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Dr. Antonio Ferri's Contribution to Supersonic Transport Sonic-Boom Technology

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Substantial advances were made in the 1960s and 1970s in the development and application of theories relevant to the design of low-boom, supersonic-cruise aircraft. Dr. Antonio Ferri was one of the leaders in this area of research. The papers that he published, and many that he inspired, still serve as a foundation, or benchmark, for those attempting to advance "low-boom" technology with today's new capabilities. Many of his ideas are as pertinent today as when he first published them. The present paper briefly summarizes some of Dr. Ferri's most prominent and useful contributions with the aid of figures and quotes from his original papers.

Nomenclature

A_e	=	equivalent axisymmetric area
B	=	$\sqrt{(M^2-1)}$
C_D	=	drag coefficient
C_L	=	lift coefficient
h	=	airplane flight altitude or distance from model
k	=	arbitrary constant; see Figs. 5 and 6
L	=	total area of body
L_1	=	area of forebody; also lift at canard in Fig. 1
L_2	=	lift of wing in Fig. 1
l	=	overall length of body or aricraft
l_1	=	length at forebody
l_2	=	length at afterbody
M	=	Mach number
N	=	ratio of glide C_L to cruise C_L (equal to C_{L_i}); see Fig. 3
p	=	flowfield pressure, lb/ft^2
p_∞	=	ambient pressure, lb/ft^2
r	=	radius from body axis
w	=	weight
x	=	distance measured along longitudinal axis from body or airplane nose
x_1, x_2	=	start and end x locations of parabolic expansion; see Fig. 23
x_2, x_3	=	start and end x locations of parabolic compression; see Fig. 23
α	=	initial flight-path angle of pullup maneuver, also cone angle
α_1	=	cone angle at body apex
α_2	=	incremental angle of body surface between x_2 and x_3; Figs. 23 and 25
Δ_p	=	$p - p_\infty$
θ	=	ray-path azimuth angle
ϕ	=	potential function

Subscripts

h	=	value at flight altitude
ground	=	value at ground level
max	=	maximum value
$\theta\theta$	=	second derivation with respect to θ

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Introduction

ONE of the many subjects that Antonio Ferri contributed his genius to is sonic boom. It was a critical area in the days leading up to the design of the U.S. supersonic transport (SST) and remains an environmental concern to this day. As is well known, sonic booms are the result of a supersonic aircraft's compression and expansion wave systems being propagated to the ground to form what is often referred to as an N wave. The strength of this wave depends on many things, including the amount and distribution of lift carried by the aircraft's wings, the wing and fuselage thickness and volume distributions, Mach number, and, of course, the atmosphere. Whereas longitudinal, lateral, and vertical distributions of volume and lift all play a part, much of technology in the 1950s, 1960s, and 1970s relied on approximations yielding "equivalent" axisymmetric-body distributions. Nevertheless, flight tests of a wide range of aircraft attest to the efficacy of this methodology.[1,2] Ferri fully understood the physics and mathematics of sonic booms and turned his attention to determining what an aircraft should look like if the boom were minimized. He outlined, in general, the technical tasks that needed to be addressed at the Third Conference on Sonic Boom Research[3] along with some other more "political" problems:

> The formation of sonic boom by supersonic airplanes is a physical phenomenon that cannot be eliminated when the airplane has lift and can only be reduced or modified; therefore, any technical effort in this field should be directed to answering the following basic questions;
> 1) What is the level of minimum practical values that can be obtained if the airplane design is optimized for minimum sonic boom?
> 2) What is the minimum value acceptable if the airplane flies over a populated area?
> 3) What are the penalties of performance, and what is a possible compromise if the airplane is designed for acceptable sonic booms?

Ferri's work was primarily aimed at question 1, but with question 3 receiving some attention as well. The sonic boom research carried out in the past decade has also concentrated on items 1 and 3, building on many of Dr. Ferri's ideas. Most of the research to define the public acceptance of sonic boom, item 2, was carried out in the 1960s. In the following sections, many of Dr. Ferri's most significant sonic-boom papers are summarized in chronological order.

First and Second Sonic Boom Conferences

The first visible evidence of Ferri's interest in sonic booms is in the proceedings of NASA's first Sonic Boom Conference[4] in April of 1967. Here he summarized his views in two short paragraphs in the "Contributing Remarks" section. The following year (May 1968) he was a full participant due, in part, to an initiative by

NASA's Research Division of the Office of Advanced Research and Technology. Schwartz, the Division Chief, wrote in the preface to the proceedings of the Second Conference on Sonic Boom Research[5]:

> Also, it was concluded at last year's meeting, April 12, 1967, that there was a clear need for the active participation of knowledgeable aerodynamicists and engineers in sonic boom research in order to elevate our level of understanding. Accordingly, the Research Division of the Office of Advanced Research and Technology, NASA Headquarters, established the following seven research programs in six universities to complement the in-house program at the NASA Ames and Langley Research Centers and to investigate the 10 basic research areas:
> New York University—A. Ferri and L. Ting—Low boom configurations, N-wave reflections
> Cornell University—E. L. Resler, Jr. and F. K. Moore—No boom-lifting configurations, farfield theory
> The Aeronautics Research Institute of Sweden—M. T. Landahl—Nonlinear effects
> Colorado University—A. Busemann—Boom reduction
> Princeton University—W. D. Hayes—Second-order wave theory, geometric acoustics propagation through a caustic (ray envelope)
> Cornell University—A. R. Seebass and A. R. George—Azimuthal redistribution
> Columbia University—M. B. Friedmann—Theory of the superboom

Schwartz also commented[5] on a number of papers presented at the Second Conference, including the one by Ferri and Ismail.[6] Schwartz wrote[5]:

> Antonio Ferri showed that redistribution of lift along the length of present SST configurations results in near-field effects that provide maximum sonic boom overpressure on the order of 1 pound per square foot at no expense to the lift-to-drag ratio of the airplane at cruise. This is a significant reduction compared with the maximum boom overpressure of 2 pounds per square foot for present configurations selected for the supersonic transport. For a given lift and volume of an aircraft there is a lower bound to the far-field overpressure. This results from the fact that, while the lift contribution to sonic boom can be reduced by the addition of suitable volume elements, there is no way of avoiding the boom attributed to lift alone without modifying the Bernoulli constant of the flow. Thus, Ferri has attempted to approach these lower bounds with aircraft configurations that have realistic skin friction and wave drag contributions and not unusual structural requirements.

