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AN OPTICAL TECHNIQUE FOR EXAMINING AIRCRAFT SHOCK WAVE STRUCTURES IN FLIGHT

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INTRODUCTION

The detailed properties of sonic booms have to be better understood before commercial, next generation, supersonic and hypersonic aircraft can be properly developed. Experimental tests and measurements are needed to help sort the physical details of the flows at realistic test conditions. Some of these tests can be made in wind tunnels, but the need for full flight conditions simulation, the problem of tunnel wall interference, and the short distance the shocks can be examined from the aircraft, limit the usefulness of wind tunnel tests.

Previous measurement techniques for examining the flow field of aircraft in flight have included pressure measurements on the aircraft, ground based pressure measurements, and flow field measurements made with chase aircraft. Obtaining data with chase planes is a slow and difficult process, and is limited in how close it can be obtained to the test aircraft. A need clearly existed for a better technique to examine the shock structure from the plane to large distances from the plane.

A new technique has been recently developed to obtain schlieren photographs of aircraft in flight (SAF). Preliminary results have been obtained, and the technique holds promise as a tool to study the shape and approximate strength of the shock wave structure around the test aircraft, and examine shock wave details all the way from the aircraft to near the ground. The current paper describes this approach, and gives some preliminary test results.

WIND TUNNEL SCHLIEREN PHOTOGRAPH

The photograph in figure 1 was obtained with a focusing schlieren system in the 0.3 m Transonic Cryogenic Tunnel. It illustrates a failed attempt to obtain a Mach 1.2 flow field over a large shuttle model. The interaction between the body shock and the tunnel wall resulted in a partially started flow, with both supersonic and subsonic regions. This picture demonstrates the difficulty of testing reasonably large models in supersonic wind tunnels. The large amount of flow detail visible also shows the value of direct flow visualization.

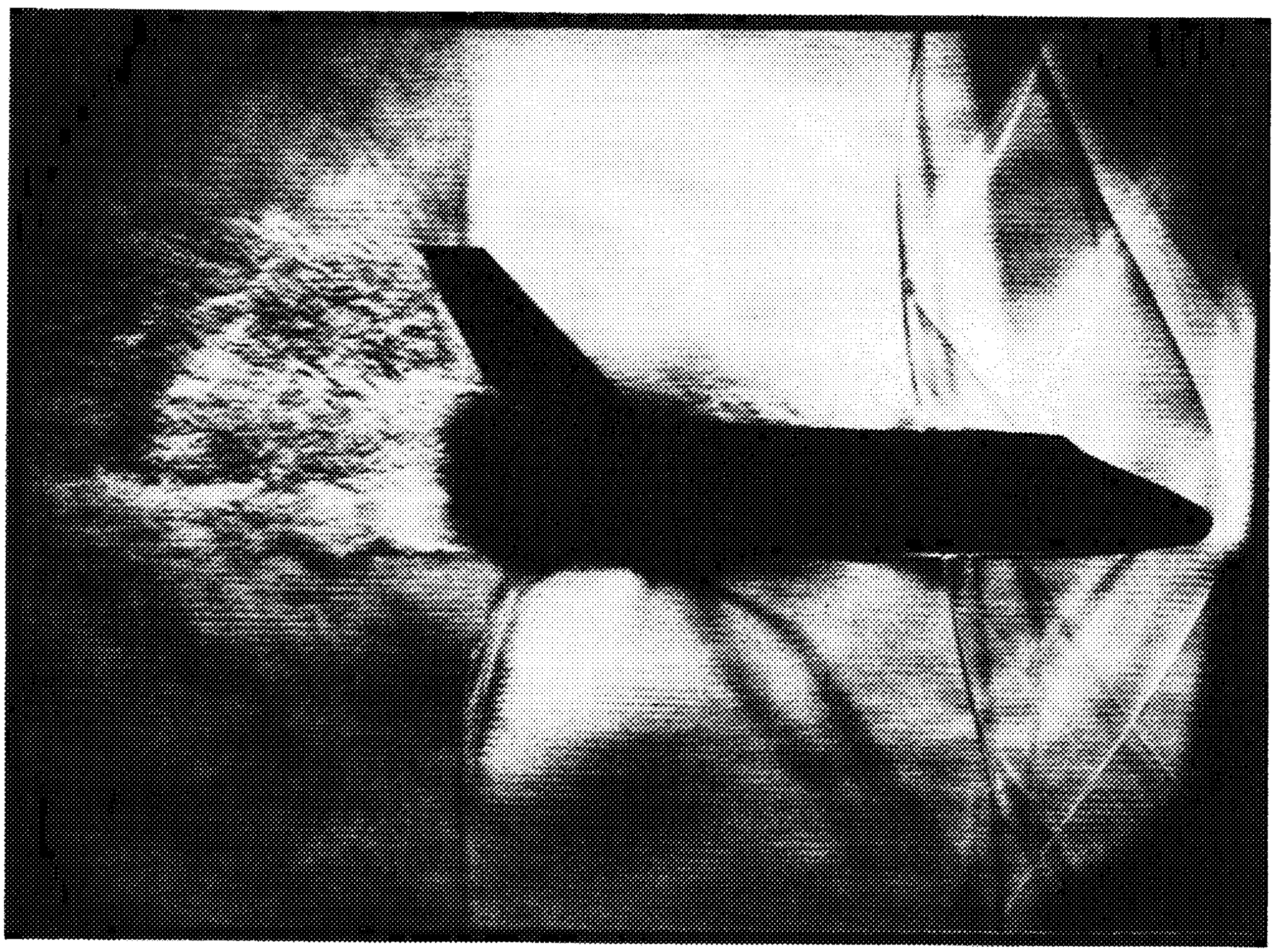

Figure 1. Focusing schlieren of shuttle model in 0.3 m TCT.

