Flow Visualization of Aircraft in Flight by Means of Background Oriented Schlieren Using Celestial Objects

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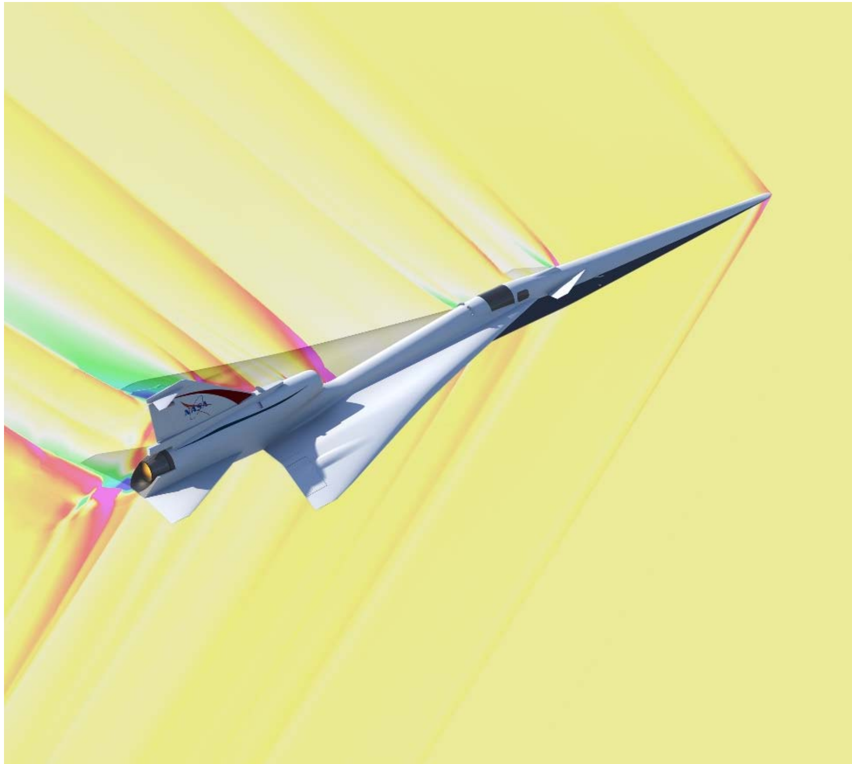
OUTLINE

- 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

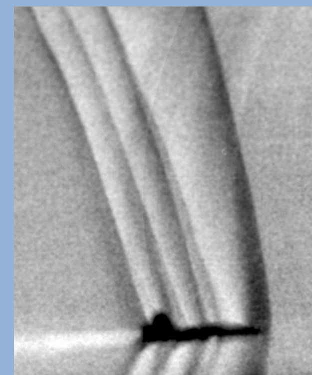
- NASA Commercial Supersonic Technology
  - Desire for a schlieren system for full scale aircraft in flight to visualize shockwaves generated by supersonic aircraft
    - Validate/refine shock modeling for low boom airframe design

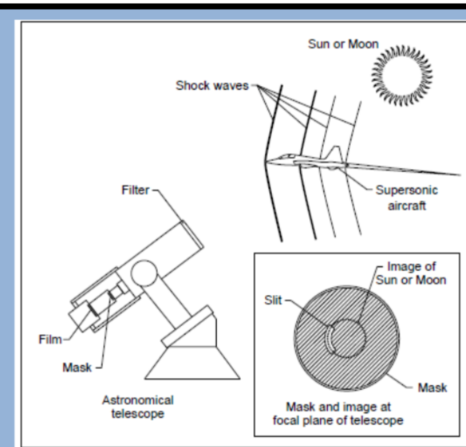


Background - Existing full scale schlieren systems

Ground to air solar edge schlieren

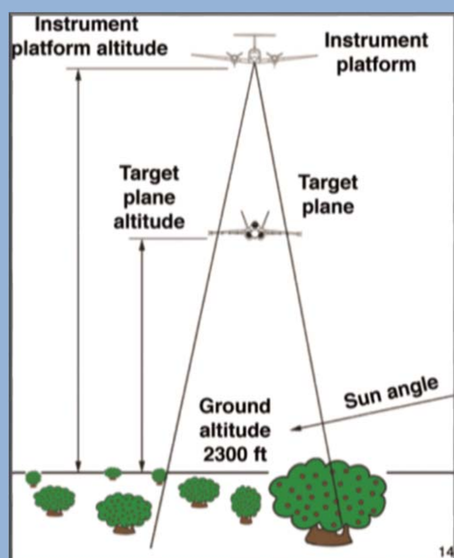
- Schlieren for Aircraft in Flight (SAF)
  - NASA, Weinstein 1993
- Ground to Air Schlieren Photography System (GASPS)
  - Digital equivalent of SAF, Metrolaser Inc.

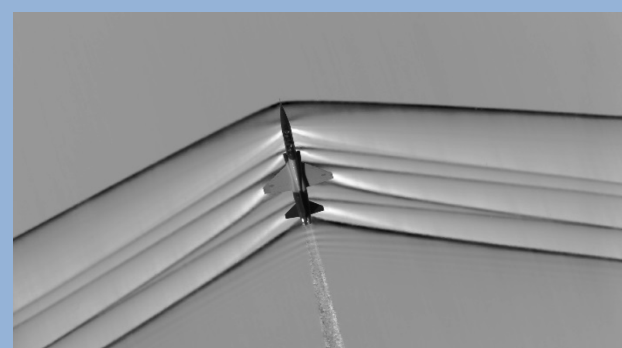




Air to Air Background Oriented Schlieren (AirBOS)

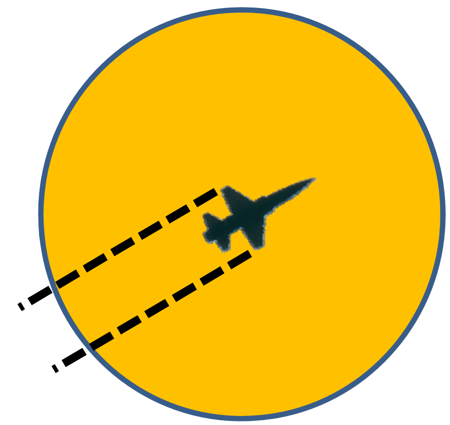
NASA, Heineck, Banks. 2015





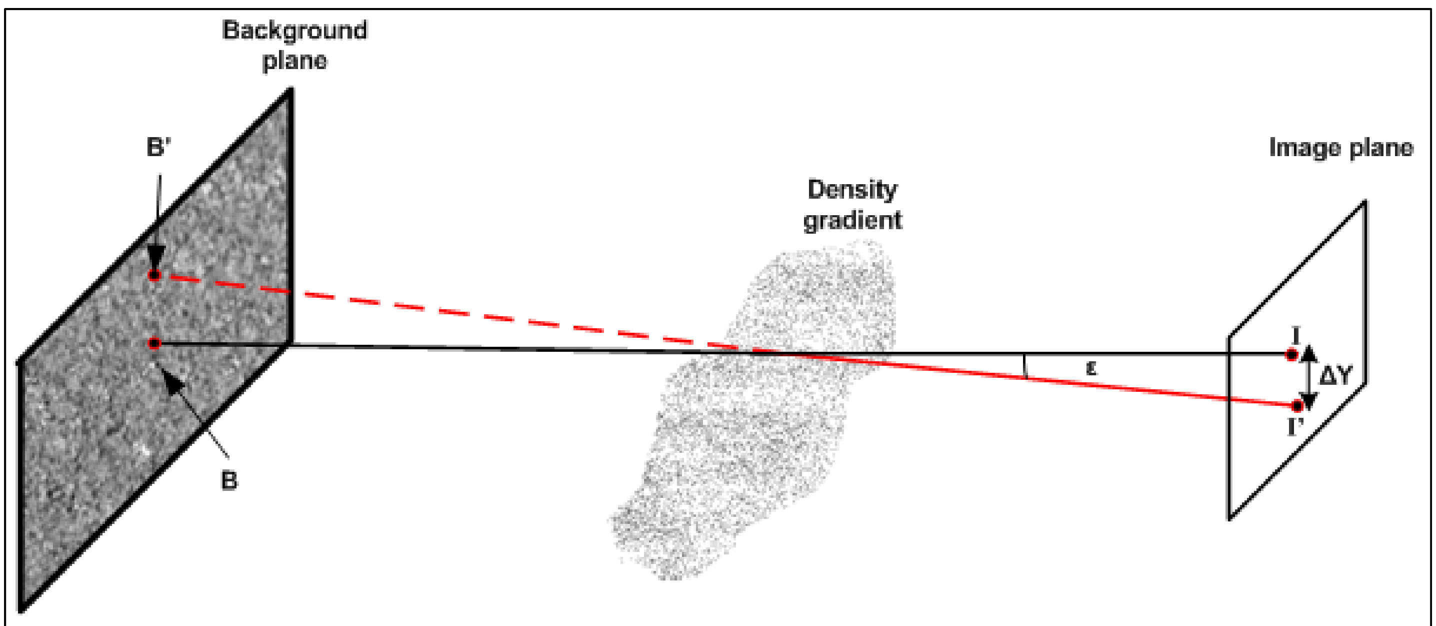
Gaps in capability for existing systems

- 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)



