Background Oriented Schlieren (BOS) of a Supersonic Aircraft in Flight

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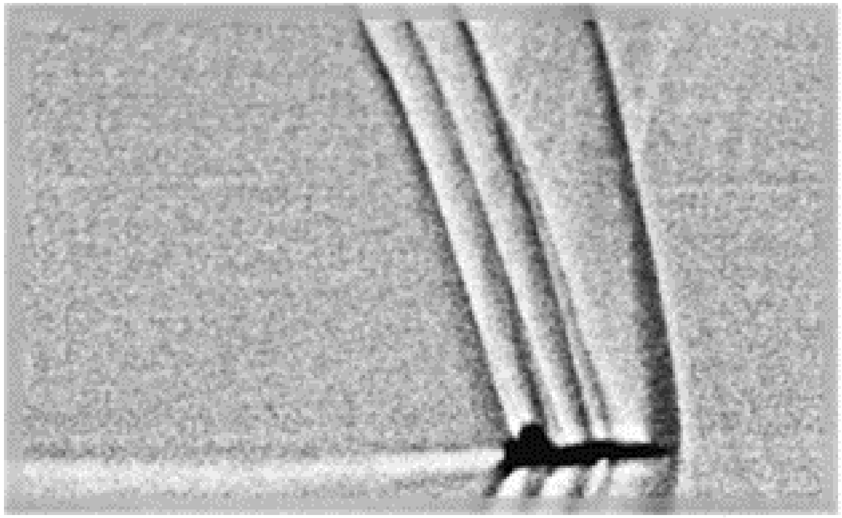
Introduction

- **Schlieren imaging for aerodynamics research was limited to ground test facilities**
- **Weinstein introduced the first reliable method for flight test in 1994**
- **Retroreflective Background Oriented Schlieren was demonstrated to work for full-scale aircraft in flight in 2012 (DLR Goettingen)**
- **First AirBOS flight in April, 2011 was successful, but restricted.**



Weinstein's sun-edge streak camera image of a T-38

RBOS of a BO-105 in slow forward flight
Raffel et. al. , DLR Goettingen

NASA CST Project

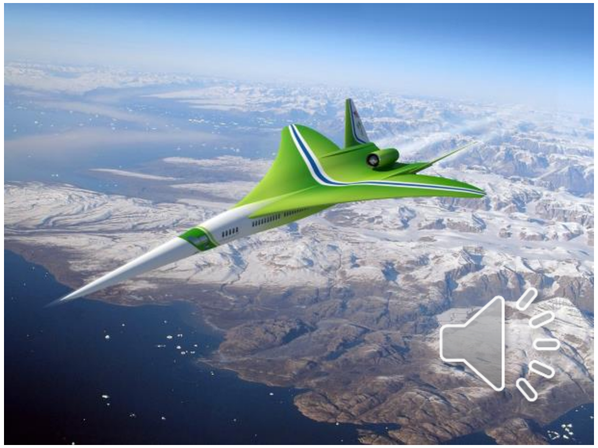
Artist rendering of Boeing Demonstrator

Artist rendering of Locheed Demonstrator

- **Research on the reduction of sonic boom for land overflight: current barrier to return to civil supersonic aviation**
- **An X-plane proposed: Low-Boom demonstrator called QueSST for boom research**
- **The Program invested in three schlieren methods: AirBOS, Ground-to-Air Schlieren Photography System (GASPS), and a hybrid method dubbed Background Oriented Schlieren with Celestial Objects (BOSCO) to support QueSST**

Simulated Sonic Booms

Sonic Boom rendering of Concorde

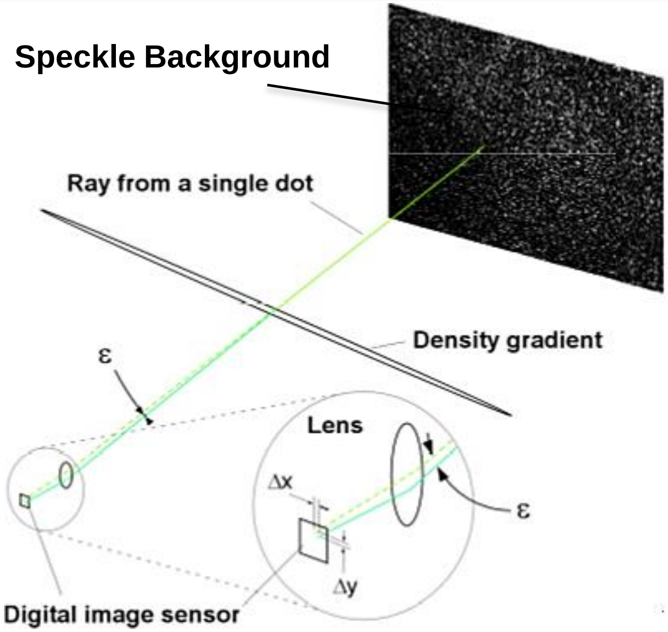


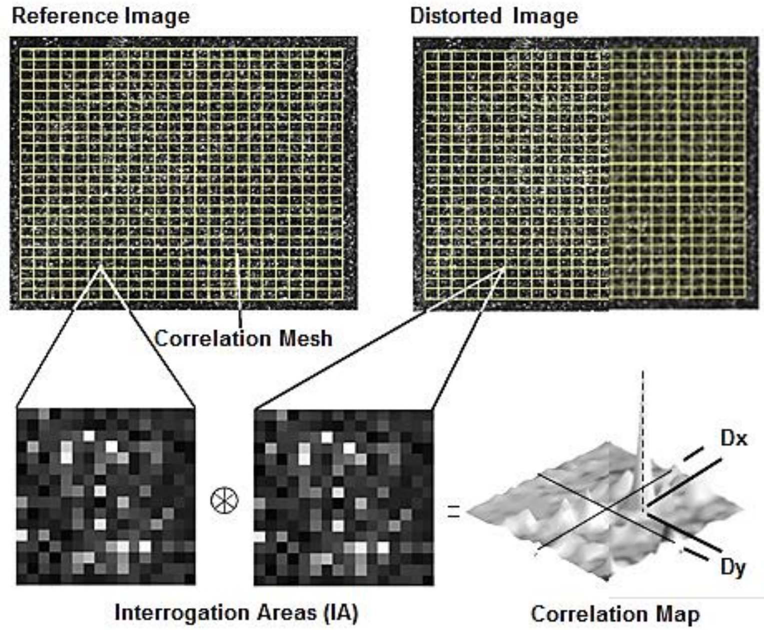
Sonic Boom rendering of Locheed Demonstrator

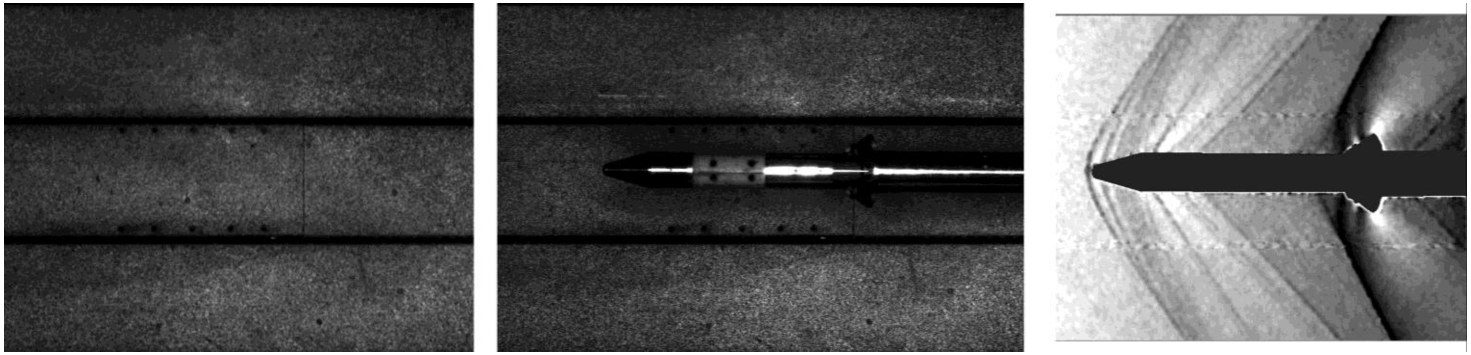
Sonic Boom rendering of Boeing Demonstrator

