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Catherine M. Bahm and Edward A. Haering, Jr.

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GROUND-RECORDED SONIC BOOM SIGNATURES

OF

F-18 AIRCRAFT IN FORMATION FLIGHT

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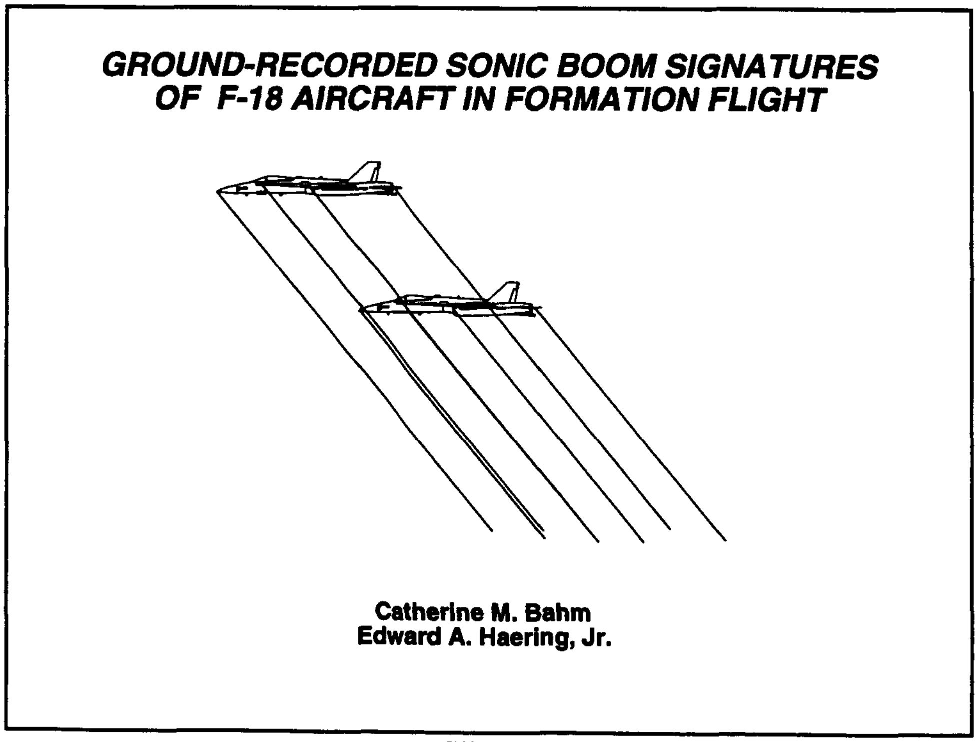
ABSTRACT

Two F-18 aircraft were flown, one above the other, in two formations, in order for the shock systems of the two aircraft to merge and propagate to the ground. The first formation had the canopy of the lower F-18 in the tail shock of the upper F-18 (called tail-canopy). The second formation had the canopy of the lower F-18 in the inlet shock of the upper F-18 (called inlet-canopy). The flight conditions were Mach 1.22 and an altitude of 23,500 ft . An array of five sonic boom recorders was used on the ground to record the sonic boom signatures. This paper describes the flight test technique and the ground level sonic boom signatures. The tail-canopy formation resulted in two, separated, N-wave signatures. Such signatures probably resulted from aircraft positioning error. The inlet-canopy formation yielded a single modified signature; two recorders measured an approximate flattop signature. Loudness calculations indicated that the single inlet-canopy signatures were quieter than the two, separated tail-canopy signatures. Signficant loudness occurs after a sonic boom signature. Such loudness probably comes from the aircraft engines.



Slide 1

INTRODUCTION

When an aircraft travels supersonically through the air, shockwaves form at multiple components on the aircraft. As these shockwaves travel through the atmosphere, they typically coalesce to become an N-wave. An N-wave is characterized by a sharp rise to maximum overpressure (bow shock), a linear decrease to the maximum underpressure, and a sharp rise back to ambient pressure (tail shock). These sharp pressure rises are heard as sonic booms. The public generally responds negatively to sonic booms. This response is a concern in developing the High Speed Civil Transport, HSCT. Sheperd and Sullivan (1991) showed that minimizing the maximum overpressure and increasing the bow shock rise time produces less objectionable booms. Research is underway on techniques for modifying the sonic boom signatures to produce less objectionable booms (Mack and Darden, 1980).

The sonic boom signature of an aircraft can be modified through careful design of the distribution of volume along its length; however, modifying the signature near the aircraft does not ensure that the signature will remain modified to the ground. Whether or not a modified signature remains modified to the ground can only be verified through a flight test with propagation through a real atmosphere. An existing aircraft could have its volume distribution modified and then be flight tested but at a significant cost for the modification. A low-cost flight test approach was proposed which would use two SR-71 aircraft flying in formation, one above the other, to produce modified signatures through interaction of the two shock wave systems. The combined size of two SR-71 aircraft would approximate the size of an HSCT.

To assess the feasibility of such an experiment with two SR-71 aircraft, a precursor flight using two F-18 aircraft was flown on May 24, 1994, at the National Aeronautics and Space Administration, Dryden Flight Research Center, Edwards, California. This flight had two objectives. The first objective was to evaluate this formation aircraft flight test technique for two SR-71 aircraft. The second objective was to measure and evaluate the sonic boom signature characteristics from the merged shock waves.

Introduction and Objectives

Introduction

- **Can modified sonic boom signatures propagate to the ground and remain modified?**
  - **Sonic boom propagation research**
  - **Implications for HSCT design**
- **Flight test of modified aircraft proposed -- high modification cost**
- **Lower cost program with two SR-71 aircraft flying in formation proposed**
- **Feasibility flight using two F-18 aircraft flying in formation to generate modified ground sonic boom signatures**

Objectives

- **Evaluate formation aircraft flight test technique for SR-71 aircraft**
- **Measure and evaluate ground signature characteristics**

Slide 2

This presentation describes the flight test technique used and the recorded ground-level sonic boom signatures. Loudness of these sonic booms was calculated and is presented here.

Outline

- **F-18 formation flight test technique**
- **Ten signatures from five 8-bit PATS**
- **Loudness calculations**
- **Concluding remarks**

Slide 3

FLIGHT TEST TECHNIQUE

The following subsections describe the flight test technique. This description includes how the aircraft were positioned relative to each other, the sonic boom recorder array, and the aircraft flight conditions.

Aircraft Positioning

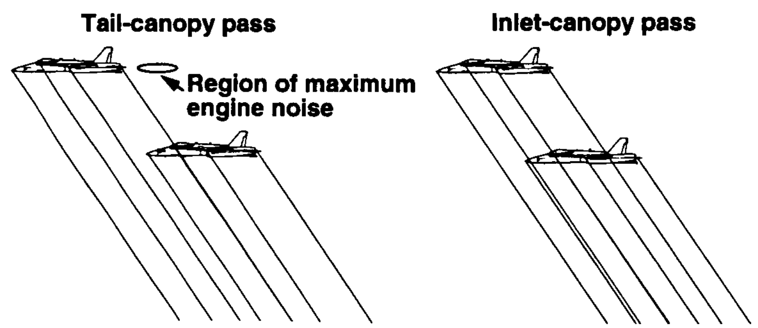
Two F-18 aircraft were flown in formation, one underneath the other, so their shock waves would interact. Two passes of the F-18 aircraft were flown over a ground array of sonic boom recorders. For the first pass, pilot A positioned the canopy of the lower F-18 aircraft in what was thought to be the tail shock of the upper F-18 (tail-canopy). Slide 4 shows this formation. Pilot A used the engine noise of the upper aircraft to position the lower aircraft. When the lower aircraft would creep forward of the desired location, the engine noise of the upper aircraft would abruptly stop. It was thought that this abrupt stop to the engine noise was caused by the tail shock, so pilot A remained at the division between hearing and not hearing the engine noise.

