Reports

Concorde Sonic Booms as an Atmospheric Probe

Abstract. *Infrasound generated by the sonic boom from the inbound Concorde supersonic transport is recorded at Palisades, New York (Lamont-Doherty Geological Observatory), as a series of impulses from distances varying from 165 to about 1000 kilometers. Refraction effects determined by temperature and wind conditions return the signal to the surface from both stratospheric (40 to 50 kilometers) and thermospheric (100 to 130 kilometers) levels. The frequency of the recorded signal is a function of the level of reflection; the frequency decreases from impulse stretching as the atmosphere becomes more rarified relative to the sound pressure. The horizontal trace velocity of the signal across the array of instruments is equal to the acoustic velocity at the reflection level. The sonic boom can thus be used to provide temperature-wind parameters at reflection levels estimated from the signal frequency. Daily observed signal variations have indicated significant variations in these parameters.*

Although the sonic booms from supersonic transports have been responsible for irritating and sometimes damaging side effects, the resulting sound may have important geophysical applications as a probe of the atmosphere. In this report we describe the signal and indicate its potential value.

Since the advent of scheduled Concorde supersonic flights between Europe and Washington, D.C., on 24 May 1976, strange, sharp, acoustic impulses have been recorded by the array of low-frequency microphones at the Lamont-Doherty Geological Observatory, Palisades, New York. Similar signals were also recorded on an irregular basis during the Concorde test period. The impulses consist of short trains of waves of relatively high amplitude and low frequency which were very coherent across our tripartite array of detectors (separation, about 1 km). The arrival times of these signals agree with the Concorde arrivals, which alternate daily from late morning to early evening. In each case we detect the first impulse about ½ hour prior to the landing time. An acoustic array that we installed for detection of meteors at the Meteor Radar Laboratory of the University of New Hampshire, Durham, has also been detecting these signals at the appropriate times. Most of the discussion in this report is restricted to the more complete Lamont-Doherty data.

The strength and number of impulses recorded from any one Concorde flight vary daily and seasonally as a result of variations in atmospheric propagation conditions. After establishing the relationship between these cause-and-effect conditions, we intend by inversion to estimate atmospheric properties from variations in the characteristics of Concorde sonic signals. Usable signals have been detected 85 percent of the time. At other times strong wind noise overwhelmed the signal despite our use of Daniels noise-reducing pipes (*1*). With moderate winds that obscure the visual signal, correlation techniques permit signal extraction.

Typical summer and autumn cases are shown in Fig. 1, a and b, respectively. The most obvious difference between the two is the marked decrease in amplitudes of the first relatively high-frequency group of waves (group A) from summer to autumn. Moreover, the later low-frequency groups (groups B, C, and D) become more numerous in autumn. In general, in summer or autumn, when the first high-frequency group is very strong, the later low-frequency groups are weak or absent. Maximum pressure amplitudes reach 20 μbar (20 dyne/cm^2). The frequency of the waves in group A is from 0.5 to 2 hertz with maximum energy between 1 and 2 hertz. Wave groups B, C, and D have frequencies of 0.13 to 0.3 hertz (3- to 8-second periods). Figure 1, c, d, and e, shows important variations from the seasonal routine (discussed below). We interpret all of these signals as weakened shock waves from the supersonic motion of the Concorde.

The flight path of the Concorde as it approaches the eastern coast is shown in Fig. 2 (*2*). The plane begins its descent from 16.8 km (55,000 feet) at a speed of Mach 2 (603 m/sec or 1,350 mile/hour) just south of Nantucket. It becomes subsonic at an elevation of 11.9 km (39,000 feet), about 56 km (35 miles) from the coast of New Jersey. From the signal lag times across our array we have calculated directions of arrival for successive wave groups as shown by the rays extending from Palisades to the flight path. The accuracy of locations of sources for signals arriving from the east is poor for the Lamont-Doherty array because the direction of travel is almost parallel to the flight track. This uncertainty is indicated by the broken lines. No directions have yet been determined for Durham because the full recording system is not yet complete. Because of the supersonic speed of the plane, the signal generated last arrives first. Subsequent arrivals come from progressively earlier points on the plane's track.

Points A, B, and C are approximately the source locations of the corresponding signals labeled in Fig. 1. The arrival directions are based on signal time delays among our detectors that can be estimated with our analytical equipment to ± 0.1 second, which corresponds to a direction accuracy of ± 4°.