NASA CST Project needs schlieren imaging to see these booms

The BOS Method

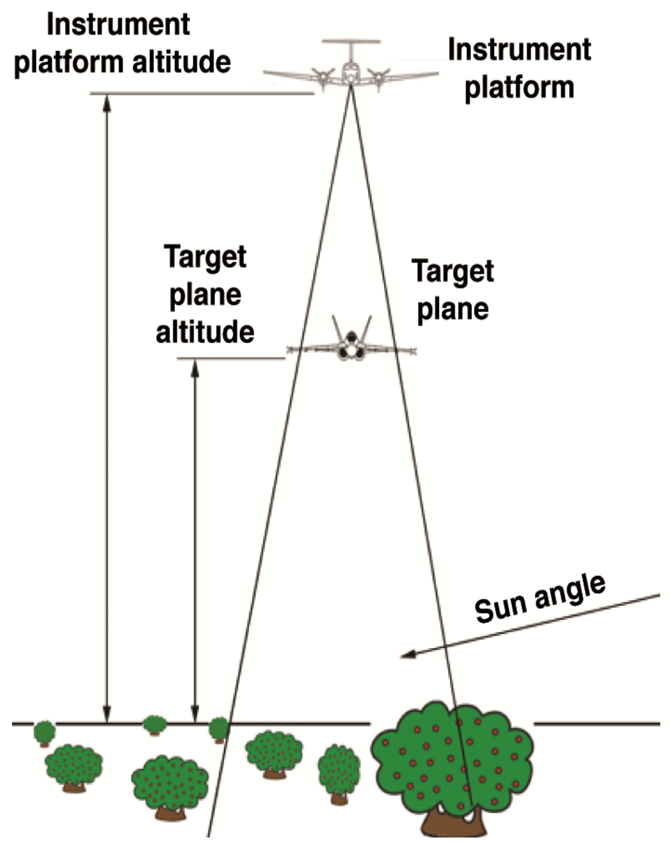


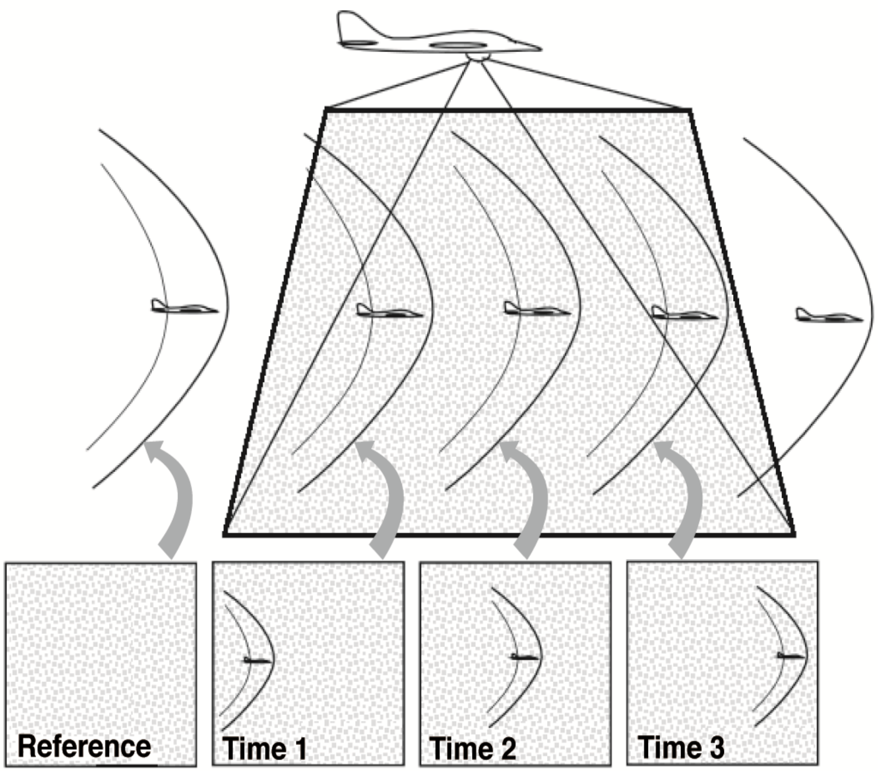




2008 Wind tunnel test: reference, data image and result of an abort motor tower at M=1.3

The AirBOS Method





Use the flora as speckle background

Record the under-pass of target plane

AirBOS Implementation

- **Fly in the Black Mountain Supersonic Corridor near Edwards AFB**
- **Characterize the Mojave Desert flora in the Supersonic Corridor: Creosote bushes with scattered Joshua trees**
- **Bushes average 10 feet (3.1 m) diameter; too few trees to be of concern**
- **Dark green against light gray soil; red filter enhances contrast**

Observer plane

NASA Beechcraft B-200 Super King Air

- *Fly at 30,000 ft MSL (Highest practical altitude)*
- *Low stall speed – 99 knots (75 with full flaps)*
- *Already equipped with high-quality nadir port window*
- *GPS navigation*

Target plane

Air Force T-38, operated by the Test Pilot School at Edwards AFB

Supersonic flight achieved by full acceleration during a shallow dive, leveling for the flyby

Imaging system design

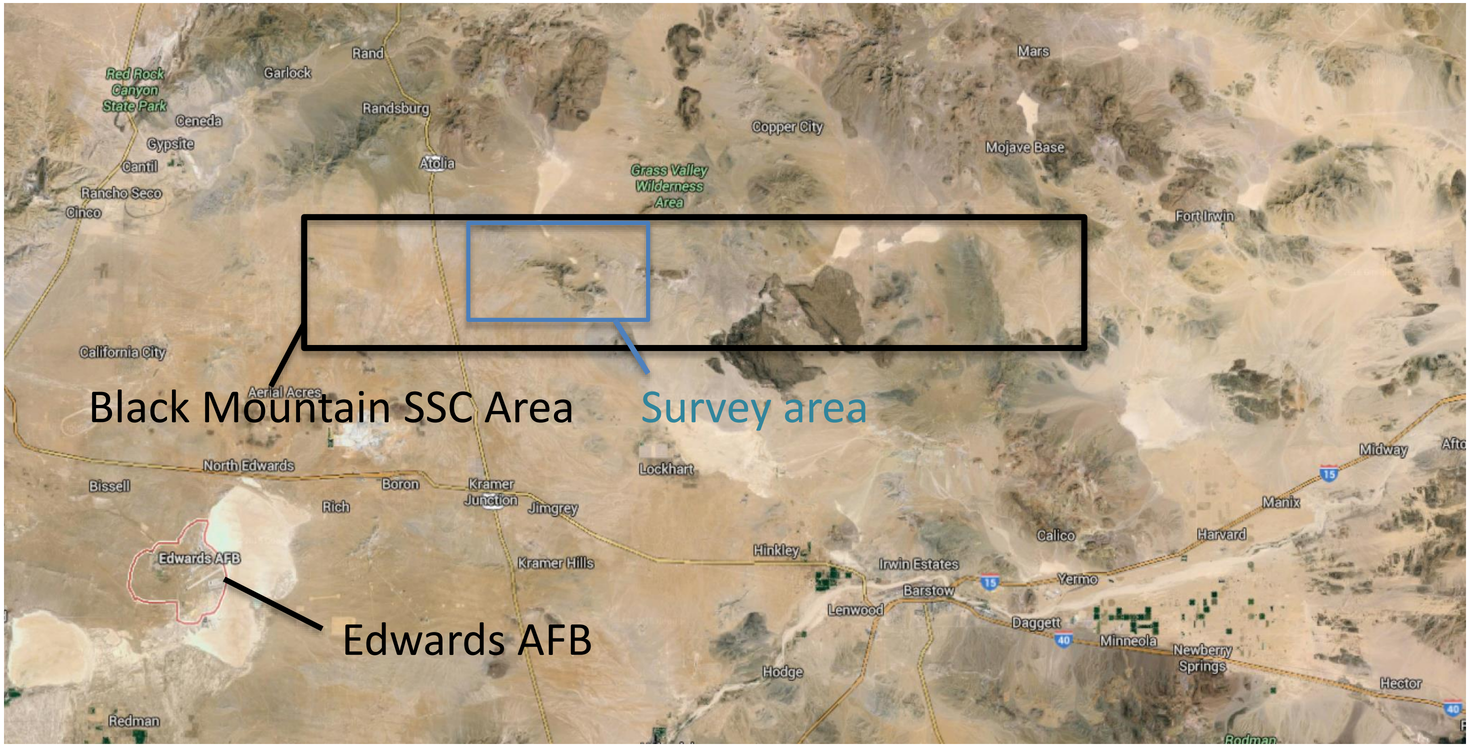
- **Calculate the proper lens focal length to optimize speckle size**
  - **Phantom V641, with 2650 x 1600 pixel and 10 – micron pitch**
  - **Speckle distribution should be 2-5 pixels**
  - **Spreadsheet calculates pixel resolution and field of view on ground and at target location**