For the second pass, the lower F-18 aircraft was positioned so that its canopy was in the inlet shock of the upper F-18 (inlet-canopy) (slide 4). Pilot A could see the inlet shock and used this view as a positioning cue.

Pilot A commented that the lower aircraft was positioned at approximately one body length (56 ft) and centered below the lead F-18 aircraft for both passes. This pilot also noted that use of such cues allowed the aircraft to remain within ±10 ft longitudinally of the desired location.

Aircraft Formations

- **Tail-canopy pass**
  - **Engine noise used for positioning cue, abruptly quiet forward of certain point**
  - **Engine noise generated 5 to 15 nozzle radii behind aircraft**
  - **Lower F-18 bow shock may have been behind upper F-18 tail shock**
- **Inlet-canopy pass**
  - **Pilot could see inlet shock**



Drawings to scale

Slide 4

After the flight, it was realized that the region of maximum noise from a jet engine in afterburner is about 5 to 15 nozzle radii behind the engine, and the noise rapidly decreases forward of this point (slide 4) (Tam, 1991). The engine noise cue may be inappropriate for locating the tail shock of an aircraft. As a result,the lower F-18 aircraft could have been positioned too far aft on the tail-canopy pass for the shock waves of the two aircraft to combine.

Both aircraft were tracked by separate AN/FPS-16 radars (Haering and Whitmore, 1995). The upper F-18 aircraft had a radar beacon which gives accurate ground-based radar tracking. The lower F-18 aircraft did not have a beacon. This aircraft was skin tracked, which provides greatly reduced accuracy. Although the flight conditions and location of the upper F-18 could be accurately determined, the radar data quality from the lower F-18 was insufficient to measure relative aircraft separation. As a result, only pilot observations were used to indicate relative separation. Differentially corrected carrier phase Global Positioning System, GPS, data could be used on a future test of this type to accurately determine the relative aircraft separation (Haering, Ehernberger, and Whitmore, 1995).

The pilot of the upper F-18 aircraft held airspeed and altitude as steady as possible and could not see the lower F-18 aircraft. The pilot of the lower aircraft looked up at the upper F-18 aircraft to maintain a safe separation. Similar to most fighter aircraft, an F-18 aircraft has a bubble canopy that gives excellent visibility in multiple directions. By comparison, the small windows to the front and sides of an SR-71 aircraft provide the pilot with no upward visibility. This aircraft is also large and relatively slow to respond, which makes the formation flying task difficult. After the flight of the two F-18 aircraft, pilot A stated that flying such a mission with two SR-71 aircraft would be extremely difficult because of its reduced visibility and maneuverability.

Aircraft Relative Separation

- **Engine noise may be poor cue to find tail shock**
- **Radar data proved insufficient for relative aircraft separation**
- **DGPS should be used on any future test**
- **Pilot comments about using two SR-71 aircraft**
  - **Has less upward visibility**
  - **Has less maneuverability**
  - **Would be extremely difficult to fly in formation**

Slide 5

Sonic Boom Recorder Array

A ground array consisting of five sonic boom pressure recorders provided the signature data for this experiment. These recorders were placed along a 2-mile line with approximately one-half mile between each recorder. Traveling at Mach 1.22, the aircraft crossed the recorders at approximately 2-sec intervals.

The sonic boom signatures were recorded using the 8-bit PATS, Portable Automated Triggering System (Norris, 1995). These PATS were set to trigger on pressure fluctuations greater than approximately 0.3 psf, and their full-scale range varied from ±4 to ±13 psf. Because these recorders are 8-bit systems, their resolutions were from 0.03 to 0.10 psf. Each PATS recorded two sonic boom events and two calibration signals.

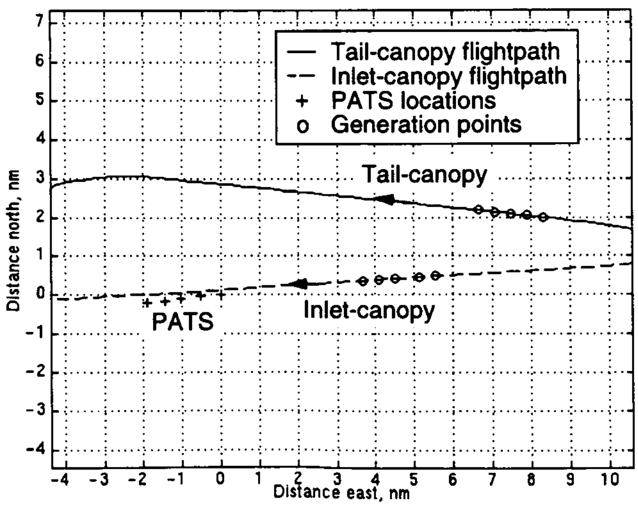
Aircraft Flight Conditions

A prediction method was used to calculate the sonic boom generation point for each sonic boom recorder (Carlson, 1978). Table 1 lists the results of this method. Slide 6 shows the flightpaths, the location of the five PATS recorders, and their corresponding generation points. The aircraft flew about 3 miles north of the recorders for the tail-canopy pass and almost directly over the recorders for the inlet-canopy pass.

The aircraft flight conditions at the generation points were determined using the ground-based radar data of the upper F-18 aircraft (Haering and Whitmore, 1995) and an atmospheric analysis (Ehernberger, et. al., 1992). The aircraft flight conditions during the tail-canopy pass were Mach 1.22 at an altitude of 23,600 ft, and the inlet-canopy pass flight conditions were Mach 1.22 and an altitude of 23,300 ft.

PATS, Flightpaths, and Generation Points

- **PATS placed along 2-mile line, 1/2 mile between each**
- **Carlson method used to determine generation points**
- **Tail-canopy pass about 3 nm off-track, Mach=1.22, alt=23,600 ft**
- **Inlet-canopy pass almost on-track, Mach=1.22, alt=23,300 ft**



Slide 6

	Tail-canopy pass		Inlet-canopy pass	
PATS number	Distance, ft	Delta time, sec	Distance, ft	Delta time, sec
5	50,400	53.2	33,597	38.5
8	51,391	54.9	33,554	39.4
3	51,758	53.5	33,661	37.8
6	52,879	56.6	34,531	39.7
9	53,162	56.6	33,716	38.9
mean	51,918	54.9	33,812	38.8

