Tip Vortex and Wake Characteristics of a Counterrotating Open Rotor

Dale E. Van Zante and Mark P. Wernet

One of the primary noise sources for Open Rotor systems is the interaction of the forward rotor tip vortex and blade wake with the aft rotor. NASA has collaborated with General Electric on the testing of a new generation of low noise, counter-rotating Open Rotor systems. Three-dimensional particle image velocimetry measurements were acquired in the intra-rotor gap of the Historical Baseline blade set. The velocity measurements are of sufficient resolution to characterize the tip vortex size and trajectory as well as the rotor wake decay and turbulence character. The tip clearance vortex trajectory is compared to results from previously developed models. Forward rotor wake velocity profiles are shown. Results are presented in a form as to assist numerical modeling of Open Rotor system aerodynamics and acoustics.

National Aeronautics and Space Administration

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Presented by: Dr. Ken Suder

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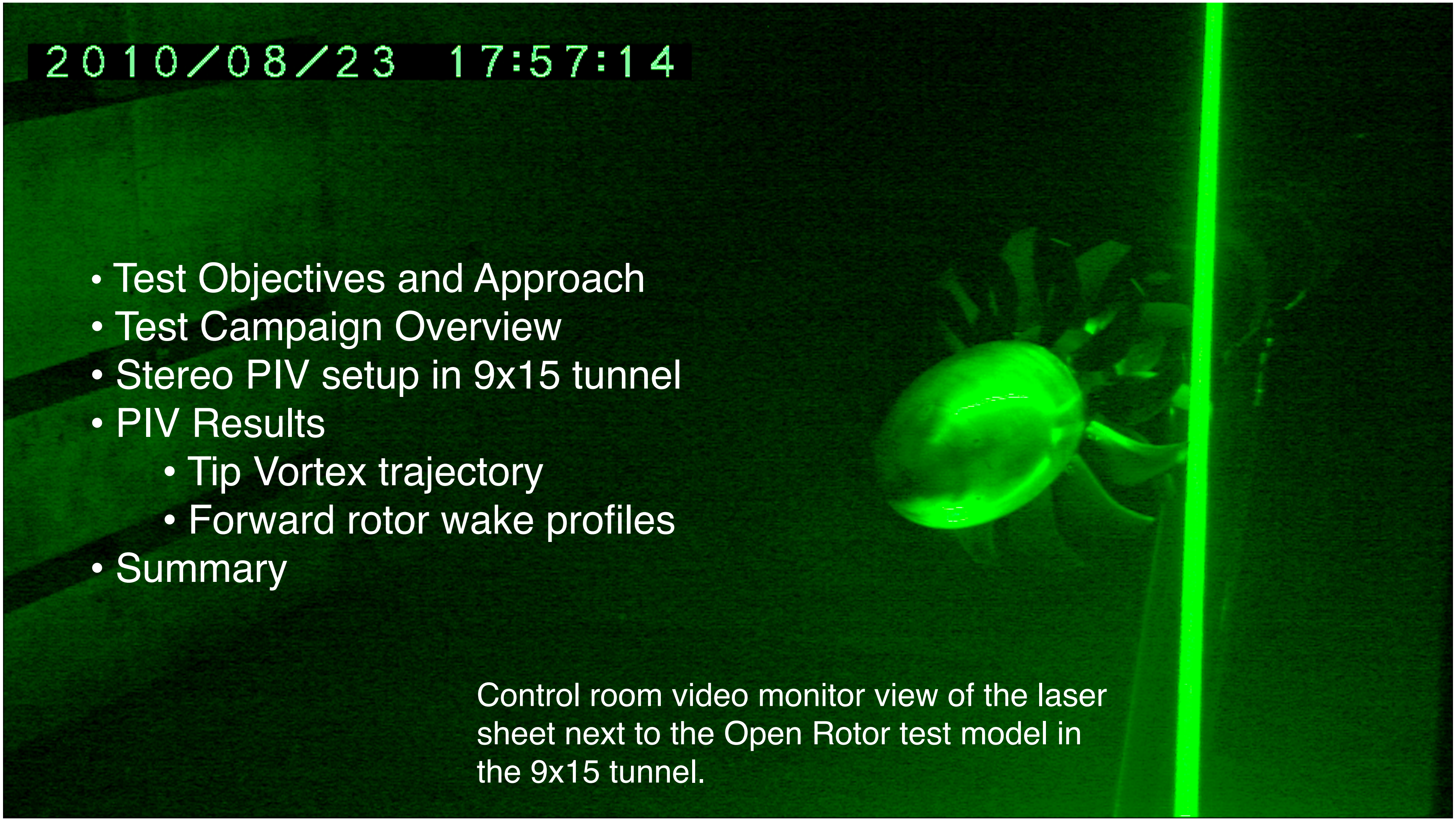
Outline



- Test Objectives and Approach
- Test Campaign Overview
- Stereo PIV setup in 9x15 tunnel
- PIV Results
    - Tip Vortex trajectory
    - Forward rotor wake profiles
- Summary

Control room video monitor view of the laser sheet next to the Open Rotor test model in the 9x15 tunnel.

