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# ACOUSTICS 2012

## Sonic boom and infrasound emission from Concorde airliner

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Any phenomenon of an impulsive nature, such as an explosion, a gun shot or a clap of thunder, generates an infrasonic emission which is propagated at very long distance, as the atmospheric absorption has only a limited influence on it. The sonic boom of aircraft, launchers or meteorites obviously belongs to this category. During its propagation, the signal is distorted and becomes a rumble, the duration of which can reach several minutes at a distance of about one thousand kilometers. However, it is often possible to make the distinction between the emission and the natural background noise and to relate it to the sound source of origin by using goniometry and spectrum analysis. In this respect, the recordings of the sonic boom and the flight data of the "Concorde" airliner provide an interesting and complete experimental data base. Examples of exploitation of signals and of numerical simulations (sonic boom shape, direct and reverse propagation taking into account the meteorology of the day) are given for distances of 100, 300, 1000 and 3000 km.

## 1 Introduction

The ballistic wave generated by projectiles and the sonic boom produced by aircraft are related phenomena, both caused by the impact of a material body moving at a supersonic speed against the atmosphere. Scientists started working on these phenomena as early as the end of the XIXth Century and the beginning of the XXth Century in Austria [1] and in France [2], then in the United States [3] and in the United Kingdom [4]. Once the sound barrier was broken in 1947 (possibly in 1945), aerodynamic research on projectiles was extended to the sonic boom produced by aircraft [5]. In France, the project of bringing into service the supersonic Concorde airliner was at the origin of many campaigns of measurements. These were first conducted using military aircraft [6], then Concorde itself [7]. These measurements were made at distances not exceeding 30 km, while the pressure wave of the sonic boom keeps its characteristic N shape [8]. At more than 100 km, the sonic boom can no longer be heard. However, the resulting infrasonic waves can still be recorded at 1000 km and even greater distances. This particularity is most useful for the study of phenomena related to atmospheric propagation [9-10-11] or the characterization of the sound source through the resolution of the reverse problem, i.e. starting from the signals [12].

## 2 Ballistic Wave

The aerodynamic wake of supersonic projectiles could be photographed in the 1880s [1]. Figure 1 is part of reference [2] and represents a rifle bullet travelling at a speed close to Mach 3. The forward shock wave (or Mach cone) is in fact a cone whose normal speed is supersonic in all points of its surface due to strong local pressures. The rear shock wave has a slightly concave shape but the opening of the cone that it generates is very close to the Mach angle  $\alpha$  determined by the relation  $\sin \alpha = 1/M$ . This rear wave has a particularity: it corresponds to an overpressure in the vicinity of the bullet then to a depression front as it moves away from the bullet. So the U shaped wave turns into an N shaped wave as shown at Fig 2 (below) due to the influence of non-linear phenomena which characterize an area submitted to significant variations of pressure and temperature. It should be noted that the representation of the wave on a time scale is inverted, with the forward front of the wake being on the left and the rear front on the right.

Due to the divergence of the wake (very similar to the wake of a ship), the length of the N wave and the duration of its passage  $\Delta T$  at a given point grow along with the distance  $R$  between the point and the trajectory, while its amplitude  $\Delta P$  decreases. The laws ruling these variations

( $R^{1/4}$  for  $\Delta T$ ,  $R^{-3/4}$  for  $\Delta P$ ) were found simultaneously in Russia (Landau, 1942) and in the United States (Du Mond, 1944) while the theoretical formulas allowing to calculate  $\Delta P$  and  $\Delta T$  in function of the speed and the shape of the projectile were established by Whitham after WW2 [4]. These formulas are valid for ballistic waves generated by a wide variety of light weapons projectiles (calibers from 7,62 to 40 mm).

