# Ground to Air flow visualization using Solar Calcium-K line Background Oriented Schlieren

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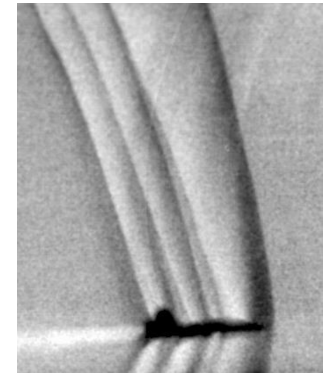
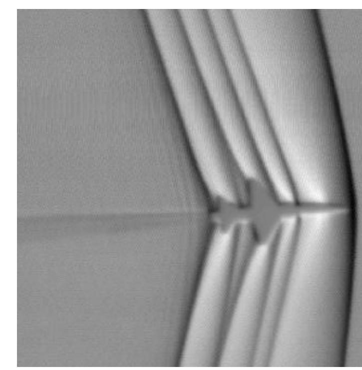
# BACKGROUND



- Desire for a schlieren system for full scale aircraft in flight to visualize shockwaves generated by supersonic aircraft
- Sun based full scale in-flight schlieren systems
  - Schlieren for Aircraft in Flight (SAF)– NASA, Weinstein 1993
  - Ground to Air Schlieren Photography System (GASPS) – Metrolaser Inc., NASA
- These systems use forms of streak photography to compile refractive distortions on the solar limb into a schlieren image

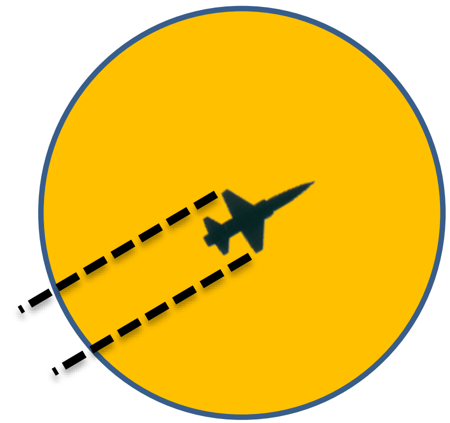


SAF



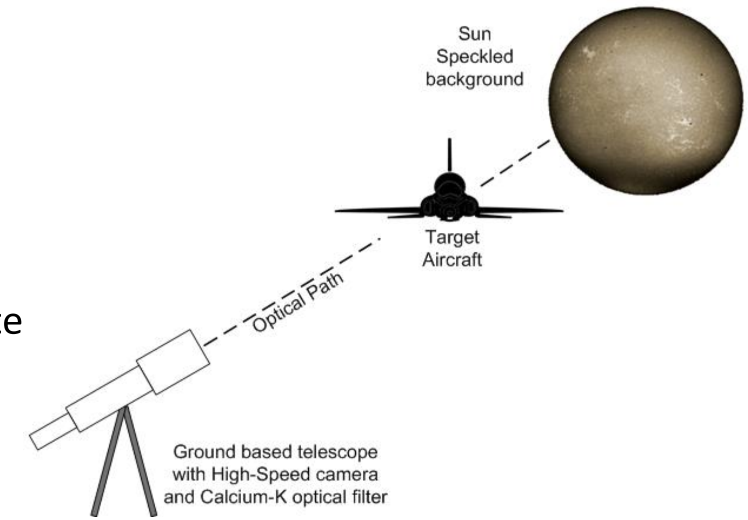
GASPS

- Limitations of the solar limb method
  - Flow features roughly orthogonal to the solar limb are not imaged
  - 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.
- Background Oriented Schlieren
  - Can have x and y magnitudes for the full flow field. Schlieren images can be output along any "knife edge" direction.
  - Possible to observe dynamic features



# BOSCO CONCEPT

- GASPS data hinted at refraction of the solar disk image when shockwaves would cause sunspots to “twinkle”
- Investigated solar filters which view specific emission lines of certain elements
  - Popular consumer filters:
    - α emission line of Hydrogen (H- α), ~ 656 nanomete wavelength
    - K emission line of Calcium (CaK), ~ 393 nanometer wavelength
  - CaKEBOS - Initial proof of concept test of BOSCO used a Calcium-K filter
    - Low cost and integrated easily to our existing GASPS system

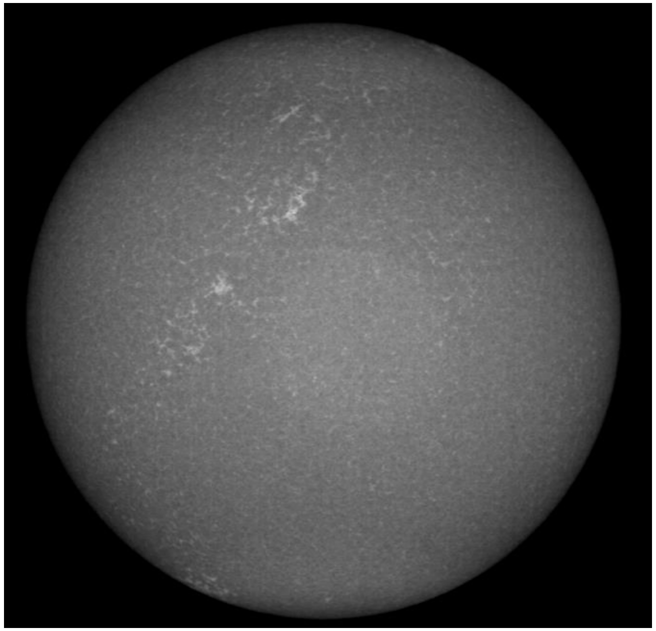


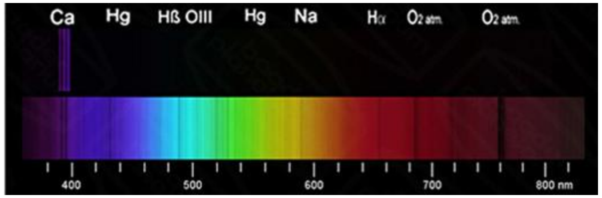
# Calcium-K Eclipse Background Oriented Schlieren



- The Calcium K filter only lets light through that is emitted by calcium ions in the sun's chromosphere. Since these ions exist mainly in areas of strong magnetic fields, the sun's surface has a granular appearance.

