Planning for Airborne Schlieren Imaging of X-59 QueSST

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Agenda:

Introduction to the Task

X59 Low Boom Flight Demonstrator mission (LBFD)

Data requirements for schlieren imaging

Three potential methods

Testing for the vibration environment

Testing for the pressure/temperature environment

Current state of hardware and software

Summation

Motivation

- NASA Commercial Supersonic Technology / FDC
  - Desire for a schlieren system for full scale aircraft in flight to visualize shockwaves generated by supersonic aircraft
  - Primary use for X-59 Quiet Supersonic Technology demonstrator
    - Validate/refine shock modeling for low boom airframe design
    - MUST image downward propagating shocks

Photo Credit: Lockheed Martin

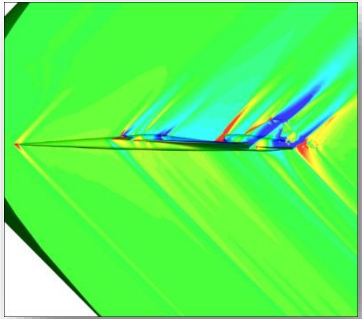


Photo Credit: NASA/James Jensen

Credit: Lockheed Martin and NASA

Three In-Flight Schlieren Methods

- AirBOS, Air-to-air Background Oriented Schlieren
  - Downward looking at desert bushes or ocean sun glint
  - Wide view, very detailed, easier flying
  - Can fly in formation, or from slow observer

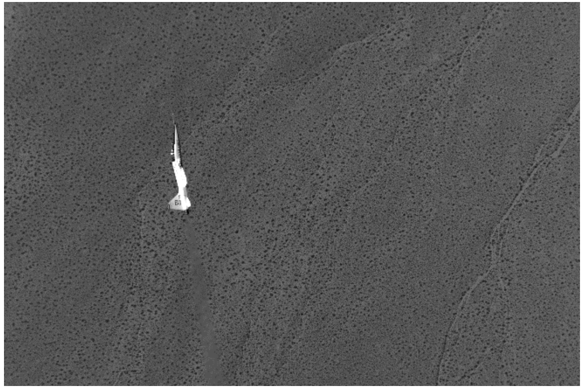
  Profile view requires aggressive maneuvers to get lower side shocks

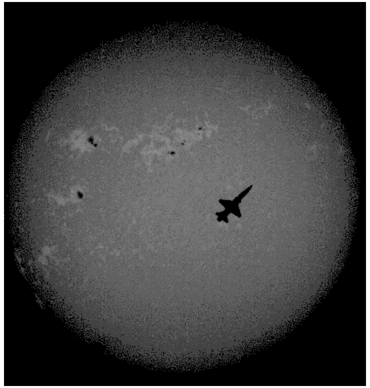
- BOSCO, BOS using Celestial Objects
  - Spectral imaging gives visual texture to the sun
  - Ground-to-air currently
  - Potential for lower side shocks

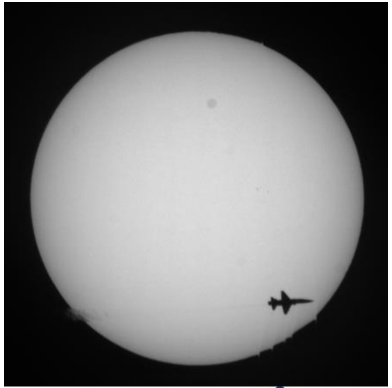
  0.5 deg field of view

- Sun-edge Distortion
  - Capture the perimeter of Sun being distorted with TR imaging
  - Extract from each frame 10-20 pixel rings, align sequence
  - Same flight planning as BOSCO, more forgiving

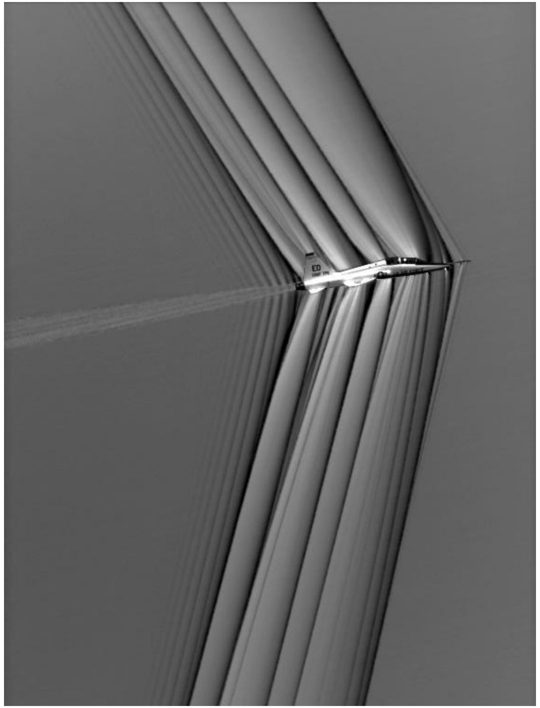
  Least amount of detail of the shocks, 0.5 deg fov