REFRACTION IMAGE OF F-111 FLOW FIELD

Figure 2 shows an F-111 flying just over Mach 1, with a non uniform background sky. The strong shock waves distort the image of the background sky by refraction, enough to displace features and make the shocks visible. The low sensitivity of this technique, and the need for the non uniform background greatly limits this direct imaging technique.

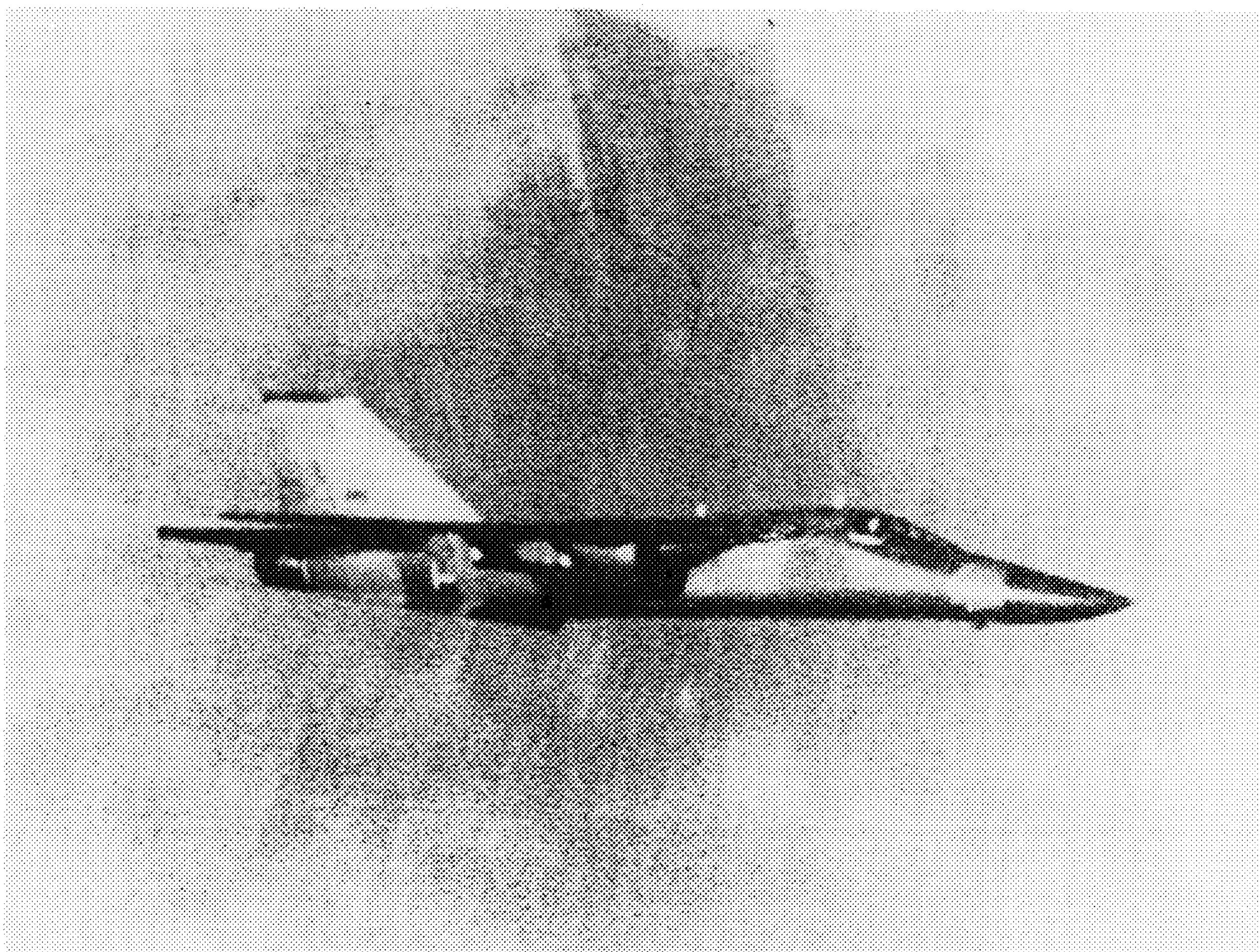

Figure 2. Refraction image of F-111 flow field

FOCUSING SCHLIEREN

The new flow visualization technique, which will be described later, uses some of the features of focusing schlieren systems. A brief description of focusing schlieren is given to help understand the new concept.

The features of a focusing schlieren system are shown in figure 3. An array of points or lines from a source grid are imaged by a camera lens. A photographic negative image of the source grid is then obtained to use as a cutoff grid. Each point on the source grid now has a corresponding "knife edge" spatial filter, and each source and cutoff point pair make an uncollimated conventional schlieren system with a very small field of view. However, the multiple sources from the source grid are selected to be close enough together so that each point on the final test section image is obtained from several source points. The net result is that a large field of view is obtained, with different parts of the source grid being used to obtain different parts of the image. The field of view is now determined by the total size of the source grid (rather than lens diameter).