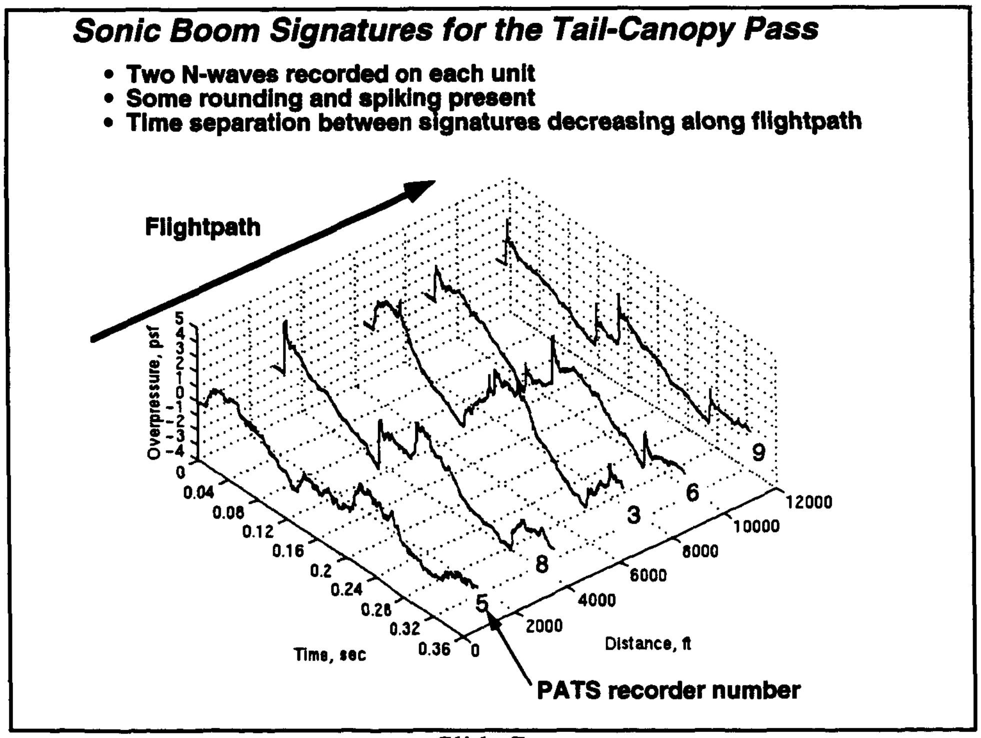
Results of Carlson generation point prediction.

SONIC BOOM SIGNATURES

The recorded sonic boom signatures from the tail-canopy pass and the inlet-canopy pass are discussed next. Atmospheric effects are evident in the signatures. A single N-wave signature is compared to a modified signature. Lastly, the sonic boom trailer is described.

Tail-Canopy Pass

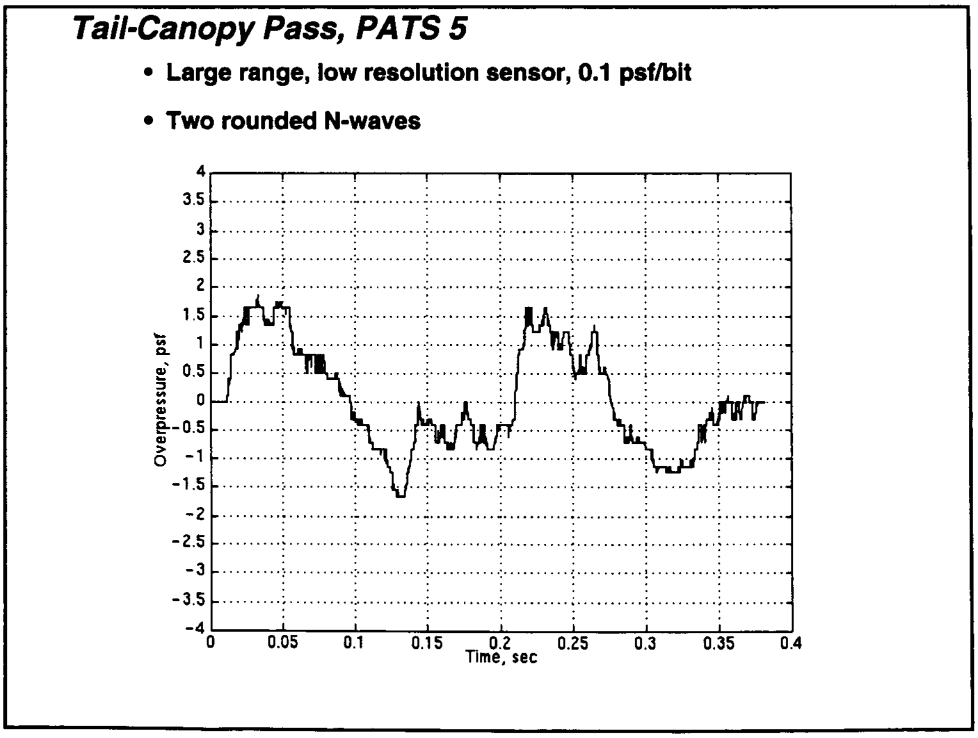
Slide 7a shows the sonic booms that were recorded in the tail-canopy pass. This plot shows the overpressure as a function of time for each of the sonic boom signatures and as a function of distance from the first PATS recorder. The signature at zero distance was the first signature recorded. The number by each signature denotes the PATS number. Slides 7b through 7f show individual plots of each of the tail-canopy signatures. Slide 7b shows the signature recorded by the first recorder, PATS 5, which has the lowest resolution, 0.10 psf/bit. Slides 7c, 7d, 7e, and 7f are the signatures recorded by PATS 8, 3, 6, and 9, respectively.



Slide 7a

It was hoped that a modified N-wave would be recorded on the ground; however, the signatures recorded for the tail-canopy pass contained two, separated N-waves. One reason these sonic boom signatures did not combine might be that the lower F-18 was too far aft because of the engine noise position mentioned earlier. In addition, because the lower F-18 aircraft was positioned underneath the upper F-18, the shock structure of the two aircraft would only be combined in a small corridor directly below the aircraft and possibly not 3 miles laterally off track where the recorders were located. Lastly, the time separation between the two signatures appears to decrease with each recording, possibly because the lower F-18 aircraft was creeping forward relative to the upper F-18 aircraft.

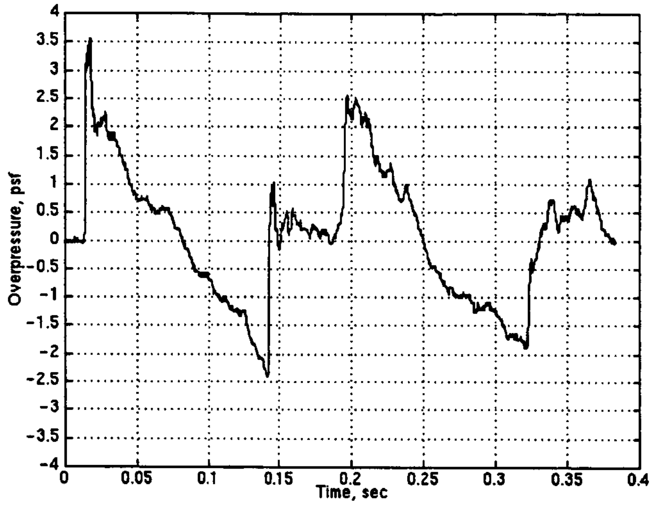
An anomaly was found while studying the recorded signatures in slide 7d. Normally spiking caused by turbulence occurs as the pressure rises to the maximum overpressure. In the case of the signature in slide 7d, spiking occurred about 0.03 sec after the initial rise to maximum overpressure, which is a rare occurrence. This rare, delayed spiking also occurred on a signature from an F-4 aircraft (Lee and Downing, 1991).