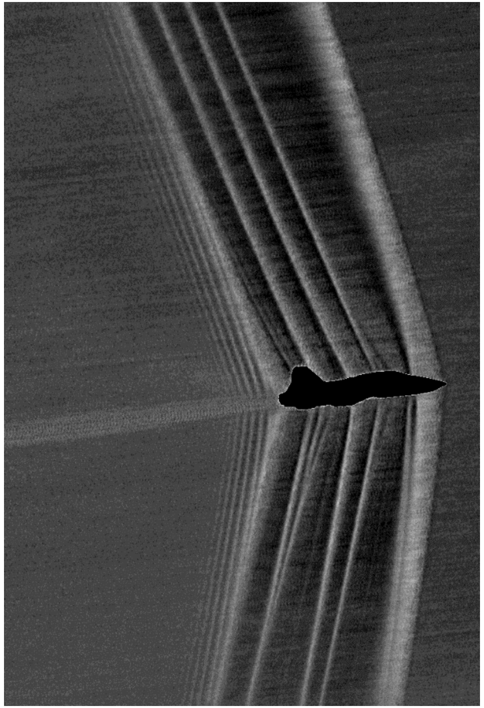




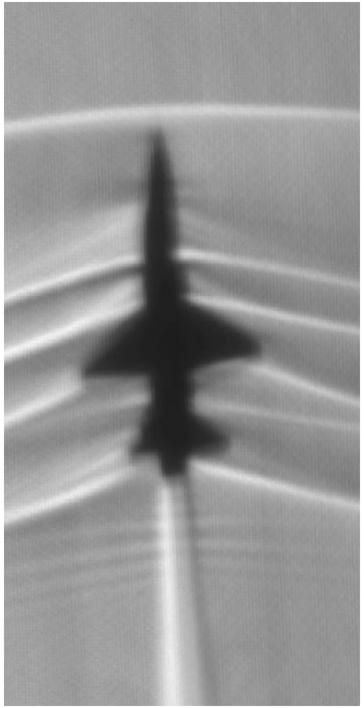
Examples of the Three Methods of a T-38



AirBOS



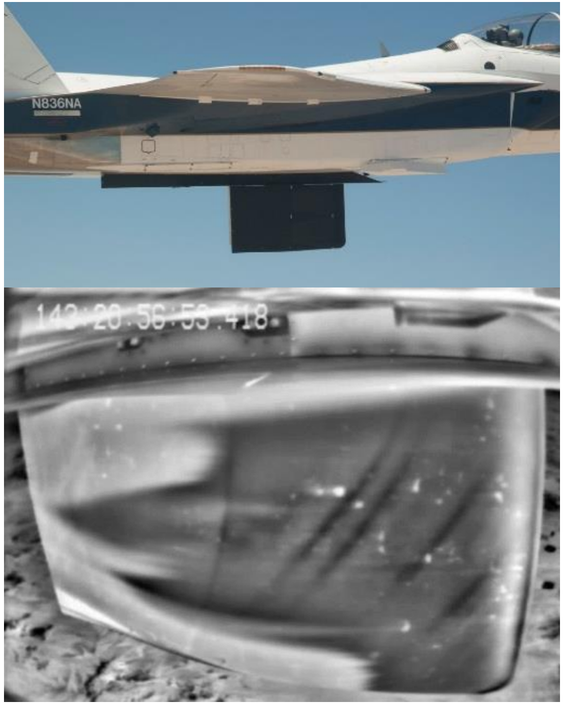
AirBOSCO with Hα



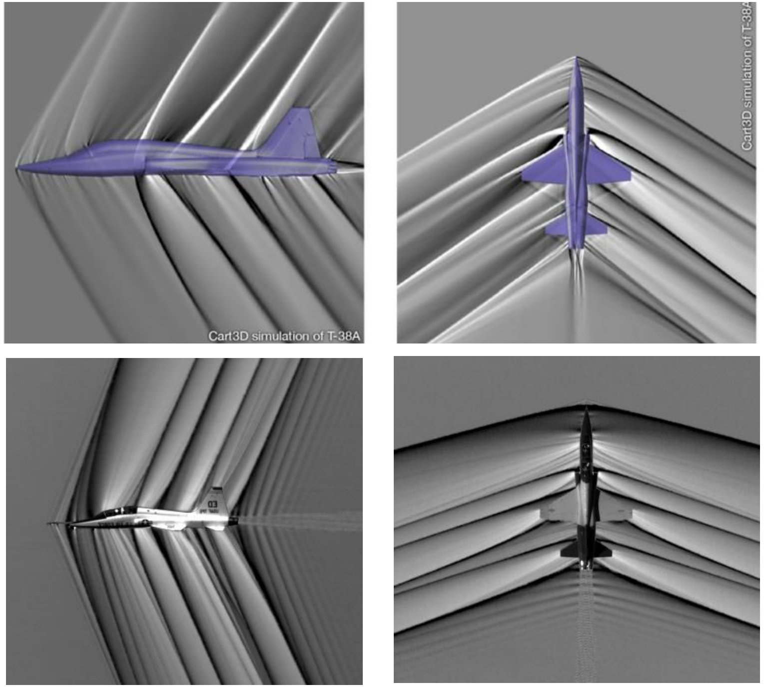
Sun Edge Distortion

CFD Validation: Primary driver for schlieren data

Evidence CFD not correctly predicting all shocks



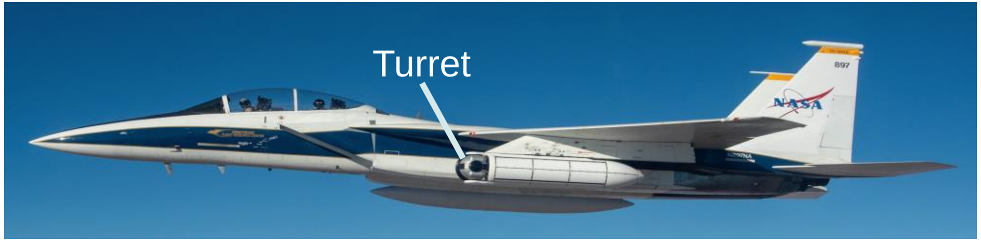
Unidentified shock impingement on laminar flow test article