Lens	Camera			Half Angles		Altitudes			FOV at Target Aircraft			FOV at Ground		
Lens fl (mm)	ccd nx (pixels)	ccd ny (pixels)	pixel size (µm)	X (Deg)	Y (Deg)	Observer a/c (Ft)	Target a/c (Ft)	Ratio	Δxfov (Ft)	Δyfov (Ft)	Resolution (pixels/ft)	Δxfov (Ft)	Δyfov (Ft)	Resolution (pixel / ft)
105	640	512	25	4.36	3.49	27000	13500	0.5	2057.14	1645.71	0.31	4114.29	3291.43	0.16
180	2560	1600	10	4.07	2.54	30000	26000	0.75	568.89	355.56	4.50	4266.67	2666.67	0.60
180	2560	1600	10	4.07	2.54	30000	28000	0.9	284.44	177.78	9.00	4266.67	2666.67	0.60

Sample of table for two cameras and target aircraft separation distances

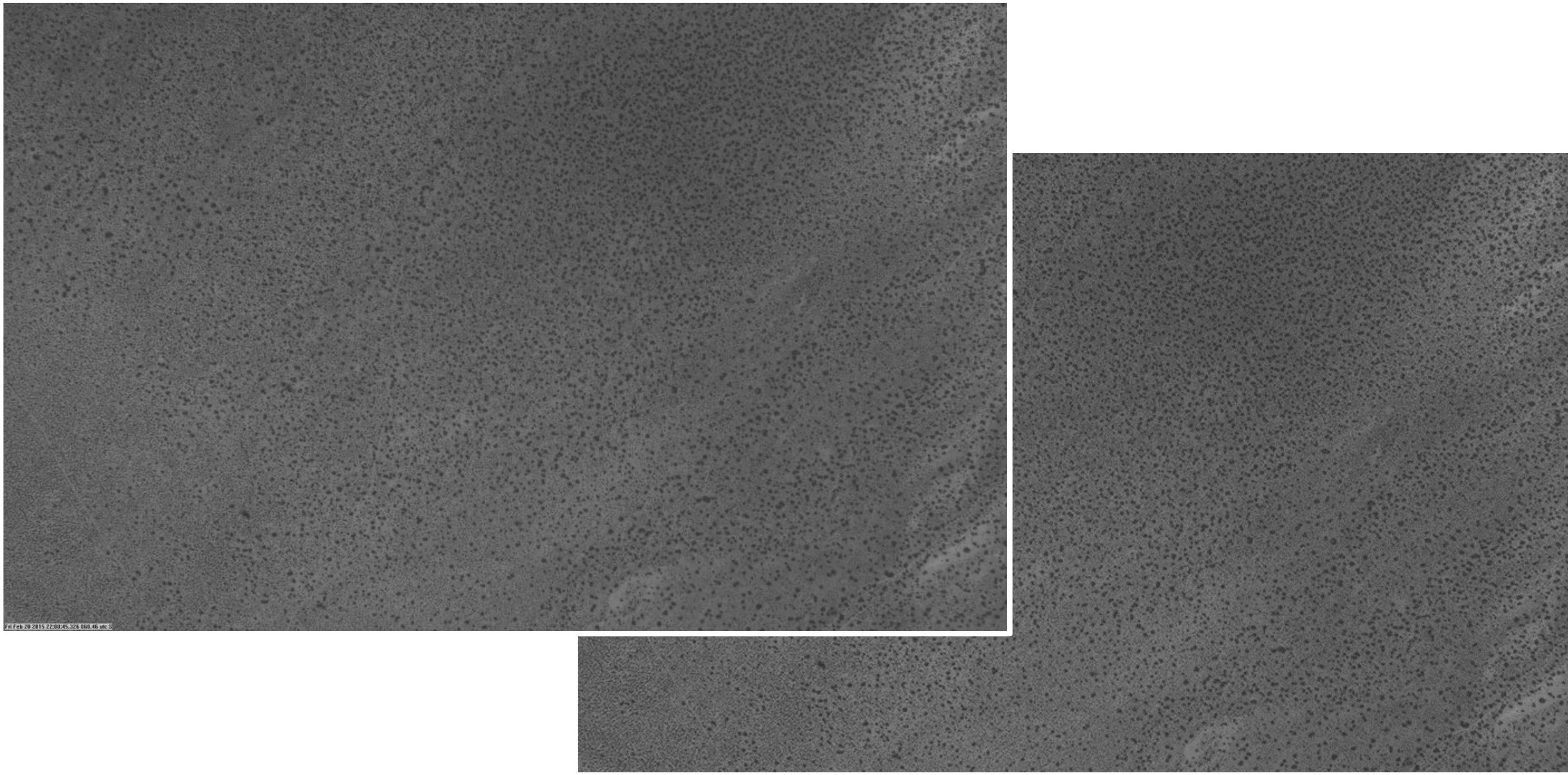
AirBOS Implementation

- **Survey the Black Mountain SS Flight Corridor at 30,000 ft altitude**
  - **Photographically survey large area, find consistent flora**
  - **Test for cross correlation performance**
  - **Design flight pattern to hit the "sweet spot" where the acceleration can be achieved, but turn around is within the corridor**



