# Concorde Booms and the Mysterious East Coast Noises

**Peter H Rogers**

*Postal:*
School of Mechanical Engineering
Georgia Institute of Technology
Atlanta, Georgia 30326
USA

*Email:*
peter.rogers@gatech.edu

**Domenic J. Maglieri**

*Postal:*
Eagle Aeronautics, Inc.
732 Thimble Shoals Boulevard
Building C204
Newport News, Virginia 23606
USA

*Email:*
maglieri@eagleaeronautics.com

*Concorde's primary and secondary booms significantly altered the role it set out to play in scheduled commercial supersonic travel. Could the Mach 2 Concorde have been the source of the alarming East Coast Mystery Booms of the late '70s?*

## Introduction

The last commercial flight of the only operational civil supersonic transport (SST), the Concorde (**Figure 1**), was completed on October 24, 2003. This brought an end to almost 30 years of civil supersonic travel and the cessation of its sonic booms. Over its life span, much has been learned from this 400,000-pound, 100-passenger, Mach 2.0 commercial supersonic transport and its operations that is of significant value toward the development of the next generation of commercial aircraft that will be designed to cruise supersonically over land. It has been 60 years since the concept of bringing to life an aircraft that would provide the public scheduled commercial supersonic travel. It is the purpose of this article to provide to present and future generations a brief overview of the Concorde, how its sonic boom altered the role it was expected to play in scheduled commercial supersonic commercial travel, and the notoriety it gathered during the 1977-1978 mysterious east coast acoustic disturbances.

***Figure 1.*** *The Concorde Supersonic Transport on its last ever flight in 2003. Photo by Adrian Pingstone.*

## Concorde

Before the Concorde, the civil aviation market was dominated by US subsonic aircraft. Britain and France, anxious to have a more significant role in the design of the next generation of commercial aircraft, jointly decided to take a giant leap in air travel and go with the supersonic transport. This decision was based in part on the assumption that the experience gained regarding supersonic operations through their military programs could be applicable to passenger travel. The Concorde project began with a request from the Royal Aircraft Establishment in the early 1950s to form a committee to study the SST concept. This group met in February 1954 and issued their study report April 1955. On October 1, 1956, the Supersonic Transport Advisory Committee was formed with the task of developing an SST design and finding industry partners to build it. Two prototypes were built in 1965: the French 001 and the British 002.

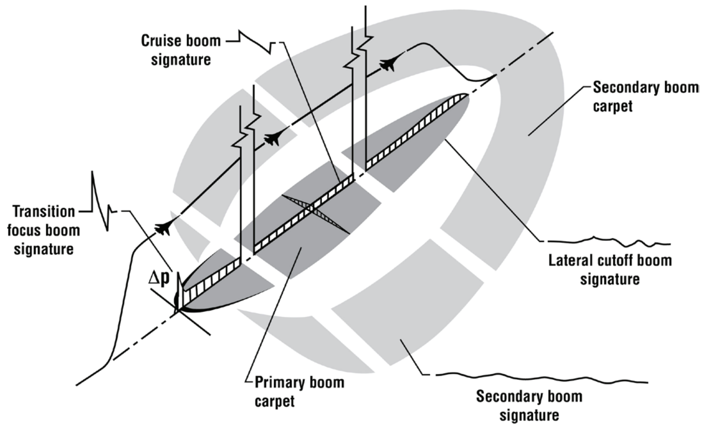


***Figure 2.*** *Nature of the sonic boom ground footprint for a transatlantic flight by the Concorde. See text for description. Δp, Difference between the sonic boom pressure and the ambient pressure. From Maglieri et al. (2014).*

The French aircraft flew supersonic on October 1, 1969. In the interim, development costs had increased significantly. This, along with the cancellation of the US SST in 1971 and the oil crisis in 1973 (Concorde's fuel consumption was about 16 passenger miles per gallon compared with about 54 passenger miles per gallon of fuel for the Douglas DC-10), resulted in only 20 aircraft being built; 6 were prototypes and the other 14 Anglo-French-built Concordes were placed in commercial service with 7 each being assigned to British Airways and Air France.

Since the first commercial passenger carrying flight in 1976, these 14 aircraft flew a combined total of some 240,000 hours. The highest number of hours flown by any one Concorde per year was 926, which is low in comparison to some 2,000-3,000 hours flown by subsonic long-haul transports. It is estimated that one-third of all Concorde flight hours were flown at Mach 2. Thus, the Concorde fleet would have accumulated some 80,000 supersonic flight hours, more than the combined total of all of the world's military aircraft.

Much has been written about the Concorde highlighting high-ticket, operational, and maintenance costs; low utilization; high development and subsidy costs; its sonic boom; and its excessive airport community noise. However, as stated by McLean (1985, p. 58), "In spite of being cast as a transportation 'heavy' by critics around the world, the British/French Concorde ranks as one of the foremost technical achievements that has ever been made. The two nations that developed this aircraft not only spoke different languages, but also used different measurement systems. Yet, out of this unusual alliance came the first and, so far, only commercial supersonic transport in regular passenger service. Like it or not, the Concorde is a remarkable airplane. It reduced the trip times between continents to one-half of those of the best subsonic jet transports, an accomplishment that would have been cheered in bygone years. The Concorde is perhaps the world's most tested transport airplane and, in its operations to date, has experienced no major accidents and has had no passenger fatalities."

