National Aeronautics and Space Administration

NASA TECHNOLOGY TRANSFER PROGRAM

BRINGING NASA TECHNOLOGY DOWN TO EARTH

Synthetic Schlieren Techniques for Flight Testing

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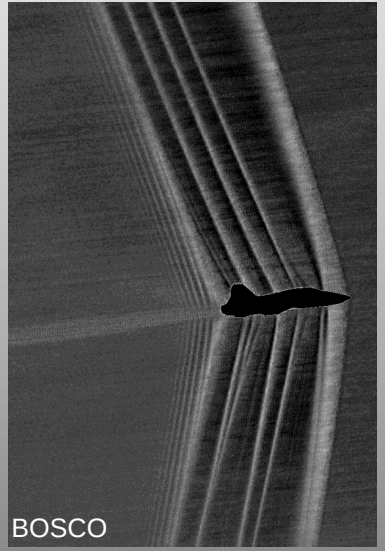
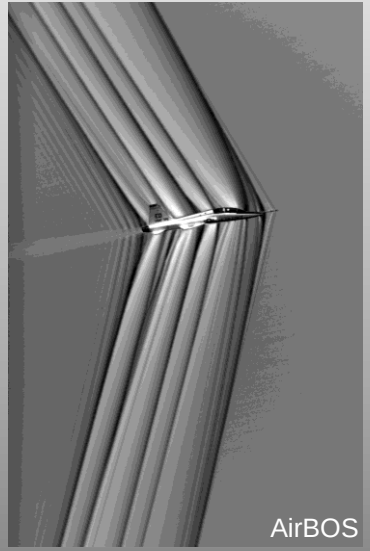
Agenda

- Introduction
- Background
- Methods
  - BOSCO
  - AirBOS
- Data processing
- Current and Near-Term Applications
  - X-59 LBFD imaging
  - Quantitative solutions
- Summary


Image Credit: Lockheed Martin


BOSCO


AirBOS

NASA Commercial Supersonic Technology

- **NASA wanted schlieren system to visualize shockwaves generated by full-size supersonic aircraft in flight**
- **Primary driver was to validate and refine shock modeling for low-boom airframe design**
  - Also provided evidence that CFD was not correctly predicting all shocks


Image Credit: Lockheed Martin

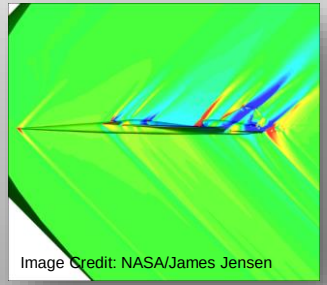
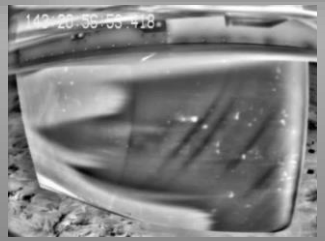
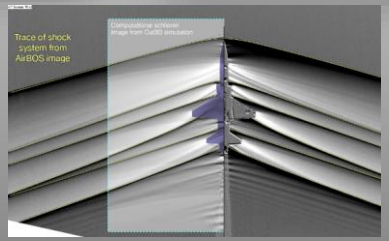


Image Credit: NASA/James Jensen

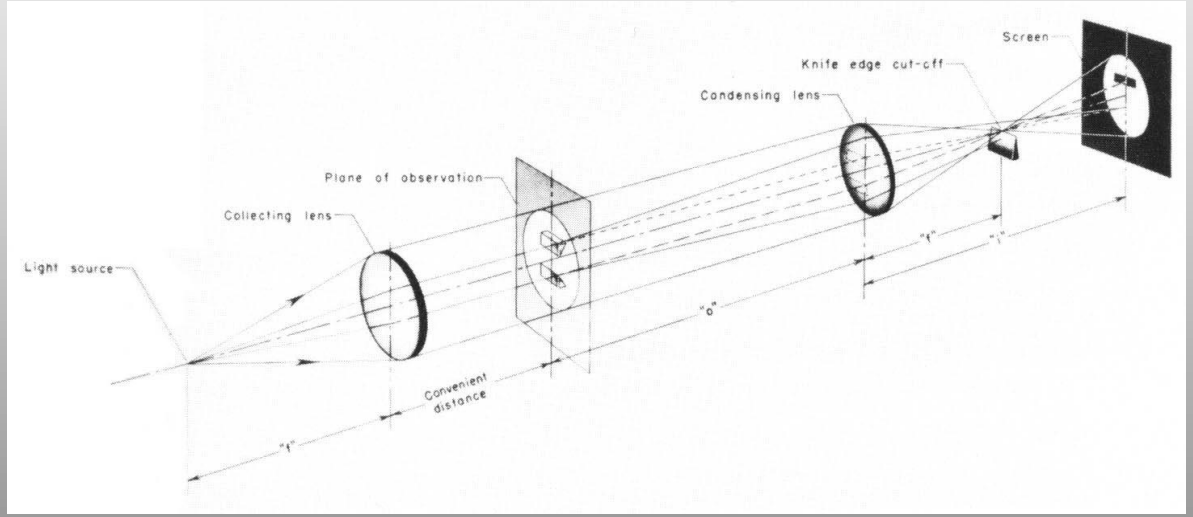

Image Credit: Lockheed Martin/NASA



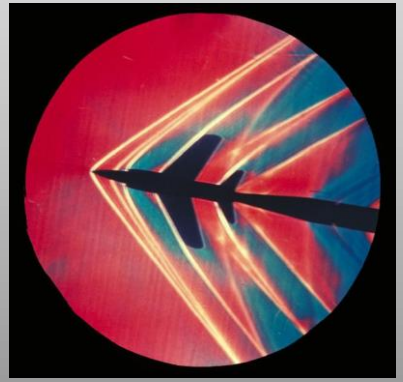


Classical Schlieren

- **Requires very precise optics and specialized light source**
  - Method derived from technique to test optics
  - Commonly used in transonic and supersonic wind tunnels
- **Would be impossible to implement in flight**

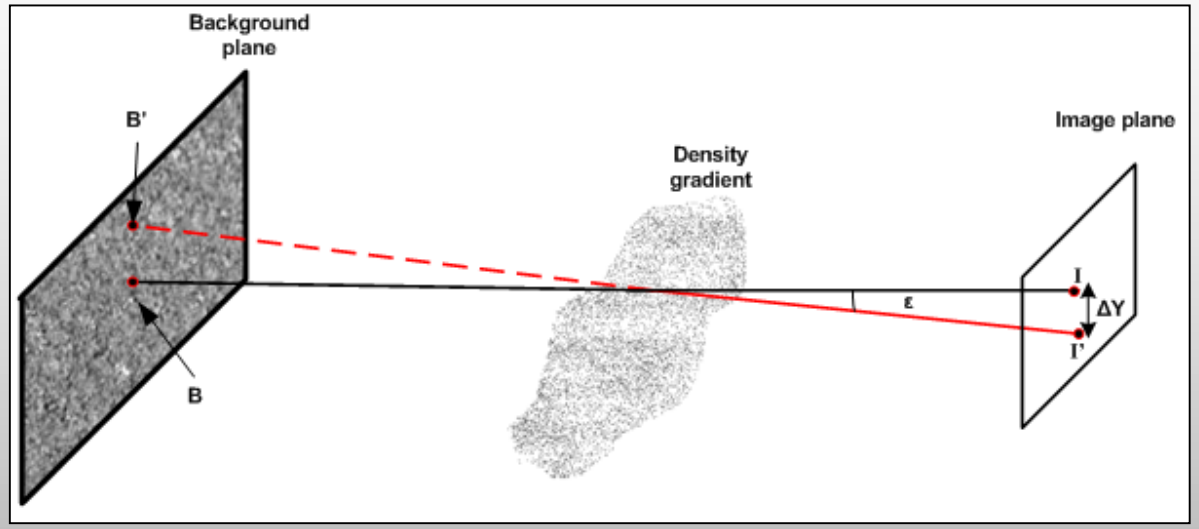


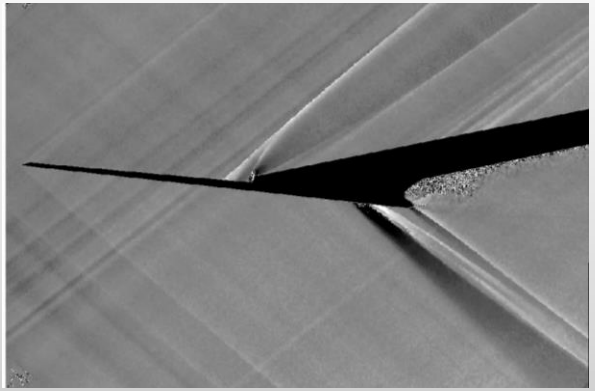
Schlieren optics layout, gradients imaged perpendicular to knife edge



Schlieren image of a wind tunnel model

Background Oriented Schlieren





BOS image of wind tunnel model

- Deduces shock waves (i.e., density gradient) by the apparent shifting of objects in the background caused by refraction of the light rays
- Image processing is used to resolve the shock waves (density gradient)

Image Processing

- Schlieren “image” is a contour plot of measured distortion caused by the refractive index gradient
- Distortion can be measured two ways, each using an undistorted image of the background compared to the distorted image of the background

