

SOUND PROPAGATION OF SONIC BOOMS THROUGH REAL ATMOSPHERES EMITTED FROM A NEW SUPERSONIC BUSINESS AIRCRAFT

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Abstract: Supersonic air transport generates sonic booms that can affect people, animals and structures.

There is a renewed interest in high-speed transport for civilian application.

The widely used standard atmosphere for sonic boom prediction is neither capable of describing topographical variation, nor temporal variations, nor the impact of wind on the propagation of a sonic boom. However, within the frame of the 6th FP EU-project HISAC (HIgh Speed AirCRAFT), our ray tracing studies are performed through real atmospheres from emissions of a supersonic aircraft that can impact people in case of overland flights. Obviously, the mountains are affected more often by the noise carpet than the lowlands.

The used ERA-40 data over the domain of Europe are appropriate to define flight tracks for supersonic aircrafts that avoid the noise carpet of sonic booms at the ground depending on the actual state of the atmosphere. A key role plays the atmospheric refraction due to temperature and wind gradients and the atmospheric absorption due to the humidity.

Primary use of improved prediction possibility is expected to operational route planning, especially as supersonic activity increases. Recently, flight demonstration of shaped sonic boom that generates low overpressure N-waves show the potential for quiet overland supersonic flights.

Keywords: *supersonic aircraft, sound propagation, mountainous area*

INTRODUCTION

The human response to aircraft noise is complicated because of the multitude of factors involved. Up to now civil supersonic flights, i.e. faster than sound are forbidden above land. However, it is highly probable, that civil supersonic aviation will be reinstated in the future, as the travel market is steadily growing, both for leisure and business purposes. A major key for an economically profitable civil supersonic transport is to overcome the obstacle of overland flights for a supersonic civil aircraft.

The impact of sonic boom needs carefully evaluated and precise noise regulations for sonic boom need to be devised. In this context the EU integrated project HISAC (High Speed AirCRAFT) will try to find answers by modifications in aircraft design that limit the environmental impact of sonic boom.

The sonic boom is a steady state phenomenon. It is generated continuously as the aircraft flies supersonically and not only at that moment when the aircraft breaks the sound barrier. The sonic boom is emitted by the aircraft and propagates along sound rays until it touches the observer at the ground. The observer hears the sonic boom when passed through by the wavefront. Sonic boom is the noise from shock waves, as heard at ground. Sonic booms are weak shocks, the typical overpressure at the ground is up to $100 \text{ Pa} = 1 \text{ hPa}$.

Depending on the flight and atmospheric conditions, the shock wave formed by supersonic flight can reach the observer on the ground in four forms – primary boom, secondary boom, focused boom, and shadow zone (Blumrich et al., 2005). In this study the focus is put on the primary boom. The primary boom refers to shock waves leaving the aircraft downwards and propagating directly to the ground. The typical pressure signature at the ground is a double shock N-wave, characterised by two sudden rises in pressure of $10 - 100 \text{ Pa}$, separated by $0.1 - 0.3 \text{ s}$, the corresponding sound pressure level would be $114 - 134 \text{ dB}$. The primary carpet, defined as the area on the ground where primary boom is heard, is an elliptical strip below the aircraft. The primary boom is the most annoying type of booms, it is so startling because there is no precursor (Coulouvrat, 2006).

The noise carpet of a sonic boom at the ground depends on the source and the propagation through the atmosphere. The used ray tracing theory for the sound propagation describes the location of the sound wave from the source through the atmosphere to the ground. The wave front of the sonic boom may touch the ground more or less directly or it may be distorted and refracted accordingly the real temperature and wind profile. As these atmospheric parameters vary widely in time and space, the sonic boom characteristics also vary widely. The frequency of booms touching the ground and those not touching the ground are identified.

