DOI: 10.61782/fa.2023.0361

forum acusticum 2023

THE ROLE OF TOPOGRAPHY FOR SECONDARY SONIC BOOM REFLECTION

Victor W. Sparrow[1*] **Kimberly A. Riegel**[2]
[1] Graduate Program in Acoustics, Pennsylvania State Univ., USA
[2] Department of Physics, Farmingdale State College, USA

ABSTRACT

This paper describes an initial investigation on the reflection of secondary sonic booms, based on the surface topography. It is hypothesized that the type of secondary sonic booms resulting from a primary boom surface reflection could be substantially affected by the topography. A primary boom impacting a flat ocean will provide for a coherent reflected wave. In contrast, a primary boom impacting typical surface topography of the land will produce a more diffuse reflection. Assuming additional propagation effects such as atmospheric absorption would be similar in the two cases, the difference between coherent or diffuse reflections might explain why secondary booms reflecting over typical land surfaces would produce decreased sound levels and therefore be less problematic than for the same booms reflecting over a calm ocean surface.

Keywords: sonic boom, secondary sonic boom, supersonic, topography, reflection.

1. INTRODUCTION

New supersonic demonstrator aircraft are anticipating first flights within a year and a return of civil supersonic operations within the decade. During supersonic operations such new aircraft will create sonic booms. Advanced ongoing research work aims to quiet the sonic booms for the future second generation of supersonic aircraft, known as low-boom, aircraft.

*__Corresponding author__: vws1@psu.edu.

But in the near term, these new first generation supersonic aircraft will produce sonic boom sounds quite similar to those from the British-French commercial supersonic aircraft Concorde.

When Concorde was in operation its primary sonic boom, that boom proceeding down from the aircraft to the ground, was well characterized. Concorde almost always flew supersonically over the ocean to minimize its sonic boom being heard by people on land. However, this primary boom reflected from the ground, and additional considerable sound energy propagated up above the aircraft. Both the energy heading initially upward (called Type I) and the boom reflecting from the ground (called Type II) could return to the ground if the upper atmospheric winds were substantial and in the same direction as the sound rays. Therefore, depending on the upper atmospheric winds, these secondary booms could be heard at locations distant from the primary sonic boom carpet.

Secondary sonic booms were regularly reported on land near coastlines during Concorde's early commercial operation. These secondary booms were mitigated at the time by increasing coastal buffer distances, the distance between the coastline and the location where the supersonic aircraft transitions from supersonic to subsonic flight. Having a sufficient coastal buffer distance can serve that no noticeable secondary sonic boom would be perceived on land. With an insufficient coastal buffer distance, secondary booms could be heard and were sometimes reported to local authorities.

Pioneering work to measure and understand secondary sonic booms from Concorde was undertaken by Rickley and Pierce in 1980. They defined the Type I and Type II nomenclature mentioned above. Their and other contributions were reviewed in a 2020 literature review by Sparrow and Riegel.

It was reported that the sounds heard by residents were from Type II secondary booms, those that came from primary sonic booms reflecting from the earth's surface. Hence, it seems that understanding this reflection of the Type II secondary booms could be important.

This paper shows some initial efforts to characterize the reflection of the Type II secondary sonic booms. The next section provides some background of related work. Section three provides some initial observations, Section four explores a model problem using ray tracing, and Section five draws some preliminary conclusions.

2. PREVIOUS RESEARCH

There is a dearth of careful studies on the reflection of sonic booms from the topography of the earth's surface. Early work was done by Bauer and Bagley in 1970 at model scale using high velocity projectiles, but mostly focused on building reflections rather than that from natural outdoor surfaces. In the late 1990s and early 2000s there was work by Rochat and Sparrow regarding penetration of sonic boom noise into the ocean, which also included reflected sonic boom above the ocean surface. This work aimed to understand if ocean swell could focus sonic boom energy just under the ocean surface, and the focusing was found to be inconsequential. (The work of Sohn, *et al.,* experimentally found in a real ocean with real sonic booms overhead that there was negligible focusing underwater.)

More recently Emmanuelli, Dragna, *et al.* have simulated sonic boom reflection from both earth topography and urban landscapes. The techniques use finite difference time domain simulations in a manner somewhat similar to Rochat and Sparrow, but with much more accurate solvers and very large grids. The primary interest was to assess increases in sound levels at the ground surface, although their plots clearly show the sound reflecting at angles other than the incident angle.