Inflight Background Oriented Schlieren Flow Visualization

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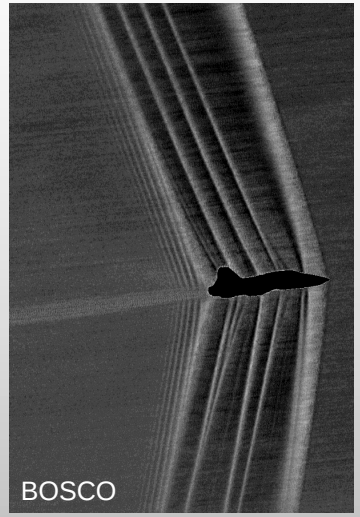
- **Background Oriented Schlieren using Celestial Objects (BOSCO)**
  - Current implementation is ground-to-air
  - Able to obtain side views 1-G level
  - 0.5 field-of-view limitation - mosaic for wider effective field of view
  - Plan for air-to-air BOSCO capability in the future
- **Air-to-air Background Oriented Schlieren (AirBOS)**
  - Downward looking, using desert vegetation or ocean speckles
  - Wide field of view, very detailed
  - Top view unless aggressive maneuvers to get side view
  - AirBOS with Simultaneous Referencing (AirBOS-SR) allows acquisition during formation flight and oblique viewing



27 Years of Schlieren – T-38 Aircraft

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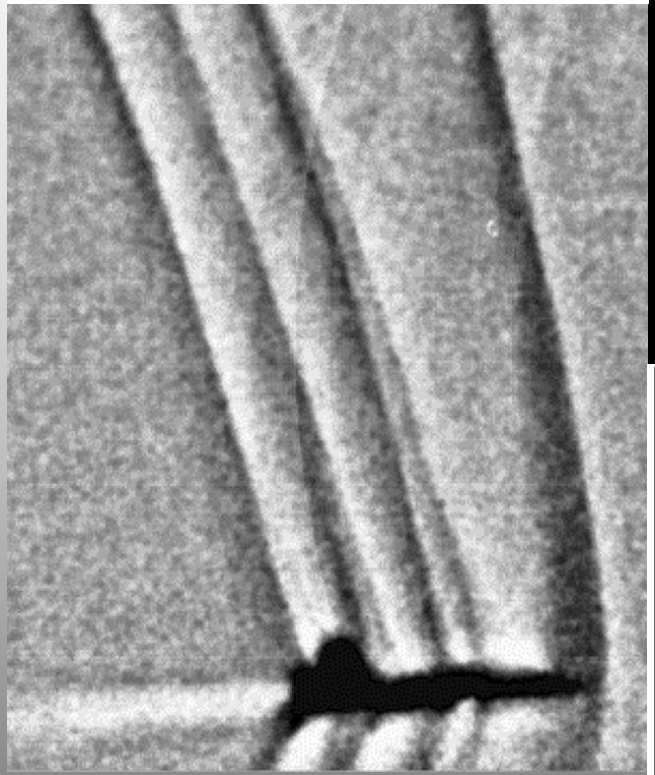
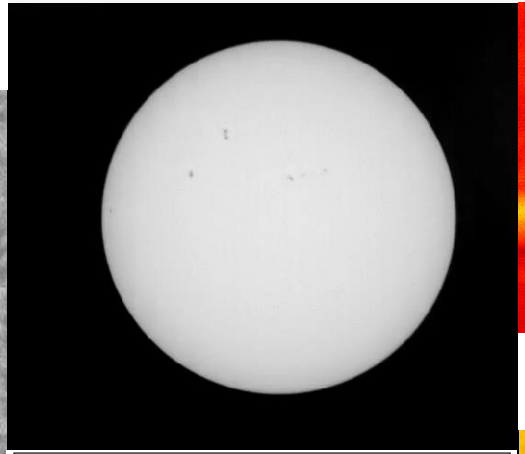
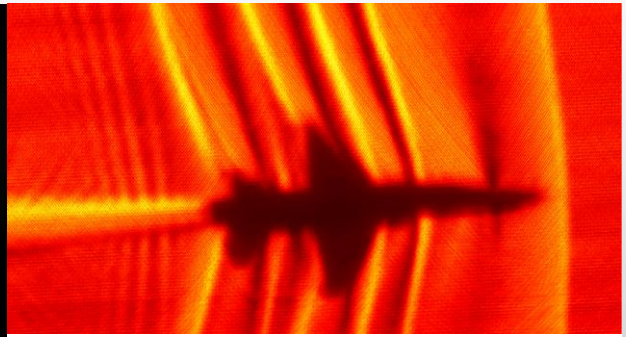
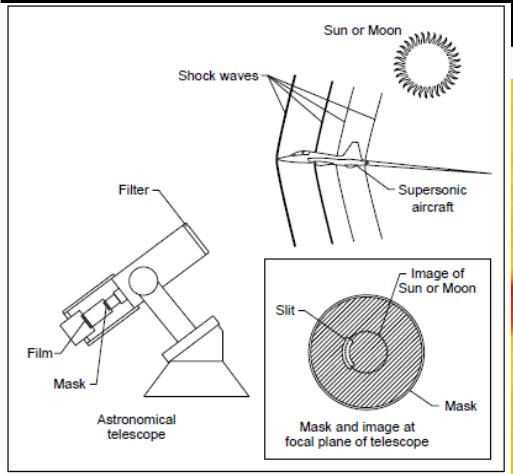
8mm movie film streak camera, physical mask, 12/13/1993, Leonard Weinstein, NASA LaRC

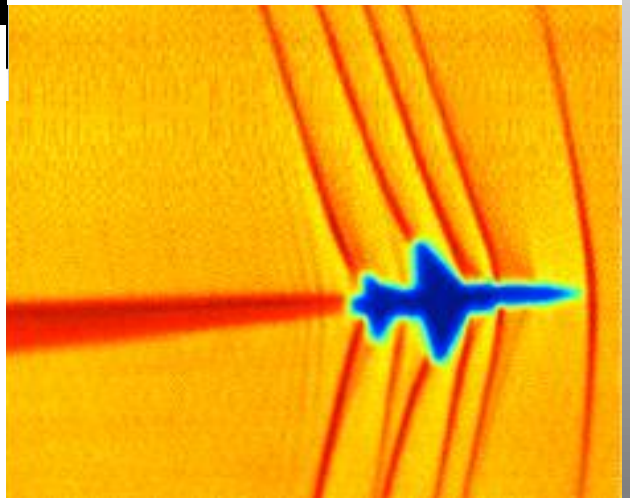






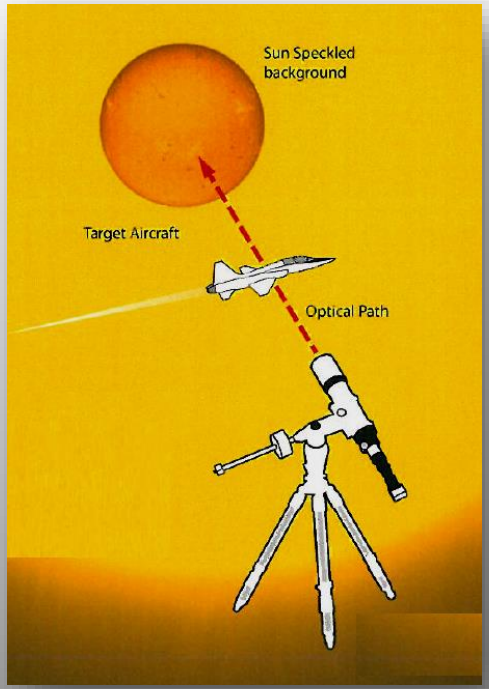
Digital image and mask, 2013-2016, NASA Armstrong algorithms

