Schlieren Methods for Supersonic Aircraft in Flight

JT Heineck
Experimental Aero-physics Branch
NASA Ames Research Center
Moffett Field, CA

Ed Haering and Dan Banks
Aerodynamics and Propulsion Branch
NASA Armstrong Flight Research Center
Edwards, CA

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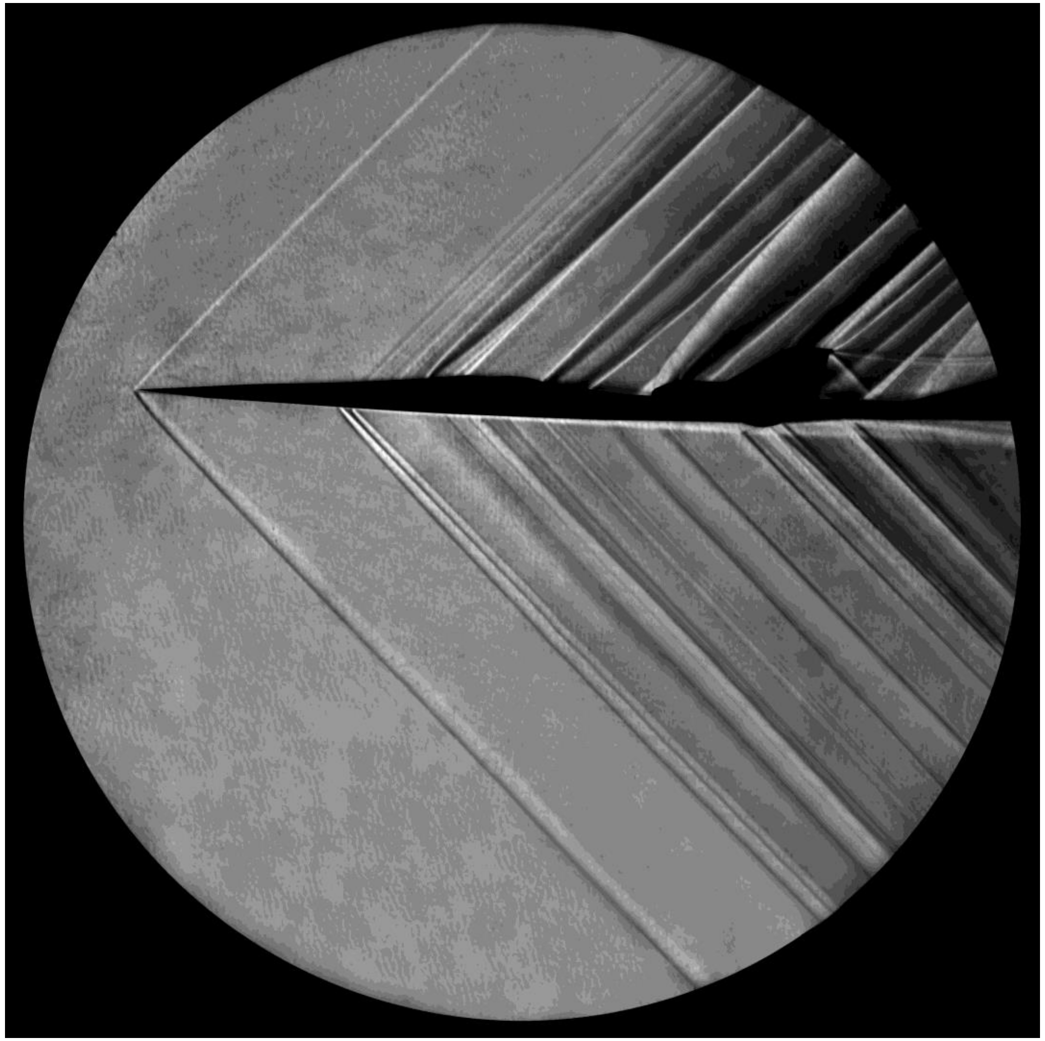
Why Develop Airborne Schlieren Methods? X-59

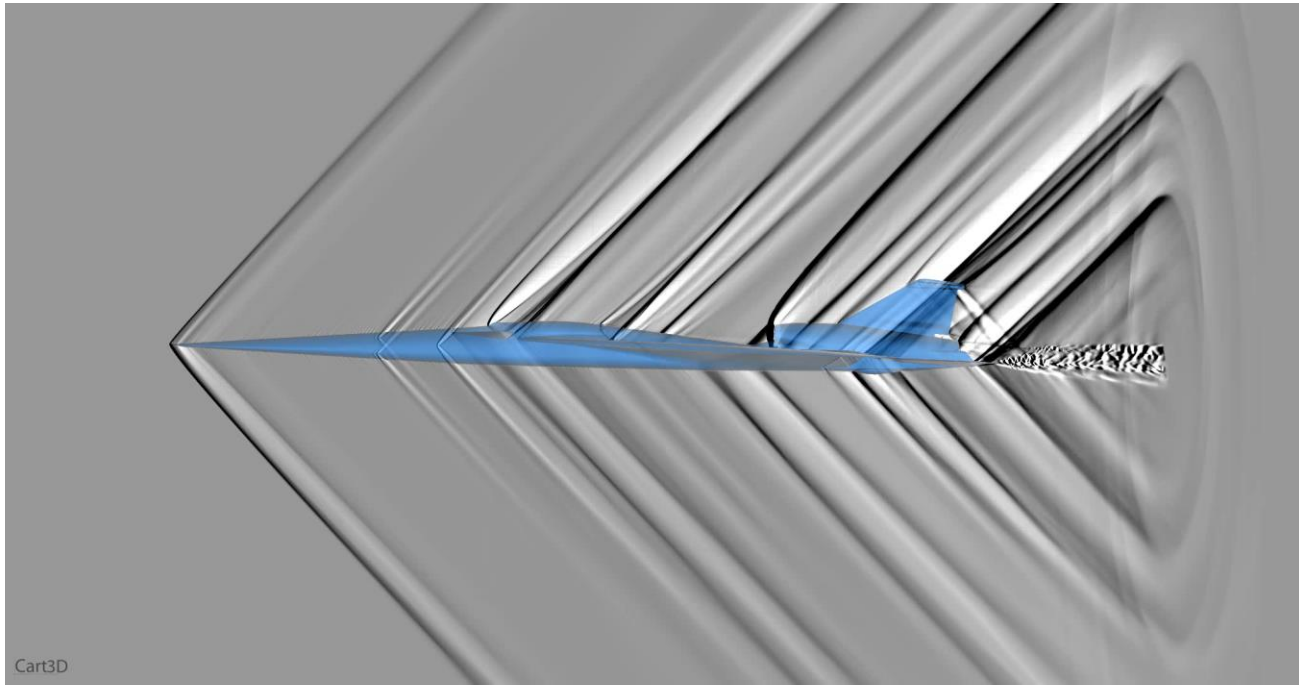
- **X-59 Quesst project: a low-boom signature X plane**
  - Validate/refine shock modeling for low boom airframe design
  - Aircraft to be used to assess community acceptance of overland supersonic flight
  - Designed to fly at 55,000 ft (16,750 m) at M=1.4
  - Schlieren imaging must be done from another aircraft flying along with X-59
  - Same chase plane will measure the near-field shock structure with a new shock sensing probe
  - A 30-n.m. (55.5 km) acoustic array on the ground will measure the boom signature

Image Credit: Lockheed Martin

Current schlieren imagery of X-59 Quesst



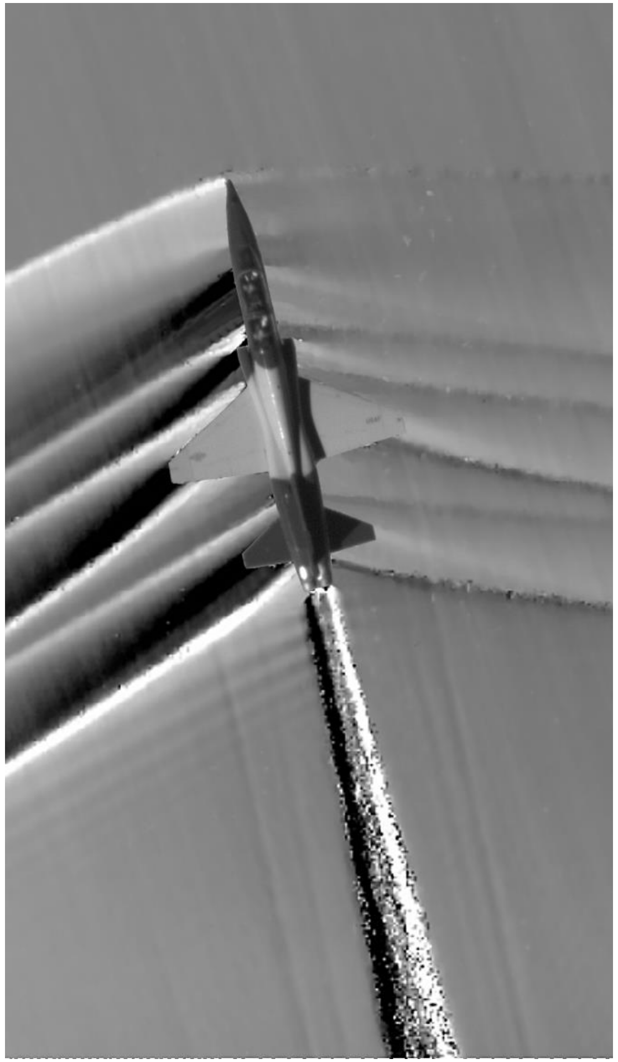
Horizontal knife-edge schlieren image from NASA Glenn 8-x 6- Foot SWT
Jonathan Ponder, NASA Glenn



Schlieren "rotisserie" derived from OVERFLOW solution
Marian Nemec, Patrick Moran, NASA Ames

History of Schlieren Imaging of Aircraft

- Weinstein in 1993 used a modified telescope with an arc slit to capture shockwaves, recording to film
- Weinstein in 1995 proved the concept of a digital version of this method
- In 2000 Raffel and Richard captured rotor blade tip vortices of a UH-60 in hover using Natural Background BOS
- 2011 Banks and Heineck and made use of the desert floor as a BOS background. (AirBOS)
- In 2013, an SBIR grant to Spectabit used digital imaging of the whole Sun disk, then processed the distorted perimeter to create a time delay integration showing the shockwaves.
- In 2015 Haering and Hill used etalons (Hα and CaK) to enhance the surface features of the sun, making it a BOS background, coining BOSCO – Background oriented Schlieren with Celestial Objects
- 2012-17 Raffel and colleagues used speckled retroreflective panels on a hangar, farmland, and quarries with BOS to capture helicopter wakes