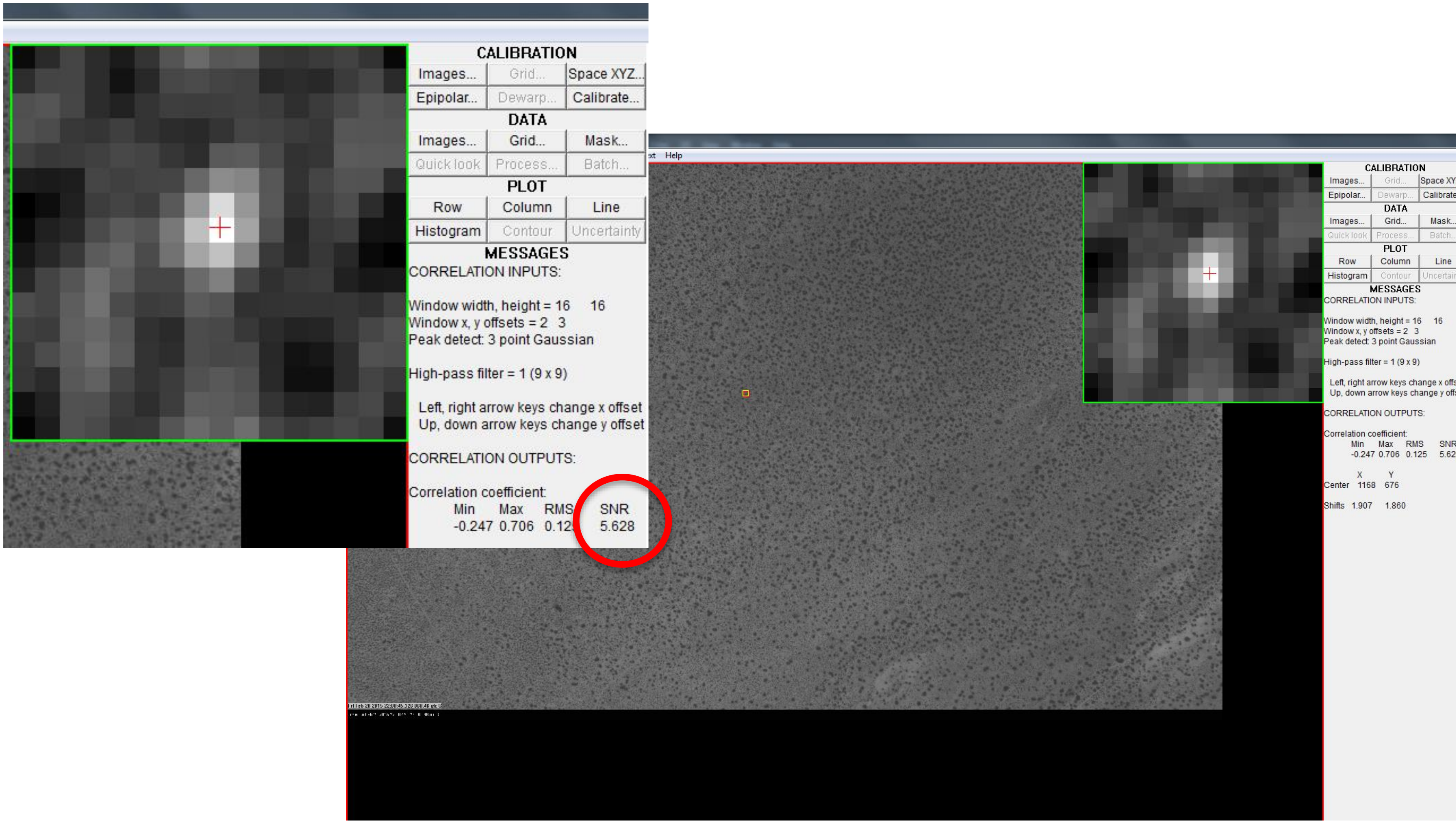
Google Earth view of area of Supersonic Corridor and Edwards AFB

Determining the Sweet-spot



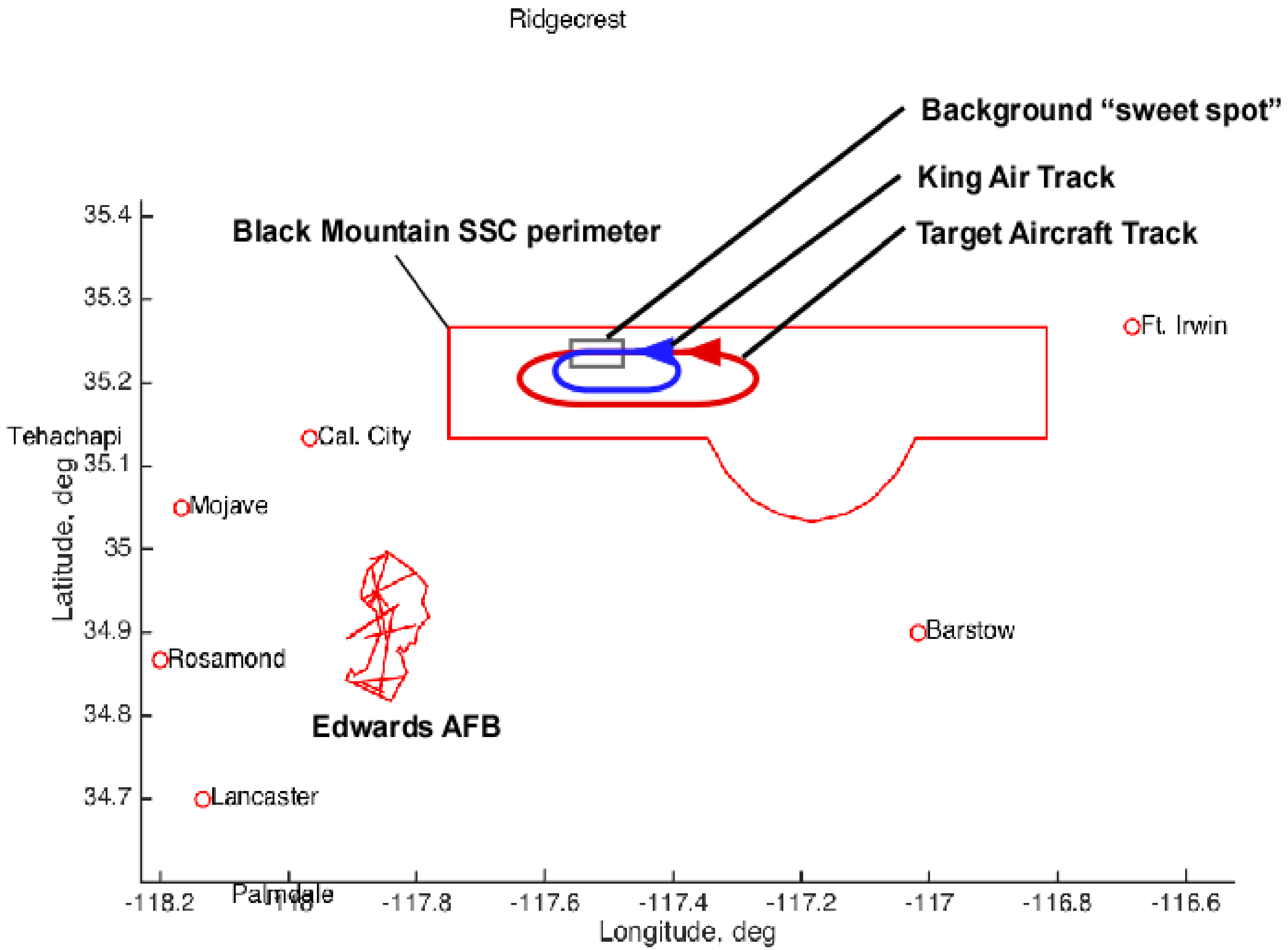
Evaluate two successive frames from the reconnaissance flight using cross correlation

Determining the Sweet-spot



Assure SNR of 5 or higher in the cross-correlation product using the anticipated window size

Flight Plan


Ridgecrest
Background "sweet spot"
King Air Track
Target Aircraft Track
Black Mountain SSC perimeter
Ft. Irwin
Tehachapi
Cal. City
Mojave
Barstow
Rosamond
Edwards AFB
Lancaster
Palmdale
Latitude, deg
35.4
35.3
35.2
35.1
35
34.9
34.8
34.7
-118.2
-118
-117.8
-117.6
-117.4
-117.2
-117
-116.8
-116.6
Longitude, deg