The horizontal distance traveled by the high-frequency signal originating from around point A is about 165 km. This distance and the elevation of the plane (13 to 14 km) are such that, for a reasonable atmospheric temperature structure, no direct sound will reach Palisades. For example, the formula that determines the distance at which the grazing (farthest) ray hits the surface is

$$x = 2\,(T_0 h/\gamma)^{1/2}$$

where T_0 is the surface temperature (in degrees Kelvin), h is the elevation of the source, and γ is the vertical temperature gradient. For an average temperature gradient of 6°K/per kilometer, with the source at 13 km and the surface temperature at 296°K, x is 51 km. However, weak scattered or diffracted signal is always possible. Beyond this distance, no direct rays will strike the surface. We consequently explain the strong summer high-frequency wave group (group A) as a return from the stratosphere (about 50 km) where the temperature maximum and the prevailing summer easterly winds provide a sound speed that will permit reflection.

At Lamont-Doherty, group A is composed of two prominent signal arrivals separated by about 1 minute. We believe that the first part of this doublet represents the signal that propagated into the upper stratosphere and was then reflected to the surface (see the ray diagram insert in Fig. 2). The second part of the group represents the signal reflected from the stratosphere after first being reflected off the surface as in the ray diagram. With the use of a reasonable sound speed structure of the atmosphere, the arrival time differences of about a minute can be explained in terms of these propagation paths.

In winter, however, stratospheric reflections are not possible from the direction of group A because of strong prevailing westerly winds at that level. However, a weak diffracted or scattered signal can become apparent at these times such as the weak initial signal (group A) in Fig. 1b. Occasionally during autumn or winter the initial signal can become very strong (Fig. 1c). This signal increase indicates a significant change in atmospheric structure, underscoring the value of the signal as an atmospheric probe.

Wave groups B, C, and D in all cases are interpreted as reflections from the thermosphere above 100 km. The exact level of reflection depends on the particular temperature and wind structure at the time. Successive arrivals are interpreted as successive thermospheric reflections of signals originating from points farther out on the flight path. These successive reflections are responsible for the decreasing amplitude and the approximate 10- to 11-minute delay in successive low-frequency arrivals. The delay is the time required for the sound to travel the reflection path between the surface and the thermosphere minus the time required for the plane to travel the horizontal distance between surface skip points. For reasonable atmospheric parameters and reflection heights the computed delay is 11 to 12 minutes; there is thus good correlation with the observed delay between signal arrivals. Also, the arrival time difference between wave group A and wave group B, about 7 minutes, is explainable as the difference in travel time between the waves coming from the stratosphere and those coming from the thermosphere.

One of the most interesting aspects of the waves generated by the sonic boom is the decrease in frequency from about 1 hertz (1-second period) for group A to about 0.15 hertz (7-second period) for wave group B. Frequently, in autumn or winter, a wave group with an intermediate frequency of about 0.3 hertz (3 seconds) is also observed arriving about 4 minutes after group A (Fig. 1d). The successive wave packets have the following average horizontal trace velocities, respectively: 369, 392, and 434 m/sec. These velocities, which correspond to the acoustic velocities at the reflection levels (*3*), indicate that these levels are about 50 km for group A, 105 km for the intermediate group, and 125 km for group B.

The decrease in frequency is due to the stretching of the shock wave as it propagates through the low-density region of the upper atmosphere (*4*). Daniels (*5*) has calculated the frequency of waves reflected from 30 to 110 km after generation by a supersonic transport. His peak frequencies of 1.014 and 0.127 hertz are in good agreement with our observations. Even within a particular low-frequency wave group, for example,