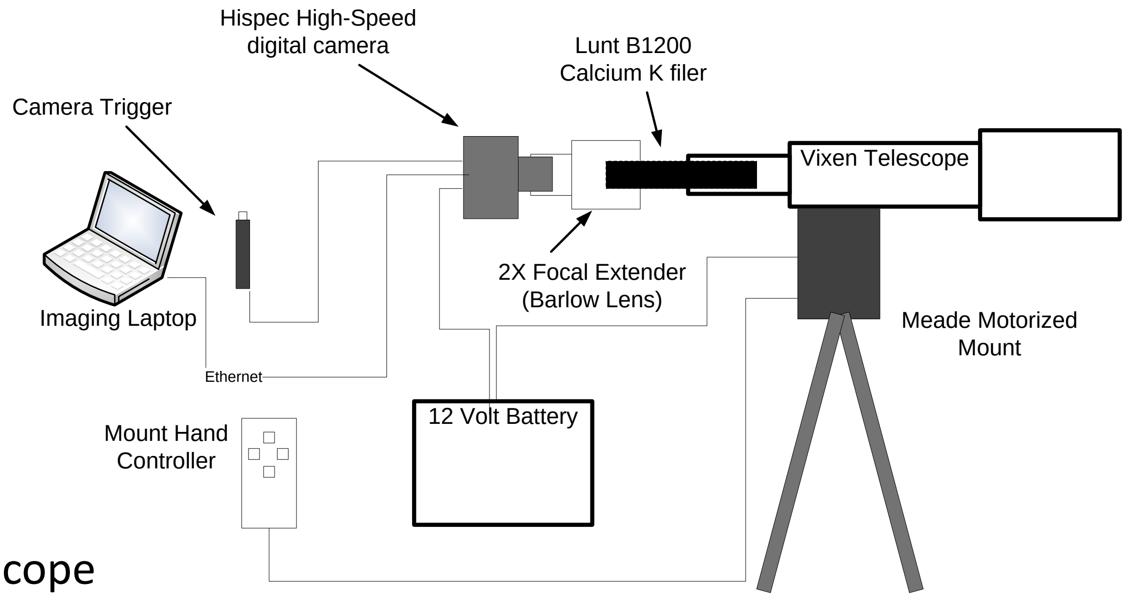
- These granulation cells act as the speckle background for the BOS technique





# CaKEBOS System



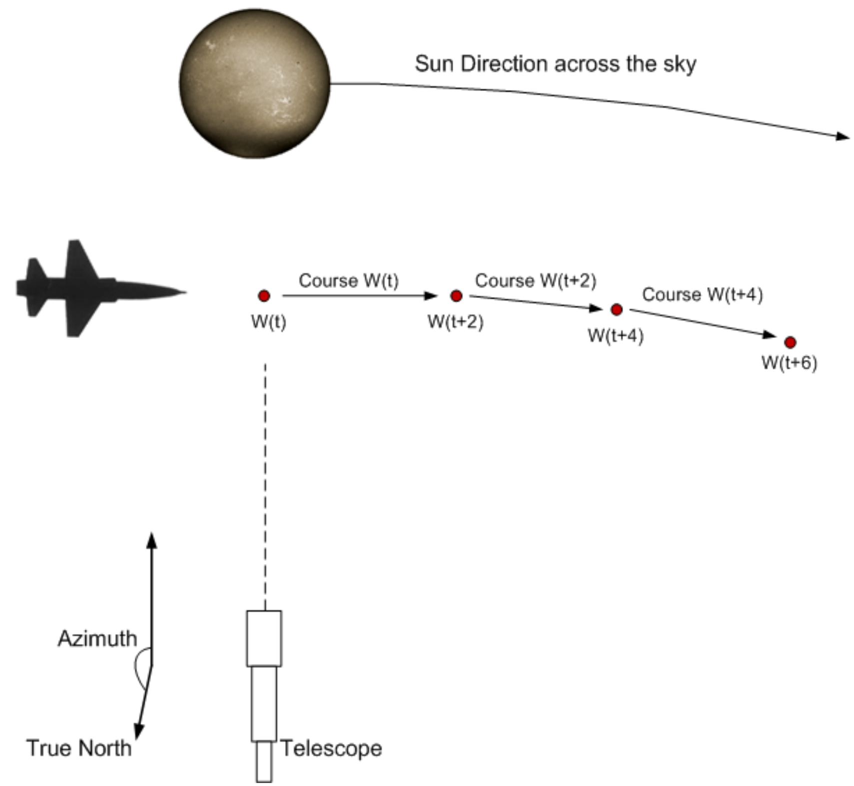



- 80 mm f/7.5 refractor telescope
- Calcium K filter: 393.4nm, 4 angstrom band pass
- 2x Focal extender – Effective focal length: 1200mm
- Fastec Hispec 2 camera
  - 1280X1024
  - 506 Frames/sec
  - 400 µs integration time
- Manual solar tracking
- Manually triggered at pilot's "mark" call or visual eclipse