Concorde's exemplary safety record ended tragically with the crash of Air France flight 053 on July 25, 2000 (Riding, 2000). The accident marked the beginning of the end for the Concorde and commercial supersonic travel.

## Sonic Boom Footprint

Considerable criticism about the Concorde derived from the sonic boom trail it imposed along the ground during its supersonic flight. The nature of the sonic boom ground footprint for a flight such as that of the Concorde, during which the aircraft cruises supersonically for a large portion of the distance, is shown in **Figure 2**. Two ground exposure patterns in which booms are observed are shown.

The primary sonic boom "carpet" is the region on the ground ensonified by the part of the sonic boom that propagates directly downward from the aircraft to the ground. It begins with the transition focus boom region resulting from acceleration of the aircraft from subsonic to supersonic speeds. This focus is a one-time occurrence; it does not move with the aircraft and is unavoidable. It is followed by the N-wave boom signatures produced during the climb-and-cruise phase of flight. (The pressure waveform of the carpet boom has the shape of the letter "N" as seen in **Figures 2** and **3**.) The primary carpet booms are observed shortly after the passage of the aircraft and result from wave propagation through only that part of the atmosphere below the aircraft. The secondary boom "carpet" is the region on the ground ensonified by the boom that initially goes upward from the aircraft but is refracted back to the ground by winds in the stratosphere above the plane. Between the primary and secondary carpets exists a region in which no booms are observed. The secondary booms arrive some 10-15 minutes after the passage of the aircraft, and these disturbances tend to be very weak in intensity (on the order of 1-10 pascals versus around 100 pascals for the primary booms) but persist over longer periods of time (on the order of 5-10 seconds).

The manner in which the atmosphere above and below the aircraft is involved in developing the primary and secondary boom carpets is shown in the ray diagram in **Figure 4**. On the right side of **Figure 4** are examples of temperature and wind profiles for a given atmosphere. Note that there is a portion of the higher atmosphere in which the temperature increases as the altitude increases, and the associated wave propagation speed thus increases compared with that in the lower portions of the atmosphere, causing upward propagating rays to be curved (refracted) back toward the ground. The wind speed gradient will also influence refraction and may reinforce, or counteract, the effects due to temperature gradient.

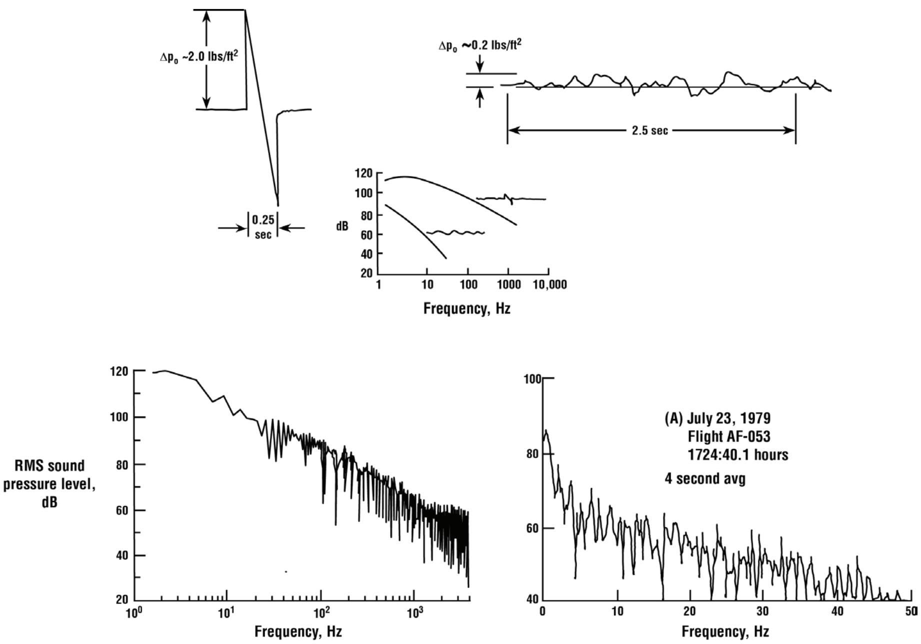


***Figure 3.*** *Comparison of Concorde primary and secondary sonic boom signatures and spectra. One pound per square foot (psf) equals 47.88 pascals. Adapted from Holbeche (1972) and Rickley and Pierce (1980).*

On the left side of **Figure 4** is a ray diagram showing a variety of ray paths that the booms travel for an aircraft in supersonic flight at an altitude of 18 kilometers, traveling toward the viewer. The downward-propagating rays, shown by the solid lines, impact the ground to form the primary boom carpet, as in **Figure 4**. At a lateral distance of about 40 kilometers (25 nautical miles) in the example shown, the rays refract away from the ground and thus define the lateral extent of the primary boom carpet. Also indicated is a secondary boom carpet at about 120-160 kilometers from the flight track, in which the dashed-line rays impact. These dashed-line rays arrive in two different ways: either they travel directly to the secondary carpet as a result of bending in the upper atmosphere or they may first be a part of the primary carpet, reflect upward from the surface, and then bend downward after traveling through a portion of the upper atmosphere.

