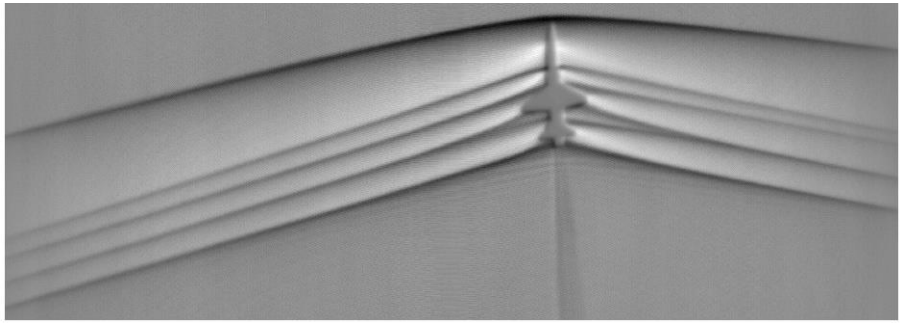
IMAGING SHOCKWAVES AND VORTICES ON FULL-SCALE AIRCRAFT USING SCHLIEREN PHOTOGRAPHY WITH THE SUN'S LIMB FROM THE GROUND AND FROM AN AIRCRAFT



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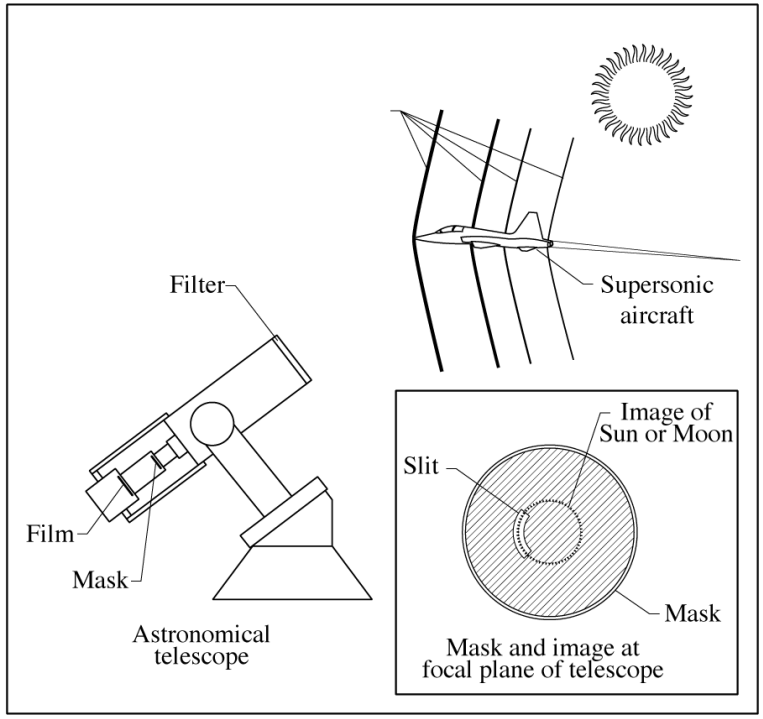
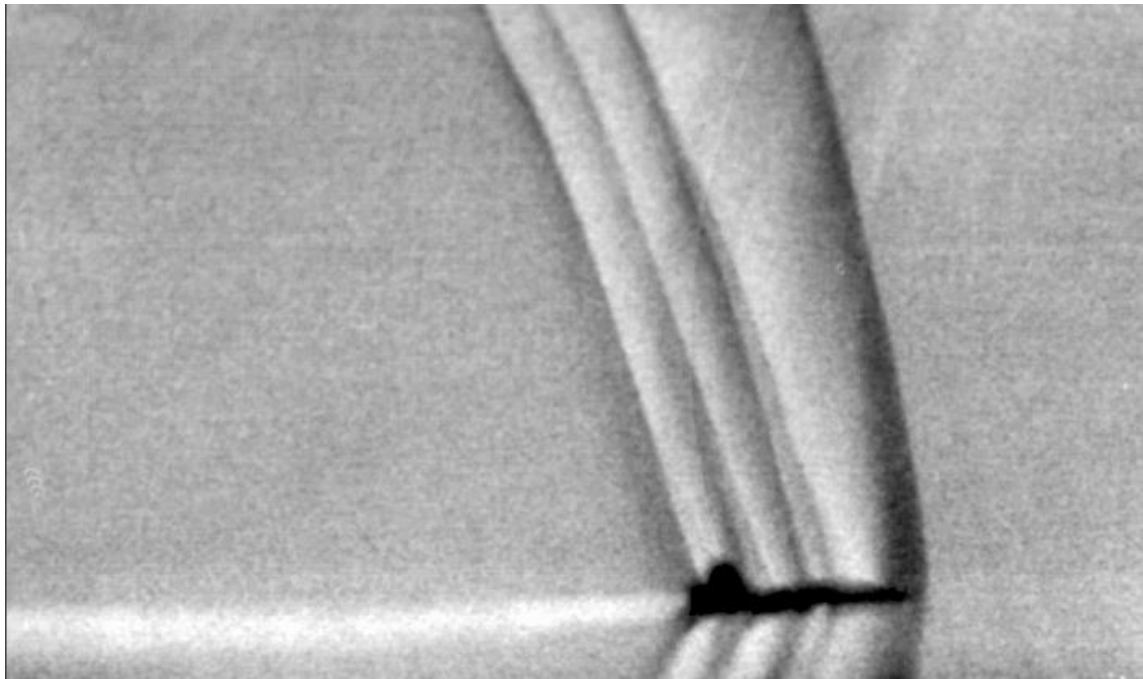
BACKGROUND