AirBOS image with horizontal gradient

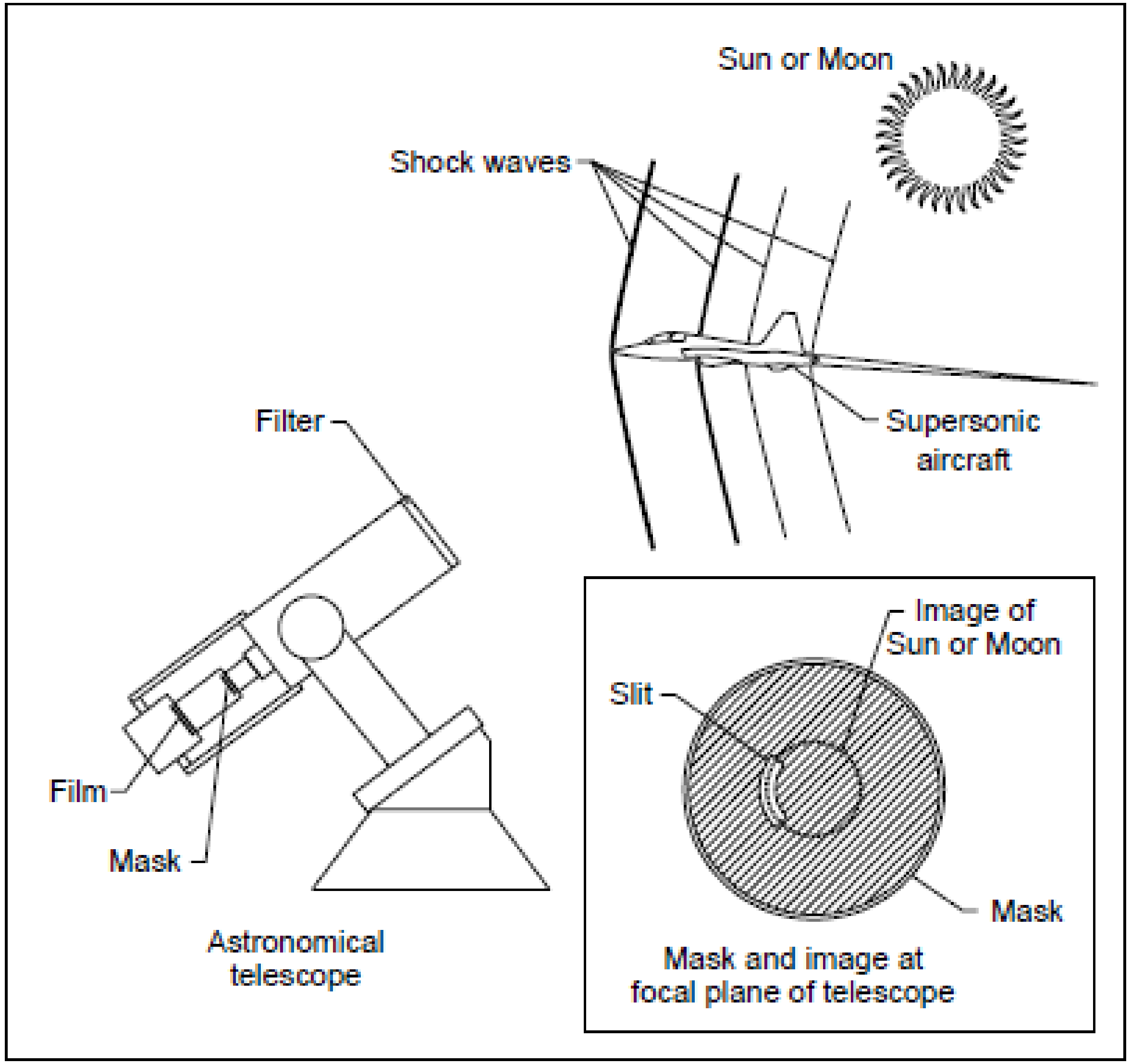
Target Aircraft

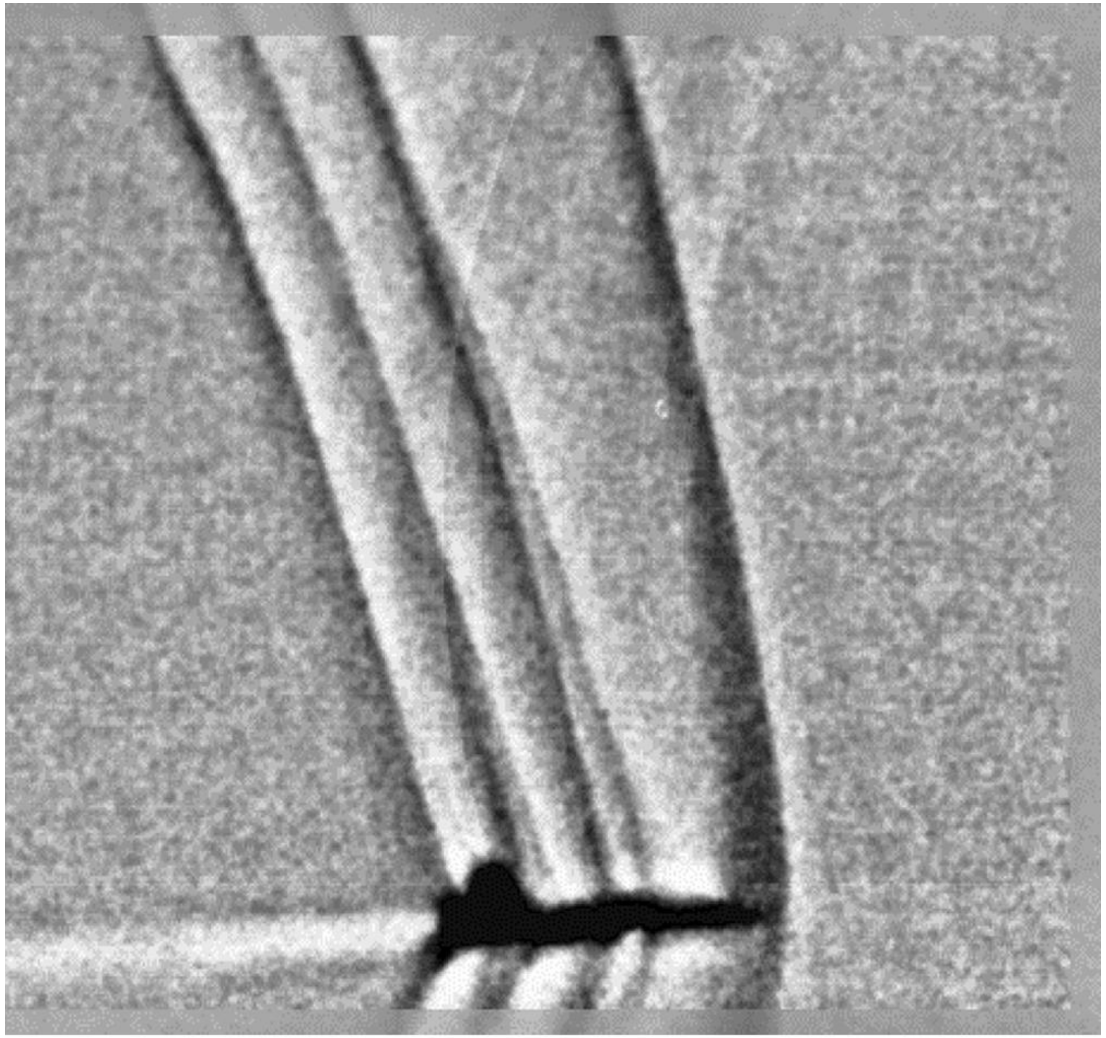
Air Force T-38, operated by the Test Pilot School at Edwards AFB

Supersonic flight achieved by full acceleration during a shallow dive, leveling for the flyby

Ground-to-Air Solar Edge Schlieren

T-38, 12/13/1993, Leonard Weinstein, NASA LaRC



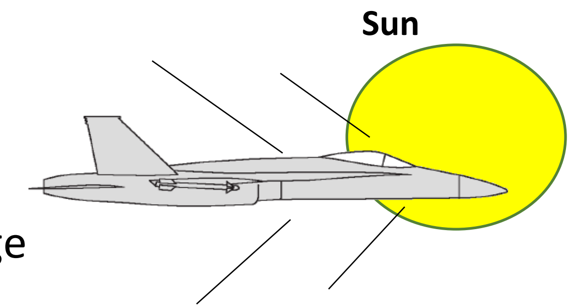


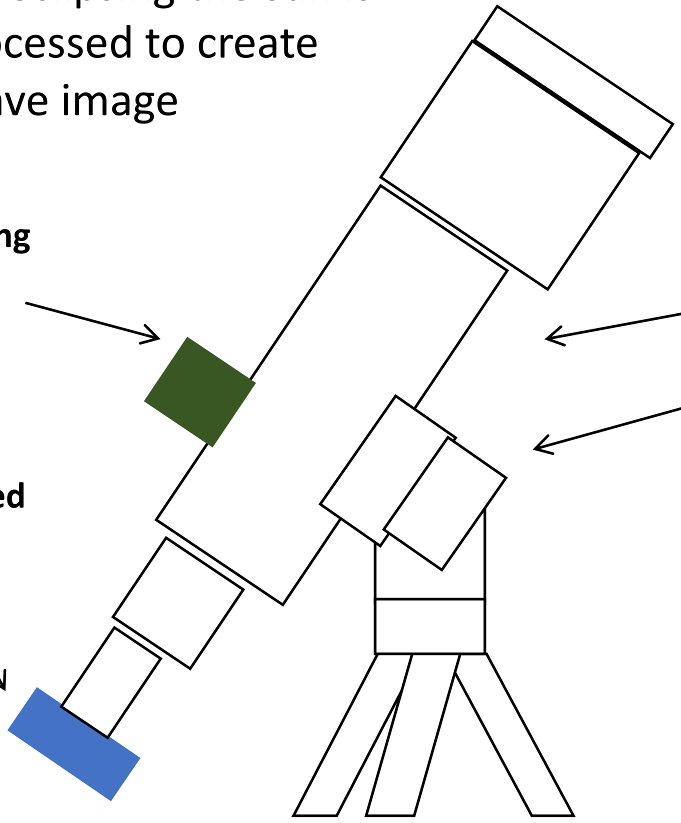
Weinstein's first in-flight schlieren image

Ground-To-Air Schlieren Photography System (GASPS)

Functional Descriptions:

- Track the position of the sun
- High-speed camera records shockwave ripples in sun edge
- Sequence of images with the airplane eclipsing the sun is post-processed to create shockwave image