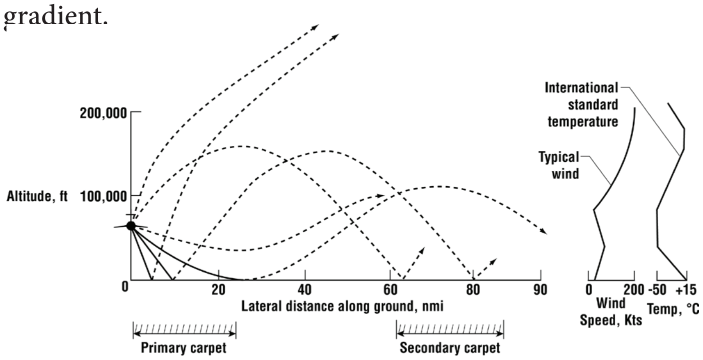


***Figure 4.*** *Ray path diagram in plane normal to that of flight illustrating the manner in which the atmosphere above and below is involved in developing the primary and secondary boom carpets. One nautical mile equals 1.852 kilometer. From Maglieri et al. (2014).*

Early on in the development of the Concorde, there was serious concern that its primary carpet boom levels would be too excessive to allow overland supersonic operations. Early commercial flight operations eventually proved this to be the case. Concorde supersonic flying would henceforth be confined to overwater operations, primarily Atlantic routes, due its limited range, thereby limiting utilization of the plane. On the other hand, the booms near the lateral cutoff and the secondary booms, which do not have an N-wave character and are much lower in intensity, are not apt to be the source of serious community response problems. Near the lateral cutoff, primary booms usually resemble low rumbles or rolling thunder. Secondary booms, however, are generally not audible (0.1-1.0 hertz) but can cause building vibrations that are readily felt. It will be shown later in this article that secondary booms also played an influential role in further defining Concorde's operating procedures.

## Secondary Sonic Booms

Secondary booms, also referred to as "over-the-top" booms, were more of an unknown quantity during the design-and-development days of the Concorde. They too, like primary booms, are inherent to supersonic flight. The distinct differences between secondary and primary boom signatures

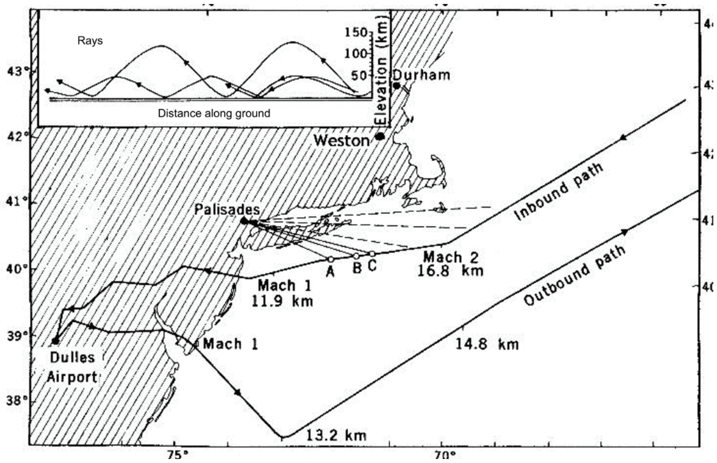


*Figure 5. Map showing the inbound and outbound flight paths of Concorde into Washington Dulles International Airport, VA. Inset shows schematic ray tracing indicating ray paths through the stratosphere (~40-50 kilometers) and the thermosphere (100-130 kilometers). From Balachandra et al. (1977).*

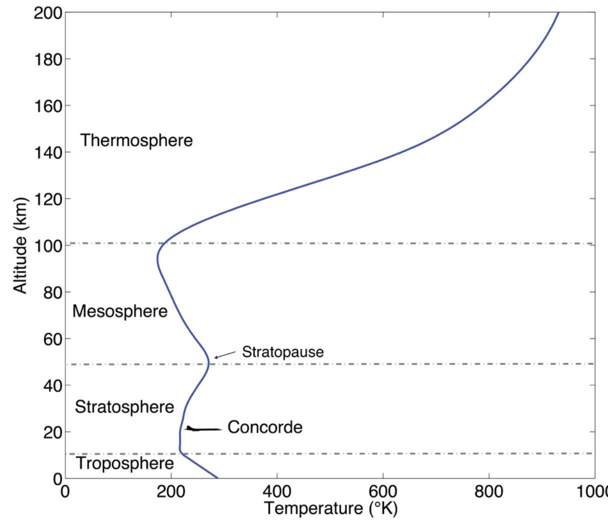


*Figure 6. Typical temperature profile for the atmosphere based U.S. Standard Atmosphere, 1976. From NASA (1976).*

may be seen with the aid of **Figure 3**. The top left of **Figure 3** shows the cruise carpet boom signature from the Concorde and to the right is the resulting secondary boom signature. Note that the Concorde secondary boom is considerably lower in overpressure and frequency than the primary boom.