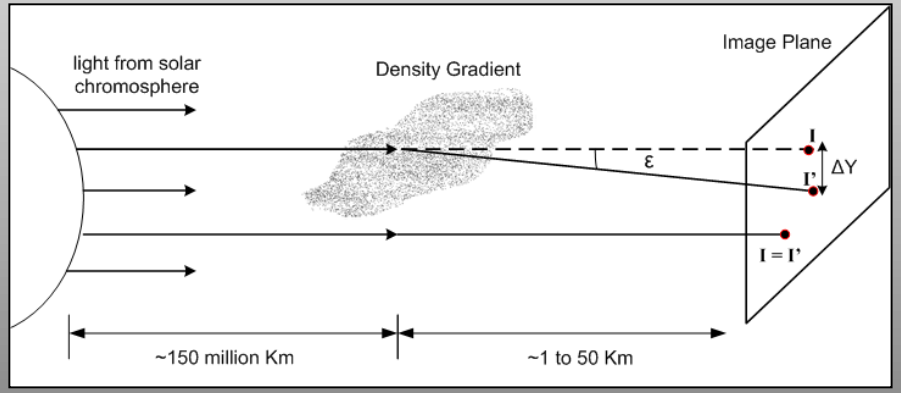




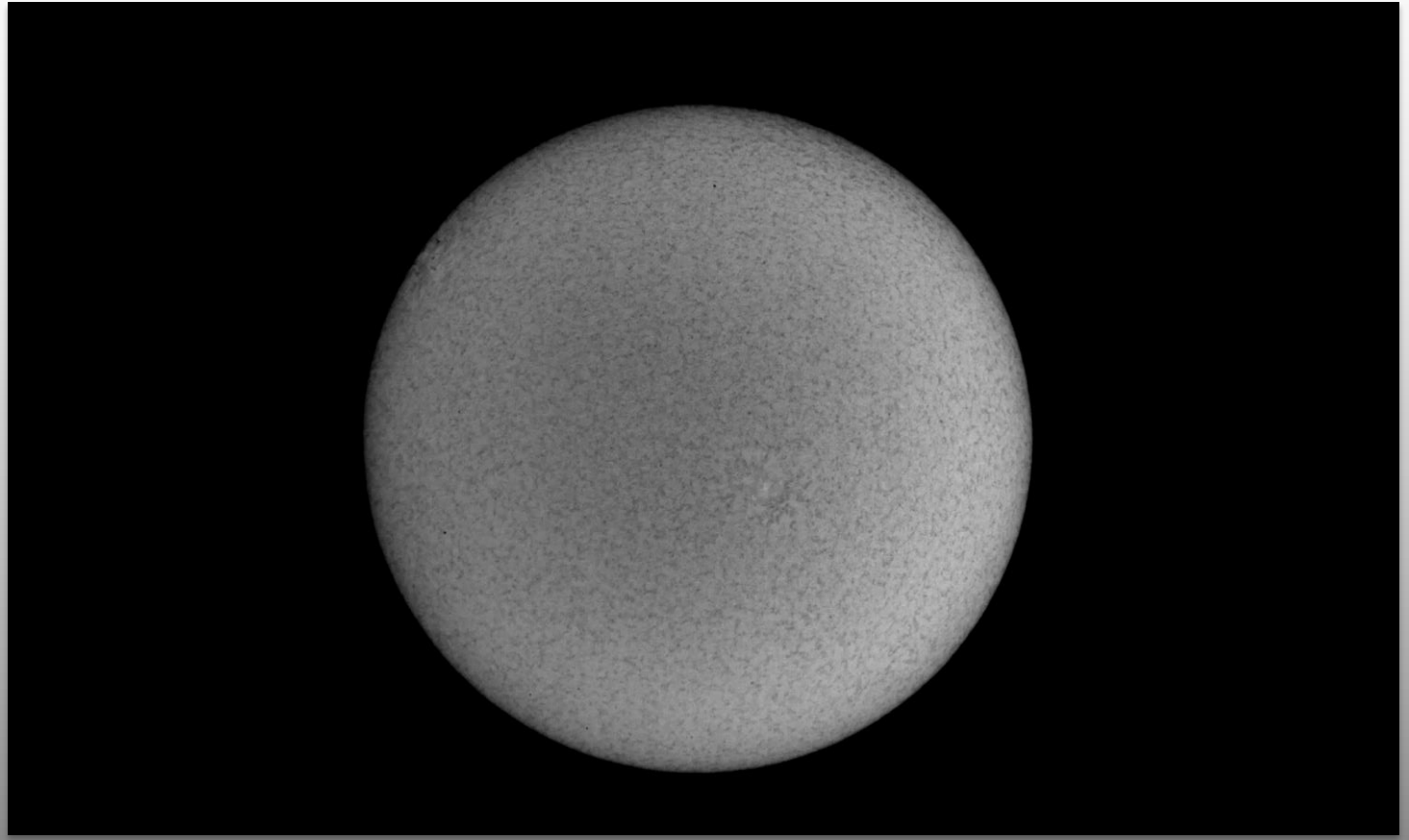
BOSCO Concept

- **Uses narrow band optical filters to give the sun a textured appearance, which allows for the BOS method**
  - α emission line of Hydrogen (H-α), ~656 nanometer wavelength
  - K emission line of Calcium (CaK), ~393 nanometer wavelength
- **Advantages**
  - Relatively inexpensive and simple
  - Ability to image from below and to the side of the target aircraft



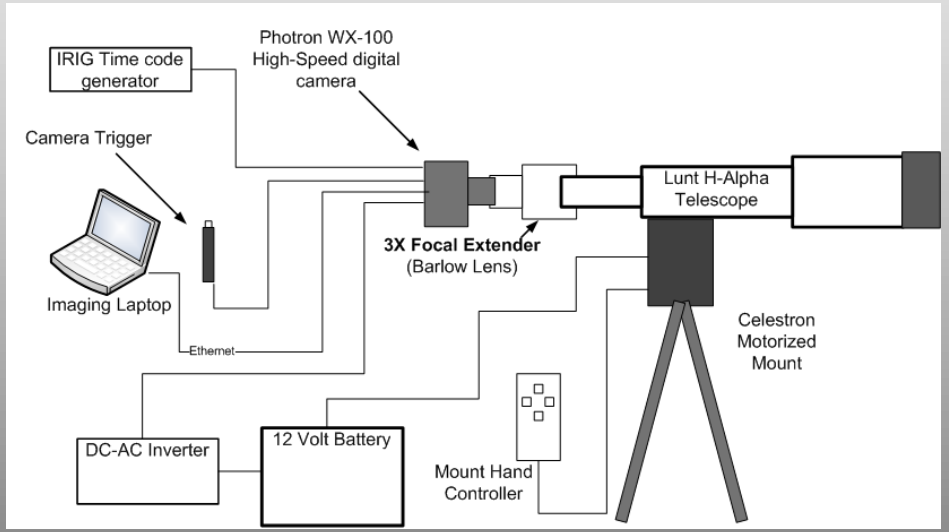


BOSCO – Phase II Raw Data



BOSCO System (H-α)

- 100 mm f/7 refractor telescope with H Alpha filter
- 3x Focal extender – Effective focal length: 2100 mm
- Photron WX-100 camera
- Manual solar tracking
- Manually triggered at pilot's "mark" call or visual eclipse

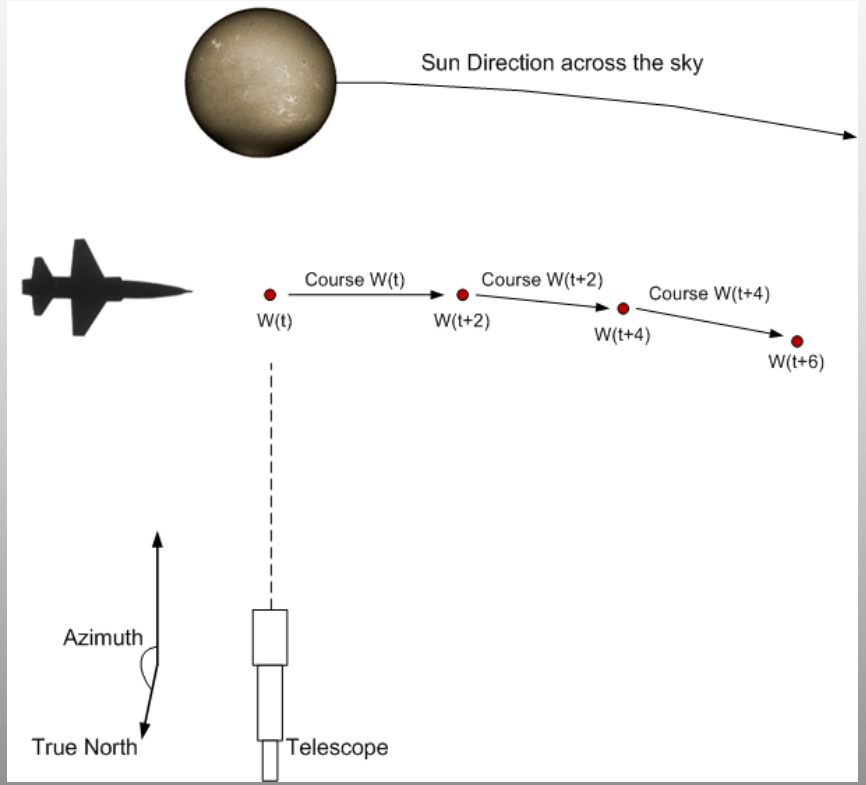


Compact Imager

Telescope Imager

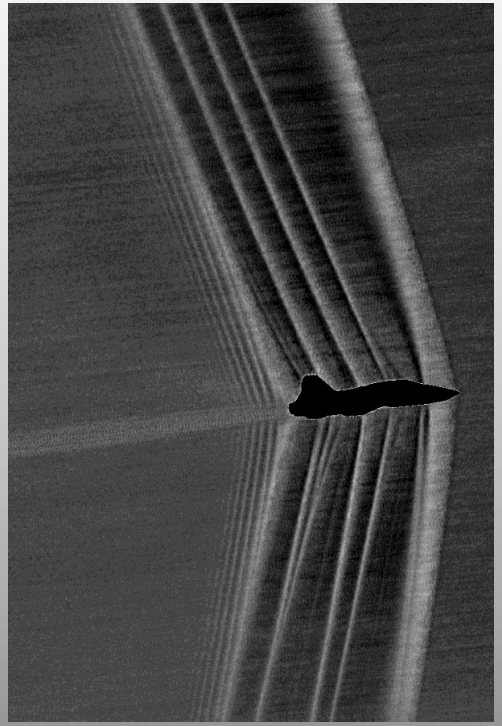
BOSCO Test Operations

- **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 way point timing:**
  - Course of the aircraft followed the sun direction across the sky
  - Flights occurred near the maximum solar elevation angle