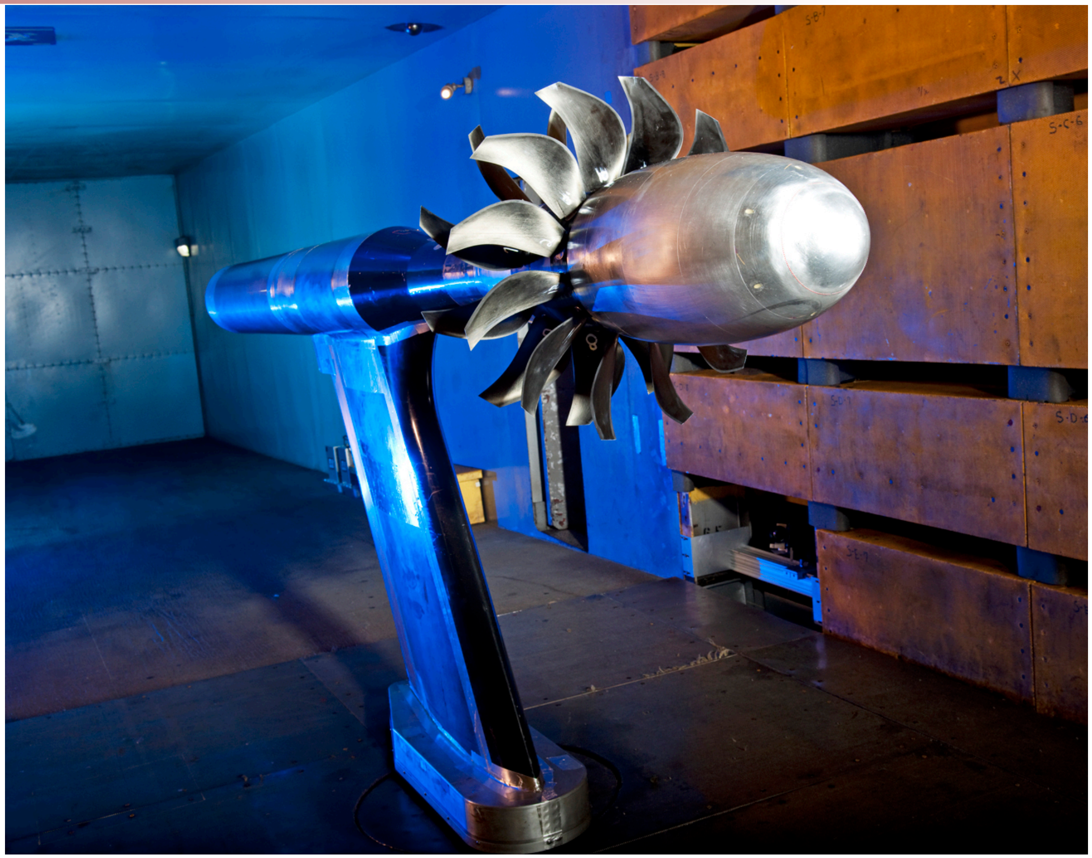
Test Objectives and Approach

OBJECTIVE

- Explore the design space for lower noise while maintaining the high propulsive efficiency from a counter-rotating open rotor system.

OVERALL APPROACH

- Collaborate with GE and FAA/CLEEN program to evaluate advanced open rotor blade sets designed to minimize noise.
- Tests will be performed in the NASA 9x15 to measure noise and in the 8x6 transonic wind tunnel to validate performance.
- Installation effects such as pylon integration were also investigated.



The NASA Environmentally Responsible Aviation Project sponsored a detailed Open Rotor test series in the summer of 2010.

The ERA Diagnostics Test

Acoustic Phased Array	**Farfield acoustics with Pylon**	**Pressure Sensitive Paint**	**Stereo Particle Image Velocimetry**	**Acoustic Shielding**

The goal of the ERA Diagnostics Test was a comprehensive data set that will identify noise sources and enable improved performance and acoustic modeling of open rotor systems.

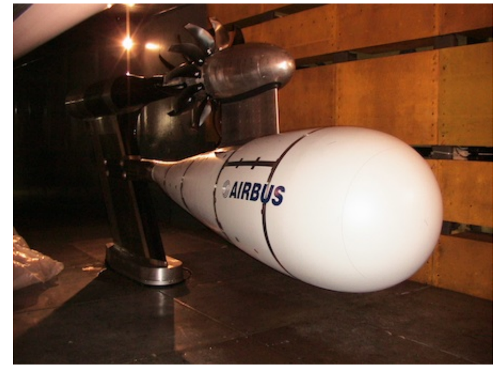
The Stereo PIV measurements overviewed today are part of this comprehensive, detailed data set on Open Rotor aero and acoustics.