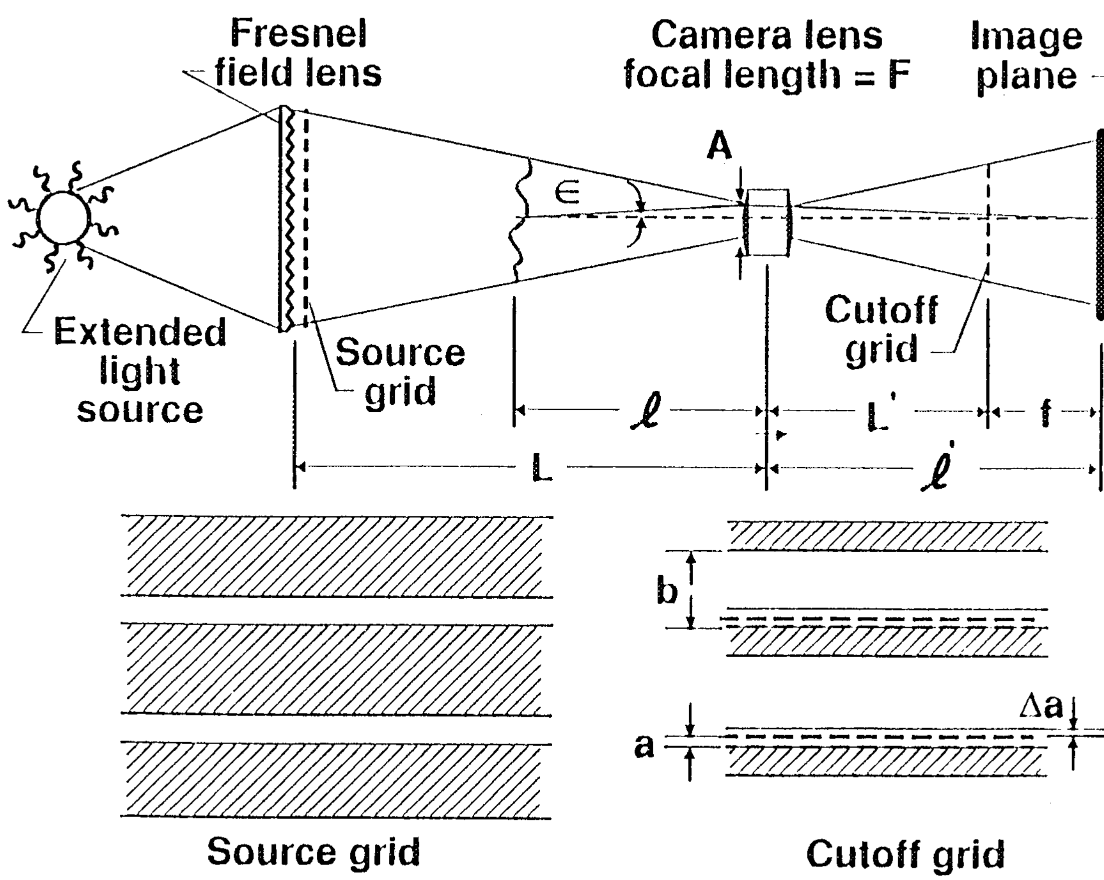

Figure 3. Details of Focusing schlieren system.

SCHLIEREN FOR AIRCRAFT IN FLIGHT SETUP

The schlieren for aircraft in flight (SAF) was developed by combining some of the features of astronomical photography with focusing schlieren and streak photography. The setup used is shown in figure 4. A telescope is used to track the sun (or moon) so that the image is stationary at the focus. A neutral filter is used to lower intensity to a safe level. An opaque mask with a narrow curved slit is positioned to block all but a thin portion of the edge of the sun and a small region of sky next to the edge. A thin region at the edge of the sun is thus the light source, and the mask is the cutoff, for a single curved grid line as in a focusing schlieren system. An aircraft is flow through a field of view crossing this sliver of light, and the aircraft image is sharply focused on to a film plane. The film is moved to follow the aircraft image movement. A narrow slice of a schlieren image of the aircraft flow field is formed at each instant of time, and over the full exposure this slice is scanned along the image. This produces a composite streak camera schlieren image of the flow field examined.

