Ice Growth Measurements from Image Data

to Support Ice-Crystal and Mixed-Phase Accretion Testing

This paper describes the imaging techniques as well as the analysis methods used to measure the ice thickness and growth rate in support of ice-crystal icing tests performed at the National Research Council of Canada (NRC) Research Altitude Test Facility (RATFac). A detailed description of the camera setup, which involves both still and video cameras, as well as the analysis methods using the NASA Spotlight software, are presented. Two cases, one from two different test entries, showing significant ice growth are analyzed in detail describing the ice thickness and growth rate which is generally linear. Estimates of the bias uncertainty are presented for all measurements. Finally some of the challenges related to the imaging and analysis methods are discussed as well as methods used to overcome them.

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to Support Ice-Crystal and Mixed-Phase Accretion Testing

- **Peter M. Struk**
- *NASA Glenn Research Center, Cleveland, Ohio*

- **Christopher J. Lynch**
- *Wyle Information Systems, Cleveland, Ohio, 44135*

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- *American Institute of Aeronautics and Astronautics*

Outline

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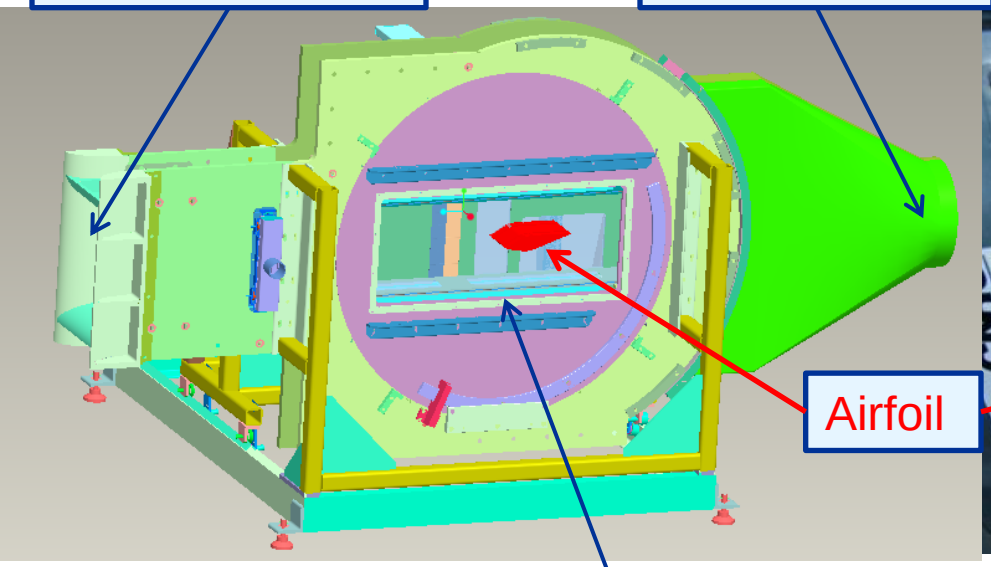
- **Acknowledgements**

Introduction

- **Experiments underway to understand fundamentals of mixed-phase and ice crystal icing in jet engines**
  - NASA & NRC collaborations have had 3 test entries:
    - Nov 2010
    - Mar 2011
    - Mar & Apr 2012
- **Traditional methods of recording ice shapes (e.g. tracings and castings) were not easily adaptable to this experiment**
- **Experiments have gathered numerous still & video imagery**
  - Goal is to extract 2D and 3D shapes from imagery
  - As a first step, leading edge ice-growth measured and is the focus of this paper

Test Facility

- **Tests conducted in an icing cascade tunnel located in NRC Research Altitude Test Facility (RATFac) altitude chamber.**



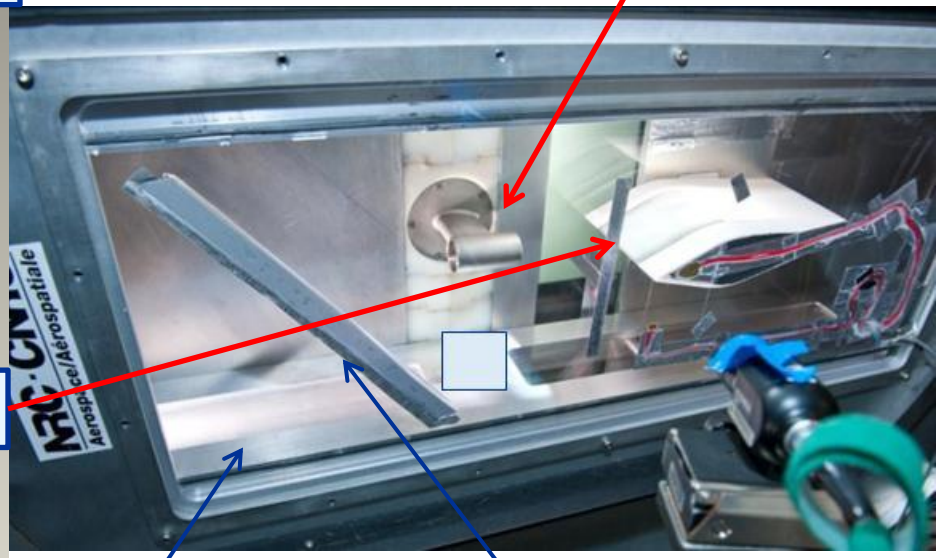
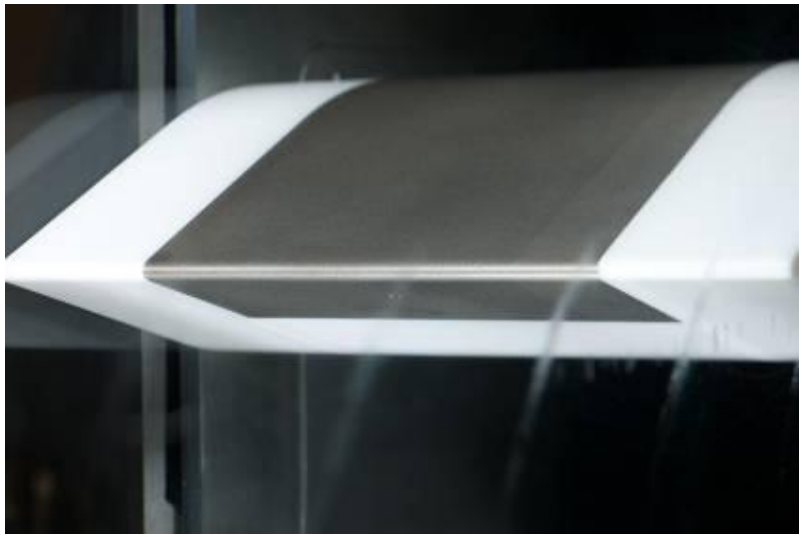
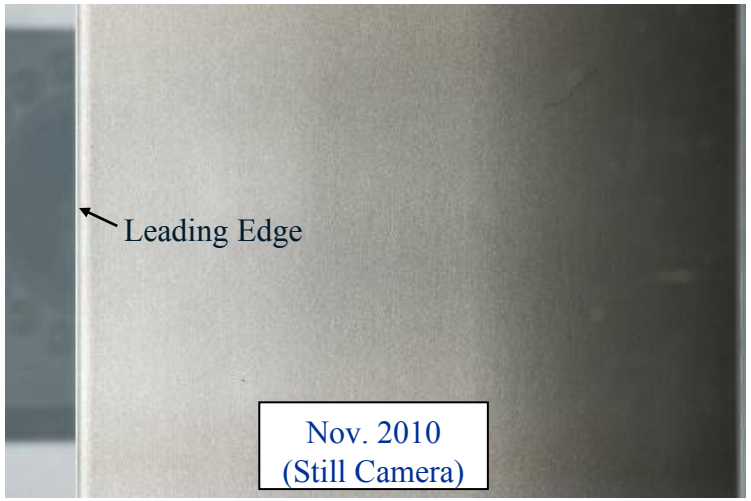
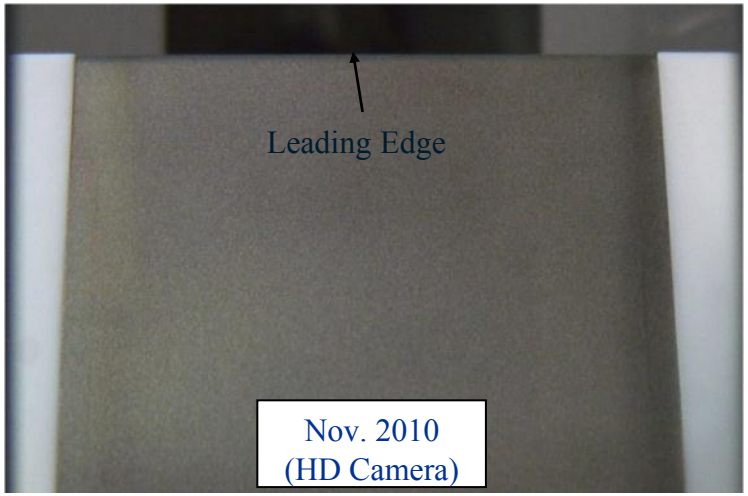