BOSCO Results

- **Aircraft banked (60 deg) 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 Ca-K imagers, resulting in reduced resolution

AirBOSCO installed in second aircraft to allow wings-level test aircraft, test at sunrise/sunset

AirBOS Concept

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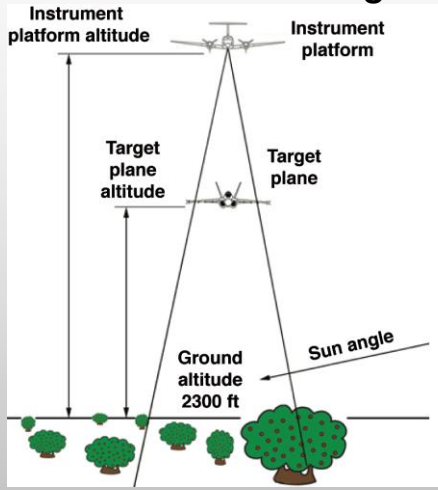
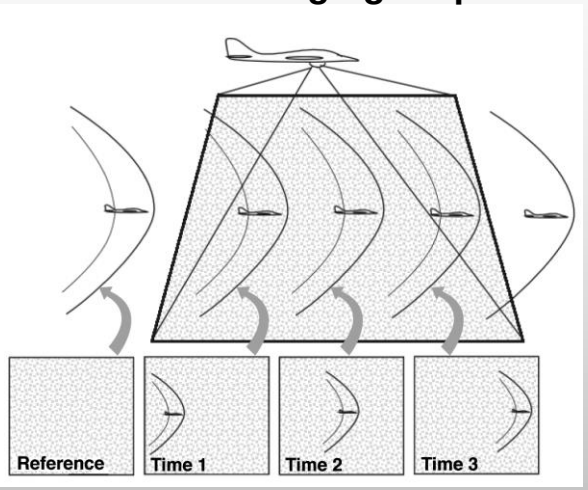
Aircraft Positioning