Ferri and Ismail's results[6] had as a thesis that lift, which could be approximated by equivalent volume elements, had to be spread out longitudinally and in such a way to minimize the pressure jump across the bow shock. Several different approaches were examined to do this. One was to divide the lift between a canard and wing with the lift, consequently, spread out over the entire length of the configuration. Figure 1, from Ferri and Ismail's paper, shows that with the canard of a simplified configuration carrying one-third of the total lift, sonic boom signatures with a stair-step or double shock were produced. The leading shock's pressure jump is 1.12 lb/ft^2 (for the configuration whose overall length is 300 ft). These results also

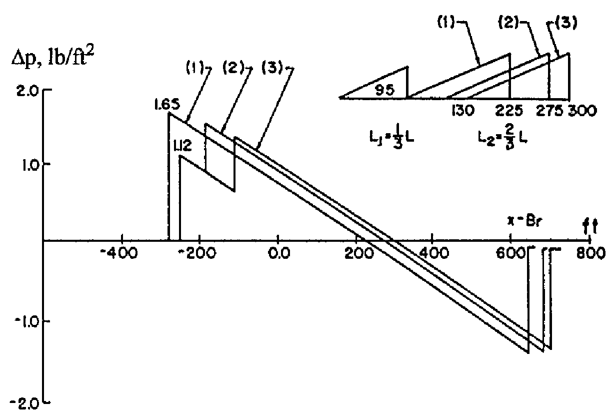


Fig. 1 Sonic boom signature of the configurations shown (from Ref. 6).

indicated as the canard and wing are moved apart, further reductions might be possible.

Several more realistic low-boom configurations were offered by Ferri that took advantage of the interaction of the fuselage's flowfield with the wing to produce more lift for a given drag. (This phenomena is discussed in some detail in the paper.[6]) Figure 2 illustrates one of these configurations and indicates a boom of 1.08 lb/ft^2. The dashed lines in Fig. 2 represent a more conventional geometry.

The concluding remarks of Ref. 6 are particularly insightful, that is, "From these preliminary considerations, it appears that airplanes having lifting surfaces extended to the front of the fuselage, and utilizing interference effects can be effective in reducing maximum sonic boom overpressure, because it utilizes near-field effects."

Third Sonic Boom Conference

Ferri presented two papers at the Third Sonic Boom Conference, one entitled "Airplane Configurations for Low Sonic Boom,"[3] and the other "Observations on Problems Related to Experimental Determination of Sonic Boom."[7] The latter was by Ferri and Wang. The first of these two papers constitutes a further extension of the low-boom ideas put forth at the Second Sonic Boom Conference, plus a scheme for tailoring the flight path of a supersonic transport to achieve boom relief over a specific area. Ferri stated that the latter

> . . . would be useful to reduce substantially the sonic boom when airplanes fly in the proximity of cities. This could be done if the airplane reduces its lift by means of a maneuver. An airplane flying at high velocity could perform a pull-up maneuver of a few degrees before reaching the point where the sonic boom peak value should be reduced and then fly a lower lift trajectory over the selected point. The airplane could then fly for several miles producing a signal that is substantially reduced.

Figure 3 (from Ref. 3) shows the distance over which the boom would be reduced for different values of the reduced C_L ratio to

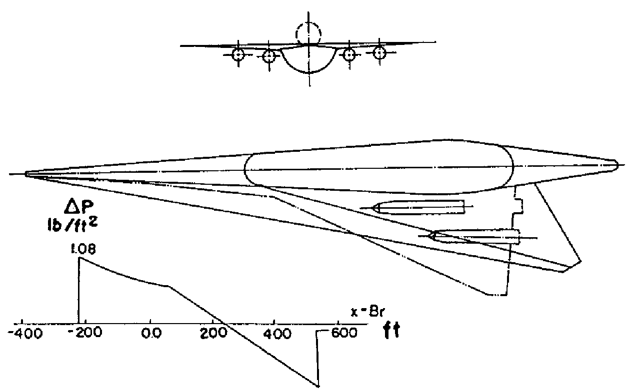


Fig. 2 Possible configuration for supersonic airplane (from Ref. 6).

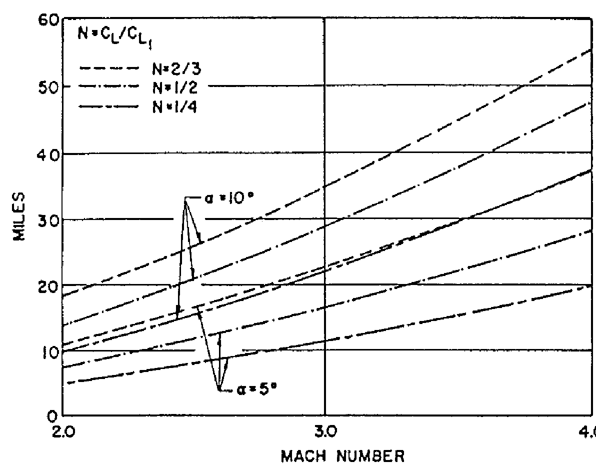


Fig. 3 Range as a function of flight Mach number for a constant C_L constant speed trajectory starting at 40.000 ft and angle α and terminating at the same altitude (from Ref. 3).

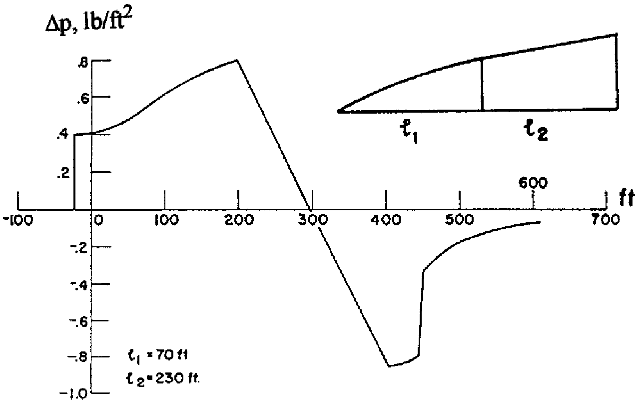


Fig. 4 Sonic boom signature corresponding to an airplane 300 ft long flying at $M = 2.7$ and 40.000-ft altitude at a lift equal to two-thirds of the lift required for horizontal flight. Airplane weight is 460,000 lb. Equivalent area of the front part is equal to one-ninth of the total (from Ref. 3).

