2020 Literature Review on Secondary Sonic Boom

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2020 LITERATURE REVIEW ON SECONDARY SONIC BOOM

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ABSTRACT

This Forum Acusticum paper provides a literature review regarding secondary sonic booms as of October 2020. It is hoped that this document will be useful for anyone studying secondary sonic booms in the future.

1. INTRODUCTION

As the prospects for renewed supersonic civilian flight increase in the near future, many individuals are assessing the environmental acceptability of such flights. Sonic booms are the shock waves created by any object traveling faster than the local speed of sound. This paper will focus on the sonic booms created by supersonic aircraft. The primary sonic boom is the sound which travels directly from the aircraft altitude to the ground, creating a carpet on the ground that is called the primary sonic boom carpet. That being said, a secondary sonic boom is any sonic boom that is NOT a primary sonic boom. There are many different ways the sound energy from a sonic boom can make it to the ground, and the literature pertaining to the different types of secondary sonic booms will be reviewed in this paper.

The purpose of this document is to provide a comprehensive literature review for secondary sonic booms. The authors have found few good resources describing what is known about secondary booms, as the measurement and predictions are scattered in multiple journals, theses, and research reports. The current paper has been prepared to make it easier for anyone interested in secondary booms to be knowledgeable of key papers on the topic as well as specialized studies that are not well known. A number of key sonic boom experts were consulted regarding this paper to ensure that there are no major omissions from the literature cited. After a brief review of secondary booms, the literature is presented primarily chronologically.

The importance of secondary sonic booms cannot be underestimated. If aircraft manufacturers are successful in building passenger airliners producing N-wave sonic booms similar to Concorde, secondary sonic booms will be produced similar to Concorde. As will be described, the public did not consider this noise acceptable in the past, and these secondary sonic booms likely would place operational constraints on the new aircraft. However, if they build aircraft geometrically shaped to minimize the primary sonic boom so it is quiet, it is possible the secondary sonic boom might not be heard at all.

2. BRIEF OVERVIEW OF SECONDARY BOOM

For those who are not already familiar with secondary sonic booms, a brief summary is provided here. Secondary boom can result from the primary sonic boom reflecting from the ground surface, or it can occur due to sound rays traveling upward from the aircraft. Either way, secondary booms are often called “over the top” sonic booms, abbreviated OTT. This is because the sound energy from secondary sonic booms always travels to an altitude above that of the aircraft before reaching the ground, and this does not happen for primary booms. We include in our definition of secondary boom all instances of the sonic boom energy being above the aircraft altitude, regardless of how many times the sound hits the ground. So called “tertiary sonic booms” are those cases which have impacted the ground as a secondary sonic boom once already, travel back into the atmosphere above the aircraft altitude a second time, and then impact the ground again. But we will still classify them as a type of secondary sonic boom.

Figure 1 diagrams a few of the different types of secondary booms. The type I or direct secondary boom initially travels upward from the aircraft. In contrast, the type II or indirect secondary sonic boom is a result of a ground reflection of the primary sonic boom. Note that any of the currently envisioned supersonic passenger aircraft very likely would have a cruise altitude above 10 to 12 km, putting it above the troposphere into the lower portion of the stratosphere. So even accounting for usual atmospheric absorption effects, some of the type I secondary boom sound energy would refract back down to the ground from the stratosphere, if the stratospheric winds allow it.

The sonic boom energy can also travel upwards through the stratosphere and the mesosphere into the thermosphere where it can eventually return to the ground and be detected. These long ray paths result in much weaker secondary sonic boom amplitudes compared to the secondary booms only reaching the stratosphere.

It should also be understood that secondary booms are not always heard on the ground. This is because secondary sonic boom energy is either substantially absorbed by the atmosphere, or it cannot always reach the ground due to refraction. Often, a strong stratospheric wind in the same direction as the aircraft travel is required for the sound to be heard, but this is not always the case. The difficulty of characterizing the upper atmospheric winds has always made the study of secondary sonic booms more challenging.