Imaging Sequence



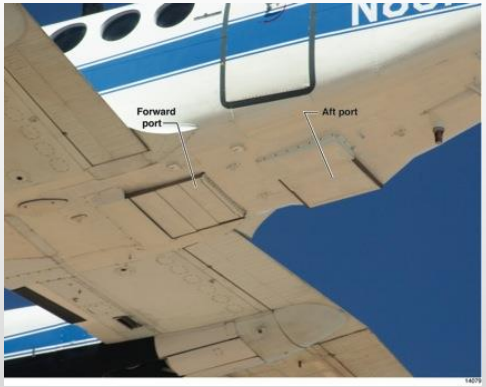
Use the flora as speckle background

Record the under-pass of target plane

Desert bush Close up

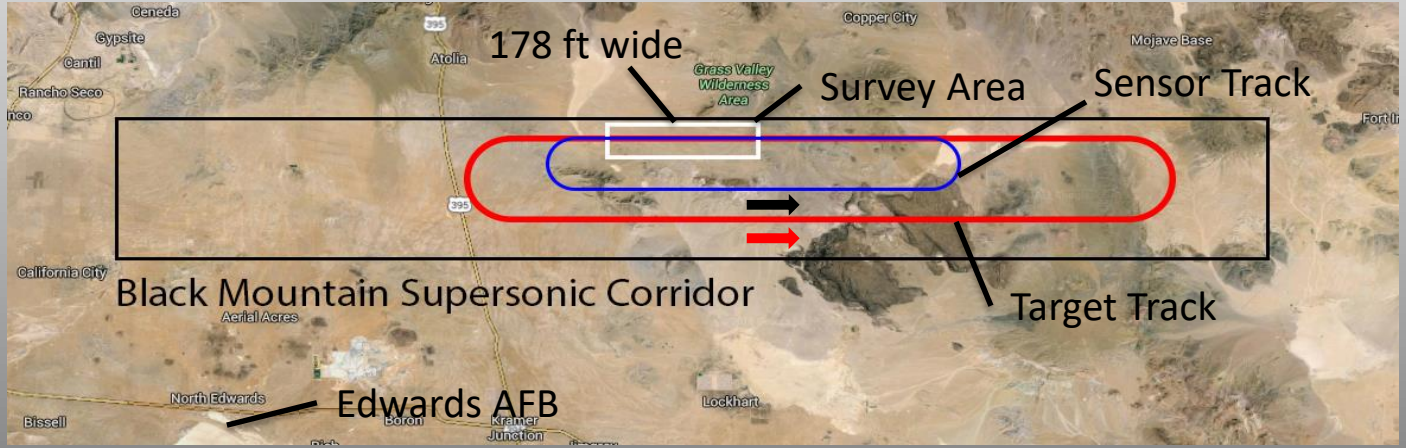
Desert bush(es) from altitude

AirBOS Operations

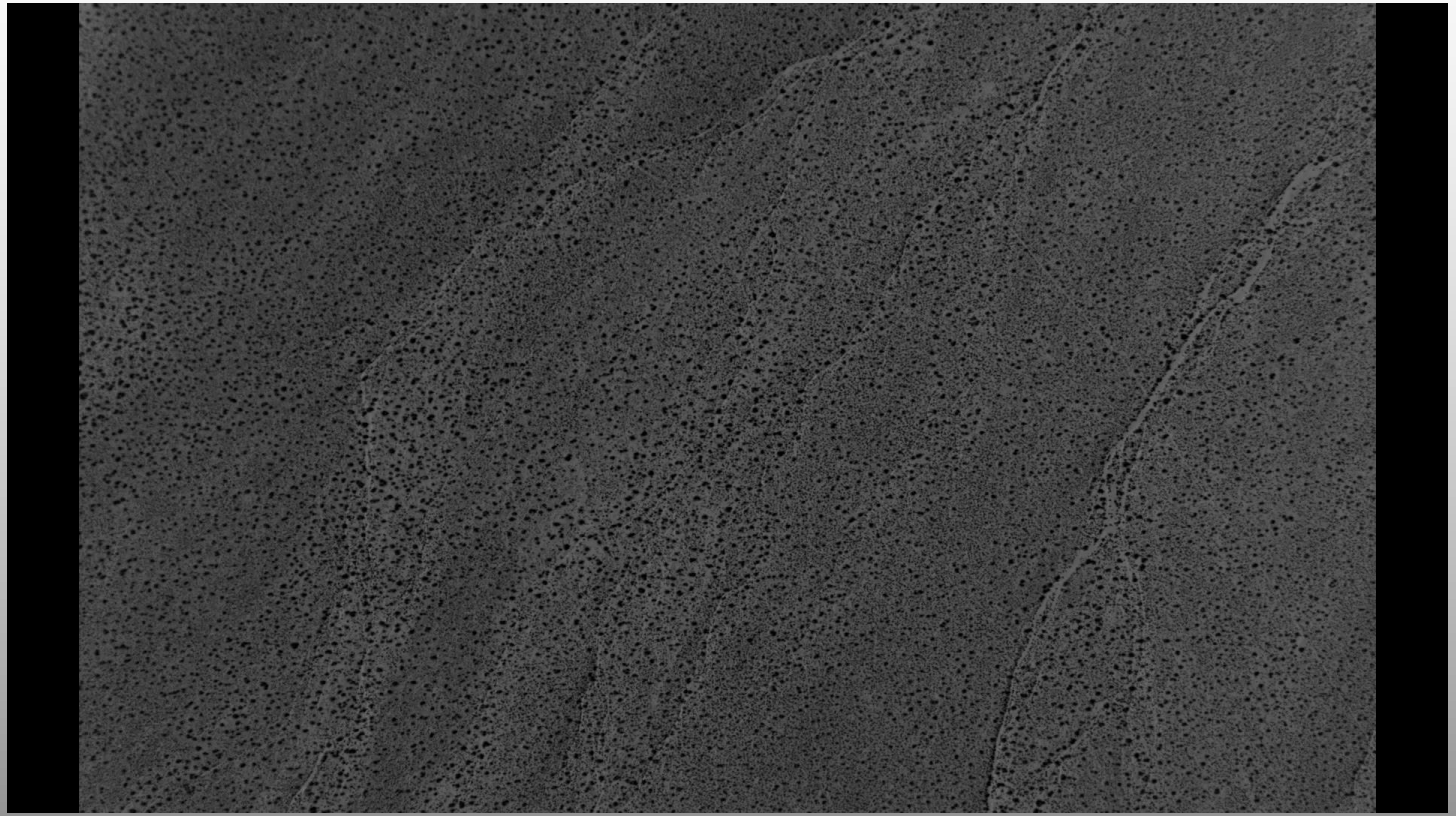


NASA Beechcraft B-200 Super King Air

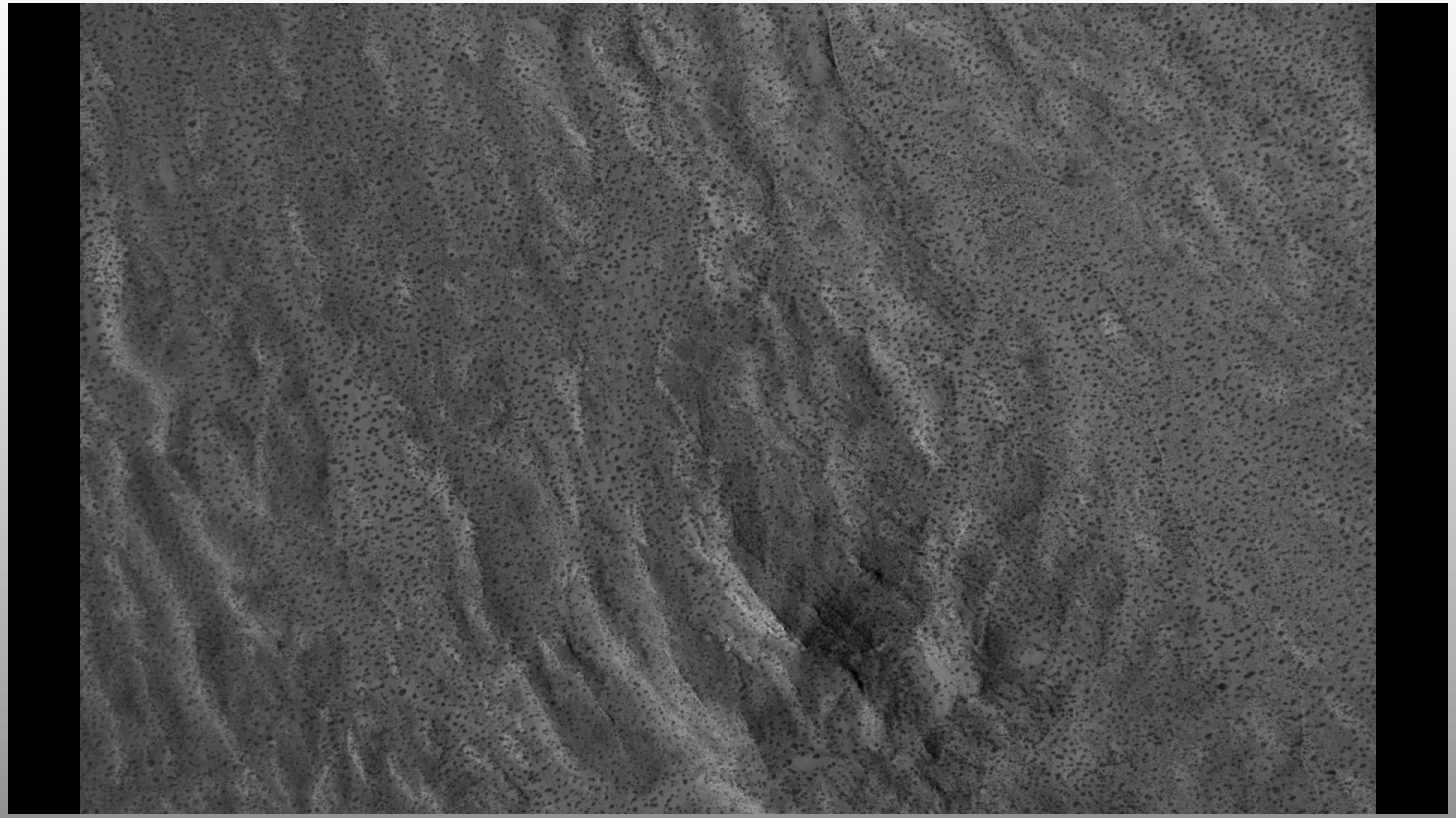
Air Force TPS T-38



AirBOS4 Results



AirBOS4 Results



AirBOS-SR Concept (Simplified)

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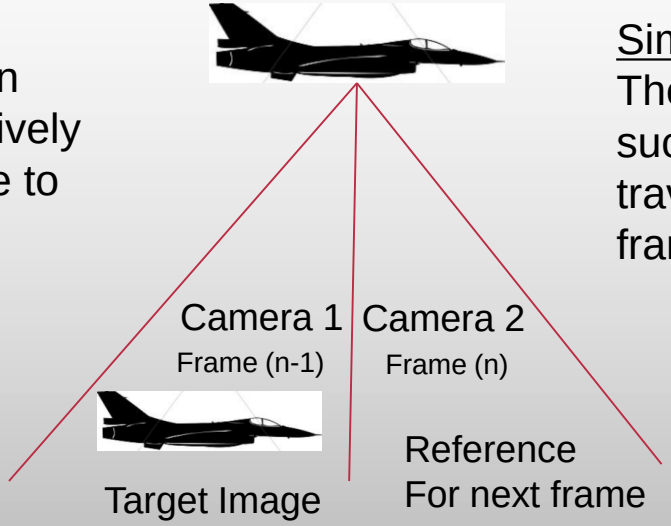
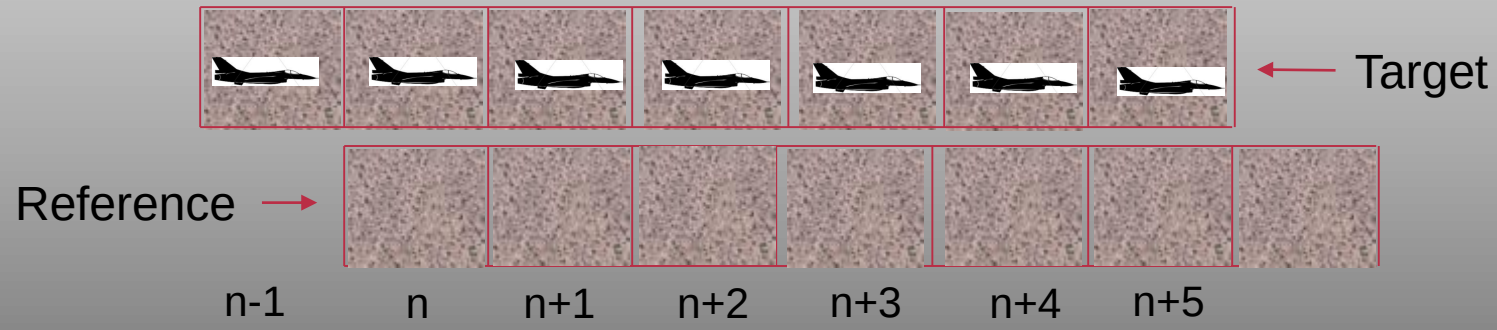
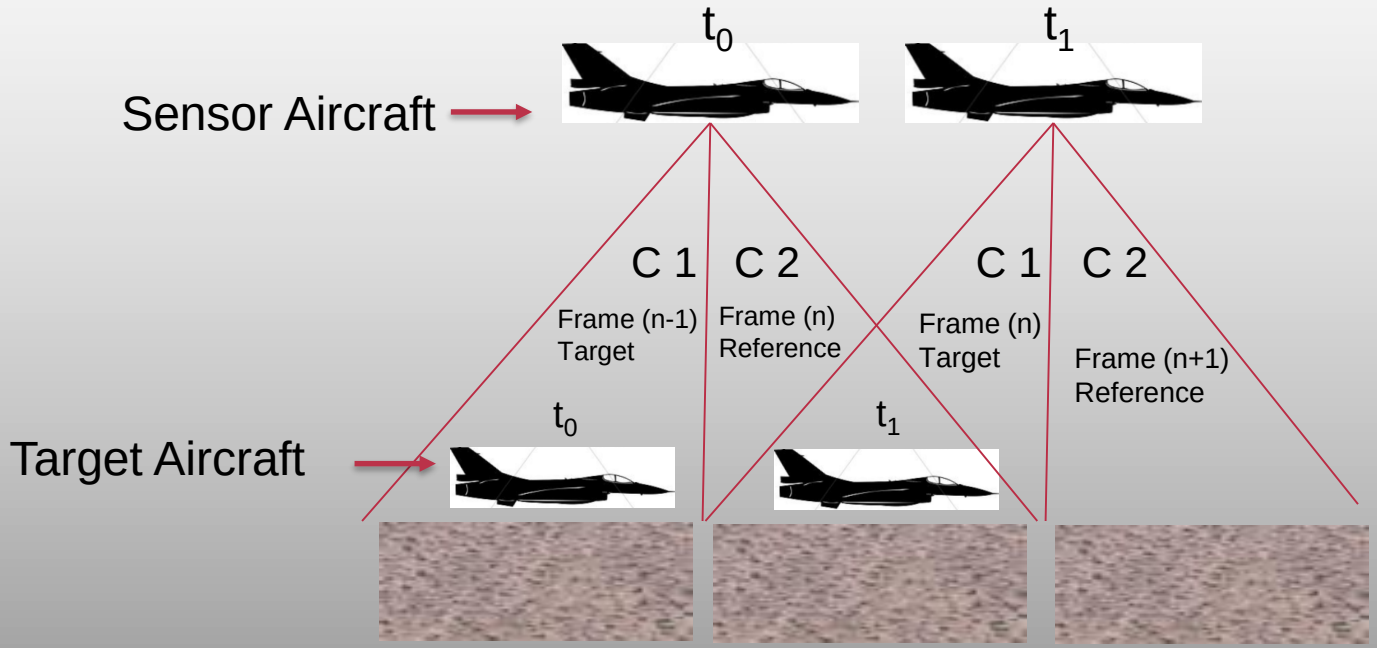
Aircraft are in formation such that there is relatively little movement relative to each other.