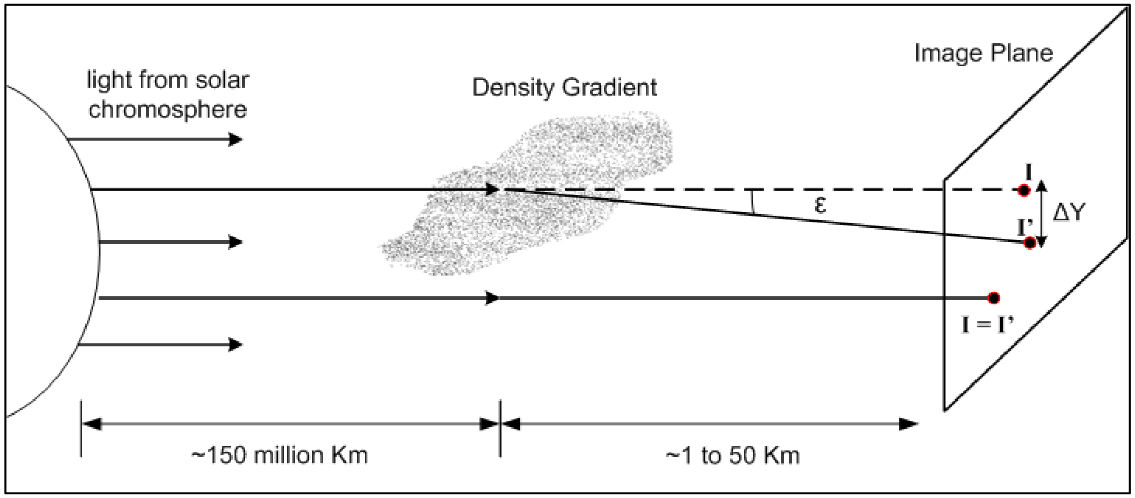
Background Oriented Schlieren Concept

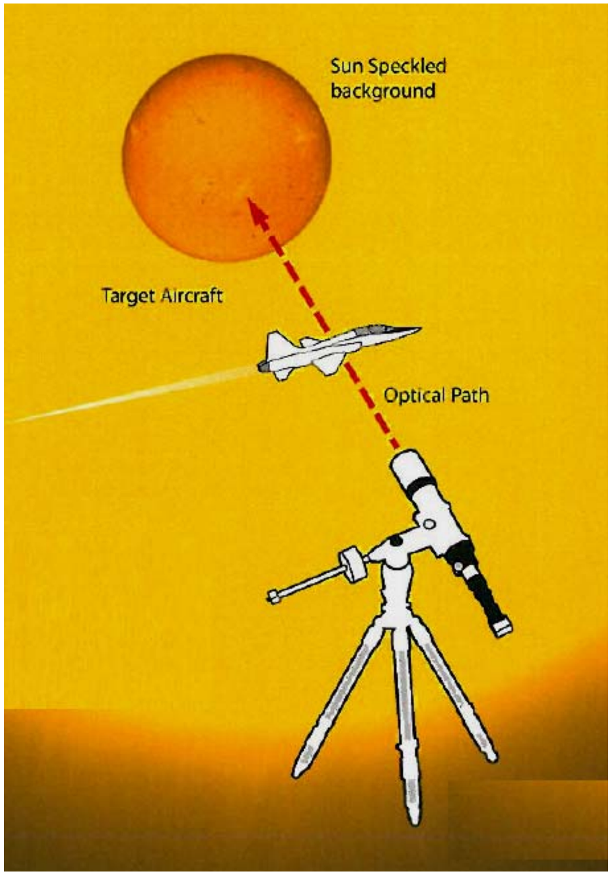
– Visualizes light ray deflections by calculating movement of features in a background
– Provides a full 2-D measurement proportional to the gradient of air density with one image pair
  - With no density gradient, a ray from B will be imaged at point I
  - With a density gradient, a ray from B will 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



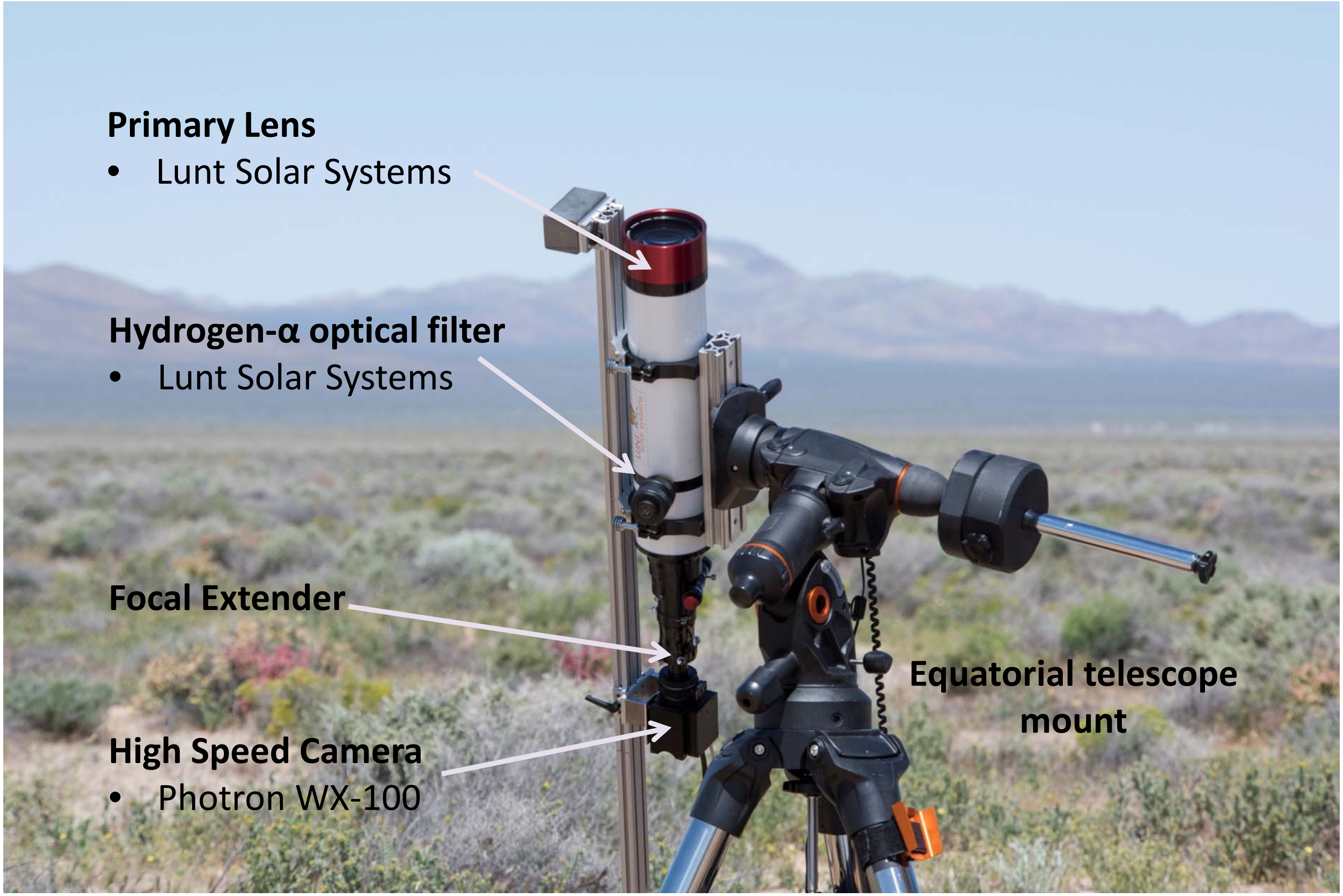
Background Oriented Schlieren using Celestial Objects (BOSCO)

- 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



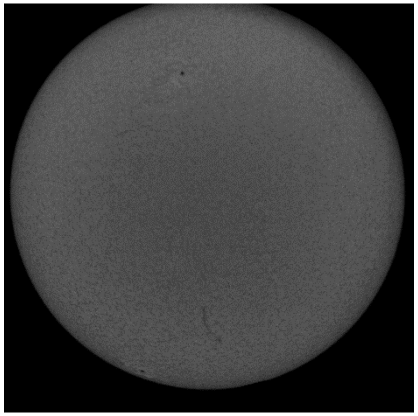


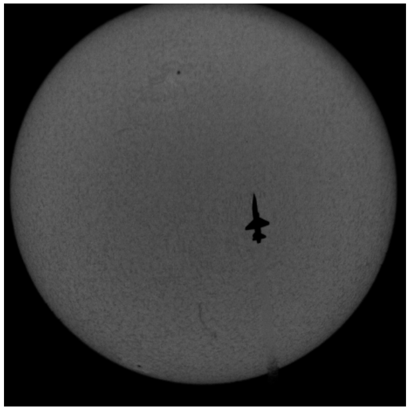
BOSCO – IMAGING INSTRUMENTATION



BOSCO - PROCESSING

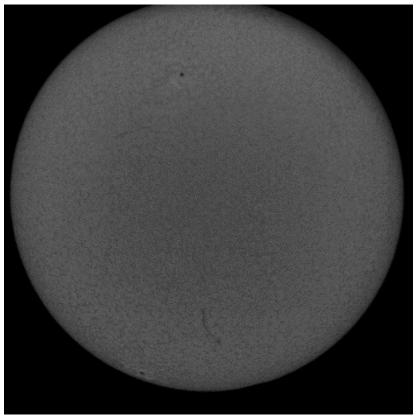
- Optical Flow
  - Developed for computer vision applications in the 1970's/80's
  - Uses the "brightness constancy criterion" – brightness is constant between 2 image pairs, differences in brightness correspond to motion
  - Outputs "flow" vectors, 2D solutions of pixel displacement