METHODS

Geometrical acoustics is generally a good approximation since the wavelength is much smaller than the length-scale of propagation involved, and also the length-scale of atmospheric variation. The rays obey the Fermat's principle (that optical rays are least-time paths), which had been proved for acoustical rays in moving media as late as 1965. Meteorological conditions, both wind velocity and temperature vertical gradients, moderate the sound speed and the sound waves bent towards the lower speed region. The ray tracing methods used for sound propagation are much similar to those used in optics. Consequently, Snell's law of refraction is of primal importance.

At supersonic aircraft speeds a linear superposition of sound waves occurs spreading from its successive positions of the source (aircraft trajectory) at the speed of sound that is directly dependent on the ambient temperature. The wavefronts overlap and form an envelope, called Mach envelope and the envelope is the location of the sonic boom.

The semivertical angle of the Mach cone is the Mach angle $\Theta_M = \arcsin(1/M)$, i.e. the faster the aircraft speed, the smaller the angle Θ_M . Boomrays are called those rays that are emitted perpendicular to the Mach envelope at angle $\Theta_B = \arccos(1/M)$. The Mach envelope can be thought of tips of boomrays. Small Mach numbers corresponding to big Mach angles lead to rays that are directed flatter into the atmosphere and those rays are more capable to be refracted back without touching the ground than rays emitted from aircraft with high Mach speeds.

Tracing the boomrays is the standard method to follow the path of the shock wave in sonic boom prediction methods, the so-called ray theory approach.

DATA

The aircraft data are assumed realistically and composed from aircraft speed, flight direction and aircraft altitude.

The meteorological data were extracted from ERA-40 re-analysis database of the European Centre for Medium Range Weather Forecast (ECMWF, Uppala et al., 2005). ERA-40 is a high-quality global analyses of the atmosphere, land and ocean-wave conditions for the past four decades, available since 2003. The data assimilation system bases on observations from aerological profiles, surface reports, buoys, satellite data and others.

For this study data of the European domain are used with a horizontal resolution of 1.125° in latitude and longitude, which is roughly 100 km. The vertical resolution spans over 30 m at the ground to 2 km in 25 km altitude. The meteorological parameters of 11 years from 1990 to 2001, every day at 4 times (00, 06, 12, and 18 UTC) at each of the 1600 grid points and 41 levels are: altitude, pressure, temperature, specific humidity, and horizontal wind. This data set provides an opportunity to test sonic boom farfield propagation for atmospheric effects, and to examine the net effect of wind and temperature profiles on the refraction of acoustic rays.

RESULTS

The applied ray tracing method considers both, aircraft specifications and meteorological effects. From the daily temperature profile the sound speed profiles are determined, typically the sound speed increases from about 290 m/s in the stratosphere to about 340 m/s at the ground. A typical travel time of the acoustic wave from the stratosphere to the ground is about 90 s. The downward increase of 10 to 20% in sound speed is modified by the wind velocity. Strong winds blowing against the flight direction can produce a shadow zone in the downwind region very far away.

Figure 1 (left) shows the natural variation of temperature profiles obviously deviate from the standard atmosphere profile with ± 15 to 20 K for all altitudes. Further, the evident variation of the daily wind profiles reveals the typical wind maximum near 10 km, just below the tropopause, where the temperature profile has a prominent sharp bend. Rather strong winds occur in the winter half in altitudes between 10 and 20 km where a supersonic cruise is expected (Figure 1, mid).

Under favourable natural conditions an acoustic ray (Figure 1, right) can be bent upwards and the boom is not heard at the ground. An aircraft over Munich that cruises daily with 1.15 Mach in 14 km altitude to the

West would generate within one year about 2/3 rays that never touch the ground. However, on about 1/3 days per year the sonic boom would have been audible.