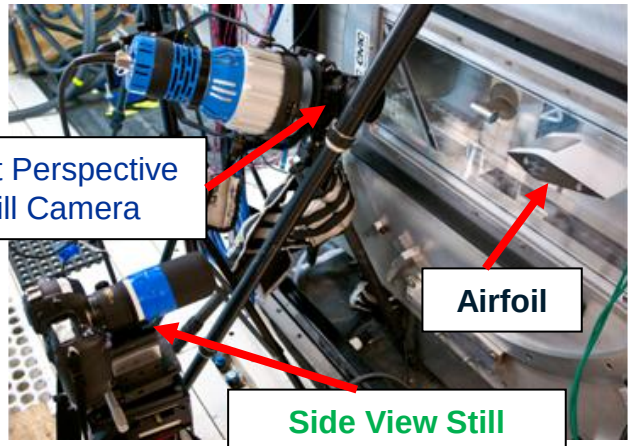
Image Views

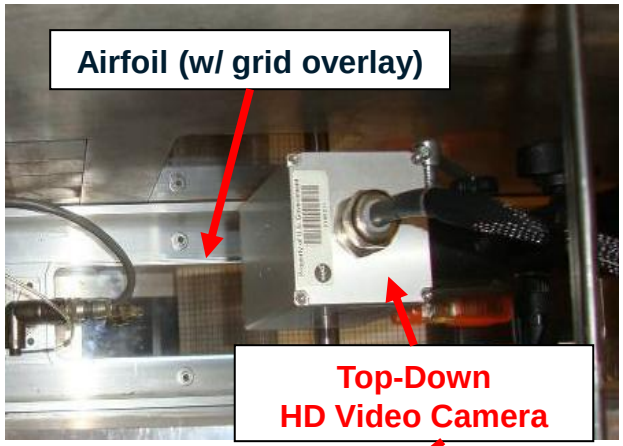


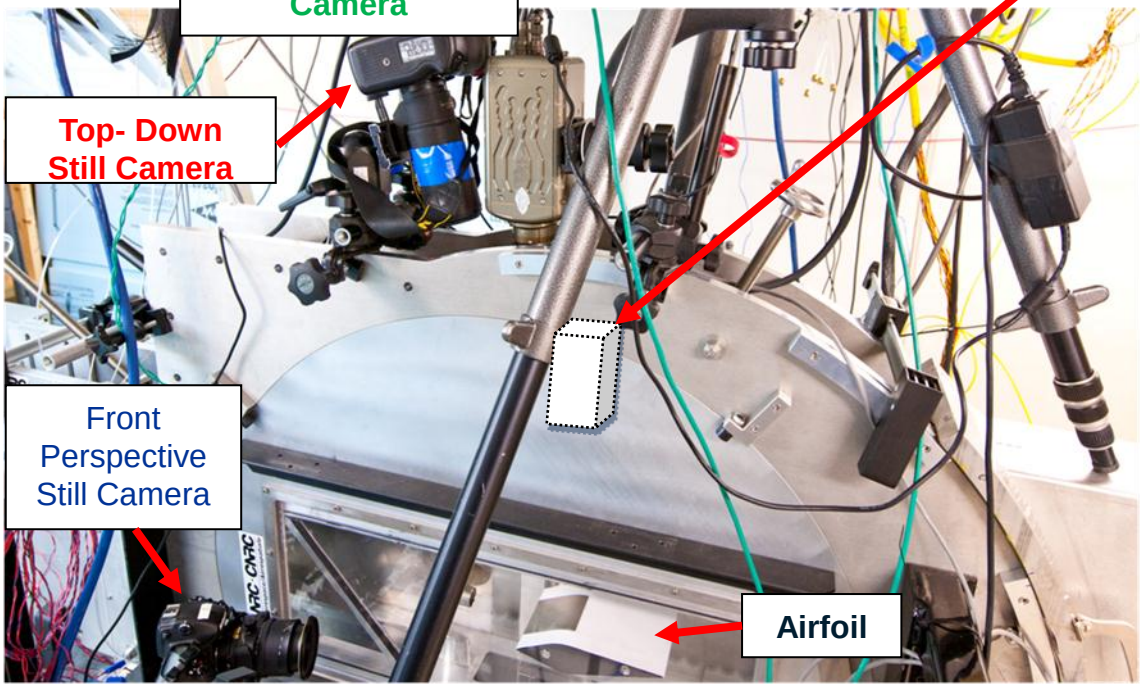

Leading Edge
Nov. 2010
(Still Camera)

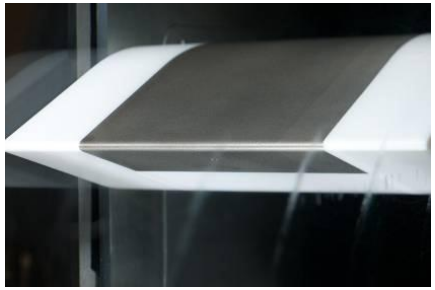

Leading Edge
Nov. 2010
(HD Camera)