The infrasound community has generated a handful references related to the reflection of infrasound from terrain. These papers usually assume an explosive point source, quite different than for the far field cylindrical (near plane wave) character of sonic booms. Because of the long distances that secondary booms travel, with almost all of their high frequency energy being lost to atmospheric absorption, secondary booms can be considered "near infrasound" with most of their energy being below 100 Hz. Hence, it makes sense that topographic effects for secondary booms will likely have some similarity to topographic effects on infrasound.

In 2012 McKenna, *et al.* examined measured infrasound with portable arrays and determined that the amplitude of the infrasound was affected by topography. Their results indicated that terrain features led to a complex scattering scenario. Very recently, terrain reflections have been incorporated into infrasound propagation models. In 2020 Blom investigated the influence of an isolated hill and showed the striking influence of the topography. For example, see Fig. 2 of (Blom 2020) where the sound field can completely disappear beyond a terrain feature as the sound is directed skyward, depending on the hill placement. Further in 2022 Waxler *et al.* introduced a new parabolic equation model for infrasound including a "basement" formulation, below a flat ground surface, to include terrain effects. Acknowledging the limitations of their new model, their results show substantial differences in infrasound propagation when topography is introduced.

3. TOPOGRAPHICAL REFLECTION

An important difference between a primary sonic boom reflecting from an ocean surface and from the land has to do with the flatness of the surface. Yes, there can be swell on the ocean, but carefully measured surface slopes and our common understanding is that the ocean surface can be much flatter than surfaces on the land. In addition to this, the land surface can have variety of surface types, but ocean surfaces are regarded as acoustically hard. Hence, one expects that because of the substantial difference in characteristic impedances between air and water, one can approximate a flat ocean surface as a perfect reflector of acoustic energy with a pressure reflection coefficient of $R = 2$.

This means that primary sonic boom should be reflected quite effectively from a flat ocean surface, and this will ensure that the reflected wave has a reflection angle and amplitude essentially identical to those of the incident wave. In contrast, a primary sonic boom reflecting from a typical ground surface may lose some high-frequency energy upon reflection, and the reflection may not be specular. That is, depending on the surface roughness, the primary sonic boom may be scattered in multiple directions, dependent on the distribution of the sonic boom energy across the frequency spectrum. Generally, one expects that higher frequencies are more likely to be diffusely scattered for higher wavenumber fluctuations in the ground surface. Yes, low frequencies can be scattered as well, but this very much requires larger terrain features in the ground surface. As will be seen in Section 4, the grade angles do not have to be large for an effect.

From such a simple viewpoint, a few observations can be made. Firstly, there are likely to be substantial differences between primary sonic boom reflection over somewhat calm water surfaces and flat ground surfaces (think Midwest United States) compared to reflections over ground surfaces with substantial slope changes such as mountains and city-scapes. For the flatter surfaces, primary sonic booms should reflect quite similar to specular reflection, with most sonic boom energy heading away from the surface at similar reflected angles. On the other hand, when the primary sonic boom reflects from topographic gradients, the sonic boom energy is reflected in a complicated way, with different spectral components leaving the surface at different reflected angles. This will greatly affect the amplitude and spectrum of the reflected, now secondary, sonic boom. To provide support for some of these hypotheses, an initial model problem is now put forward.

4. AN INITIAL MODEL PROBLEM

4.1 Preliminary considerations

Before a full computational exploration of the reflection of secondary sonic booms is attempted, which is beyond the scope of this presentation, it will be useful to consider a model problem. Such a model problem will use a geometry corresponding to actual sonic boom reflections. Here we take the geometry as outputs from NASA's PCBoom suite of tools, for the case of a Concorde supersonic aircraft decelerating into a coastline, as if the aircraft were completing the supersonic portion of its flight. It should be noted that PCBoom is one of the few available programs that models secondary boom propagation. Our research team has concerns about the pressure versus time signatures that the current version of PCBoom is producing for secondary booms, so we will focus only on the actual ray path computed by PCBoom.

Table 1. Typical Type II ray geometry for Concorde.