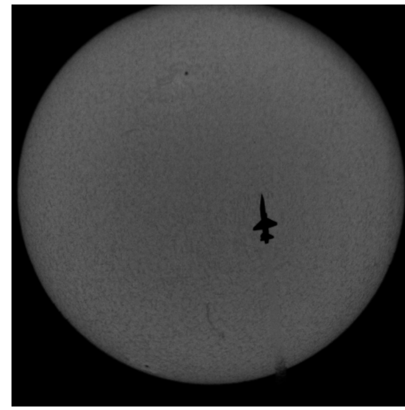


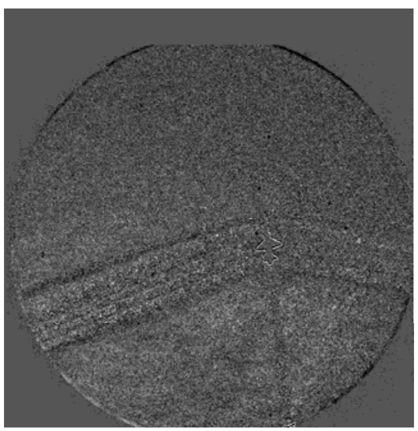
BOSCO – IMAGE PROCESSING

A frame before the aircraft eclipses is used for the reference background

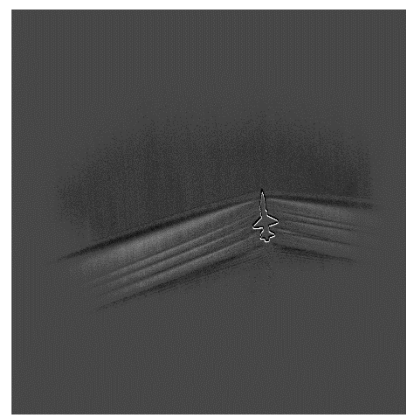


Each eclipse frame is aligned with the background frame





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



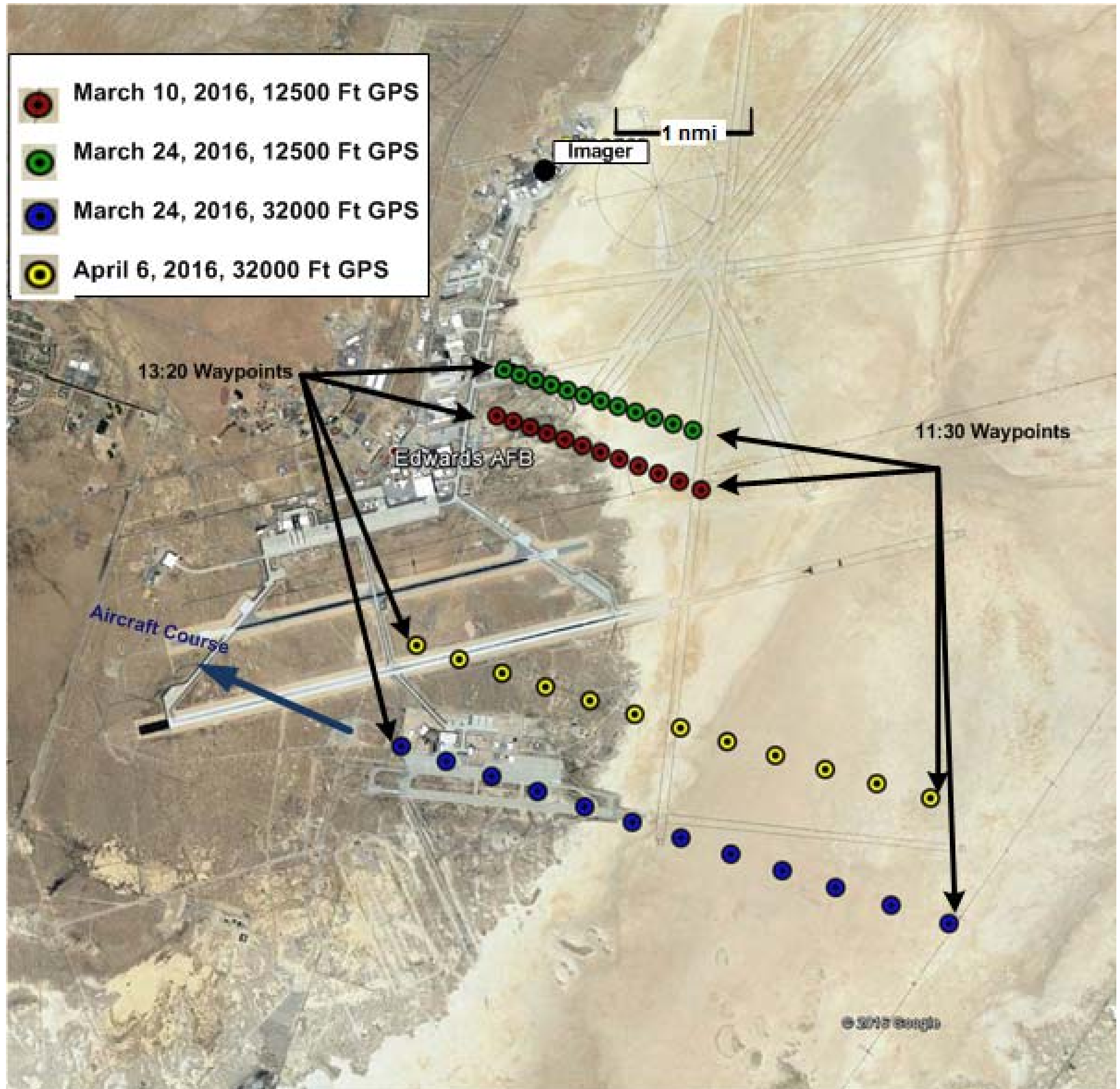
This is repeated for all frames in the eclipse. The median of all the results of all the fames is taken, resulting in the final de-noised schlieren image

BOSCO - TEST OPERATIONS

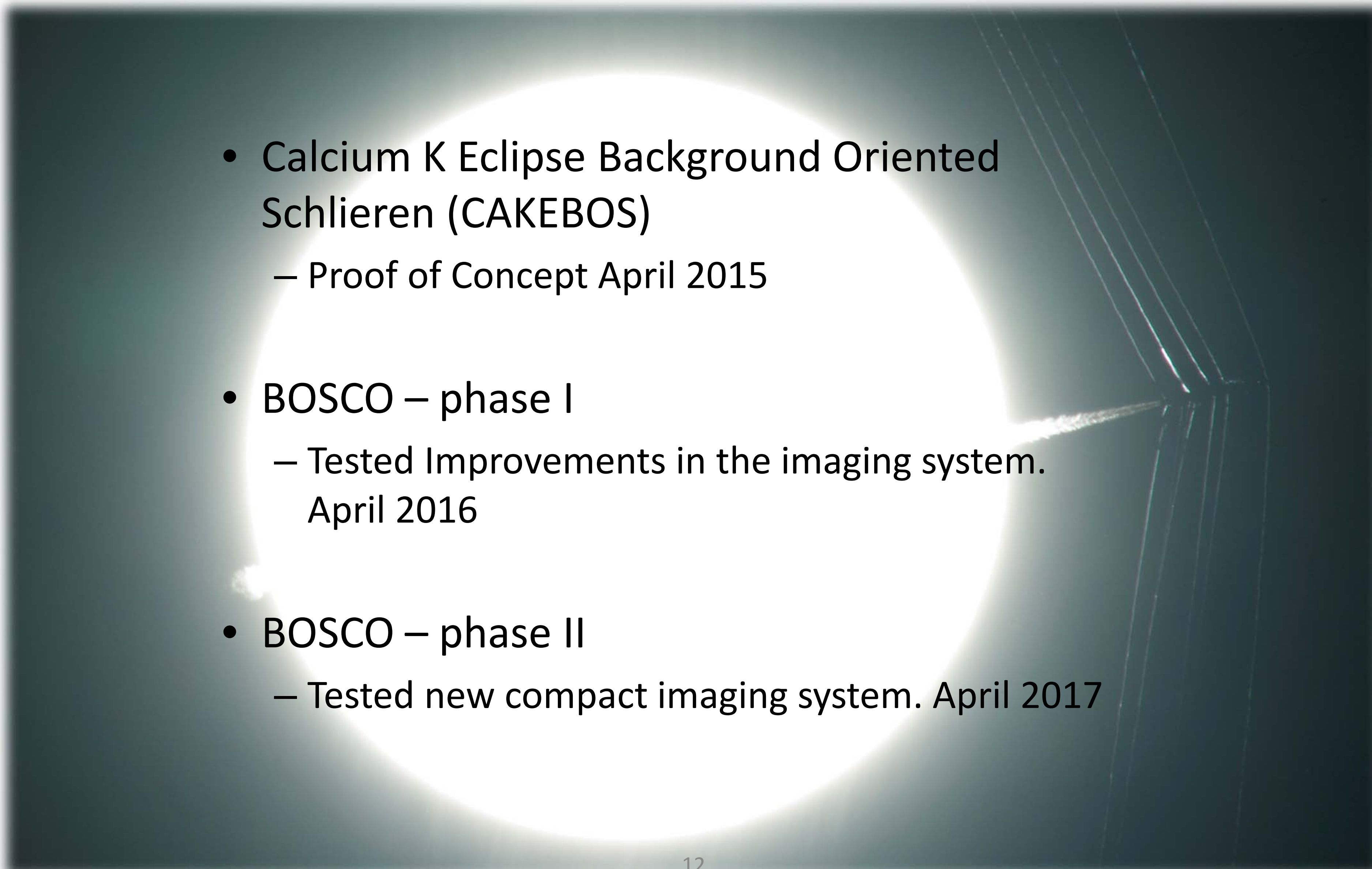
- Aircraft waypoints were calculated based on time of eclipse, ground position of the imager, and desired altitude of the aircraft.