Camera Setup – November 2010

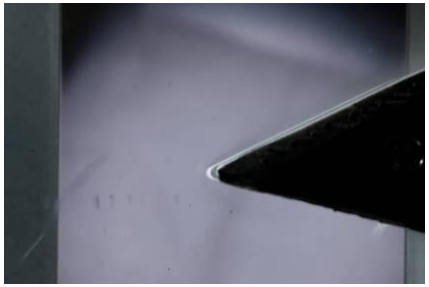








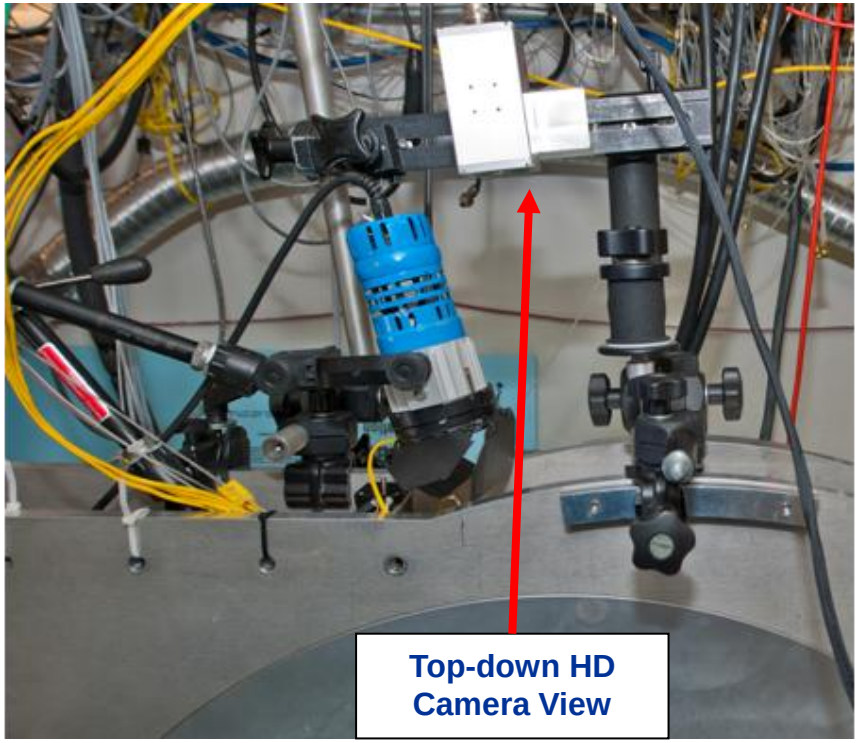
Front Perspective View

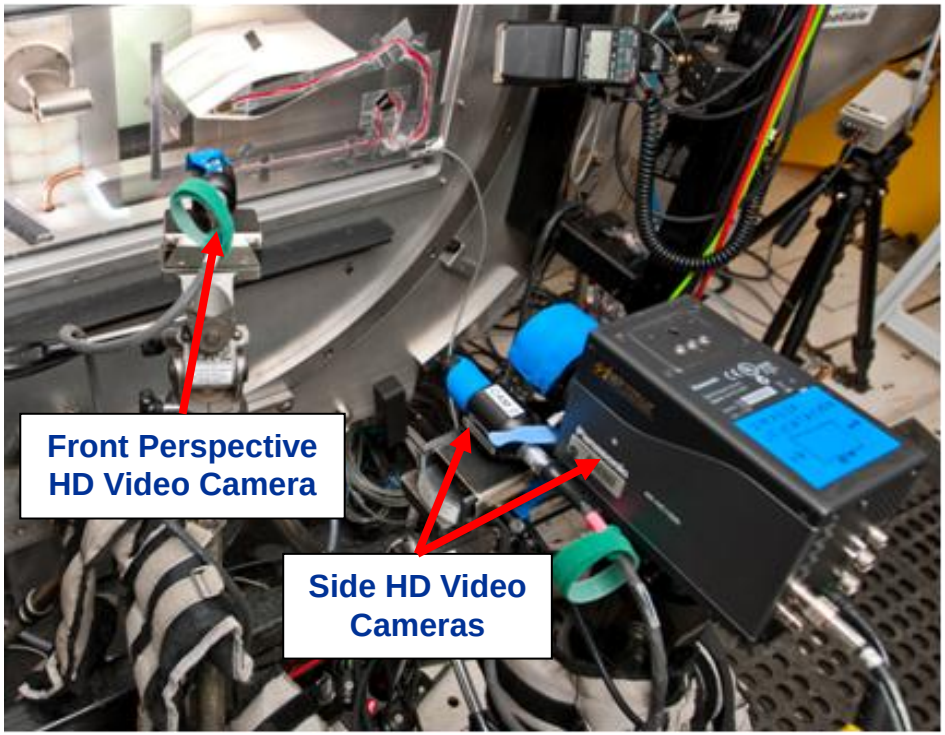


Side View

Top Down View

Camera Setup – March 2011



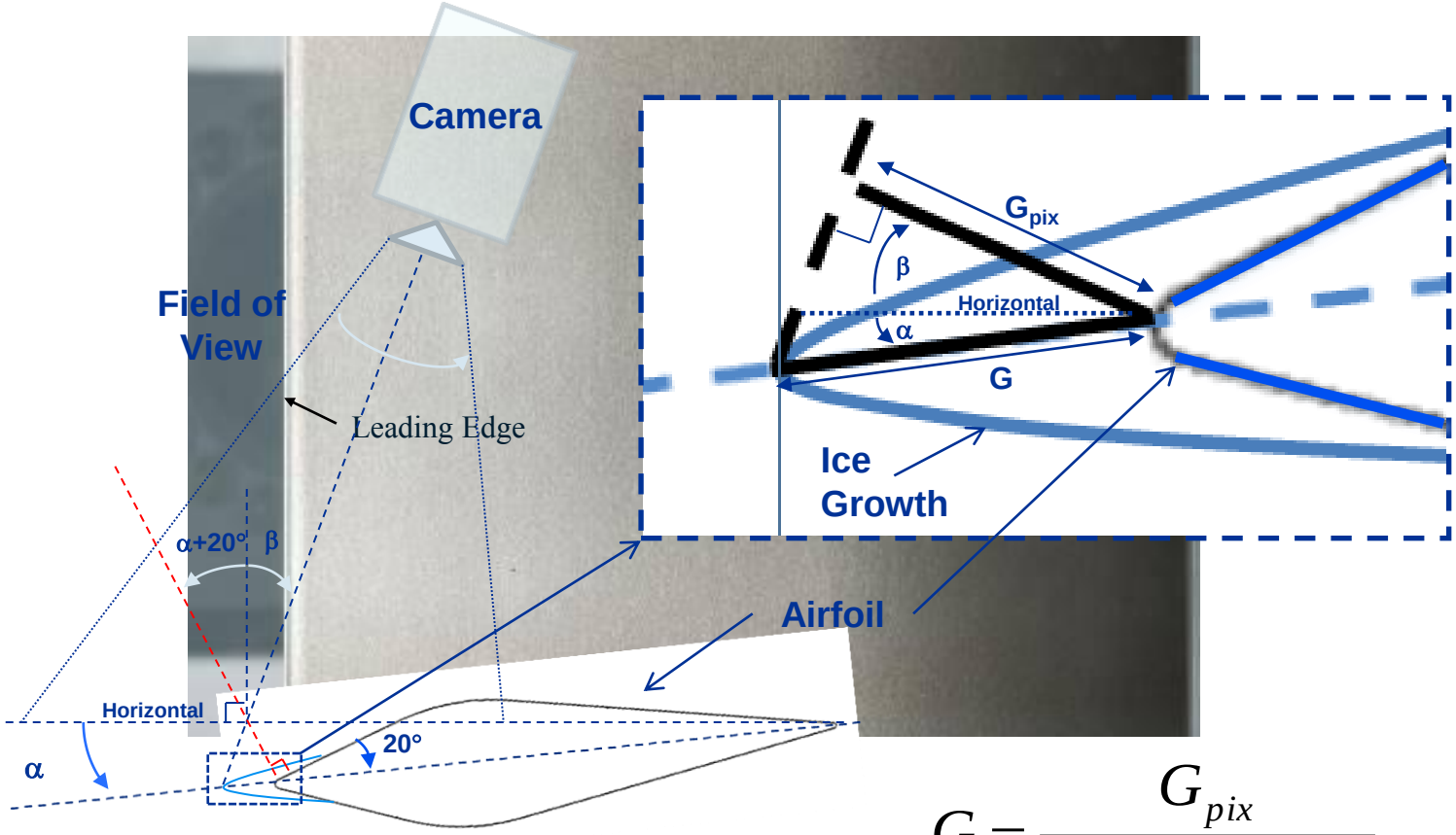


HD Video Cameras:

Sony FCB-H11 (1280x720P)
Iconix HD-RH1 (1280x720 P)
Panasonic AK-HC1500 (1280x720 P)

Image Analysis

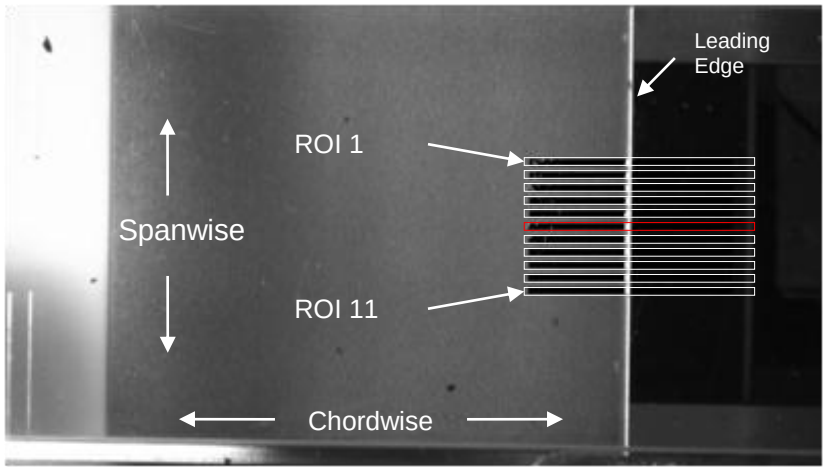
Objective: Measured leading edge ice thickness as a function of time

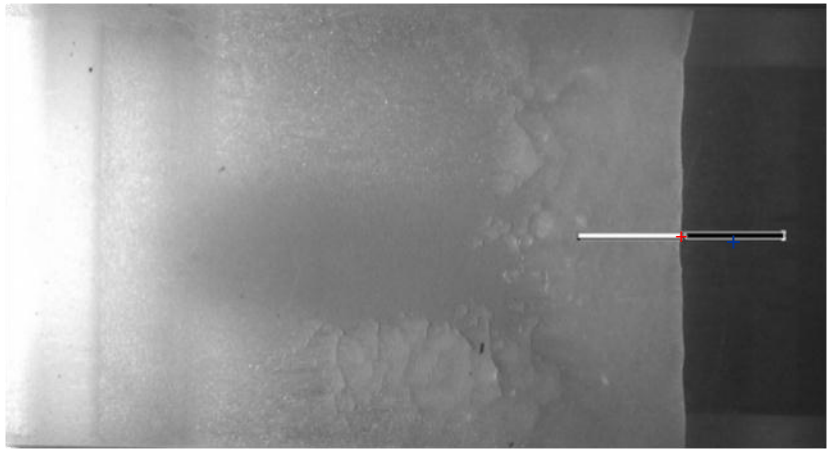


$$G = \frac{G_{pix}}{S \cdot \cos(\alpha + \beta)}$$

Measurement Process (1 of 2)

- **Region of interest (ROI) definition**
  - 11 pix spanwise x 200 pix chordwise
  - Single or multiple ROIs used
  - Measurement (red cross +) constrained to spanwise midpoint of a given ROI
- **Edge Detection**