Test Campaign Overview

History (1/3)

Drive rig rehab
and installation

First research run.
Oct 28



GE/Airbus entry start
Dec 14

2009

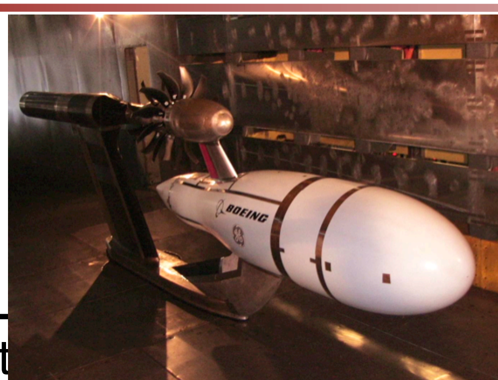
Aug	Sep	Oct	Nov	Dec

Drive rig checkout.
Sep 24 – Oct 27

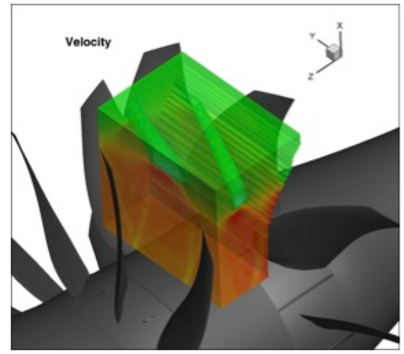
Linear array checkout.
Dec 7-11

History (2/3)

GE/Airbus test complete.
Feb 12



GE/Boeing test.
Apr 5 – 28.



ERA Diagnostics Test.
Jul 19 – Sep 7

2010											
Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec

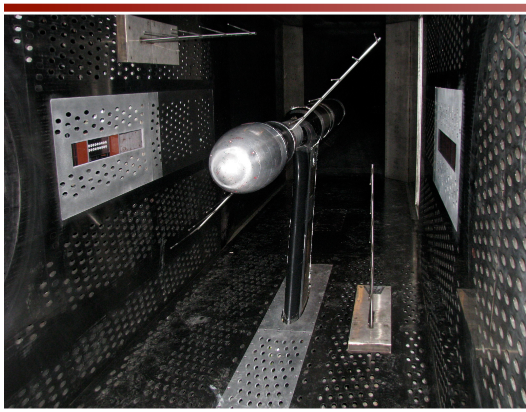
FAVOR test (ATP)

GRC annual Facility Shutdown

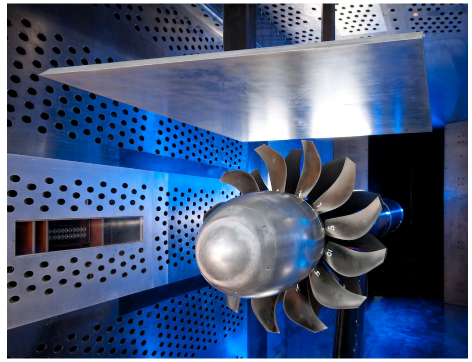
Low Boom Inlet Test (SUP)

Open Rotor Install In the 8x6

History (3/3)



