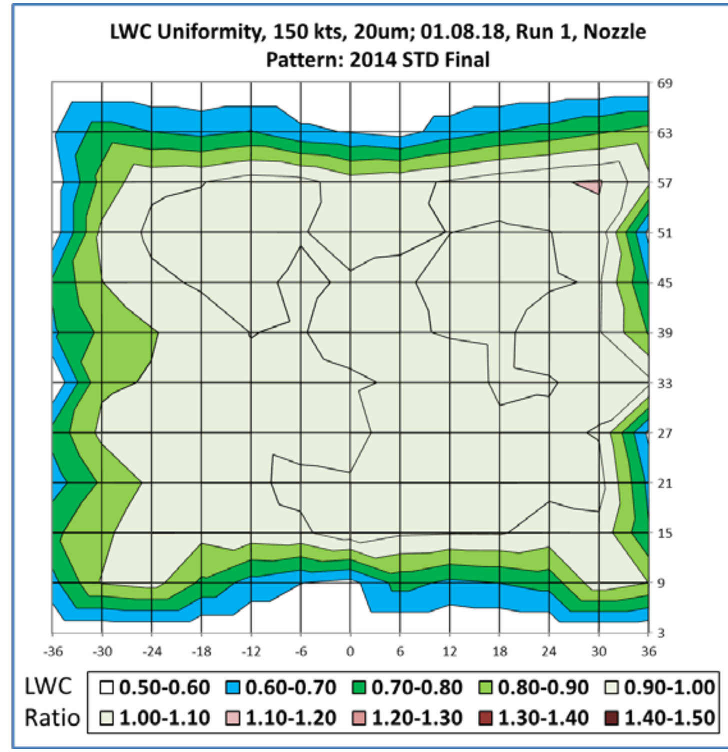
- Only the results from the Standard Baseline Grid Spray comparison will be shown in this presentation.

* Mean Volumetric Diameter (MVD)
** Liquid Water Content (LWC)

Results / Analysis – Standard Baseline Grid Spray



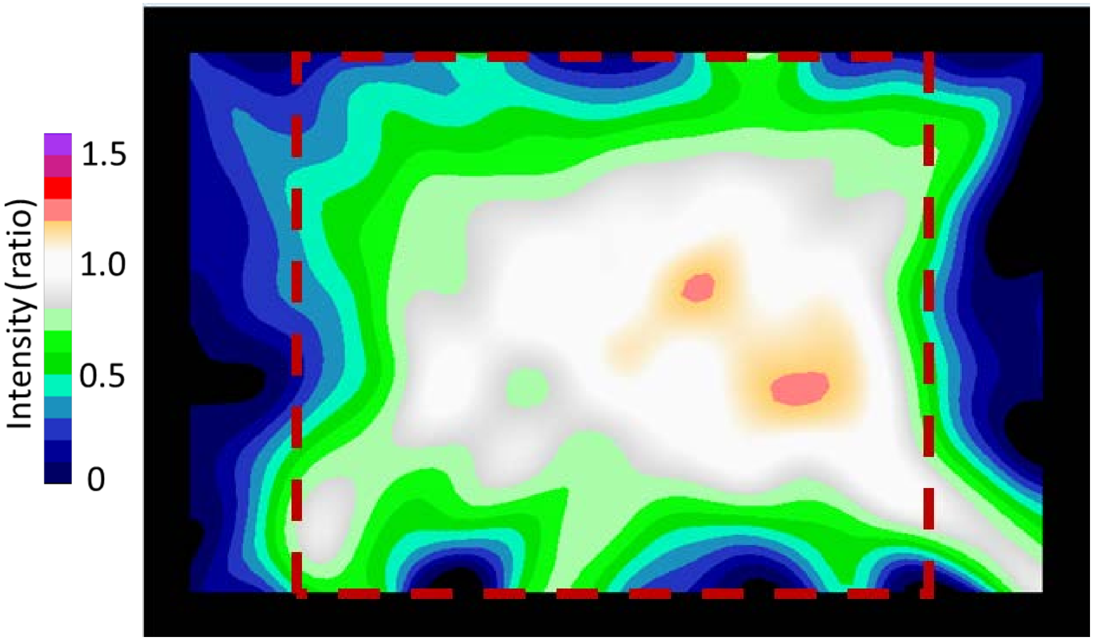
Mean Tomographic Reconstruction (7 test runs)