  - Needed to determine threshold grey level corresponding to ice edge
  - Linear contrast stretch enhancement in ROI (see next slide)
  - Used constant intensity for most cases
  - Typically looked for edge from right to left
- **Automated Analysis**
  - At 60 fps → 10,800 frame in 3 min.
  - Software would proceed frame by frame until it failed to detect an edge
  - Can watch analysis in graphically





Measurement Process (2 of 2)

- **Multiple ROIs effective for non-uniform spanwise accretion cases**

- **Obscuration issue due to water or ice runback:**
  - Create masking ROI to cover airfoil
  - Larger contrast adjustment region was required.
  - Looked for edge from left to right
  - In one case (thus far), manual measurements were required

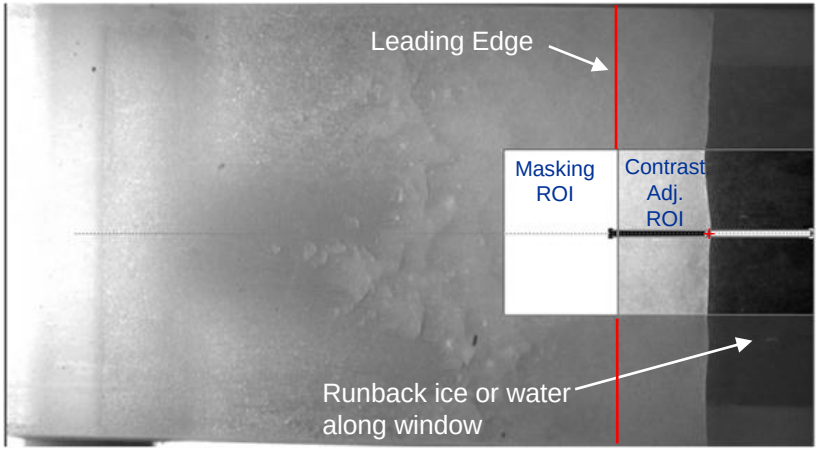


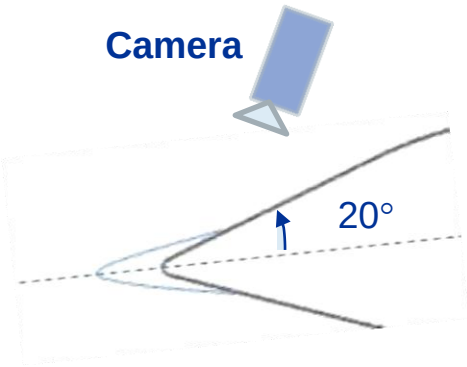
Image to Physical Size Scaling (Nov – 2010)