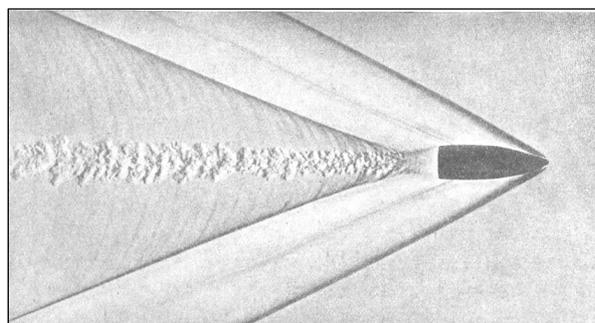


Figure 1 : Wake of a rifle bullet at a supersonic speed

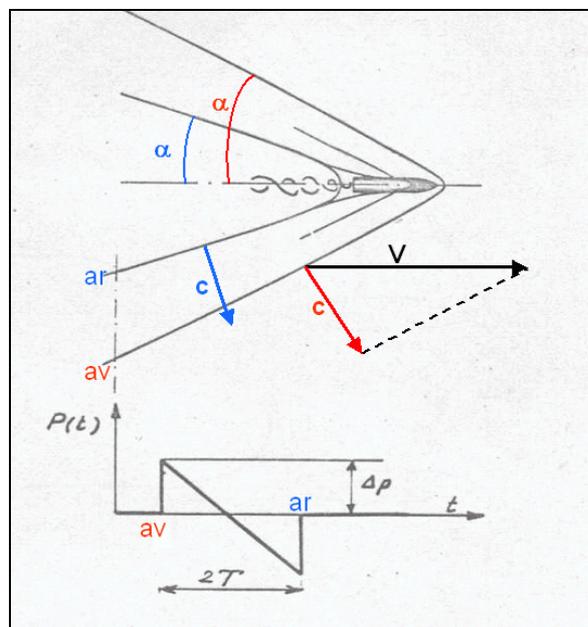


Figure 2 : Supersonic wake, and N-wave outline

The spectrum of the N wave is formed by a succession of arches whose pseudo-period is determined by the duration of the passage of the wave (blue curves at Fig 3). On a logarithmic scale, the slope of the envelope of spectra (red curve) is -6 dB per octave, what is common to all the spectra of short signals.

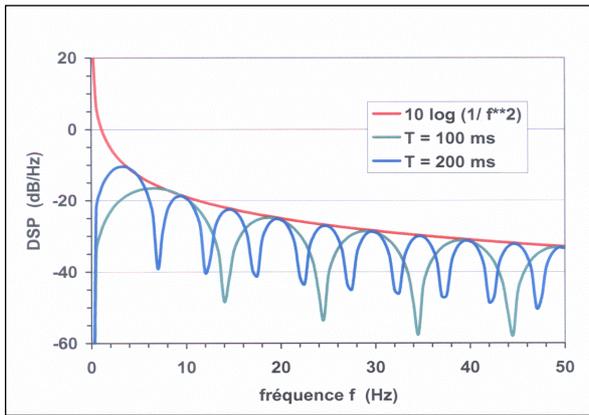


Figure 3 : N-wave spectra and tangent curve

### 3 Sonic Boom

Later on, Whitham’s formulas were extended to aircraft, with the introduction of a function of lift. One of the consequences is to increase the amplitude of the overpressure as opposed to that of the depression, particularly in case of an amplification caused by the acceleration or the maneuver performed by the aircraft. Fig 4 shows the profile of the sonic boom of a Mirage III fighter accelerating at an altitude of 1000 feet. The shape of the wave is less regular than that of an axisymmetric moving body but under the influence of non-linear effects, it becomes simpler during propagation and tends to take the shape of an N after a few kilometers.