Cameras and Layout

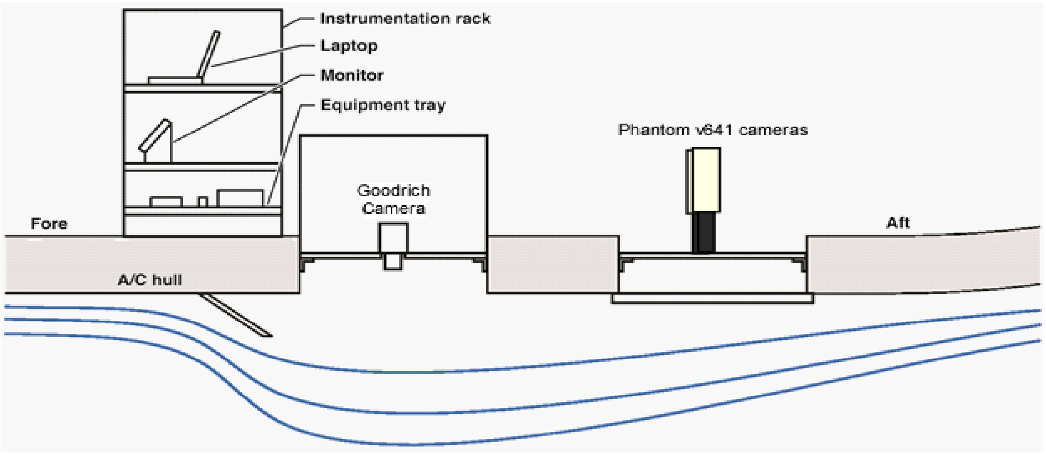
Phantom V641 monochrome, 2560 x 1600 pixels, 10 micron pitch, 180 mm lens

- **8 GB of internal memory, ~ 2 seconds of record time @ 1000 fps**
- **#25 Red filter, enhance contrast of bushes against the bright soil**
- **"Pickle" switch trigger by operator**

Two cameras: redundancy and potential for stereo and multi-stream referencing

Legacy camera for 2011 work: Goodrich SUI SU640-SDWHVis-1.7RT InGaS

- **640 x 512 pixel sensor, 25 micrometer pixel pitch, and fitted with a 105 mm lens**
- **Used mainly as real-time spotting camera**



Schematic of cabin layout

Two cameras, mounted vertically

Data Acquisition

Pilots flew identical tracks using independent GPS units

Radio communication between target plane pilot, observer plane, and control room

- **Countdown provided by Control Room based on radar tracking**
- **Camera operator set recording in circular buffer mode, watched live feed**
- **Manually triggered "record" point.**
- **Captured images before and after trigger point**
- **Downloaded buffer to laptop – up to 15 minutes, but usually trimmed to 7 min**
- **Reported to Control Room "Love" or "No Love"**
- **Love got a High-Five by operators, Control Room explodes as if we landed on Mars**

Data Processing

1. Reference-to-data registration: First-order projective transform

- ***Aligns the displaced backgrounds caused moving observer***
- ***Corrects perspective distortion caused by pitch and roll during acquisition***

$$x = \frac{a_1 x' + a_2 y' + a_3}{c_1 x' + c_2 y' + 1}$$

$$y = \frac{b_1 x' + b_2 y' + b_3}{c_1 x' + c_{2y'} + 1}$$

- ***Four points at corner of images are chosen, large-window CC performed***
- ***Cross correlation between the two images yields*** Δx ***and*** Δy ***at each location,*** x' ***and*** y' ***are solved to then calculate the eight coefficients***

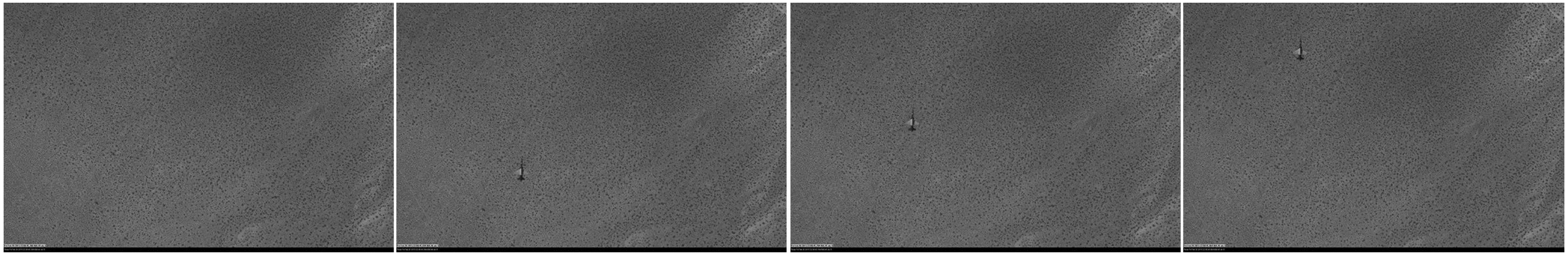
$$x' = x + \Delta x$$

$$y' = y + \Delta y$$

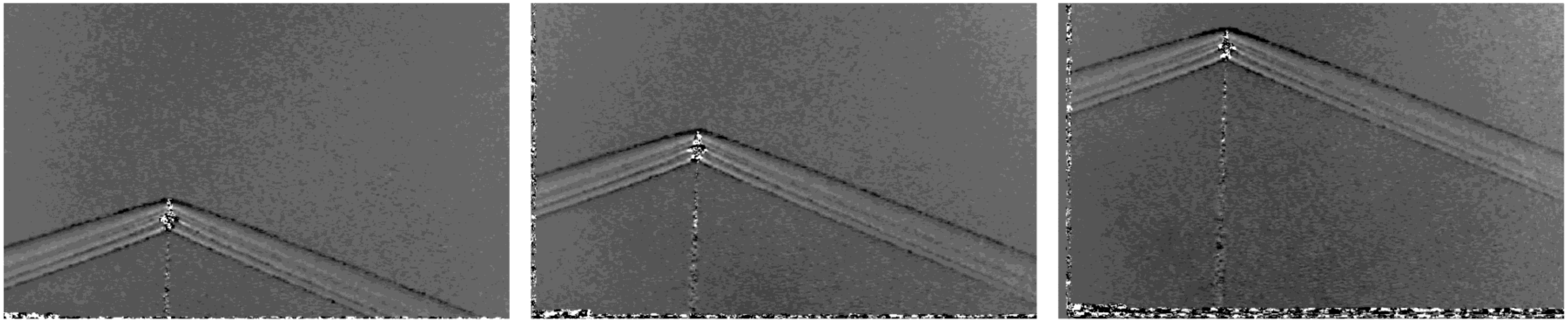
2. Image cross correlation at defined grid nodes yields Dx and Dy due to density gradient shift