- **Scale factor S**
  - Image units (pixels) to physical units (mm)
  - Perspective effect
    - Not primary view
    - ~36° (20°+6°+ ~10°) between imaging plane & airfoil cover
    - Square pixels
  - Calculated S at ½ ice thickness
    - Not precisely same plane as ice growth
    - Contributes to uncertainty

$$S = \frac{l_p}{l_a}$$

pixel length

actual length



$$S = 13.003 \pm 0.093 \frac{pix}{mm}$$

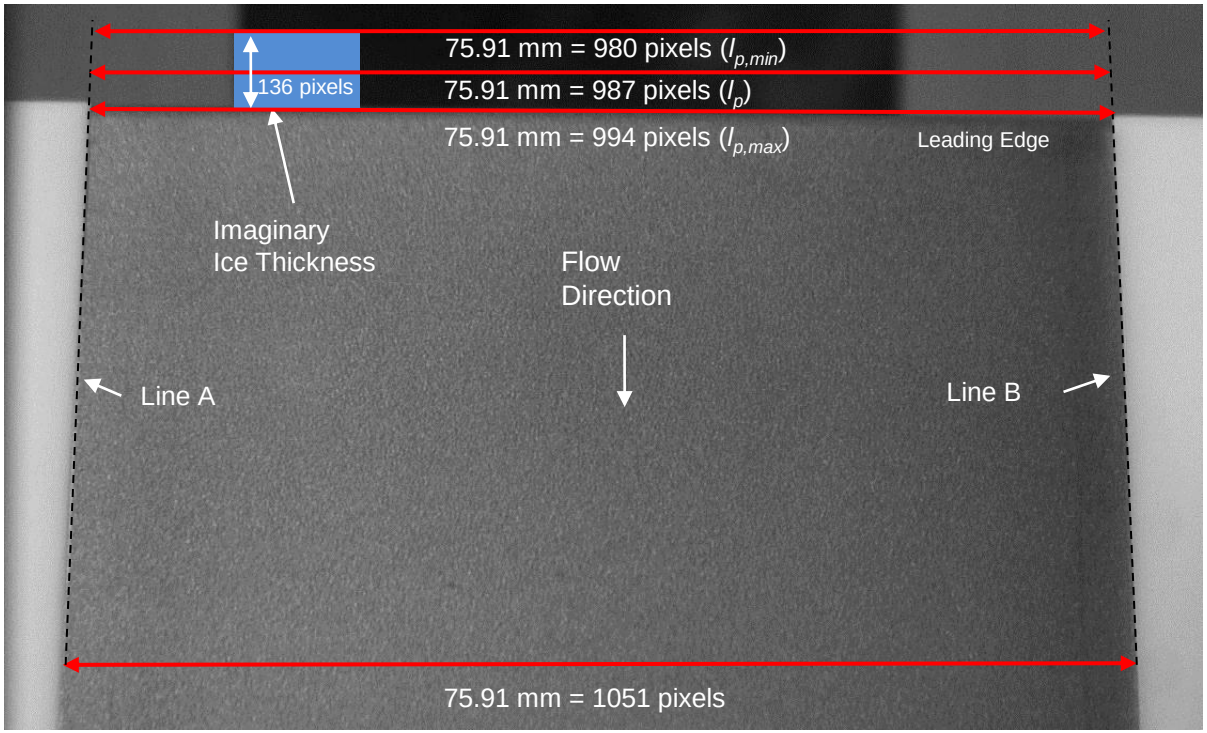
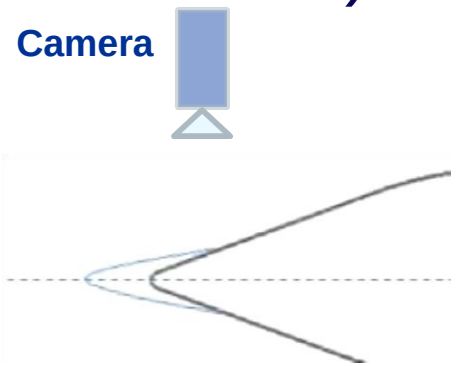


Image to Physical Size Scaling (Mar – 2011)

- **Grid overlay used**
  - Printed on transparency
  - 220±0.4 mm = 43 squares
  - Each grid 5.12 ± 0.01 mm

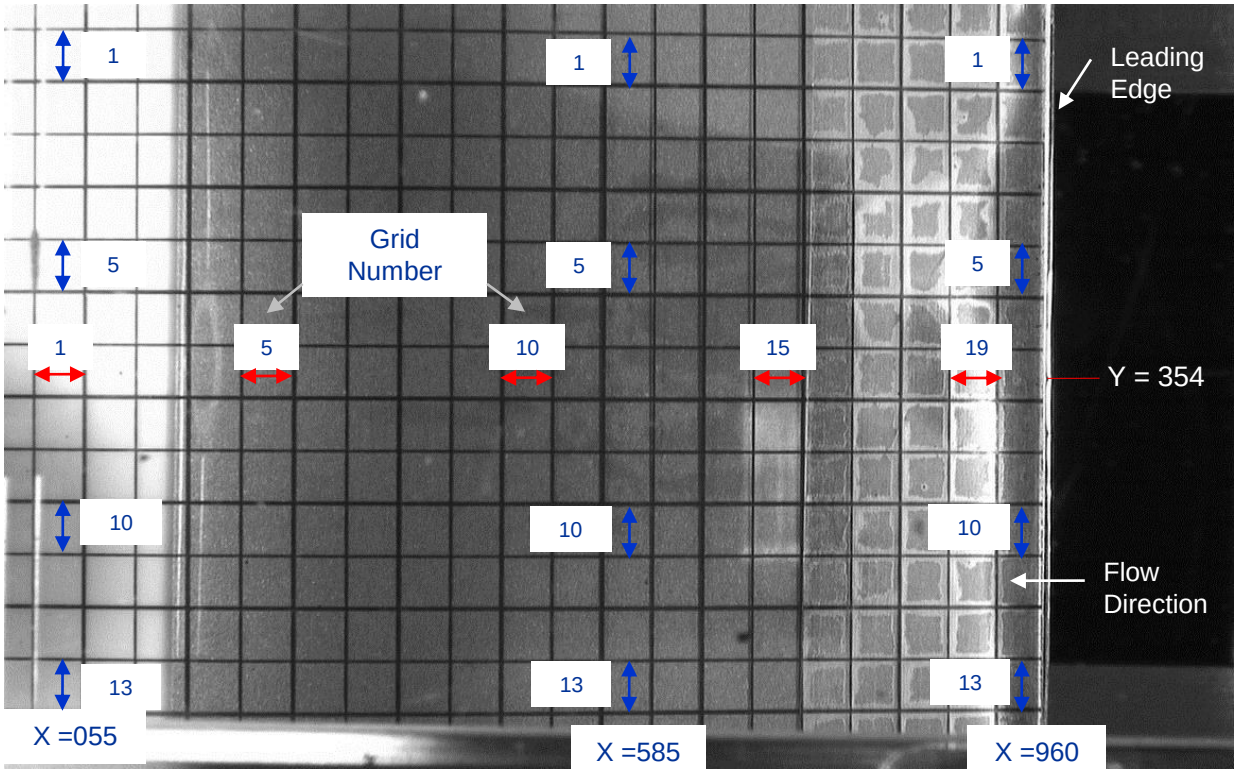
$$S = \frac{l_p}{l_a}$$



- **Perspective effect**
  - Now video primary view
  - Ice growth plane & imaging plane parallel
  - ~20° between imaging plane & airfoil cover