Slide 7b

Tail-Canopy Pass, PATS 8

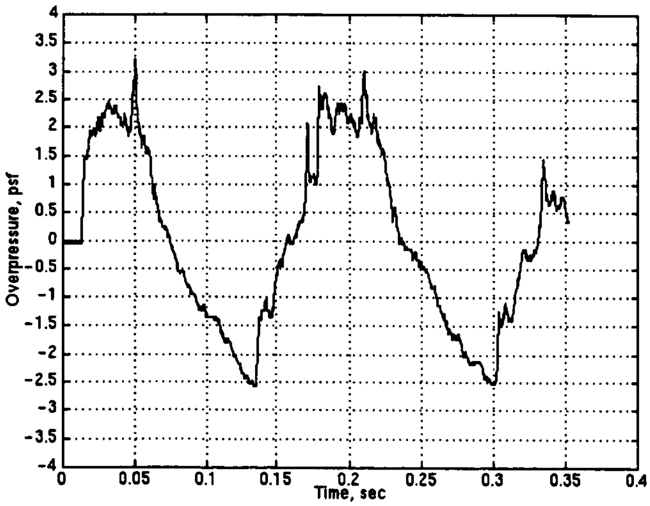
- **Two N-waves**
- **Spiking on first N-wave**



Slide 7c

Tail-Canopy Pass, PATS 3

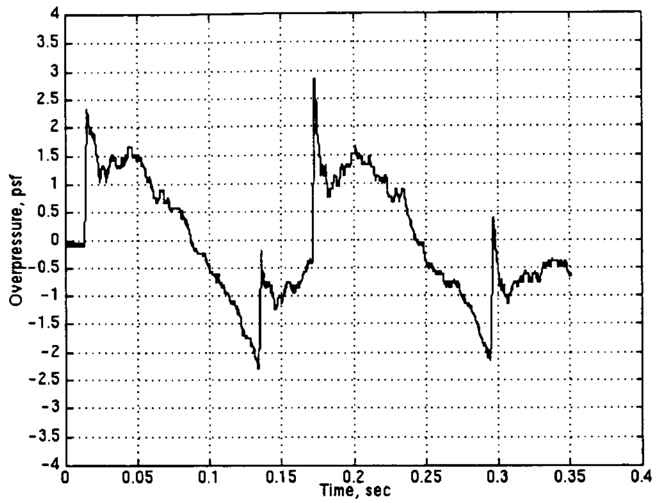
- **Two N-waves very close to each other in time**
- **Rounding on first signature**
- **Spiking occurred after maximum overpressure, rare occurence**



Slide 7d

Tail-Canopy Pass, PATS 6

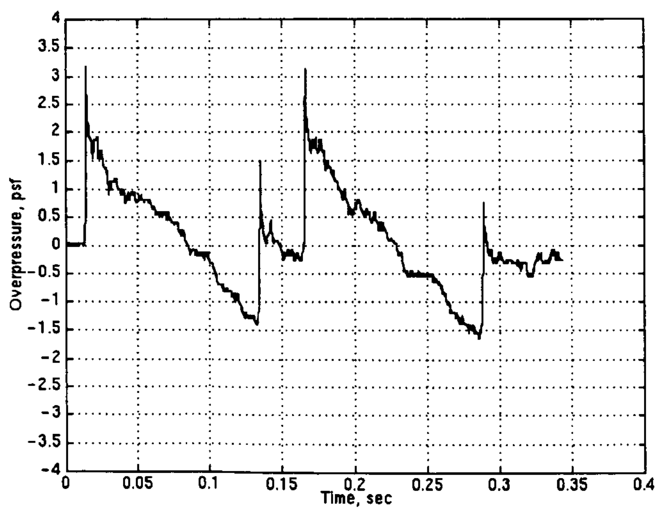
- **Two N-waves**
- **Spiking on both N-waves**



Slide 7e

Tail-Canopy Pass, PATS 9

- **Two N-waves**
- **Spiking on both N-waves**



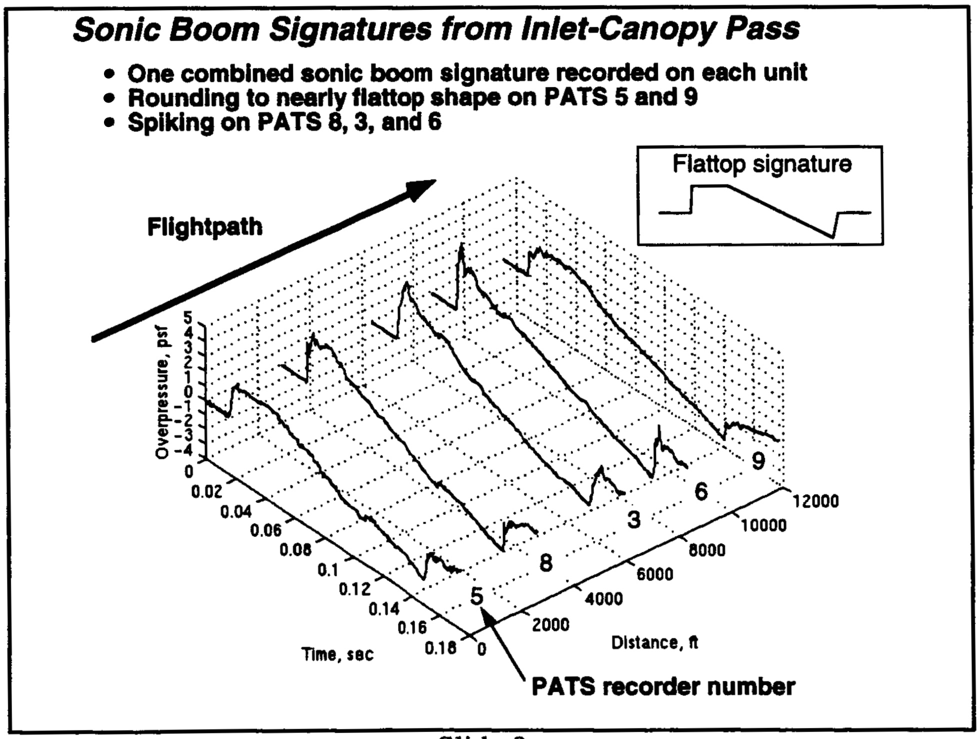
Slide 7f

Inlet-Canopy Pass

The sonic booms recorded during the inlet-canopy pass can be seen in slide 8a. Individual plots of each of the inlet-canopy signatures are shown in slides 8b through 8f. Slides 8a-8f show that the positioning of the F-18 aircraft allowed the shockwaves from the two aircraft to coalesce and generate a single sonic boom signature on the ground. Slides 8b and 8f show rounded signatures that approximate a flattop shape.

Atmospheric Effects

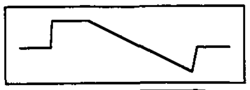
Slides 7a through 8f show that some of the signatures contain a peaked, or spiked, overpressure, while other signatures are rounded. The variation between the signatures in each of the passes probably results from the atmospheric conditions that the shockwaves passed through. Certain atmospheric conditions can cause spiking and rounding of the N-wave and can also increase the rise time to maximum overpressure (Likens and Blackstock, 1992; and Garrick and Maglieri, 1968).