A further indication of the significant difference between the secondary and primary boom signatures may be obtained by comparing their frequency spectra as shown in the lower portion of **Figure 3**. The primary N-wave boom spectrum contains a considerable amount of energy out beyond 1,000 hertz (Holbeche, 1972), whereas the secondary boom energy is confined to frequencies below ~50 hertz (Rickley and Pierce, 1980).

One of the earliest observations of secondary booms occurred during controlled NASA sonic boom flight tests over Wallops Island, VA, in July-August of 1959 (Lina and Maglieri, 1960). Microbarograph measurements were recorded some 195 kilometers distant.

In 1974, Liszka (1978) carried out an unpublished flight experiment to measure the secondary booms from a small supersonic aircraft that propagated 600-900 kilometers. During the winter months of 1976-1977 and 1977-1978, the Concorde infrasonic signals (secondary booms) were recorded regularly at measurement stations in northern Sweden at distances up to 5,000 kilometers from the Concorde flights between the United States and Europe. Relatively high signal amplitudes up to 0.1 newtons per square meter were observed.

It was reported by Lessen and Pryce (1978) that during the fall of 1976 and thereafter, noises were heard, mostly indoors, in the southwest part of England, the majority of these occurring about 9:30 p.m. The regularity of the noises suggested that they were from inbound Concorde flights. The study showed that the sounds leaving the aircraft in an upward and downward direction were influenced by the temperature and winds in the upper atmosphere. The authors eventually developed ray-tracing techniques to delineate the carpet booms.

In 1976, the issue of Concorde booms over the southwest of England was discussed in great detail in the House of Commons by Penhaligon (1978). The noise had been described as secondary booms. He reminded the ministers that it was indicated that the boom skirt would be no more than 20 kilometers wide (referring to the primary boom carpet), yet the same booms were heard at places 65-80 kilometers apart. It was also stated that virtually all of the complaints were made about inward flights and he asked that the Concorde slow down earlier. He was informed that such a change in operations would increase fuel use, resulting in a load factor penalty of some 12 passengers.

On the US side, shortly after the Concorde entered into commercial service in mid-1976, strange, sharp acoustic impulses were recorded by Balanchandra et al. (1977) with the low-frequency array of microphones at the Lamont-Doherty Geological Observatory, Palisades, NY, and from Durham, NH. The arrival times of the signals correlated well with Concorde arrivals. **Figure 5** shows the Concorde flight paths in and out of Washington Dulles International Airport (Balanchandra et al., 1977). Altitude and Mach number are marked on the tracks. Points A, B, and C are average source locations for the three signals recorded at Palisades, NY. Acoustic signals were recorded on both the inbound and outbound flights at Durham, NH. Of interest is the schematic ray tracing, shown in the upper left inset in **Figure 5**, that indicates ray paths through the stratosphere (about 40-50 kilometers) and the thermosphere (100-130 kilometers). The received signals associated with propagation through the stratosphere were much stronger than those propagating through the thermosphere. A typical temperature profile for the atmosphere illustrating the various atmospheric layers is shown in **Figure 6**.

## The Mysterious East Coast Booms

The secondary sonic booms went essentially unnoticed in the United States until 1977 when mysterious east coast acoustic disturbances were reported (Shapely, 1978). These mysterious sounds were observed from December 2, 1977 through February 15, 1978, principally in the Charleston, SC, area and on the New Jersey coast. People were saying they heard booms, some low rumblings, and other explosive sounds. A number of suggested causes were put forth that ranged from methane gas bubbles venting from faults in the ocean's floor to lasers being beamed from Russian space platforms. Predictably, the January 24, 1978, issue of the *National Enquirer* carried a front-page banner headline proclaiming *Mystery Blasts Linked To UFOs*. One of the things that fueled the intense interest and concern about these events was the persistent suggestion that they might be a precursor to a major earthquake. This was particularly troubling to residents of Charleston because the city was struck by a huge earthquake in 1886. On December 28, 1977, the Department of Defense tasked the Naval Research Laboratory (NRL) to carry out a 60-day intensive investigation to determine the cause of these startling acoustic events.

According to citizen reports, the disturbances, most frequently observed indoors, included window rattles and house vibrations, with the noise consistently identified as coming from the direction of the ocean. Acoustic and seismic measurements of these disturbances were being made at the Lamont Observatory and at the Weston Observatory at Boston College (see **Figure 5**) observatories. Analysis of the Weston data showed that nearly all the signals occurred on workdays. Signals were rarely detected on Saturdays, Sundays, or national holidays or during nonworking hours. This temporal pattern strongly suggested that the events were due to human activity. The NRL's investigation of possible causes led them to rule out man-made causes such as military research and development activities, military ordnance, civilian use of high explosives, missile reentry, and low-altitude satellites. Natural phenomena such as meteorites, winter lightning, biogenic and tectonic methane, and direct seismic generation were thoroughly reviewed and classified as unlikely causes of the events, even without consideration of the their temporal pattern.