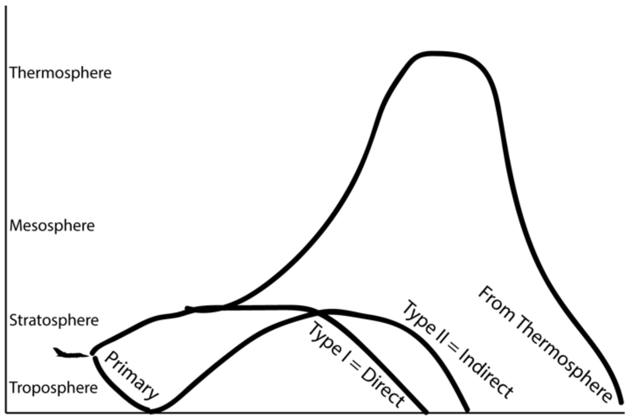

Figure 1: Simplified sketch (not to scale) of the primary, Type I, Type II, and thermospheric rays. The latter three rays can all reflect back up again, but these additional rays are not shown for clarity. The thermospheric ray is shown as diverging upward from the Type I ray, but an additional thermospheric ray can be launched from the Type II ray. It further should be noted that these rays do not necessarily travel directly straight ahead of the aircraft's direction of flight but are spread to angles to both the right and left sides of the aircraft, if atmospheric conditions allow that.

Secondary booms are much quieter than primary booms, so much more research over the years has been focused on primary booms compared to secondary booms. Only a handful of studies to date have actually recorded secondary sonic booms using scientific acoustical measurement equipment. It is thought that quite often the sounds of secondary sonic booms are not associated with the aircraft that produced them since the sounds appear so distant from their source. Secondary sonic booms can also be measured by seismological equipment, and there is much more of this data reported compared to acoustical measurements.

Because of their long propagation paths compared to primary sonic booms, secondary sonic booms lose almost all of their high frequency content by the time they are heard on the ground. This is because the well-known effects of atmospheric absorption are much stronger at high frequencies. Hence, secondary booms have most of their energy at frequencies of 50 Hz or less. This makes secondary booms sound like a low-frequency rumble, something like distant thunder. Such low frequencies can cause house vibration and the subsequent rattling of windows and plates, glasses, and bric-a-brac on shelves or in curio cabinets.

3. FIRST REPORTS

Although a few specialists were aware of the phenomenon of secondary sonic booms in the 1950's and 60's, the focus in that time period was almost purely on understanding the primary sonic boom as that was the noise source of interest. For example, there was no mention of secondary sonic booms, whatsoever, in the First, Second, or Third Sonic Boom Conferences NASA sponsored in the 1960s [1-3]. There was no mention either in the November 1970 Sonic Boom Symposium held at the Acoustical Society of America meeting in Houston, TX, USA [4]. An overview of the emergence of secondary sonic booms in conjunction with mysterious noises off the East Coast of the United States was described by Rogers and Maglieri [5], and this is a really good source of some early references, some of which are repeated in the present literature review.

Maglieri and Rogers note an early observation of secondary booms using microbarographs detected 195 kilometers distant from a flight test in 1959. In 1966 Marcos reported experiments where the upward going sonic boom from a supersonic aircraft was shown to perturb the reflected radio waves from the daytime E-layer of the ionosphere at approximately 110 km in altitude [6]. This was reported in the work of Liszka and Olsson in Sweden in 1971, where they performed experiments with a Saab-35 Draken supersonic aircraft and detected the sound on the ground after the sonic booms reflected from the stratosphere at about 40 km altitude. The ground measurements were made by cross-correlating the 2 Hz signals between two spaced piezoelectric microphones [7].

"Distant seismic effects" were also reported in 1973 by Grover from some of the initial Concorde test flights in the UK in 1970, and these measurements were attributed to Concorde induced infrasonic waves in the atmosphere. [8]

In 1975 a meteorologist with the U.S. National Weather service in Tucson, AZ, USA reported that his office received many telephone calls regarding "vibrating tremors" from residents [9]. Local seismic stations were quiet, so earthquakes were ruled out. It was noticed that a strong jet stream was in place that April which was often exceeding 150 mph (67 m/s). It was determined that supersonic military training was occurring in Sells, AZ, approximately 70 miles (114 km) west-southwest of Tucson. Since this location was directly upwind of the calls received, it was inferred that the tremors were associated with the military aircraft training. And when the strong jet stream ended, the public's reports of the tremors ended.