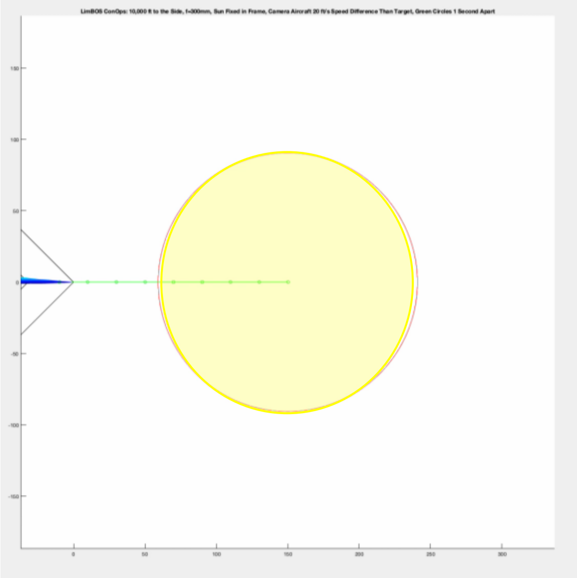
CFD v AirBOS results on T-38

Air-to-Air Formation: Imaging Pod on the NASA F-15

- Side-view of X-59 is priority 1, Sun imaging method
- Use of imaging pod to fly in formation with X59@ ~55k+ feet (~23km)
- Pod takes three cameras, ranges 180° h,
- +/- 35 ° v, mounts on either wing
- New program/electronics to uplink X59 to F15 for formation flight coordination – ALIGNS
- Programmed to track sun
- High vibration and unconditioned environment