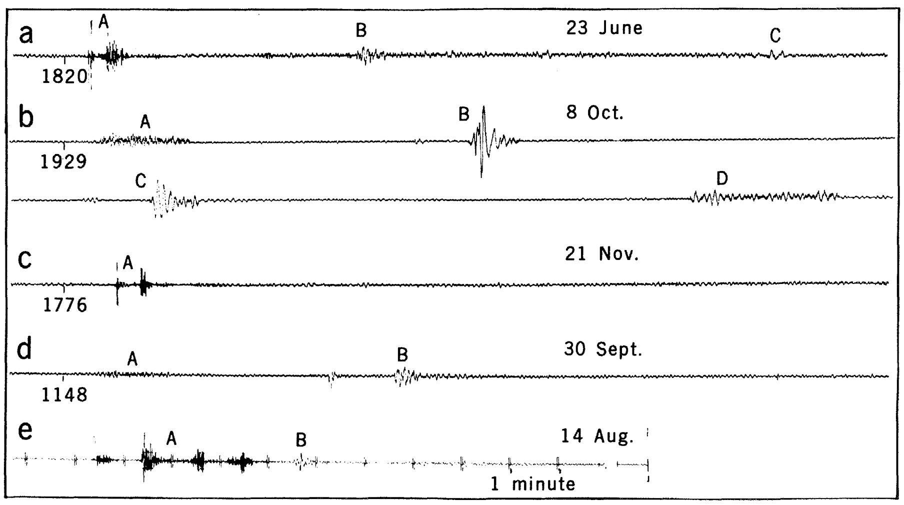

Fig. 1. Examples of infrasound recorded at long range in the 0.1- to 1-hertz passband of the Concorde supersonic transport: (a through d) records from Palisades, New York (Lamont-Doherty Geological Observatory); (e) record from Durham, New Hampshire. The time scale, the same for all records, is shown by minute marks on (e). The maximum signal amplitude shown is about 5 μbar, but the first arrival received in a higher passband has an amplitude of about 20 μbar. Variations in signal strength and number result from varying atmospheric propagation conditions explained in the text. [In (b) at least one additional later signal has been detected, representing four skips from the thermosphere over a distance of about 1000 km.]

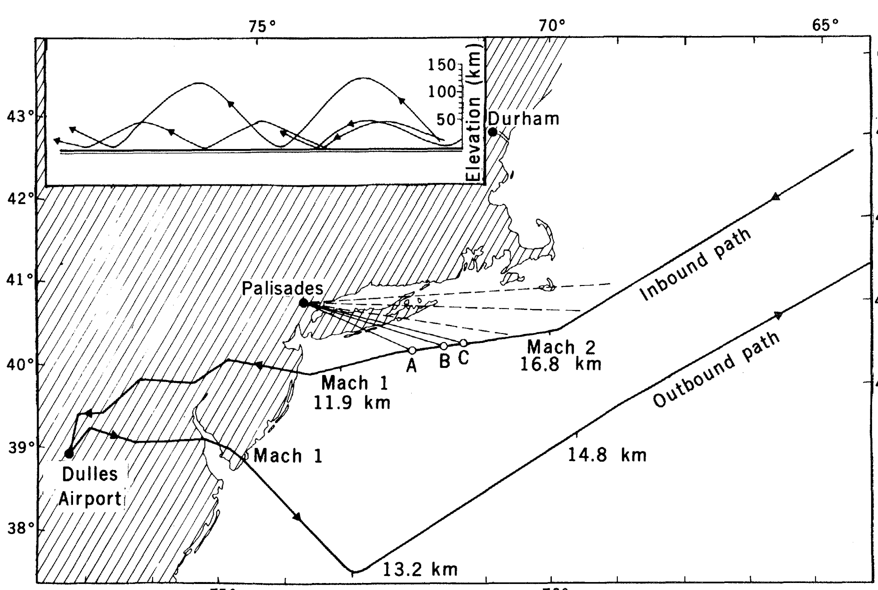

Fig. 2. Map showing the inbound and outbound flight paths of the Concorde supersonic transport. Elevation and speed are marked on the tracks. Points A, B, and C are average source locations for the first three signals received at Palisades. Although both inbound and outbound signals are recorded at Durham, instrumentation for directional determinations has not been completed at this site. The inset shows a schematic ray tracing indicating ray paths through the stratosphere (about 40 to 50 km) and the thermosphere (100 to 130 km).

group B (Fig. 1b), the wave frequency decreases with time. This decrease is caused by successively higher reflection levels in the thermosphere from about 100 to 125 km for ray paths having slightly varying vertical angles of propagation.

The scientific value of the sonic booms from supersonic planes lies in the fact that they can be used as a probe of the upper atmosphere. The frequency of the received signal is an indication of the reflection height, and the observed trace velocity gives the sound velocity at this reflection height when corrected for the effects of nonlinearity resulting from the overpressure of the impulse. Thus we are in a position to determine the sound velocity from one or more reflection heights (depending on the number of signals received) in regions that are extremely difficult to observe otherwise. The Concorde flies a known route on a regular basis, thus providing sound sources at known positions in time and space. The great variations in amplitude, frequency, velocity, and arrival times of the recorded acoustic signal are all caused by the daily variations in the temperature-wind profile of the atmosphere. To determine these parameters we intend to use data from the present Lamont-Doherty array as well as from other arrays to be installed at critical locations.