Quantity	Value
Primary boom horizontal distance from aircraft	24 438 m
Secondary boom horizontal distance from aircraft	261 012 m
Turning point altitude	46 899 m

4.2 Geometry without topography

As Concorde descends near the coastline, it is decelerating. As an example, we will examine when Concorde is at Mach 1.2 and an altitude of 13763 m. For this moment, a typical ray geometry traced by PCBoom is given in Table 1 for a Type II secondary sonic boom. This is all at an angle of 11° from the direction of aircraft travel. For this model problem, we only focus on two-dimensional ray tracing in the direction of propagation, and ignore the three-dimensional aspects included in PCBoom.

4.3 Effective sound speed profile

For the scenario run in PCBoom the temperature profile and winds correspond to a Concorde case from Rickley and Pierce. A smoother profile is needed for the calculations described below, and hence an analytical effective sound speed profile was developed to mimic the effective sound speed profile of Rickley and Pierce's Figure 45, and this is shown in Figure 1. Note that the portion of the profile responsible for the secondary booms returning to the ground is the portion to the RIGHT of 340 m/s, the assumed sound speed at the ground.

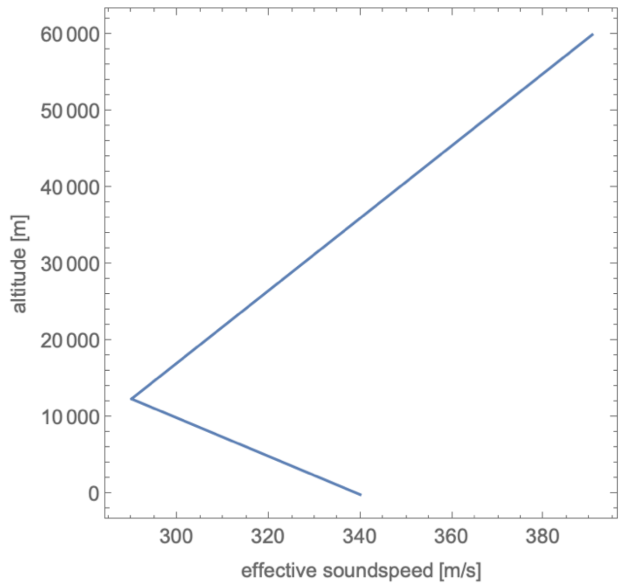

Figure 1. Analytical sound speed profile corresponding to this example.

In m/s, this profile can be written as

$$c_{eff}=340(1-11.76 \times 10^{-6}\ z) \quad \text{for } 0 < z < 12500 \text{ m, and} \tag{1a}$$

c_{eff}=290(1+7.3x10^{-6} (z-12500)) (1b)
for z > 12500 m.

4.4 Ray Tracing in Mathematica

Since an analytical profile is available, it is quite simple to perform numerical ray tracing in Mathematica. The analytical derivatives of the profile above are available, and this simplifies the modeling considerably. The ray trace approach taken here is identical to the direct integration method highlighted in Jensen, *et al.*, in their Chap. 3.
Here the ray tracing is performed only to determine where the rays land, based on their launch angle. There is no need to account for terms such as nonlinearity and the 90° phase shift at the turning point of the ray. Those are key points for determining the amplitude of the ray, but they are not necessary for determining the ray landing location.

4.5 Ray tube diameters and topography

Salamons has extensively used the concept of ray tube diameters for two-dimensional ray tracing. See Chap. 4 and Appendix L of (Salomons, 2001). The pressure amplitude of the signal along the ray is multiplied by a focusing factor proportional to the inverse square root of the ray tube diameter. Hence, a substantial increase in ray tube diameter implies that the sound level decreases.

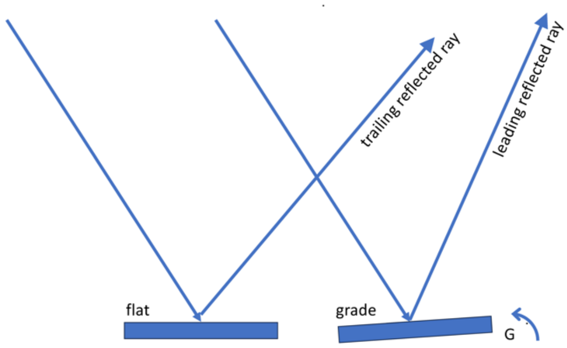

Figure 2. Leading and trailing rays in a ray bundle interacting with simplified topography.