8x6 Tare Runs
Feb 9



Gen-1 8x6 Test
Feb 28 – Aug 25

Gen-2 8x6 Test
Aug 26 – Sep 9

Gen-2 9x15 Test
Nov 10 – Jan 19

2011

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec

Force balance instrumentation issues
Mar 9 an

Jan. 19, 2012
End of Gen-2
Test

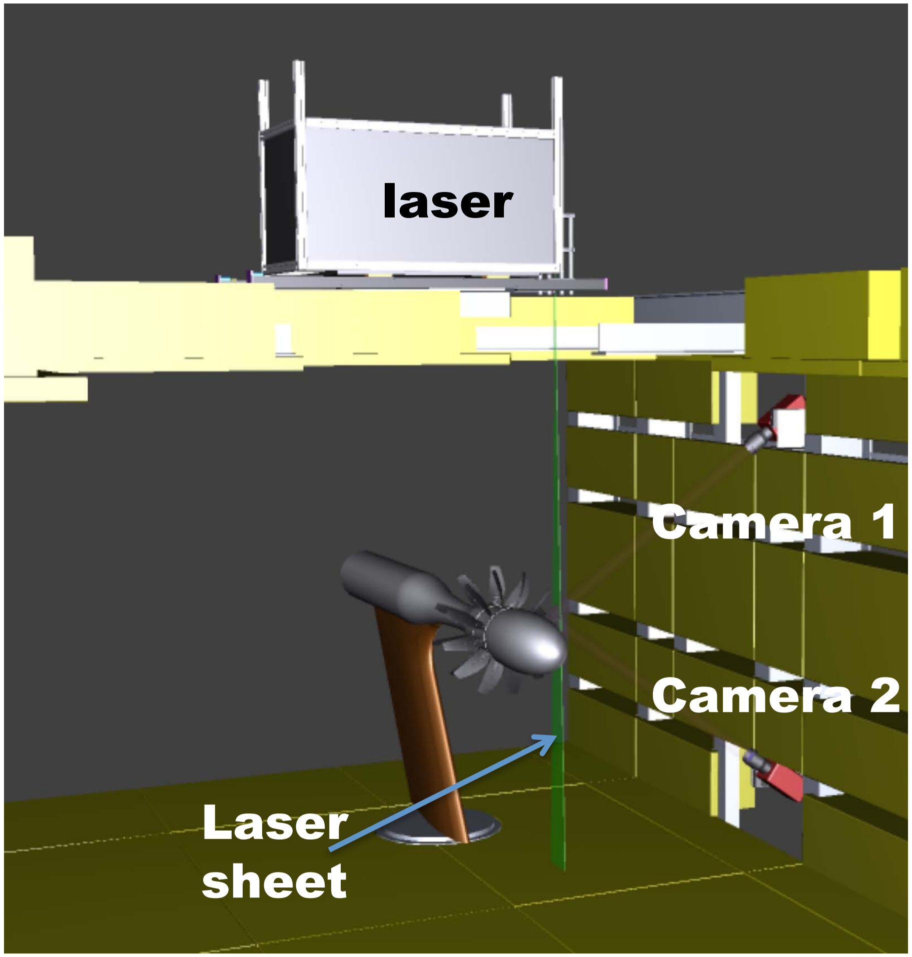
PIV Setup in the 9x15

Requirements and Constraints:
• Image the forward blade wake and tip vortex from the hub to outboard of the blade tip.
• Image the maximum axial extent of the intra-blade gap without the laser sheet intersecting either the forward or aft blade.

To meet these requirements:

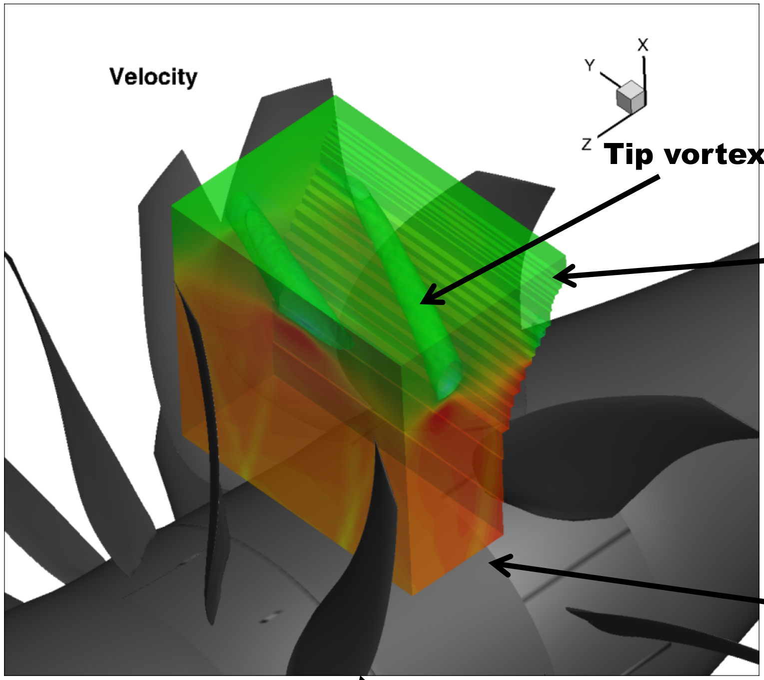
1. The lasers were mounted on top of the test section.
2. The cameras were mounted in the walls.

The laser sheet was on the side of the model and parallel to the rotation axis.