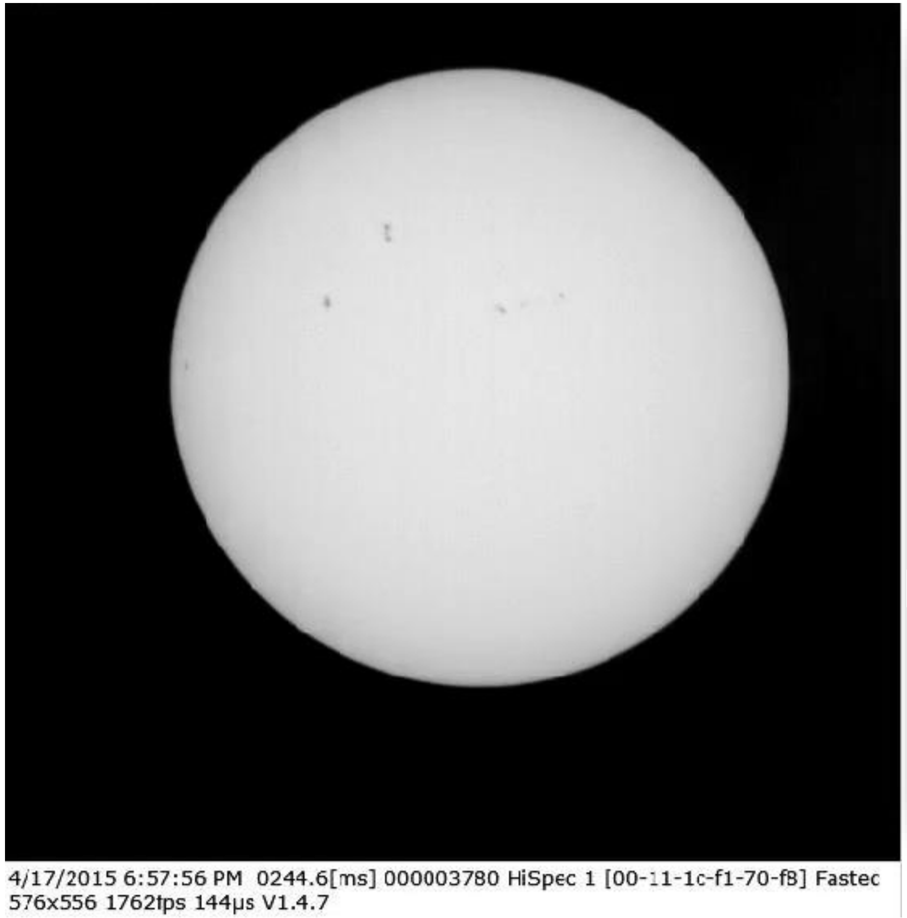


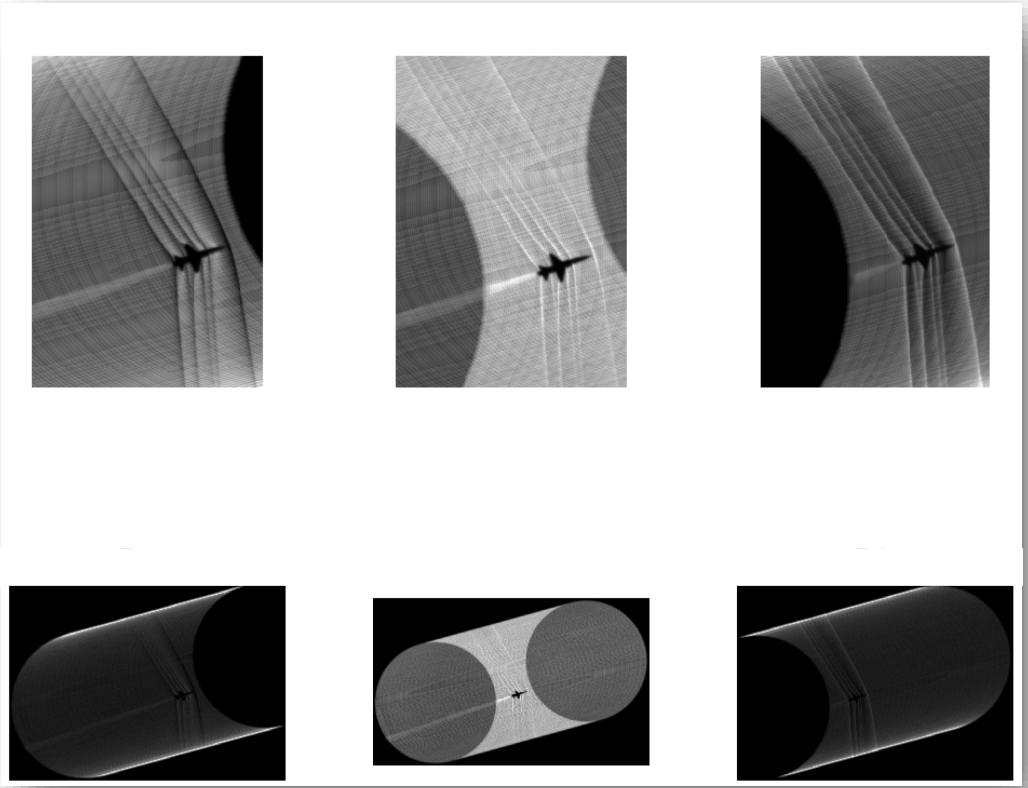


Off-the-shelf telescope with tracker and high-speed camera

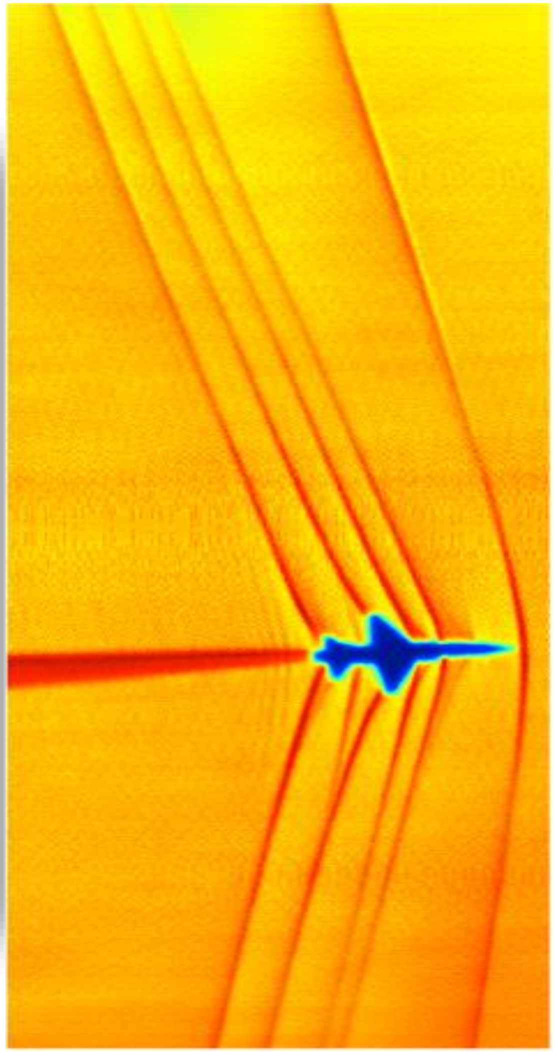
Limb-of-Sun Background Oriented Schlieren (LimbBos)

Sun Edge Distortion, Digital Method



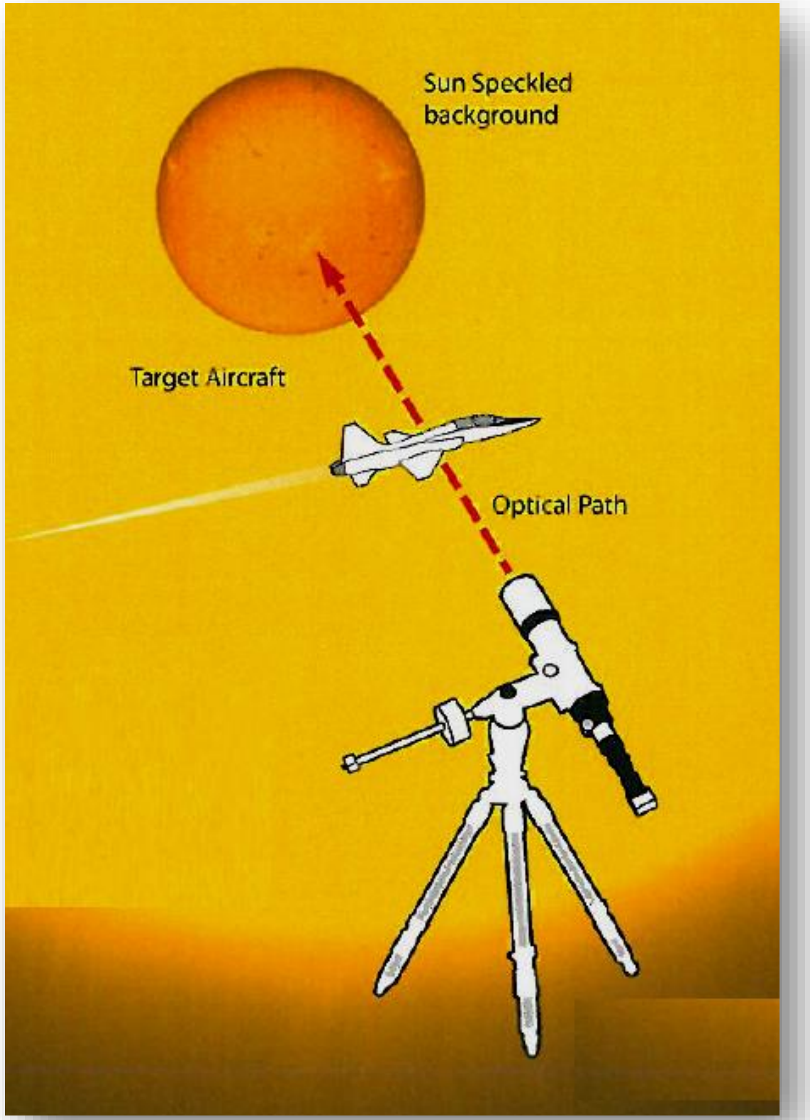


Extraction of solar perimeter and reconstruction by pixel distance of aircraft displacement

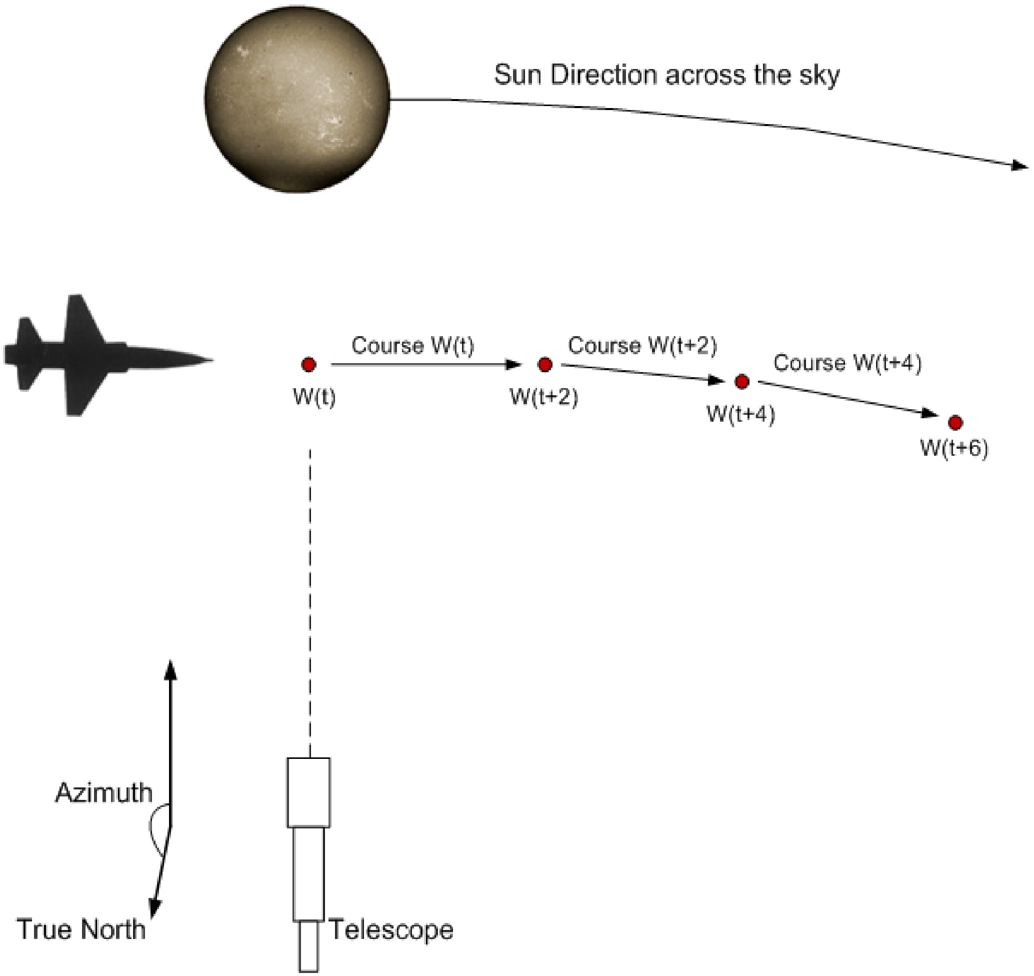


BOSCO Concept

- Uses narrow-band optical filters to give the sun a textured appearance. The texture allows for the BOS method.
    - α-emission line of Hydrogen (H- α), ~ 656 nanometer wavelength
    - K emission line of Calcium (CaK), ~ 393 nanometer wavelength
        - Proof of concept test used CaK on GASPS system
- Advantages:
    - Relatively inexpensive and simple
    - Ability to image from below and to the side of the target aircraft

