inter.noise 2000
The 29th International Congress and Exhibition on Noise Control Engineering
27-30 August 2000, Nice, FRANCE

I-INCE Classification: 7.4

ARIANE 5 AT LIFT OFF: LOCALIZATION AND RANKING OF ACOUSTIC SOURCES

G. Elias

ONERA, 29, avenue de la Division Leclerc, 92320, Chatillon, France

Tel.: 01 46 73 48 18 / Fax: 01 46 73 41 66 / Email: elias@onera.fr

Keywords:
ARRAY SIGNAL PROCESSING, ACOUSTIC LOCALIZATION, LAUNCHER ACOUSTICS, JET NOISE

ABSTRACT

At Ariane 5 takeoff, the acoustic environment is very complex due to the interaction of the jets of the three engines with the launch pad. To localize the acoustic sources seen from the fairing and provide input data for vibroacoustic codes aiming to compute the pressure field under the fairing, a microphone array has been flush-mounted around the fairing. After discussing the signal processing method, results are presented for the flights 503 and 504. They emphasize in particular the modification of the main noise sources structure following the modification of the flue exit between the two flights, aiming to noise reduction.

1 - INTRODUCTION

For the Ariane 5 launcher, the acoustic loads reach their maximum under the fairing during takeoff. These loads come mainly from the noise of the jets of the three engines equipping the launcher, i.e. the main engine and the two boosters [1], [2], [3]. At liftoff, the structure of these jets is very complex. Indeed, at an altitude of 0 m, the jet of the main engine is deviated in a discovered flue, whereas the jets of the boosters are deviated in covered flues. At a higher altitude, the jets no more enter the flues, but impinge the launch pad. Moreover, in order to reduce the noise, water injection devices are used. Even semi-empirical predicting methods exist for this kind of situation, only a method of noise source localization using an array of microphones makes it possible to exhibit the main sources of noise. To correctly predict the noise transmitted under the fairing in each frequency band, it is necessary to know the sound level on the external wall of the fairing together with the structure of the incident field. Indeed, for the same level of incident noise, the transmitted field depends on the angle of incidence. The vibroacoustic codes thus need a description of the incident field by a simple model, made up of a reduced number of uncorrelated plane waves. Once again, this modeling can be accomplished using an array of microphones. At last, a method of localization makes it possible to easily test the effectiveness of noise reduction device acting on a particular noise source.

To meet all these aims, the external wall of the fairing was equipped with an array of twelve flush mounted microphones during flights 503 and 504 of Ariane 5. We present here the localization method used to process the data, which is an adaptation of the conventional beamforming method. It first takes into account that the microphones are located on a cylindrical wall, and not in free field It also includes the non stationary character of the signals during the takeoff, due to the fast change in the structure of the jets when the launcher rises. The method is applied to flight 503, and the localization maps obtained for different altitudes are discussed. To reduce the noise emitted by the jets in the low frequency range at the first stage of the flight, the launching pad has been modified between flights 503 and 504, with the side flues lengthened. The localization of the noise sources for the flight 504 shows that this objective was achieved. At last, a model based on a set of uncorrelated plane wave is presented to provide data for the vibroacoustic codes.

2 - LOCALIZATION METHOD

The acoustic antenna is at 35 m above the central engine exhaust location, and is 7 m in height (figure 1). It is made of three circles of radius $a = 2.7$ m (radius of the fairing) separated by 3.5 m and equipped each with 4 microphones all the 90°. Its field of interest covers the low frequency band, typically from 20 Hz to 100 Hz. In this frequency band, the jets are in the Fraunhofer region of the antenna, so that the incident field can be described by a set of plane waves. The direction of an incident plane wave is defined by its polar angles ϑ and φ in the reference frame of the antenna, with the origin at the antenna center and with axis Oz (axis of the launcher) downwards directed. For the localization maps, one considers only the directions coming from the lower half space $0 < \vartheta < \pi/2$. These directions are mapped onto the plane XOY with $X = \sqrt{2}\sin(\vartheta/2)\cos\varphi$ and $Y = \sqrt{2}\sin(\vartheta/2)\sin\varphi$. They are found inside the circle $X^2 + Y^2 = 1$. The sampling of the directions is carried out with a step $\boldsymbol{\Delta}X = \boldsymbol{\Delta}Y = 1/25$ and the maps thus consist of 1976 directions of plane waves. For an incident plane wave of frequency f and amplitude A, the pressure received on the m^{th} microphone of the array (with co-ordinates $x_m = a\cos\varphi_m$, $y_m = \mathrm{a}\sin\varphi_{\mathbf{m}}$, z_m) reads $\mathrm{p_m}(\mathrm{f}) = \mathrm{AT_m}(\mathrm{f}, \vartheta, \varphi)$, where T_m is a transfer function taking account of the diffraction of the incident wave by the fairing. Describing the cap as a rigid cylinder, this leads to:

$$T_m(f,\vartheta,\varphi) = \frac{2ie^{ikz_m\cos\vartheta}}{\pi ka\sin\vartheta}\left\{\frac{1}{H_0'(ka\sin\vartheta)} + 2\sum_{n=1}^{\infty} i^n \frac{\cos n(\varphi-\varphi_m)}{H_n'(ka\sin\vartheta)}\right\} \tag{1}$$

where k is the wave number and H_n the first kind Hankel's function of order n. To find the amplitude and the direction of the incident wave from the signals recorded by the microphones, the conventional localization method consists in minimizing:

$$E(f,A,\vartheta,\varphi) = \sum_{m=1}^{12} |p_m(f) - AT_m(f,\vartheta,\varphi)|^2$$

Figure 1: Ariane 5 fairing equipped with 12 microphones.

The minimization results in locating the source at the maximum of the array coherence function:

$$\gamma^2(f,\vartheta,\varphi) = \frac{\left|\sum_{m=1}^{12} p_m^*(f)\,T_m(f,\vartheta,\varphi)\right|^2}{\left\{\sum_{m=1}^{12} |p_m^*(f)|^2\right\}\left\{\sum_{m=1}^{12} |T_m(f,\vartheta,\varphi)|^2\right\}} \tag{2}$$

This function varies between 0 and 1. It reaches unity only when the received field reduces to a single incident plane wave. For stationary broadband random pressure fields, the localization function is computed using the periodogram method, by dividing first the available duration T of the signals into a great number of blocks of duration T_1, by computing then the Fourier's transforms on these blocks

with a frequency resolution $\Delta f = 1/T_1$, and at last by carrying out the averages on all the sections. For the present application, it is not possible to operate this way, because the signals are non-stationary, due the change in the jets structure when the launcher rises. They remain about stationary only at a time scale $T \approx 0.5$ s. It is thus not possible to locate the sources in narrow frequency bands. On the other hand, the localization remains possible in third octave bands, which fulfill above 20 Hz the condition $T\Delta f_t >> 1$, where Δf_t is the third octave band spectral extent. In practice, the Fourier's transform is performed over the duration T, that is with a spectral resolution $\Delta f = 1/T$. The summation is carried out not on various time sections, but on all the frequencies inside the third octave band considered.
In more details, the takeoff starts at date H_0 with the lighting of the main engine. At H_0+7 s, the booster rockets are lit, and the launcher starts to rise. It reaches an altitude of 60 m at H_0+12 s. The localization is carried out during this period. The signals of the microphones are sampled with a sampling frequency f_e = 568 Hz, after low-pass filtering in the band $0 - 200$ Hz. They are cut out in blocks of 256 samples and of duration $T = 0.45$ s, and are thus analyzed using FFT with a resolution Δf = 2.22 Hz. Before the localization, the transfer functions for the 1976 directions of plane waves and the twelve positions of microphones are computed using (1) by step Δf. Up to 100 Hz, the maximum value of the reduced wave number ka is equal to 5, and the series containing the Hankel's functions converge very quickly. For each block, the numerator and the denominator of (1) are separately computed for each frequency, and the results are summed over the frequencies included in the nine third octave bands with center frequency f_c ranging from 25 Hz to 100 Hz. The localization maps $\gamma^2\,(t, f_c, \vartheta, \varphi)$ are thus obtained, where t is the time corresponding to the middle of each block.

3 - LOCALIZATION RESULTS

Figure 2 presents a view of part of the discovered central flue and of a side flue covered in the configuration of flight 503. The angular positions of the axis of the rocket and the exit of the three flues seen from the center of the array are located on the localization maps by black and white squares. These positions depend on the altitude and are tightened when the rocket rises.