AirBOS Results

5000-foot Separation Distance



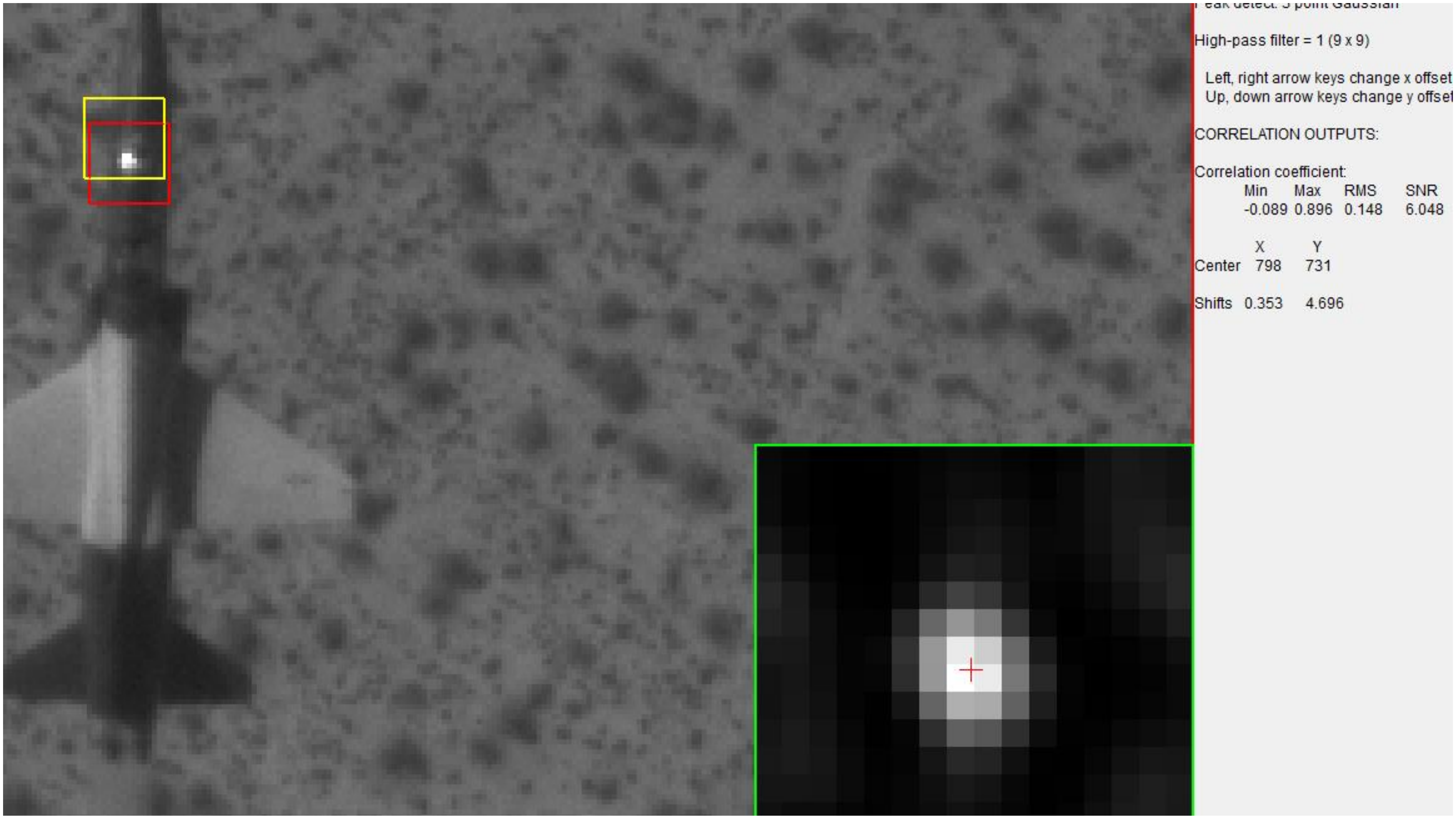
Reference plus three raw image data sequences



Cross correlation product sof above data sequences

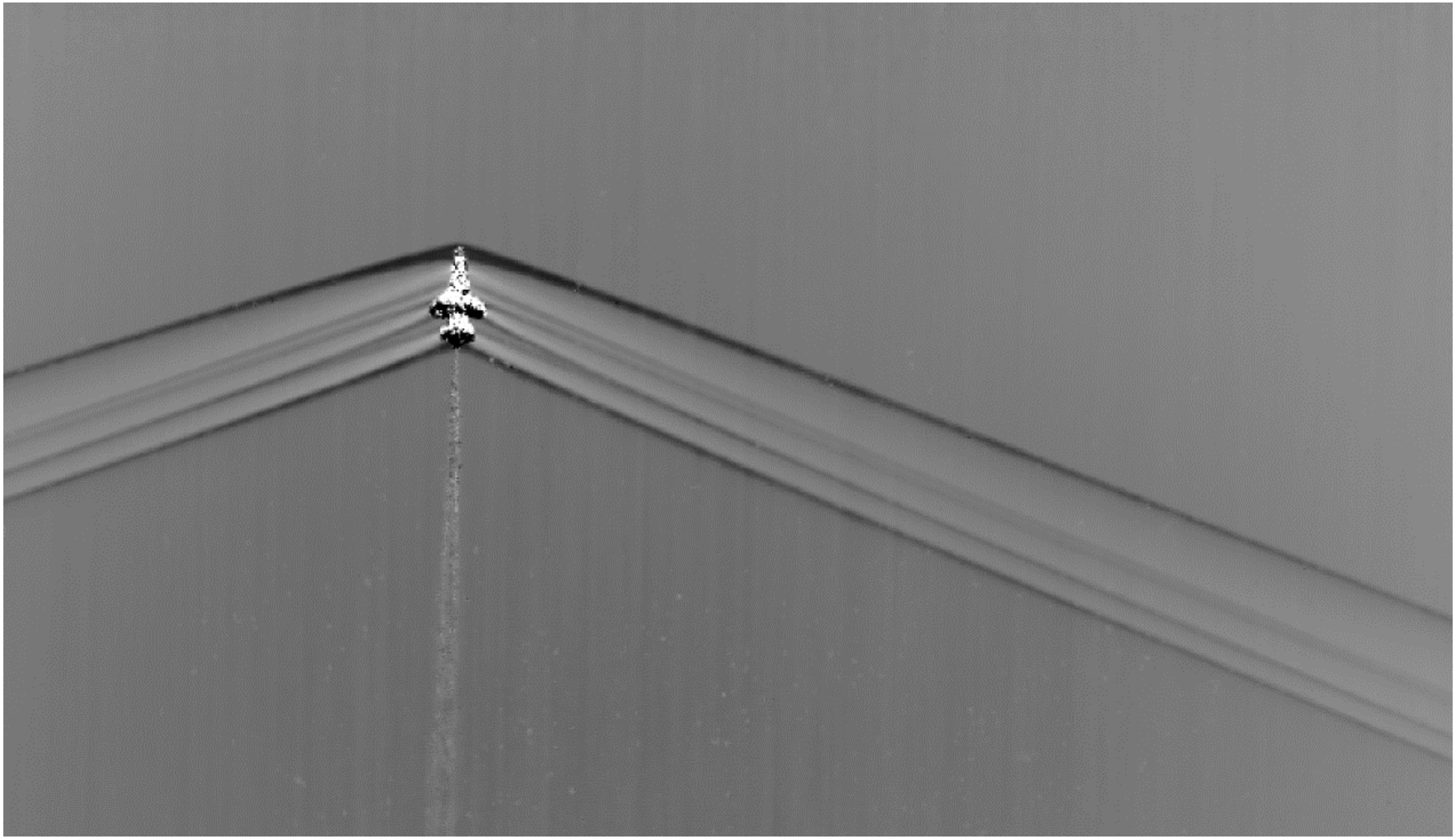
- ***32 x 32 refined to 16x16 IA,***
- ***9 x9 pixel High Pass filter,***
- ***3 pixel Grid node density***
- ***3-point Gaussian peak finder***