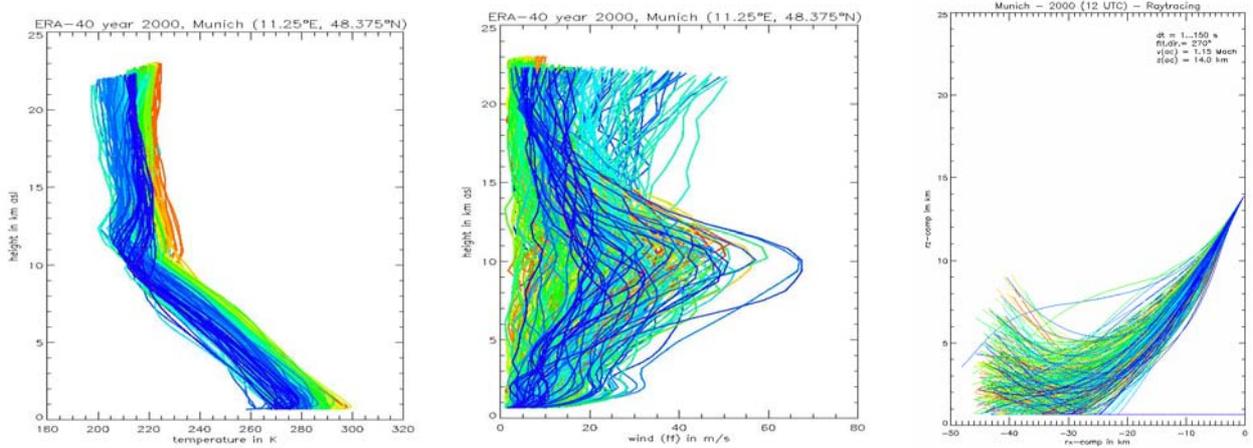


Figure 1: Daily temperature (left) and wind (mid) profiles of the year 2000 for the ERA-40 grid point Munich and determined acoustic rays (right) for these profiles. The colour changes from bluish in winter to reddish in summer, spring and fall are in green.