The planned pod for imaging the X-59 QueSST

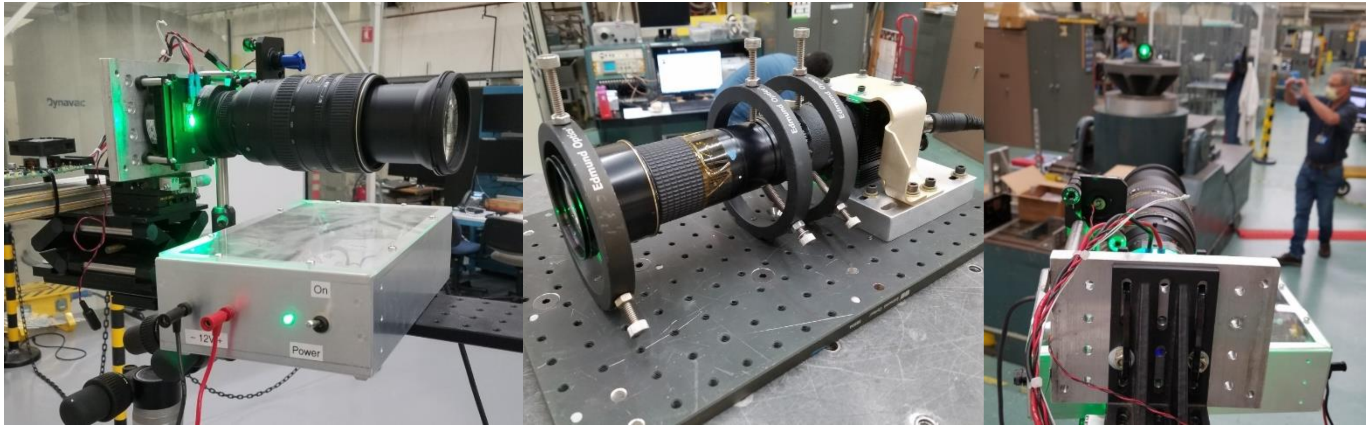


Pattern for imaging the downward shocks

Environmental Testing: Image blur due to vibration

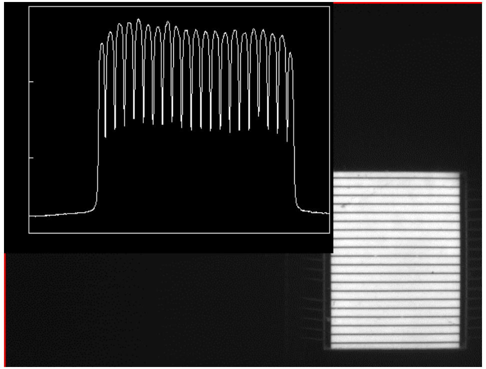
3-axis accelerometers for in-flight vibe of turret, programmed vibe table to match
IDT O10 camera/lens combos tested on vibe table at measured levels

- A high-intensity LED was collimated and re-imaged on flight camera
- Analysis showed optimal integration time for Sun-edge optics
- AirBOSCO optics with etalon required 200 microsecond integration time:
  - *Significant image blur eliminated technique*