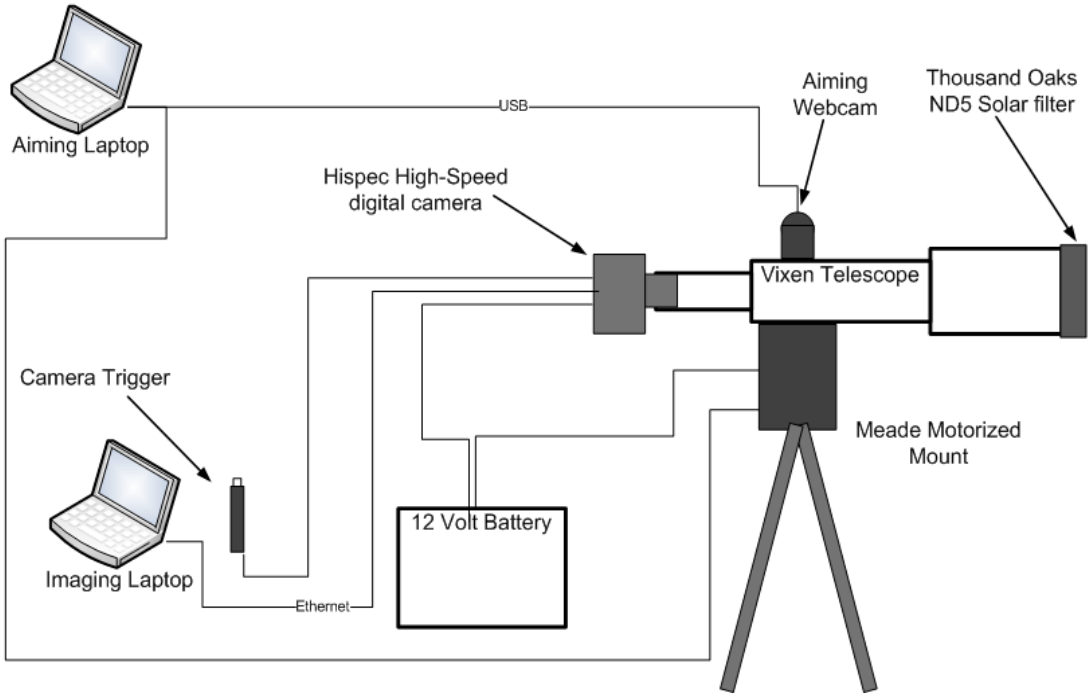
- First schlieren image of full-scale supersonic aircraft by Leonard Weinstein, NASA Langley, 12/13/1993
- Time delay integration streak camera used
- Accurate alignment of optics needed
- Film advancement rate must match image speed
- Only density changes perpendicular to limb imaged, ~1 dimension





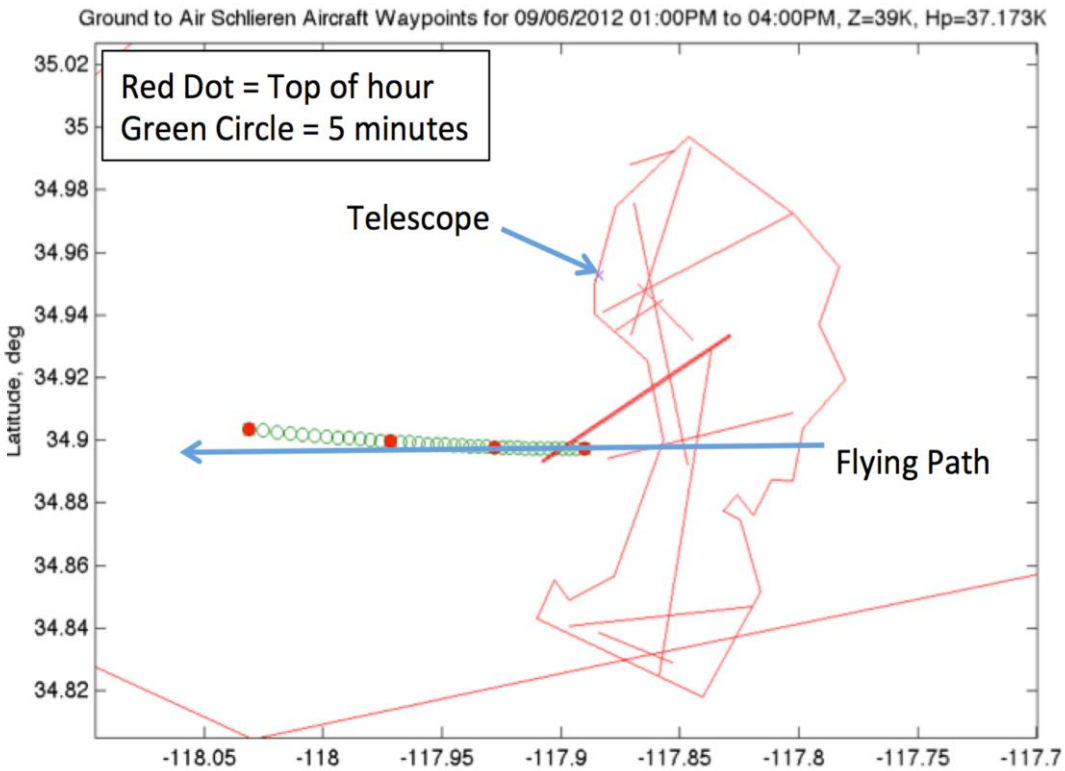
ADVANCED GROUND SYSTEM

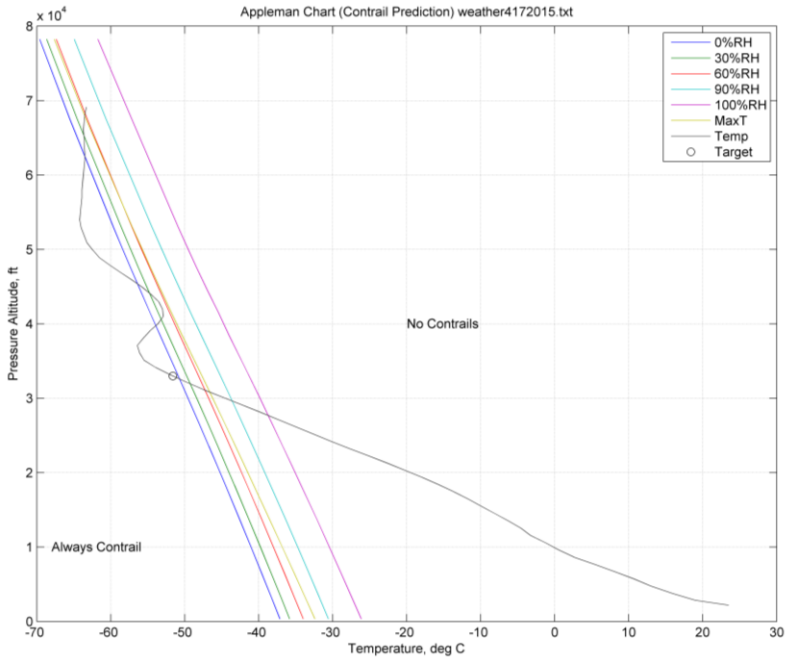
- Two Small Business Innovative Research contracts with MetroLaser (spun off to Spectabit Optics, LLC), with Leonard Weinstein as a consultant
- High frame-rate area camera, entire limb imaged
- Modern cameras and computers give high resolution
- Area camera allows for camera shake, misalignment
- Analysis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