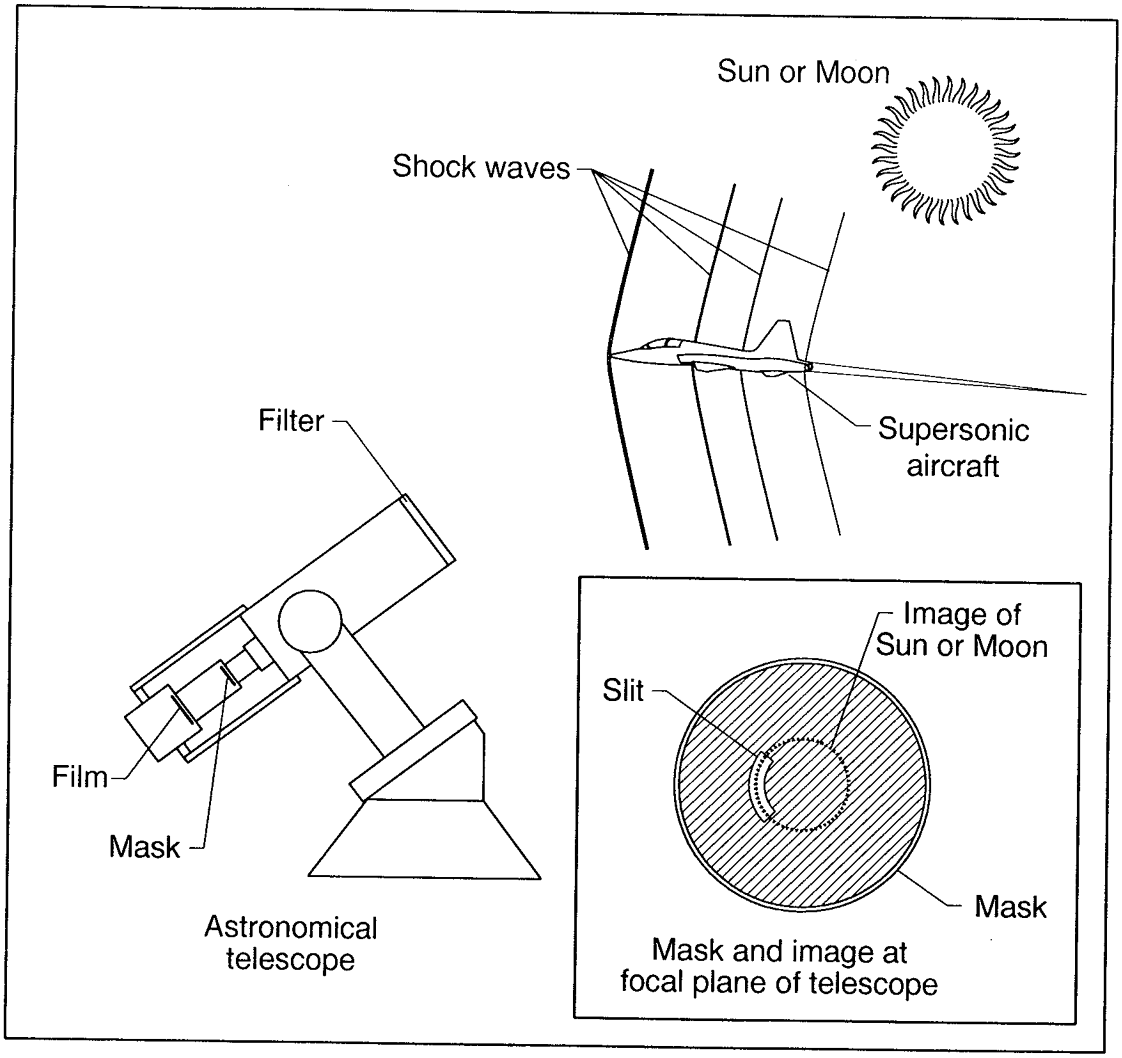

Figure 4. Setup of schlieren for aircraft in flight.

RESOLUTION AND FIELD OF VIEW FOR SAF

The maximum possible resolution of detail in images is affected by several factors. The maximum resolution (diffraction limit) of a telescope is determined by the telescope aperture. In addition, the atmospheric turbulence, accuracy of focus, tracking accuracy during exposure, and film limitations may result in less than diffraction limited resolution. Unless the telescope is on a high mountain, or in a chase plane, the daytime atmospheric limited resolution is seldom better than 1 arcsec, and more often closer to 2 arcsec. To prevent significant additional limitation due to the telescope, a telescope of at least 5 inch aperture is desired (which can approach 1 arcsec resolution with near diffraction limited performance). For the following table, a net image resolution of 2 arcsec was assumed for all causes combined.

The field of view photographed is the physical height at the aircraft distance corresponding to the angle of the portion of the sun used for a grid line. The sun covers slightly over 1/2 degree, and about 1/3 degree is used for the grid line in SAF. This angle was used to compute the field of view in the table.

Table I. Resolution and Field of View as a Function of Slant Range

SLANT RANGE (ft.)	(for 2 arcsec) RESOLUTION (inches)	(for 1/3 deg) FIELD OF VIEW (ft.)
8,000	0.9	46
16,000	1.9	92
32,000	3.7	184
64,000	7.4	368
128,000	14.9	736

PHOTOGRAPH OF SETUP AT WALLOPS FLIGHT FACILITY

The prototype system used to demonstrate the SAF concept used an 8 inch aperture, f/10 telescope, which was large enough to carry a reasonable amount of equipment, and was still small enough to carry around and set up easily.

The SAF system was carried to Wallops Flight Facility and set on the end of a runway. Figure 5 shows the system set up for the initial effort. Several tests flights were made with a T-38 at M=0.9 (but with supersonic flow over the wings) at a slant range of 16,000 ft., to try and photograph the flow field at high resolution. The flights were required to be subsonic for these tests since they were made over land. The field of view was only 46 ft. at that range. A combination of clouds, equipment problems, and the difficulty of passing through this small area prevented success in the early flights.

Figure 5. SAF set up on runway at Wallops.

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

SAF OF T-38 AT 32,000 FT. AND M=1.1

The aircraft range was increased to 32,000 ft. and the plane was flown fully supersonic for additional tests. This resulted in a 92 ft. field of view, and a large extent of supersonic flow. Assateague island (close to Wallops) was selected as the site to set up the SAF equipment. This location was used because the supersonic flights had to be made over water, 5 miles away from land, to prevent sonic booms from bothering people.

At 10:30 a.m.on Dec. 13, 1993, the T-38 was flown at M=1.1 at an altitude of 13,700 ft. This resulted in a 32,000 ft. slant range from the camera. The Wallops ILS system was used to guide the plane through the test area. The photo shown in figure 6 was the first SAF photo of the T-38 flow field.

The image is very grainy because of the film used for the preliminary test. In addition, the relay lens used to reimage the aircraft onto the film was not well corrected except near the center of the image. Since the plane was near the edge of the field of view, the image was noticeably less sharp around the plane. In addition, some banding (curved streaks due to uneven film motion) resulted in uneven exposure of the image. Even with these limitations, the image clearly showed the shock wave details. About one plane length above the aircraft, 6 shocks are seen to merge into 4.