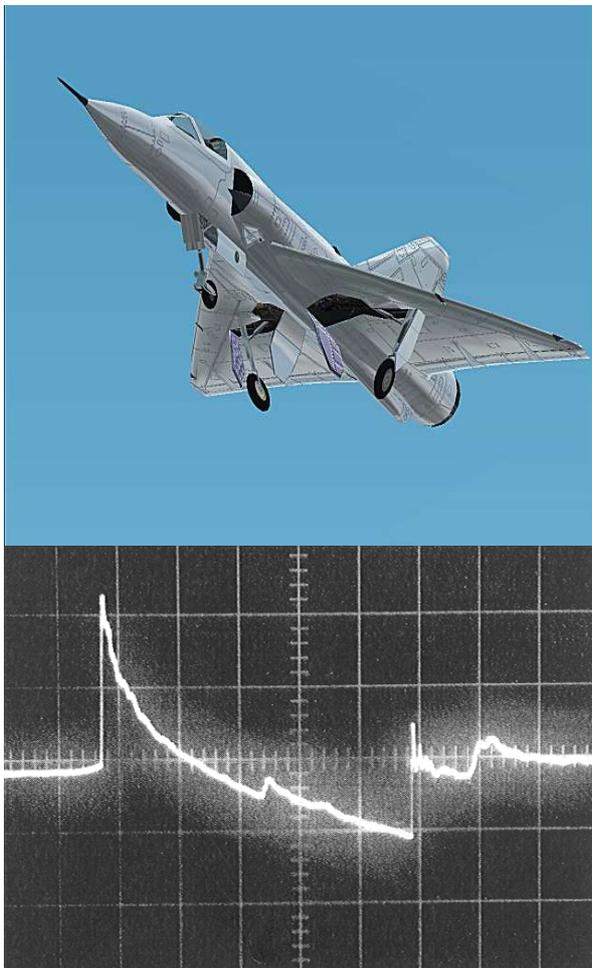


Figure 4 : Sonic boom of a Mirage III in acceleration

When the distance of propagation reaches 20 or 30 km, the atmosphere will have reduced both the non-linear effects (through heat absorption) and the high frequencies of the signal, which eventually causes the vertical fronts of the N wave to disappear, as shown at Fig 5.

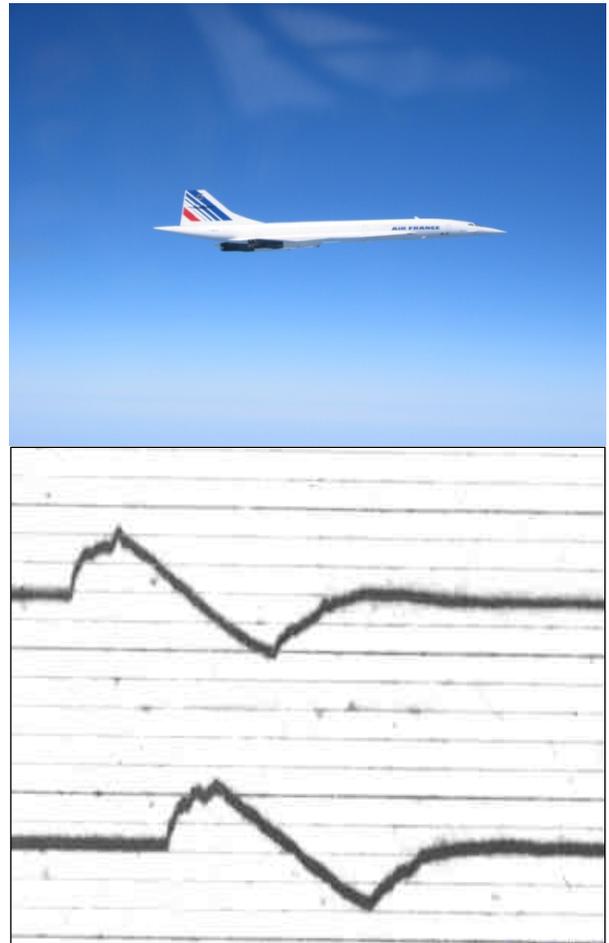


Figure 5 : Sonic booms of Concorde at 30 km

This distortion will continue with the appearance of another phenomenon called rumble [10], which consists in the duplication of the signal into a succession of multiple echoes the total duration of which grows along with the distance to the sound source. It is this phenomenon, combined with aerologic factors and sound reflection and scattering at ground level [11], which transforms -for example- the sound of a thunderbolt into the rumble of thunder.

### 4 Effects of distance

In 1976, after Concorde became commercially operational, ONERA, CEA and other organizations kept studying the repercussions of the sonic boom caused by Air France and British Airways flights above North Atlantic and the Channel. We will study the results of measures made in Brittany, Normandy, Aquitaine (South Western France) and Sweden. They provide an interesting data base for distances from 100 to 3000 km. The most interesting result is that the length of the signal (or the various times of arrival of the signal) varies from one second at 100 km to ten minutes at 3000 km.

The beginning of an explanation is provided by Fig 6, which represents a part of the sound rays coming from the Mach cone (Simoun 3D computer code). The complex routes imposed by the weather conditions tend to scatter the signal in space and time. The primary carpet of the sonic boom reaches the sea and the city of Lannion, located at about 100 km of the emission point. Fig 7 gives the signal recorded in Lannion, Fig 8 shows its spectrum (blue curve). As we can see, it is still close to the theoretical spectrum of an N wave (red curve).