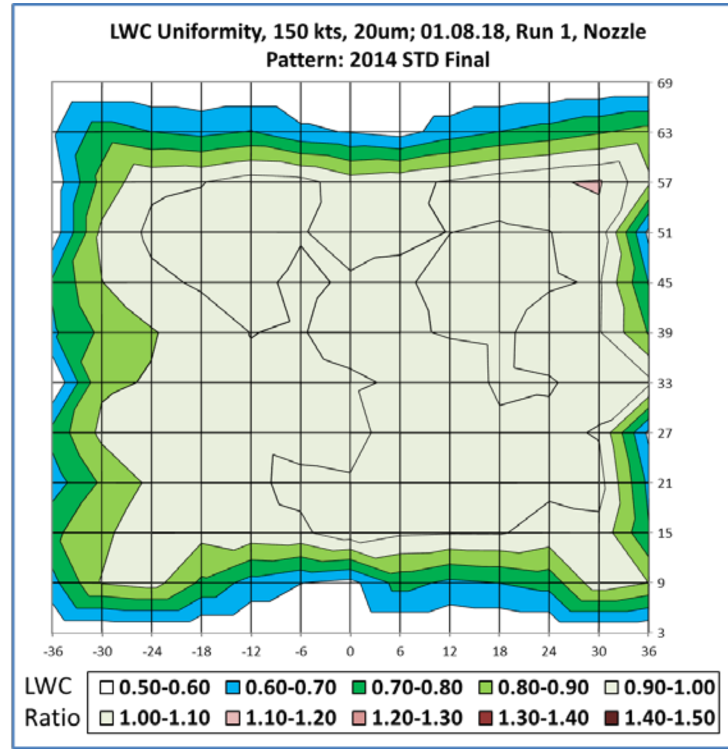
Calibration grid map from Jan 2018

- 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



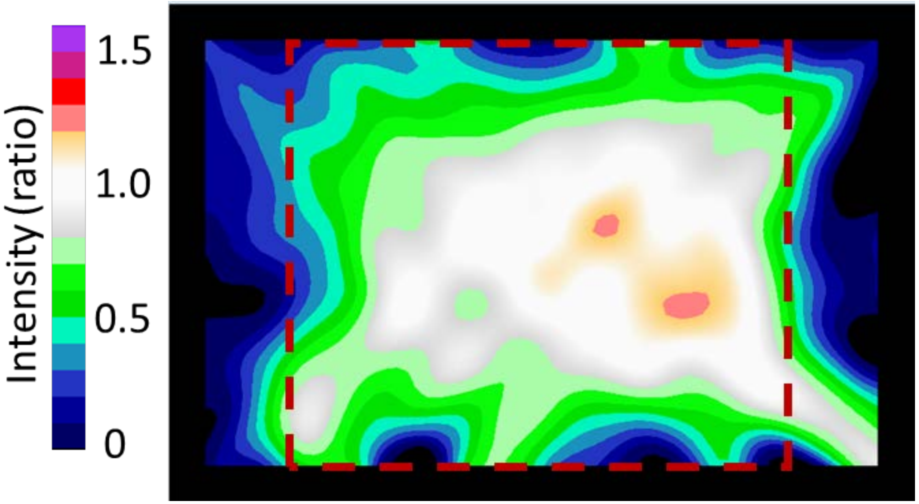
Mean Tomographic Reconstruction (7 test runs)



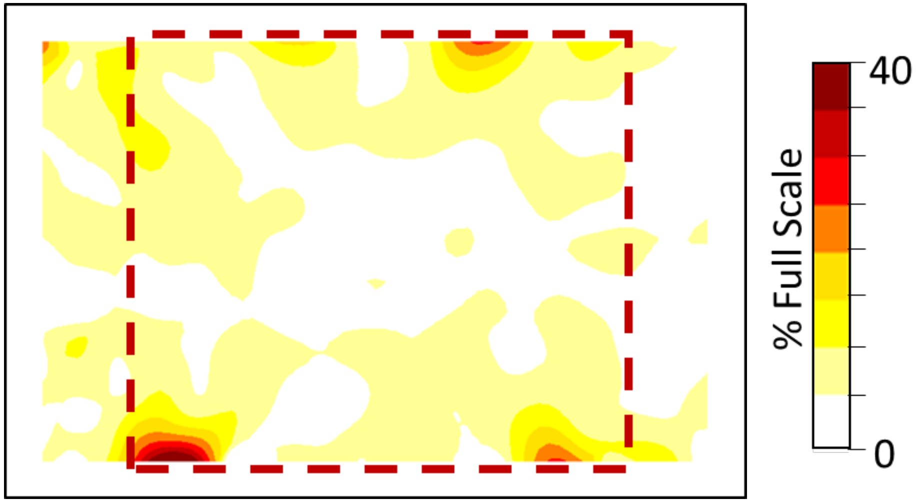
Calibration grid map from Jan 2018

- 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



Mean Tomographic Reconstruction (7 test runs)