- 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



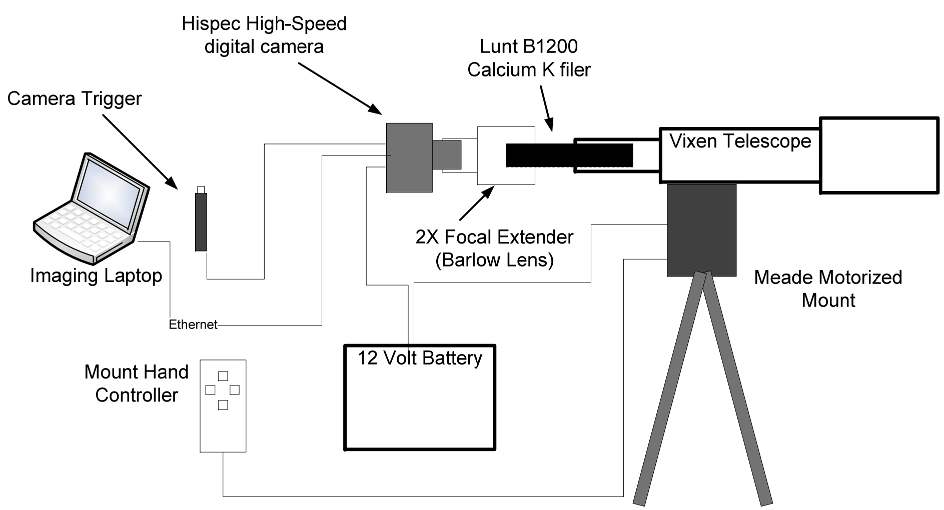
Flight Tests

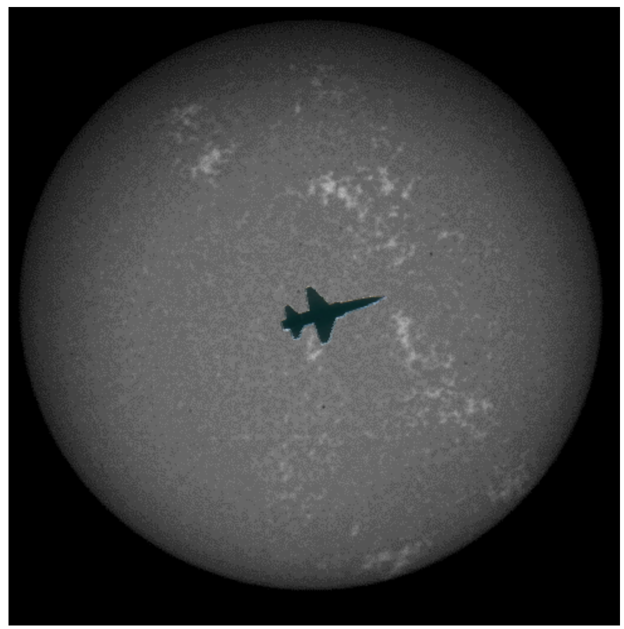


- Calcium K Eclipse Background Oriented Schlieren (CAKEBOS)
  - Proof of Concept April 2015
- BOSCO – phase I
  - Tested Improvements in the imaging system. April 2016
- BOSCO – phase II
  - Tested new compact imaging system. April 2017

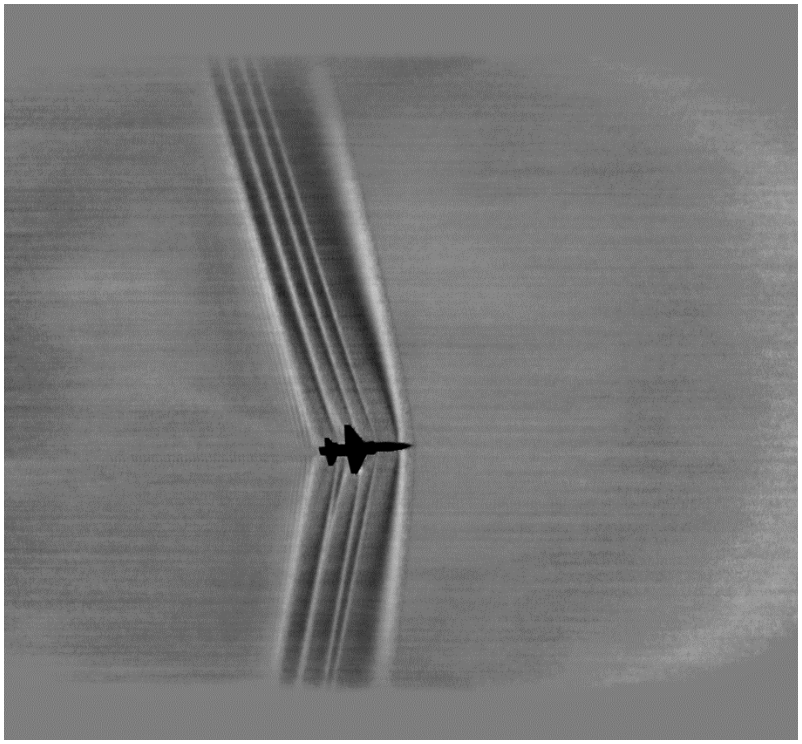
Calcium-K Eclipse Background Oriented Schlieren (CaKEBOS) April 2015