FLIGHT PLANNING

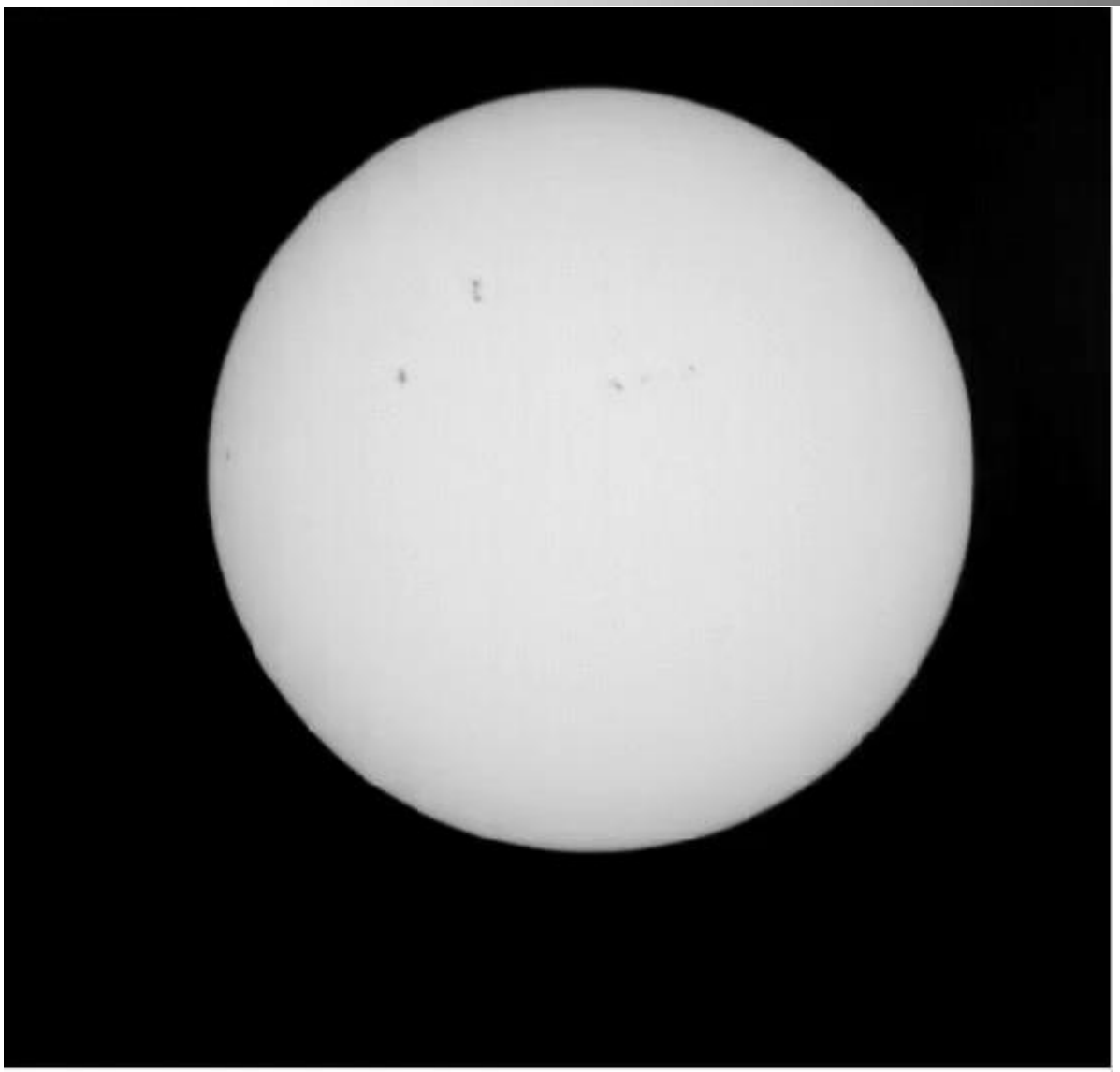
- Best results by flying near zenith, East-West
- Pilot use Garmin 496 GPS to hit eclipse point
- Watching contrails or radio calls used to trigger images





Appleman chart predicts contrails

RAW IMAGES



4/17/2015 6:57:56 PM 0244.6[ms] 000003780 HiSpec 1 [00-11-1c-f1-70-f8] Fastec 576x556 1762fps 144µs V1.4.7

Synthetic Time Delay Integration

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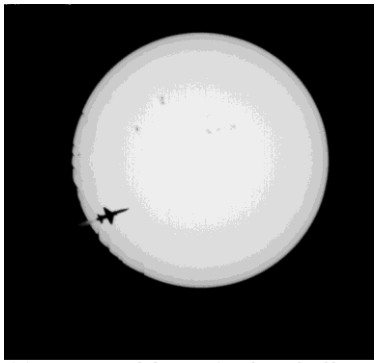
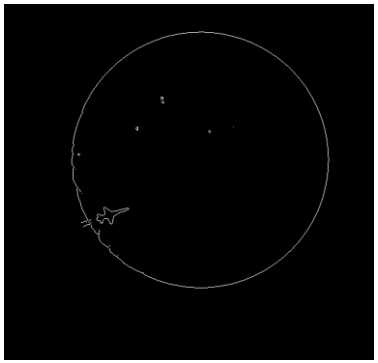
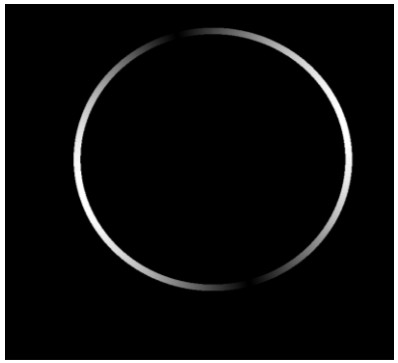
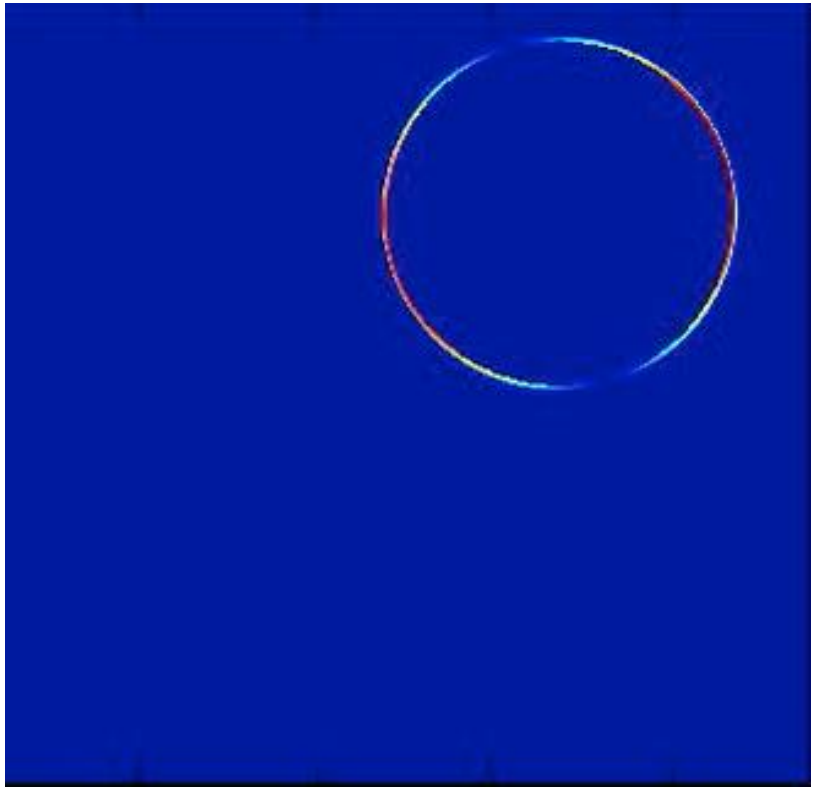