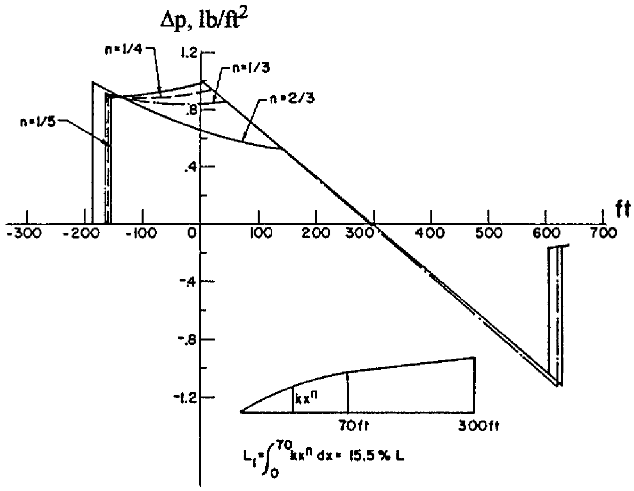


Fig. 5 Effect of distribution of equivalent area in the front part; airplane characteristics are $l = 300$ ft, weight = 460,000 lb, $M = 2.7$, $h = 60{,}000$ ft, L_1 frontal 15.5% of total, and $l_1 = 70$ ft (from Ref. 3).

the trim C_L for straight and level flight for an initial altitude of 40,000 ft. Two values of the initial angle of the trajectory, α, were considered. At a Mach number of 2.7, distances from 10 to 30 miles are achieved, depending on the α angle and the C_L ratio. Only one sonic boom result is given, and it is shown in Fig. 4 (from Ref. 3). In this illustration, the altitude is low enough so that the far-field N wave is not achieved and the initial shock pressure jump is reduced to a remarkable 0.4 lb/ft^2.

As noted earlier, the major part of Ferri's low-boom paper[3] concerned configuration optimization for low levels of sonic boom, including the effects of airplane length, the distribution and amount of area in the front part of the configuration, and weight. Sonic booms for both single-wing and biplane (Ferri's terminology) concepts were examined. Only a few sample results are given here.

The methodology used by Dr. Ferri to design these configurations and those of subsequent papers can be termed F-function or equivalent-body techniques. He notes the following in Ref. 3:

> The results obtained have been derived by using two different numerical programs: (1) the program generated by Carlson [see Refs. 8 and 9] at NASA Langley Research Center (required modifications have been introduced in the original program) with the assumption of constant atmospheric pressure averaged between the flight altitude and ground $p = \sqrt{(P_h P_{\text{ground}})}$, and (2) the additional program generated by W. Hayes [see Ref. 10]. The latter program permits analyzing maneuvers, takes into account variable density for horizontal flight, and requires somewhat longer computing time. Some data have been obtained with both programs.

The equivalent distribution and amount of area in the front part of a configuration is clearly an important parameter in any sonic boom study. Ferri varied both of these quantities using an x^n description of the longitudinal variation of fuselage (equivalent axisymmetric body) cross-section radius. The total area at the front part is defined in Fig. 5, and for the results of Fig. 5 was kept at 15.5% of the total. The distribution of area in the rear part was kept constant and assumed to be linear. Ferri notes that for all cases in Fig. 5 near-field effects are obtained, that is, the far-field N wave is not produced with values of pressure rise on the order of 0.89 lb/ft^2 for area distributions with exponents ranging from one-third to one-fifth.

If the exponent of x is kept at one-third and the area in front is allowed to vary from 9 to 23% of the total, then the boom signatures of Fig. 6 are obtained. Figure 6 clearly shows the importance of the amount of equivalent area in the front and that the boom (for the conditions stated in the legend) was the least for $L_1 = 15.5\%$ of L. Figure 7 shows two possible configurations that correspond to $n = \frac{1}{3}$, $L_1 = 70$ ft, and $L_1/L = 15.5\%$ with an overall length of 300 ft. Also shown in Fig. 7a is the baseline configuration (dotted line), which has a pressure jump on the order of 1.9 for the same conditions as in Figs. 5 and 6.

Several configuration-length sensitivity studies were presented in the low-boom paper[3]; one showed that far-field N waves were obtained for a length of 250 ft, whereas at 300 ft and beyond, a

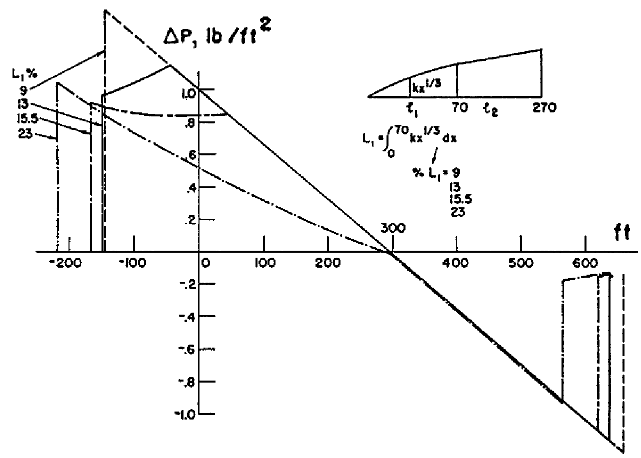


Fig. 6 Sonic booms corresponding to $M = 2.7$, $h = 60{,}000$ ft, weight = 460,000 lb, total length = 300 ft, different equivalent area in the front part, and $l_1 = 70$ ft (from Ref. 3).

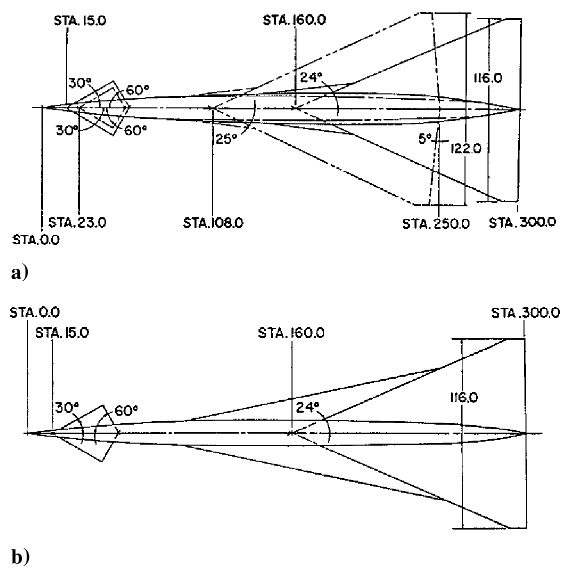


Fig. 7 Possible airplane configurations corresponding to sonic boom shown in Fig. 6 for $L_1 = 0.155$ L: - - - -, actual configuration used for first-generation SST (from Ref. 3).