PIV Setup in the 9x15

Further PIV details

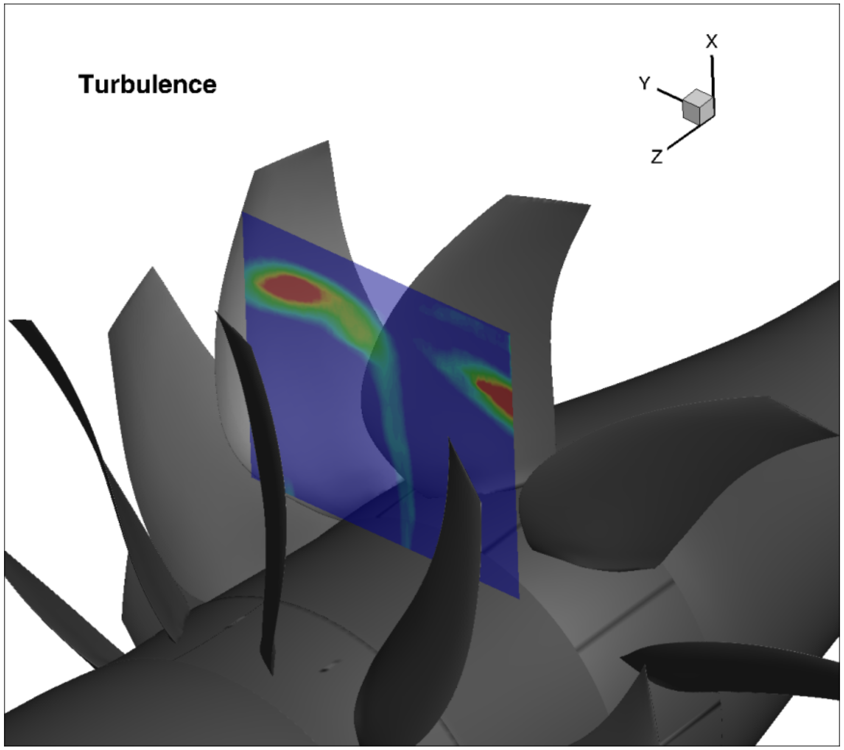


Smaller measurement plane spacing was used near the blade tip to capture the vortex with good radial resolution.

The width of the laser sheet was clipped at the lower span locations using a mechanical shutter.
This allowed the maximum axial measurement extent without hitting the blade with the laser sheet.

Measurements are phase locked to the forward rotor position.
Two phase angles were acquired for each pitch angle/rotor speed condition.
The aft rotor is at random position (not possible to sync both rotors/lasers/cameras).

PIV Processing



Because each camera is mounted to a separate translation stage and views the light sheet plane through a different window – a unique 5-plane calibration was acquired for each of the 31 measurement planes in the test matrix.

Flow seeding was done with Vicount 5500 smoke generators for 0.2-0.3 µm particles.

Princeton Instruments ES-4020 cameras (2048x2048 pixels) were used to capture 400 image pairs per plane.

The image data were processed with a NASA developed cross-correlation processing software called PIVPROC.

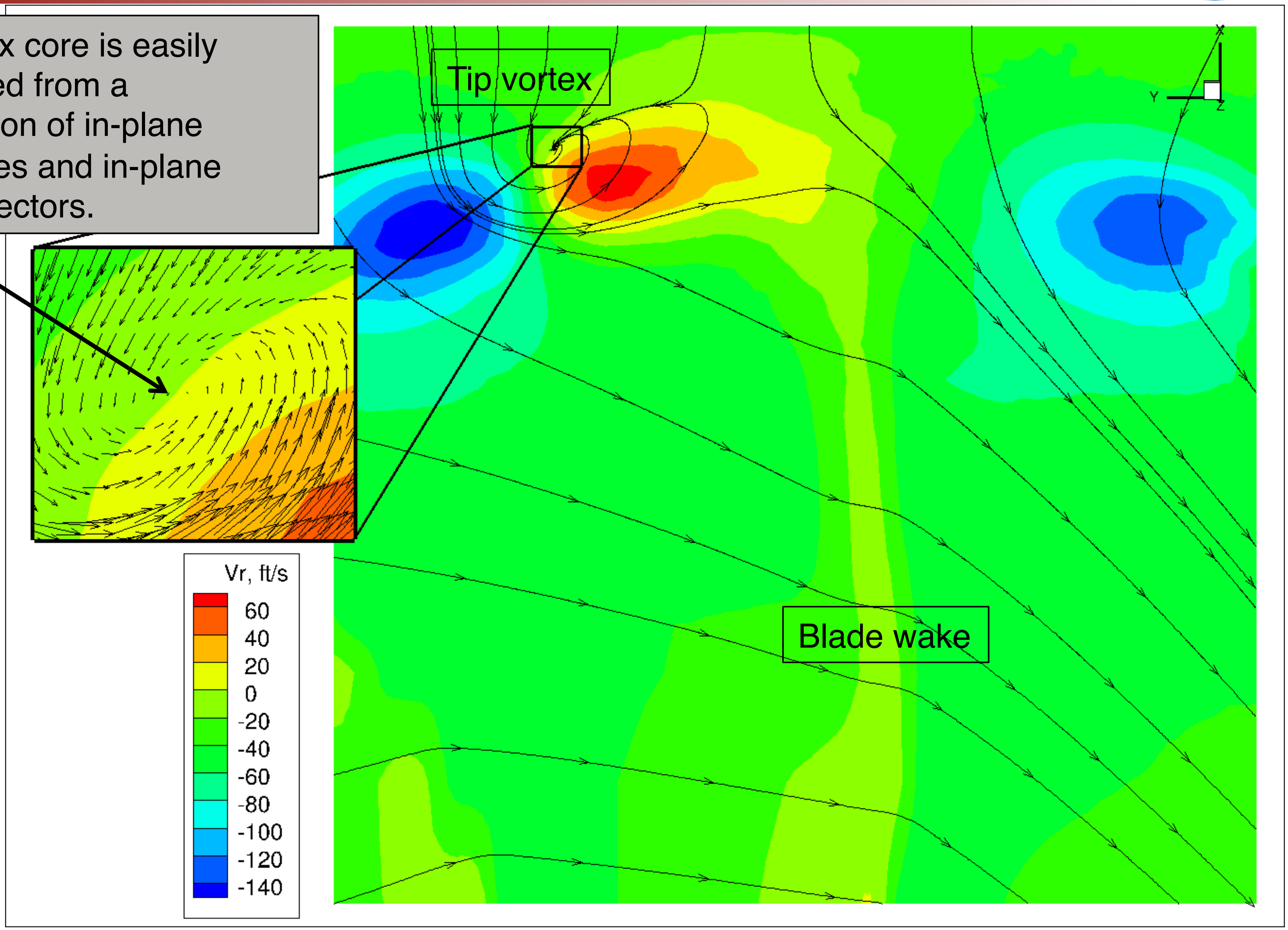
The software uses subregion image shifting and multi-pass correlation for improved spatial resolution. The measurements have an in-plane resolution of 1.43 mm.