- 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



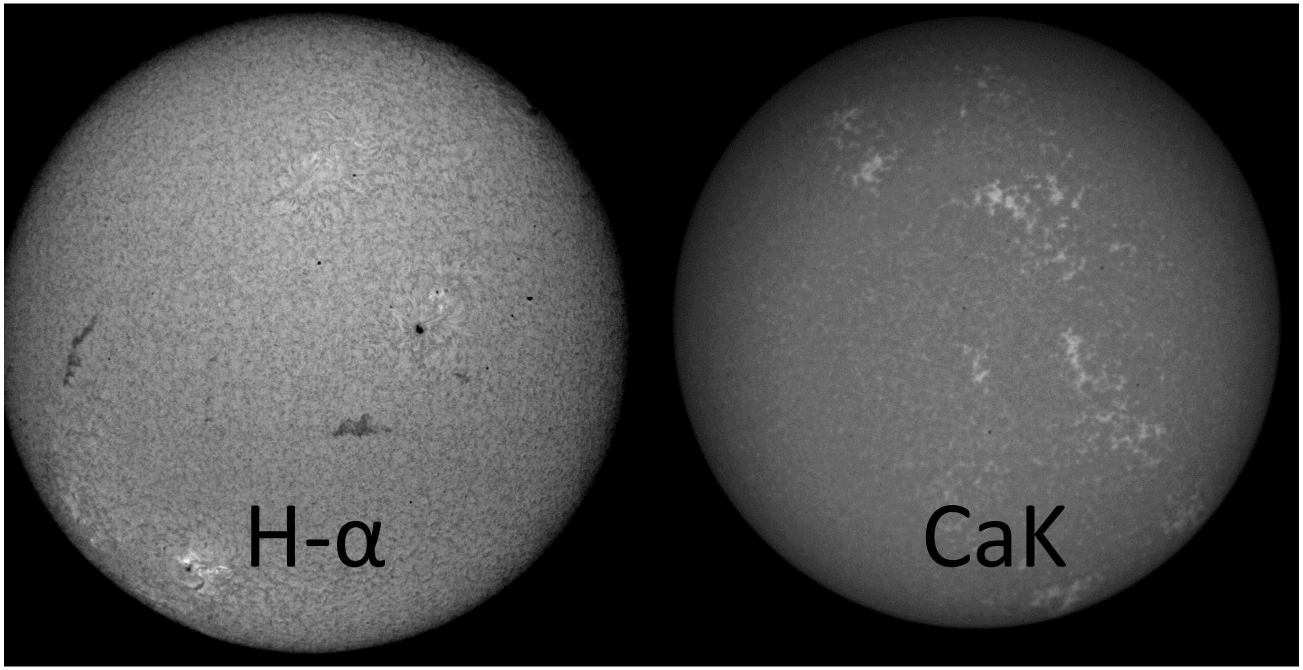
Horizontal density gradient

Vertical density gradient

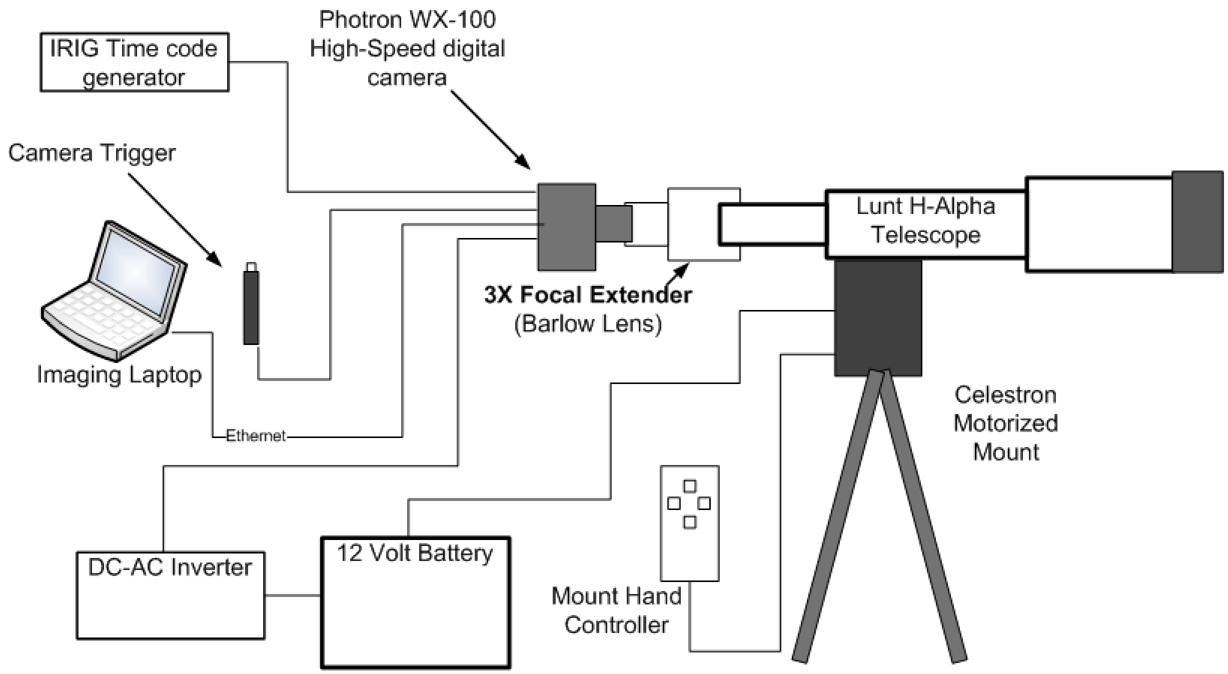
T-38 30000ft AGL, 6.5 mile range, Mach 1.05

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

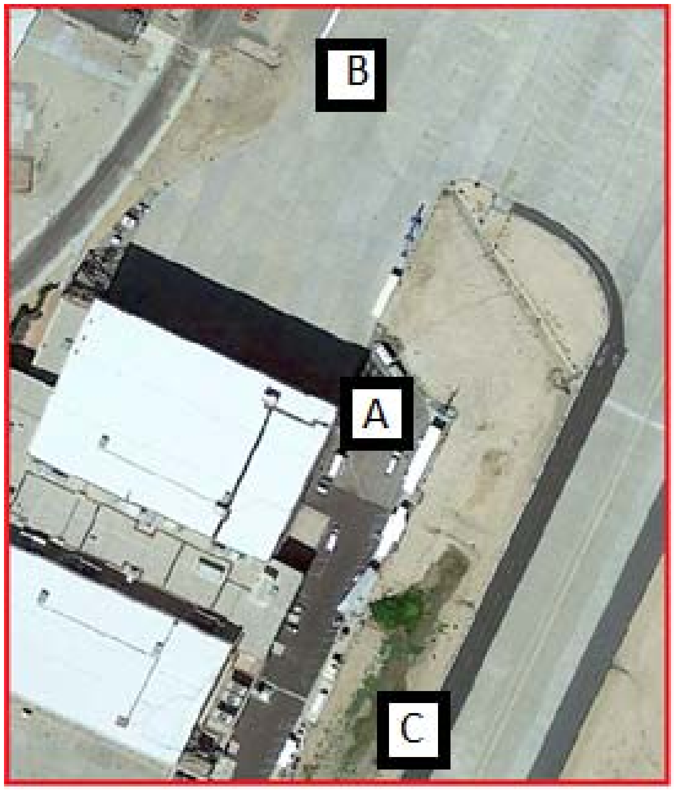


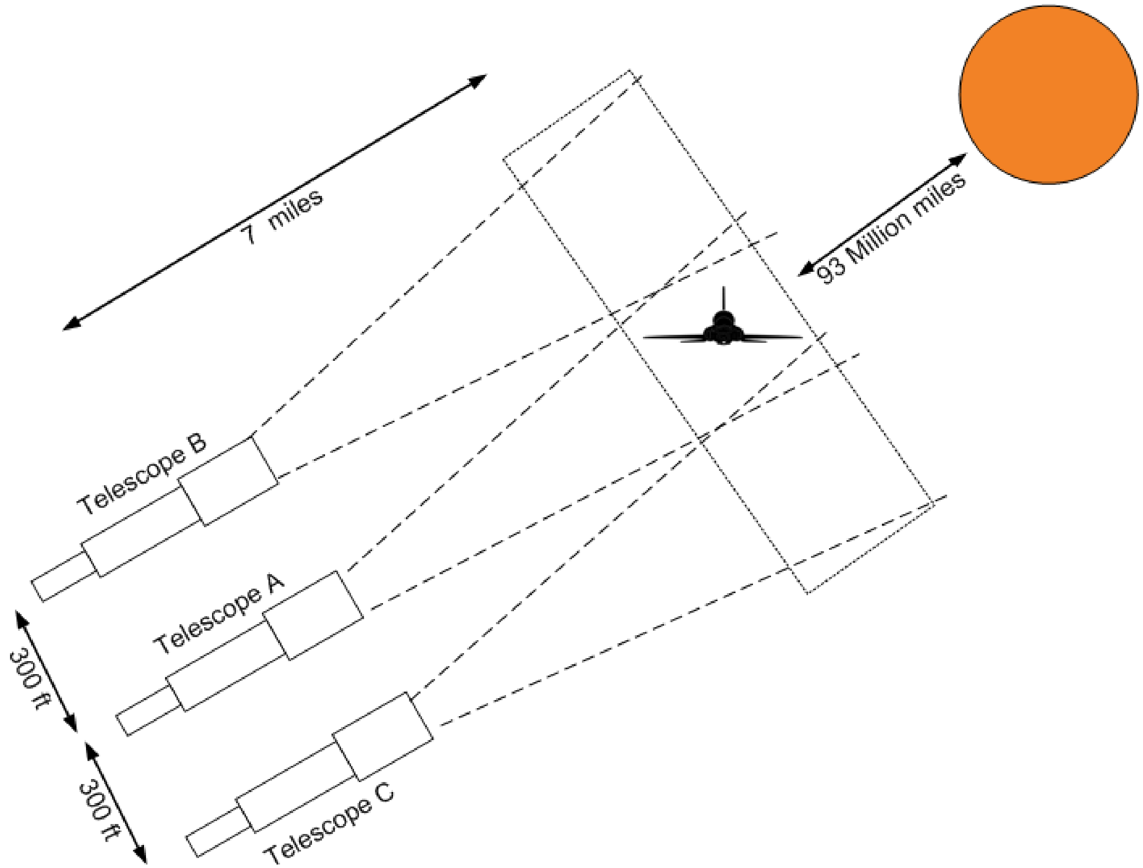
BOSCO System (H-α)



