FLOW VISUALIZATION OF AIRCRAFT IN FLIGHT BY MEANS OF BACKGROUND ORIENTED SCHLIEREN USING CELESTIAL OBJECTS

NASA Armstrong Flight Research Center
Edwards, CA

Presented By:
Larry Cliatt
NASA Armstrong Flight Research Center
OUTLINE

• Background and Motivation
• BOSCO Concept
  – Background Oriented Schlieren
  – Imaging system
  – Test operation concepts
• Flight Tests
  – CaKEBOS (2015)
  – BOSCO Phase I (2016)
  – BOSCO Phase II (2017)
• Future Work
MOTIVATION

• NASA Commercial Supersonic Technology
  – Desire for a schlieren system for full scale aircraft in flight to visualize shockwaves generated by supersonic aircraft
  • Validate/refine shock modeling for low boom airframe design
BACKGROUND - EXISTING FULL SCALE SCHLIEREN SYSTEMS

Ground to air solar edge schlieren

- Schlieren for Aircraft in Flight (SAF)
  - NASA, Weinstein 1993
- Ground to Air Schlieren Photography System (GASPS)
  - Digital equivalent of SAF, Metrolaser Inc.

Air to Air Background Oriented Schlieren (AirBOS)
NASA, Heineck, Banks. 2015
Gaps in capability for existing systems

• SAF (Ground to air solar edge)
  – Flow features roughly orthogonal to the solar limb are not imaged. Not a fully 2-D map of air density gradients
  – Resolution of the system is tied to camera frame rate. Increasing the sensor size requires a proportional increase in frame rate. Hardware has an inverse relationship.

• AirBOS
  – Images are mainly plan-form. Aggressive maneuvering is required for side views.
  – Camera aircraft must fly higher altitude than aircraft to be imaged. (low boom demonstrator to fly > 50kft)
– Visualizes light ray deflections by calculating movement of features in a background
– Provides a full 2-D measurement proportional to the gradient of air density with one image pair
  • With no density gradient, a ray from B will be imaged at point I
  • With a density gradient, a ray from B will be imaged at I’, making it appear it is at point B’
  • Finding the difference in location of B and B’ gives a measure of ray deflection and therefore density gradient
Background Oriented Schlieren using Celestial Objects (BOSCO)

- Uses narrow band optical filters to give the sun a textured appearance. The texture allows for the BOS method.
- Advantages:
  - Full 2D measurement of a BOS system
  - Ability to image from below and to the side of the target aircraft
Primary Lens
- Lunt Solar Systems

Hydrogen-α optical filter
- Lunt Solar Systems

Focal Extender

High Speed Camera
- Photron WX-100

Equatorial telescope mount
• Optical Flow
  – Developed for computer vision applications in the 1970’s/80’s
  – Uses the “brightness constancy criterion” – brightness is constant between 2 image pairs, differences in brightness correspond to motion
  – Outputs “flow” vectors, 2D solutions of pixel displacement
A frame before the aircraft eclipses is used for the reference background.

Each eclipse frame is aligned with the background frame.

Optical Flow is performed on the image pair resulting in a magnitude of pixel displacements.

This is repeated for all frames in the eclipse. The median of all the results of all the frames is taken, resulting in the final de-noised schlieren image.
• Aircraft waypoints were calculated based on time of eclipse, ground position of the imager, and desired altitude of the aircraft.

• Course of the aircraft followed the sun direction across the sky, and flights occurred near the maximum solar elevation angle, to minimize the need for accurate waypoint timing.