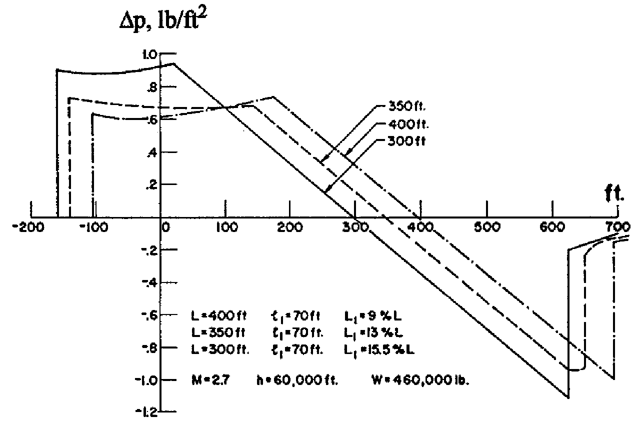


Fig. 8 Effect of length on sonic boom signature (from Ref. 3).

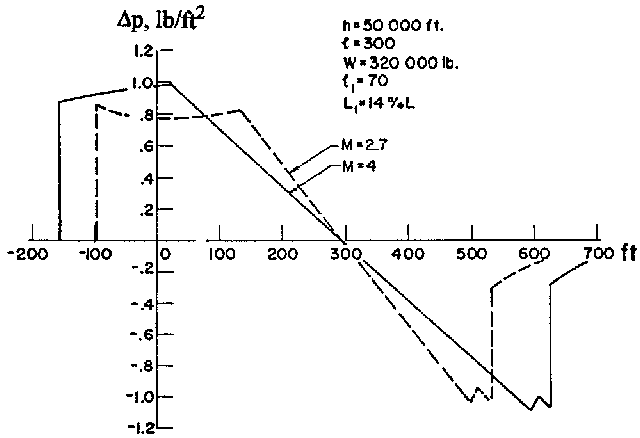


Fig. 9 Sonic boom for two airplanes with same weight and equivalent area distribution flying at $M = 4$ and 2.7 (from Ref. 3).

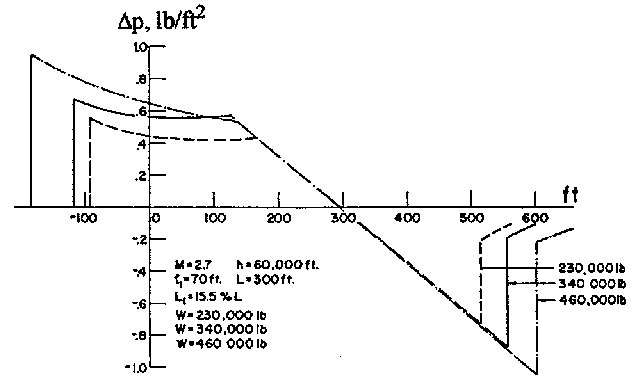


Fig. 10 Sonic boom signature as a function of airplane weight (from Ref. 3).

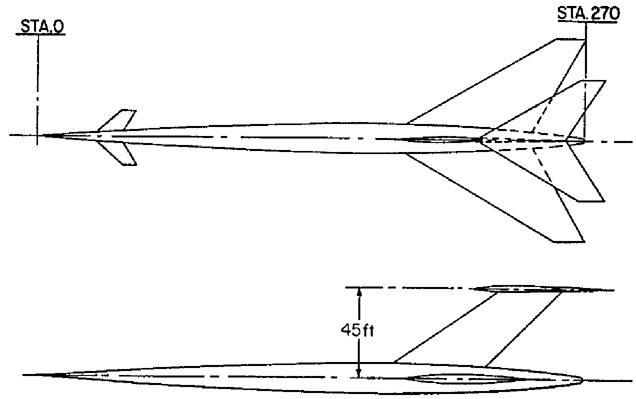


Fig. 11 Possible biplane configuration (from Ref. 3).

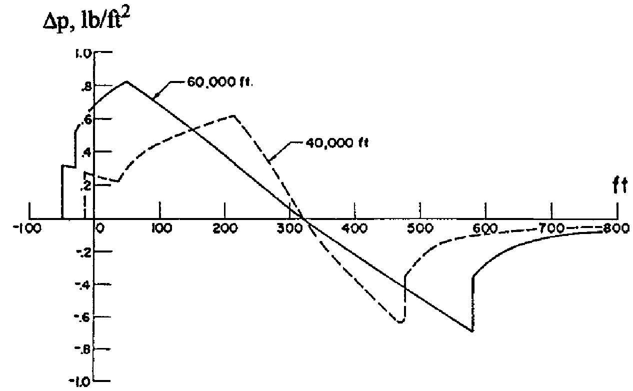


Fig. 12 Sonic boom signature of a biplane configuration at $M = 2.7$ and $h = 40{,}000$ and 60,000 ft, with length = 300 ft, height = 45 ft, and weight = 320,000 lb (from Ref. 3).

near-field signature was realized that reduced the strength of the initial pressure jump. Figure 8 shows boom signatures for configurations with overall lengths of 300, 350, and 400 ft. Areas of the front part of the configuration and the other pertinent parameters are given in Fig. 8. These results clearly indicate that significant boom reductions are possible for configuration lengths beyond 300 ft. A possible 350-ft configuration, similar to those of Fig. 7, with $\Delta p_{\max}$ of 0.7 lb/ft^2 is given in the paper.

The effect of Mach number and weight are illustrated by sonic boom signatures for Mach numbers of 2.7 and 4.0 (weight equal to 320,000 lb) and weights from 230,000 to 460,000 lb (Mach number equal to 2.7) in Figs. 9 and 10. Generally, as Mach number or weight increase at a given altitude, the strength of the boom increases. As Figs. 9 and 10 indicate, booms are less sensitive to Mach number than weight (for the range of conditions chosen). In all cases, the boom pressure jumps are less than 1.0 lb/ft^2. Note that the Mach plot (Fig. 9) is at an altitude of 50,000 ft and that the weight plot (Fig. 10) is at an altitude of 60,000 ft; consequently, the boom shown in Fig. 9 would be lower if these results were for an altitude of 60,000 ft.