Standard Deviation (7 test runs)

- 0 to 10% variation from reading-to-reading shown in the standard deviation plot in the center region of the core flow
- This is with in reason and with-in what was expected

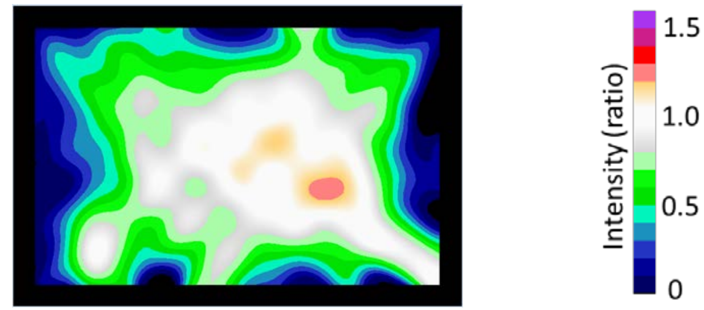
✓ **Overall, regardless of slight differences observed from the calibration maps, the measurements matched the overall shape of the uniformity plots and ratios generated by the manually measured grid.**

✓ **Showed that the system has potential to make the desired cloud uniformity measurements in the IRT**

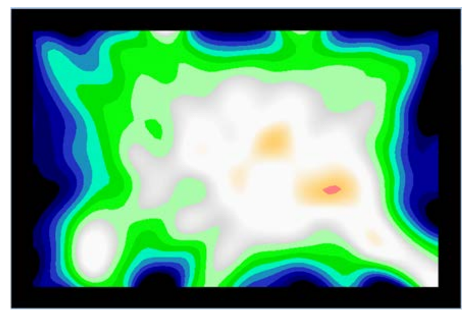
Results / Analysis – Sensitivity Checks

- 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**

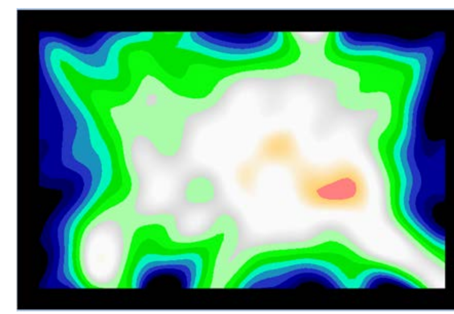
✓ Intensity does vary as f(x) of LWC



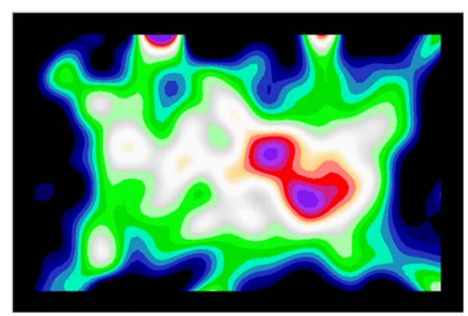
Mod1 Baseline, MVD=21.5 µm, LWC=0.70 g/m3