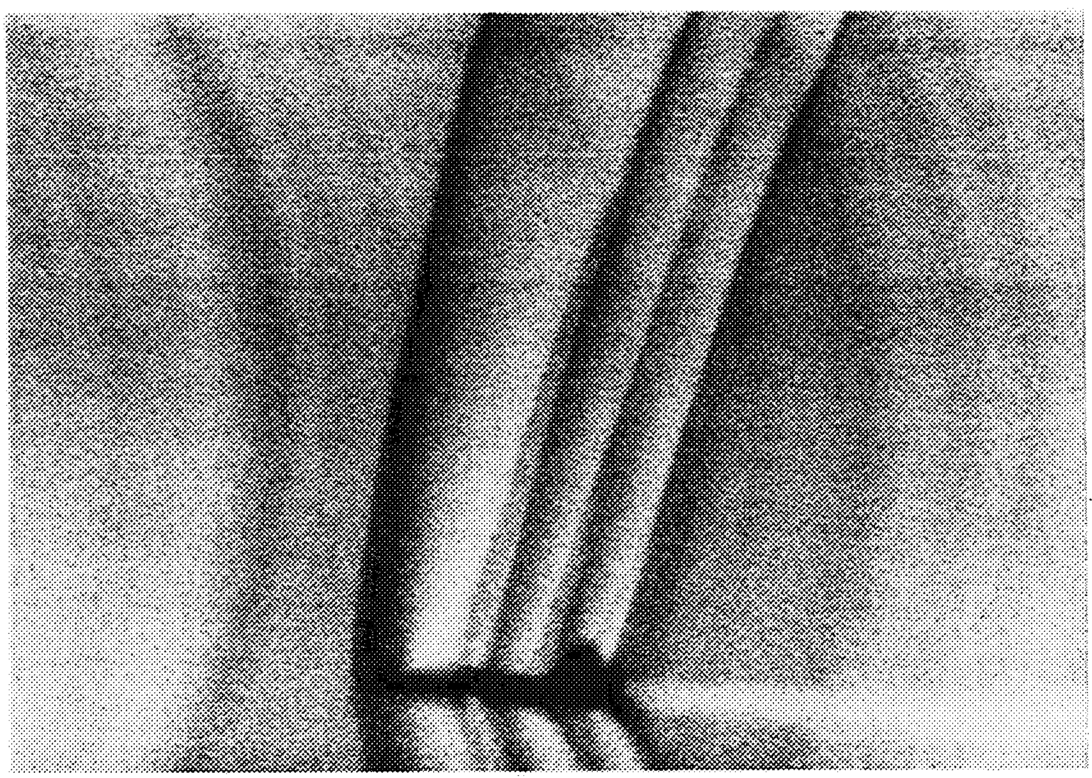

Figure 6. SAF of T-38 at 32,000 ft. slant range and M=1.1.

USE OF SAF TO STUDY SONIC BOOMS

The demonstration of SAF as a tool to examine the flow field of aircraft in flight led to the possibility of using it as part of a sonic boom study. A joint cooperative effort was initiated at Langley to evaluate the possible use of SAF to examine both near and far field shock structure for aircraft used in these studies.

A shock wave system weakens as it moves away from a supersonic aircraft, and the shock system also distorts as it moves through local variations in the atmosphere. In addition, the aircraft used in sonic boom studies are generally flown at significantly higher altitudes than the T-38 flight was. This means that lower atmospheric densities are encountered, and the resolution is reduced for more distant subjects. The SAF system was taken out to Dryden Flight Facility to evaluate these effects, and see if limitation would be encountered.

Modifications were made to overcome some of the problems encountered in the Wallops test. A finer grain film was selected to cut graininess. The relay optical system was modified to obtain better sharpness on the outer part of the image. The film used was also selected to have higher contrast, to increase sensitivity. This last feature also made the "banding" much worse, but it was thought this would not prevent evaluation of the performance, even though it would make bad looking pictures.

The need to fly at fairly large altitudes combined with the desire to keep slant range reasonably small, and the need for the atmosphere to be as undisturbed as possible, constrained the flights to mid morning.

CONVENTIONAL PHOTOGRAPH OF F-18 IN FLIGHT

F-18's were selected to do the SAF evaluation flight tests at Dryden. This aircraft was easily capable of reaching the desired mach number and altitude desired, and was available for the test. Figure 7 shows a conventional photograph of an F-18 in flight to show details of the aircraft.

Figure 7. Conventional photograph of F-18 in flight.

GALILEO HILL

The SAF system was set up on the peak of Galileo Hill in California City. This is close to Dryden, and was in a good location to obtain SAF pictures. Figure 8 shows the hill, which is about 700 ft taller than the surrounding area.