# CAKEBOS TEST OPERATIONS

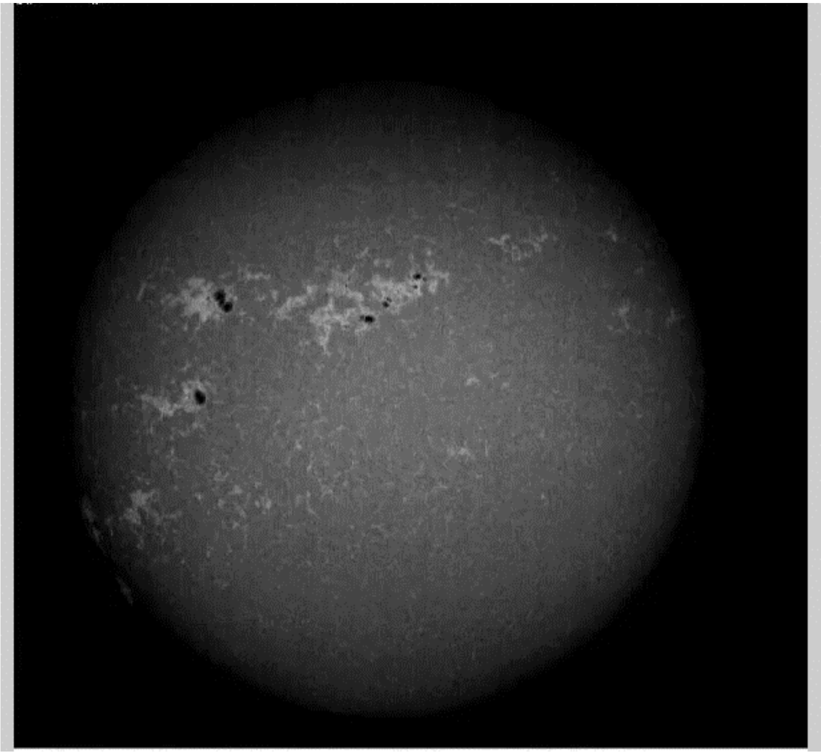


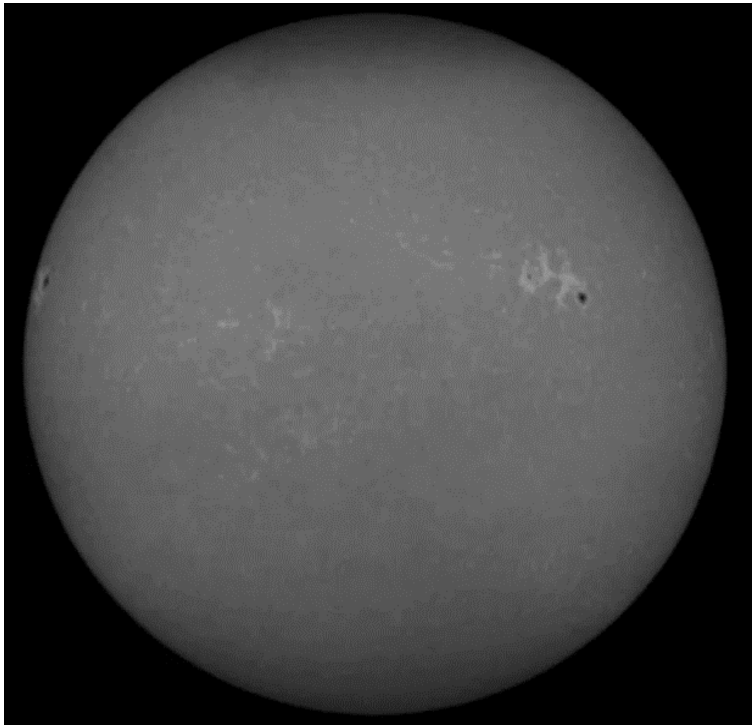
- Aircraft waypoints were given in GPS coordinates and were calculated based on time of eclipse, ground position of the imager, and desired altitude of the aircraft.
- Waypoints were calculated on the order of 2 minutes.
- Course of the aircraft followed the sun direction across the sky, and flights occurred near the maximum solar elevation angle, to minimize the need for accurate waypoint timing.



# Raw Data

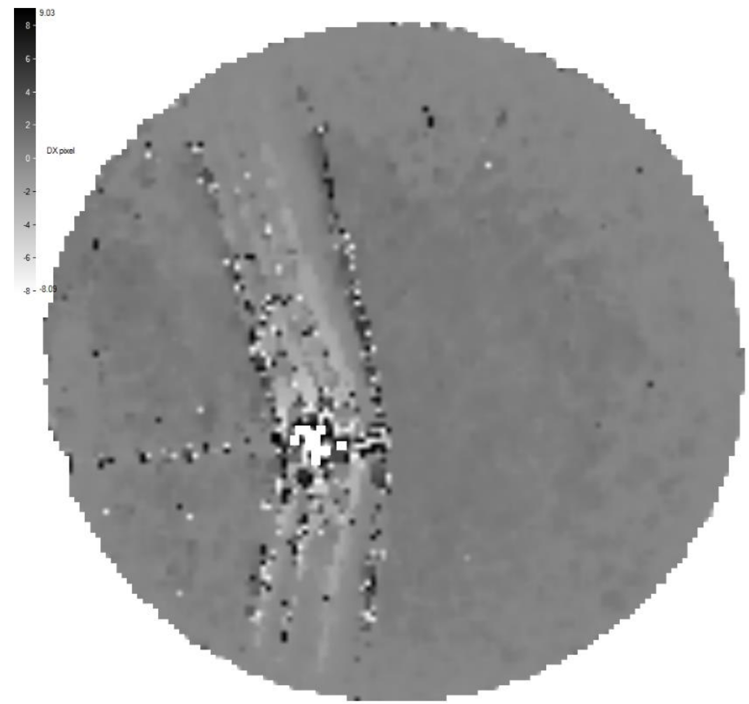






# CaKEBOS Analysis

- Initial image processing was done using cross correlation methods traditionally used for BOS
- Lack of discrete, high contrast speckles yielded poor correlation peaks
- Large interrogation windows reduced already limited resolution




50 averaged cross-correlation results

- 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 just as cross correlation does

# CAKEBOS ANALYSIS



- Image processing script was written utilizing the OpenCV package's optical flow functions
  - Horn and Schunck (HS) - Global Method, uses image derivatives. Minimizes global energy with smoothness parameter α.
  - Lucas and Kanade (LK) – Local Method, uses image derivatives. Uses least squares about a local neighborhood to estimate motion
  - Farnebäck (FB) - Local Method, estimates pixel neighborhood as a polynomial

$$\frac{\partial I}{\partial x}\frac{\delta x}{\delta t} + \frac{\partial I}{\partial y}\frac{\delta y}{\delta t} + \frac{\partial I}{\partial t} = 0$$

Brightness Constancy

$$E = \int\int\left(\frac{\partial I}{\partial x}\frac{\delta x}{\delta t} + \frac{\partial I}{\partial y}\frac{\delta y}{\delta t} + \frac{\partial I}{\partial t} + \propto^2 \left(|\Delta\delta x|^2 + |\Delta\delta y|^2\right)\right) d\,xdy$$

H-S Global energy

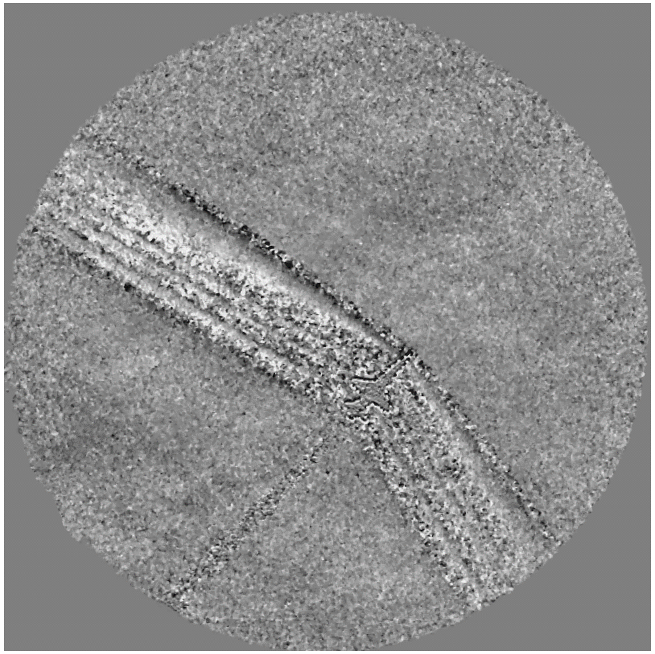
$$f_1(x,y) = (x,y)A_1\binom{x}{y} + b_1^T\binom{x}{y} + c_1$$