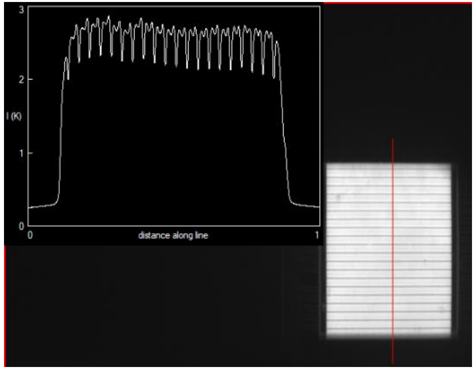


LED and 400 mm lens, stabilized Sun-edge camera / lens, projection alignment

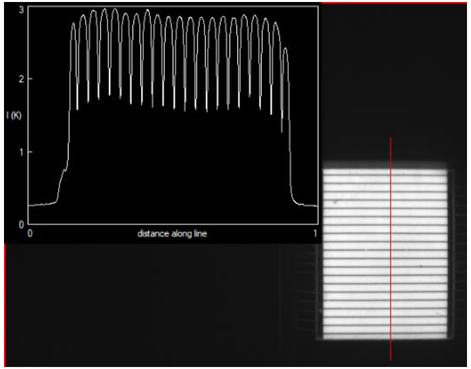
Profile plots of imaged LED



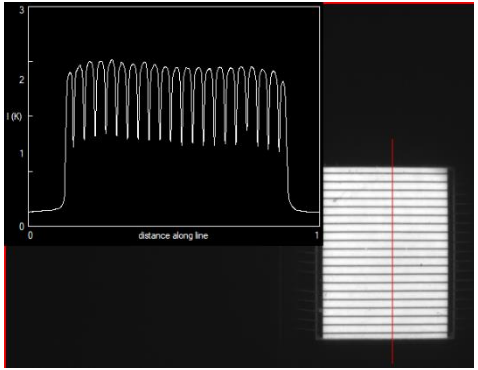
Reference



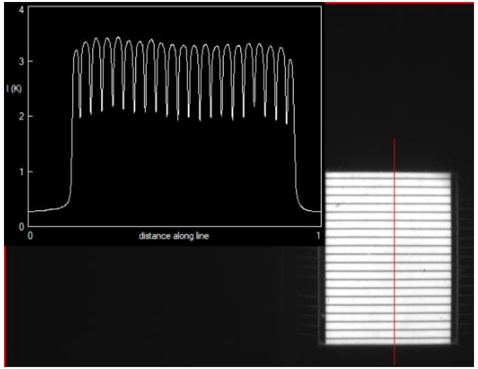
1 microsec



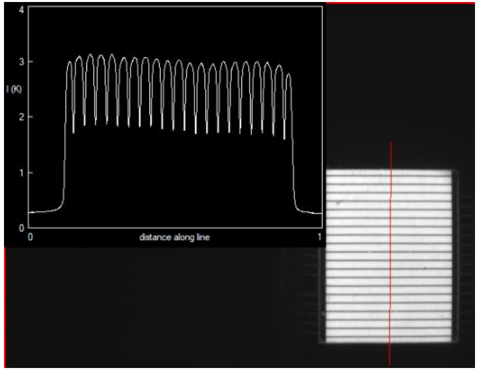
10 microsec



25 microsec

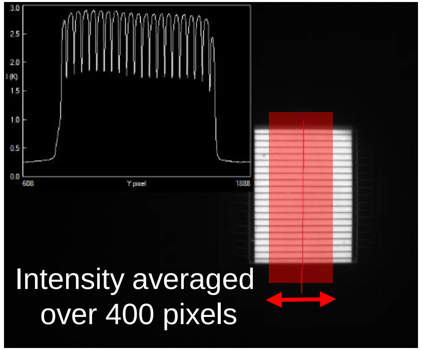


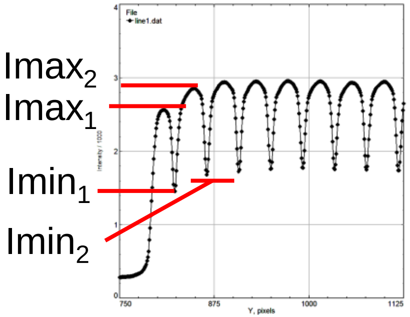
50 microsec



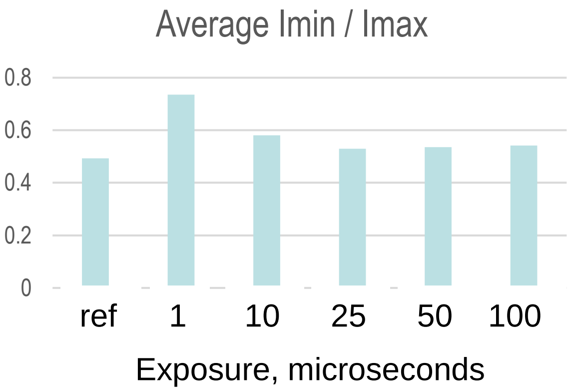
100 microsec

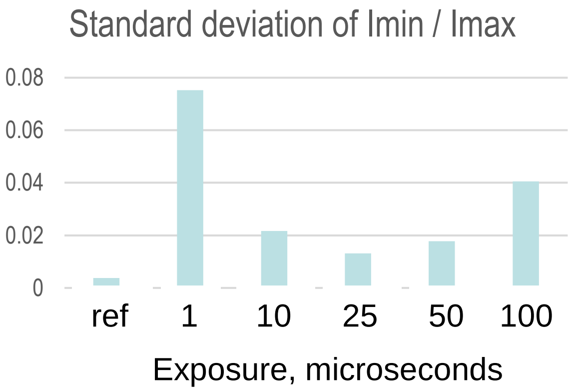
Optimized Exposure: Ghosting v. Motion Blur