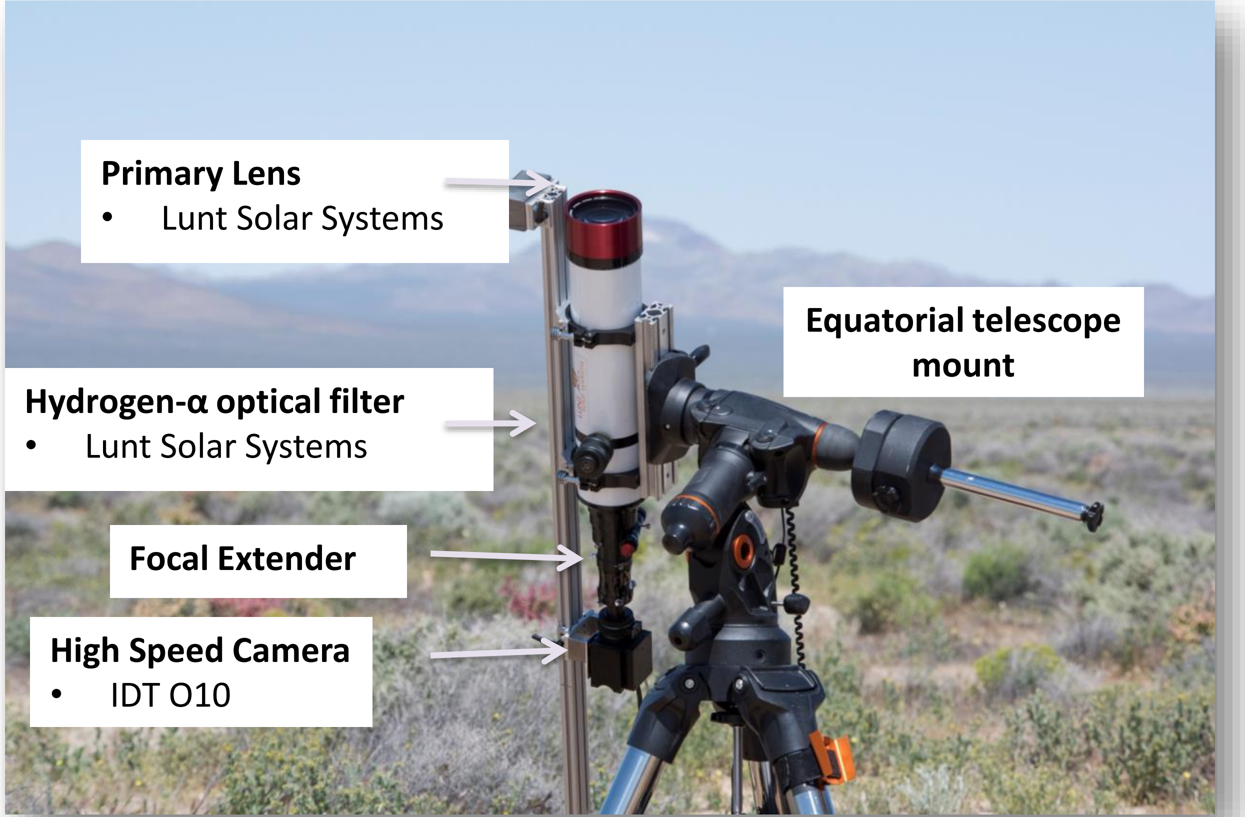


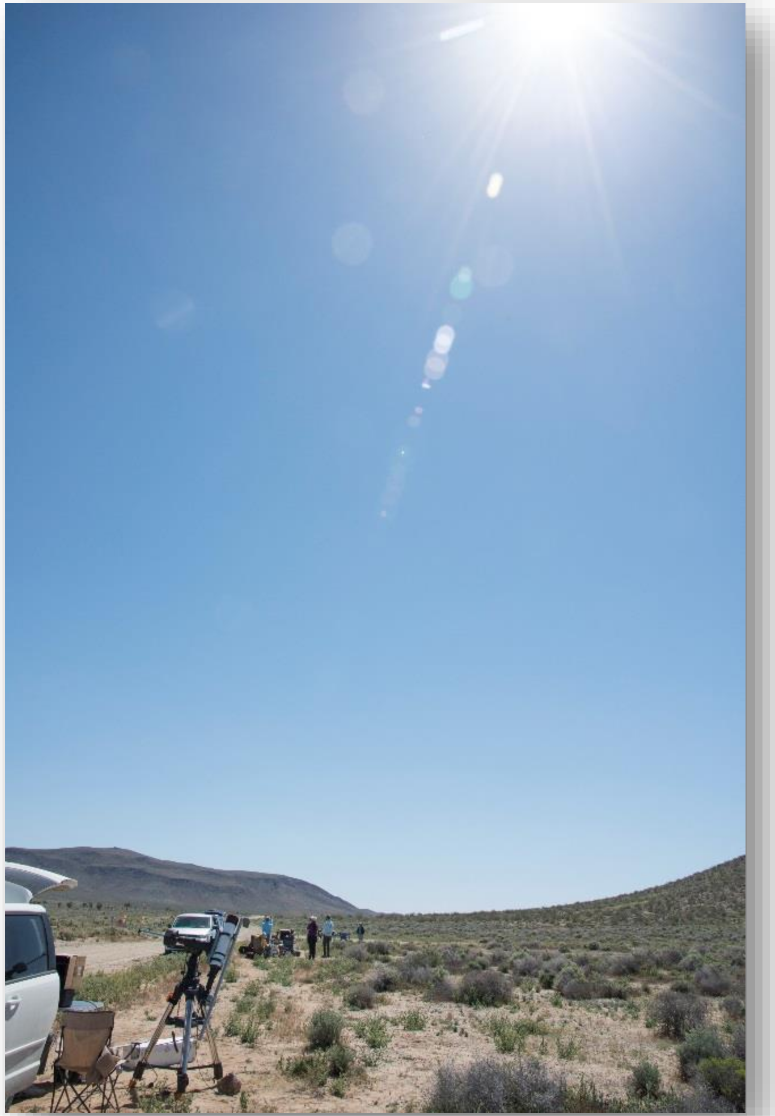
BOSCO (and GASPS) Flight Test Operations



- **Aircraft waypoints were given in GPS coordinates and were calculated based on:**
  - Time of eclipse
  - Ground position of the imager
  - Desired altitude of the aircraft.
- **Waypoints were calculated on the order of 2 minutes to minimize need for accurate waypoint timing**:
  - Course of the aircraft followed the sun direction across the sky
  - Flights occurred near the maximum solar elevation angle

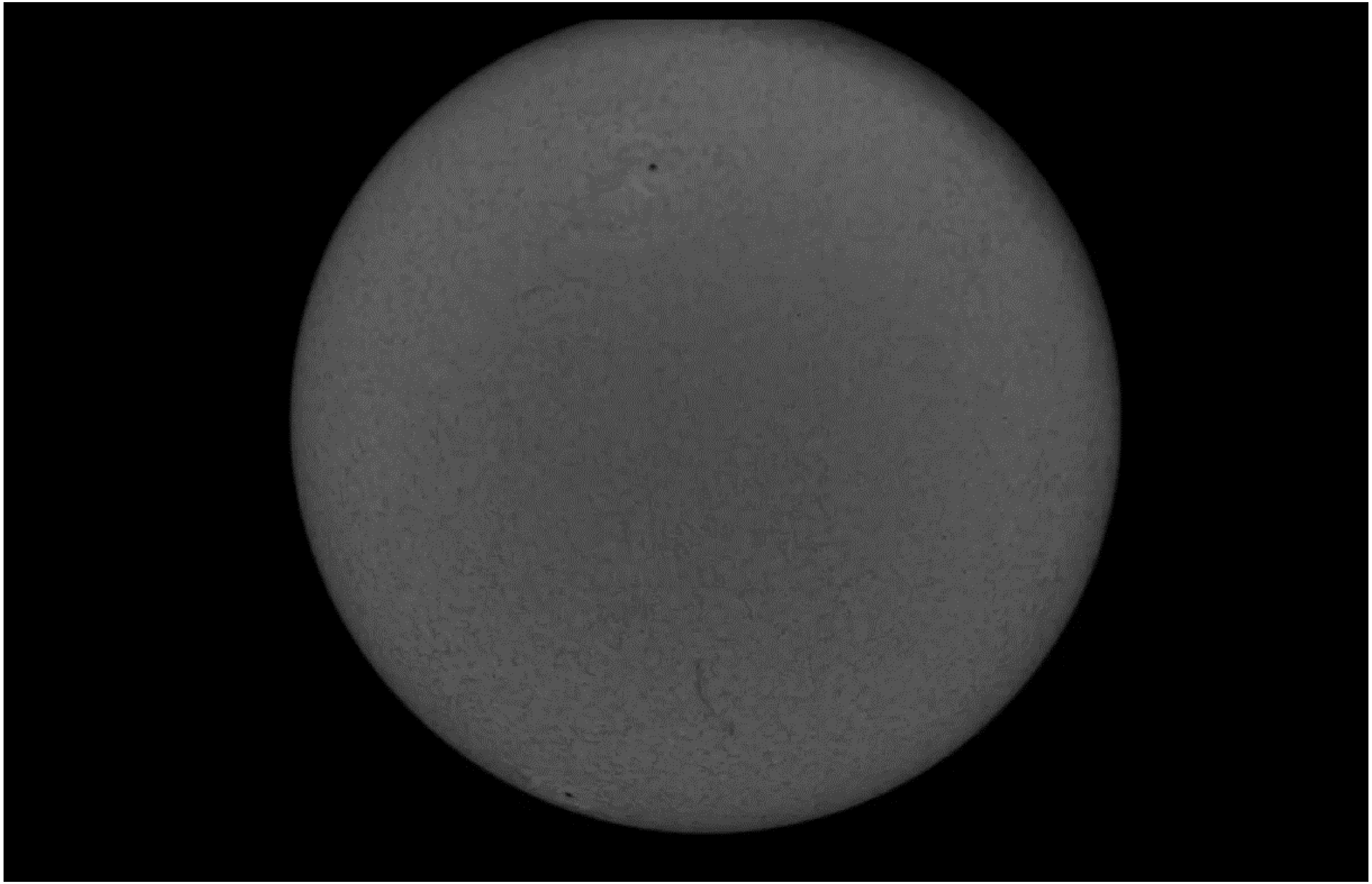
BOSCO Test Set-up





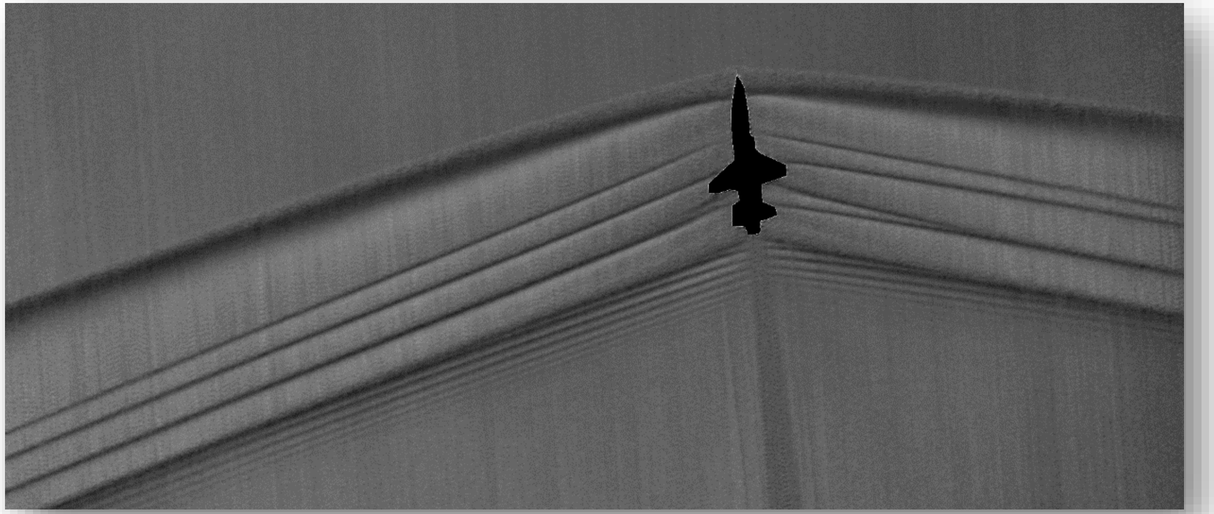
- Telescope fitted with Ca-K or H-α filter
- Equatorial mount with auto tracker
  - Manual fine adjustment
- High-speed, high-definition camera
- Communication with target aircraft