FB Polynomial estimation

# CaKEBOS image processing

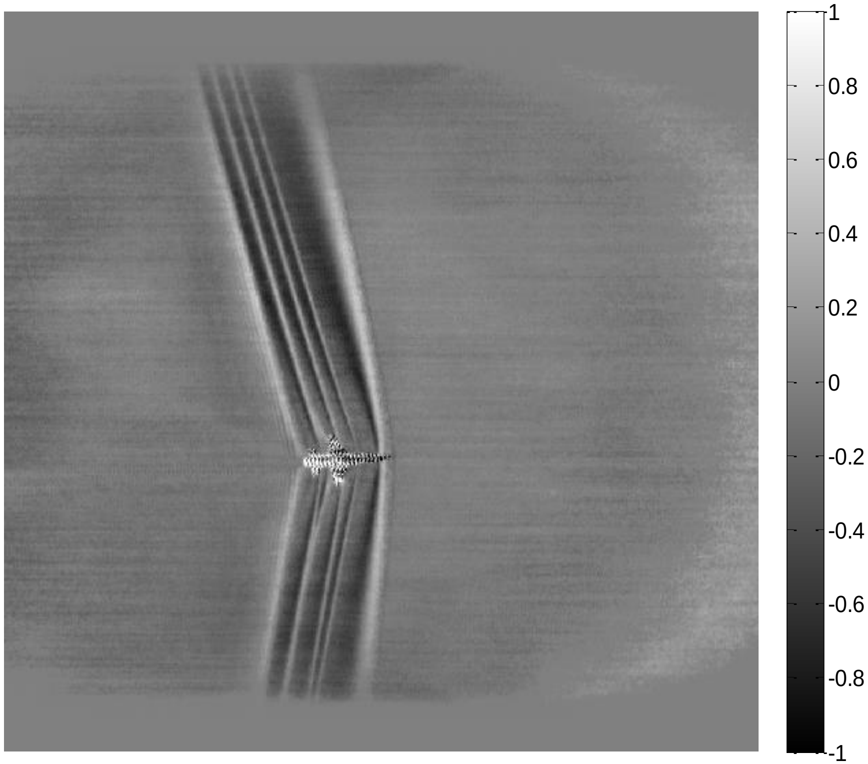


- The first 10 frames before the aircraft entered the field of view were used as reference backgrounds.
- Optical flow was performed on each frame with the aircraft in the field of view against the 10 background frames.
- The median pixel value of the 10 optical flow results were taken to get a single optical flow result for each frame with the aircraft in the field of view
- Each frame was shifted to a central point based on the aircraft trajectory.
- The final schlieren images were created by taking the median pixel values of all the shifted frames.