- **Used S at leading edge**
  - 631 ± 2 pixels
  - 66.56 ± 0.13 mm

$$S = 9.480 \pm 0.035 \frac{pix}{mm}$$



Uncertainty Calculation

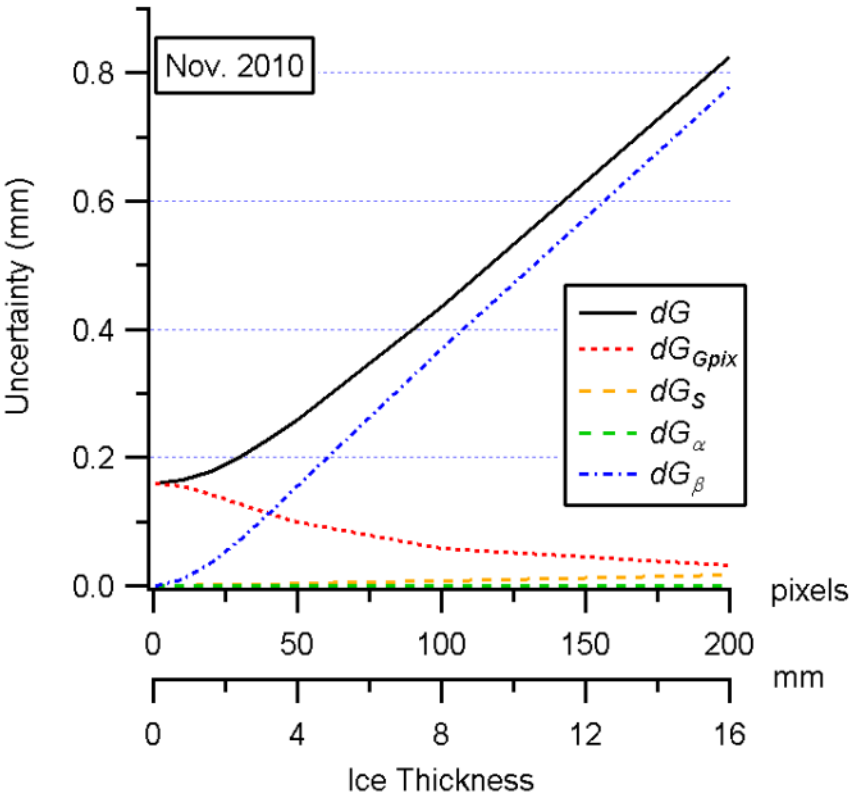
$$G = \frac{G_{pix}}{S \cdot \cos(\alpha + \beta)} \rightarrow dG = \left(\left[\frac{\partial G}{\partial G_{pix}} dG_{pix} \right]^2 + \left[\frac{\partial G}{\partial S} dS \right]^2 + \left[\frac{\partial G}{\partial \alpha} d\alpha \right]^2 + \left[\frac{\partial G}{\partial \beta} d\beta \right]^2 \right)^{1/2}$$

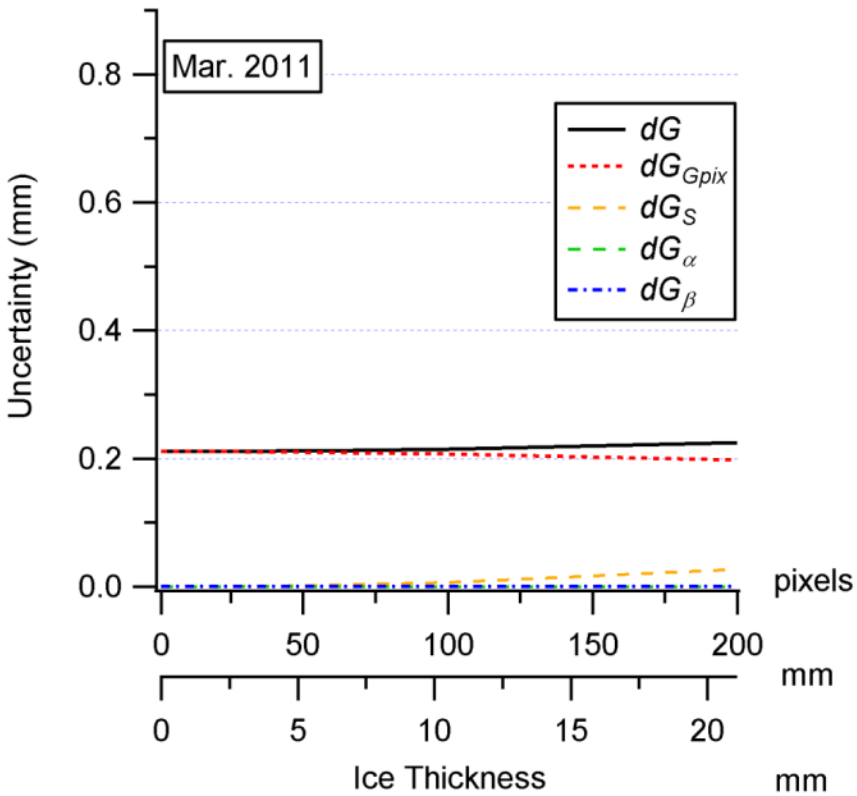
$$\frac{\partial G}{\partial G_{pix}} = \frac{1}{S \cdot \cos(\alpha + \beta)} \qquad \frac{\partial G}{\partial S} = \frac{-t_{pix}}{S^2 \cdot \cos(\alpha + \beta)} \quad \cdots \leftarrow$$

Sensitivity Coefficients

Parameter	Date	Case	Value	Uncertainty
G_{pix}	Nov. 2010	All	0-200 pixels	±2 pixels
	Mar. 2011	All	0-200 pixels	±2 pixels
S	Nov. 2010	144	13.003 pix/mm	± 0.093 pix/mm
	Mar. 2011	Mar. 8	9.480 pix/mm	± 0.035 pix/mm
α	Nov. 2010	All	0 or 6°	± 0.2°
	Mar. 2011	All	0 or 6°	± 0.2°
β	Nov. 2010	All	+10°	± 10°
	Mar. 2011	All	-6°	± 3°