To model topography in the simplest way in the context of ray tracing, we will examine the ray tube diameters when the leading ray in a ray bundle encounters topography but the trailing ray in a ray bundle does not. See Fig. 2 showing a close-up of where a primary boom ray bundle impacts the ground surface. It is assumed that the leading ray will encounter a grade in the ground surface corresponding to angle G, here given in degrees. The trailing ray will always encounter the flat ground surface. Both leading and trailing rays are nearly parallel before primary boom reflection, but leave the ground surface at different angles and the ray tube diameter can vary substantially. Via Mathematica, we now calculate the sound decrease due to the change in the ray tube diameter based on the leading ray and trailing ray. The leading ray elevation angle is adjusted according to grade angle G. It is assumed that the grade angle in between the leading and trailing ray reflection points is somewhere between 0 deg. and G. All reflection is assumed specular.

4.6 Results from ray tracing

The ray trajectory for the trailing ray is computed once, since that ground is always assumed to be flat, but the leading ray trajectory is computed for different grade angles G. Here G was varied between -5 and +5 degrees to give a sample range. No attempt was made to model genuinely rough or mountainous terrain with larger grade angles. The change in sound pressure levels due to the change in ray tube diameters for this case of secondary sonic booms is given in Eqn. (2) .

$$\Delta L_p = 20log_{10}\left(\left(D_i/D_f\right)^{1/2}\right) \quad (2)$$

Here D_i is the initial ray tube diameter, assumed here to be 100 m. D_f is the final ray tube diameter obtained from the ray tracing. Table 2 shows the change in sound pressure levels of these Type II secondary sonic booms given the change in ray tube diameters because of the grade in the topography. To help visualize the model problem calculation, Fig. 3 shows the ray trajectories with grade angles G = -4, -2, 0, +2, and +4 as solid lines. Note that the secondary sonic booms might be heard approximately 250 km from where the primary booms are heard.

Table 2. Change in Type II secondary sonic boom sound pressure levels due to topography.

Angle G [deg.]	L_p [dB]
5	-24.2
4	-22.8
3	-21.1
2	-18.9
1	-15.3
0	0.0
-1	-13.8
-2	-15.8
-3	-16.4
-4	-15.8
-5	-13.4

4.7 Discussion

Because of the long distances involved in Type II secondary sonic boom propagation, Table 2 shows that almost any grade angle G results in a decrease in sound level compared to the flat ground case. There is a greater level decrease for the larger positive angles. But for all the angles investigated here, both positive and negative grade angles result in a level decrease. In the case where the grade angle is positive the leading and trailing rays in the ray bundle cross over, and there is a caustic, but this occurs up in the air and does not occur at the secondary boom ground position. When there is a negative grade angle the leading ray never travels as high in the atmosphere as does the trailing ray, but positive grade angles result in the leading ray attaining higher heights before returning to the ground. In either case, the result is that the ray tube diameter is increased and the resulting sound level decreases for almost all cases where the leading and trailing rays encounter different grade angles.
Rickley and Pierce measured ocean-reflected Type II secondary sonic booms at sound levels of approximately 45-55 dBA. With reflection over topography, this would lead to sound levels which would be even lower by approximately 15 dB or more, based on Table 2. At levels of 30 dB or lower, the Type II secondary sonic booms might be inaudible, depending on the ambient background noise.

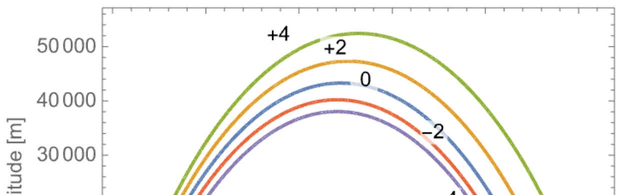

Figure 3. Sample calculated ray trajectories for the model problem. The origin is where the primary sonic boom is reflected. Hence, only sample Type II secondary sonic boom rays are shown, depending on the grade angle G in deg, ranging from -4 to 4. The secondary booms might be heard about 250 km from where the primary booms would be heard.

At the same time, we recognize there we have made many simplifications in this model problem, and these results should be verified with improved ray methods and full-wave approaches such as FDTD. For example, the current model does not account for frequency-dependent effects. And the model says nothing about Type I secondary sonic booms.