- 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

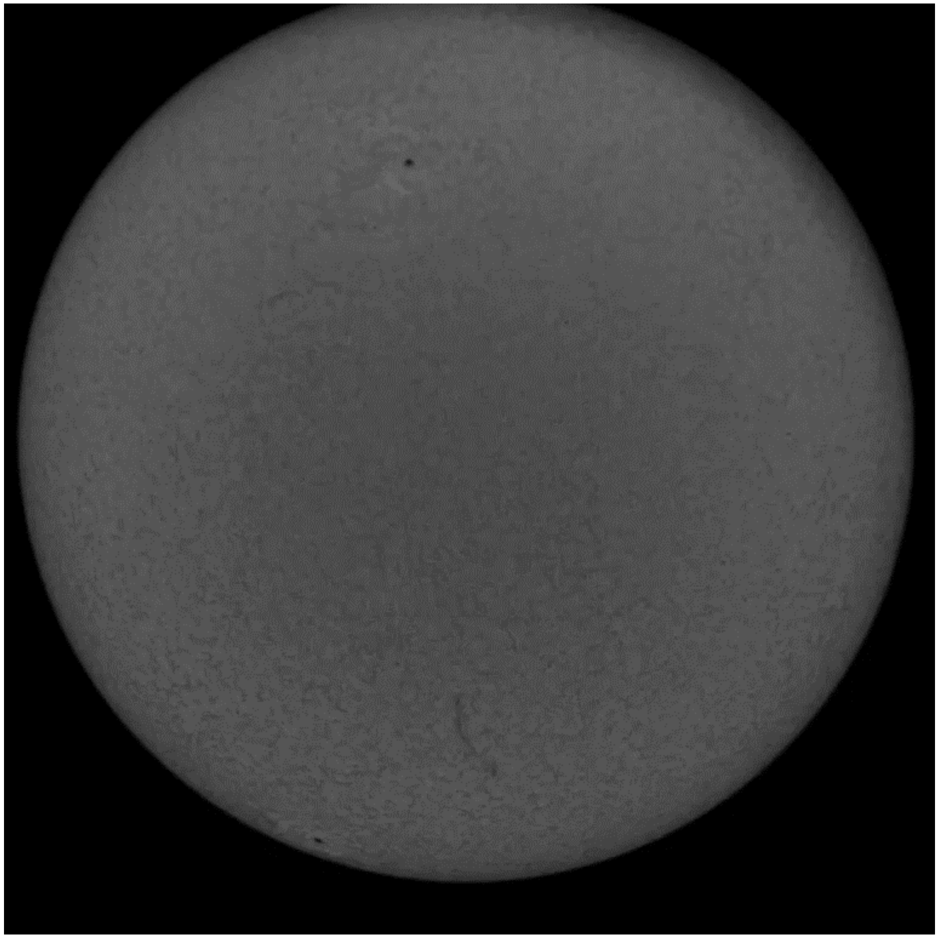
BOSCO – 3 Imager Array





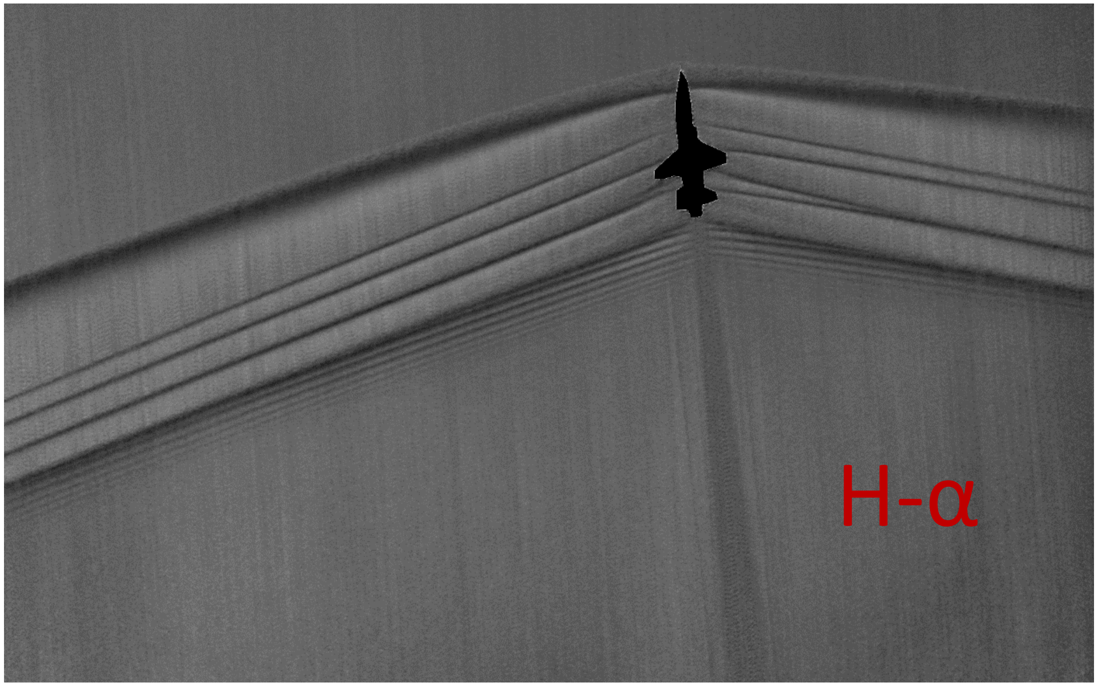
To increase the field of view of the system, 3 imagers were used in a spaced array in the direction perpendicular to the aircraft course