Uncertainty Estimate



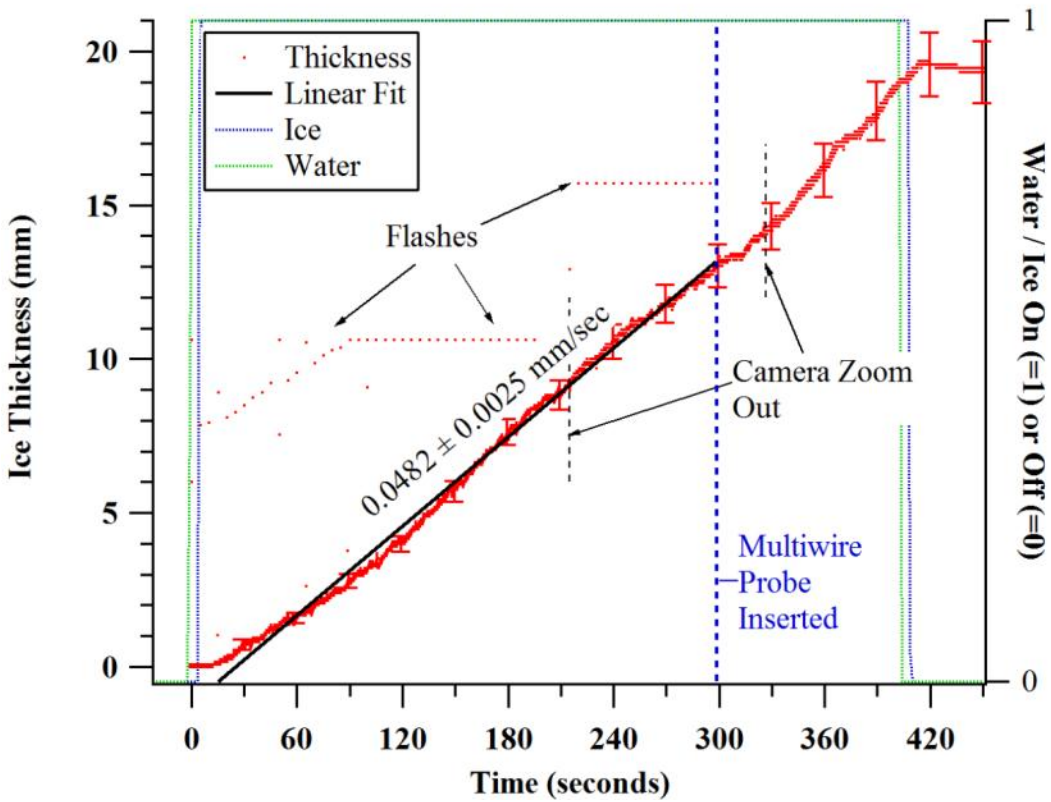


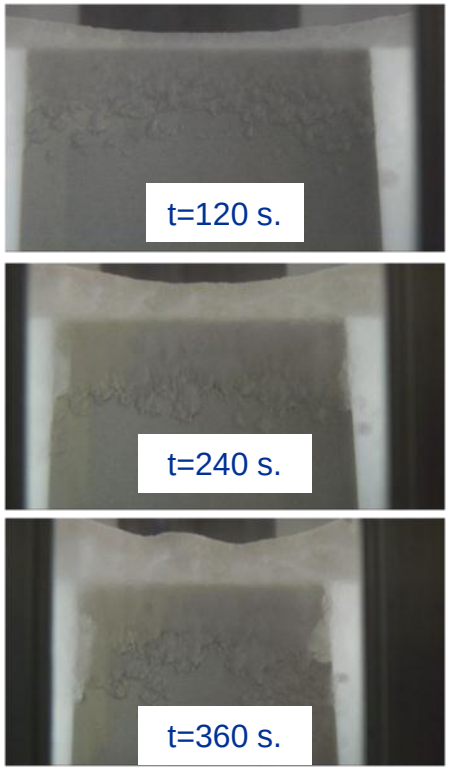
Reported uncertainty is due to measurement bias
Run-to-run variation yet to be determined

Results (1 of 2, Nov 2010)

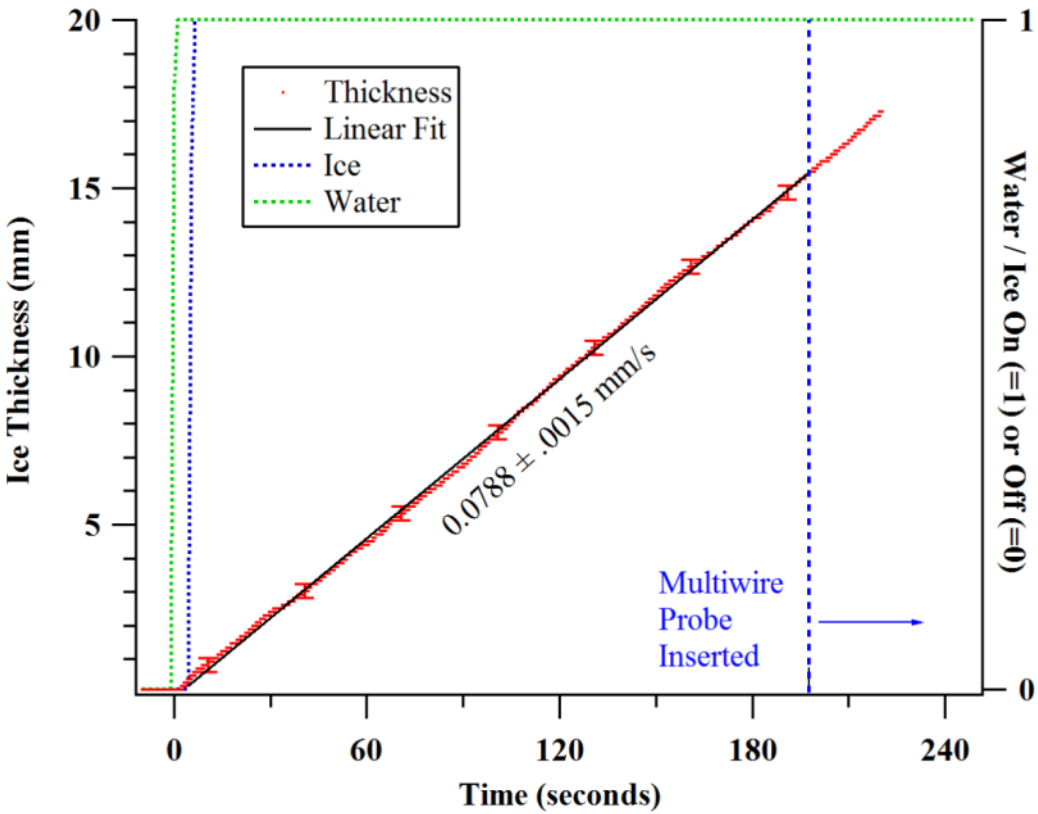
- **One case from Nov 2010 & Mar 2011**
  - Similar but not identical conditions
- **Origin at water or ice flow initiation**
  - Manual activation, ice growth delay
- **Probe inserted ~ 1 min. near end**