Sonic boom sensitivity to altitude was specifically examined for a biplane concept, such as that shown in Fig 11. Figure 12 shows sonic boom signatures for altitudes of 40,000 and 60,000 ft, where the lower altitude signature is clearly lower in magnitude due to the shape of the signature and the near-field effect. Several other biplane concepts and associated boom signatures are given in the low-boom paper[3] and, like the single-wing boom signatures, have initial pressure jumps in the 0.6–0.8-lb/ft^2 range. Overall, the low-boom paper introduced a number of new configuration concepts and consolidated the idea that the high-pressure jumps of fully developed N waves are not necessary if the equivalent longitudinal volume distribution can be properly tailored and the configuration is sufficiently long.

Ferri[3] had the opinion that the configurations studied would not require a significant reduction in the lift-to-drag ratio, but their weight might increase over that of a "conventional" concept. He concludes by suggesting that two further steps should be taken: "i.e.: 1) the acceptance of such levels of disturbances should be determined by measuring the shape and level of present disturbances currently generated in city operations and by additional flight tests; and 2) the incorporation of such concepts in practical, usable configurations for second-generation SST's should be investigated."

The Ferri and Wang papers at the Third Conference on Sonic Boom Research[7] concerns the calculation and measurement of sonic booms in wind tunnels with emphasis on the latter. Four separate subjects are discussed, including 1) support interference, 2) uniformity of flow, 3) difficulties at high Mach numbers, and 4) Reynolds number effects.

Whereas many people consider experimental data, corrected for the most obvious anomalies of the test section flow, to be the most

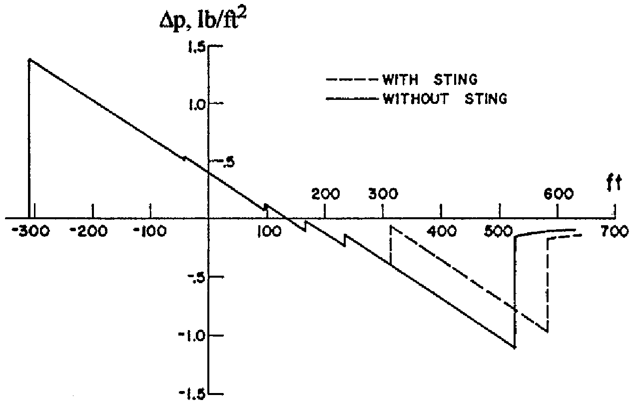


Fig. 13 Effect of sting for configuration with far-field signature (from Ref. 7).

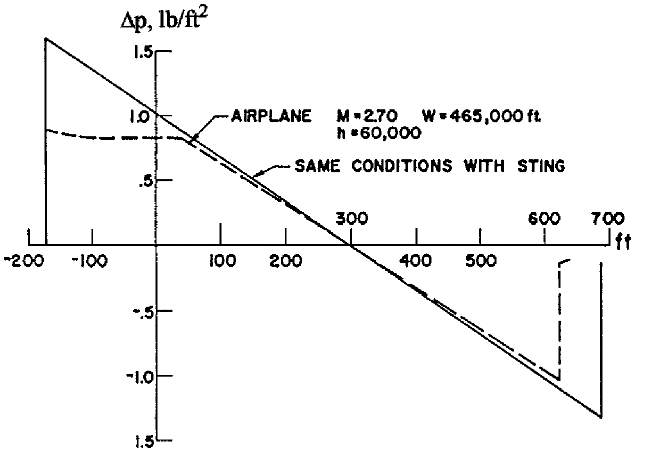
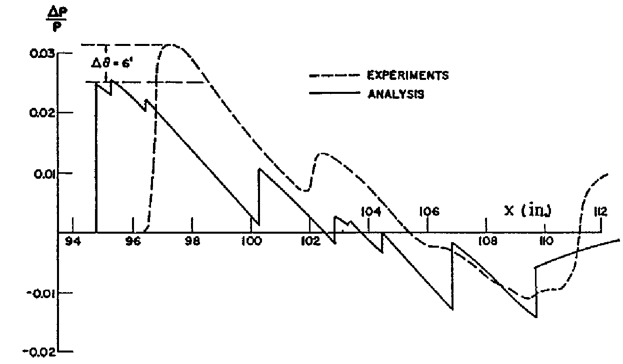
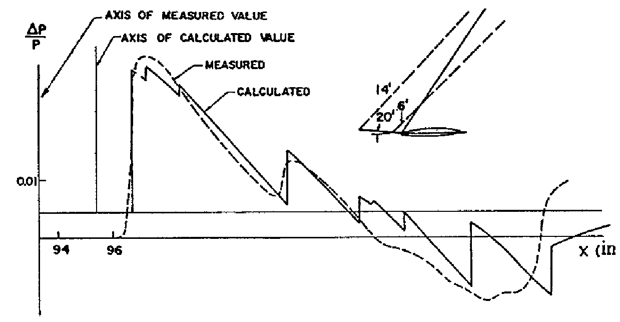


Fig. 14 Effect of presence of sting (from Ref. 7).



a) Uncorrected



b) Corrected

Fig. 15 Sonic boom for $h/l = 3.58$ and $M = 2.7$ (from Ref. 7).

accurate available, Ferri and Wang recognized in their "experimental problems" paper that this may not be so for sonic boom experiments. The use of stings and struts to suspend a model in a wind tunnel test section, along with the nonuniform flow in test sections, produce errors in the wave system emanating from the model as well as the character of the propagation of the wave system and, thus, in the measurement of the sonic boom signature. The authors note:

> A variation of 0.01 in Mach number corresponds to $\Delta P/P = 0.011$ at $M = 2$ and 0.015 at $M = 4$. The corresponding angular deviation decreases with Mach number and goes from 16′ [16 minutes] to 8′ as Mach number increases from $M = 2$ to 4. The deviations due to nonuniformity existing in the wind tunnel increase with Mach number; therefore, at high Mach numbers, these effects are of extreme importance.

Conventional sting-mounted models require modifications to their back end to enable a smooth transition from the real aircraft geometry to the cross section of the sting. Sting supports, however, not only cause modifications to the back end, but also represent an extension to the length of the model. These changes can have a significant impact on sonic boom signatures, both near and far field. A far-field sonic boom signature comparison is shown in Fig. 13, where the sting modification affects only the trailing shock. Figure 14 shows a near-field result, where the sting changes both the front and back shock pressure jumps.

To illustrate the effect of flow nonuniformities, typical experimental and analytical near-field pressure distributions are shown in Fig. 15. One set (Fig. 15a) is uncorrected and the other is corrected (Fig. 15b) so that the position and magnitude of the front pressure jump agree. The correction required is on the order of 6′ (6 minutes) for the shock strength, plus an additional 14′ for the position. Other examples are given in Ref. 7 to make the point that "it is very difficult to measure the sonic boom signature in wind tunnels at large values h/l" (where h is the radial distance from the model centerline to the measuring station and l is model length).