Simplified scenario:
The speed and frame rate are set such that the target aircraft traverses the equivalent of one frame each increment



AirBOS-SR Concept (Simplified)

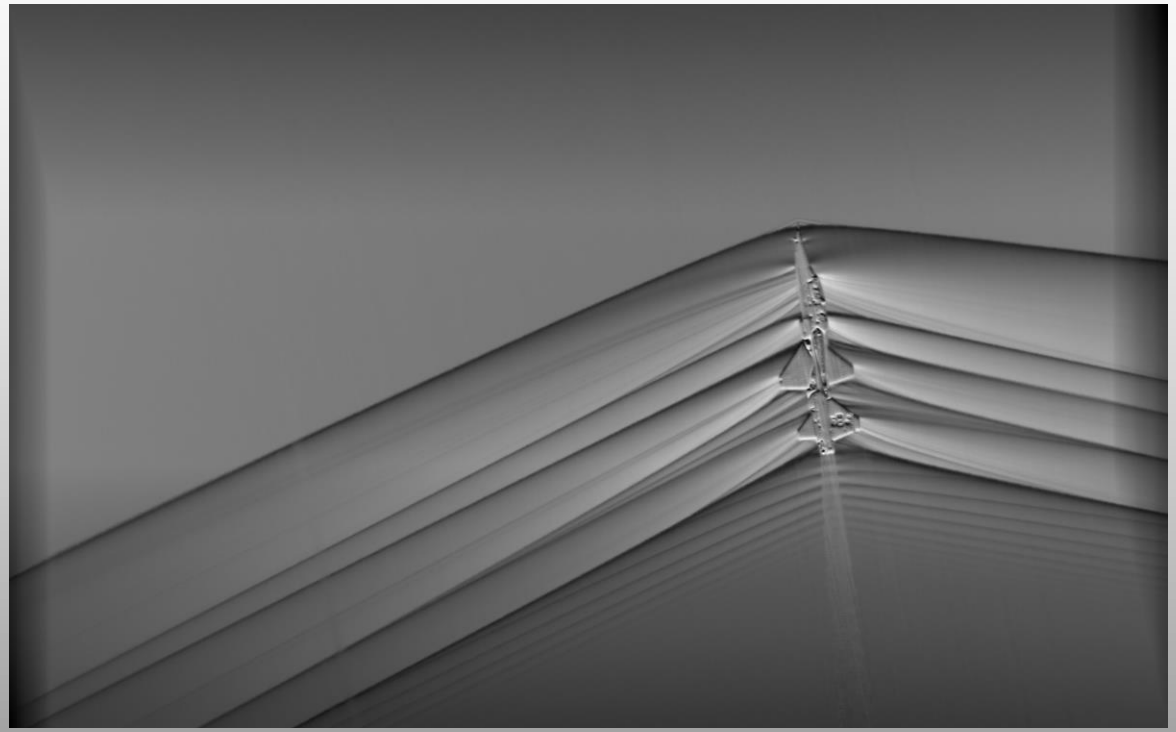


C1 = camera aft frame (or camera 1)

C2 = camera forward frame (or camera 2)

AirBOS VS AirBOS-SR

- The reference frames (10) are taken before the target enters the frame. This is the standard processing method using 10 reference frames.



Original Processing of Data Set

AirBOS-SR Simulation

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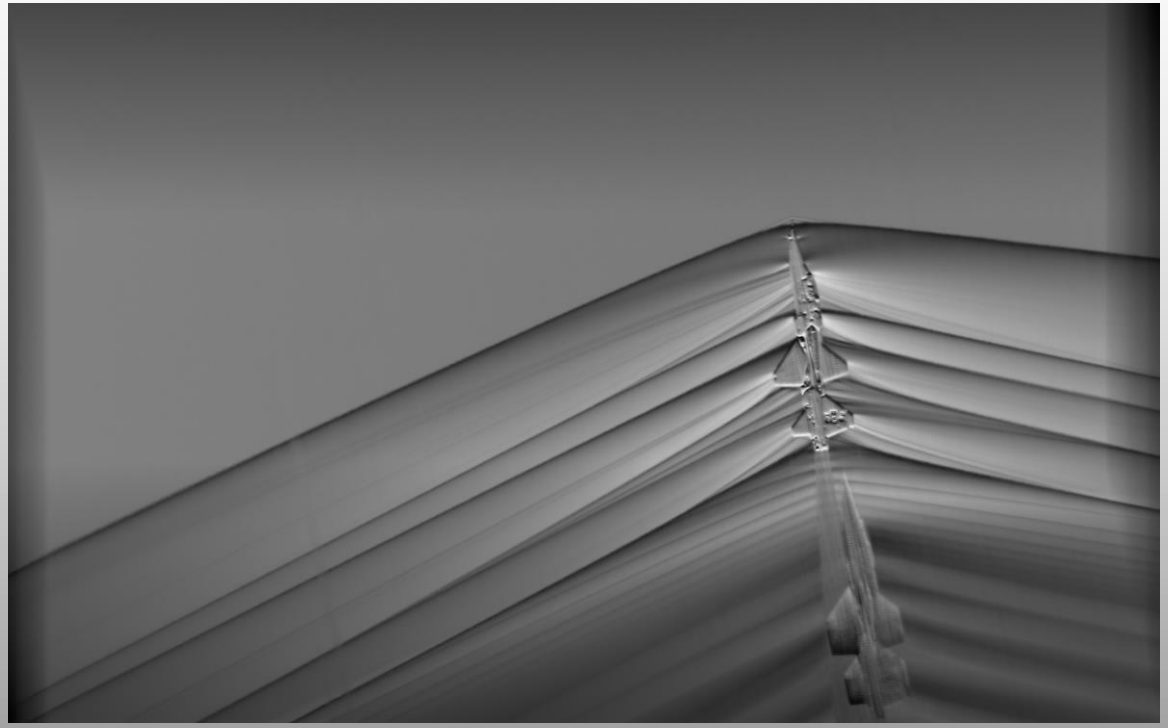
- The reference frames (10) are taken in an advancing mode although this had the aircraft in the frame which caused the ghost image.
- The “ghosting” is a figment of the simulation, but even if it did happen with AirBOS-SR the image is still well resolved forward of the ghost.