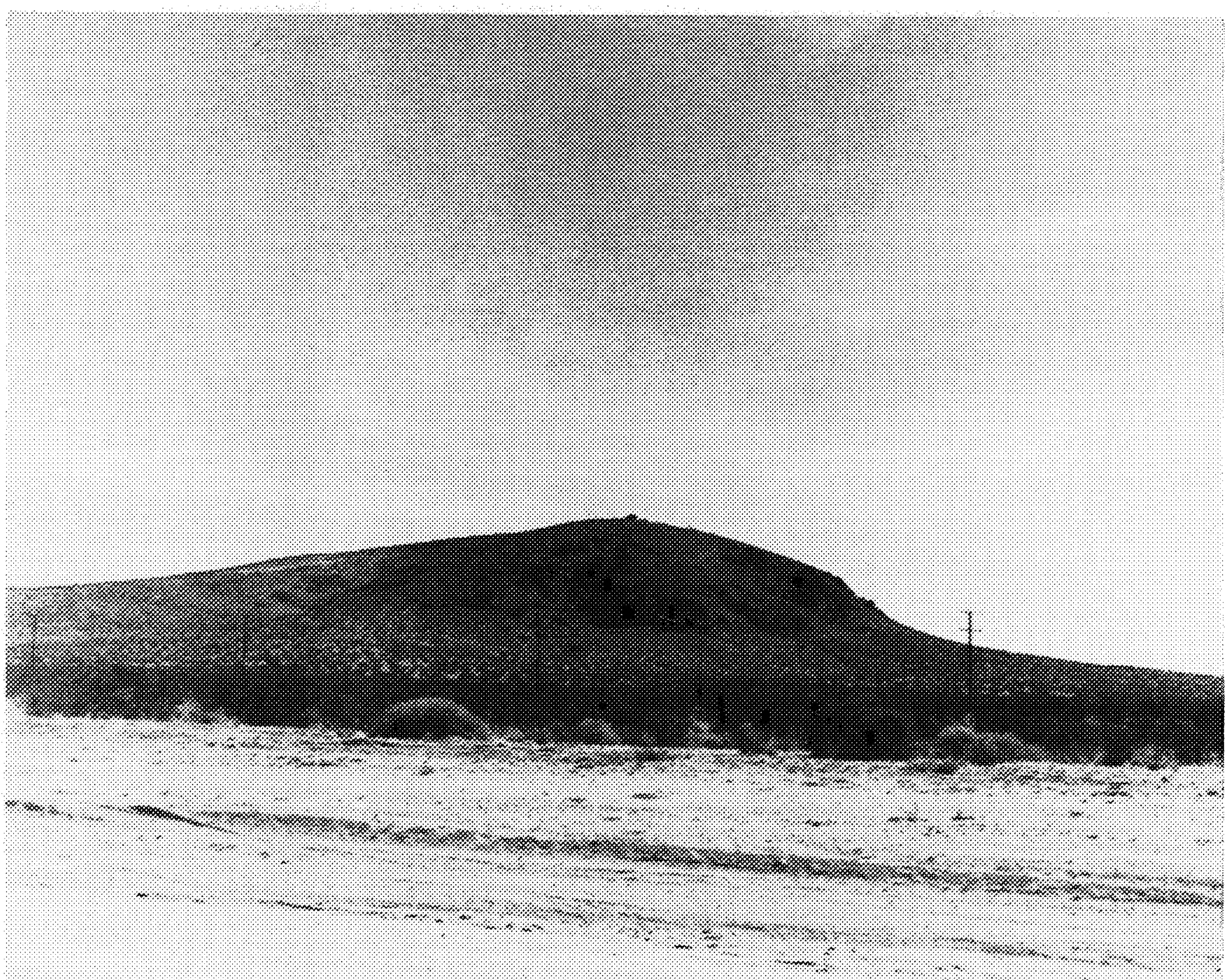

Figure 8. Photograph of Galileo hill.

SAF OF F-18 AT 60,000 FT RANGE AND M=1.4

On April 13,1994, the first SAF test was made at Dryden. Two F-18's were flown at M=1.4, one mile apart, with the trailing plane 300 ft. below the leading plane. This was done to increase the chance of photographing at least one of the planes. The leading plane was about 35,000 ft. above sea level, and the SAF system was about 3,200 ft. above sea level. This resulted in a slant range of about 60,000 ft. from the planes to the camera at closest approach. The viewing angle of the sun results in an oblique view rather than a side view of the aircraft. The photograph shown in figure 9 was taken just after 9 a.m., and shows the flow field around the lead plane.

SAF is sensitive to density gradients normal to the local grid line. Since the grid line curves, and since the shocks swept back, the best orientation of grid is to curve back toward the shock direction. The photo in the figure had the grid reversed, and this resulted in lower sensitivity, especially near the edges of the photo.

The camera was also slightly out of focus, so the resolution was lower than expected. The image banding was very bad, as was expected, but did not prevent the flow field from being seen. The aircraft shape shows up well, and shocks are clearly visible, even though the plane was about 12 miles away.

