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.
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 $M=1.3$
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

<table>
<thead>
<tr>
<th>Lens fl (mm)</th>
<th>Lens</th>
<th>Camera</th>
<th>Half Angles</th>
<th>Altitudes</th>
<th>FOV at Target Aircraft</th>
<th>FOV at Ground</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ccd nx (pixels)</td>
<td>ccd ny (pixels)</td>
<td>pixel size (μm)</td>
<td>X (Deg)</td>
<td>Y (Deg)</td>
<td>Observer a/c (Ft)</td>
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<tr>
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<td>640</td>
<td>512</td>
<td>25</td>
<td>4.36</td>
<td>3.49</td>
<td>27000</td>
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<tr>
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<td>2560</td>
<td>1600</td>
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<td>4.07</td>
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</table>

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

Flt. Irwin

Cal. City

Mojave

Rosamond

Edwards AFB

Barstow

Lancaster

Palmale
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-SDWHVvis-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
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
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

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

\[
y = \frac{b_1 x' + b_2 y' + b_3}{c_1 x' + c_2 y' + 1}
\]

- Four points at corner of images are chosen, large-window CC performed
- Cross correlation between the two images yields \(\Delta x\) and \(\Delta y\) 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 \(D_x\) and \(D_y\) 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
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
Results from 200 sequences aligned and averaged, $D_x$
(vertical knife edge)
AirBOS Results

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

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