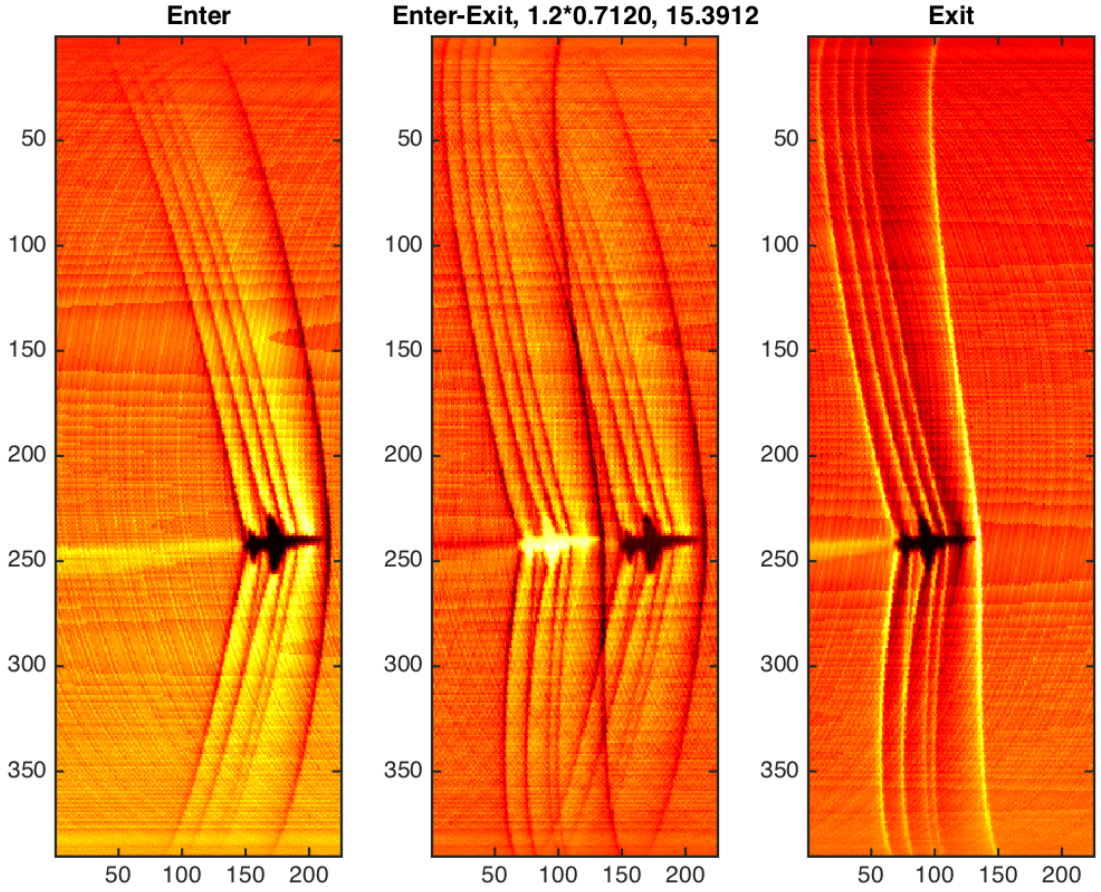






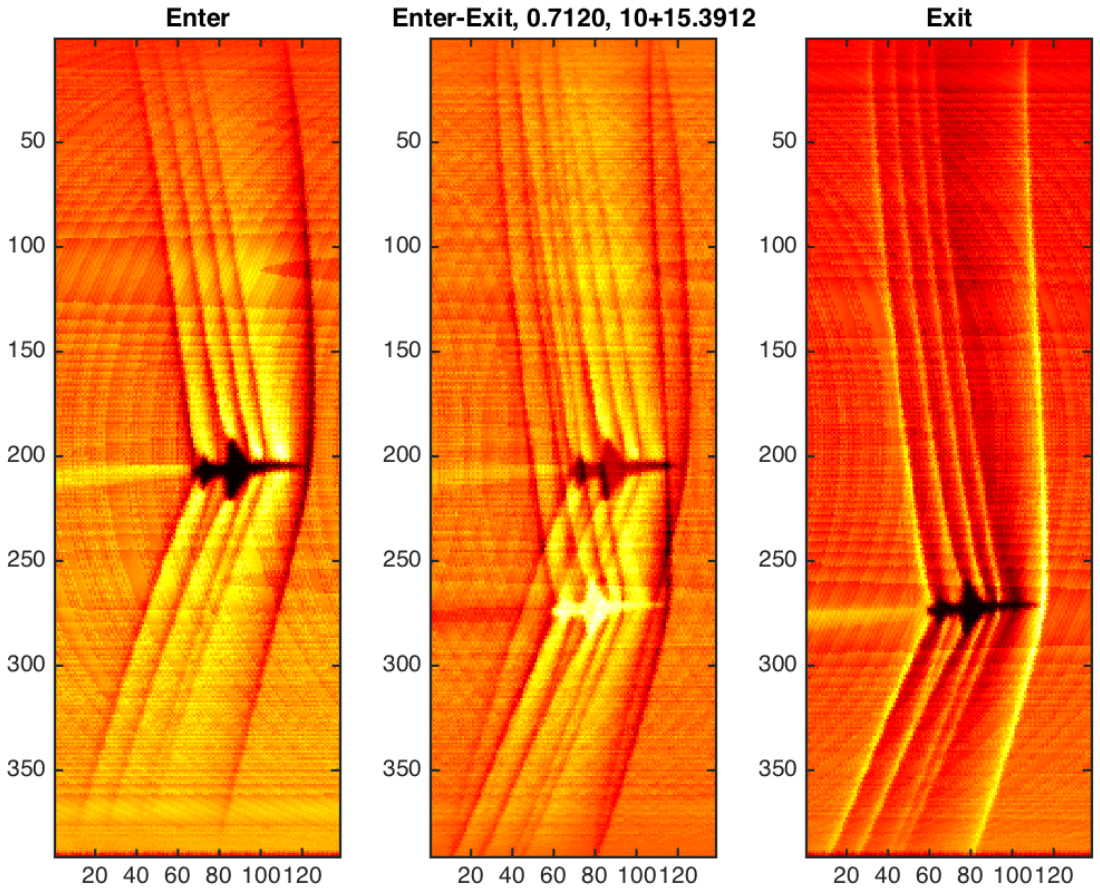
Errors in Pixels Per Frame

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



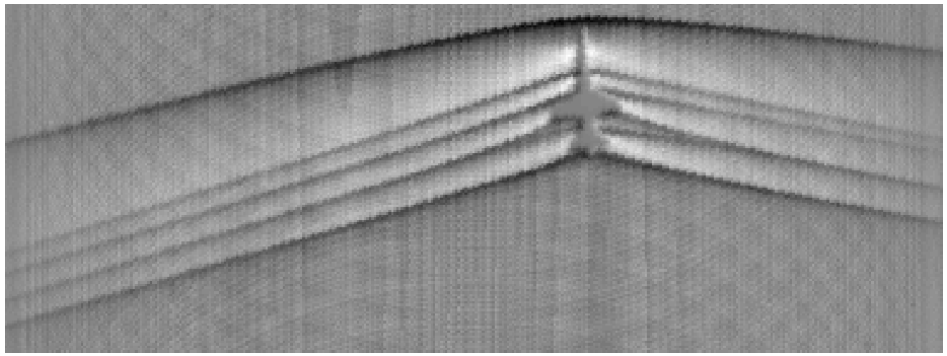
ERRORS IN CAMERA ANGLE

- Effect of 10 deg error in camera angle
- Can use measured offset to get the correct angle
- $\emptyset_{opt} = \emptyset_{original} - \sin^{-1}(v/D)180^{\circ}/\pi$