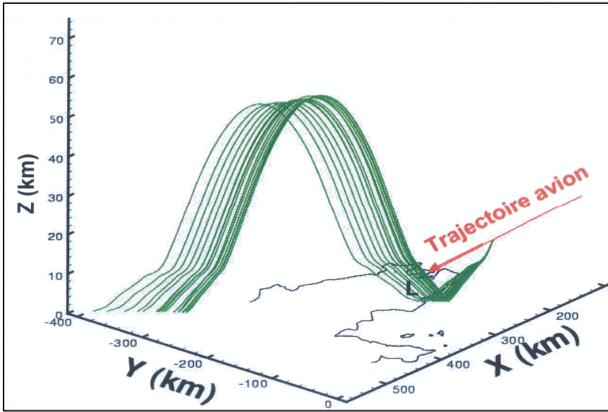


Figure 6 : Sound ray tracing in approach of Brittany

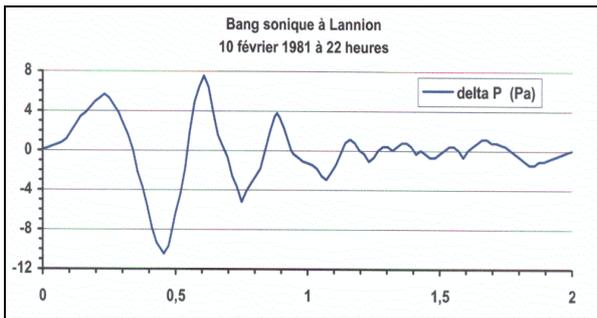


Figure 7 : Sonic boom recorded at Lannion

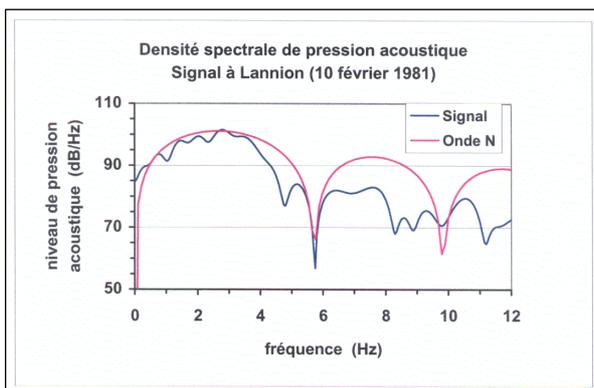


Figure 8 : Real and theoretical spectra of sonic boom

Fig 9 indicates the timing of the arrivals of the signal at the CEA station located in Flers in Normandy. These arrivals, sent from various points of the aircraft route, keep coming in over a few minutes. However, the main arrival (S1 to S3) which is shown in detail at Fig 10, does not last for more than 36 seconds. A method was designed to determine roughly the distance at which the emission point is located [12-13]. Knowing that the slope of the envelope of the spectrum of the initial signal is -6 dB per octave, we

can calculate the evolution of this slope caused by atmospheric absorption for a trajectory supposedly culminating at an altitude of 60km. (see Fig 6). As the absorption grows along with the frequency, the slope of the envelope curve gets steeper as the distance grows while the comparison with the spectrum of the signal allows making an estimation of the propagation distance. Fig 11 shows that the spectrum of the signal (red curve) roughly follows the theoretical envelope of the spectrum of the N wave at 300 km. The advantage of this method is that it is independent from the size, speed and altitude of the aircraft emitting the signal. Besides, the light blue curve at Fig 11 corresponds to the natural background noise heard in the absence of a useful signal: we realize that its slope is precisely -6 dB per octave, which may be a problem in the case of a less favorable signal/noise ratio.

