IMAGING SHOCKWAVES AND VORTICES ON FULL-SCALE AIRCRAFT USING SCHLIEREN PHOTOGRAPHY WITH THE SUN’S LIMB FROM THE GROUND AND FROM AN AIRCRAFT

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BACKGROUND

- First schlieren image of full-scale supersonic aircraft by Leonard Weinstein, NASA Langley, 12/13/1993
- Time delay integration streak camera used
- Accurate alignment of optics needed
- Film advancement rate must match image speed
- Only density changes perpendicular to limb imaged, ~1 dimension
Advanced Ground System

- Two Small Business Innovative Research contracts with MetroLaser (spun off to Spectabit Optics, LLC), with Leonard Weinstein as a consultant
- High frame-rate area camera, entire limb imaged
- Modern cameras and computers give high resolution
- Area camera allows for camera shake, misalignment
- Analysis after flight, allows for flexibility
- GASPS: Ground to Air Schlieren Photography System
**FLIGHT PLANNING**

- Best results by flying near zenith, East-West
- Pilot use Garmin 496 GPS to hit eclipse point
- Watching contrails or radio calls used to trigger images

**Appleman chart predicts contrails**
SYNTHETIC TIME DELAY INTEGRATION
**Errors in Pixels Per Frame**

- $PPF = f \frac{V_{perp}}{R S_p} FPS$
- Effect of 20% error in speed:
- Can use measured offset of two images for optimum speed
- $PPF_{opt} = PPF_{original} - h(frame_{exit} - frame_{enter})$
**ERRORS IN CAMERA ANGLE**

- Effect of 10 deg error in camera angle
- Can use measured offset to get the correct angle
- \[ \phi_{opt} = \phi_{original} - \sin^{-1}(v/D)180^\circ / \pi \]
• Using the correct pixel per frame and camera angle gives a unified image

• Using 10 subpixels per real pixel increases acuity, Mach lines in the plume can now be seen
ADDITIONAL FEATURES FAR AFT

- Elliptical patterns far behind aircraft
- Double image earlier shown to be speed error
- This is a range ($R$) error: $PPF = f \frac{V_{\text{perp}}}{R S_p} \text{ FPS}$
FAR AFT SHOCKS IMAGED

- Adjusting the pixel per frame collapses far aft shocks from ellipses to lines
- Aircraft at 32,000 ft altitude, far aft shocks at 38,736 ft
- Enter/exit side imaging allows quantitative measure of distance
CUTOFF MACH CONE

- Far aft shocks are backside of Mach cone after cutoff
- Shape of calzone sandwich
• Spectabit Optics LLC
• Polar remapping of each frame
• Angle vs. time
PASS RESULTS

• Tremendously detailed images

Vortex can be seen if aircraft near limb
OTHER FLOW PHENOMENON IN PLUME

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Air to Air Imagery

- Flow under aircraft of most interest: would like side view
- Used improvised gear in F-18 rear seat to target aircraft
- Fastec TS3 camera, 80-400mm zoom lens
- Handheld in cramped, bright F-18
- Relative GPS and pilot display to eclipse point
- Much larger image, more details
- ASPS: Airborne Schlieren Photography System
CONCLUDING REMARKS

• Distortions of Sun’s limb can image shockwaves and vortices of full-scale aircraft in flight
• Area camera and post processing more forgiving of misalignments, camera motion
• Backside of Mach cutoff shockwaves imaged
• Quantitative measurement of range to shockwaves made
• Use of handheld GPS and flying along locus of eclipse points yielded aircraft eclipses most of the time
• GPS data can yield close processing parameters, doubling of silhouette can yield optimum parameters
• PASS analysis gives more detail than STDI analysis
• Airborne version demonstrated
  – Allows for imaging below aircraft
  – Greater detail because of shorter range