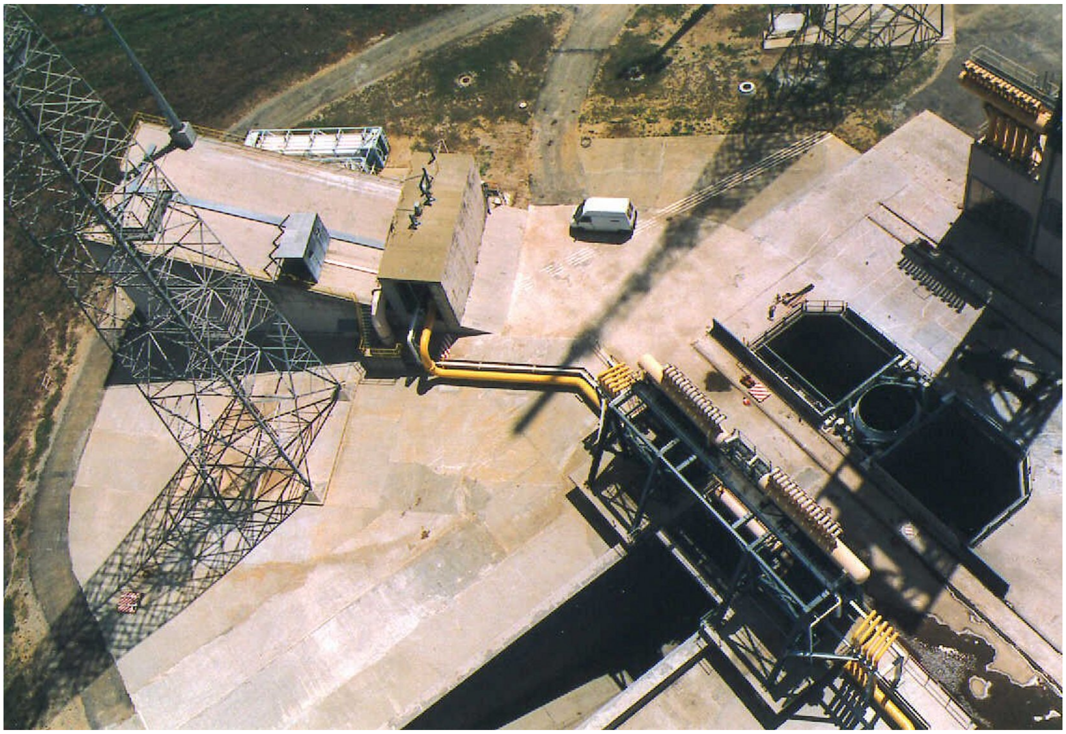
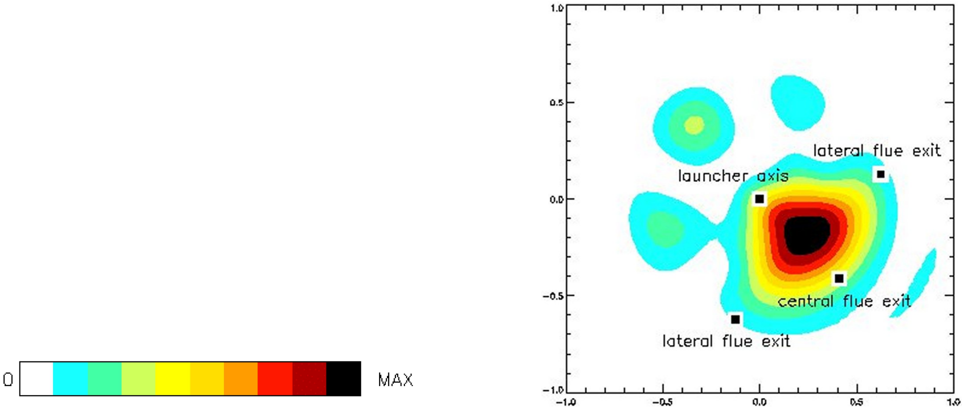
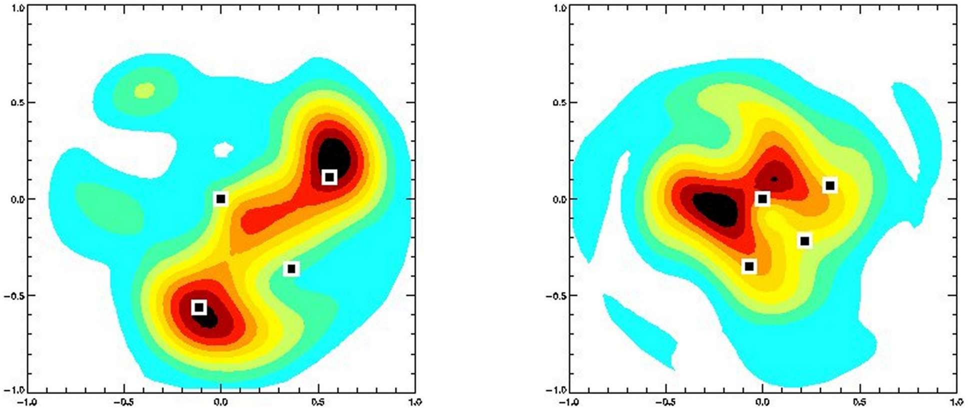


Figure 2: Launch pad for flight 503.