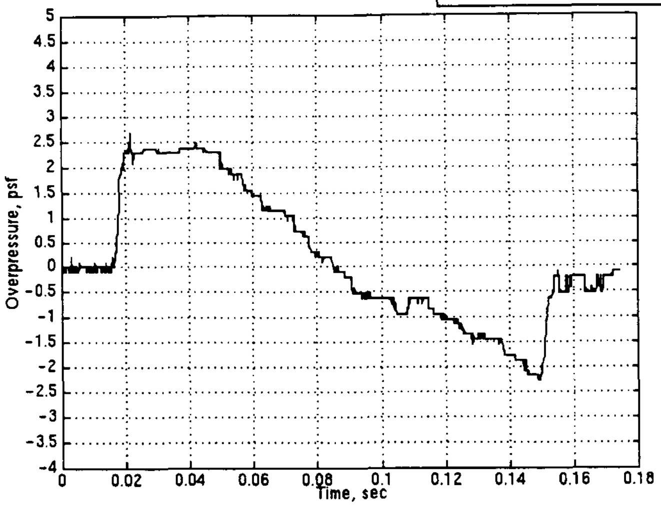


Slide 8a

Inlet-Canopy Pass, PATS 5

- One sonic boom signature
- Rounding to nearly flattop shape

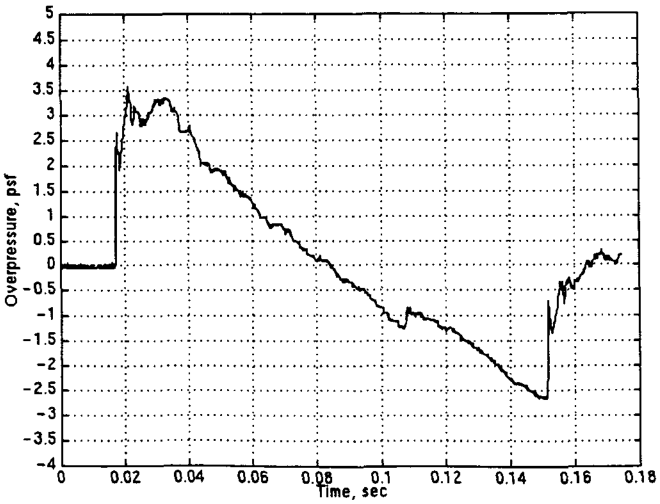




Slide 8b

Inlet-Canopy Pass, PATS 8

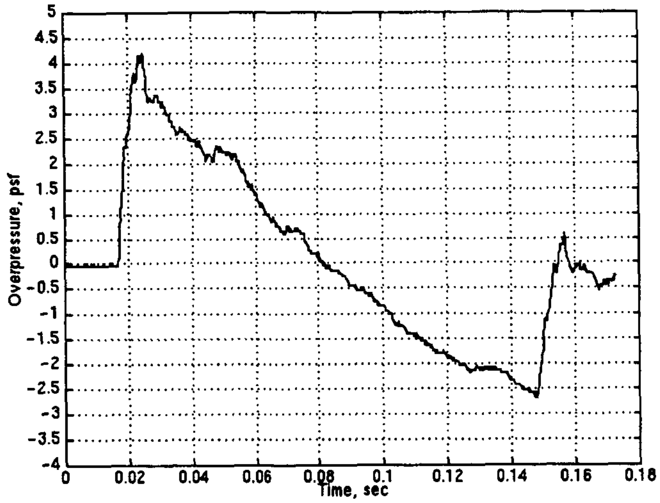
- One sonic boom signature
- Spiking
- Possibly not completely combined shocks



Slide 8c

Inlet-Canopy Pass, PATS 3

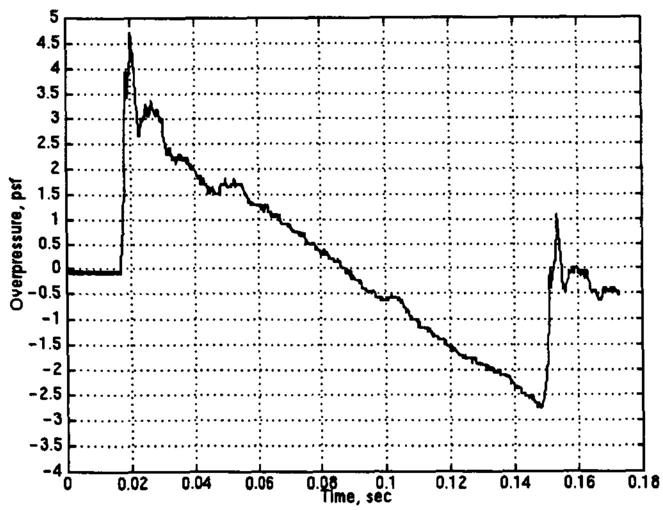
- **One sonic boom signature**
- **N-wave shape with possible spiking**



Slide 8d

Inlet-Canopy Pass, PATS 6

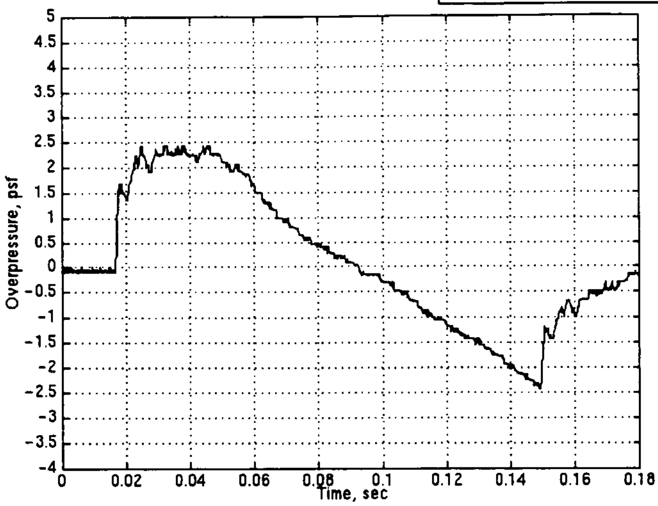
- **One sonic boom signature**
- **N-wave shape with spiking**



Slide 8e

Inlet-Canopy Pass, PATS 9

- **One sonic boom signature**
- **Rounding to nearly flattop shape**



Slide 8f

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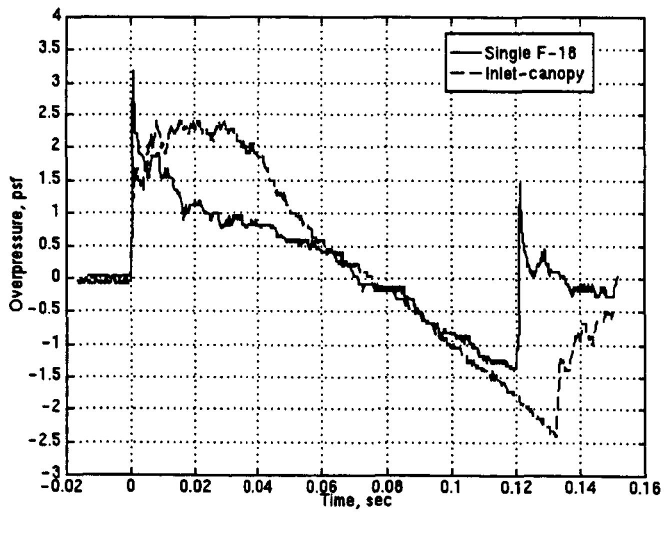
Single and Modified Signatures

Because two N-waves were recorded during the tail-canopy pass, it has been assumed that the longitudinal separation between the aircraft was great enough that no interaction between the shockwaves was measured at the sonic boom recorders. Under that assumption, a comparison was made between the first N-wave of the tail-canopy pass (one F-18 aircraft) and the single N-wave recorded during the inlet-canopy pass (two F-18 aircraft) of the same recorder (PATS 9 in slide 9). The maximum overpressure of the signature from the inlet-canopy pass is greater than that of the single F-18 signature if the spiking is ignored. There are two reasons for this occurrence. First, coalescing of the shocks from both aircraft reinforces the maximum overpressure. Second, the inlet-canopy pass occurred directly over the sonic boom recorders, while the tail-canopy pass occurred at a 3-mile lateral offset (slide 6). Note also that the length of the inlet-canopy pass signature is longer than that of the single F-18 aircraft. This result was expected because the length of the signature depends on the length of the aircraft.