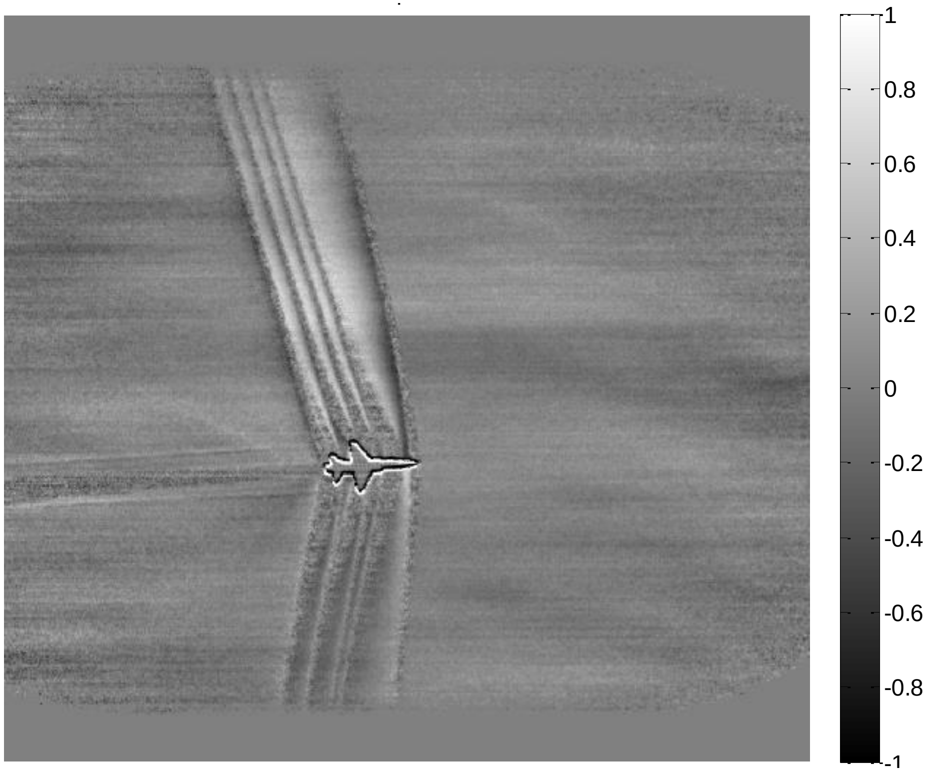


Optical flow result for a single frame with 10 reference backgrounds

# CaKEBOS Results – 70 averaged images



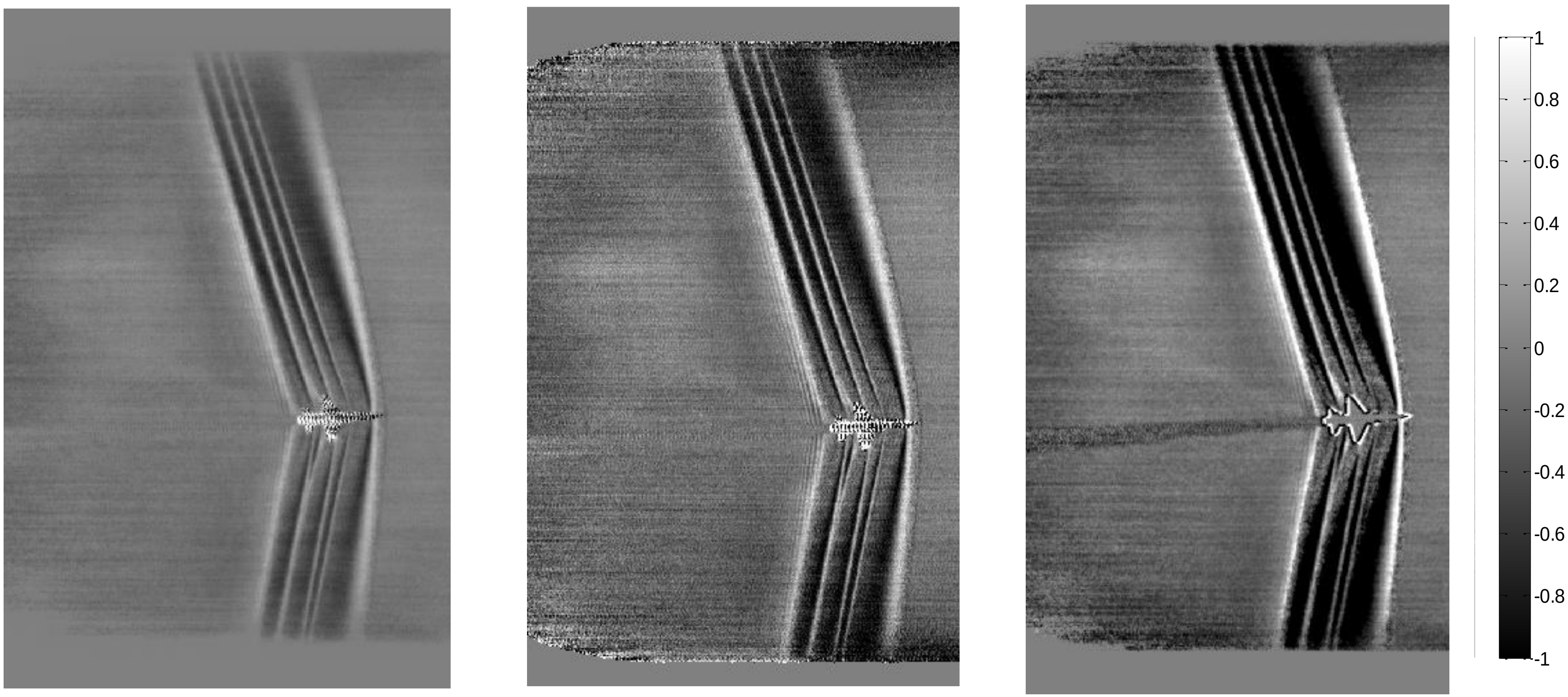

X pixel displacement




Y pixel displacement

# CaKEBOS Image Processing – X displacement, 70 images



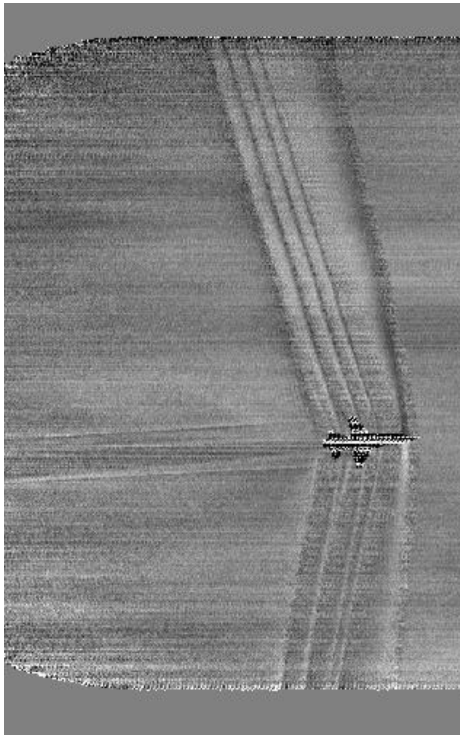



H-S L-K FB

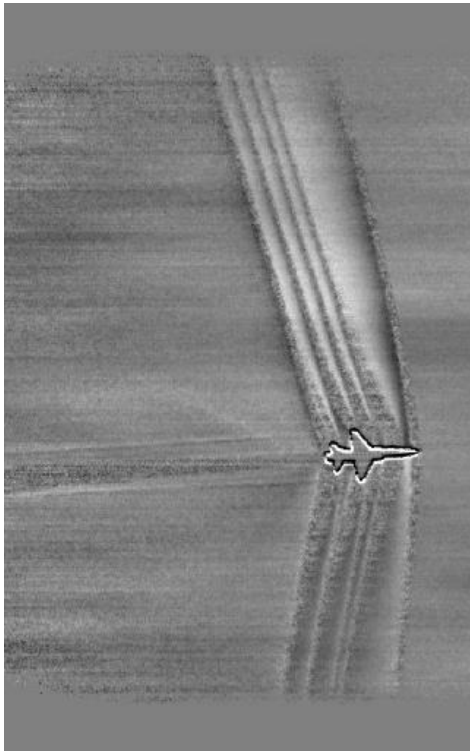
# CaKEBOS Image Processing – Y displacement, 70 images