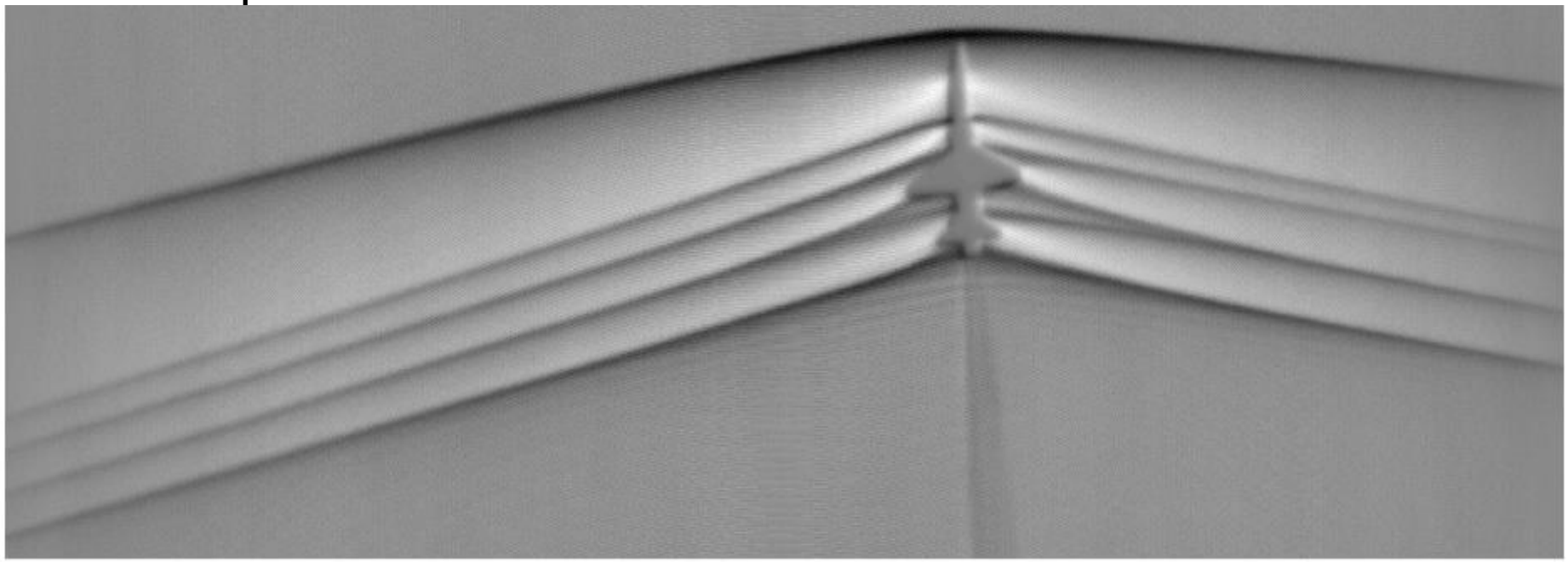


Combined Image and Subpixel Processing

- Using the correct pixel per frame and camera angle gives a unified image

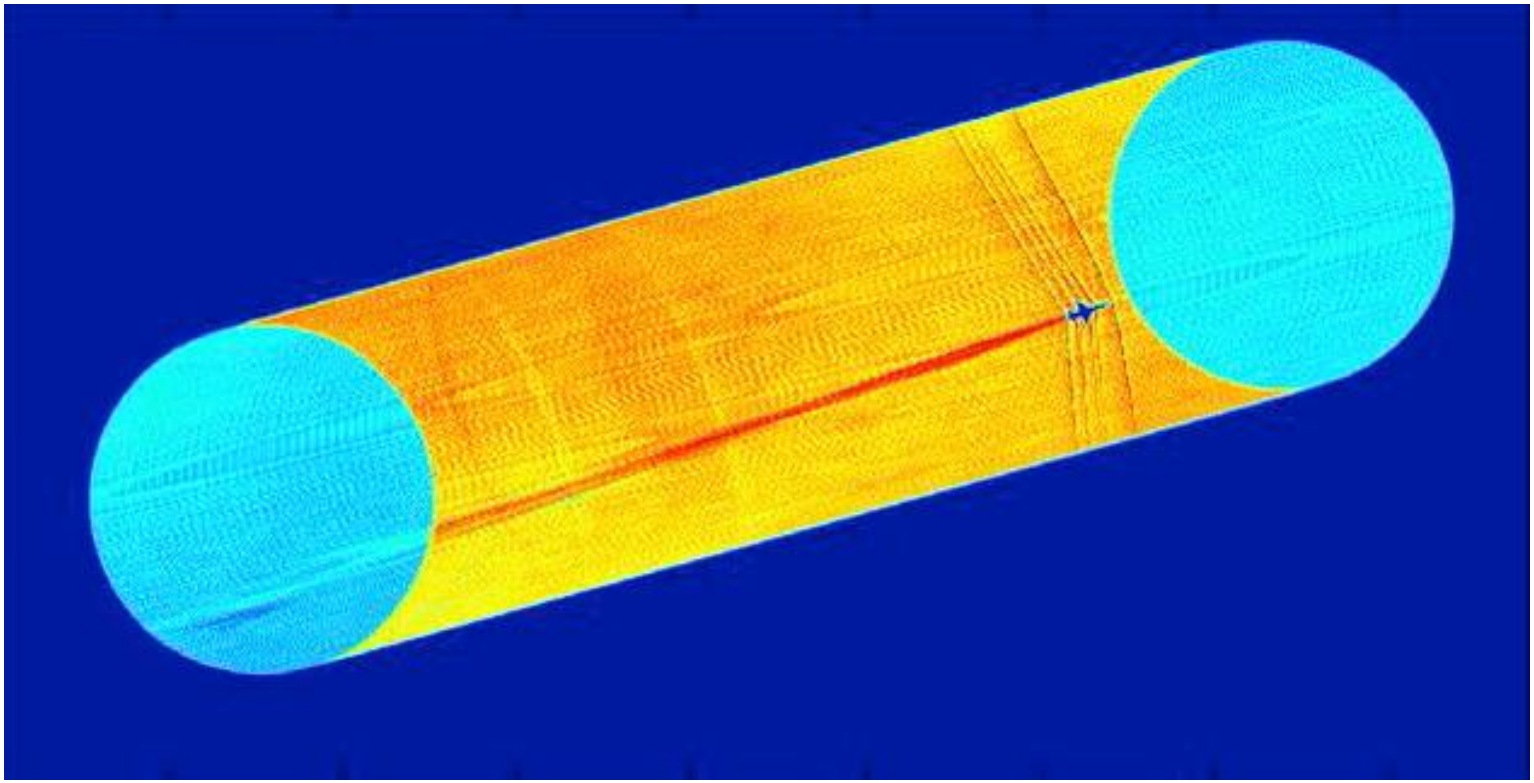


- Using 10 subpixels per real pixel increases acuity, Mach lines in the plume can now be seen