Additionally, subregion distortion processing and Symmetric Phase Only Filtering (SPOF) correlation processing were used to further enhance the data set quality.

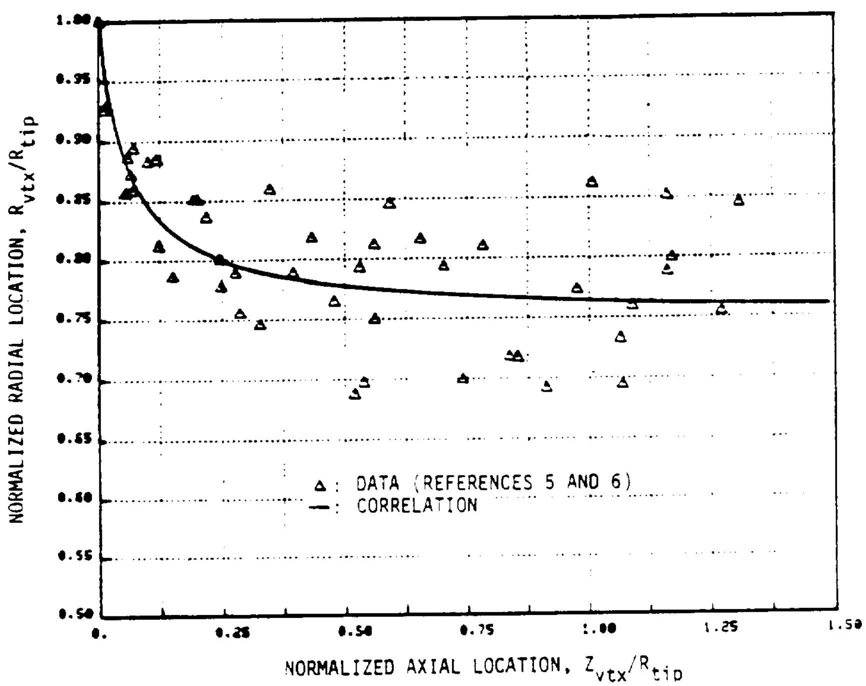
PIV Results
Tip Vortex Trajectory

Vortex core location

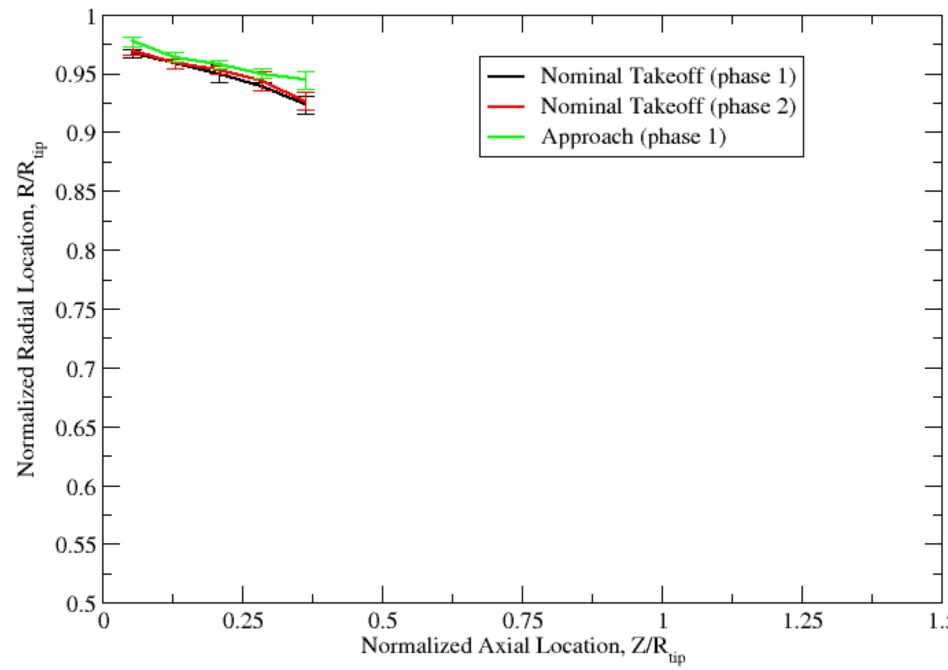
The vortex core is easily determined from a combination of in-plane streamlines and in-plane velocity vectors.