The NRL then focused on military operations. They found that there were military aircraft capable of supersonic flight in all of the warning areas adjacent to the New Jersey and South Carolina coastlines. Sonic booms from supersonic operation in these warning areas were not usually a concern to residents because the primary booms do not propagate to the coast under normal atmospheric conditions. Ray tracings based on atmospheric conditions existing on the same day that supersonic flights were made showed that the booms should be observable as far away as 100 kilometers for flights above 5,000 meters.

The NRL examined the Concorde flights in and out of John F. Kennedy International Airport (New York) and Washington Dulles International Airport and found no correlation between their operation and the reported acoustic events in New Jersey and Charleston, SC. In its March 3, 1978, early release of the findings (final report, NRL, 1979), the NRL stated that the most likely source of these events appeared to be high-performance military aircraft operating supersonically and that the degree of disturbance to the citizens was influenced by atmospheric propagation conditions.

There was immediate disagreement with the NRL conclusions from Jeremy Stone, president of the Federation of American Scientists (Shapely, 1978; Sullivan, 1978), who suspected that somehow, despite evidence to the contrary, the east coast booms were due to the Concorde. Probably the strongest reason to suspect the Concorde was the timing of the onset of the east coast booms. The NRL report (1978) states that no events were observed at Weston in November "until November 28 when five events appeared as though a switch had been thrown." Concorde service to New York began on November 22, 1977. Stone enlisted the help of IBM physicist Richard Garwin, a National Medal of Science winner, to come up with a plausible way in which a sonic boom could travel faster than the aircraft that generated it. According to geometrical acoustics, the upward going sonic booms (both the one that goes directly up and the one that reflects from the water) will turn and return to earth when it reaches

**Concorde was a technological marvel that astounded the world with its beauty and speed. Its sonic boom was its Achilles heel, but was it the cause of those mysterious east coast noises?**

an altitude where the local sound speed is equal to the speed of the aircraft. Because the sound speed is proportional to the square root of the absolute temperature, this requires a temperature four times the temperature at the altitude of the Mach 2 Concorde. The required temperature would be reached in the thermosphere at an altitude of 160 kilometers (see **Figure 6**). Garwin (1978) hypothesized that what he called a "hyperboom," somehow got detached from the aircraft when it maneuvered and propagated at a very high altitude at a speed faster than that of the aircraft and could reach the US coast over an hour before the aircraft. Moreover, Garwin, a longtime opponent of the Concorde (Sullivan, 1978), also hypothesized that the thermospheric waves could negatively alter the tenuous thermosphere, thereby causing chemical reactions and winds (Garwin, 1978).

On March 8, 1978, in a meeting attended by Presidential Science Advisor Frank Press, Transportation Secretary Brock Adams, NRL Director Alan Berman, Stone, and Garwin charged that the NRL had erred and that the Concorde was the culprit in the east coast booms and also may be causing the destruction of the thermosphere.

Garwin's environmental argument was based on the conservation of energy. The acoustic Mach number of a sound wave is a dimensionless measure of the strength of a sound wave, which would be indicative of the effect of the wave on its environment. In the far field, it is given by $M_{ac} = v / c = p / \rho c^2$ , where $v$ is the acoustic particle velocity. Garwin's model showed that $M_{ac}(z_{TP}) / M_{ac}(0)$ was proportional to $\sqrt{\rho(0) / \rho(z_{TP})}$, where $z_{TP}$ is the altitude at the turning point.

For the Mach 2 Concorde at the turning point (160 kilometers), the density is $1.14 \times 10^{-12}$ grams per cubic centimeter, more than nine orders of magnitude smaller than it is on the ground, resulting in a very large $M_{ac}$ at that altitude. Garwin's linear model included the effect of spreading of the conical wave front but was subject to criticism because it did not include nonlinearity, refraction, linear attenuation, and the focusing at the turning-point caustic where adjacent rays cross.

At the March 8 meeting, the NRL was tasked by Adams and Press to investigate the Stone-Garwin hypothesis, that is, specifically to determine what does happen to the upward going Concorde sonic boom as it propagates to and from its turning point in the thermosphere. Adams also requested that Press arrange for an independent review of the Navy's results.