4. CONCORDE ARRIVES

When the Concorde began flying across the Atlantic Ocean, overall interest and research on secondary sonic booms substantially increased. Concorde began landing at Dulles Intl. Airport near Washington, DC, USA in May of 1976, and "strange, sharp, acoustic impulses" began to be heard. This was documented by Balachandran, Donn, and Rind, all from the Lamont-Doherty Geological Observatory of Columbia University in Palisades, New York USA in 1977 [10]. Their evidence was good that the events were linked to Concorde flights. Donn also published a follow-up article in 1978 [11] as well as with Rind in 1979 [12]. Liszka, expanding on his previous work, also made many recordings of Concorde secondary booms during the winter in Sweden in 1976-77 and 1977-78 [13].

The secondary booms were widely heard in Southwest United Kingdom (UK) starting in the fall of 1976, likely corresponding to the winter season and typical seasonal winds bringing secondary booms to the ground in the UK during British Airways flights back into London. Lessen and Pryce [14] reported that "The overwhelming majority of these reports noted the noises occurred about nine o'clock in the evening on most nights of the week" and that the noises were "mostly heard indoors," and they "resembled in some respects those of a thunderstorm at a distance or possibly an explosion."

Later in 1978, there was a debate in the UK House of Commons regarding Concorde [15]. The complaints of residents had made this a political issue with the sounds in the UK, and this seems to be one of the first times the words "secondary boom" were officially used. Clearly British Airways had understood and mitigated the "primary boom" by keeping the primary carpet off shore, but the debate was whether the "secondary boom" should be moved further from land by the aircraft decelerating further from the UK coast line. Its great reading and is recommended.

The Rogers and Maglieri article mentioned previously does a great job of describing the situation with the mystery sounds on the U.S. East Coast, thus that story won't be repeated here. Serious research was performed in 1978 at the U.S. Naval Research Laboratory (NRL) dispelling a number of "interesting" claims related to the noises [50] and further work was conducted at NRL by Gardner and Rogers [16]. This work was also cited by George and Kim, who reported the secondary boom effects to the aerospace community in 1979 [17]. Gardner and Rogers focused their work on the secondary sonic boom which travels into the thermosphere. Their method was primarily analytical (not numerical ray tracing), and the work appeared in peer reviewed form in January 1980 [18].

5. CONVINCING EVIDENCE, INTO THE 1980'S

Concorde began flying into New York's JFK airport in 23 November 1977 [19], and in the summer of 1978 the secondary sonic boom sounds began to be heard in the New England region of the United States. There were many reports by community members which reached the FAA, which was called into action. The FAA's Office of Environment and Energy brought in the National Transportation System Center (now called Volpe) to make measurements and solidify the link between the noises and Concorde. The result was the impactful report [20] of Edward Rickley and Allan Pierce, the latter author on a 1-year intergovernmental personnel agreement (IPA) from the Georgia Institute of Technology. This document should be read cover to cover by everyone interested in secondary sonic booms. It is the report which was used as evidence, behind closed doors, to convince Air France and British Airways, to decelerate Concorde to subsonic speeds further from the coastline to keep the initial secondary sonic booms over the water instead of on land [21]. The report gives a very thorough analysis including careful measurements of the received signals, numerical ray trace predictions, clearly linking the sounds heard to specific Concorde flights. A key finding was that high-altitude winds were very important, determining whether the secondary booms reached the ground. A strong stratospheric wind toward the West was required in the summer months to allow secondary booms to reach the U.S. East Coast for Concorde arriving from Europe. (Just as the strong stratospheric wind toward the East occurred in winter to enable secondary booms to be heard in Europe.) In addition, here are four short excerpts related to the perception of the sounds:

"These events were reported as muffled 'thumps' and low-frequency 'rumbles' and occurred predominantly in the morning hours between 8:00 and 10:30 am. Reports were received from citizens as far north as Maine and along New England coastal regions of New Hampshire, Massachusetts, and Rhode Island." [20, p. 1]