BOSCO- Hα Raw Data

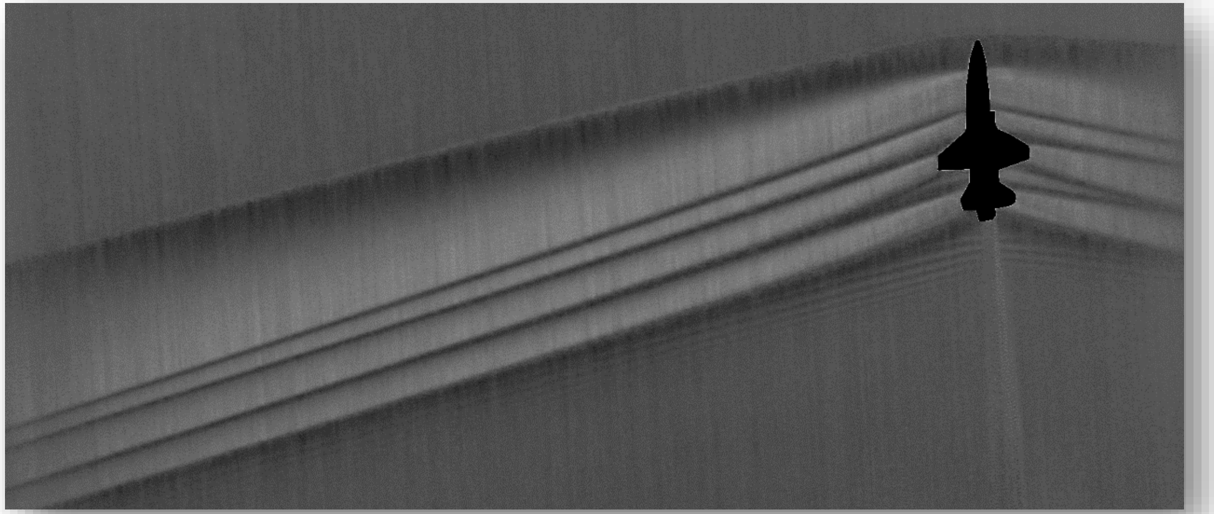


BOSCO Results

- **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

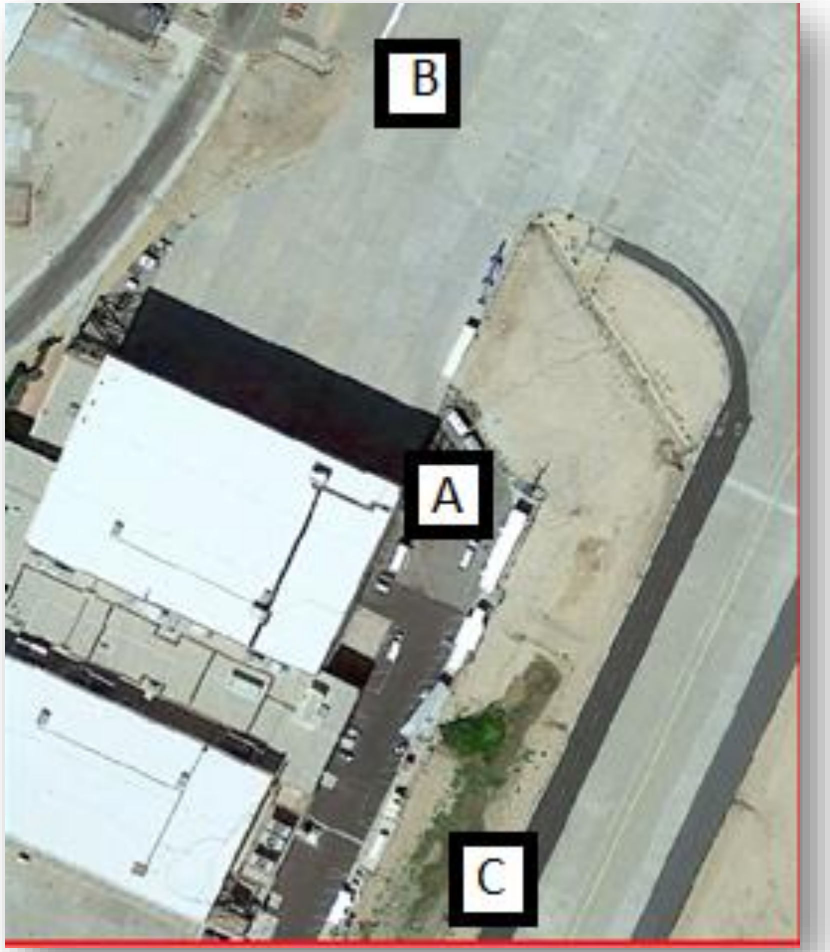


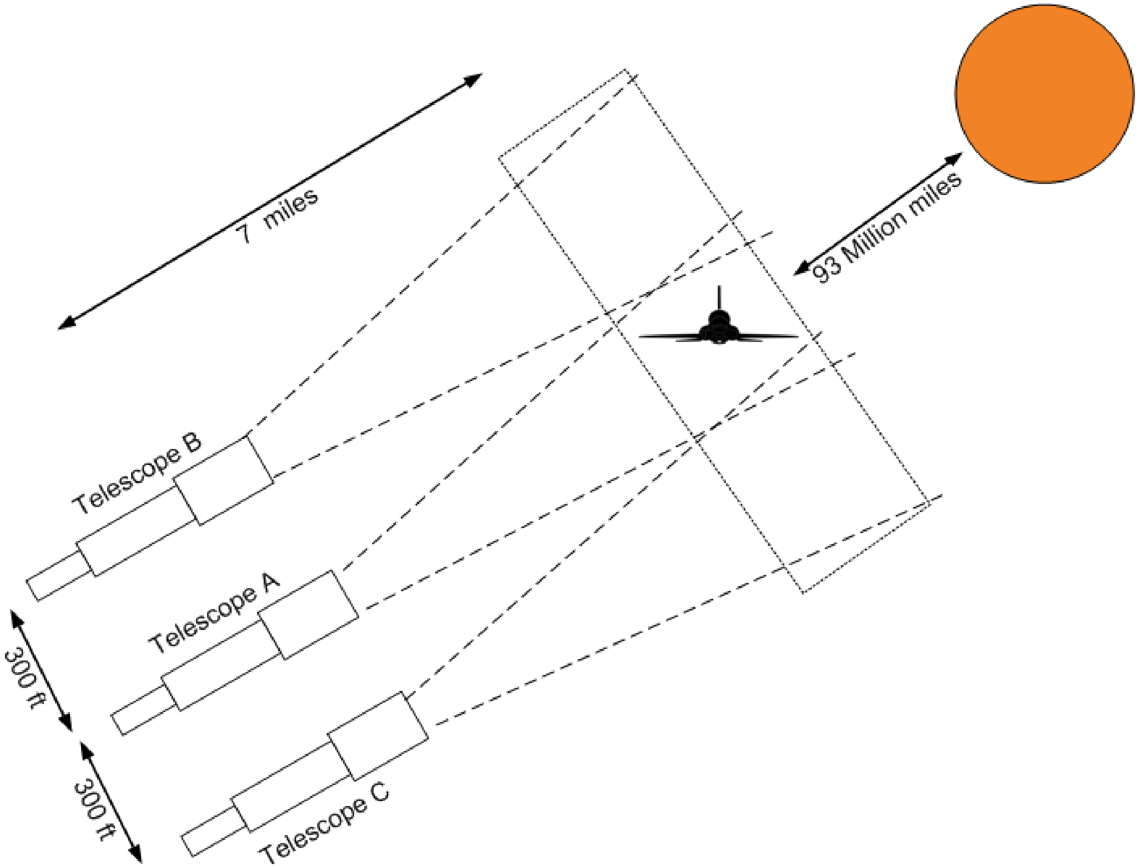
H-α



CaK

BOSCO – 3 Imager Array

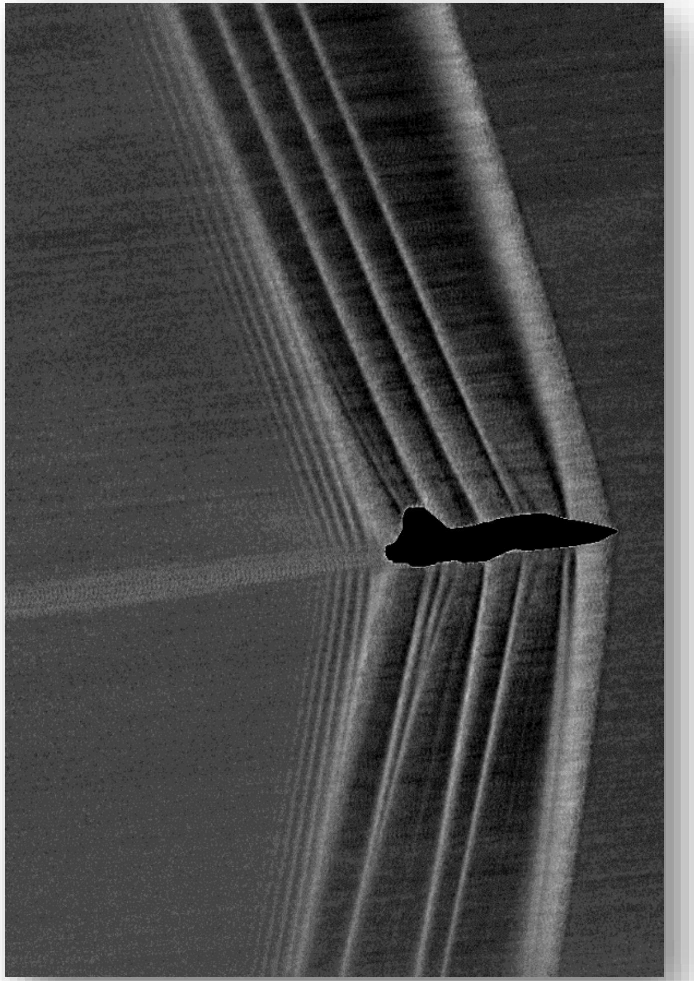




To increase the field of view of the system, three imagers were used in a spaced array in the direction perpendicular to the aircraft course

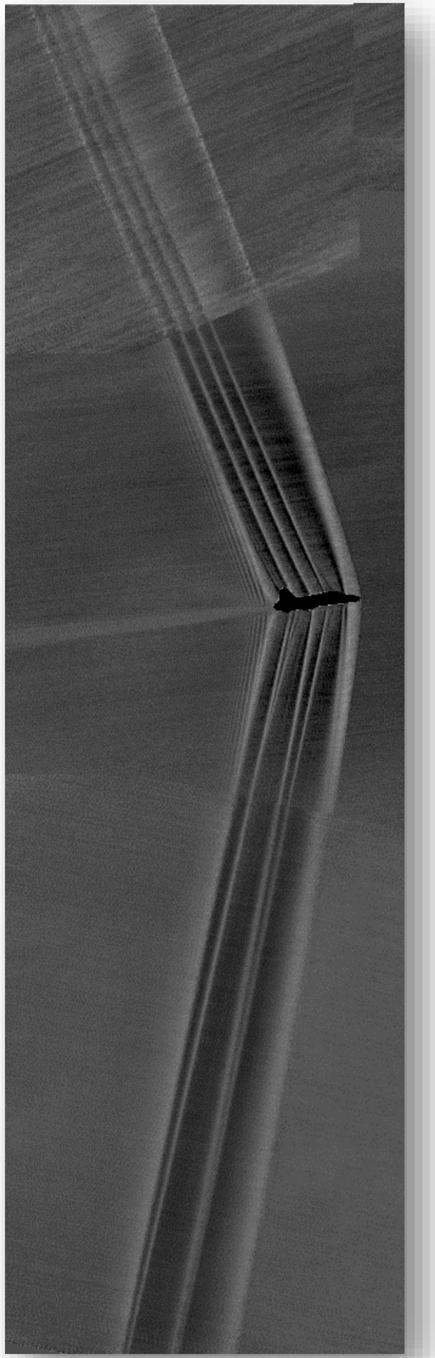
BOSCO – 3 Imager Array Results

- Aircraft banked (30 deg) at sun elevation angle for direct side view
  - Direct side view is of most interest in imaging Quesst

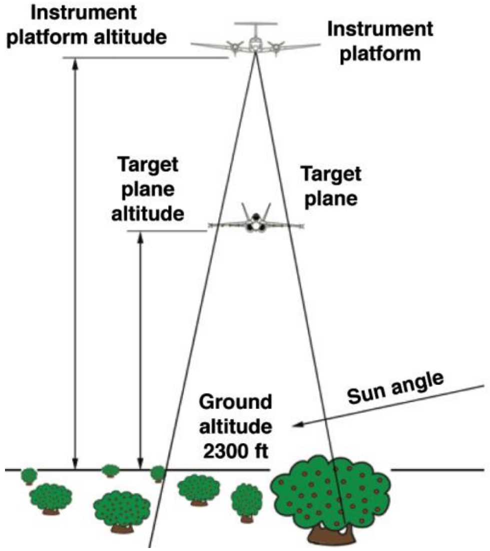


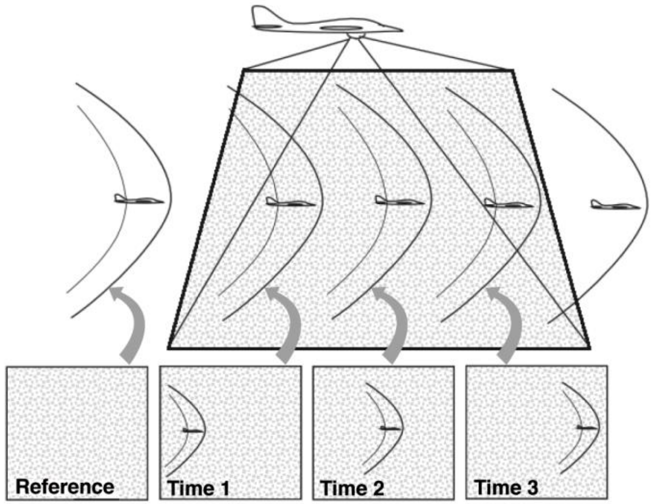
3 Image, wide field of view

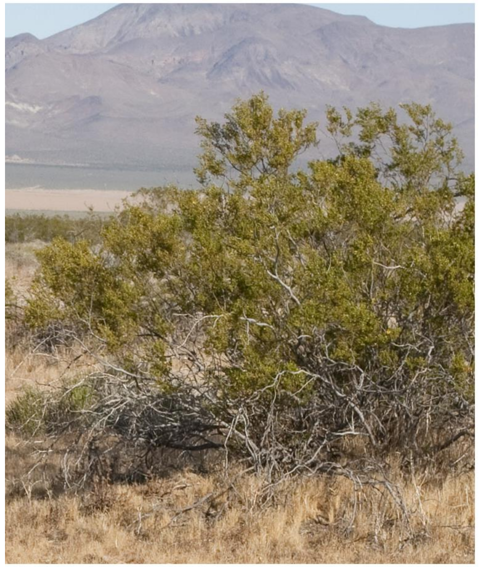
The top and bottom images in the composite used the older Ca-K imagers, resulting in reduced resolution