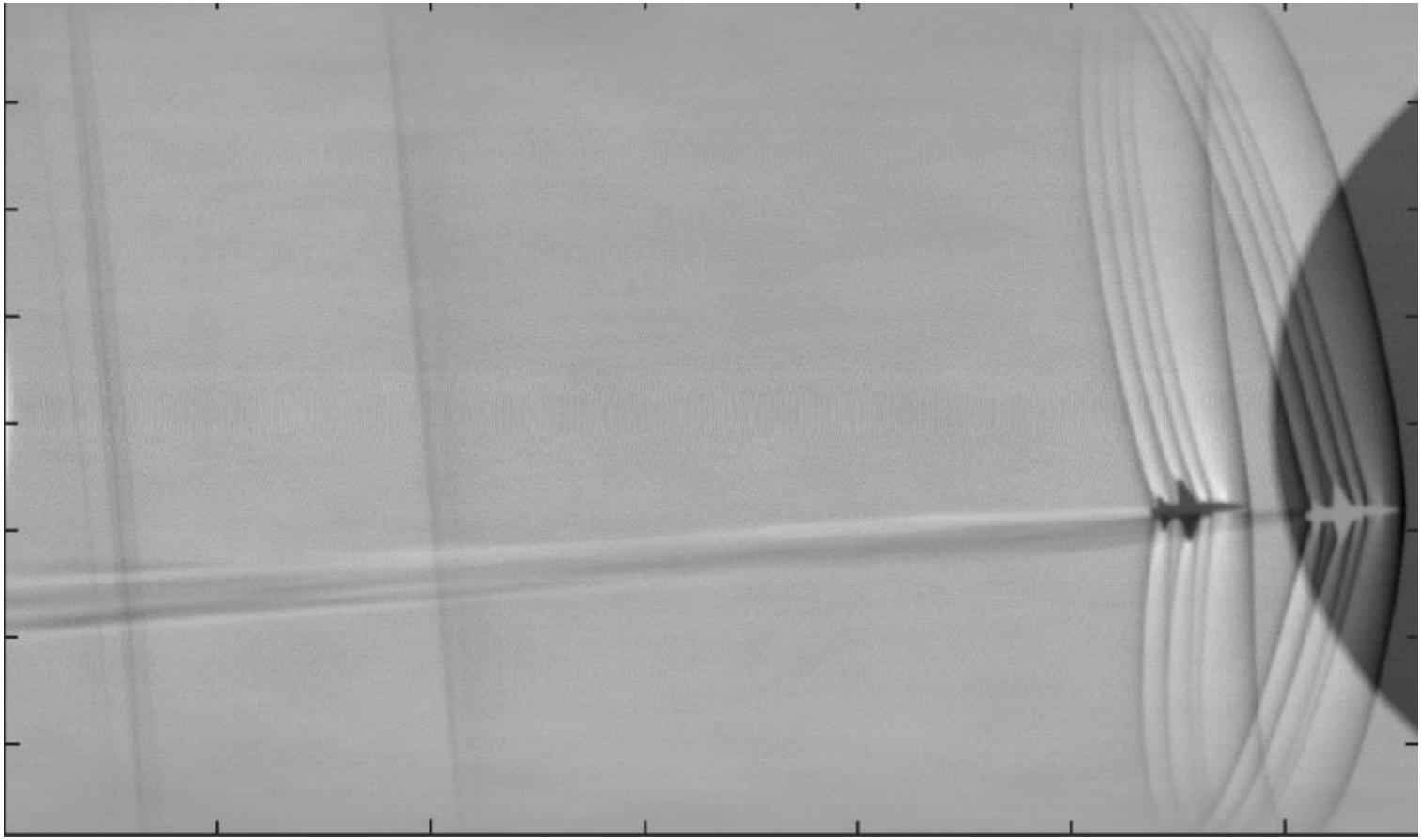
Additional Features far aft

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



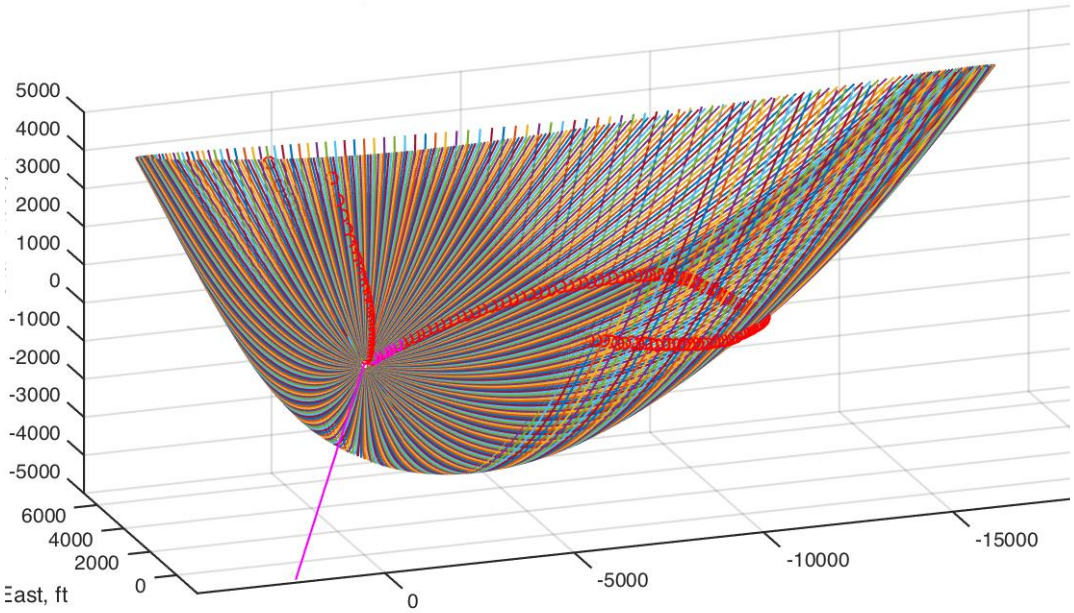
Far Aft Shocks Imaged

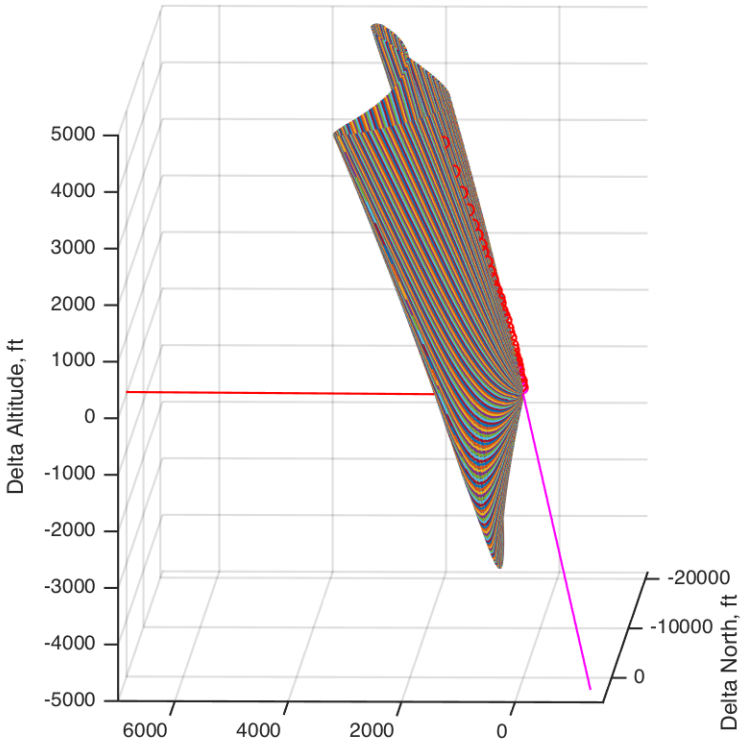
- Adjusting the pixel per frame collapses far aft shocks from ellipses to lines
- Aircraft at 32,000 ft altitude, far aft shocks at 38,736 ft
- Enter/exit side imaging allows quantitative measure of distance

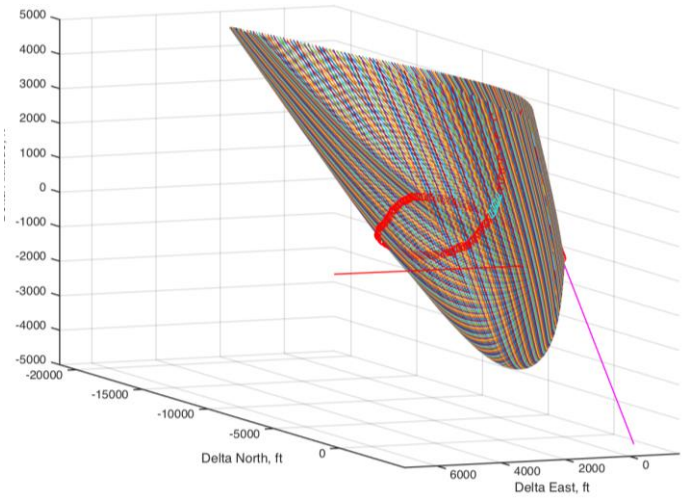


CUTOFF MACH CONE

- Far aft shocks are backside of Mach cone after cutoff
- Shape of calzone sandwich