Single F-18 and Inlet-Canopy

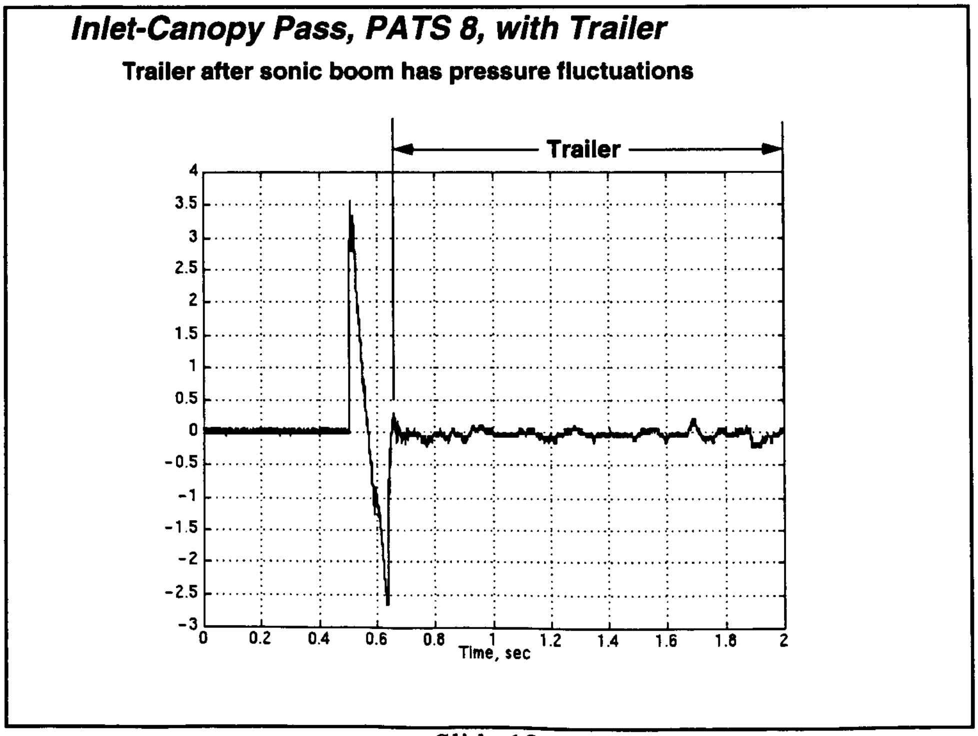
- **Inlet-canopy signature has higher maximum overpressure**
- **Inlet-canopy signature is longer than from single F-18**



Slide 9

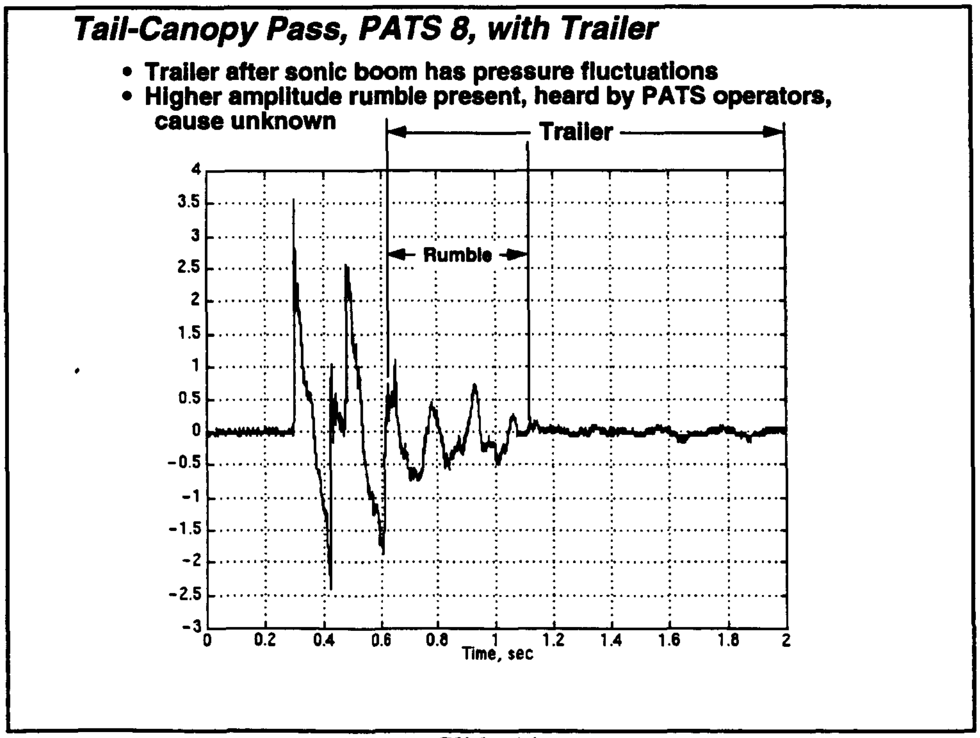
Sonic Boom Trailer

Because the PATS records 2 sec of data and a typical sonic boom signature is usually less than 0.2 sec long, there is additional data (or a trailer) after the signature. Slide 10 shows the signature and trailer recorded by PATS 8 during the inlet-canopy pass of the F-18 aircraft. After the sonic boom signature, the pressure normally returns to ambient.



Slide 10

Slide 11 shows the entire 2 sec of data recorded by PATS 8 during the tail-canopy pass. This slide shows the two N-waves followed by high-amplitude rumble. This rumble was recorded on all recorders during the tail-canopy pass and was not recorded by any of the recorders during the inlet-canopy pass. The cause of this rumble is unknown. Maneuvering of aircraft may cause U-shaped waves after an N-wave, but these aircraft were just as steady on the tail-canopy pass as they were on the inlet-canopy pass. Additionally, a study has shown that "porpoising" an airplane with normal acceleration variations as great as ±0.5 times gravity will not affect ground signatures (Garrick and Maglieri, 1968). One cause of the rumble may be atmospheric effects that could have resulted in a reflected shock. This atmospheric effect is unlikely because the atmosphere differed over the 2-mile length of the ground array enough to affect each signature differently with rounding and spiking. Yet, all the PATS recorded the rumble on the tail-canopy pass.