AirBOS Results – Data Averaging



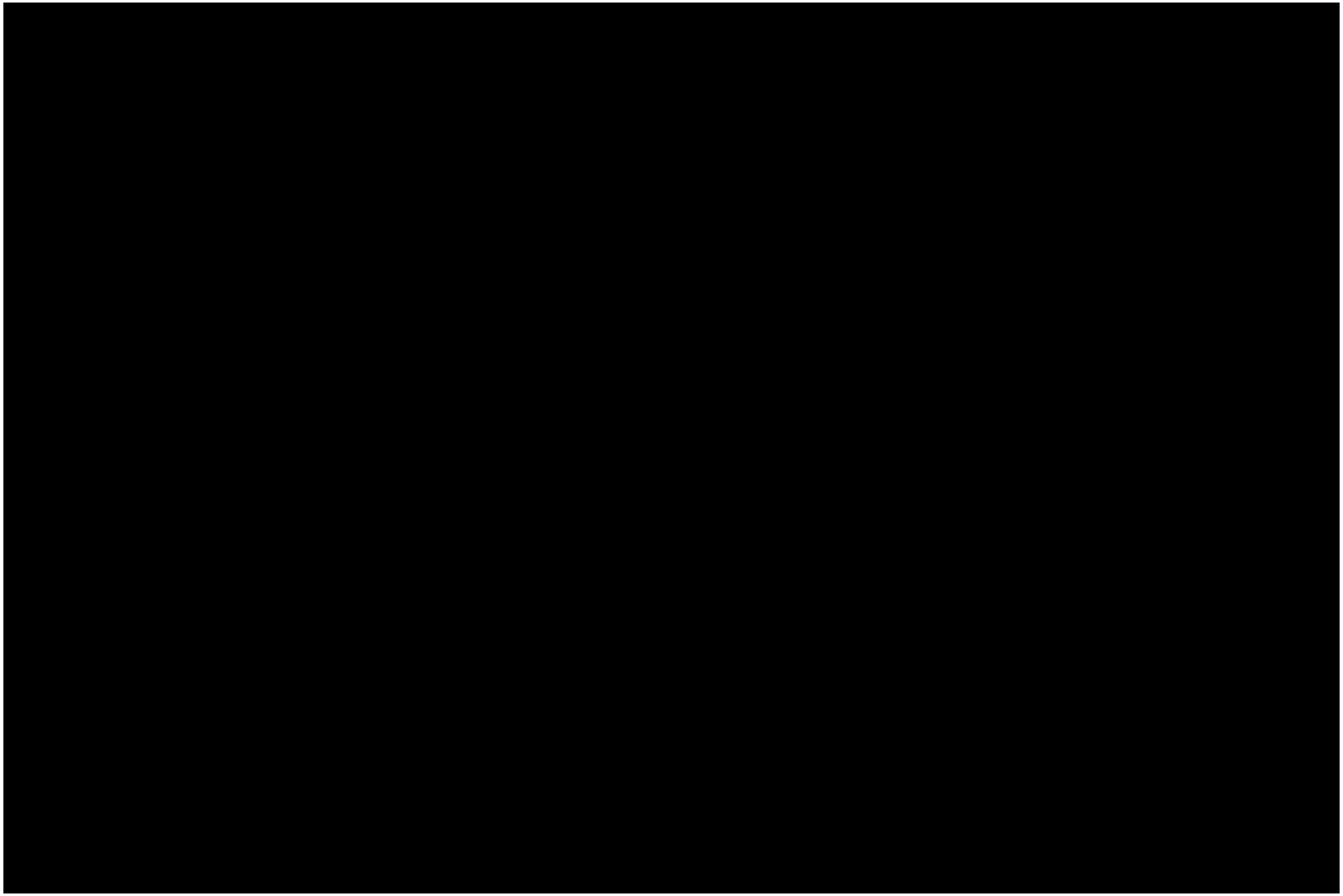
Track the movement of the aircraft using cc of glint, realign correlation grids

AirBOS Results – Data Averaging



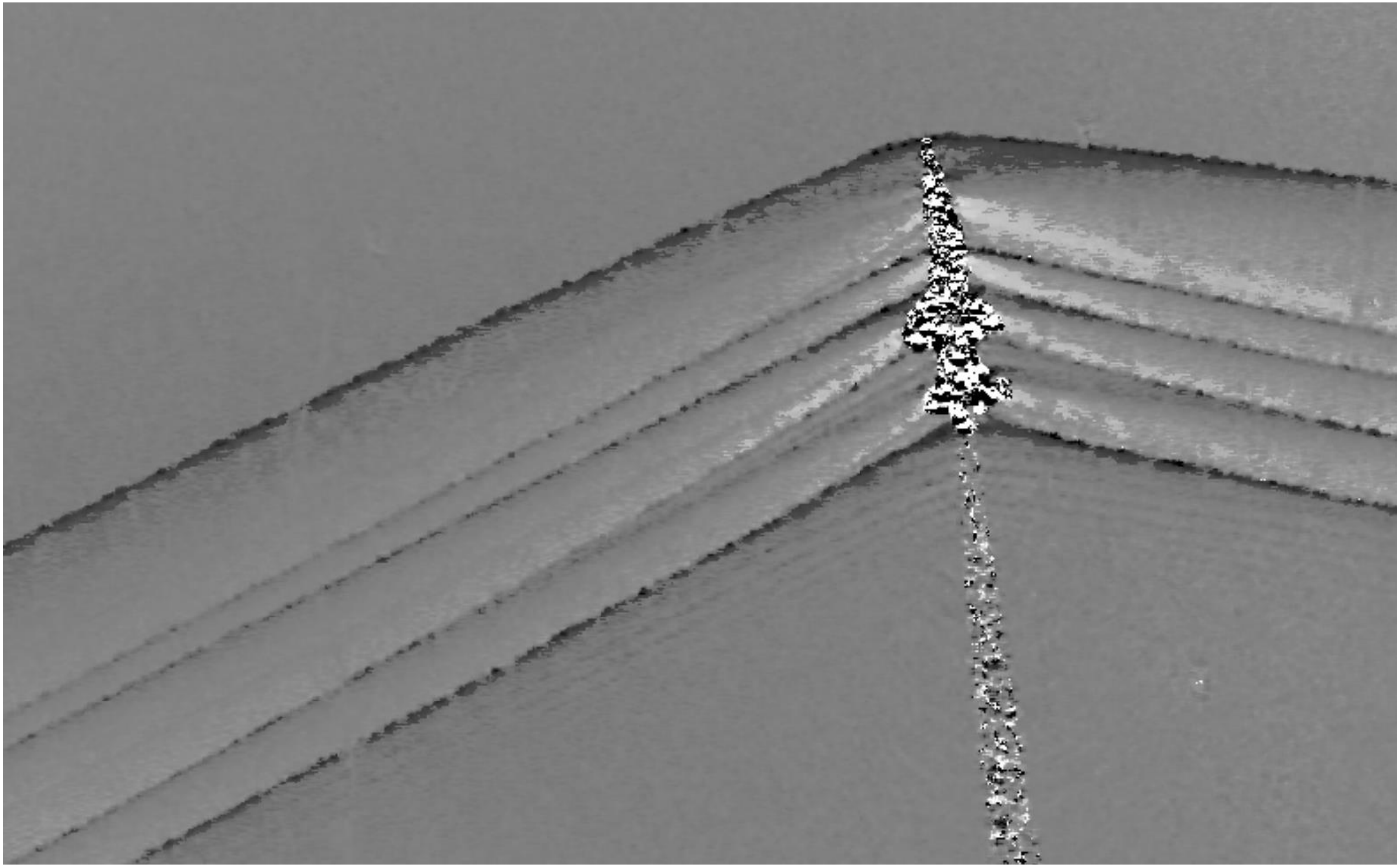
Compute the simple average of aligned grids