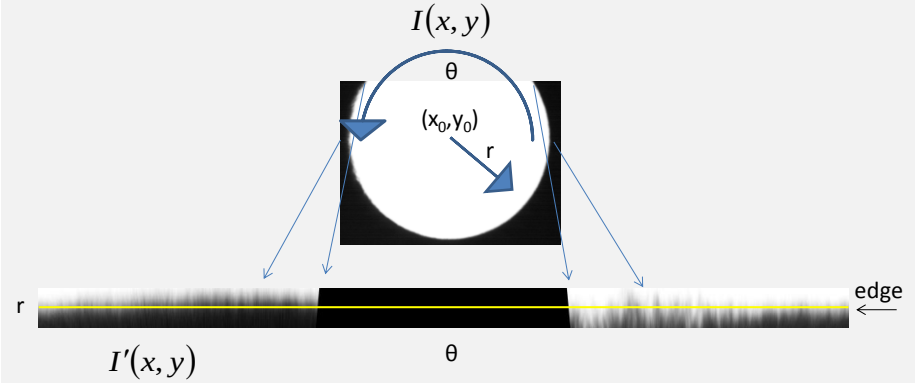


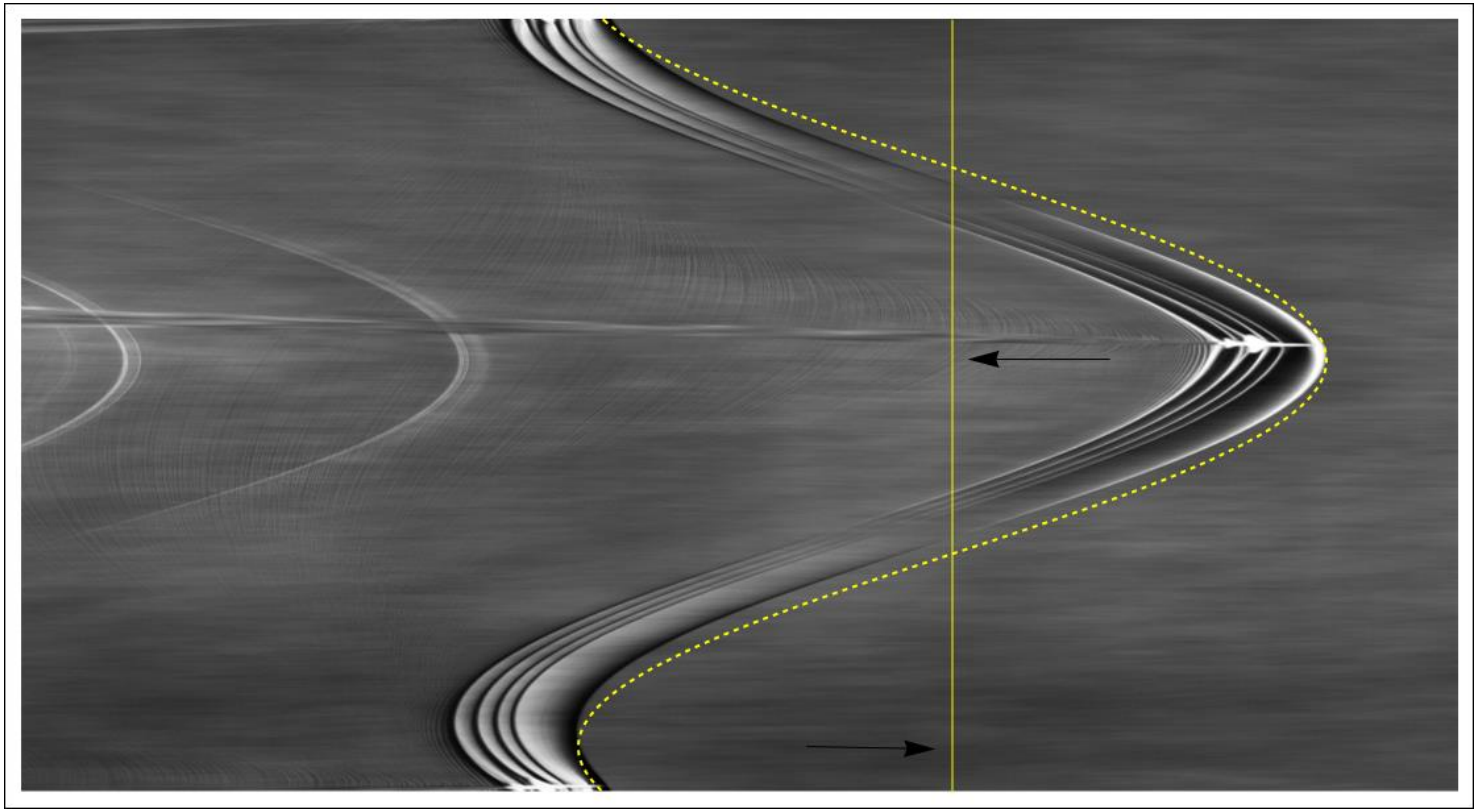
Delta East, ft

POLAR ANALYSIS SCHLIEREN SOFTWARE (PASS)

Armstrong Flight Research Center

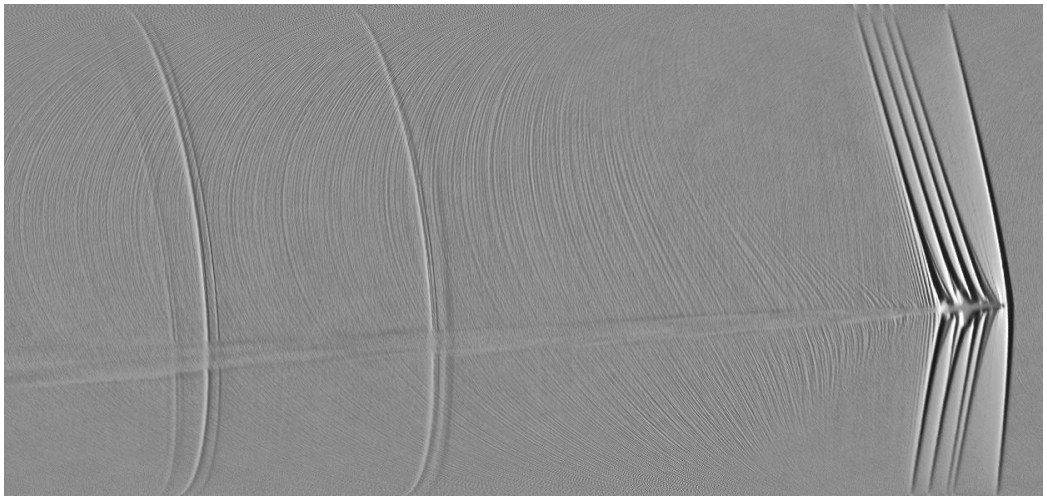
- Spectabit Optics LLC
- Polar remapping of each frame