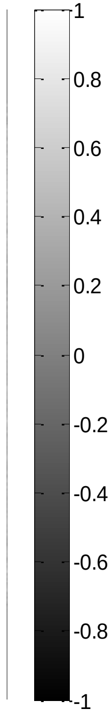
H-S



L-K

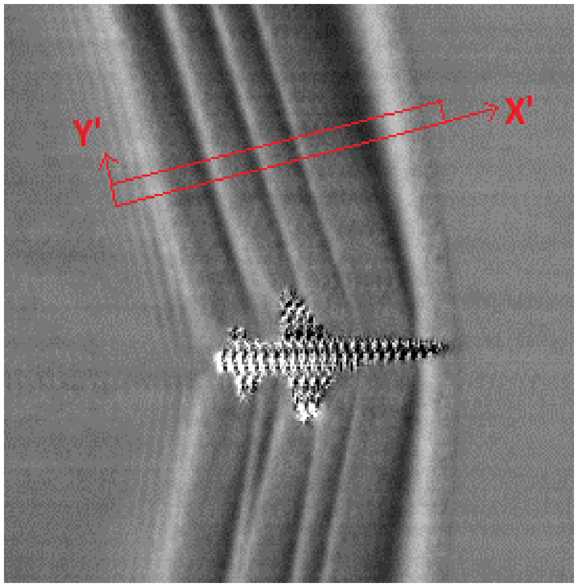


FB

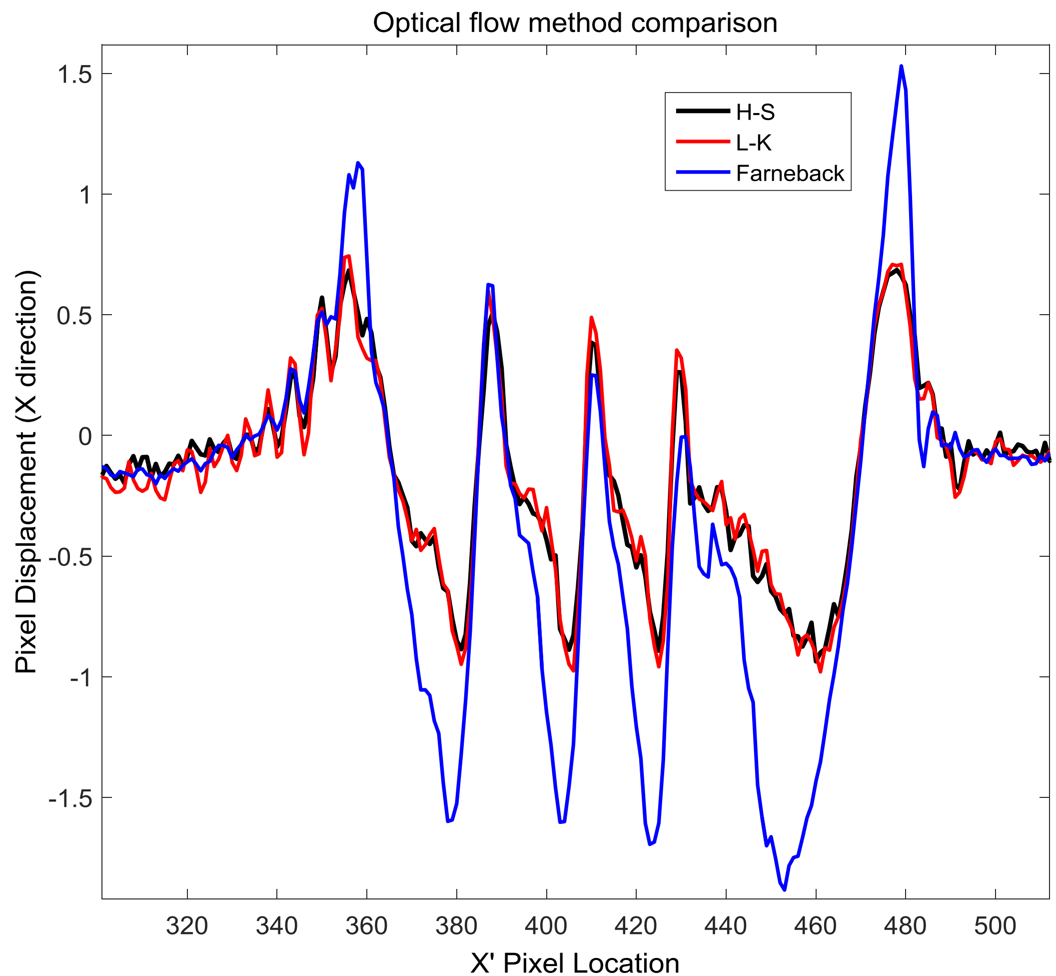


# Optical flow method comparison





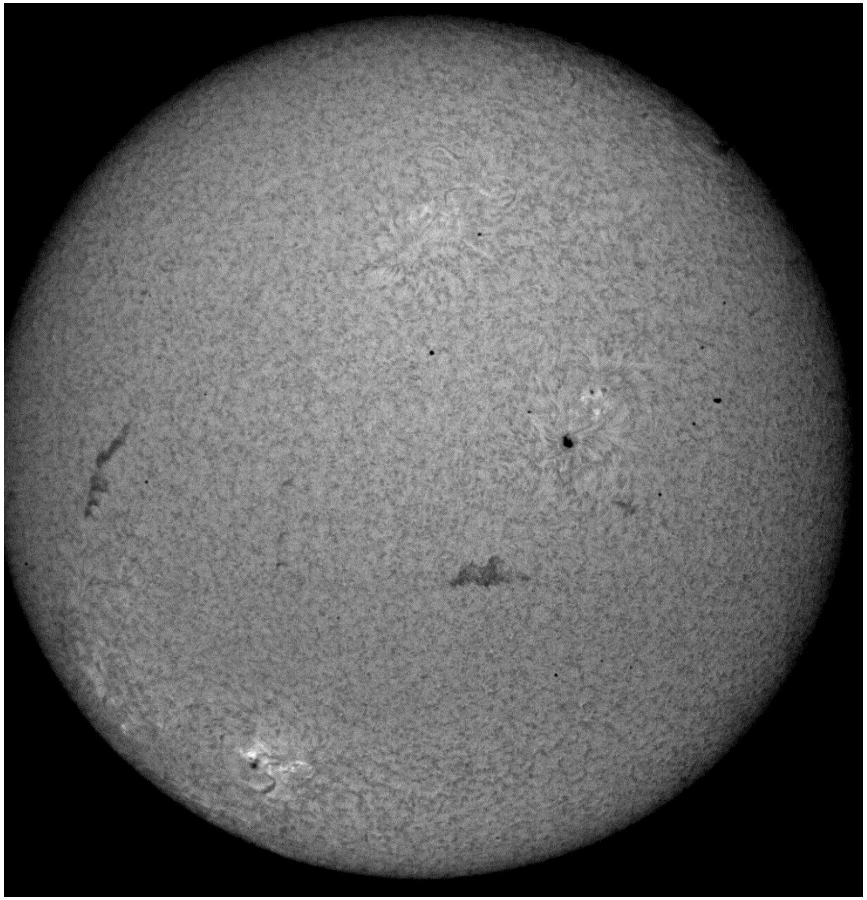

Median value of 10 pixels in the Y’ axis was used to reduce noise in the plot



# BOSCO – April 2016



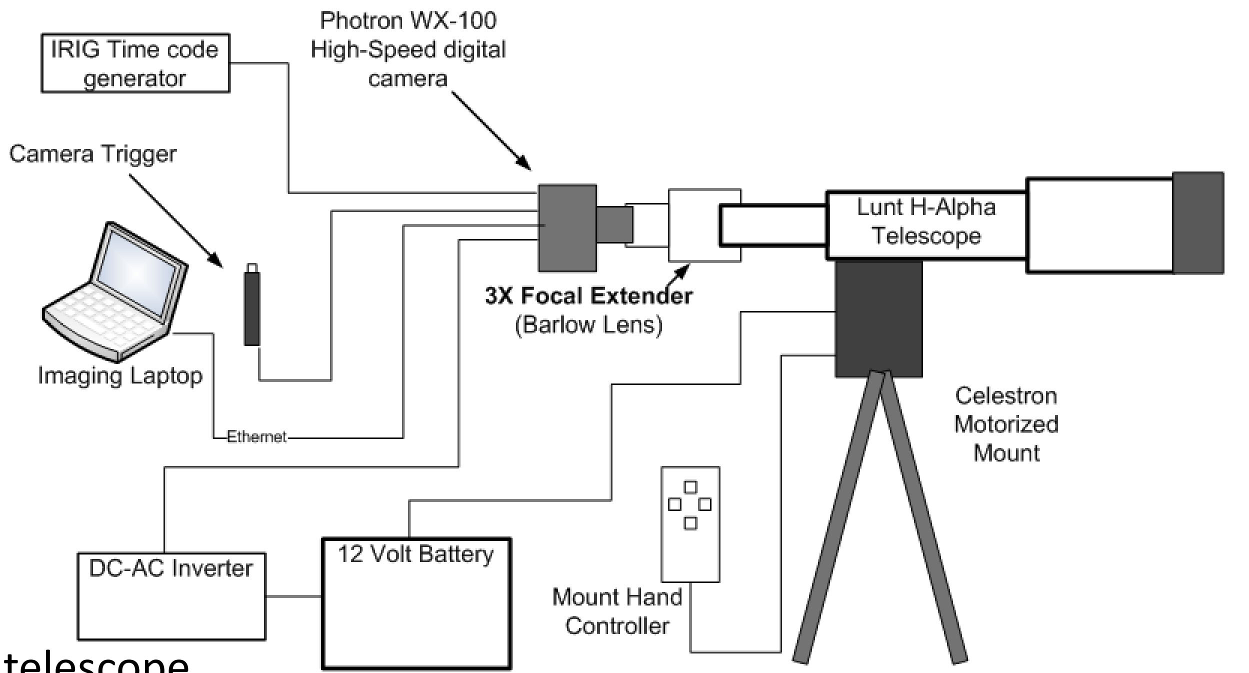
- Success of CaKEBOS allowed for equipment upgrades
  - Higher resolution Camera
    - Photron WX-100: 2048 X 2048 pixels @ 1000 frames/sec