- **Flashes (Nov 2010) only.**
- **Thickness ~13.04 ± 0.69 mm @ 298 s.**
- **Linear curve fit ~0.0482±0.0025 mm/s**
- **Camera zoom out → changes in scale**





Results (2 of 2, Mar 2011)



- **Thickness 15.49 ± 0.22 mm @198 s.**
  - Less bias uncertainty in Mar 2011 (1.4%) compared to Nov 2010 (5.3 %)
- **Linear fit 0.0788 ± 0.0015 mm/s**
  - Uncertainty comparison Mar 2011 (~2%) compared to Nov 2010 (~5 %)
- **No camera zoom during test**

Discussion

- **Factors affecting results**

- **Camera orientation:**
  - Perspective effective can be difficult to interpret
  - More optimal angle between ice growth plane and imager in Mar 2011
  - Contributes to the bias uncertainty in measurement

- **Camera zoom**
  - Trade off between large field of view and resolution

- **Window obscuration**
  - Ice and water contamination on windows
  - Can complicate analysis but can be overcome in most cases

- **Lighting / illumination**
  - Various orientations were experimented with lessons learned

Conclusions

- **Experiments gathering image data for ice accretion**
  - Not amenable to traditional ice growth measurement techniques
  - Three test entries thus far; each entry improved imaging techniques
- **1D leading-edge ice growth measurement technique presented**
  - Used NASA Spotlight software to measure ice edge within defined ROI
  - Described scale factor for conversion from image to physical units
  - Estimated uncertainly due to measurement bias
- **Presented results, one case from Nov 2010 & Mar 2011**
  - Similar but not identical conditions leading to large ice growths
- **Bias uncertainty estimate allows case-to-case comparison**
- **Results offer a new parameter, growth rate, not previously available for icing research**

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  - Dr. Andy Broeren
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  - Mr. Dan Fuleki
  - Dr. Danny Knezevici
- **Special thanks for support of this work:**
  - Mr. Jim MacLeod
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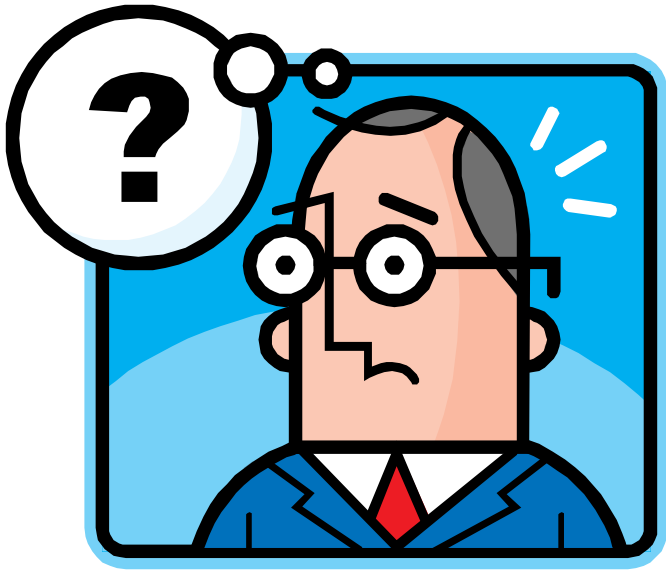
Questions



Ice Growth Measurements from Image Data

BACKUP SLIDES

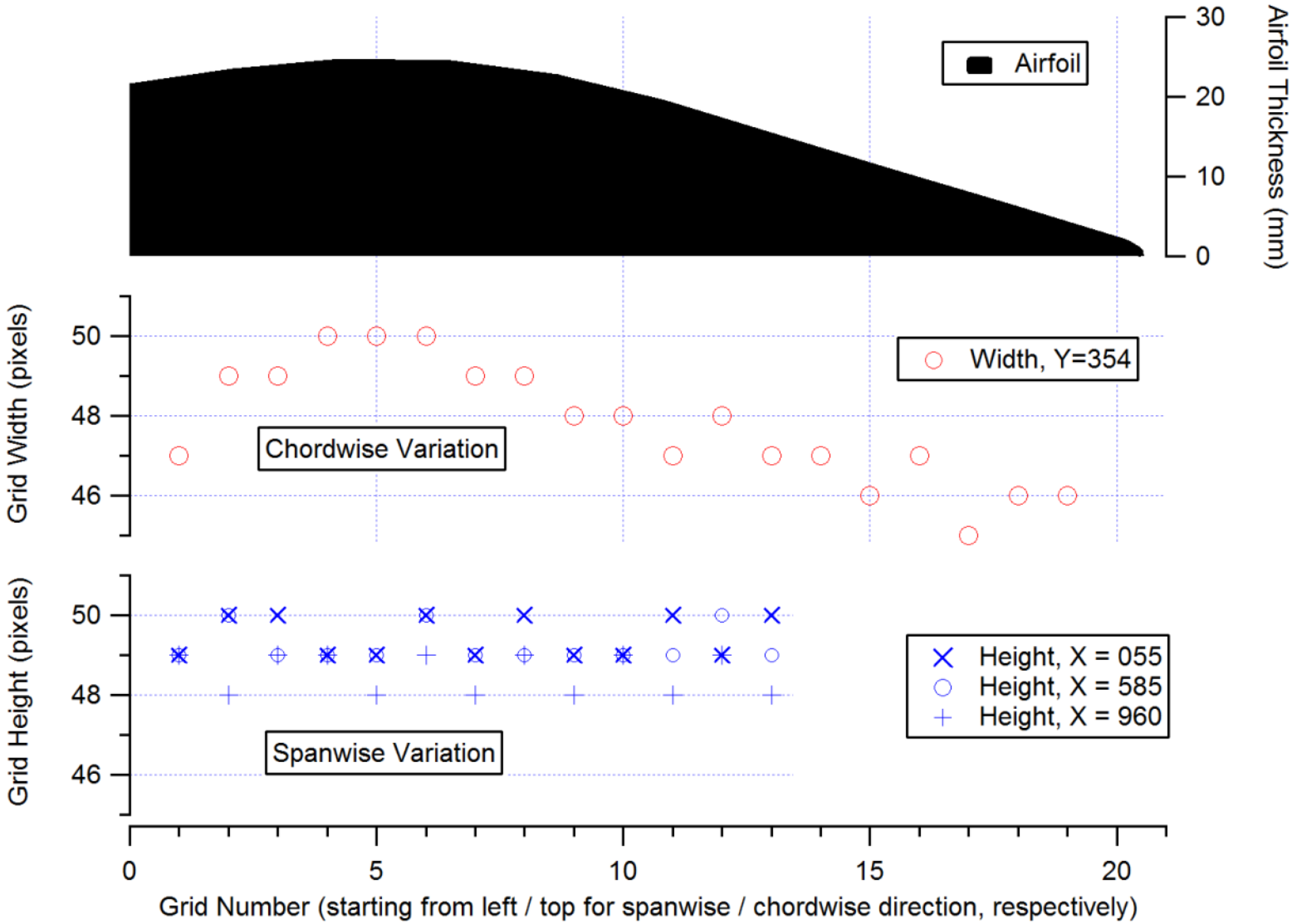



Image to Physical Size Scaling (Mar – 2011)