Figure 3 shows the localization maps normalized for each time by their maximum value, in the 63 Hz third octave band, and at the 3 altitudes 0, 9 and 57 m. For t=H_0+6.9 s, only the central engine is lit. A dominant acoustic source is found in the middle of the central flue. The same source position is curiously found at all the other frequencies, whereas it is known that, for a free jet, the higher frequencies are emitted close to the nozzle exit and the lower frequencies more downstream. At t=H_0+9.2 s, the three engines are running and the launcher is at 9 m in altitude. The localization clearly reveals as dominant sources the exit of the side flues, with still a secondary source in the middle of the central flue. Such a source structure is found for the altitudes ranging between 0 and 30 m, as long as the booster's jets enter the flues. At last, for t=H_0+11.9 s, that is for an altitude of 57 m, the jets impinge the launching pad. The source structure is more complex, and involves also probably acoustic reflections by the mast of the launching pad.



(a): Color scale. **(b):** t=6.9 s, z=0 m.



(c): t=9.2 s, z=9 m. **(d):** t=11.9 s, z=57 m.

Figure 3: Flight 503 − localization maps.

Partly following these observations, and to reduce the noise level due to the boosters under the fairing in the low frequency domain around $t = 9$ s, it was decided to lengthen the side flues. Figure 4 presents this modification, which was carried out for flight 504: the flues involve a new covered horizontal section of 30 m in length. Comparing the noise levels under the fairing between the two flights, a significant reduction was actually observed. The localization of the acoustic sources confirms that the objective was indeed achieved.

Figure 5 shows the results of the localization maps for flight 504 at the same moments as for flight 503. The only difference is that, at t=H_0+9.2 s (in fact as well as at all altitudes between 0 and 30 m), the sources at the exit of the lateral flues have completely disappeared.

4 - MODEL OF UNCORRELATED PLANE WAVES

The previous localization gives the position of the sources. Its advantage is to be very robust compared to the model having been used for its development, i.e. a single plane wave, and to give results in general correct even in the presence of multiple sources. On the other hand, it provides the amplitude of the sources only in the case of a single plane wave, or in the presence of several plane waves when they come from directions very different on the scale of the array angular resolution. It is not the case here, since the actual sources (jet noise sources) are distributed in a continuous way. It is thus necessary to use another method to provide data aiming to compute the pressure field under the fairing using a vibroacoustic code. For that a model of uncorrelated plane waves is used. For stationary random signals, the method is based on the array cross-spectral matrix. At frequency f, a distribution of incident plane waves of direction $\vec{u}$ and amplitude $s\left(\vec{u}\right)$ is considered with $< s\left(\vec{u}_1\right) s^*\left(\vec{u}_2\right) >= S\left(\vec{u}_1\right) \delta\left(\vec{u}_1 - \vec{u}_2\right)$ where $< >$ means statistical average and where $S\left(\vec{u}\right)$ is the power spectral density of the sources. The pressure received on the m^{th}

Figure 4: Lateral flue for flight 504.

microphone is equal to $p_m = \int s(\vec{u})\,T_m(\vec{u})\,d\vec{u}$ and the cross-spectrum between two microphones, that is the cofficient Γ_{mn} of the array cross-spectral density matrix, is given by $\Gamma_{mn} = \int T_m(\vec{u})\,T_n^* S(\vec{u})\,d\vec{u}$. To find $S(\vec{u})$ one minimizes

$$E = \sum_{m,n} \left| \Gamma_{mn} - \int T_m(\vec{u})\,T_n^*(\vec{u})\,S(\vec{u})\,d\vec{u} \right| \tag{3}$$

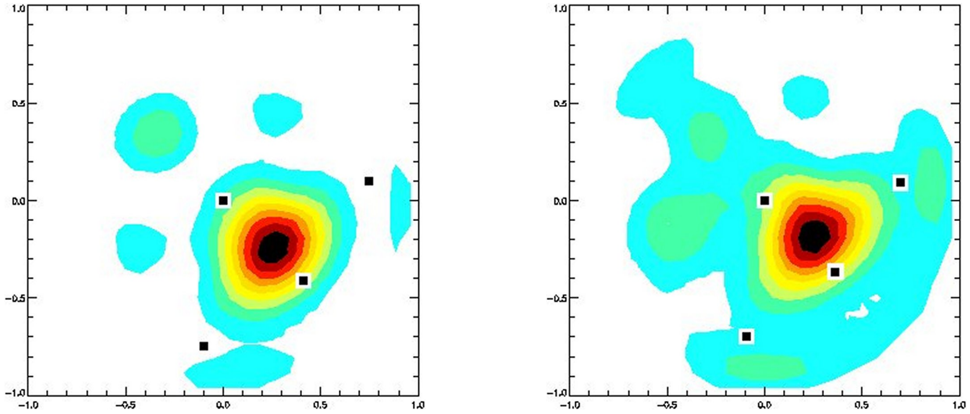
It follows that S is solution of the system