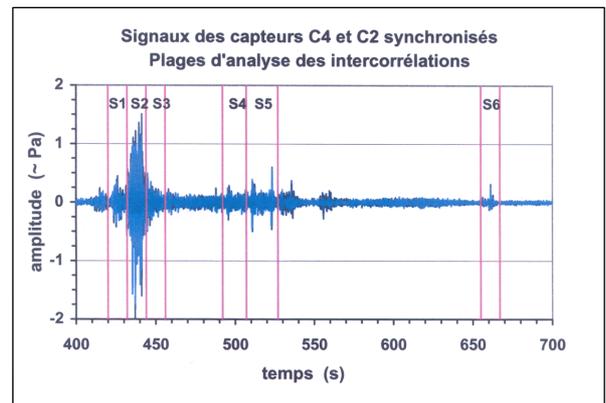


Figure 9 : Signal of Concorde recorded at Flers

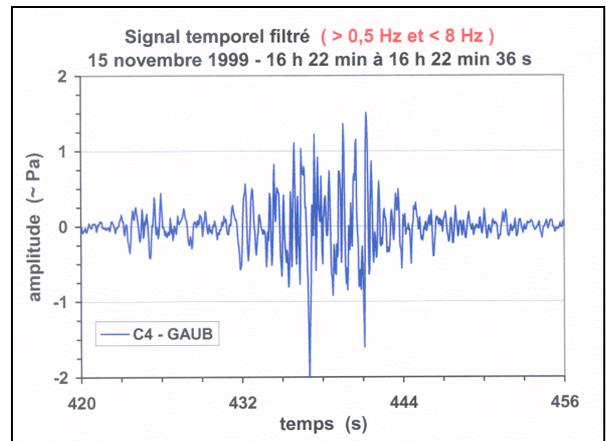


Figure 10 : Signal recorded at Flers: main arrival

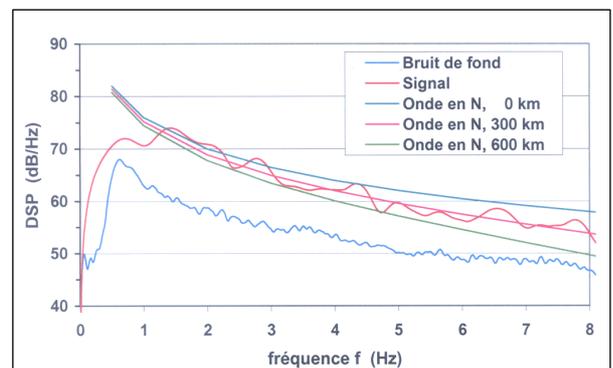


Figure 11 : Estimation of the distance of the sound source

In this particular case, we know the flight plan of the New York-Paris Concorde flight which was re-calculated by APCOS [14] in function of the weather conditions of the day. It is therefore possible to fire sound rays towards Flers, knowing the position, altitude, speed and local descent rate of the aircraft, while taking account of the rotundity of the Earth whose effects cannot be neglected at these distances. In these conditions, only a few points allow the sound rays to reach Flers, the constraint being that they must be fired perpendicularly to the Mach cone. As shown at Fig 12, we see that the possible routes actually correspond to the three groups of signal arrivals shown at Fig 9, even if the Simoun 3D calculation shows timing differences (for altitude higher than 30 km, we only have statistical season weather forecast). The main arrival shown at Fig 10 corresponds to the low stratospheric route, first to have arrived at Flers but last to have been sent on the flight path.

Another exercise consists in calculating the correlation time and the apparent speed of propagation between the captors of the Flers station network in order to determine the azimuth and the elevation angle of each stratospheric arrival (S1 à S5). The example at Fig 13 suggests the presence of a group of waves coming from a WNW direction. This direction may then be calculated more accurately. The comparison between the obtained apparent propagation speed and the local sound speed then allows the calculation of the angle of incidence of the wave front.