"Several hundred reports were received by the FAA from citizens in the Greater Boston area of sounds indicative of secondary sonic booms during the summer of 1978." [20, p. 17]"

"… technicians at the measurement site indicate they 'heard' many of the secondary sonic booms recorded." Also " . . . the technicians 'heard' the secondary sonic booms when the maximum peak-to-peak pressure changes exceed approximately 0.1 lb/ft^2 (4.8 Pa). On several days, sound level meter measurements were made on site and levels up to 58 dBA (fast scale) were measured." [20, p. 17]

"During May (1977), 55 percent of the measured events at Malden were audible to the field technicians. In June, 94 percent were audible; in July 97 percent; in August, 86 percent; in the first half of September, 53 percent. Consequently, it is concluded that, for the approach profiles currently being flown, almost every Concorde flight into JFK during the summer months generates audible sound in the Boston area." [20, p. 31]

When British Airways and Air France started decelerating Concorde further from the coastline, the public's reports of the noise subsided, and there was no follow up research to acquire additional acoustic data. However, sensitive measuring instruments continued to register the secondary booms. Additional work regarding both the secondary booms approaching Dulles and NYC was published by Weber and Donn in 1982 [22]. Weber and Donn mention that the measured signals are always greater in amplitude than what their predictions would estimate.

6. THE 1990'S AND EARLY 2000'S

With Concorde flight paths now modified to bring the secondary booms offshore, "the problem was solved." Hence, there was little continued research in the acoustics community. Research in the infrasound community continued to recognize secondary sonic booms through the late 1980s, the 1990s, and early 2000s, but there were only a few key new findings specifically on secondary sonic booms from supersonic aircraft during the period. As part of NASA's High Speed Research (HSR) program to develop a High Speed Civil Transport (HSCT) Boeing undertook a study of secondary sonic boom in the early 1990s, and this is documented in the work of Poling.[23] Poling utilized two prediction programs: Taylor's TRAPS [24] to determine the ray paths and Robinson's ZEPHYRUS [25] to estimate the actual secondary boom time signatures. Poling also found that secondary booms could be created by sufficiently low ground temperatures, and this is irrespective of wind effects. A further result was that secondary sonic booms ray paths impacted the ground more toward the front of the aircraft for lower Mach numbers, and more toward the sides of the aircraft for higher Mach numbers.

Liszka and Waldenmark continued to monitor Concorde infrasound in Sweden, and with upgraded broadband recording equipment reported on in 1995. [26]

Cates and Sturtevant published a paper [27] in 2002 where they were able to use the seismic network in southern California, USA, and clearly associated a number of sonic boom events from 1991 and 1992 with readings on the seismic network. The supersonic vehicles were the flight of an SR-71 and two Space Shuttle reentries to the atmosphere. They were able to partially explain mystery booms that had been reported by the public in southern California in the early 1990s. One observation was that the secondary booms, which they called indirect booms, occurred over a wider area than was expected.

An extensive report was published in 2002 by Le Pichon, et al., describing that the infrasonic signals from Concorde were regularly tracked, and extensive databases of the infrasonic signals were retained. [28] Excellent correlation was indicated between numerical ray tracing and measured signals, both for the stratospheric and the thermospheric ray paths.

At about the same time as Le Pichon, et al.'s work was published, Concorde stopped flying. There was a tragic and well-publicized crash in July 2000, and regular transatlantic service was halted and did not resume until November 2001. For a number of reasons Concorde service was discontinued permanently in 2003. [29] Hence after 2003 there were no more Concordes flying, and routine opportunities to measure secondary booms ceased.

One additional important contribution from the 2000s was an update to understanding of absorption in the atmosphere. Sutherland and Bass [30] extended previous work on propagation at high altitudes, and the Sutherland and Bass model is currently the best available for the altitudes of interest for secondary sonic boom propagation. The 2004 Sutherland and Bass model, and its errata corrections [31], includes molecular relaxation absorption of carbon dioxide and other trace elements that do not play a major role in the troposphere, but are important in the stratosphere, mesosphere, and thermosphere. A study comparing the usual ISO 9613-1 (ANSI S1.26) and the Sutherland and Bass models is available. [32]