  - Hydrogen alpha telescope
    - More uniform texture distribution
    - Speckle size is smaller and therefore better for BOS
    - Higher contrast



H-α

# BOSCO SYSTEM (H-A)

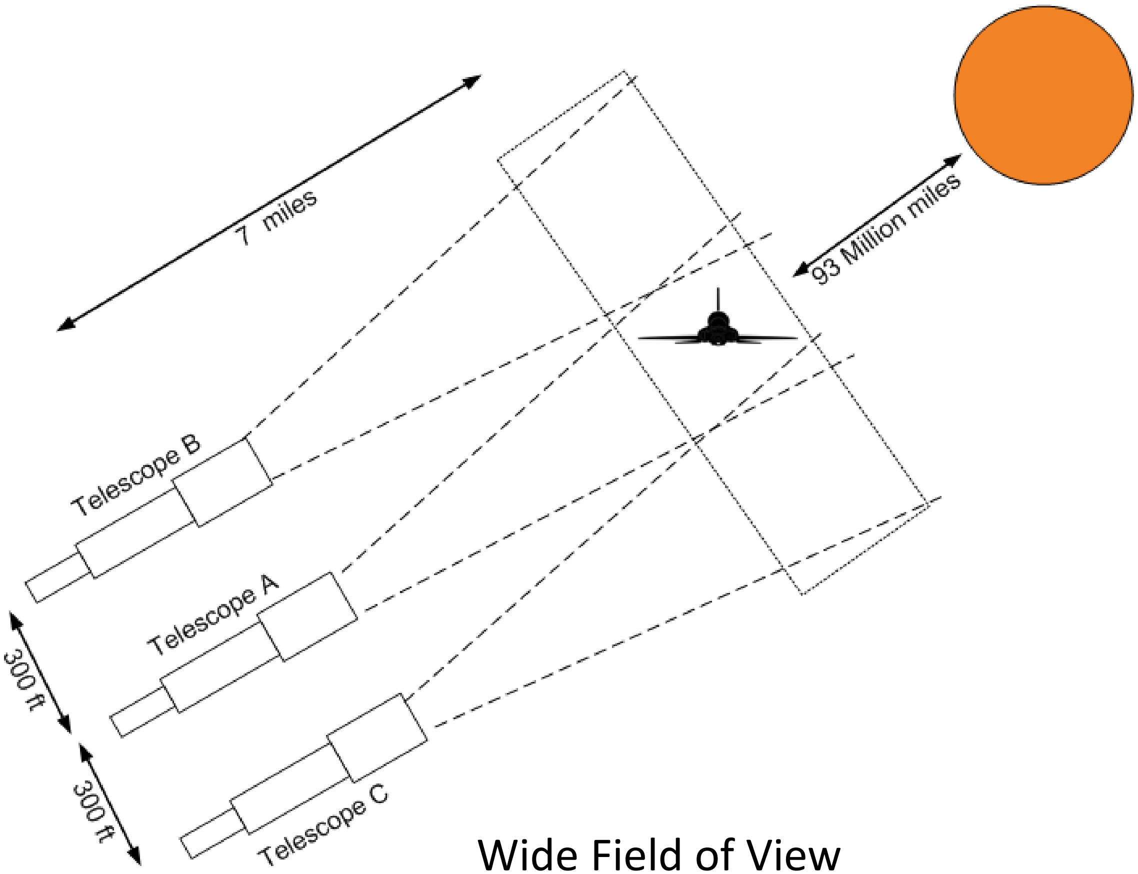





- 100 mm f/7 refractor telescope
- H Alpha filter
- 3x Focal extender – Effective focal length: 2100 mm
- Photron WX-100
  - 2048 X 2048 pixels
  - 1000 frames/sec
  - 333 µs integration time
- Manual solar tracking
- Manually triggered at pilot's "mark" call or visual eclipse