The NRL assigned the task to Peter Rogers and John Gardner. Rogers and Gardner developed a model for the thermospheric propagation of the sonic boom from Concorde aircraft. In the model they considered, only those booms that were refracted to the ground by the sound velocity gradient in the thermosphere (above 100 kilometers). From their model, they determined the boom strength as a function of altitude and the ground pressure both on and off the flight path. The model utilized a realistic atmospheric model of the density, temperature, and composition of the atmosphere versus altitude and included nonlinear stretching and attenuation of the wave, the effects of the turning-point and linear acoustic attenuation. The results are presented in **Figure 7** (Rogers and Gardner, 1980). **Figure 7** shows the predicted ground pressures for the initially upward and initially downward waves as a function of distance from the ground track. The abrupt lateral cutoff was determined by the returning rays, which were refracted upward before reaching the ground. The solid lines show the results, which considered both nonlinear effects and linear attenuation, whereas the dashed lines show the results obtained using the nonlinear theory alone. The dominant signal was from the initially downward wave. The highest pressure level (about 0.30 pascals) occurred about 400 kilometers from the ground track. The pressure measured on the ground track was a minimum and was about 0.10 pascals for the initially downward wave. This is because the ray paths along which the shocks propagate were less steeply inclined at lateral locations compared with the on-track rays. Thus, on-track rays traveled to much higher altitudes where they incurred much larger losses due to the extremely low density at altitude. It should be noted that the predicted secondary boom levels that arrived from the thermosphere were more than an order of magnitude less than the secondary boom levels propagated from the stratosphere and lower mesosphere (see **Figures 3** and **7**). This is in contrast to the primary carpet booms where the pressure was a maximum (about 100 pascals) along the ground track and decreased to zero at the lateral cutoff.

Rogers and Gardner (1980) concluded that thermospheric returns from the Concorde are of sufficiently low amplitude

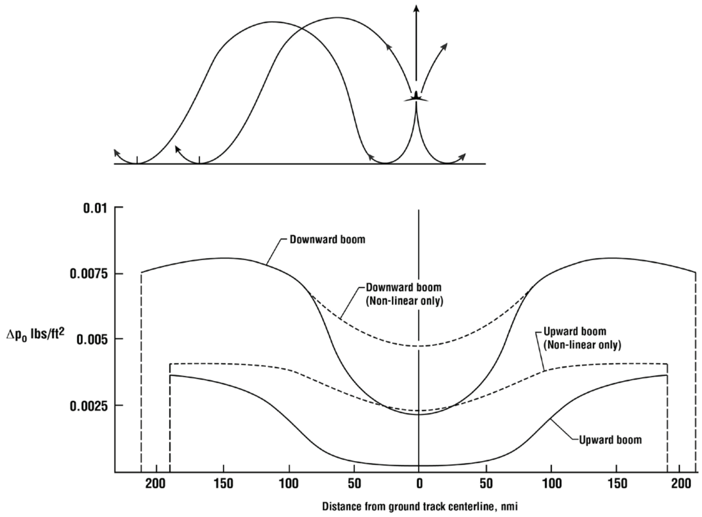


*Figure 7. Relative strength on the ground from a sonic boom returning from the thermosphere as a function of the lateral distance from the aircraft ground track. Adapted from Rogers and Gardner (1980).*

and frequency that it is unlikely that they are either responsible for the east coast events or likely to disturb the public.

With regard to Garwin's destruction-of-the-thermosphere hypothesis, results for acoustic Mach number versus altitude for Garwin's model and the Rogers and Gardner model are plotted in **Figure 8**. The red curve is Garwin's model, and the black solid line includes only nonlinear attenuation. The black dashed line includes both linear (L) and nonlinear (NL) attenuation. The acoustic Mach number for the Rogers and Gardner model never exceeds 0.2. Ninety percent of the wave's energy is attenuated below 100 kilometers, with 99% attenuated by the time the wave reaches the turning point.

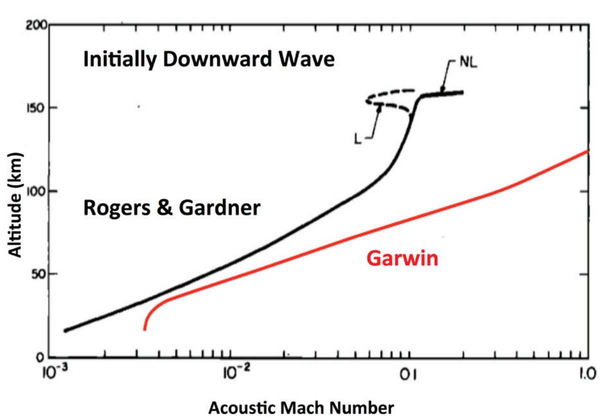


*Figure 8. Acoustic Mach number versus altitude for initially downward sonic boom from Concorde. Red line, Garwin's (1978) model; solid line, Rogers and Gardner (1980) model including nonlinear losses only; dashed line, Rogers and Gardner model including both linear and nonlinear losses. Adapted from Rogers and Gardner (1980).*

Rogers and Gardner concluded that the secondary booms from the Concorde did not have sufficient amplitude or energy to produce a deleterious effect on the thermosphere.

Rogers and Gardner completed their model in June of 1978. Press's process for an independent review of their work involved the JASONS who were asked to look into the problem, The JASON team, which included Garwin, developed a simple plane wave model that included only nonlinear stretching and attenuation (no spreading, caustics refraction, or linear attenuation). Despite its simplicity, the JASON model (MacDonald et al., 1978) produced results consistent with those of Rogers and Gardner. They concluded that Rogers and Gardner's results and conclusions were correct.