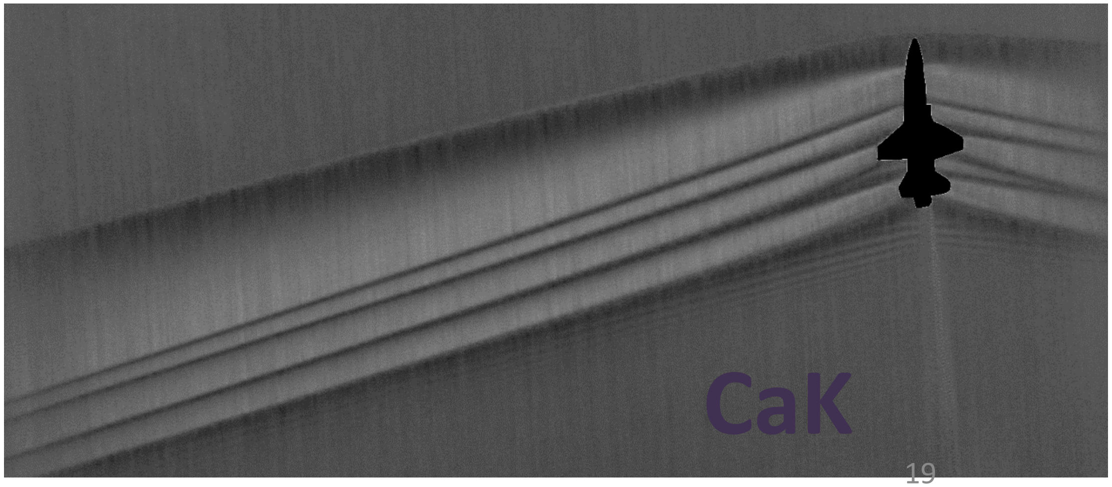
BOSCO- PHASE I RAW DATA



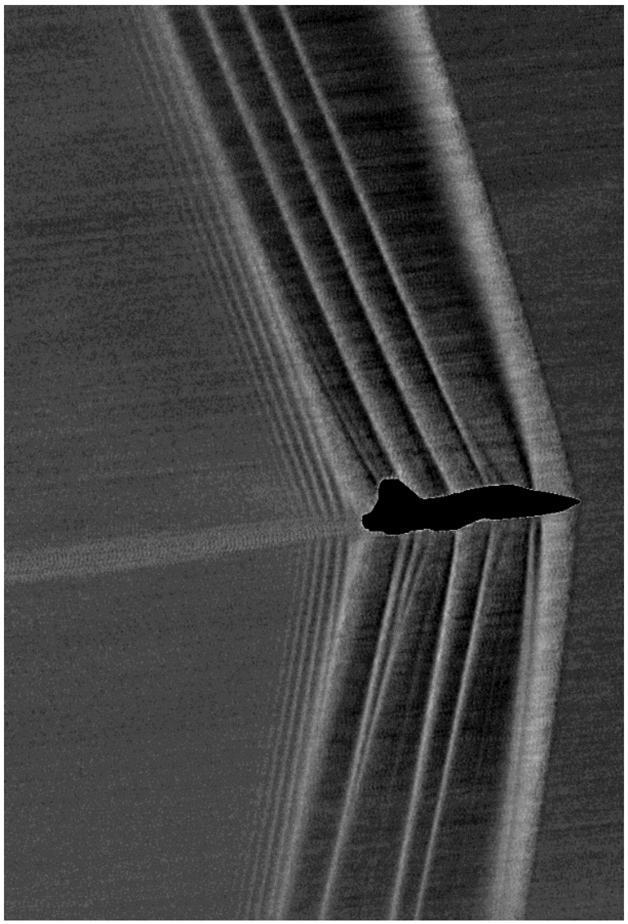
BOSCO RESULTS

- 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





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



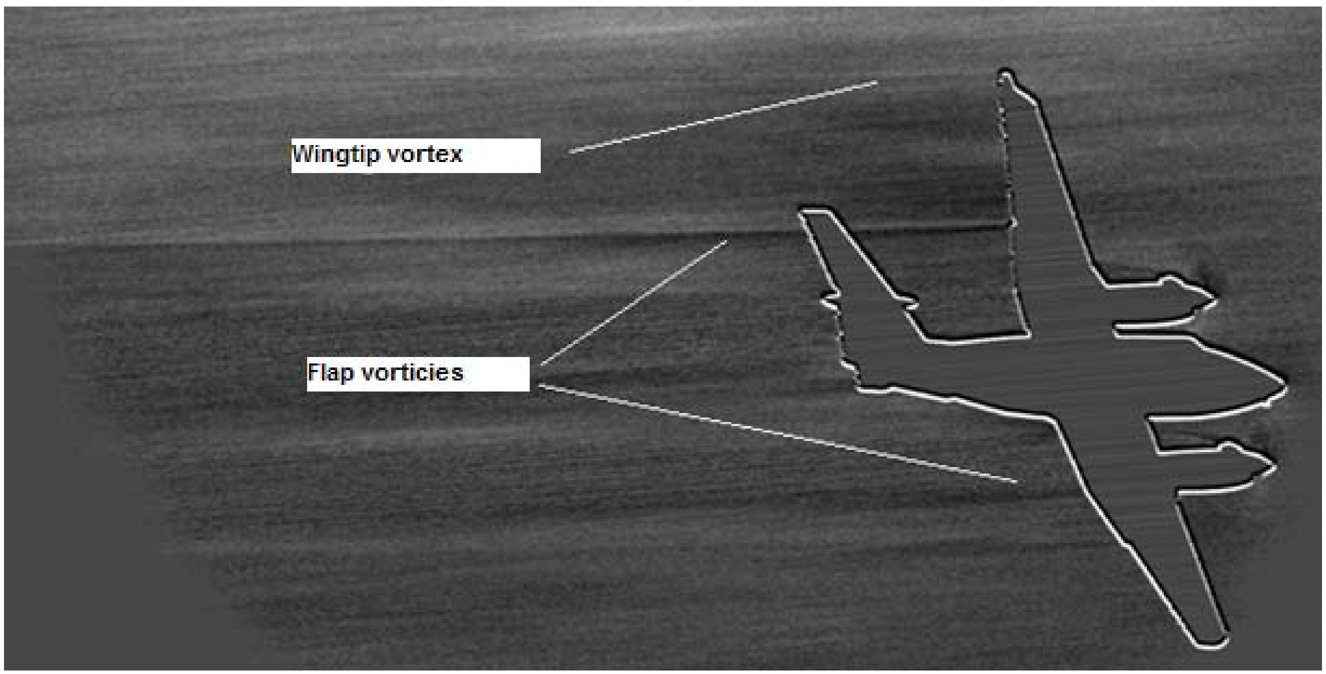
3 Image, wide field of view

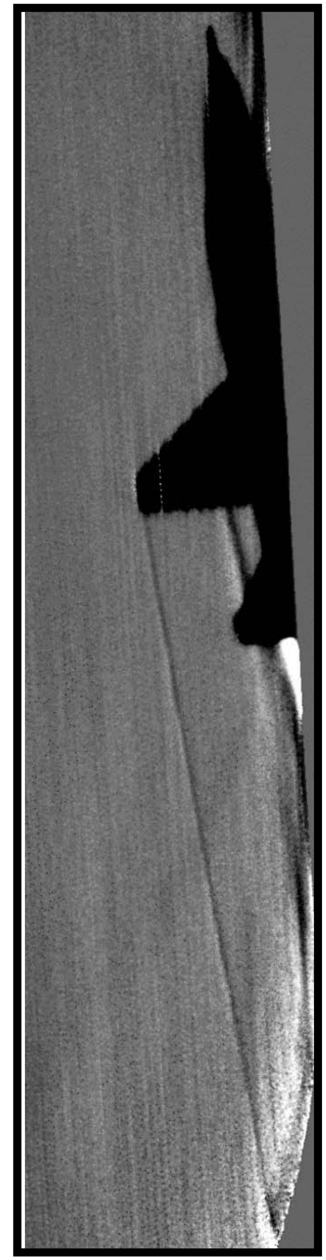
The top and bottom images in the composite used the older CaKEBOS imagers, resulting in reduced resolution

BOSCO – PHASE I: SUBSONIC RESULTS

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

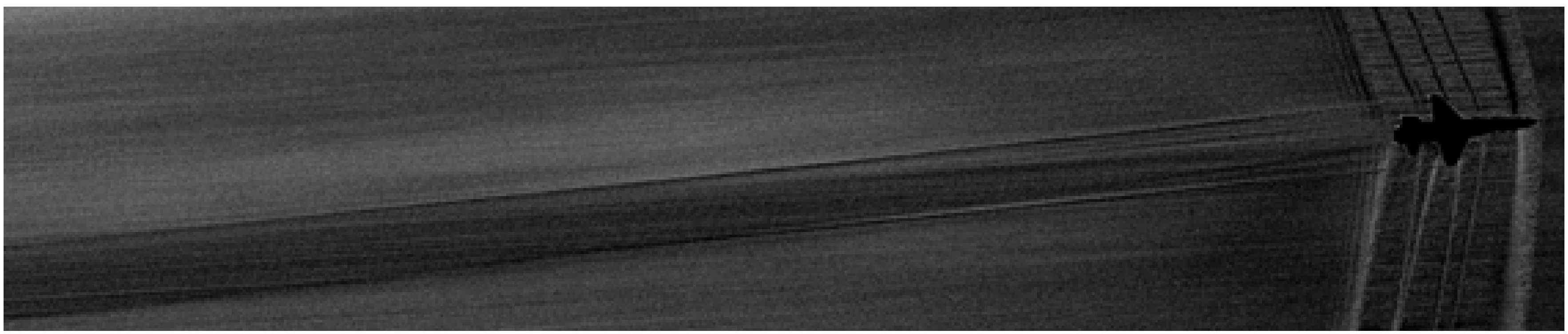




BOSCO- PHASE I: EXTENDED AFT VIEW

- 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

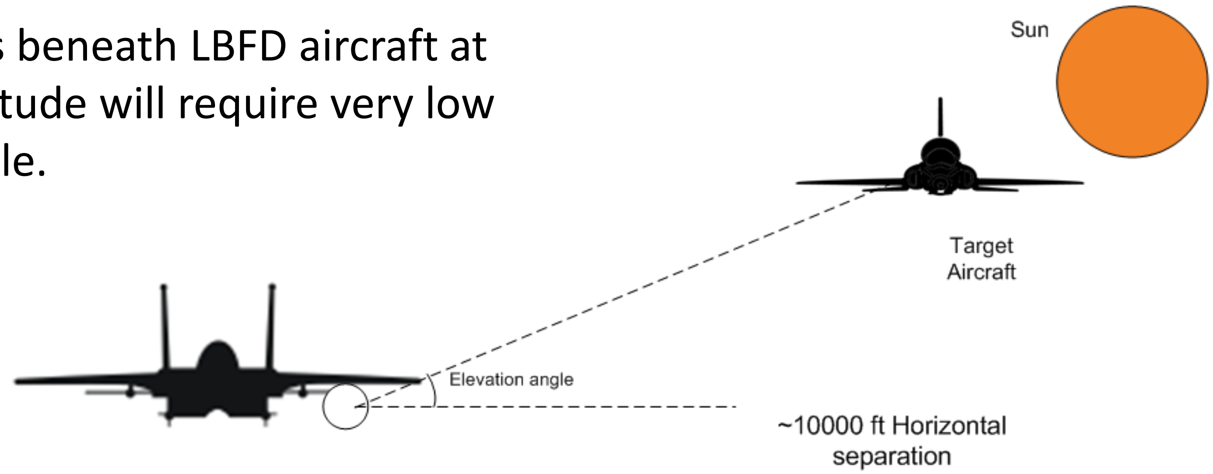


BOSCO – Phase II, April 2017

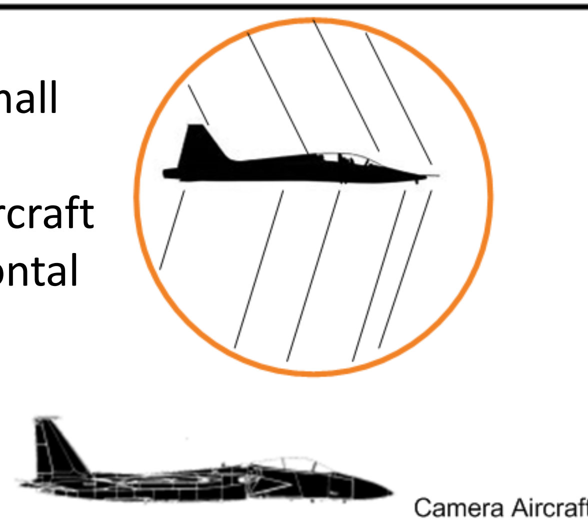
- Test of a new compact imaging system
- Closer range – 2 miles