# BOSCO SETUP

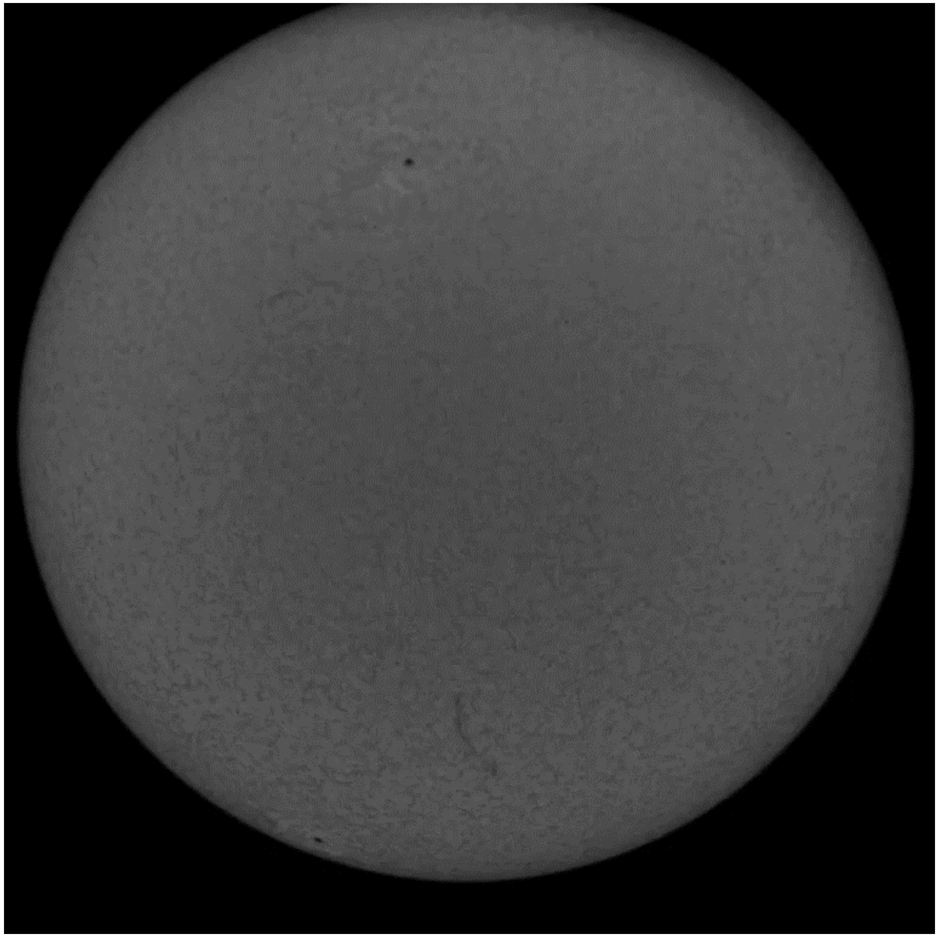

Imager A, Hydrogen - α




Wide Field of View

# BOSCO DATA

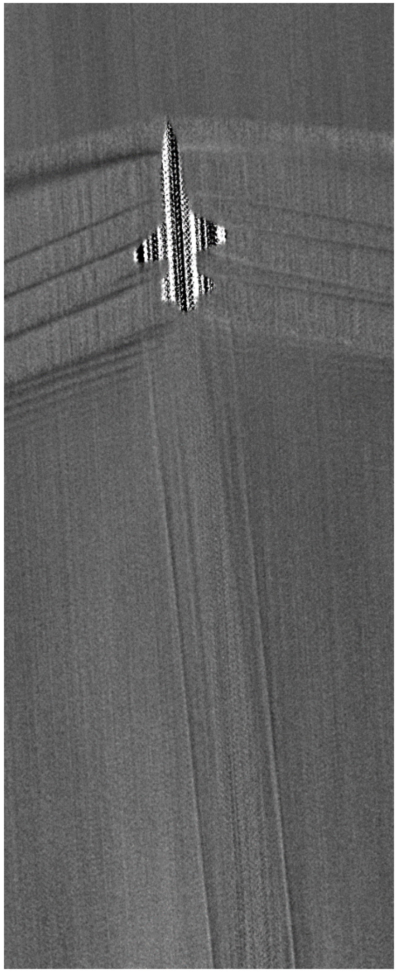




# BOSCO RESULTS



Horizontal “knife edge”

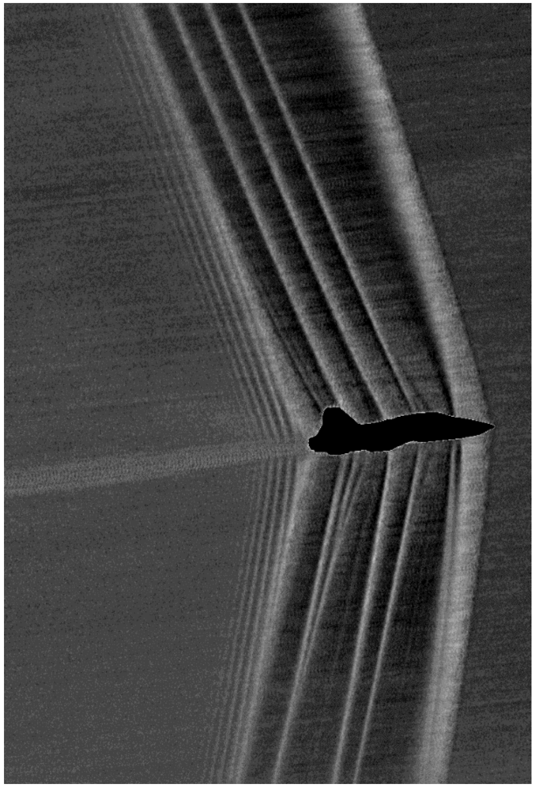


Vertical
“knife edge”

# BOSCO Results



- Aircraft banked $60^0$ for direct side view



3 Image Composite

# 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.
    - Initial results suggest H- α appears to be superior for BOS imaging
- For solar chromosphere BOS, optical flow algorithms produce much greater detail than current cross correlation methods
- Field of view can be increased with multiple camera array
- Method has pending patent
- Future work
  - Airborne system for close-in imaging
  - Would make possible low sun angle imaging without being too far away
- Non Aircraft imaging