Airborne Background Oriented Schlieren (AirBOS) Concept

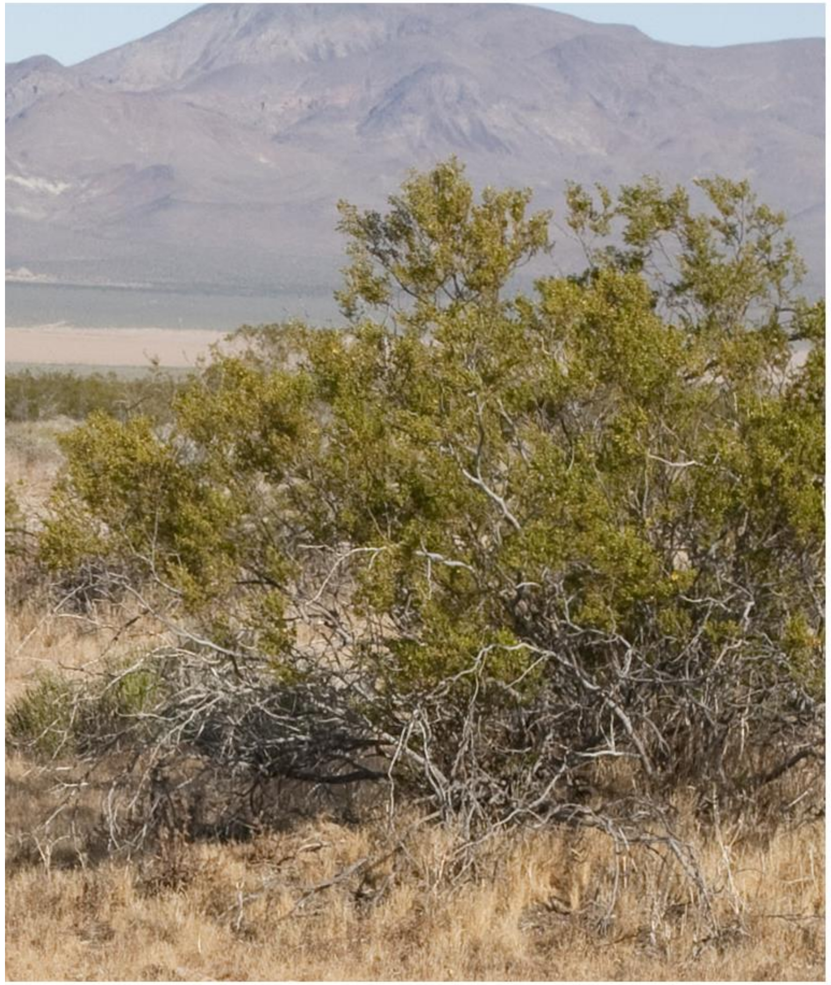





Desert bush


Desert floor from altitude

Natural Features of the Desert

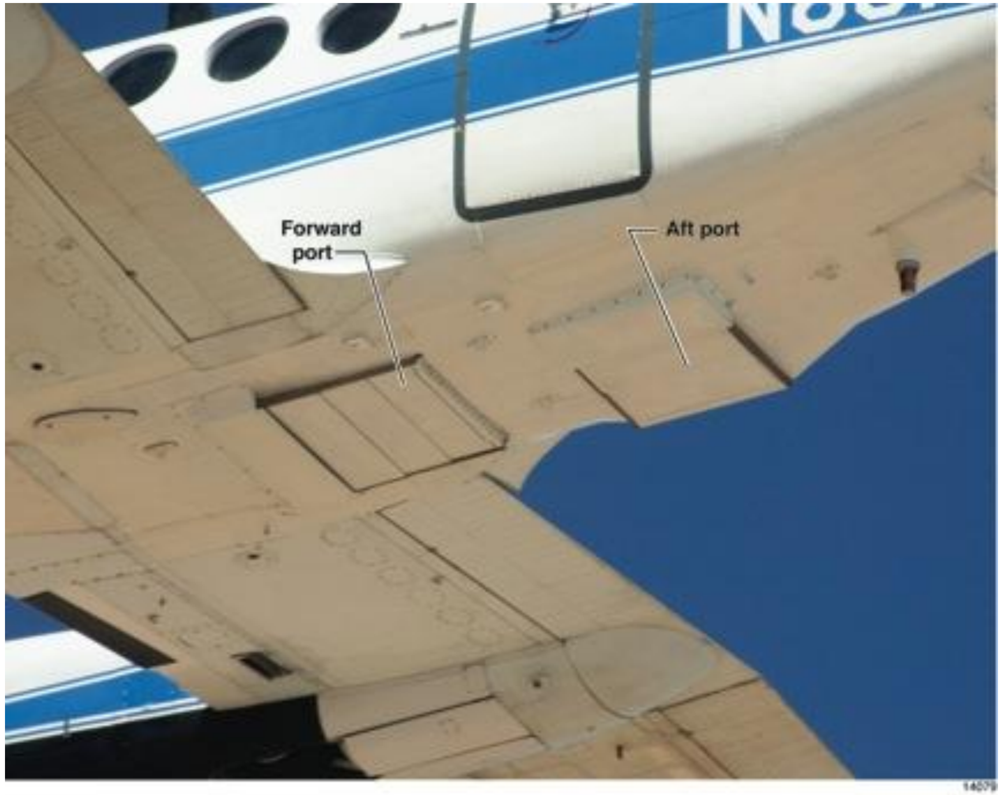


Desert Creosote Bush

Desert floor from altitude

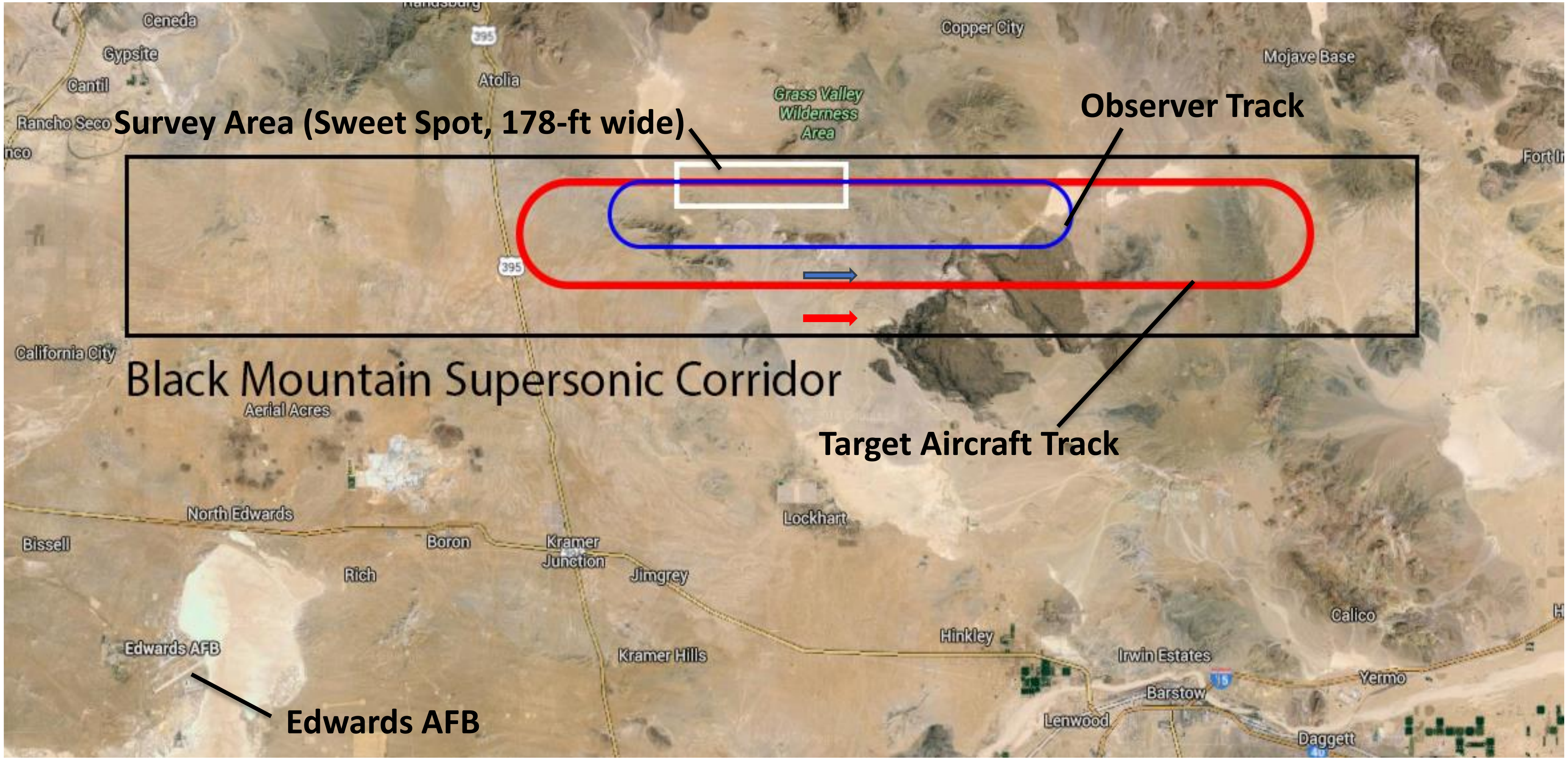
Observer Aircraft

NASA Beechcraft B-200 Super King Air, NASA T/N 801



- Flies at 30,000 ft MSL (highest practical altitude)
- Low stall speed – 99 knots (75 with full flaps)
- Used ~140 knots during image capture
- Already equipped with high-quality nadir port window
- GPS navigation

AirBOS Test Operations



Cameras and Layout

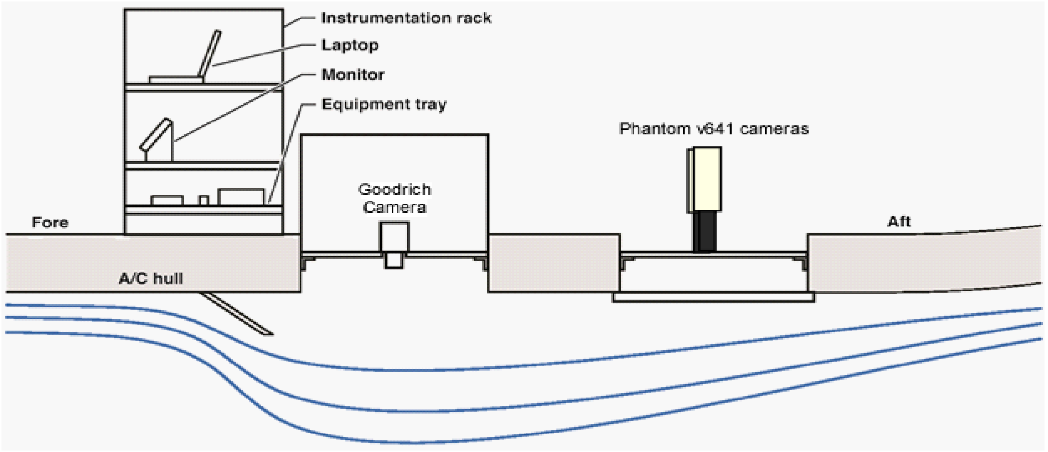
Phantom V641 monochrome, 2560 x 1600 pixels, 10-micron pitch, 180-mm lens

- 8 GB of internal memory, ~ 2 seconds of record time @ 1000 fps
- #25 Red filter, enhance contrast of bushes against the bright soil