2000-foot Separation, Raw images



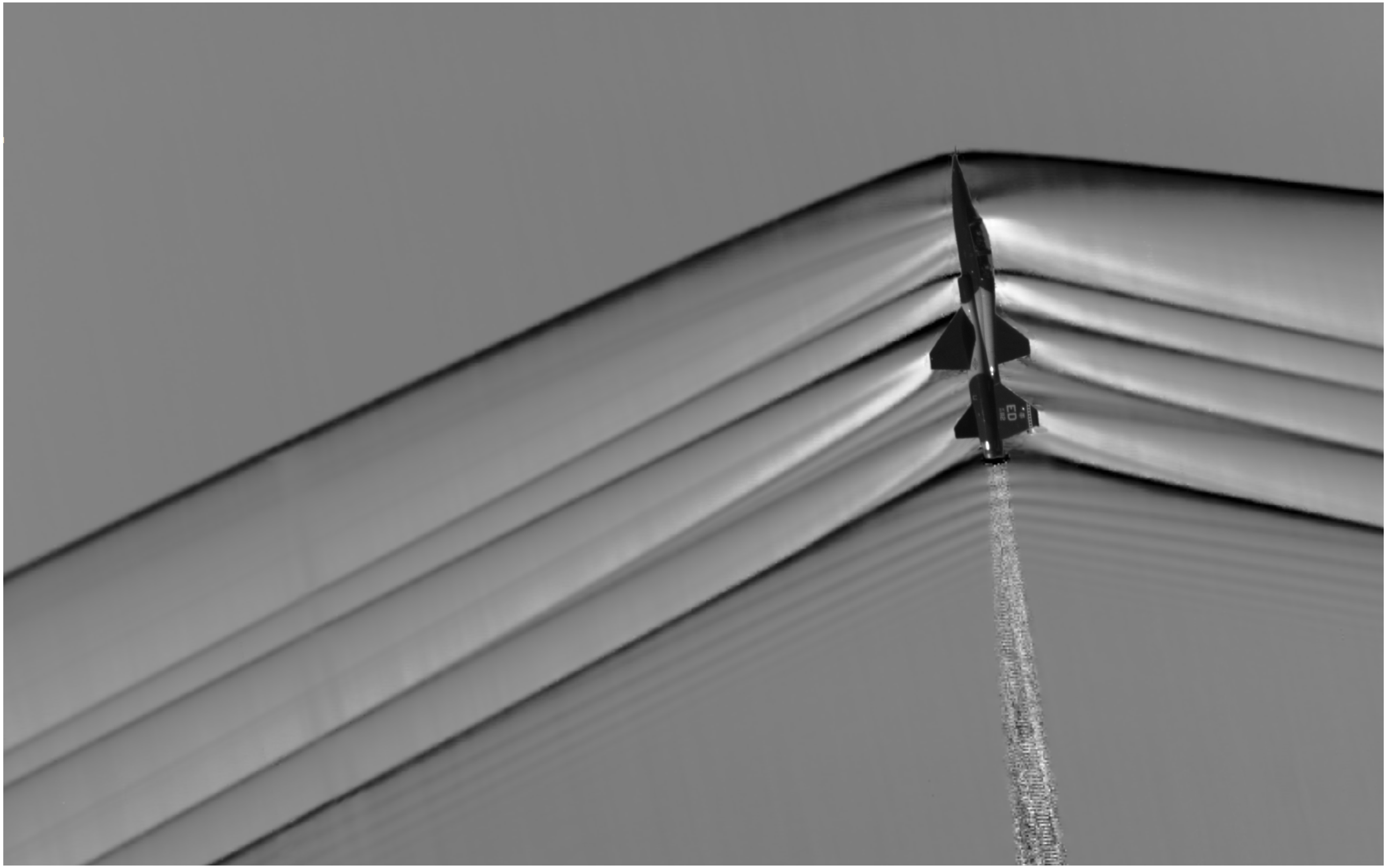
Sample movie of raw imagery, two frames skipped for brevity

Single Frame Results



T-38 at 45 deg. roll, M=1.05, single frame, 16x16 IA, 3 pixel grid

AirBOS Results

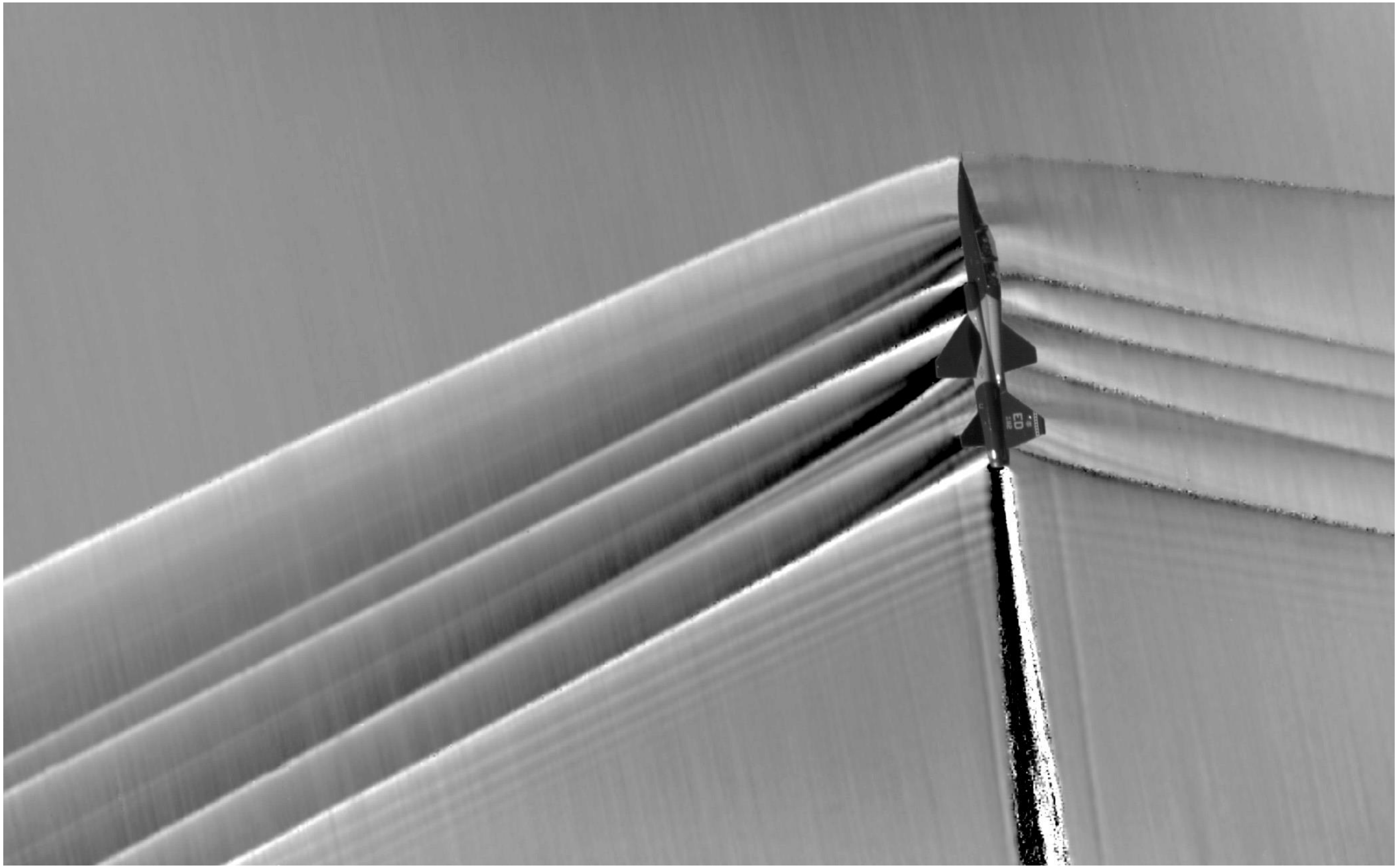


Results from 200 sequences aligned and averaged, Dy (horizontal knife edge)

AirBOS Results

Results from 200 sequences aligned and averaged, magnitude of displacement

AirBOS Results



Results from 200 sequences aligned and averaged, Dx (vertical knife edge)

AirBOS Results

Results from 200 sequences aligned and averaged, Dx (vertical knife edge)

Summary

Background Oriented Schlieren has been successfully adapted to full-scale supersonic flight

The planning and system design permit predictable results

Technique permits testing of maneuvers, monitoring tip vortex trajectories, and subsonic wakes

LATER in this Session:
Optical Flow solutions triple the resolution: Smith, et. al.

Acknowledgements

Peter Coen, CST Project Manager, for years of support for this research

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Ed Haering, NASA Armstrong, for the Intangibles