- Angle vs. time

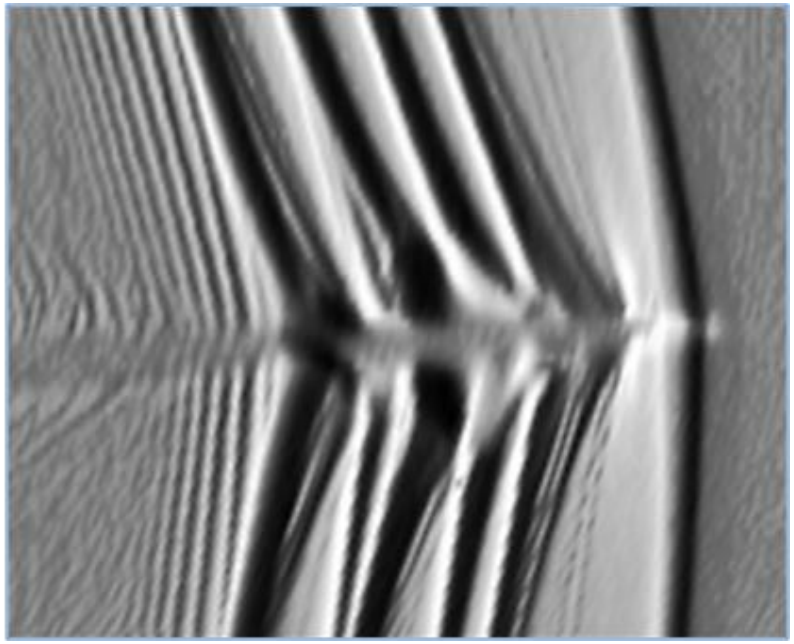




PASS RESULTS

- Tremendously detailed images



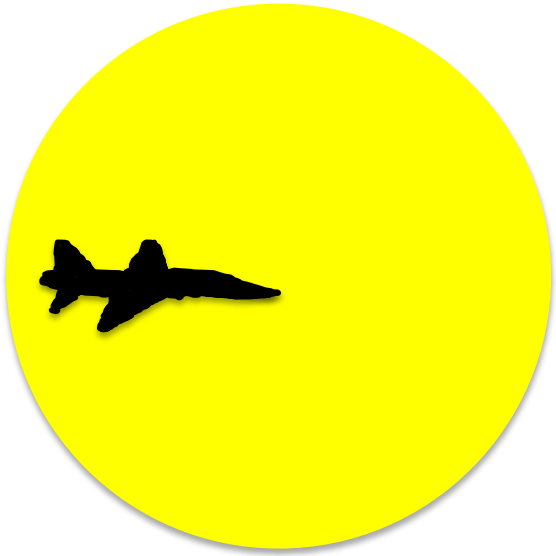


Vortex can be seen if aircraft near limb

Other Flow Phenomenon in Plume

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