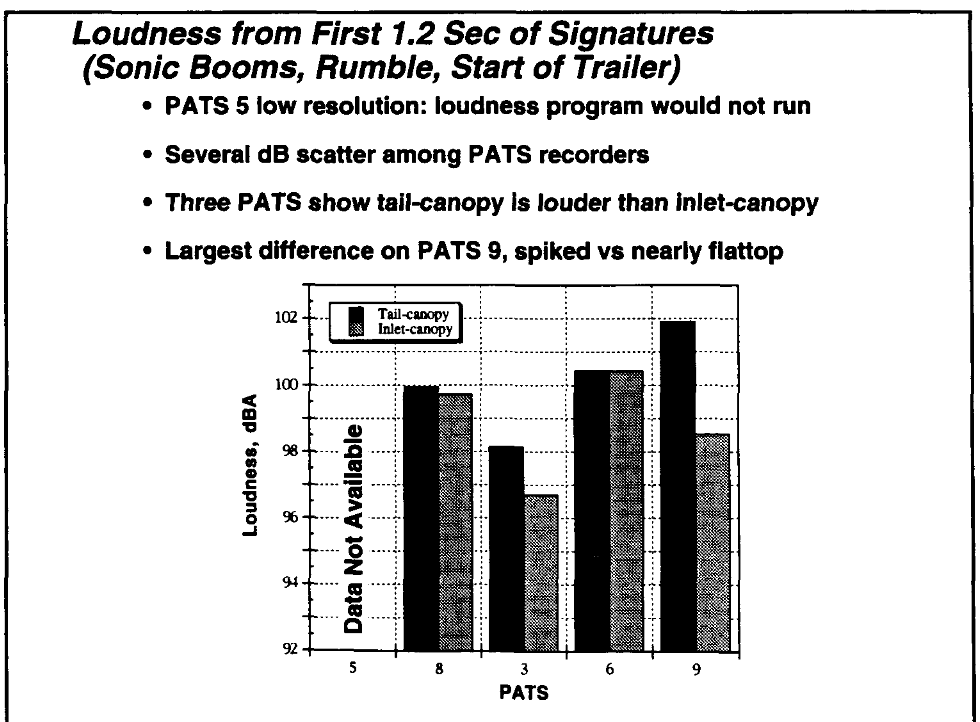
Slide 11

Calculation of Loudness

A computer program (Sheperd and Sullivan, 1991) was used to calculate the loudness of the recorded signatures. The program calculated A- and C-weighted loudness and perceived loudness for each signature. A-weighted loudness correlates well with human subjective response studies (McCurdy, 1994).

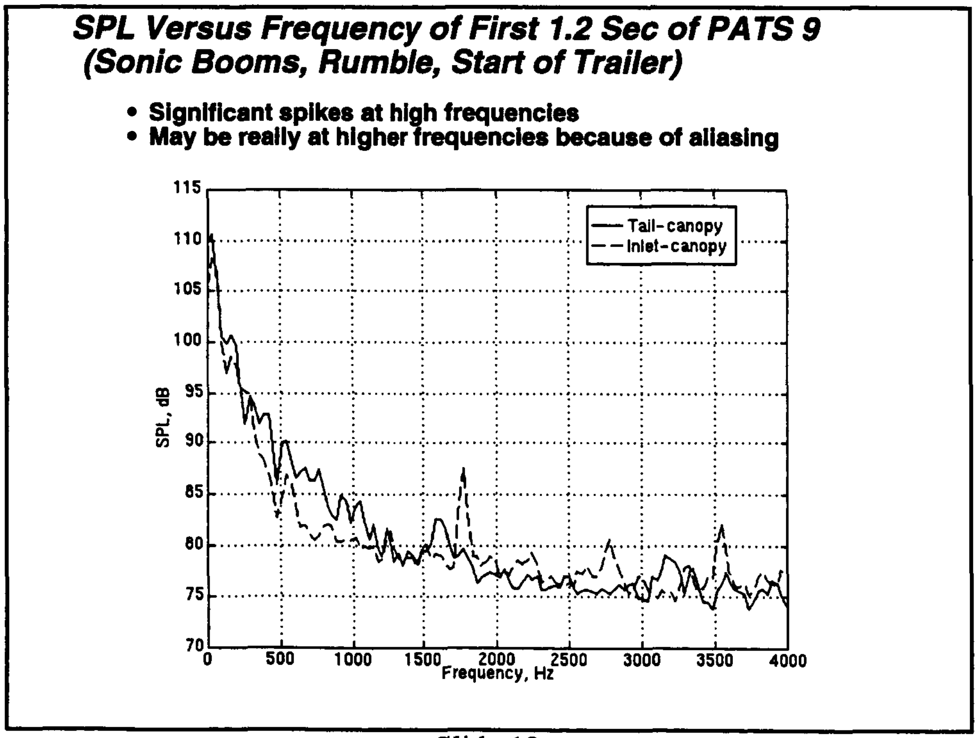
Slide 12 shows the A-weighted loudness for the first 1.2 sec for both passes, which includes both aircraft signatures from the tail-canopy pass. Equal time history segments of 1.2 sec were used for these loudness calculations, which eliminated most of the trailer. Note that the loudness program would not run using data from PATS 5, possibly because of the low resolution of this recorder.

The loudness for a given pass varied by several decibels among the recorders. The tail-canopy pass was as loud or louder than the inlet-canopy pass for all four recorders even though the inlet-canopy pass flight track was closer to the PATS array. The largest difference was seen on PATS 9 which has spiking on the tail-canopy pass and a nearly flattop signature on the inlet-canopy pass.



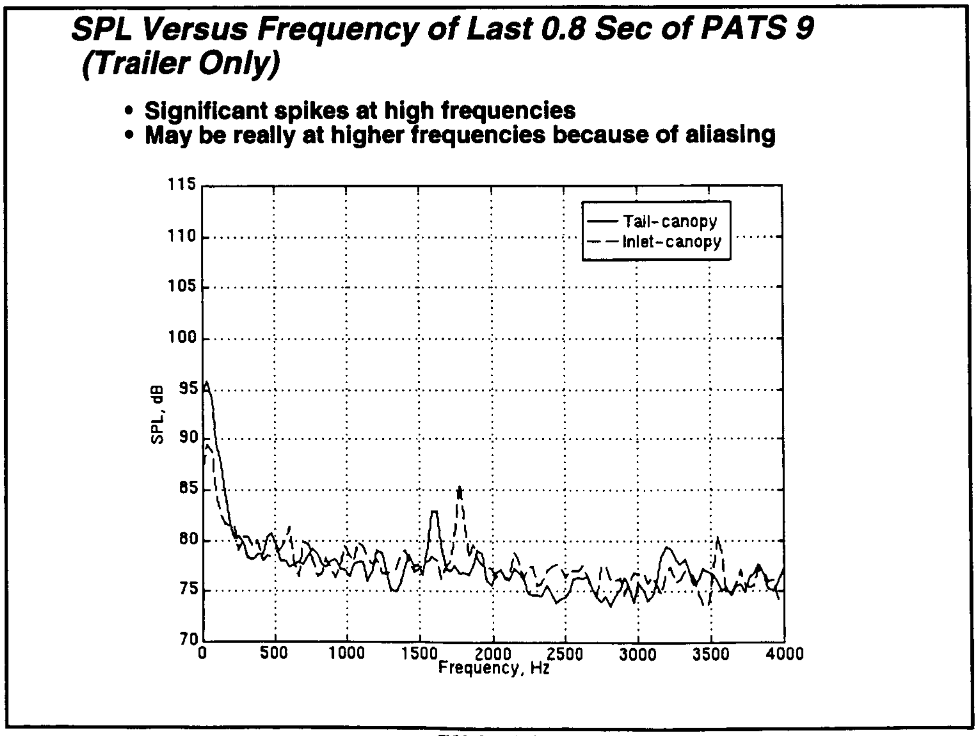
Slide 12

A plot of sound pressure level, SPL, as a function of frequency of the first 1.2 sec of PATS 9 data is shown in slide 13 for both passes. Significant spikes occur in both curves above 1500 Hz in the data, which contains the sonic boom signatures and the rumble for the tail-canopy pass. The PATS recorders do not have antialiasing filters (Norris, 1995), so the indicated frequencies of the spikes in slide 13 may actually be at higher frequencies.