7. SOBER

From 2001 to 2004 a new European Research Program (SOBER) was conducted to develop decision tools to ascertain acceptable operating routes for supersonic aircraft in the vicinity of coastlines. The work examined acceleration focus, shadow zone effects, atmospheric turbulence, and secondary sonic boom. [33] SOBER resulted in multiple publications in all of these topics. Preliminary results were presented at both the Tenth Long Range Sound Propagation symposium [34] and at a Euronoise meeting [35]. In particular, the Ph.D. dissertation of Kaouri [36] centered on the topic of secondary booms, supervised by D. Allwright. The analysis is almost entirely mathematical, clearly showing the division of the emitted rays into the primary and secondary carpets and with some rays not reaching the ground. There are many interesting results, and one is that for a decelerating supersonic body the geometry of the Mach surface is quite different from that of an accelerating body. In the decelerating case, the effects of nonlinearity are greatly diminished in calculating the resulting signature.

In related SOBER work, P. Blanc-Benon and colleagues began making numerical calculations of secondary sonic booms in the presence of realistic atmospheric data, including gravity waves. An initial presentation at the CFA/DAGA meeting in 2004 in Strasbourg provided preliminary results [37] and this was reflected in a presentation at the Eleventh Long Range Sound Propagation Symposium. [38] The group clearly showed that two different waveguides were formed in the atmosphere, one for the stratospheric waves and another for the thermospheric waves. Different aspects of the work were later refined and presented at other meetings [39-40]

Complementary work analyzing the Concorde secondary boom data was also published by Gainville at an Intl. Congress on Acoustics [41] as an update to the work of Le Pichon from 5 years earlier.

An additional analysis of Concorde secondary booms was taken up in the Ph.D. thesis of G. Ménéxiadis in 2008 [47]. This thesis is in French and contains many other references in French related to secondary booms. A portion of the thesis was published in the AIAA Journal of Aircraft in 2008 [48], describing how one could determine the location and bearing of Concorde from infrasonic measuring stations using the aircraft's secondary sonic booms. Further work by P. Delorme and G. Ménéxiadis presented at a large conference in 2008 [49] describes a possible mechanism by which the Concorde sonic boom evolves into a substantially longer duration signal over the long distances traversed by secondary booms.

Scott, et al., published a peer-reviewed journal article on the mathematical formulation for secondary booms in 2017, and this work united many of the previous formulations for both sonic booms and for explosion sources. [42]

8. U.S. SECONDARY BOOM RESEARCH SINCE SOBER

Kenneth J. Plotkin, et al., completed a rewrite of the PCBoom calculation program in 2007, and this included prediction capability for secondary sonic booms for the first time in PCBoom. [43] To handle the passage of the waveform at the caustic as it begins to refract back toward the ground "the new PCBoom uses the post-focus signature from Kandil's numeric solution as a restarting waveform. The caustic passage is thus rigorously accounted for." This is in contrast to the secondary sonic boom prior models of L. Robinson (Zephyrus) and A. Taylor (TRAPS) which had used a Hilbert transform to simulate the caustic passage. [44] However, those models did not account for energy loss during the passage. [43]

Studies on secondary sonic booms recently have been conducted at NASA Ames Research Center, Moffett Field, CA, USA between 2015 and 2020 [45] using the NCPAprop program [46] for propagating infrasonic noise. But those results have yet to be published.

Research on secondary sonic booms at The Pennsylvania State University, Queensborough Community College, and the Volpe National Transportation Systems Center all commenced in 2019, and the present literature review is an initial output of that new project.

9. DISCUSSION

There are still many aspects of secondary sonic boom that warrant additional research. Although there is good predictive capability using aircraft conditions and meteorological conditions to determine where the secondary booms can be heard, the ability to accurately predict the secondary boom signatures (or even levels) is lacking. For example, the existing literature does not seem to provide a methodology, once the secondary sonic boom is launched, to predict the fraction of energy which is reflected down from the stratosphere versus the fraction which continues traveling up to and then later down from the thermosphere.

It is hoped that the information provided in this literature review will help to enable the sonic boom community to make progress on this topic. If you know of additional references that should be included in any future updates of this literature review, PLEASE send those to the authors.

10. ACKNOWLEDGMENTS

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