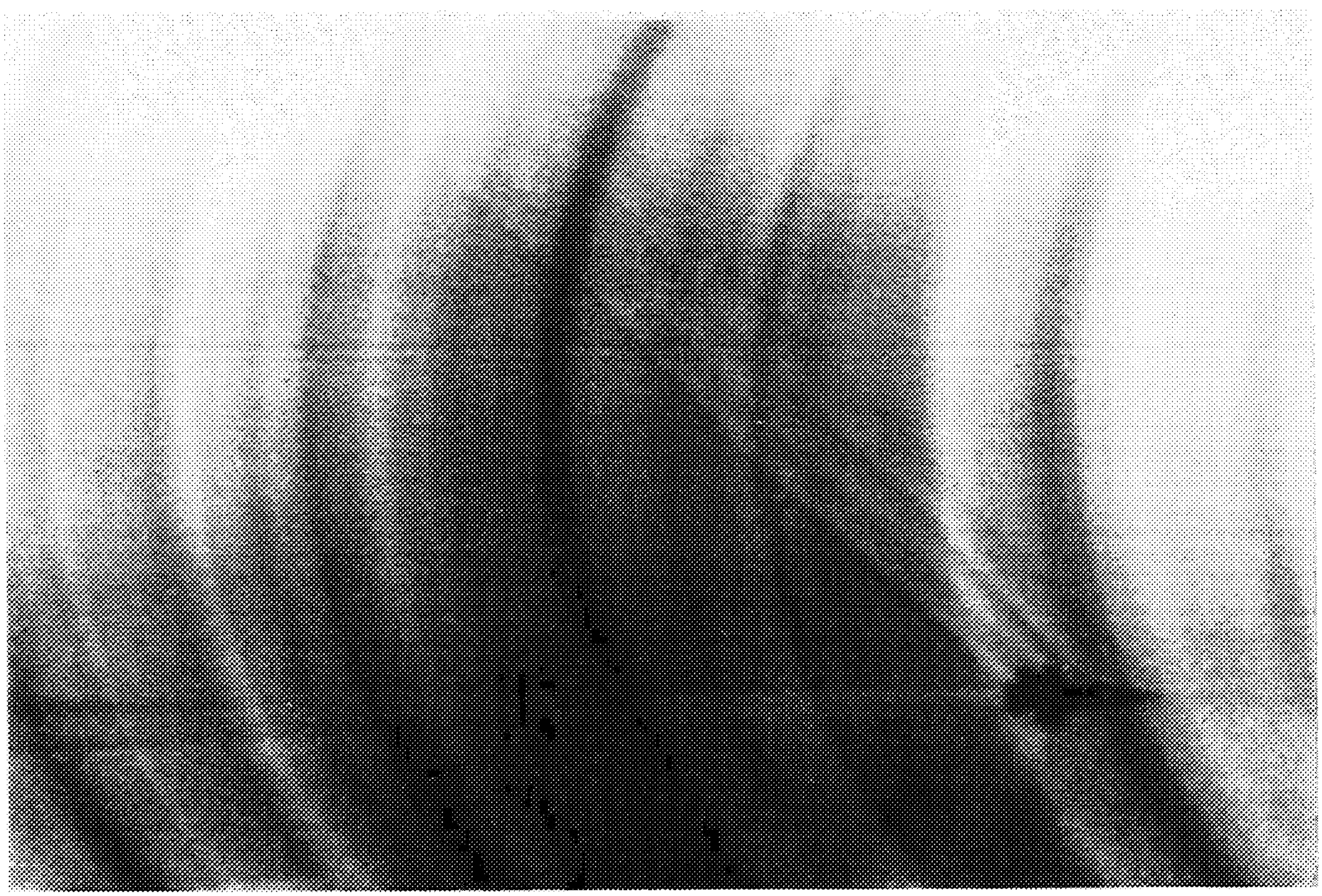

Figure 9. SAF of F-18 at 60,000 ft. slant range and M=1.4

SAF OF SHOCK 1,060 FT. BELOW F-18

On April 15, several additional flights were made by the two F-18's to try to get shock detail at different distances below the aircraft. The grid was reversed from the previous photo to obtain the best sensitivity possible. The photo shown in figure 10 was obtained just before 9 a.m., for the trailing plane. The photo shows the shock at 1,060 ft. below the plane. The complex multiple shock pattern has already merged to just two visible shocks.

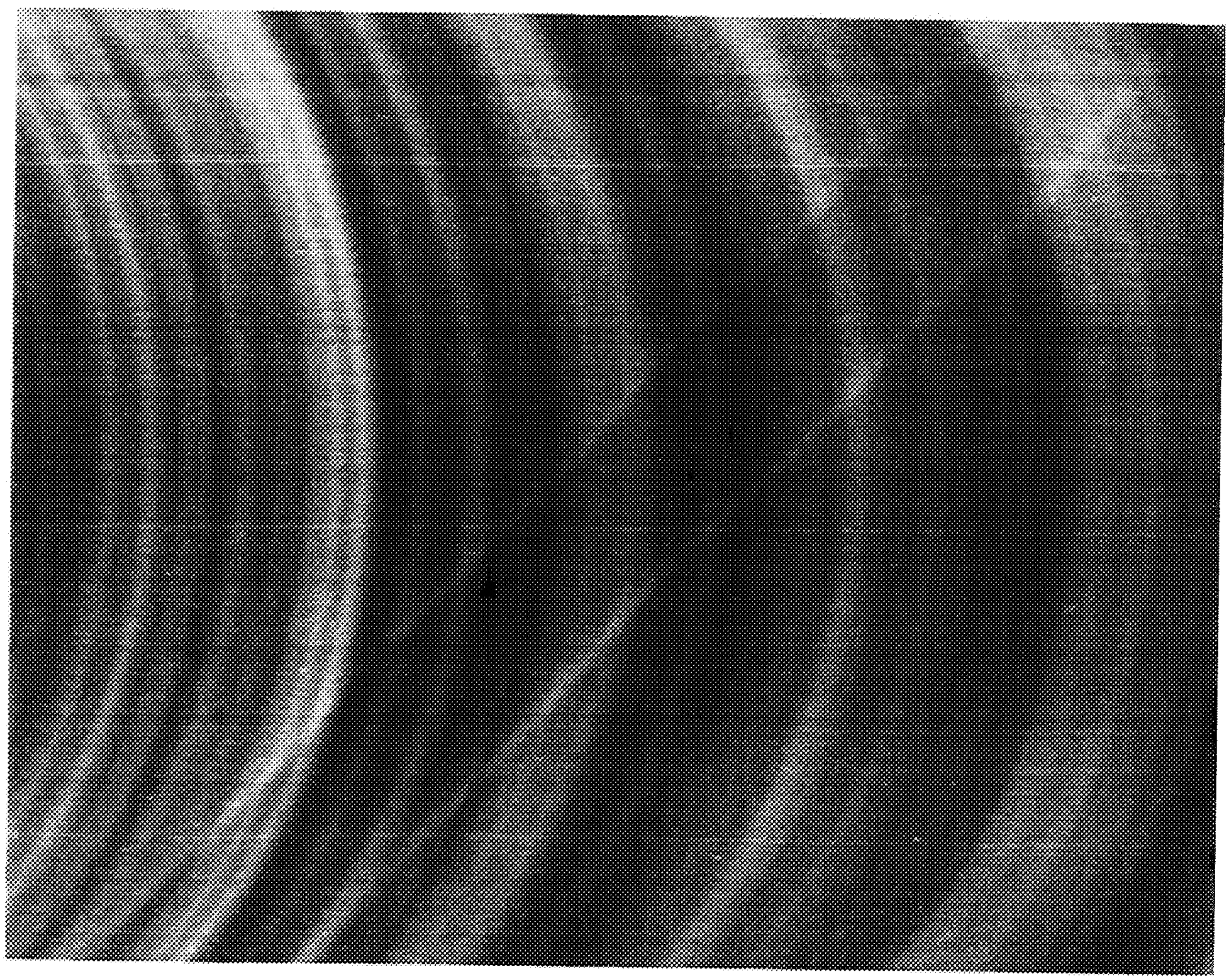

Figure 10. SAF of shock 1,060 ft.below F-18.

VARIATION OF LONGITUDINAL SHOCK SEPARATION WITH DISTANCE

Three passes by the flights made on April 15 resulted in 6 shock photos being obtained. These ranged from 510 ft. below the plane (diagonal distance) to 3,830 ft. below. The photographs for the shocks at the largest distance were not correctly exposed, so were not as good as the others. However, all shock photos were usable. The maximum distance the shocks can be photographed has not been determined, but clearly is very far from the aircraft. Figure 11 shows the change in length of the separation of front to back shock, normalized by the plane length, plotted against the diagonal distance below the aircraft.