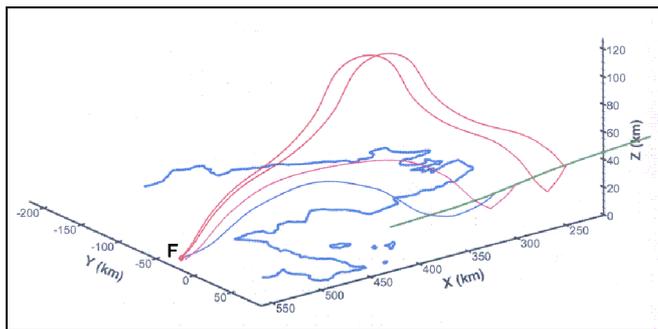


Figure 12 : Ray paths from Concorde towards Flers

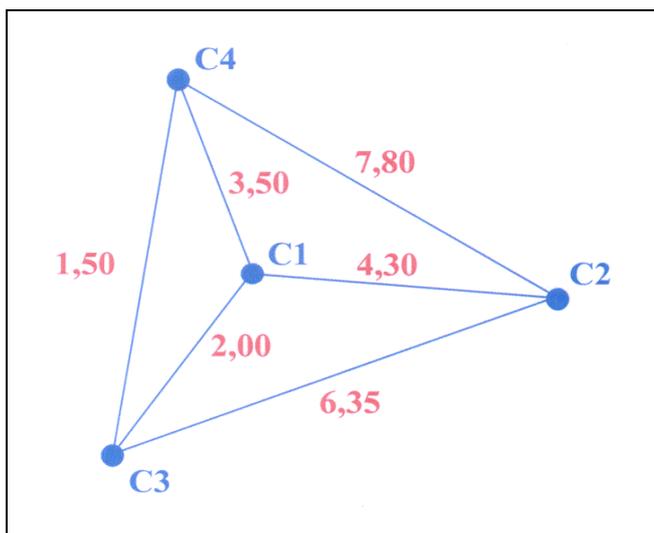


Figure 13 : Correlation times (s) between sensors at Flers

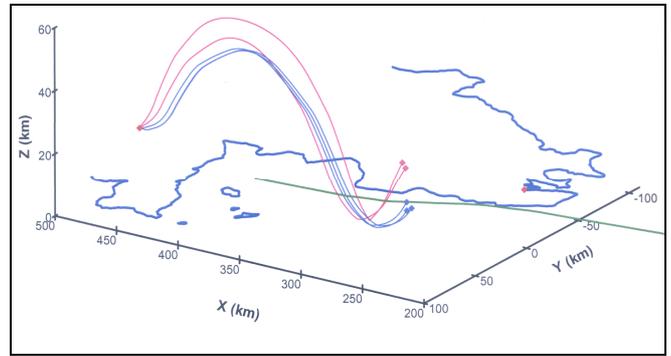


Figure 14 : Paths of reverse rays fired from Flers

Firing reverse rays in the opposite direction then becomes possible, provided the wind direction is inverted at all altitudes. We know that the paths followed by rays are not reversible in the presence of wind which is in apparent contradiction with the principle of acoustic reciprocity [15] : the original artifice at reference [13] allows to get round the difficulty. Fig 14 shows that the rays coming from the main sequence (S1 à S3) meet the trajectory of the aircraft at the right altitude. The paths are interrupted by the code at a curvilinear distance of 300 km which confirms the estimation of the distance shown at Fig 11. The emission comes from the Concorde at turning point BISKI.

## 5 The case of long distances

We have examined in Reference [13] signals coming from the Concorde, recorded in Aquitaine at orthodromic distances (arcs of a great circle) varying between 700 and 900 km from aircraft, and signals recorded in Sweden at orthodromic distances varying between 2800 and 3100 km. These signals were those of New York-Paris or New York-London flights. At these distances, it is essential to take into account the Earth rotundity to calculate the sound rays if we do not want to make serious mistakes on the arrival points.

The total duration of the signals recorded in Aquitaine is about five minutes. However, we can see at Fig 15 that the main signal (at the end of the sequence) has a duration of about one minute. In fact, the signal spectrum emerges over the background noise only from 1 Hz to 10 Hz (Fig 16), which explains why the estimation of the distance by using the theoretical slope of the sonic boom spectrum is only valid below 10 Hz. This estimation gives good results, the errors made not exceeding 10 %. The sound emission comes from the Concorde at turning point BISKI located in North-Atlantic (Fig 22).

The signals recorded in Sweden (the three listening stations are located in Lapland) come from a British Airways flight. The signal to noise ratio is obviously weaker than it is at one thousand kilometers (Fig 18). An analysis carried out by the CEA using the PMCC computer code [9] shows that the signal arrive at the Kiruna station during about ten minutes, and mainly come from two directions. Figure 20 shows the 3D reverse ray traces coming from the three stations, Kiruna being the Northernmost one (blue lines). One can see that the sound rays bounce about ten times on the sea or the ground, which may explain the duration of the reception time. However, it is obvious that one cannot distinguish the main arrival sequence, as is the case for shorter distances.