Normalized Vortex Core Trajectory



From Majjigi, et al



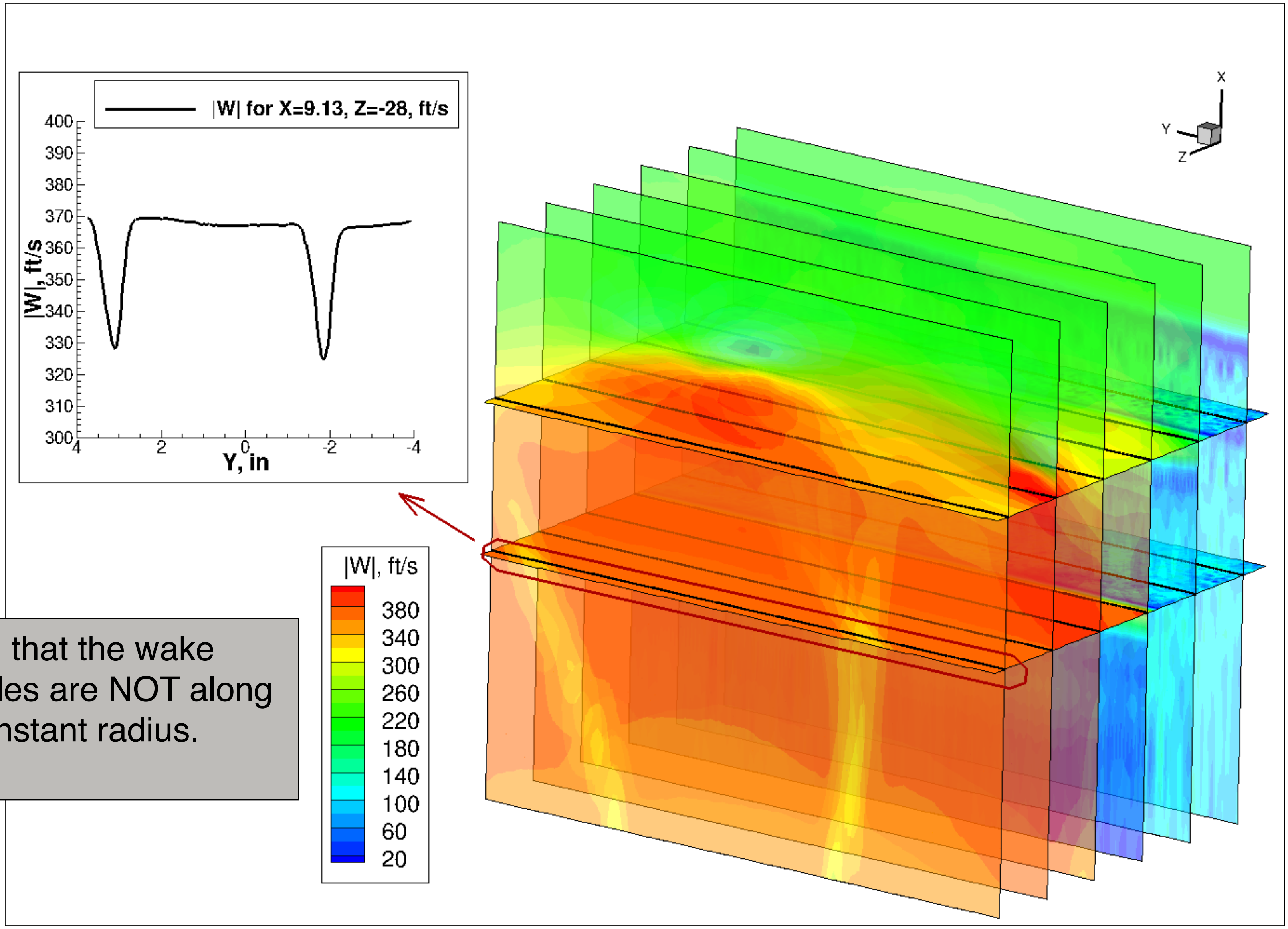
Current SPIV data

The historical data correlated by Majjigi were based on helicopter in hover measurements.

The current measurements show a trajectory character that is linear with axial location.