5. PRELIMINARY CONCLUSIONS

It is unclear whether secondary sonic booms will be heard routinely if a supersonic aircraft flies over land. The work here suggests that secondary sonic boom might be heard less frequently inland, due to nonuniform terrain, compared to regions adjacent to coastlines. This is because ocean-reflected primary booms exhibit specular reflection and most sonic boom energy is reflected at similar angles across the primary sonic boom carpet. On the other hand, secondary sonic booms caused by primary sonic booms reflecting from land surfaces with realistic topography are expected to have lower sound levels most of the time, and this is due to the increase in ray tube diameter that occurs over such long propagation paths. Topography seems to mitigate the secondary sonic boom noises, and in some situations, could make Type II secondary sonic booms a non-issue for overland supersonic operations. An exception to this might be when a supersonic aircraft flies over extended very flat ground surfaces or large lakes. Clearly, additional work is needed to confirm these hypotheses and to investigate Type I secondary sonic booms. And until the global prohibition for supersonic aircraft to fly over land is amended, it will be challenging to confirm these findings via experimental measurements with certainty.

6. ACKNOWLEDGMENTS

This research was funded by the U.S. Federal Aviation Administration Office of Environment and Energy through ASCENT, the FAA Center of Excellence for Alternative Jet Fuels and the Environment, Project 57 through FAA Award Number 13-C-AJFE-PSU under the supervision of Sandy Liu. Any opinions, findings, conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the FAA.

7. REFERENCES

[1] A. Bauer and C. Bagley, "Sonic boom modeling investigation of topographical and atmospheric effects," FAA-NO-70-10, July 1970, accessible as AD711124.

[2] P. Blom, "The influence of irregular terrain on infrasonic propagation in the troposphere," *J. Acoust. Soc. Am.*, vol. 148, no. 4, pp. 1984-1997, 2020.

[3] D. Dragna, A. Emmanuelli, S. Ollivier, and P. Blanc-Benon: "Sonic boom reflection over an isolated building and multiple buildings," *J. Acoust. Soc. Am.*, vol. 151, no. 6, pp. 3792-3806, 2022.

[4] D. Dragna, A. Emmanuelli, S. Ollivier, and P. Blanc-Benon: "Sonic boom reflection over urban areas," *J. Acoust. Soc. Am.*, vol. 152, no. 6, pp. 3323-3339, 2022.

[5] A. Emmanuelli, D. Dragna, S. Ollivier, and P. Blanc-Benon: "Characterization of topographic effects on sonic boom reflection by resolution of the Euler equations," *J. Acoust. Soc. Am.*, vol. 149, no. 4, pp. 2437-2450, 2021.

[6] F. Jensen, W. Kuperman, M. Porter, H. Schmidt, *Computational Ocean Acoustics, 2nd Ed.* (Springer, 2011).

[7] *Mathematica, Rev. 13.2*, Wolfram Research Inc., Champaign, IL, USA (2023).

[8] M. McKenna, R. Gibson, B. Walker, J. McKenna, N. Winslow, and A. Kofford, "Topographic effects on infrasound propagation," *J. Acoust. Soc. Am.*, vol. 131, no. 1, pp. 35-46, 2012.

[9] *PCBoom Version 7.3 User's Guide*, J. Page, *et al.*, NASA TM 20220016207 (Feb., 2023).

[10] E. Rickley and A. Pierce, "Detection and assessment of secondary sonic booms in New England," FAA-AEE-80-22, May 1980, accessible as ADA088160.

[11] J. Rochat and V. Sparrow: "Two-dimensional focusing of sonic boom noise penetrating an air water interface," *AIAA J.*, vol. 35, no. 1, pp. 35-39, 1997.

[12] J. Rochat and V. Sparrow: "A computational analysis of sonic booms penetrating a realistic ocean surface," *J. Acoust. Soc. Am.*, vol. 109, no. 3, pp. 899-908, 2001.

[13] E. Salomons, *Computational Atmospheric Acoustics* (Kluwer Academic, 2001).

[14] R. Sohn, F. Vernon, J. Hildebrand, and S. Webb: "Field measurements of sonic boom penetration into the ocean," *J. Acoust. Soc. Am.*, vol. 107, no. 6, pp. 3073-3083, 2000.

[15] V. Sparrow and K. Riegel, "2020 literature review on secondary sonic boom," in e-Forum Acusticum 2020, pp. 1013-1019, available at hal.archives-ouvertes.fr/FA2020/hal-03229476.

[16] R. Waxler, C. Hetzer, J. Assink, P. Blom, "A two-dimensional effective sound speed parabolic equation model for infrasound propagation with ground topography," *J. Acoust. Soc. Am.*, vol. 152, no. 6, pp. 3659-3669, 2022.