## Upper Atmospheric Sound Speed

Secondary sonic boom events in the form of "thumps" and low-frequency "rumbles" were once again reported in the New England area during the summer of 1978. Preliminary measurements by the Department of Transportation, Transportation System Center (DOT/TSC) (Rickley and Pierce, 1979) suggested some correlation with incoming Concorde flights into John F. Kennedy International Airport. In the summer of 1979, a secondary sonic boom detection and assessment program was conducted by the US DOT/TSC in New England (Rickley and Pierce, 1980). A large database of measurements was obtained regarding secondary booms.

The results of these tests showed that the upper atmospheric temperature and winds along with the aircraft operating conditions played an important role in whether and where the secondary booms will impact the ground. It is stated that a principal mechanism causing such long distance effects is refraction caused by wind and temperature gradient effects at altitudes between 20 and 60 kilometers (the stratosphere) and mesosphere (see **Figure 6**). Sound waves that carry upward traveling sonic booms to such altitudes can be bent back toward the ground if these gradients cause the sound speed to increase with altitude. Such downward refraction can also take place in the thermosphere, but the high attenuation and lengthening of the shock duration at high altitudes would render such thermospheric refracted arrivals much less likely to be audible by the time they return to the ground. This is consistent with the conclusions of Rogers and Gardner (1980).

Rickley and Pierce (1980) applied the simplest model of sonic boom propagation based on geometrical acoustics that predicts that secondary booms will reach the

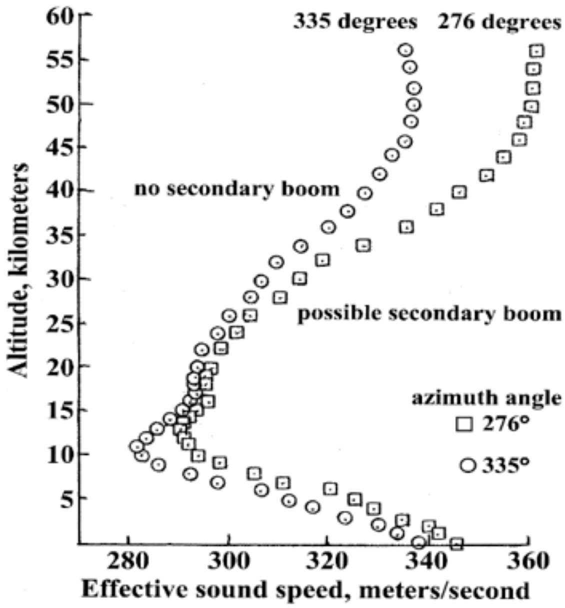


***Figure 9.*** *Effective sound speed profiles, Boston, MA, June 20, 1979, 1200 hours. From Rickley and Pierce (1980).*

ground only when the wind velocity in the direction of propagation and the sound speed, including the wind velocity in the direction of propagation at an altitude above the flight altitude, exceeds the corresponding seen at the ground as shown in **Figure 9**. Examination of **Figure 9** shows that strong winds at heights from 30 to 60 kilometers blowing east to west that are in the same direction as the Concorde incoming flight track will result in their being secondary booms in the Boston area. This hypothesis was tested and the results indicated that the probability of receiving a large amplitude event is small unless the east-to-west wind speed in the stratopause exceeds 16 meters per second. (The stratopause is the region of the atmosphere where there is a local temperature, and hence, sound speed maximum; see **Figure 6**.)

## Aircraft Operations

Relatively minor variations in the incoming Concorde arrival flight paths and operating conditions can alter the location of impact of the secondary booms. Computed secondary boom focus line sources using the TSC computational program (Rickley and Pierce, 1980) show that slight variation in Concorde flights results in a shift in the secondary boom footprints by 40 kilometers. The measurements and ray-tracing computations demonstrated that the secondary booms frequently reported by New England residents were created by the Concorde flights off the New England coast en route to John F. Kennedy International Airport in New York. A brief set of measurements made in Applebachsville, PA, also correlated with Concorde flights into Washington Dulles International Airport in Virginia. These boom disturbances, which are propagated upward to the stratosphere and lower mesosphere and refracted back downward to the ground, are an order of magnitude higher in amplitudes than the boom returns from the thermosphere and are observable not only by persons located indoors but also by those located outdoors.

In every case of complaints about Concorde-generated secondary sonic booms, rerouting of the flight tracks, and changes in operational conditions depending on atmospheric and seasonal variations, mitigated the problem, especially in earlier deceleration to Mach 1 before the coastline was reached.

## Concluding Remarks

The Concorde was a technological marvel that astounded the world with its beauty of design and speed, halving passenger flight times to distant destinations. However, it was not a financial success due to high operating and maintenance costs and low utilization. The low utilization was because its primary sonic booms and limited range confined its operations to trans-Atlantic routes. Even for trans-Atlantic routes, low-amplitude secondary booms, reaching the ground from the upper atmosphere by refraction, resulted in further restrictions on the operations of the Concorde.