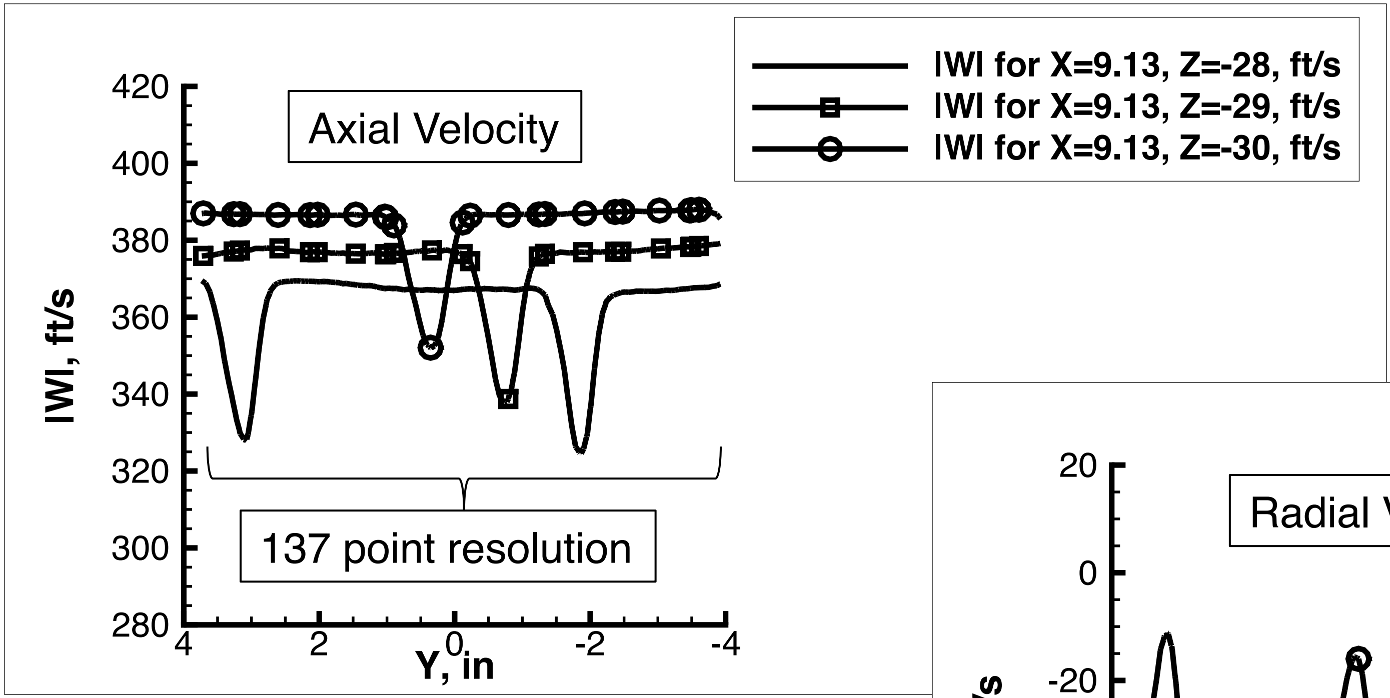
PIV Results
Wake Character

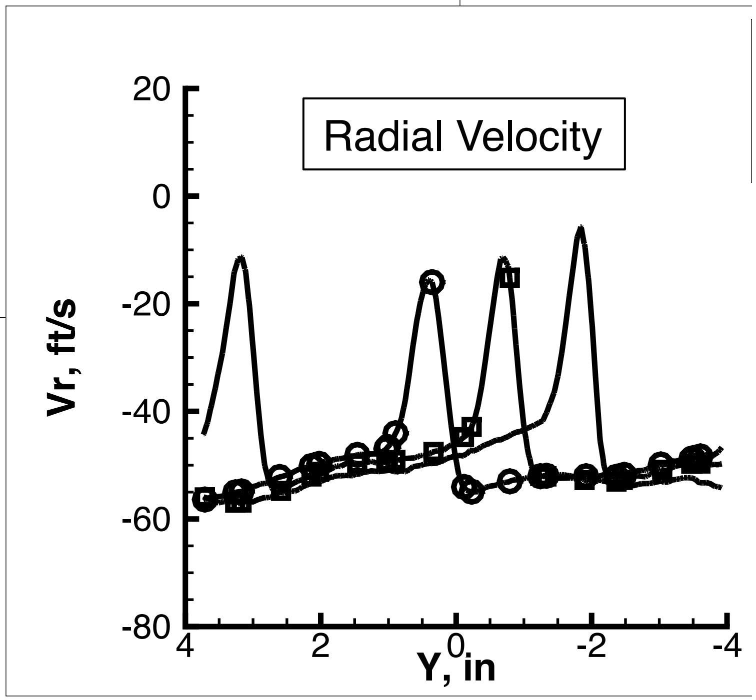
Wake profile locations



Note that the wake profiles are NOT along a constant radius.

Example wake profiles





Blade wakes show an axial velocity deficit and an increased radial velocity relative to the core flow.
Note the streamtube contraction shows as a core flow negative radial velocity.

Summary

An extensive, unique calibration procedure and careful attention to the SPIV correlation processing has yielded very high quality data sets.

The tip vortex core trajectory shows a linear behavior with axial distance from the forward rotor tip.

The forward blade wakes show the typical turbomachinery wake behavior.

Acknowledgements:

This research was sponsored by the NASA Environmentally Responsible Aviation Project.

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Csaba Horvath assisted with the figures presenting the PIV data.