BOSCO – PHASE II MOTIVATION

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

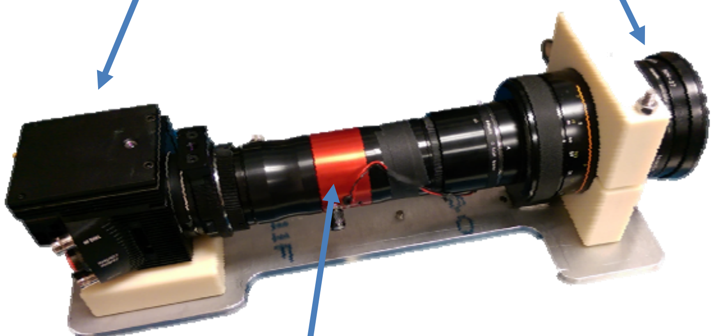


BOSCO – PHASE II

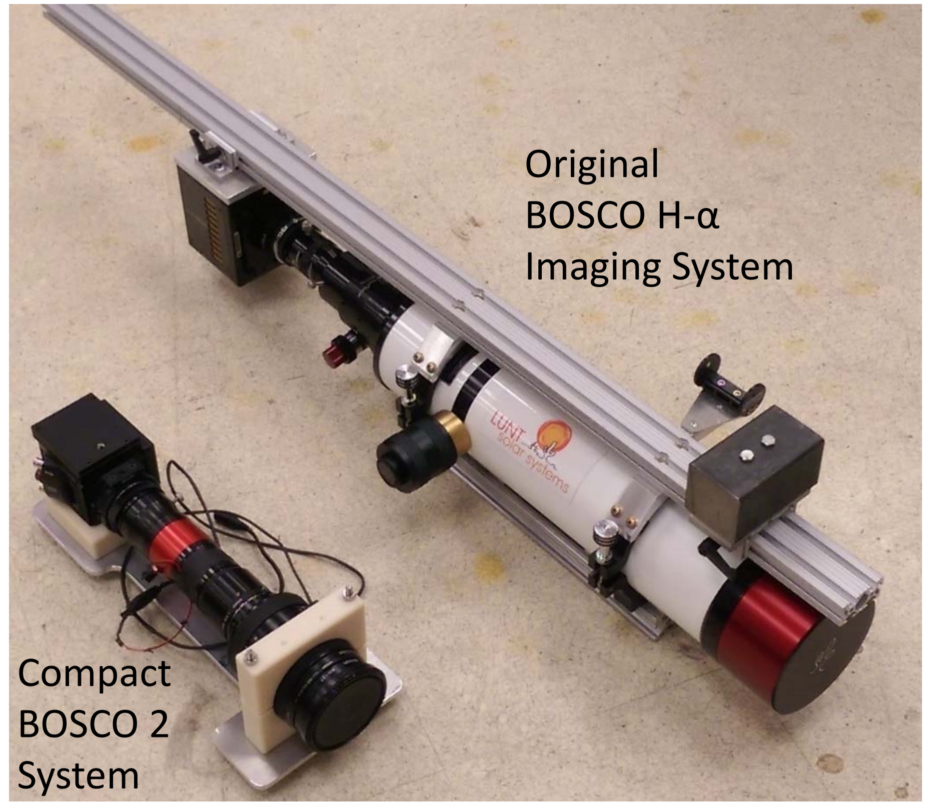
New compact imaging system for future airborne use

IDT Camera:
3800 X 2400 pixels
1000 Frames/sec

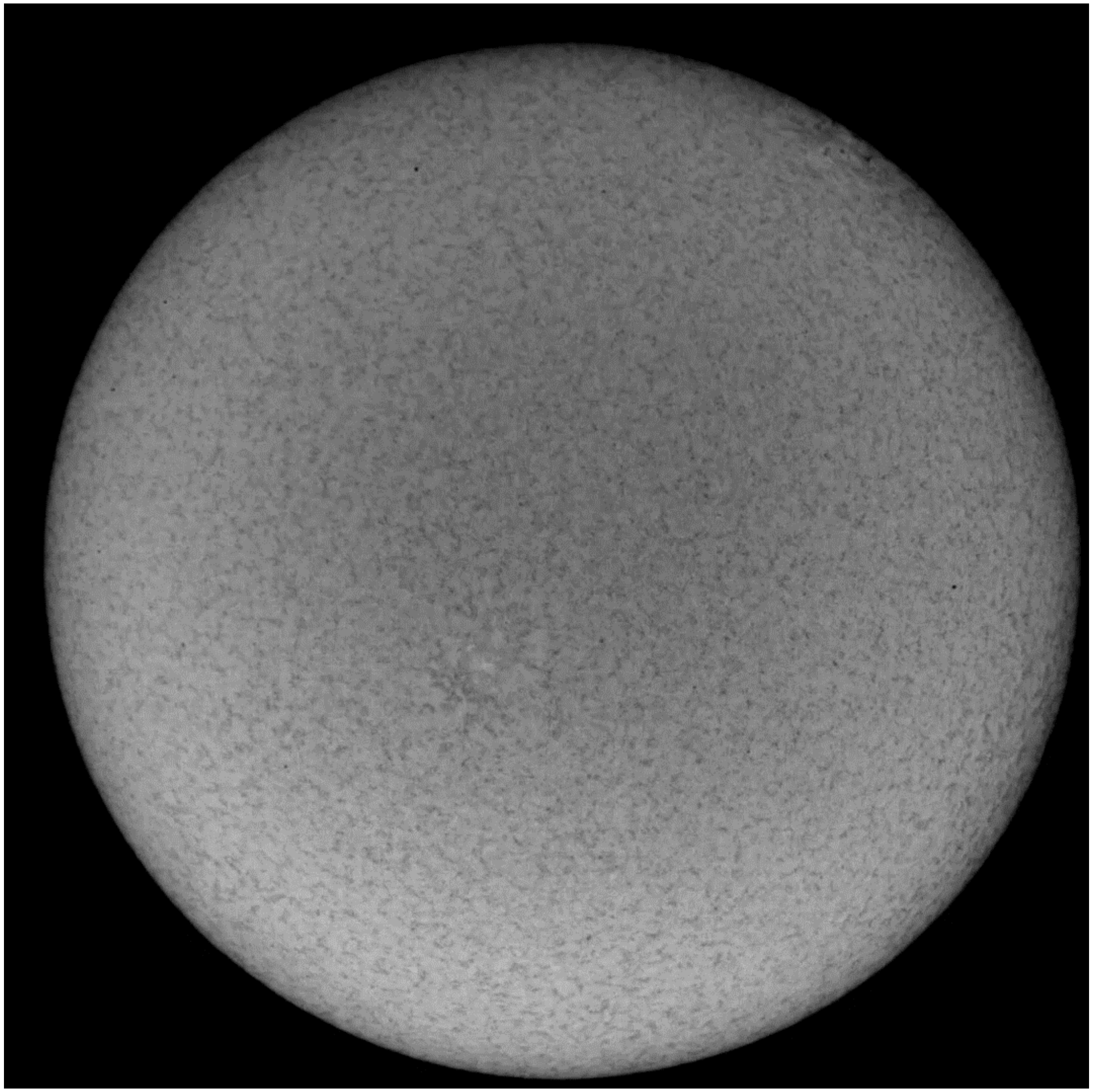
Nikon Lens
Compact 500mm
Cassegrain lens



H-α filter:
0.5 Angstrom bandpass

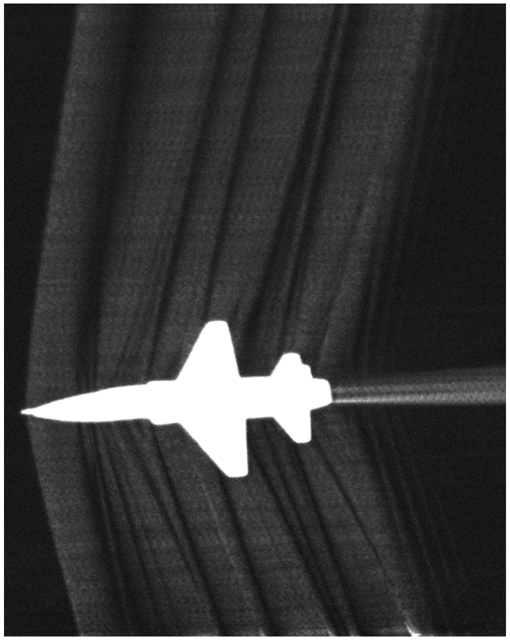


BOSCO – PHASE II RAW DATA



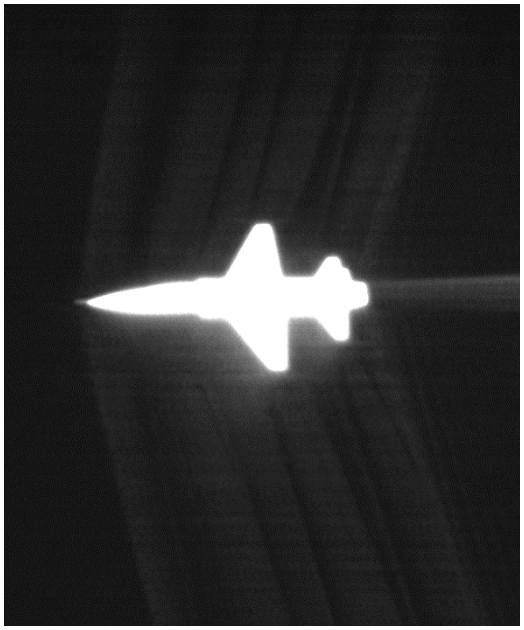
BOSCO – Phase II Results

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