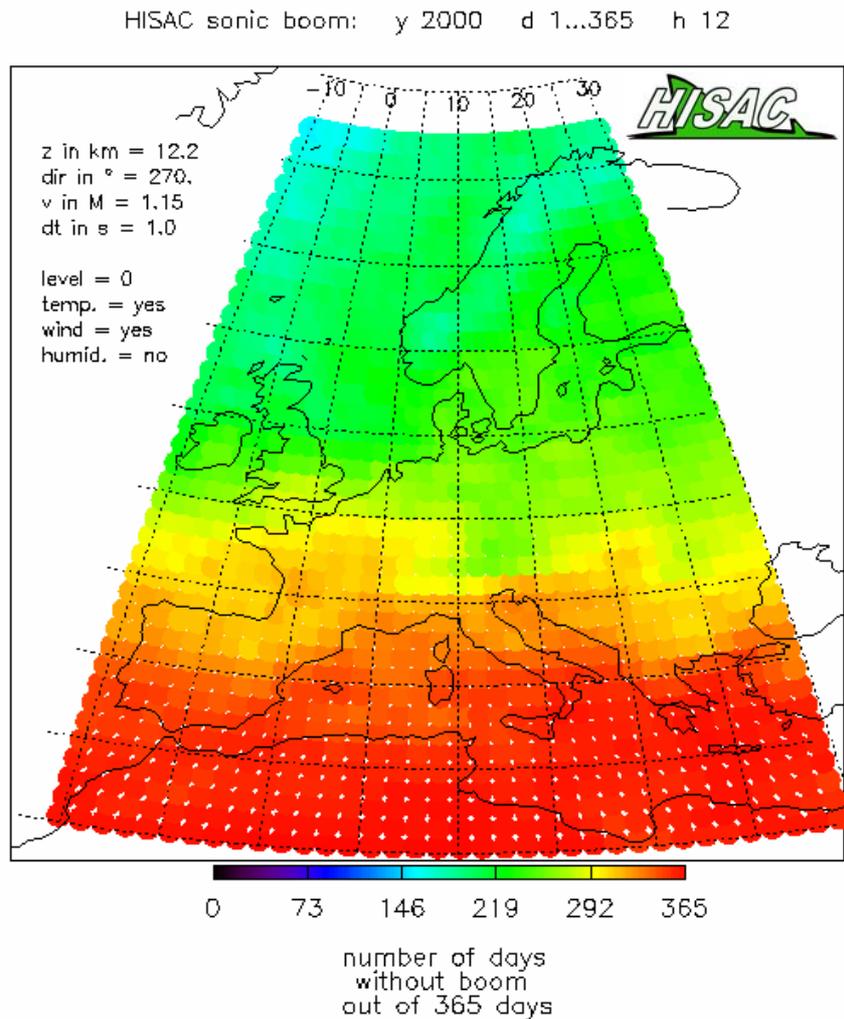


Figure 3: Considerable differences in Europe for audible sonic booms at the ground due to the natural variation of meteorological parameters.

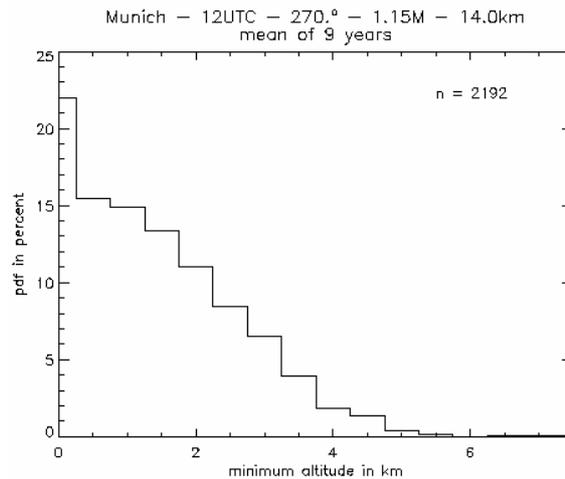


Figure 2: pdf of the minimum height of rays which do not touch the ground (1992-2000)

Figure 2 shows that the pdf of “boomless” rays (refracting upwards) descends almost linearly with altitude and most of the “boomless” rays bend upwards as recently as in the lowest layer above the ground. Therefore, it is obvious that mountainous regions are unprivileged in terms of “boomless regions” and consequently should be protected from supersonic flight routes.

DLR currently performs a realistic study on the effect of the natural variation of temperature and wind profiles on the sonic boom propagation over Europe. A definition of acceptable flight paths over continents with the restriction “no boom at the ground” does not depend only on the aircraft parameter but also on meteorological conditions. Comprehensive evaluation has been performed for different aircraft velocities, altitudes and flight directions and for several years.

An exemplary “no boom” map (Figure 3, previous pg.) is composed from 1600 grid points for which the daily acoustic rays have been determined from the ERA-40 profiles. The aircraft specifications are: flight altitude of 12.2 km, speed of 1.15 Mach, heading to the West. The colour gives the number of days per year for which a sonic boom is not heard at the ground. Mach 1.15 would save 35% of flight time and allows supersonic flight without sonic boom impacts in the Southern Mediterranean region throughout the whole year. Flight time reductions of 20 or 30% are considered to be marketable. An explanation for the obvious north-south gradient in the distribution of boomless days in Figure 6 may be that one of the key parameter is the tropopause height being usually higher in the Mediterranean than over Scandinavia. Over the Alpine mountains the same aircraft would emanate audible noise and for the worst case only 215 days were boomless. Further, regarding that the ERA-40 data do not reflect the true mountain height even less days are boomless over the Alps.

The benefit of such maps is to define flight paths for aircrafts that cruise at a much higher velocity than nowadays over continents and with possibly better acceptance by considering the meteorological effects. The so-called critical cutoff number for the standard atmosphere (1.153 M) divides boomless and audible boom regions (boom carpet). Theoretically, a slightly supersonic flight below that critical Mach number would be boomless simply because of natural refraction. However, in a real atmosphere with wind, the situation is more complex and this quantity can vary between 1.1 and 1.25 Mach due to the natural variety of meteorological parameters.

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