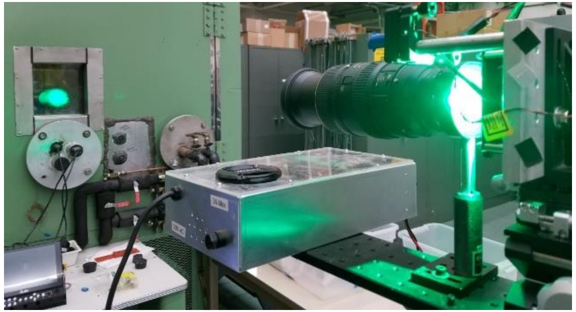


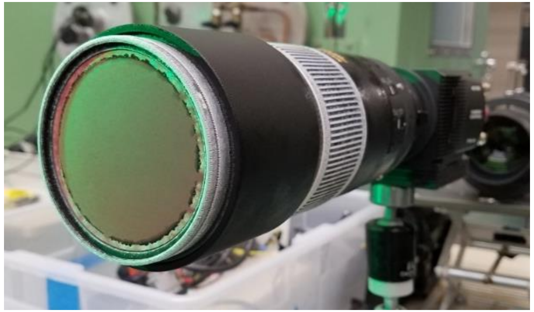
$$(Imin / Imax)_{ave} = \frac{1}{Ncycles}\sum_{i=1}^{Ncycles}\left(\frac{Imin}{Imax}\right)_i$$





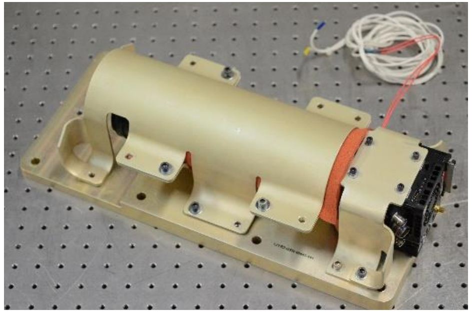
Environmental Testing: Altitude Effects





Focus shifted by Δ Cte, air density
Sun-edge config (300 mm +2x TC)
Same LED method, into chamber
Images acquired with pad heater,
PID controller set 20 C +/- 3 C

Lens with pad heater, insulation



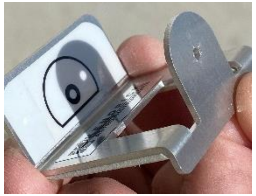
Clam-shell and camera cage design

Ref (sea-level) **60,000 ft, 20° C** **60,000, -30° C**

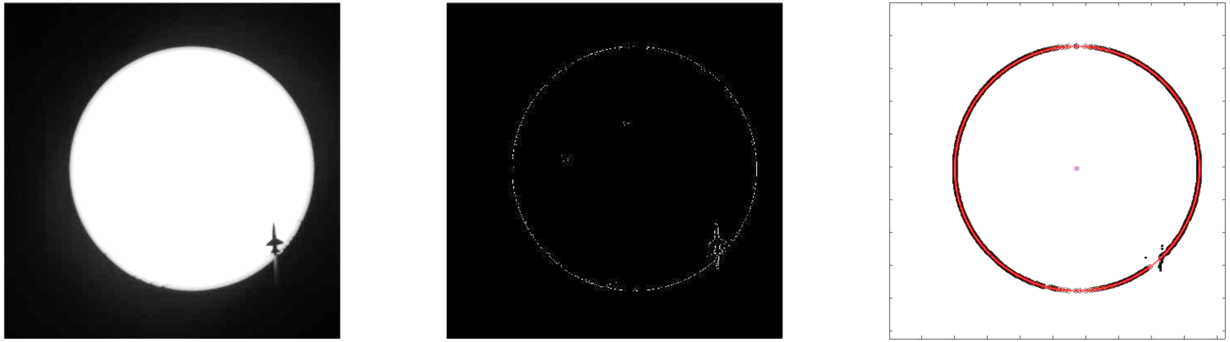
Images of LED during altitude testing show focus stability