Because signal is being generated continuously along the flight path, increased instrumental monitoring at judicious locations will provide greatly increased information about the atmosphere. For example, data from the Durham array show characteristics different from those recorded at Lamont-Doherty [note the four-part wave group A recorded at Durham (Fig. 1e)]. Also, acoustic impulses from the shock waves generated during the return trip of the Concorde to Europe have been regularly received at Durham and not at Palisades. (During the return journey, the shock wave, after the plane becomes supersonic, is directed away from Palisades and no signal is recorded.) The shock wave has a velocity component toward Durham so that impulses are detectable there (*6*).

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6. A more detailed analysis and application of such signals is being prepared (N. K. Balachandran, W. L. Donn, D. H. Rind, in preparation).
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Shoreline Forms and Shoreline Dynamics

Abstract. *Atlantic coast barrier-island shorelines are sinuous in plan view, with curvatures ranging in size from cusps to capes. The orientation of shoreline segments within the larger of these sinuous features (10 to 15 kilometers between apexes) is significantly related to shoreline dynamics.*

Atlantic coast sandbeach and barrier-island shorelines are seldom long and straight, when viewed in plan, but rather sinuous in form. Some of the along-the-shore variation is in the form of organized patterns ranging in size from beach cusps to very large shoreline arcs. Crescentic coastal landforms are products of varying sea states, tides, and sea levels. The smaller features appear, disappear, and migrate along the shoreline; the larger ones establish the spatial context for along-the-shore processes, including the distribution of erosion and storm-

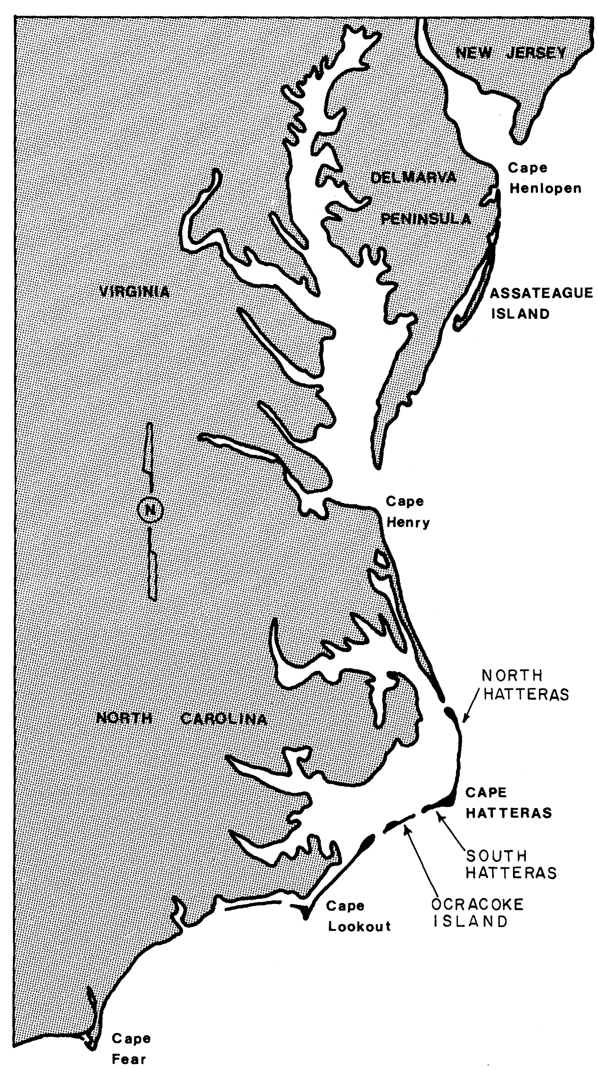

Fig. 1. Mid-Atlantic coast from New Jersey to North Carolina, where the relationship between coastal processes and coastal configuration is being investigated. Data on historical coastal erosion and current coastal orientation have been collected and analyzed for Assateague Island, Hatteras Island, and Ocracoke Island.