• Range from the imager to the aircraft increases as sun elevation decreases and as altitude difference between the imager and aircraft increases.
• Calcium K Eclipse Background Oriented Schlieren (CAKEBOS)
  – Proof of Concept April 2015

• BOSCO – phase I
  – Tested Improvements in the imaging system. April 2016

• BOSCO – phase II
  – Tested new compact imaging system. April 2017
Calcium-K Eclipse Background Oriented Schlieren (CaKEBOS) April 2015

• Proof of concept test
  – Objective: Demonstrate the feasibility of using Background Oriented Schlieren (BOS) technique in a ground to air system.
  – Used non-optimized hardware already acquired for a previous test
  – Calcium K optical filter
• Resulting images greatly exceeded expectations
  – System was limited by the digital resolution

T-38 30000ft AGL, 6.5 mile range, Mach 1.05
FLIGHT TESTS: BOSCO – PHASE I

BOSCO – Phase I, April 2016

- Success of CaKEBOS allowed for equipment upgrades
  - Higher resolution Camera
    - Photron WX-100: 2048 x 2048 pixels @ 1000 frames/sec
  - Hydrogen alpha telescope
    - More uniform texture distribution
    - Speckle size is smaller and therefore better for BOS
    - Higher contrast

H-α  CaK
• 100 mm f/7 refractor telescope
• H Alpha filter
• 3x Focal extender – Effective focal length: 2100 mm
• Photron WX-100
  • 2048 X 2048 pixels
  • 1000 frames/sec
  • 333 µs integration time
• Manual solar tracking
• Manually triggered at pilot’s “mark” call or visual eclipse
To increase the field of view of the system, 3 imagers were used in a spaced array in the direction perpendicular to the aircraft course.
BOSCO- PHASE I RAW DATA

Armstrong Flight Research Center

18
BOSCO RESULTS

- Imager design improvements verified in BOSCO – Phase I
  - H-α filter provides a better background than CaK
  - Higher digital resolution provided better schlieren image resolution
  - Higher frame rate gave more eclipse frames for improved de-noising
BOSCO-PHASE I RESULTS

• Aircraft banked at sun elevation angle for direct side view
  – Direct side view is of most interest for eventual imaging of low boom demonstrator

3 Image, wide field of view

The top and bottom images in the composite used the older CaKEBOS imagers, resulting in reduced resolution
T-38 and Beech King Air eclipsing at 10,000ft AGL
- T-38 partially eclipsed the sun resulting in ½ image
- A poor black level calibration on the camera during the King Air pass resulted in reduced quality raw data
• By processing many frames after the eclipse, flow features aft of the aircraft can be seen.

• Due to the short wingspan of the T-38, the image of the vortices are quickly Overwhelmed by the engine exhaust more than 5 body lengths aft
BOSCO – Phase II, April 2017

• Test of a new compact imaging system
• Closer range – 2 miles
Imaging of shocks beneath LBFD aircraft at normal cruise altitude will require very low sun elevation angle.

Low elevation angles will require small differential altitude; future imaging system will be airborne. Camera aircraft will operate roughly 10,000ft horizontal separation from target.
New compact imaging system for future airborne use

**IDT Camera:**
- 3800 X 2400 pixels
- 1000 Frames/sec

**Nikon Lens**
- Compact 500mm
- Cassegrain lens

**H-α filter:**
- 0.5 Angstrom bandpass

**Original BOSCO H-α Imaging System**

**Compact BOSCO 2 System**
BOSCO – PHASE II RESULTS

• Results
  o Images show much more shock detail at close range
  o The increase magnitude of background distortion at the closer range reduces the effectiveness of the optical flow image processing, resulting in noisier results
  o The reduced number of frames to de-noise with also increases noise in final images
    • Will not be an issue with airborne system
  o Compact imaging system performed satisfactory, but needs greater control over image focus

BOSCO- Phase I system
Single element, fixed focal length
Primary lens

BOSCO- Phase II system
Multi element, compact Cassegrain primary lens. Oversensitive focusing mechanism
CONCLUDING REMARKS AND FUTURE WORK

- Solar chromosphere works well as a background for BOS
  - Both Hydrogen – α line and Calcium-K line produced good results.
    - H- α superior for BOS imaging
- Field of view can be increased with multiple camera array
- Extended view aft of the aircraft can be achieved by processing frames after the eclipse
- Subsonic flow features can be imaged
- Future work
  - Investigate alternate processing methods for close range images
  - Continue development of airborne imaging platform
  - Improve focusing mechanism on compact imager