Hand-held Sun-edge Imaging Effort

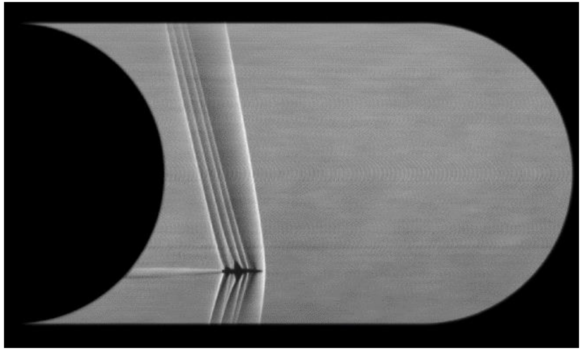
- A backup to pod mounted system
- Battery powered IDT O10 camera
  - Mission Mode: preprogrammed settings from simple trigger input from photographer
- 300 mm Reflex lens with 2x teleconverter
- External HDSDI monitor
- Gunsight for quick alignment to Sun
- Operate from rear seat in cockpit of chase aircraft



Sun-Edge Image Processing



RANSAC method: raw image, to detected perimeter, to multiple 3-point locations that fall in the model of the Sun diameter



Sequence of aligned “rings”

Random Sample Consensus (RANSAC) method: filters outliers caused by disturbances

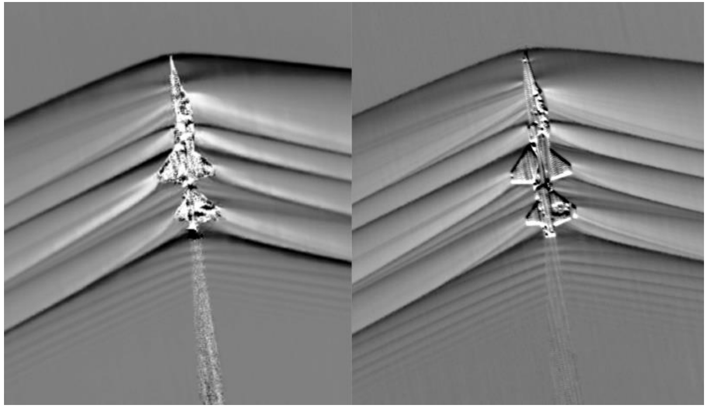
- Select three points from locus set to define arbitrary circle xc, yc, R
- Classify each data point as inlier or outlier, based on measured undistorted Sun image
- Perform many trials, then select solution with largest percentage of inliers
- Final least squares refinement with inliers

Extract perimeter of sun with distortions, line up the “rings” to create the schlieren image.

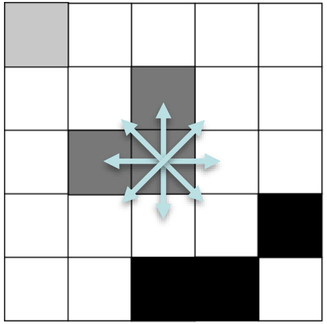
AirBOS Image Processing

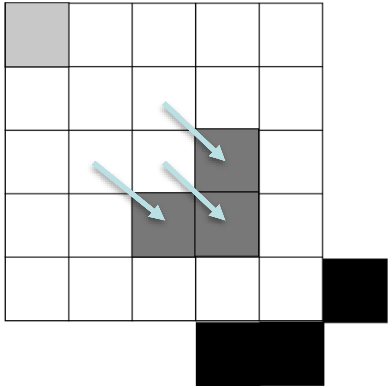
Image Processing with Optical Flow

- Similarly uses a reference background image and compares to a data image
- Mathematically measures the apparent motion due to brightness changes
  - Assumes the illumination level is constant between frames
  - The distortion caused by the shockwaves makes the bushes "move" a few pixels
  - The "motion" is detected at each pixel with a partial differential equation



Cross correlation v Optical Flow





Summary

- Spent many years developing useable flight test techniques to image shock waves for X59 QueSST
- Some apparent flow physics anomalies between actual aircraft and predictions (CFD) have been observed.
- Sun-edge distortion imaging will enable capturing downward shocks
- Image processing of BOS flight images has evolved from early cross-correlation methods to the present optical flow methods.
- Hardware and software development have been targeted to support Low Boom Flight Demo (X-59).
  - Currently working on an air-to-air system for imaging pod to be mounted on F-15 to chase future X-59 LBFD.
  - Evaluating a hand-held camera using the Sun-edge technique for operating from the cockpit
- Extensive environmental testing revealed unforeseen issues, which are being mitigated
- New software for both flight planning/guidance and image processing for schlieren data developed

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