Two cameras: redundancy and potential for stereo and multi-stream referencing

Legacy camera from 2011 AirBOS1: Goodrich SUI SU640-SDWHVis-1.7RT InGaS

- Real-time spotting camera
- Backup



Schematic of cabin layout

Two cameras, mounted vertically
Aft nadir port

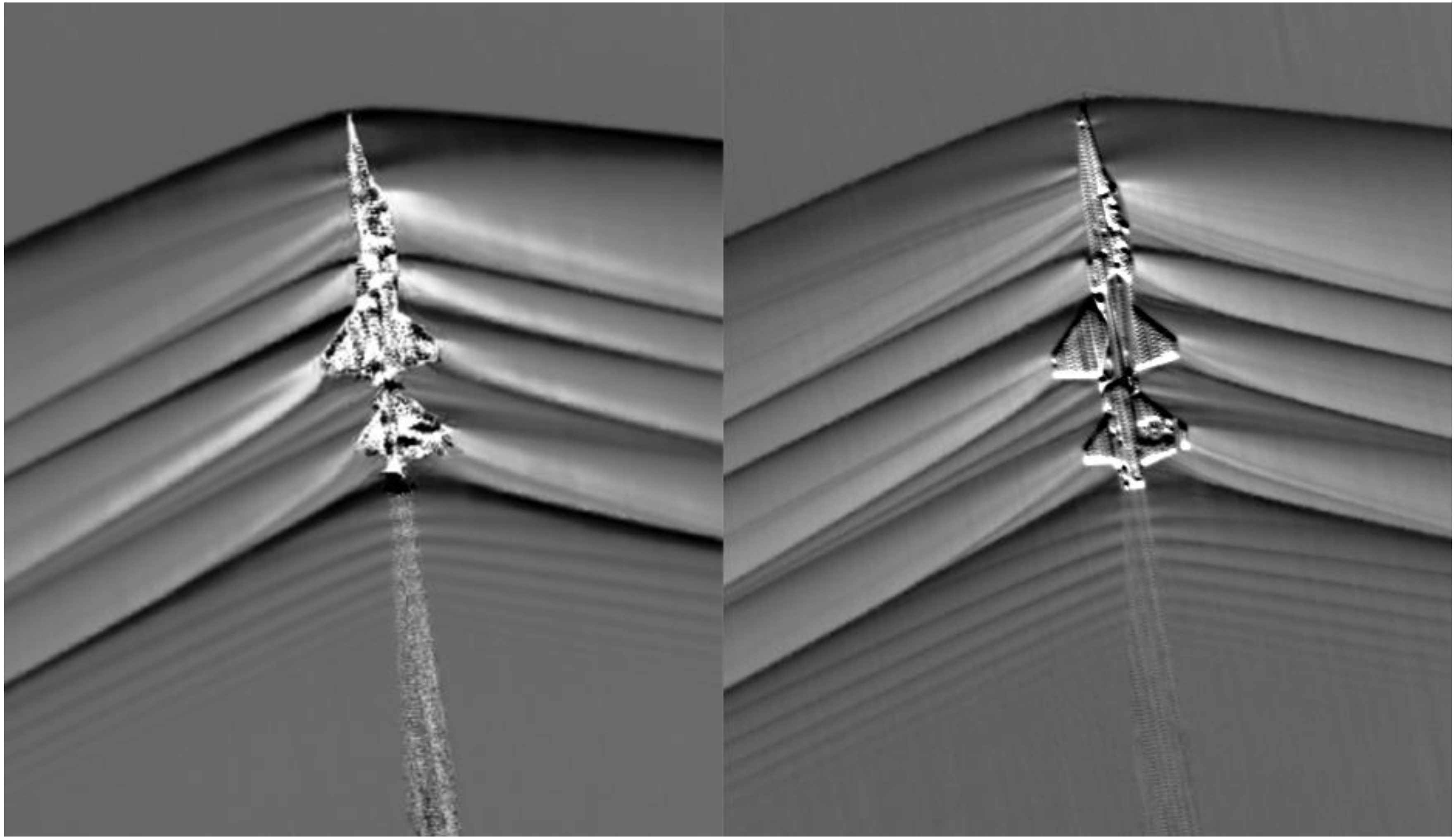
AirBOS Results

Sample movies of raw imagery

Raw image sequence, 2000 ft (610 m) separation

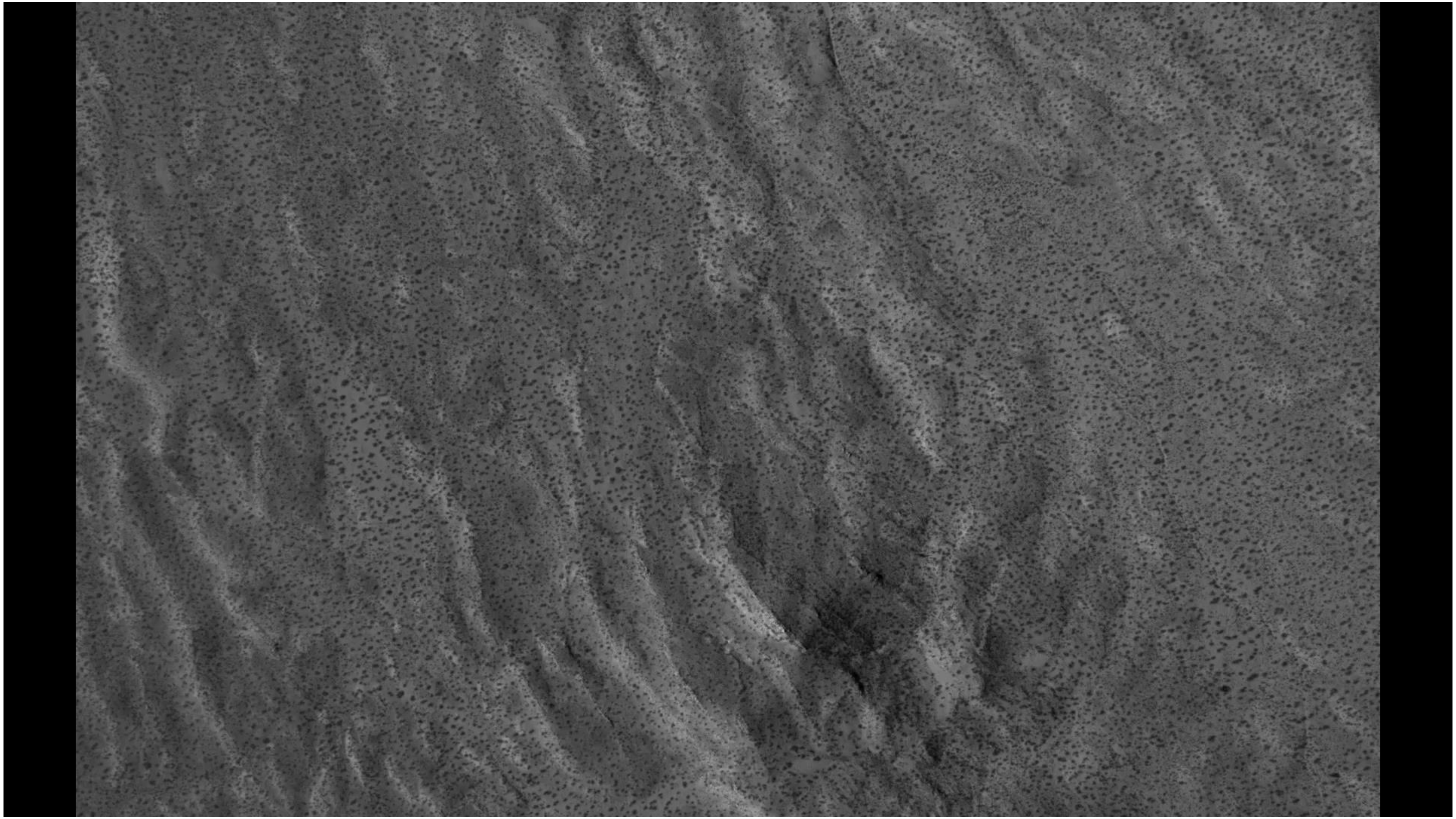
Processed image sequence

BOS processing: Cross Correlation v Optical Flow

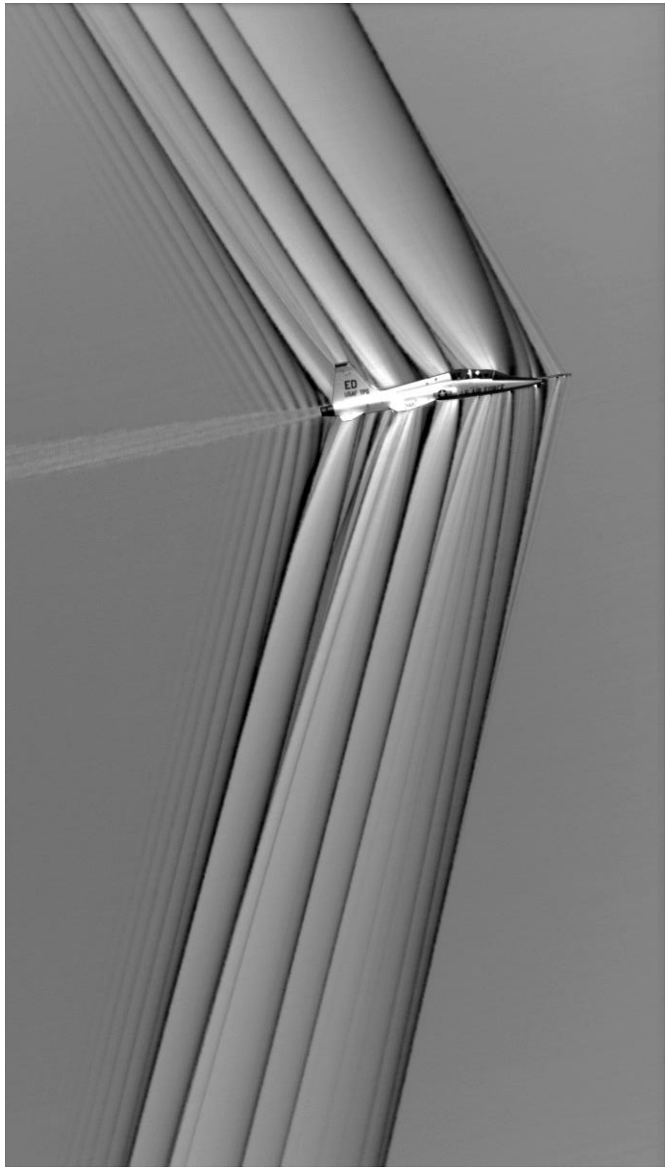


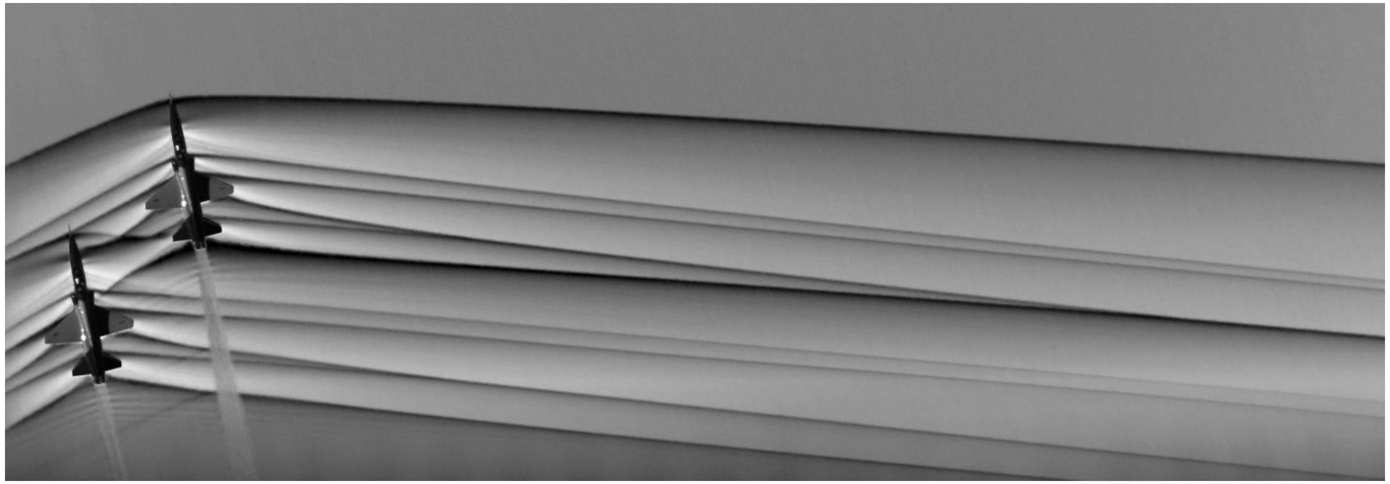
Cross correlation average (Ed Schairer) vs. Optical flow average (Neal Smith)

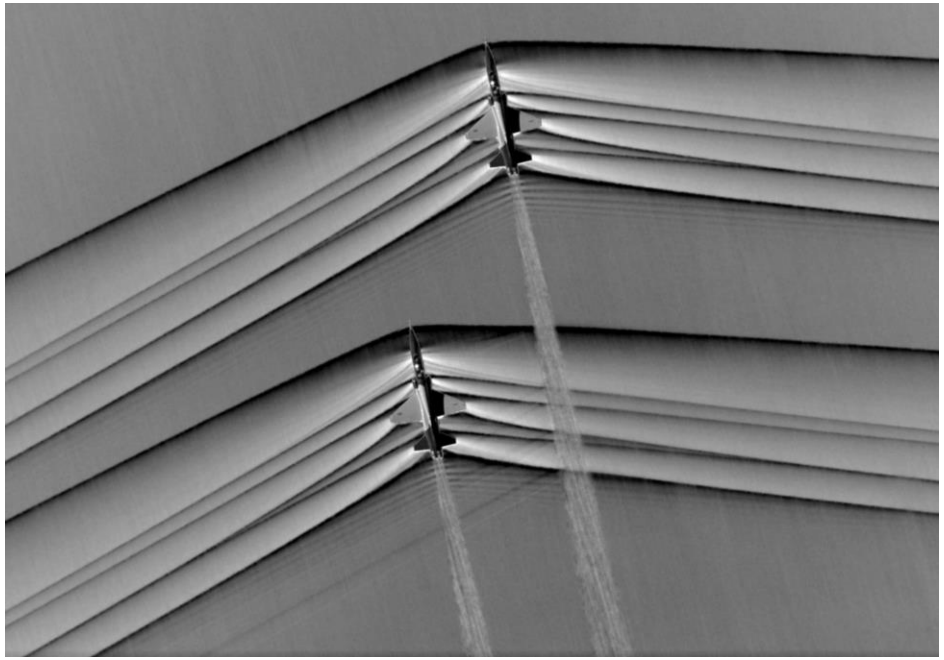
Results from the Flight Campaign in 12/2018