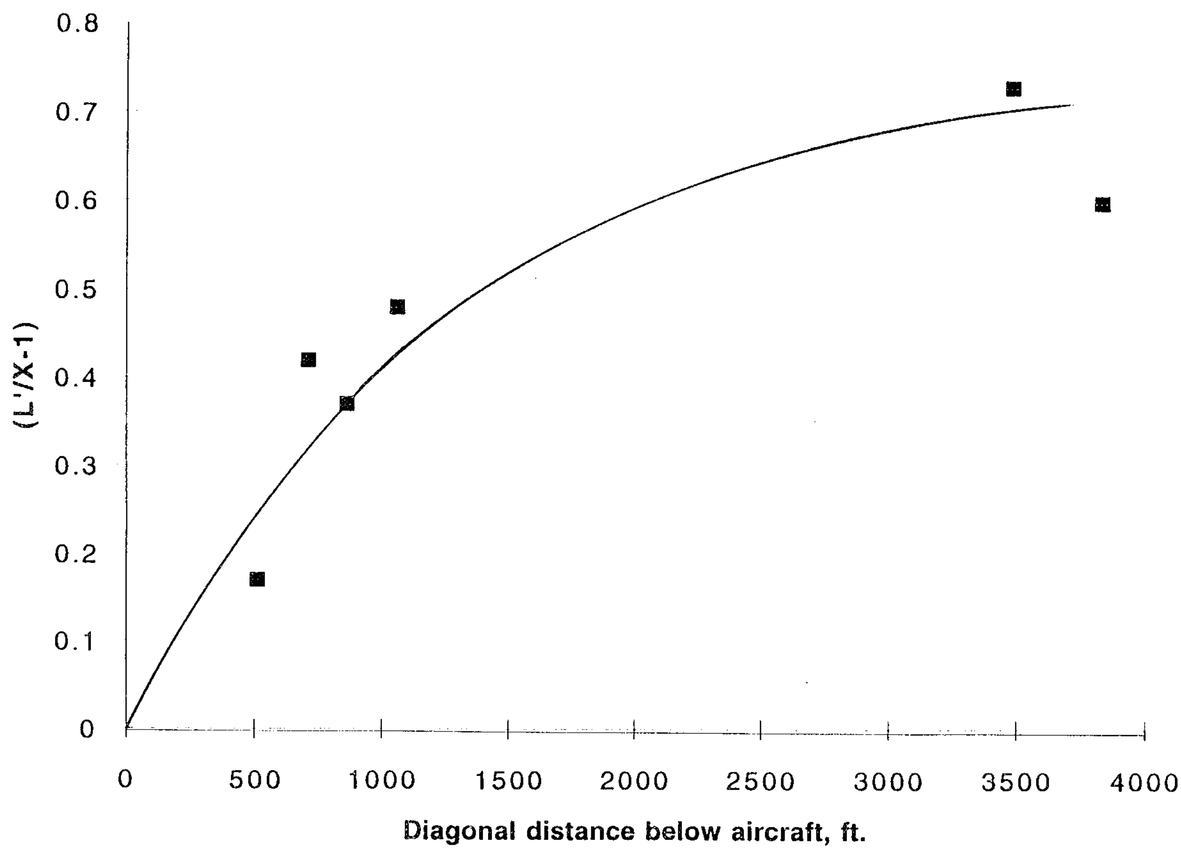

Figure 11. Variation of longitudinal shock seperation with distance below F-18.

PROBLEMS FROM PROTOTYPE SAF, AND SUGGESTED SOLUTIONS

There were several problems encountered in the prototype SAF system. A list of these, and possible ways to overcome them (including some that have been already implemented), are given in table 2.

Table II. Problems From Prototype SAF System, and Suggested Solutions

PROBLEMS	SOLUTIONS
Poor focus with low power eyepiece	Use higher power eyepiece, or auto focus
Grainy and low resolution film	Fine grain, high resolution film, or high resolution electronic imagery
Film banding	Smooth film transport, or TDI electronic imaging
Sun tracking errors	Auto sun tracker
Camera rotation with equatorial tracker	Use altazimuth rather than equitorial tracker
Fly plane through correct location	Use precision navigation, or multiple SAF cameras with overlapping fields of view

ALTERNATE VERSIONS OF SAF

The prototype SAF camera was used as a development system, and was far from optimized. Different versions can be made to better accomplish specific tasks. Table 3 shows some alternate versions and what special capabilities can be accomplished with them.

Table III. Variations of SAF Systems

VARIATION	SPECIAL CAPABILITY
Chase plane version	High resolution, possibility of near side view
Small compact system	Easy portability, flight use
TDI camera instead of film	No banding, instant replay
SAF multiple camera array (one station)	Large field of view
SAF multiple station array	Flight Dynamics
Point SAF camera with photo detector	Time history of flow field at single point
Near ground source/detector system	Near ground time history of signal

SUMMARY

The basic capability of schlieren for aircraft in flight imaging technology has been demonstrated at NASA's Wallops Flight Facility, and Dryden Flight Facility. Photos of T-38 and F-18 aircraft along with their flow fields, have been obtained at 6 and 12 miles range respectively, and shock wave pictures have been obtained as far as 3,830 ft. diagonally below the F-18.

Problems in the limitation of the initial design, operational procedures, and recording medium have been either solved, or possible solutions suggested.

An improved SAF system is currently being designed, and will be tested when ready. Use of arrays of SAF cameras, and special versions of systems should further increase the possible capabilities of this approach.

The limits of the technology have not yet been reached, but even the demonstrated capability should be useful for sonic boom studies.