Wind-tunnel tests of models that are on the order of 1 ft long, tested at atmospheric pressure, and subjected to an onset flow of Mach 2.7 will have a Reynolds number of approximately 19×10^6 based on length. (Most supersonic tunnels run at pressures much less than atmospheric because of power requirements.) In contrast, a 300-ft-long commercial transport at an altitude of 60,000 ft and traveling at a Mach number of 2.7 will have a Reynolds number of 595×10^6 based on length. The flow over local segments of the wing and tail will have their Reynolds numbers reduced by the ratio of the length of segment to the length of the airplane. The large differences between flight and wind-tunnel Reynolds numbers are a cause for concern. For wind-tunnel tests, the boundary layers will have more laminar flow, which, in turn, will yield different boundary-layer thicknesses and, consequently, different effective shapes, that is, the inviscid flow responds to the geometric shape plus the addition of the boundary-layer displacement thickness. Also, as Ferri and Wang[7] point out, the "possibility of laminar separation exists for the flow at the trailing and leading edges. Such separation will change the lift distribution for a given value of the lift." Today, Navier–Stokes codes and state-of-the-art computers enable the examination and assessment of these Reynolds number differences, but in the early 1970s when this work was performed, these capabilities were not available.

One final cautionary note by the authors in the use of axisymmetric sonic boom predictive methods is given in Ref. 7. Variations in the near-field pressure signatures (measured or calculated) from that of an equivalent axisymmetric body will cause errors in the calculated sonic boom by up to 20%. A specific geometry (cone–cylinder) is analyzed to make this point in the text.

One can summarize the accomplishments of the "experimental problems" paper[7] in this way. It quantified the errors in sonic-boom measurements obtained in wind tunnels, which require sting-mounted models and have small nonuniformities in the onset flow. These anomalies are normally inconsequential or correctable in force and moment tests but can lead one to a false sense of accuracy in sonic-boom testing. It also noted some of the shortcomings of the predictive techniques then in use.

1972 AIAA Paper Entitled "Sonic-Boom Generation, Propagation, and Minimization"

In a state-of-the-art paper[11] coauthored with Schwartz in 1972, Ferri extended many of the thoughts given in the two papers[3,7] of the Third Sonic Boom Conference just summarized. For example, additional discussion was given to public acceptance of sonic booms, the effect of three-dimensional and nonlinear effects on boom prediction, and the effect of atmospheric and ground characteristics on the reduction or amplification of the incident and reflected waves. In addition, revised new low-boom configurations were offered, and their boom signatures propagated from 65,000-ft altitude were given.

Experimental near-field wind-tunnel data[12] on the configuration of Fig. 16 were used as the basis for illustrating three-dimensional nonlinear and sting effects using various methodologies. The dashed lines in Fig. 16 indicate the geometry tested to compensate for the effect of the sting. The streamline deviation had been measured at several angular stations on a cylinder having its axis on the model axis at two distances, 0.271 and 0.558, of the model length. These experiments were performed by Sorenson of the Aeronautical Institute of Sweden in a blowdown tunnel at a Mach number of 2.718. Data analysis was performed by a team led by Ferri. The tunnel has a square test section of 19.7 in. × 19.7 in. with perforated walls for the transonic speed range and a flexible wall nozzle that allows the Mach numbers to be varied continuously between 1 and 4. A schematic of the setup is shown in Fig. 17. A substantial discussion of the details of the instrumentation and results is given in the report.[12]

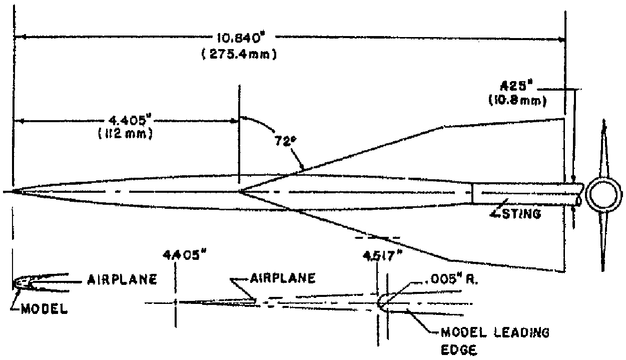


Fig. 16 Model design (from Ref. 12).

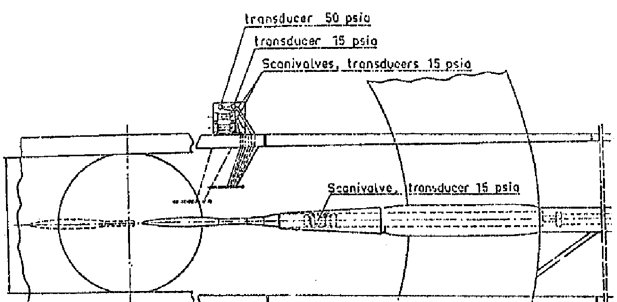


Fig. 17 Schematic view of test setup (from Ref. 12).

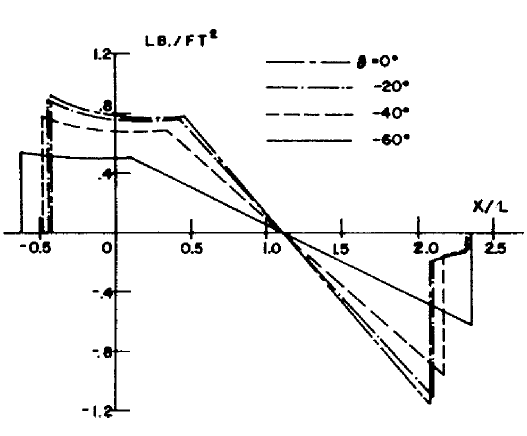


Fig. 18 Sonic boom signature $L = 300$ ft, $h = 60{,}000$ ft, $w = 460{,}000$ lb, and $M = 2.70$ with variable pressure program (from Ref. 11).

A more realistic geometry, with the same area distribution as the model shown in Fig. 16, has been postulated to predict the boom signatures on the plane of symmetry and for several angles off the plane of symmetry at $h/l = 200$. These boom signatures, shown in Fig. 18, have a flat-top type characteristic and a drop off of the initial pressure jump as one moves away from the symmetry plane. A symmetry plane boom of approximately 0.8 lb/ft² is obtained.