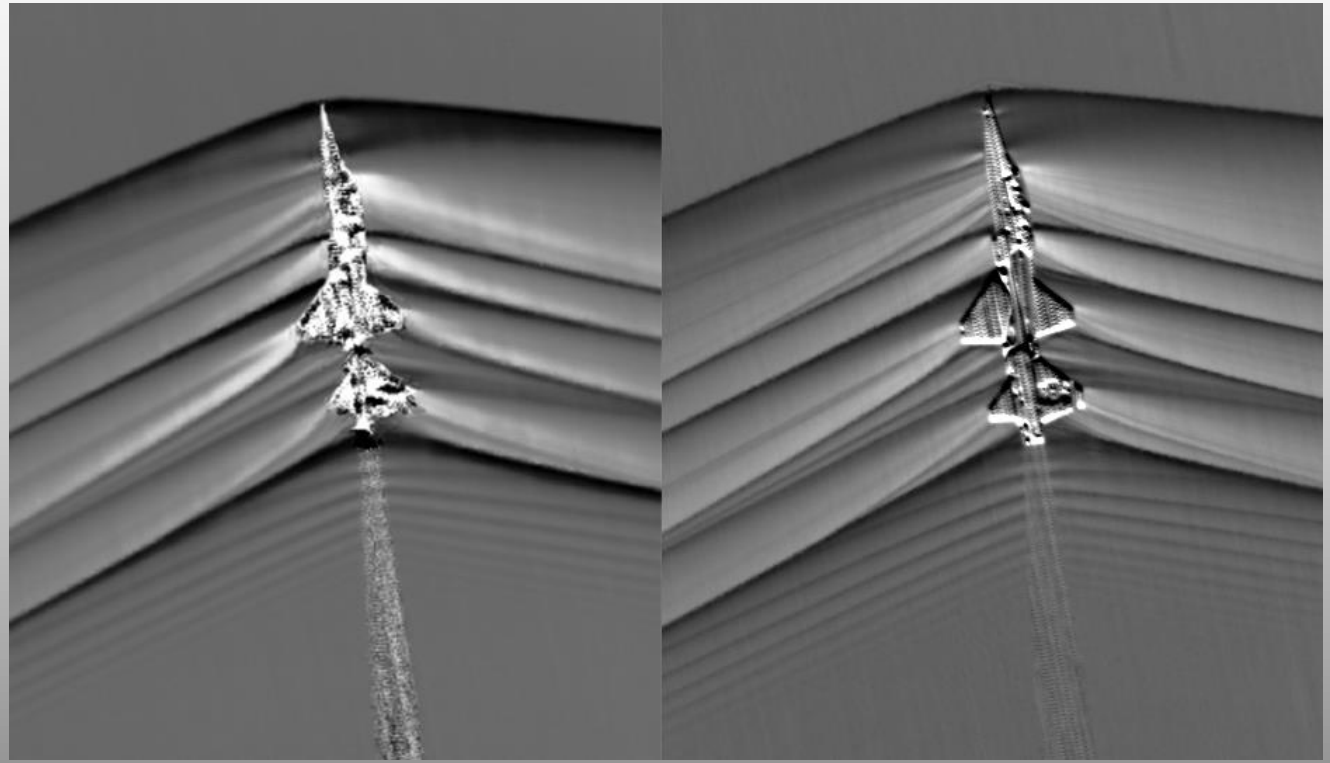


Simulation of SR Technique from Same Data Set

Image Processing

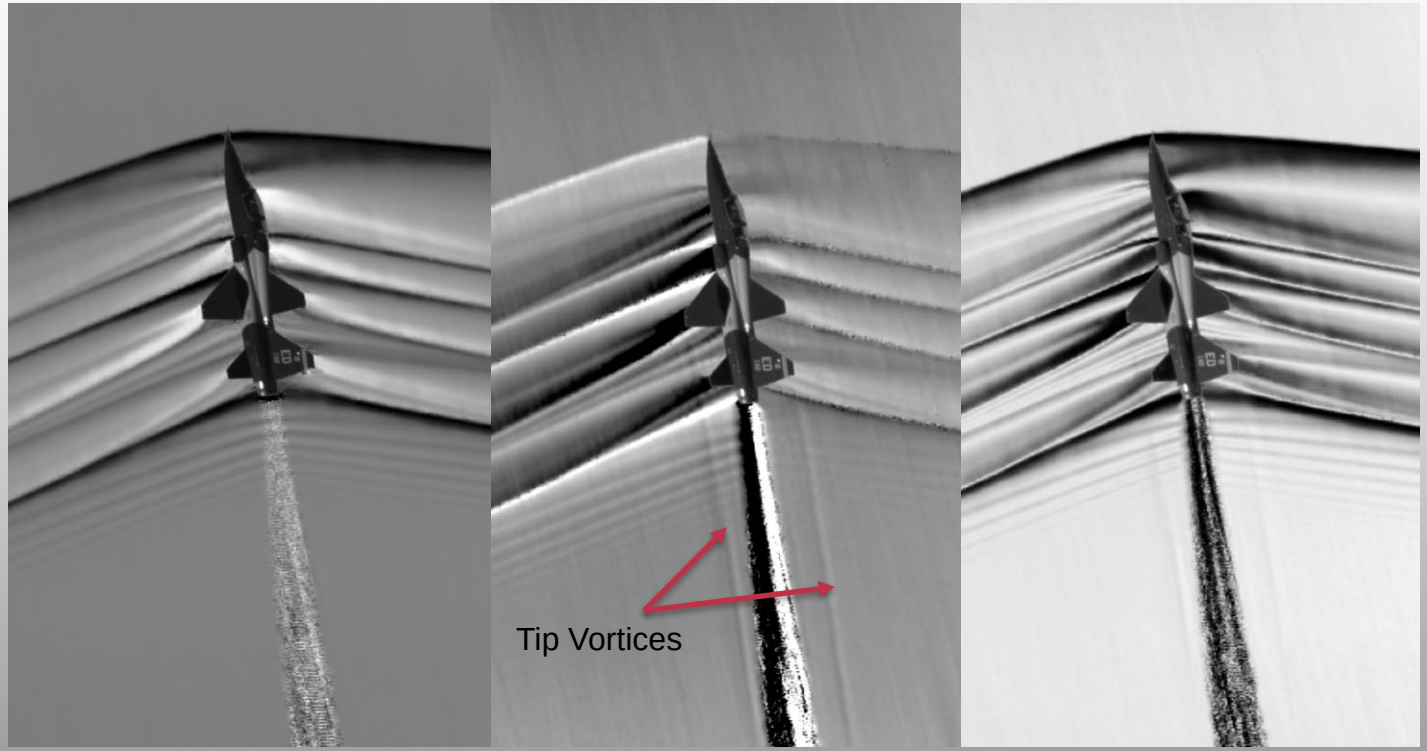
- **Commercially available packages for BOS image processing available**
  - Most use cross-correlation type algorithms
- **NASA has leaned towards optical flow type algorithms**
  - More computationally efficient
  - ARC and AFRC use in-house software packages – low level command line
  - Extra work-flow utilities allow us to do automatic registration of reference to data images, multi-reference processing, and target tracking to align the solutions

Cross Correlation v Optical Flow



Cross correlation average vs Optical flow average

Contour Plotting, the deflections in pixel units



Dy, Horizontal knife

Dx, Vertical knife

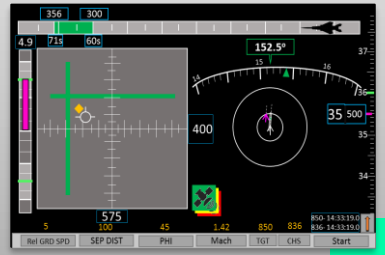
Absolute Magnitude

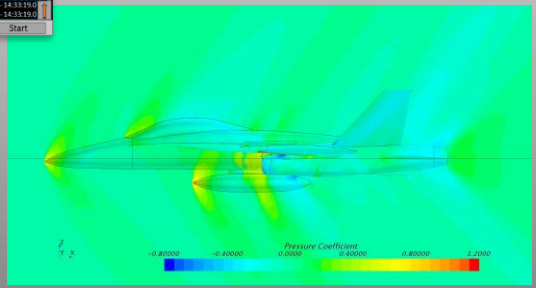
Note: Tip vortices are seen from subsonic aircraft as well

Future Work

- **LBFD (X-59) is main focus of development**
- **Air-to-air BOSCO**
  - Incorporate into Navy ATIMS5 pod
- **Oblique viewing AirBOS**
  - Incorporate into Navy ATIMS5 pod
  - Need to validate oblique viewing method
    - Passive (desert)
    - Reflective (ocean glint)
- **Quantitative schlieren**
  - Ultimately desire local pressure
  - Local density or density ratio more direct
  - Probing and CFD to close loop
  - May require tomographic imaging


Image Credit: Lockheed Martin





Summary

- **Background Oriented Schlieren (BOS)-based flight test methods have been successfully developed for both ground-to-air and air-to-air imaging of supersonic aircraft.**
- **Image processing of BOS flight images can use**
  - Traditional cross-correlation methods
  - Optical flow methods
- **Hardware and software development have thus far been targeted to support the Low Boom Flight Demo (X-59)**
  - But techniques are applicable to a wider range of aircraft and flight conditions.
- **Techniques are suitable for a wide range of applications**
  - High speed (shock waves)
  - Low speed (vortices) applications
- **Continuing research to quantify images (e.g., pressure, density)**

Questions?

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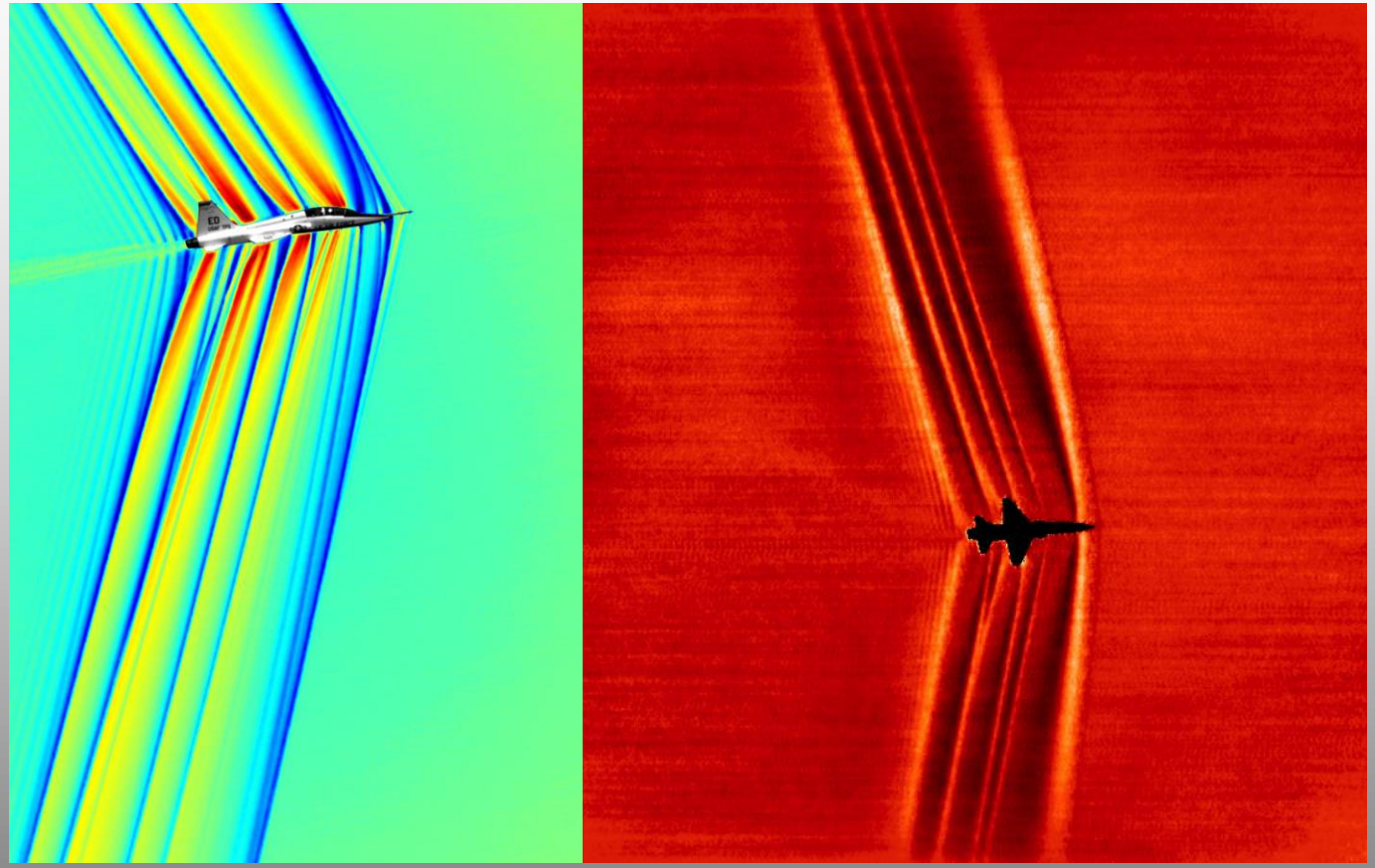