Slide 13

Slide 14 shows high-frequency spikes for the last 0.8 sec of PATS 9 data for both passes. These data contain neither the sonic boom signature nor the rumble from the tail-canopy pass, so high-frequency content was not expected; however, the PATS operators in the field noted that the aircraft engines were quite loud immediately after the sonic booms were heard. This engine noise may be the source for the high-frequency spikes in slide 14 and would be amplified by the A weighting.

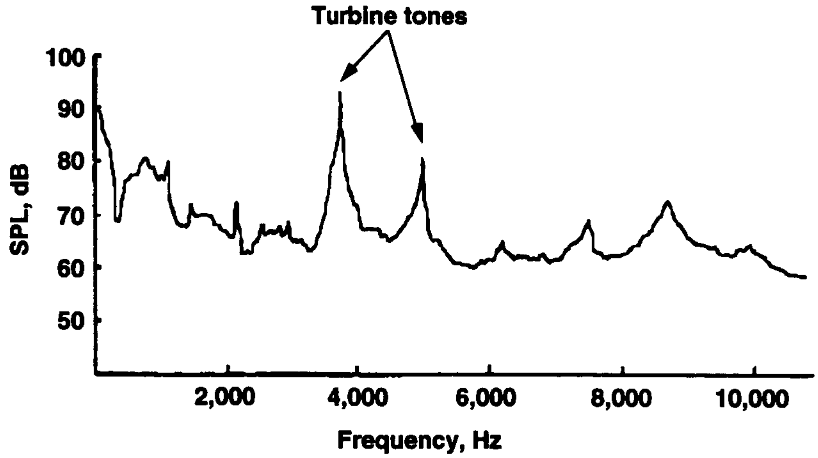


Slide 14

Slide 15 shows SPL as a function of frequency for a typical jet turbine engine (a Rolls-Royce engine). Spikes occur in the range from 1000 to 4800 Hz (Bushell, 1976)*. These high frequency spikes in slides 13, 14, and 15 suggests that high-frequency energy in the trailer of the sonic boom signature could be caused by the aircraft engine.

SPL Versus Frequency of Rolls-Royce Engine

- **Significant spikes at high frequencies**
- **Largest component from turbines**



Slide 15

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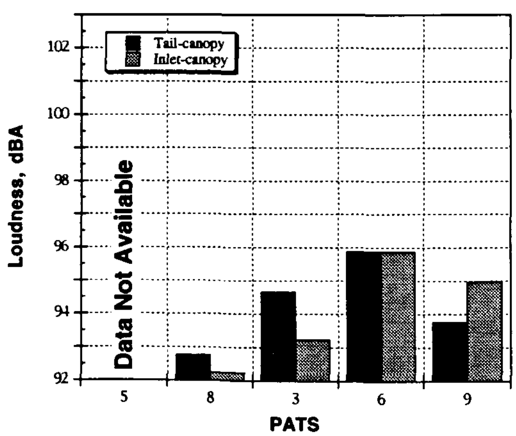
*The original version of this material was first published by the Advisory Group for Aerospace Research and Development, North Atlantic Treaty Organization (AGARD/NATO) in Lecture Series LS-80 "Aerodynamic Noise" in 1977. Used by permission.

Lastly, the loudness of the last 0.8 sec of data from each sonic boom recorder was calculated (slide 16). Even though no sonic boom signature or rumble was part of the data analyzed, there was still 92 to 96 dBA of loudness, probably from the aircraft engines. Even though sonic booms may significantly startle people and animals, the trailer loudness apart from the sonic boom may be still quite annoying. In future flight experiments measuring sonic boom loudness, care should be taken to separate the loudness of the sonic boom from that of the trailer.

Loudness from Last 0.8 Sec of Signatures (Trailer Only)

- **Significant loudness not from sonic booms**
- **Probably engine noise**



Slide 16

CONCLUDING REMARKS

A flight test technique that uses two F-18 aircraft flying in formation to generate modified ground sonic boom signatures was evalutated to determine the feasibility of the technique for possible SR-71 flight research. Results indicate that having the lower pilot see the shock of the upper aircraft for a positioning cue worked well. Using the engine noise cue for positioning may have resulted in the lower aircraft being too far aft for the shock waves to merge. Because of limited upward visibility and the relatively slow response of the SR-71 aircraft, use of two SR-71 aircraft flying in formation to generate modified ground signatures would be very difficult. Lastly, the relative separation of the two aircraft should be measured with a differentially corrected carrier phase global positioning system on any future test.

Although the flight was conducted primarily to evaluate a new flight test technique, data were recorded and analyzed that gave new insight into merged sonic booms from two aircraft. The inlet-canopy pass yielded modified signatures on the ground. Some approximated flattop signatures. These signatures had higher overpressure and longer length than signatures from a single F-18 aircraft. Modified signatures resulting from the combined signatures from two aircraft were quieter than signatures from two separated aircraft. The signatures recorded from the tail-canopy pass showed two separated signatures, which were followed by an unexplained rumble. All of the signatures showed some evidence of rounding or spiking. Lastly, aircraft engines may produce significant loudness in the trailers after the sonic booms.

Concluding Remarks

- **Formation aircraft flight test technique evaluated**
  - **Using two SR-71 aircraft in formation would be very difficult**
  - **Future tests should use Global Positioning System for position data**
- **Ground signatures from formation flight measured and evaluated**
  - **Tail-canopy pass yielded two separated N-waves**
    - **Some rounded, some spiked**
    - **Rumble after sonic boom signatures**
  - **Inlet-canopy pass yielded modified ground signature**
    - **Two signatures approximate flattop signature**
    - **Higher maximum overpressure than single F-18 aircraft**
    - **Longer signature than single F-18 aircraft**
    - **Quieter than two, separated F-18 shock signatures**
- **Sonic boom trailer has significant loudness probably caused by aircraft engines**

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13. ABSTRACT (Maximum 200 words)

Two F-18 aircraft were flown, one above the other, in two formations, in order for the shock systems of the two aircraft to merge and propagate to the ground. The first formation had the canopy of the lower F-18 in the tail shock of the upper F-18 (called tail-canopy). The second formation had the canopy of the lower F-18 in the inlet shock of the upper F-18 (called inlet-canopy). The flight conditions were Mach 1.22 and an altitude of 23,500 ft. An array of five sonic boom recorders was used on the ground to record the sonic boom signatures. This paper describes the flight test technique and the ground level sonic boom signatures. The tail-canopy formation resulted in two, separated, N-wave signatures. Such signatures probably resulted from aircraft positioning error. The inlet-canopy formation yielded a single modified signature; two recorders measured an approximate flattop signature. Loudness calculations indicated that the single inlet-canopy signatures were quieter than the two, separated tail-canopy signatures. Significant loudness occurs after a sonic boom signature. Such loudness probably comes from the aircraft engines.

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