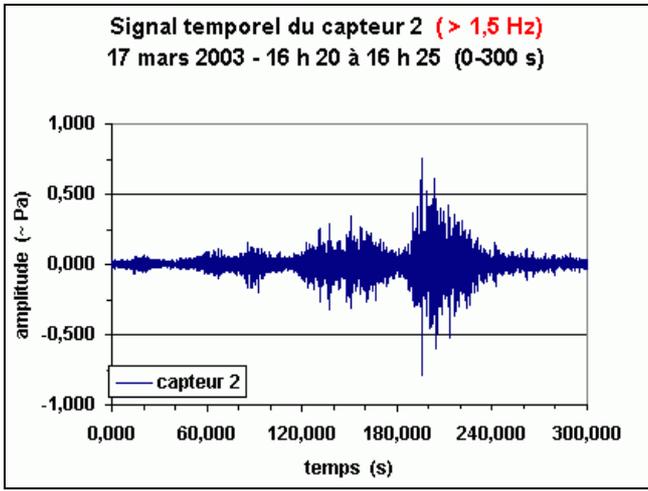


Figure 15 : Signal arrivals recorded in Aquitaine

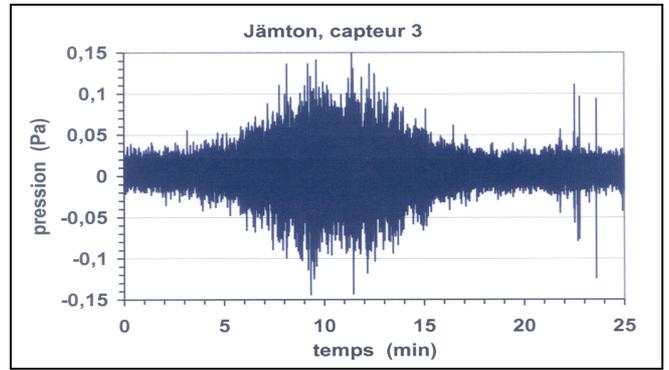


Figure 18 : Signal recorded in Sweden

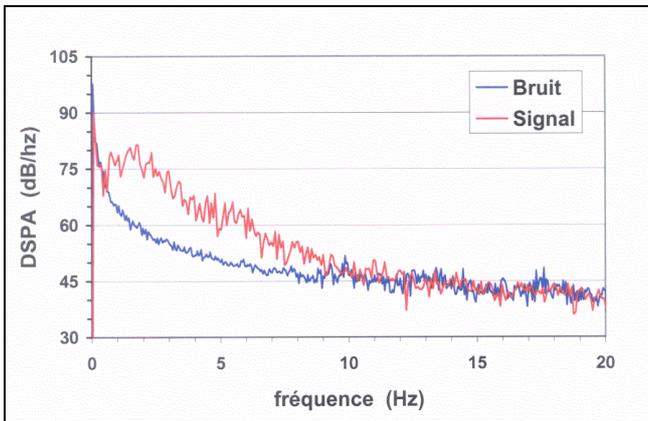


Figure 16 : Signal and natural background noise

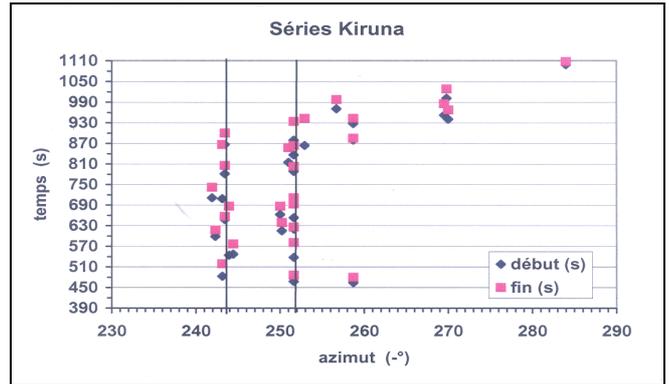


Figure 19 : Detail of the signal arrivals at Kiruna

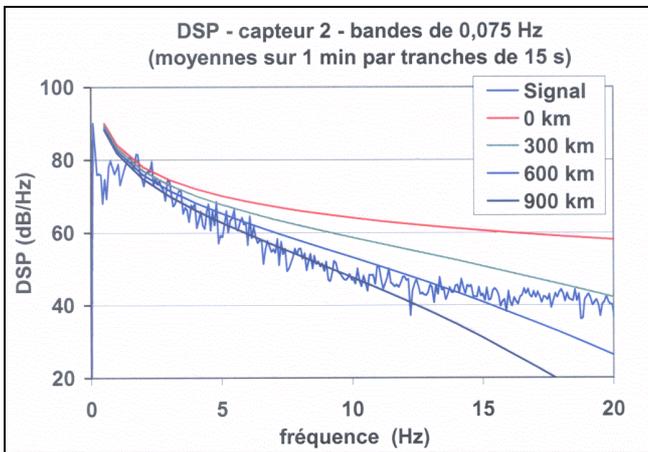


Figure 17 : Estimation of the distance of Concorde

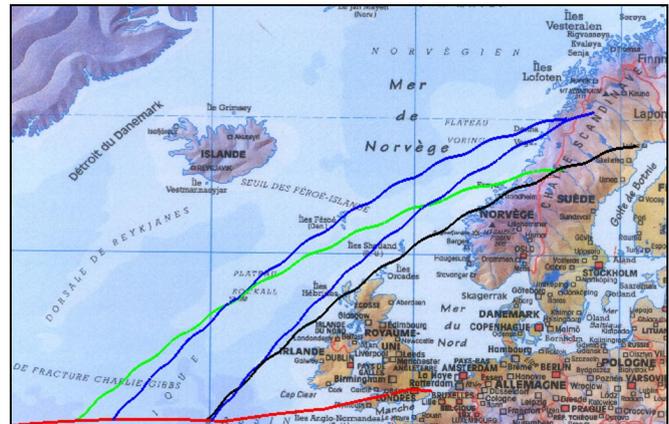


Figure 20 : Ray paths coming from B.A. Concorde flight

The propagation durations computed by Simoun 3D, the timing of the signal arrivals at the three hearing resorts, and the theoretical timetable of the airliner in its flight corridor, are remarkably coherent [13], which at least shows that the British Airways airliner was exactly on time on that day!