The Concorde was absolved of responsibility for the east coast booms. Although it is agreed that the majority of the east coast booms were due to high performance military aircraft operating offshore, many of the events cannot be explained in this way (Eos, 1978). The East Coast Mystery Booms remain a mystery to this day.

## Biosketches

**Peter H Rogers** received an SB in physics from MIT in 1965 and a PhD from Brown 1970. He worked at the Naval Research Laboratory as a Research Physicist and at ONR as Scientific Officer for Underwater Acoustics before joining the School of Mechanical Engineering at Georgia Tech in 1983. He became the Rae & Frank H. Neely Chair in 1993. He is a fellow of the Acoustical Society of America and received its Biennial Award (now the R. Lindsay Award) in1980 based largely on the work reported in this article.

**Domenic J. Maglieri** graduated from the University of Pittsburgh in 1951 with a B.S. degree in ME/AE and began his career at National Advisory Committee for Aeronautics (NACA) doing research on aircraft noise control and sonic boom. He retired from NASA in 1986 and joined Eagle Aeronautics as Director for Projects. His sonic boom involvement began in 1957 and has continued to the present, participating in every major sonic boom flight test program. He authored or co-authored over 160 publications, 100 are on sonic boom. He is an ASA Fellow, a Board Certified Member of the INCE and an AIAA Associate Fellow.

## References

Balachandra, N. K., Donn, W. L., and Rind, D. H. (1977). Concorde sonic booms as an atmospheric probe. *Science* 197, 47-49.

Eos. (1979). New investigation of east coast mystery booms. *Eos, Transactions American Geophysical Union* 60, 49. Available at http://onlinelibrary.wiley.com/doi/10.1029/EO060i005p00049-02/epdf.

Garwin, R. L. (1978). *Speculation on Long-Range Effects of Supersonic Flight.* Unpublished note.

Holbeche, T. A. (1972). *Measurements of Sonic Bangs from the Prototype Concorde 002 During Supersonic Development of Flying in the United Kingdom.* Technical Memorandum Aero 1405, Royal Aircraft Establishment.

Lessen, M., and Pryce, A. W. (1978). Now don't get rattled. *Journal of the Acoustical Society of America* 64, 1727. Available at http://dx.doi.org/10.1121/1.2033228.

Lina, L. J., and Maglieri, D. J. (1960). *Ground Measurements of Airplane Shock Wave Noise for Mach Numbers to 2.0 and Altitudes to 60,000 ft.* Technical Report NASA TN-D-235, National Aeronautics and Space Administration, Washington, DC. Available at http://catalog.hathitrust.org/Record/011445564.

Liszka, L. (1978). Long-distance focusing of Concorde sonic boom. *Journal of the Acoustical Society of America* 64, 613-635.

MacDonald, G., Flatté, S., Garwin, R., and Perkins, F. (1978). JASON 1978 *Sonic Boom Report*. Technical Report JSR-78-09 (AD A0 65294), Stanford Research Institute International, Arlington, VA. Available at http://fas.org/irp/agency/dod/jason/sonic.pdf.

Maglieri, D., Bobbitt, P., Plotkin, K., Shepherd, K., Coen, P., and Richwine, D. (2014). *Sonic Boom: Six Decades of Research.* NASA/SP-2015-622, National Aeronautics and Space Administration, Washington, DC.

McLean, F. E. (1985). *Supersonic Cruise Technology.* Technical Report NASA SP-472, National Aeronautics and Space Administration, Washington, DC.

NASA. (1976). U.S. *Standard Atmosphere,*1976. Government Printing Office, Washington, DC. Available at http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19770009539.pdf.

Naval Research Laboratory (NRL). (1978). NRL I*nvestigations of East Coast Acoustics Events, 2 December 1977-15 February* 1978. Naval Research Laboratory, Department of the Navy, Washington, DC.

Penhaligon. (1978). *Concorde (Sonic Boom).* The Official Report, House of Commons, 5th Series, 946, 1773-1788.

Rickley, E. J., and Pierce, A. D. (1979). *Detection and Assessment of Secondary Sonic Booms in New England.* DOT-TSC-FA953-PR-79-2, Department of Transportation, Washington, DC. Available at http://ntl.bts.gov/lib/35000/35100/35186/DOT-TSC-FAA-80-10.pdf.

Rickley, E. J., and Pierce, A. D. (1980). *Detection and Assessment of Secondary Sonic Booms in New England.* FAA-AEE-80-22, Federal Aviation Administration, Department of Transportation, Washington, DC.

Riding, A. (2000). *Concorde Crash: The Overview; 113 Die in First Crash of a Concorde.* The New York Times, July 26, 2000, A1.

Rogers, P. H., and Gardner, J. H. (1980). Propagation of sonic booms in the thermosphere. *Journal of the Acoustical Society of America* 67, 78-91.

Shapely, D. (1978). East coast booms: A scientific suspense tale. Science 199, 1416-1417.

Sullivan, W. (1978). *Scientist Says Data Uphold Thesis Tying Concorde to Coastal Booms U.S. Will Investigate.* New York Times, March 16, 1978, B16.