Figure 19 shows the front half of sonic-boom signatures at $r/l = 200$ determined by the use of three different propagation methods. Ferri and Schwartz[11] describe Fig. 19 as follows:

> Figure 19 indicates the sonic-boom obtained from the experiments by extrapolating the experimental data to an r/l equal to 200. Three curves are presented in this figure: (1) where three-dimensional effects and nonlinear effects are included in the extrapolation, called second order theory; (2) where only three-dimensional effects are neglected and only the measurements in the plane $\phi = 0$ are used $\phi_{\theta\theta} = 0$; and (3) where all the nonlinear effects are neglected and $\phi_{\theta\theta} = 0$ (linearized theory). The results show the importance of three-dimensional effects and the small importance of the nonlinear effects even at these small distances; therefore, they give confidence in the method proposed.

They[11] note that the double-shock boom in Fig. 19 is similar in magnitude to those of Fig. 18 and only a small change in the area distribution around 200 ft from the nose is needed to bring them into agreement. The shorter signature, labeled curve 1, is typical of the high-order methods. Several new low boom configurations are presented in Ferri and Schwartz's overview paper,[11] one of which is shown in Fig. 20. It has a 300-ft-long fuselage, and the required wing for an airplane weighing 465,000 pounds, flying at $M = 2.7$ and at an altitude of 65,000 ft. Figure 21 shows the sonic-boom signature for this configuration, which has an initial pressure jump of 0.6 lb/ft². The "tail-end" pressure jump is about the same magnitude.

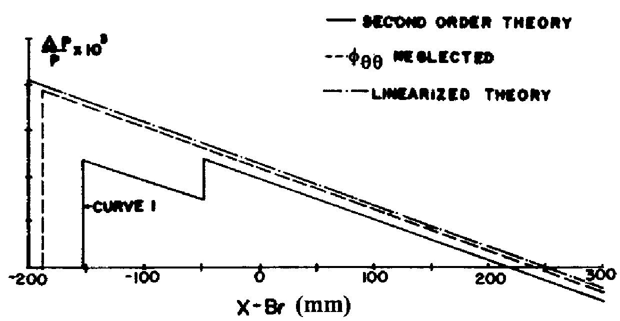


Fig. 19 Comparison of sonic boom signatures for several types of analyses $r/L = 200$: ——, second-order theory; - - -, $\phi_{\theta\theta}$ neglected; and - · -, linearized theory (from Ref. 11).

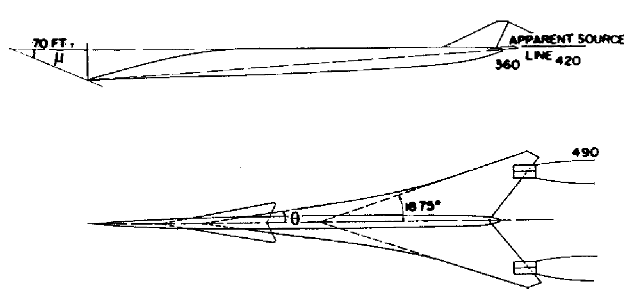


Fig. 20 Configuration of low sonic boom airplane, maximum "bang" 0.6 lb/ft², $M = 2.70$, and weight = 465,000 lb (from Ref. 11).

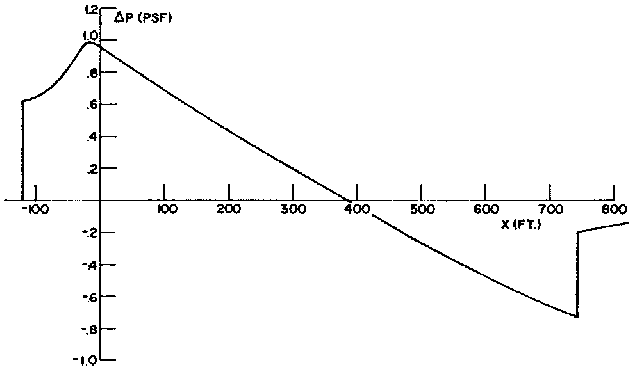


Fig. 21 Sonic boom signature of configuration shown in Fig. 20 (from Ref. 11).

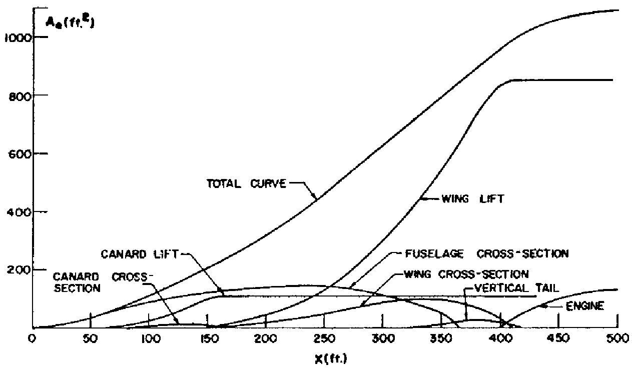
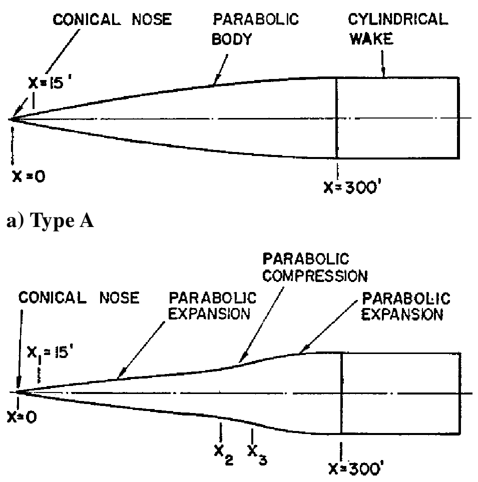


Fig. 22 Equivalent area distribution corresponding to airplane configuration shown in Fig. 20 (from Ref. 11).



a) Type A

b) Type B

Fig. 23 Schematic diagram of body shape (from Ref. 13).

As noted earlier, the fuselage of the configuration of Fig. 20 is 300 ft long. The swept-wing geometry makes the overall length about 330 ft, and the engine exhausts increase the effective length still further. Figure 22 shows the equivalent distribution for the configuration of Fig. 20 including the contributions of all major components.