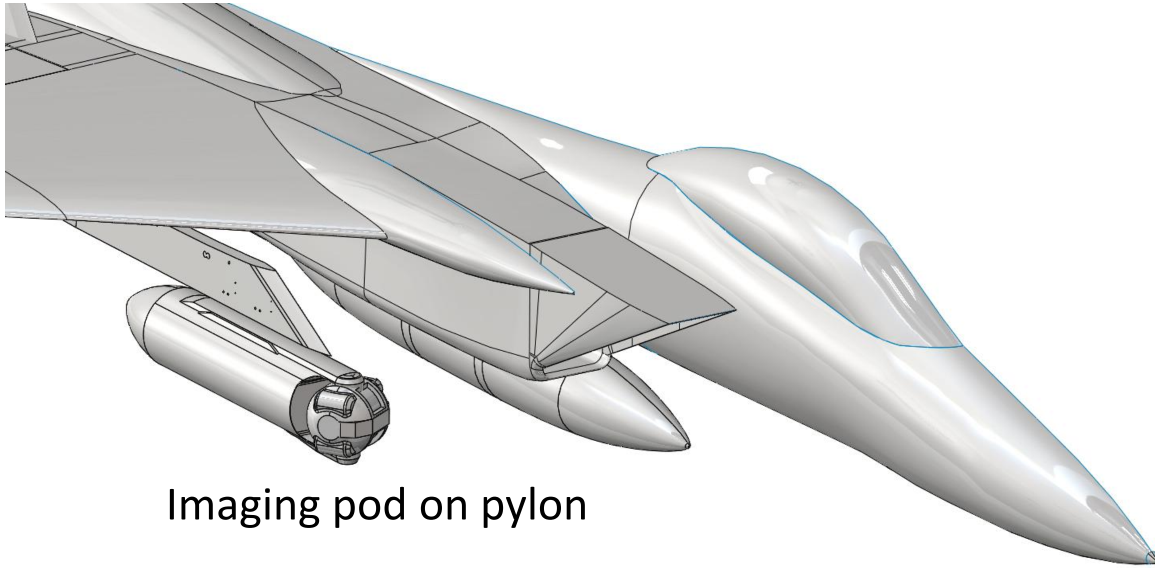
More Results from the Last Flight Campaign, 2018



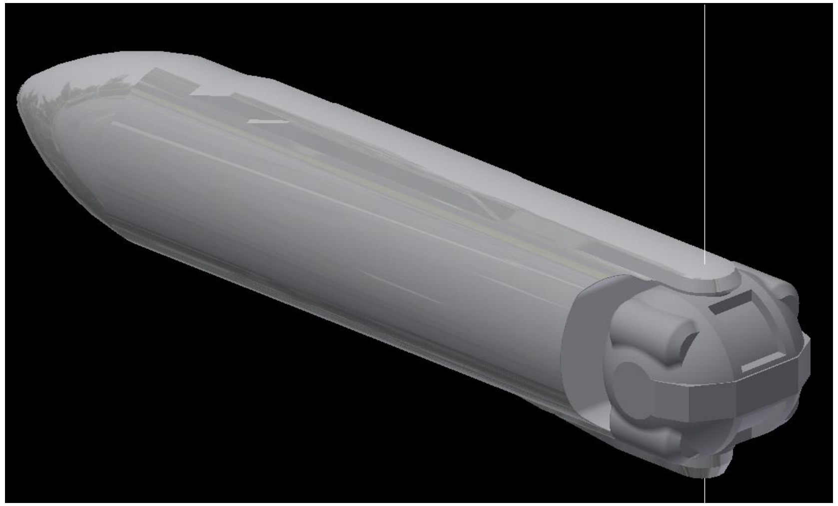




Schlieren Systems for the X-59 Quesst



Imaging pod on pylon



Imaging pod, electronics in aft

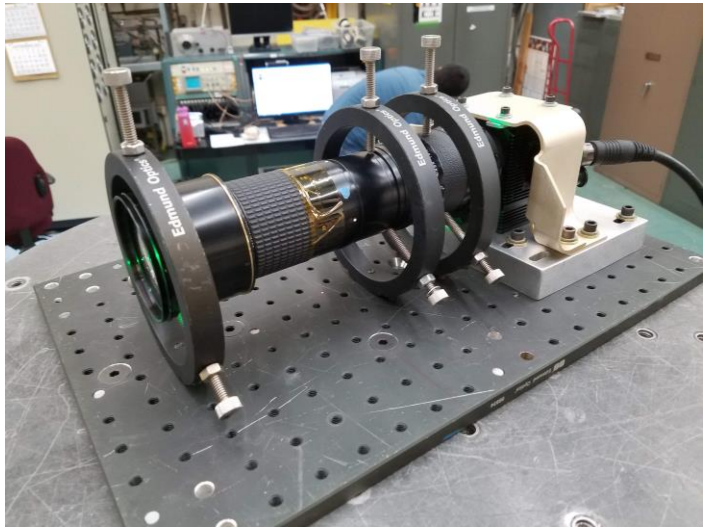
Turret for up to seven cameras

- LimbBOS and AirBOS for formation flight imaging
  - NASA operated F-15 fitted with an imaging pod on ordnance pylon
  - Flight adapted to 55,000 ft (16,750 m)
  - LimbBOS to capture 0-deg shocks (below aircraft)
  - AirBOS to capture 20-deg view from nadir
    - 2 cameras, one capturing background ahead and one focused on the aircraft
- Ground-based BOSCO and hand-held LimbBOS as backup

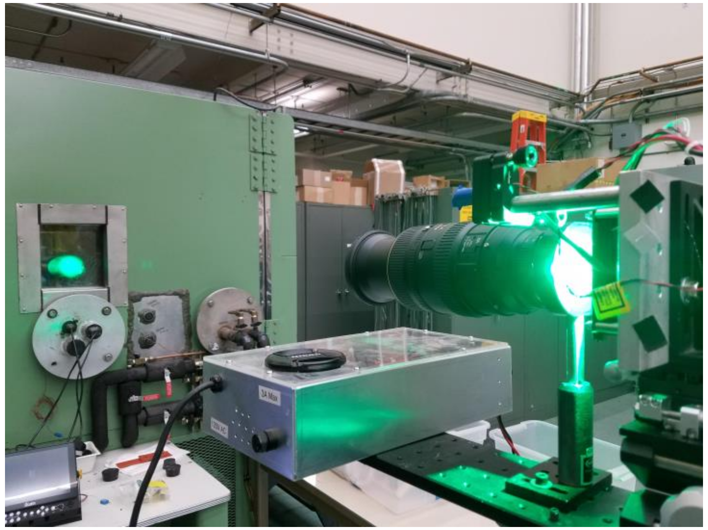
Design Process of Pod Camera System

Environmental testing

- Vibration levels measured in flight, applied to vibe table profile
- Tested image blur due to vibe: real-time view of collimated LED:
  - optimal exposure 25-μsec
  - BOSCO exposure time was too long – dropped from consideration
- Temperature and pressure tested in altitude simulation chamber:
  - Discovered focus shift caused by both temp and pressure
  - Controlled temp with heating pad and PID controller
  - Vibe levels prohibited motorized focusing: a pre-focus protocol was developed using vacuum chamber



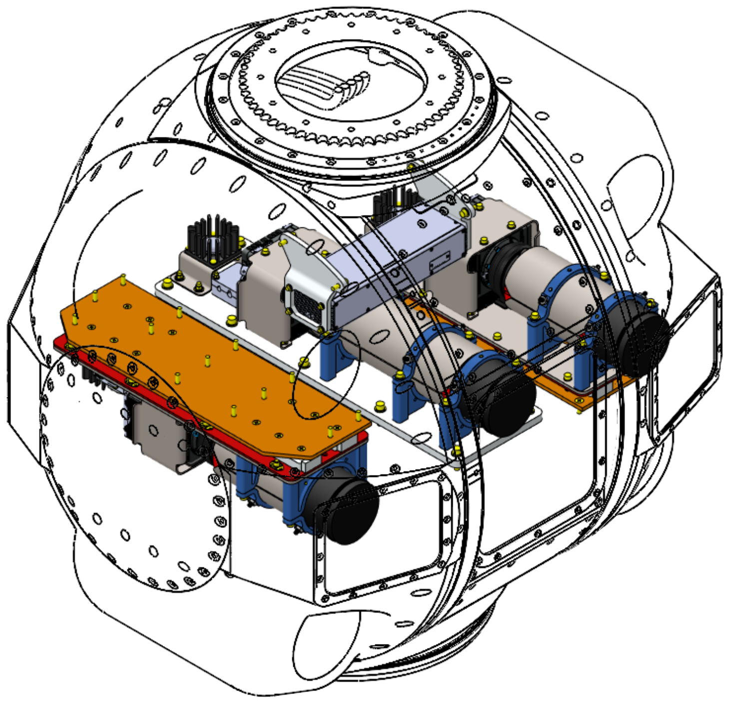
Vibration table rig

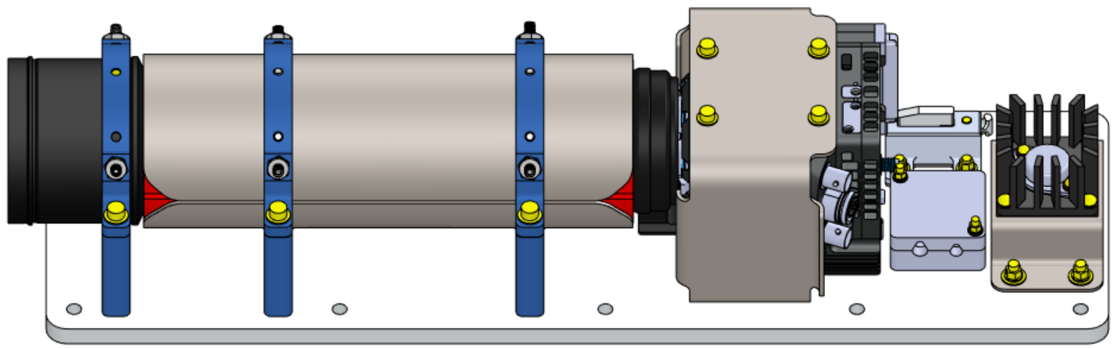


Altitude chamber with collimated LED

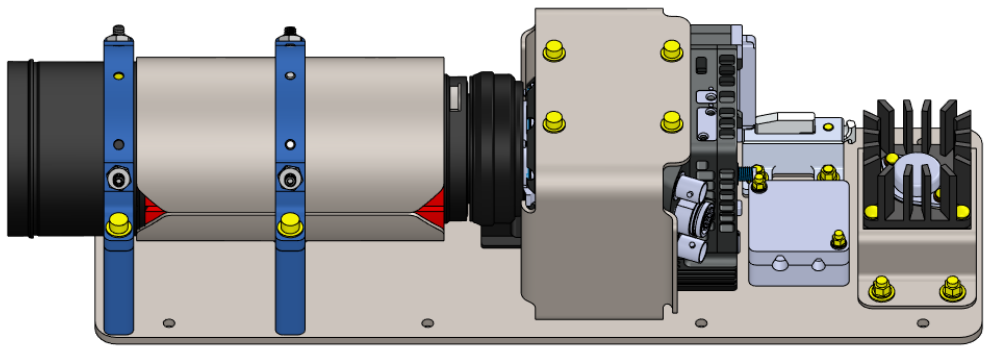
Vacuum housing for focusing protocol

Design Process of Pod Camera Systems





LimbBOS camera mount (center bay)



AirBOS camera mount (outer bays)

Final camera and lens system with mounts

- IDT model O10-4K (9-Mpix, 1-kHz frame rate) mission-programmable, ruggedized cameras
- LimbBOS: 300-mm Nikon AIS lens, solar + UV/IR cut filter, 2x teleconverter
- AirBOS: 300-mm Nikon AIS lens, #25 red filter

Summary

- NASA has developed three schlieren methods to capture shock structures of supersonic aircraft in-flight
- Each will be available for imaging the X-59 Quesst
- First testing of pod-based imaging is this Fall: F-15 to F-15
- First flight of Quesst will be in 2024
- Schlieren data flights after envelope expansion