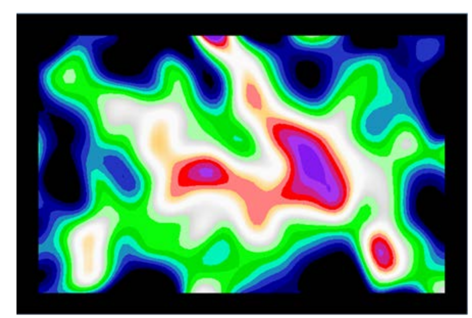
Mod1, MVD=15.3 µm, LWC=0.43 g/m3



Mod1, MVD=40.9 µm, LWC=1.19 g/m3



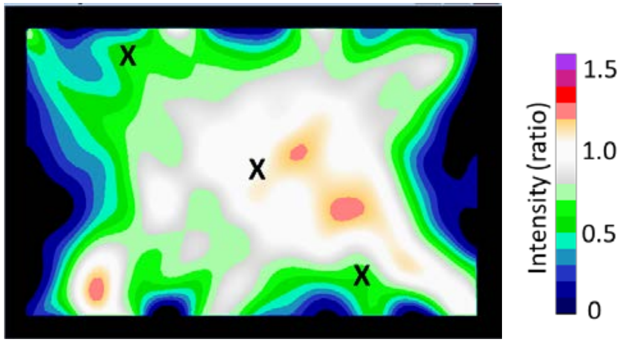
Mod1, MVD=266 µm, LWC=0.92 g/m3



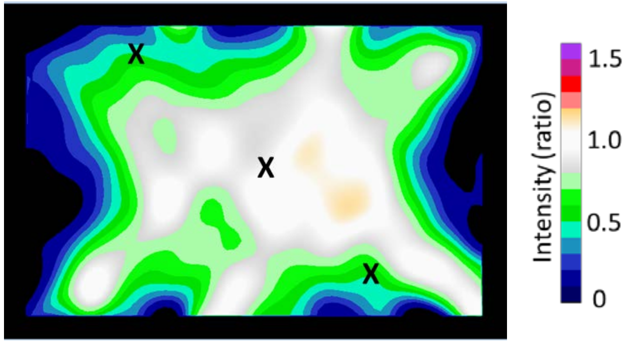
Mod1, MVD=460 µm, LWC=1.26 g/m3

Results / Analysis – Tomographic Exercises

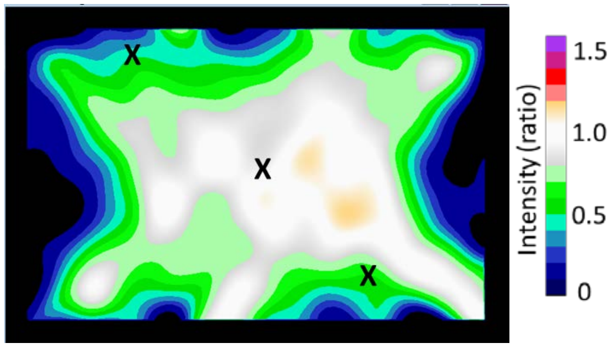
- **Purpose was to see if tomography system could detect changes due to anomalies in the spray bar system**
- Simulated “anomalies”
  - Used a high number density (ND) “Standard” spray
    - MVD=15.4 um, LWC=1.52 g/m^3
  - Turned three (3) Standard nozzles off
    - Upper LH corner, Center, Lower RH 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

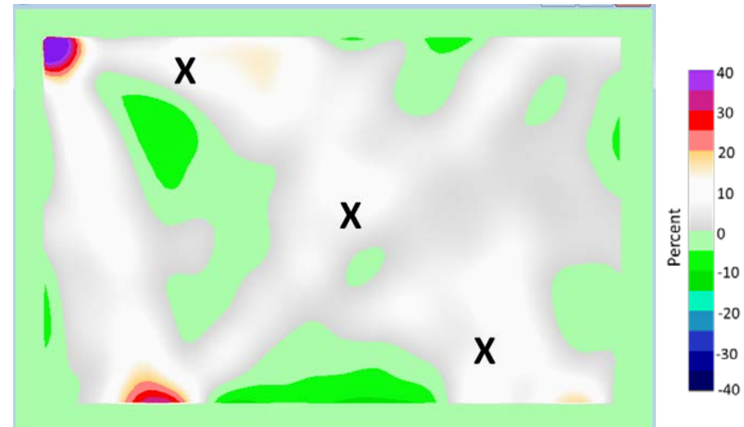


#3-Three Standard nozzles off, three Mod1 nozzles on

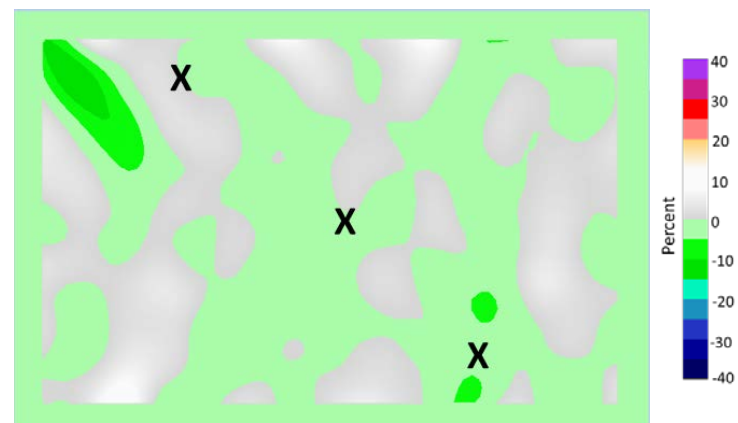
Results / Analysis – Tomographic Exercises

- 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 due 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

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

[2]Lock, 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

[3]Izen, 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

[4]Bencic, 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