NASA Technology Transfer Portal

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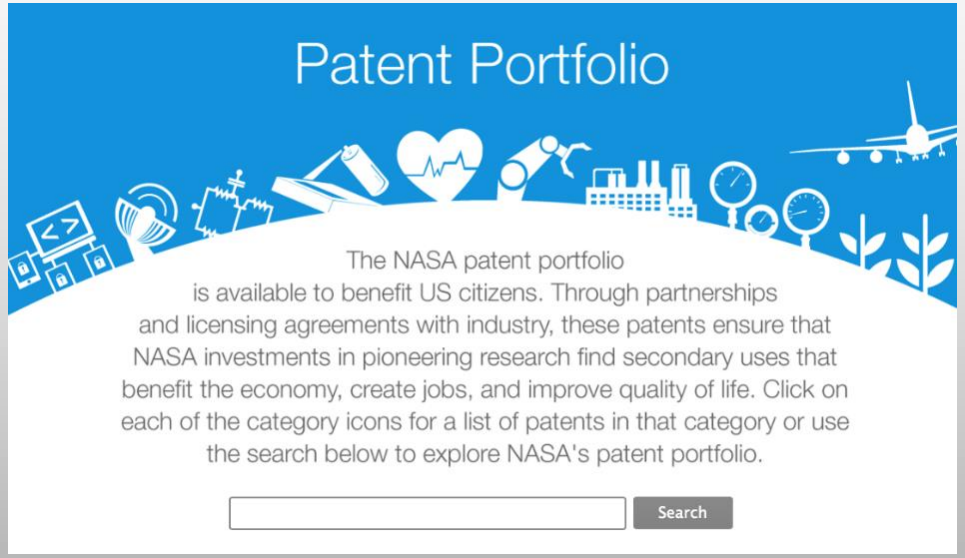

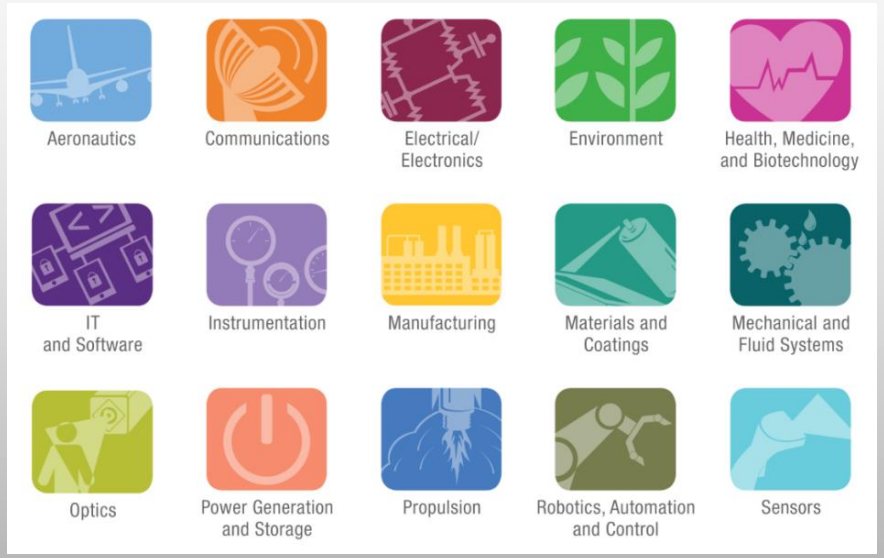

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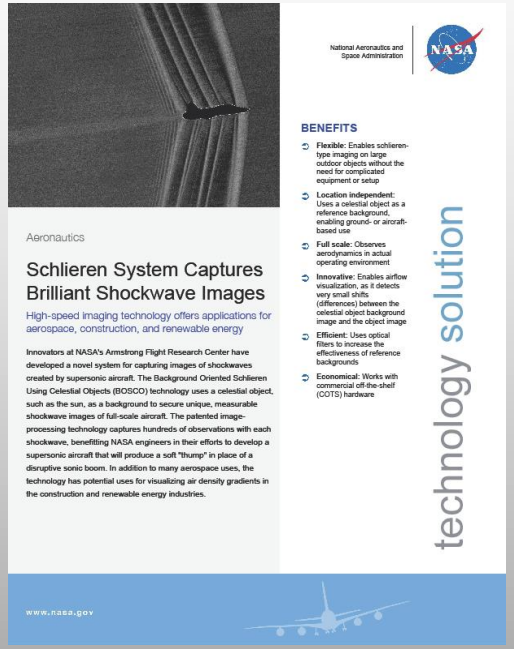
https://software.nasa.gov/



National Aeronautics and Space Administration

Aeronautics

Schlieren System Captures Brilliant Shockwave Images

High-speed imaging technology offers applications for aerospace, construction, and renewable energy

Innovators at NASA's Armstrong Flight Research Center have developed a novel system for capturing images of shockwaves created by supersonic aircraft. The Background Oriented Schlieren Using Celestial Objects (BOSCO) technology uses a celestial object, such as the sun, as a background to secure unique, measurable shockwave images of full-scale aircraft. The patented image-processing technology captures hundreds of observations with each shockwave, benefiting NASA engineers in their efforts to develop a supersonic aircraft that will produce a soft "thump" in place of a disruptive sonic boom. In addition to many aerospace uses, the technology has potential uses for visualizing air density gradients in the construction and renewable energy industries.

BENEFITS

- **Flexible:** Enables schlieren-type imaging on large outdoor objects without the need for complicated equipment or setup
- **Location independent:** Uses a celestial object as a reference background, enabling ground- or aircraft-based use
- **Full scale:** Observes aerodynamics in actual operating environment
- **Innovative:** Enables airflow visualization, as it detects very small shifts (differences) between the celestial object background image and the object image
- **Efficient:** Uses optical filters to increase the effectiveness of reference backgrounds
- **Economical:** Works with commercial off-the-shelf (COTS) hardware

technology solution

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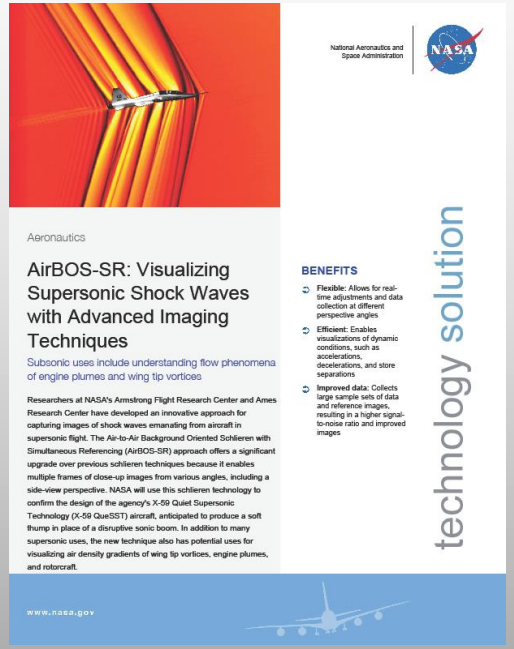

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AirBOS-SR: Visualizing Supersonic Shock Waves with Advanced Imaging Techniques

Subsonic uses include understanding flow phenomena of engine plumes and wing tip vortices

Researchers at NASA's Armstrong Flight Research Center and Ames Research Center have developed an innovative approach for capturing images of shock waves emanating from aircraft in supersonic flight. The Air-to-Air Background Oriented Schlieren with Simultaneous Referencing (AirBOS-SR) approach offers a significant upgrade over previous schlieren techniques because it enables multiple frames of close-up images from various angles, including a side-view perspective. NASA will use this schlieren technology to confirm the design of the agency's X-59 Quiet Supersonic Technology (X-59 QueSST) aircraft, anticipated to produce a soft thump in place of a disruptive sonic boom. In addition to many supersonic uses, the new technique also has potential uses for visualizing air density gradients of wing tip vortices, engine plumes, and rotorcraft.

BENEFITS

- **Flexible:** Allows for real-time adjustments and data collection at different perspective angles
- **Efficient:** Enables visualizations of dynamic conditions, such as accelerations, decelerations, and store separations
- **Improved data:** Collects large sample sets of data and reference images, resulting in a higher signal-to-noise ratio and improved images

technology solution

www.nasa.gov

BOSCO: https://technology.nasa.gov/patent/DRC-TOPS-40

AirBOS-SR: https://technology.nasa.gov/patent/DRC-TOPS-28

Questions?

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