1973 AIAA Paper Entitled "Sonic-Boom Analysis for High Altitude Flight at High Mach Number"

An AIAA paper[13] published in October of 1973, by Ferri et al., outlines the mathematical development and application of a characteristics-based method for sonic-boom calculation. It purports to include all of the nonlinear terms in the governing equations and the nonuniformity of the atmosphere with the further assumption

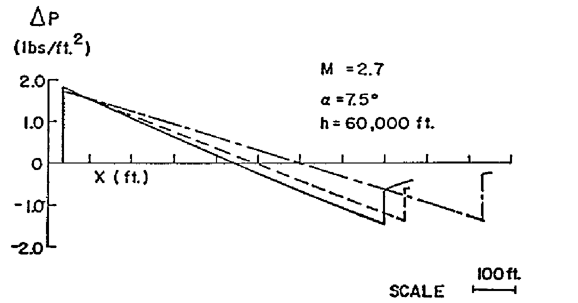


Fig. 24 Comparison of pressure signature for body shape, type A: - - -, Carlson[8]; – – –, Hayes et al.[10]; and ——, characteristics (from Ref. 13).

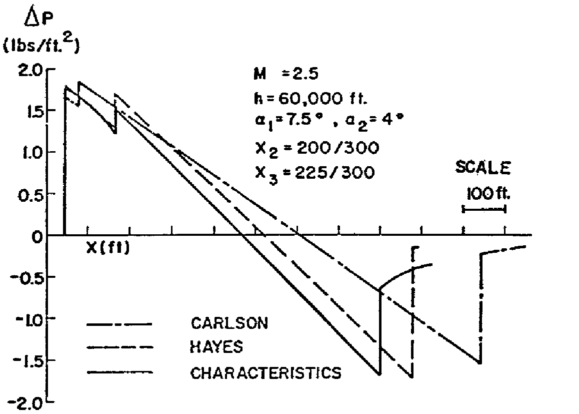


Fig. 25 Comparison of pressure signatures for body shape, type B (from Ref. 13).

of quasi-axial symmetry. Near-field solutions have to be obtained either from a three-dimensional characteristic program or from experimental data. When these near-field results are used on a cylindrical surface with radius equal to the order of a body length, for example, one or two, as the input data, a numerical program is developed for the far-field analysis in the vertical plane of symmetry for all quantities symmetric with the plane, their second circumferential derivatives and the first derivative of the circumferential velocity component. Details of the method were provided therein.

Results from the application of the methodology to two basic axisymmetric configurations (Fig. 23) are given in the paper[13] for a range of Mach numbers, altitudes, and cone half angles. One sonic-boom signature for each configuration is given here to show how the more exact method of Ferri et al. compares with the state-of-the-art methods of Carlson[8] and Hayes et al.[10] Figure 24 shows the sonic-boom signature for the type A body at a Mach number of 2.7 and an altitude of 60,000 ft. The cone angle α is 7.5 deg. It shows that the simplest method yields the longest footprint and the most exact the shortest. As Mach number increases, the differences increase.

The type B configuration result is given in Fig. 25. The flight conditions and geometric parameters are indicated in Fig. 25. Pressure-jump magnitudes similar to those in Fig. 24 are seen but double shocks are predicted with the second shock only 0.2–0.3 lb/ft^2 in strength. As in the case of the type A body, the length of the signature calculated by the characteristics method is the shortest. Predictions of the initial pressure jumps shown in Figs. 24 and 25 are roughly the same for all methods.

AIAA Dryden Lecture Entitled "Possibilities and Goals for the Future SST"

The last of Ferri's papers to be reviewed is his Dryden Lecture of 1975.[14] This paper is recommended reading for anyone interested in the technical problems and opportunities attendant to the development of a supersonic commercial transport. Societal and political arguments for an SST program are offered that are as relevant today as they were in 1975. The subjects covered are 1) economic viability;

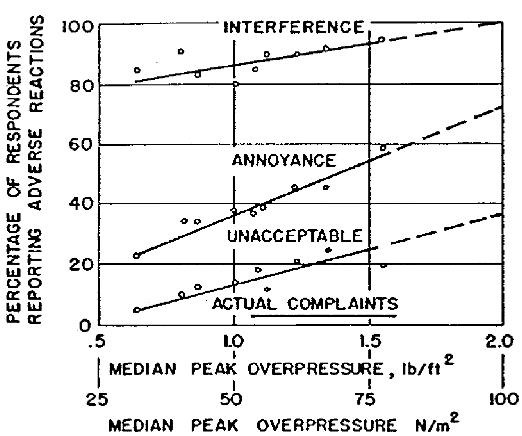


Fig. 26 Percent reporting adverse reactions to sonic boom (from Ref. 15).

2) propulsion, that is, engine developments and NO_X emissions; 3) structures and new materials, that is, potential weight reductions; 4) aerodynamics and aerodynamic design, that is, L/D and drag reduction; and 5) sonic boom, that is, atmospheric- and ground-configuration effects, public tolerance, and optimum boom shapes.

In the Dryden Lecture paper there is substantially more discussion of the public acceptance of the sonic boom than in previous papers, and data from various sources are used to make the point that pressure jumps less than 1.0 lb/ft^2 (comparable to distant thunder) might be acceptable as well as achievable. Figure 26 shows one of the plots Ferri used and is based on data from the Oklahoma City tests[15] carried out in the 1960s and indicates what might be acceptable. Ferri comments:

> Acceptability criteria are difficult to establish. Experiments performed in the 1960–1970's are probably not indicative for revealing long range conclusions because of the publicity given to the experiments and because of the novelty of the phenomenon. However, they are indicative for establishing variation of annoyance produced by different levels of sonic-boom.

He further notes that the sonic boom that is calculated and usually discussed is that directly under the track of the aircraft. The boom rapidly drops off to either side and, consequently, is less of an annoyance. In consideration of this and the prospects of reducing the maximum boom, Ferri writes, "Then for a long range airplane the possibility of flying overland especially in the last part of the range appears to have a practical possibility."

The discussion of the effects of configuration parameters on sonic boom signatures given in the Dryden Lecture is consistent with the material presented in previous papers and discussed earlier.

Summary

One cannot help being impressed by the depth and breath of Dr. Ferri's knowledge of all of the technologies that are important to the design of a successful SST. His own contributions, and those that he stimulated, have had a major impact on the progress achieved to date. He was keenly aware of the problems that still remained, of both a technical and an environmental nature. Aside from solving these problems, one of his major justifications for vigorously pursuing this technology was related to the benefits to society. He wrote:

> All scientific, military activities, and all activities related to supporting the sick and the elderly, the under privileged, are surely justified only on the basis of human sensitivity, human interest, or human ability to survive. I feel that an efficient SST can perform the mission to improve understanding, knowledge, and appreciation of characteristics, problems and interests of distance people, which in my opinion is a mission as important as other humanitarian or educational missions, and is a fundamental step toward improving stability in the world.

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