The unfavourable signal to noise ratio, more particularly over 5 Hz, required to make use of fussy techniques of signal treatment for extracting the spectrum of the useful signal (Fig 21). Yet the error concerning the propagation distance remains in an acceptable ratio: 3500 km in curvilinear distance in our example, for an orthodromic distance of 2900 km that corresponds to an actual curvilinear distance of around 3100 km.

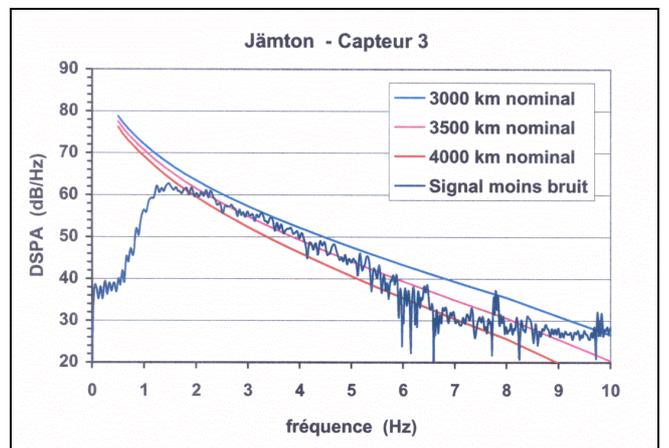


Figure 21 : Estimation of the distance of Concorde

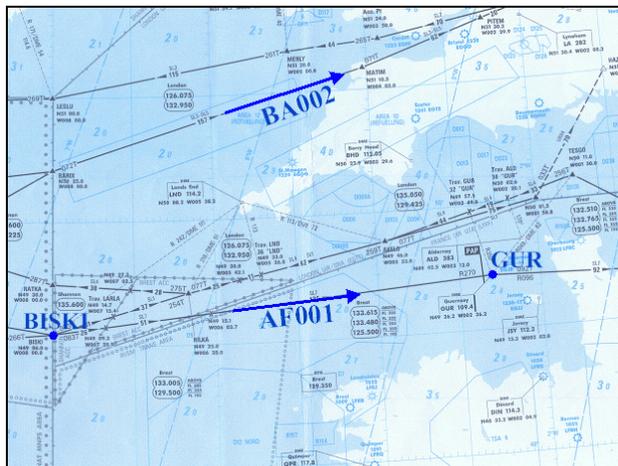


Figure 22 : Air routes used by Concorde airliner [14]

## 6 Conclusion

Using the database provided by supersonic flights of Concorde, several methods in order to analyze infrasound signals generated by the sonic boom have been examined.

Reverse ray simulations, linked up with goniometric analyses of the recorded signals in order to determine the wave train directions, allowed us to find the part of the Concorde aircraft trajectory from where the sonic boom was emitted. From this trajectory part, knowing the local flight data accurately, it was possible to reach the measurement site with direct rays emitted perpendicularly to the Mach cone, which constitutes a very restricting condition. In relation with the maximum height of the meteorological surveys of the day, the seasonal weather data have been used above 30 km in altitude.

Another method consists in calculating the distortion of the envelope of a theoretical N-wave spectrum by the atmospheric absorption, in order to compare this envelope with the signal spectrum and to estimate the propagation distance. For that, we assume that this spectrum is degraded less than the time signal. We find a satisfactory agreement between resulting envelope and signal spectrum shape at distances of around 300 and 900 km from the measurement sites.

Thus, it is possible to roughly estimate the emission point of the sonic boom from bearing and distance data, and to precise it by a reverse ray-calculation if the weather conditions and the flight data are known.

One can notice that these calculations do not depend on the flight data of the aircraft and on the measured sound levels, but depend, in some limits, on the signal-to-background noise ratio. Thus, it was interesting to test the limits of this method with infrasound signals from Concorde recorded at 3000 km away or more.

## Acknowledgments

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