$$\int \left| \sum_m T_m(\vec{u})\,T_m(\vec{u}_1) \right|^2 S(\vec{u}_1)\,d\vec{u}_1 = \sum_{mn} T_m^*(\vec{u})\,\Gamma_{mn} T_n(\vec{u}) \tag{4}$$

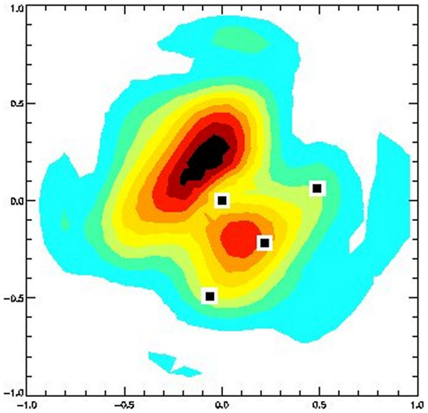
under the constraint $S(\vec{u}) > 0$.
As for the localization, this method was adapted to take into account the non-stationary character of the signals. Figure 6 shows its application to flight 503. On the figure 6-a, the conventional is plotted for the 31 Hz third octave band, for which the antenna is not very resolutive, and for t=H $_0$+9.2 s. On the figure 6-b, the uncorrelated model is applied and gives the level of the sources for the 1976 angular positions. It appears first that the method is much more resolutive, and gives the same main positions as in the 63 Hz third octave band. However, the number of positions remains much too high for a vibroacoustic code. To reduce it, a procedure based on the analysis of (3) is used. Its principle is as follows: if a source is removed, the error (3) after resolution of the system (4) increases. The problem is then to remove a maximum number of source positions, under the constraint that this increase remains weak. The application of this method leads to the figure 6-c, where there remain only 3 main sources of noise.

5 - CONCLUSION

At Ariane 5 liftoff, the sound field around the launcher is very complex because of the interaction of the jets with the launching pad. It was shown that the use of a microphone array flush mounted on the fairing allows highlighting the position of the main noise sources, their evolution when the launcher rises and their modification when a noise reduction technique is used. Moreover, such an array also allows a simple modeling of the incident field around the fairing in the low frequency domain.



(a): t=6.9 s, z=0 m. **(b):** t=9.2 s, z=9 m.



(c): t=11.9 s, z=57 m.

Figure 5: Flight 504 - localization maps.

ACKNOWLEDGEMENTS

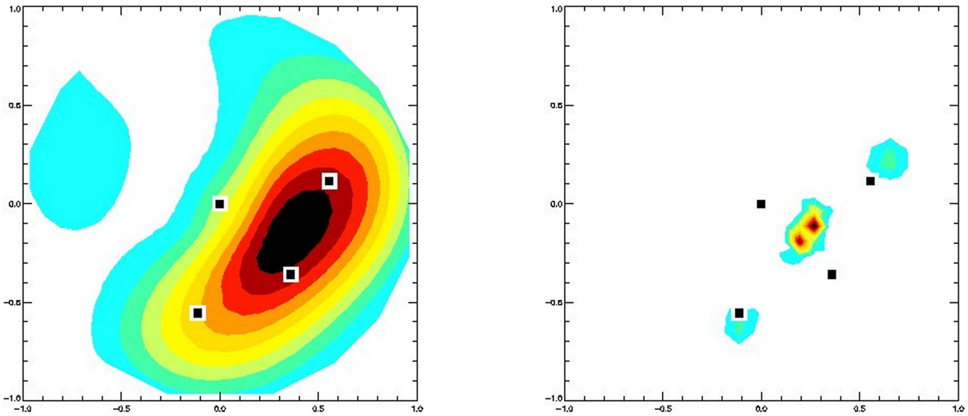
This work was supported by the Centre National des Etudes Spatiales (CNES).

REFERENCES

1. **W. Raguenet, J. Varnier, G. Elias**, Estimation du bruit de jet supersonique au travers du code DUNE, In *AAF - 35 ème Colloque d'Aérodynamique Appliquée, Lille (France)*, 1999

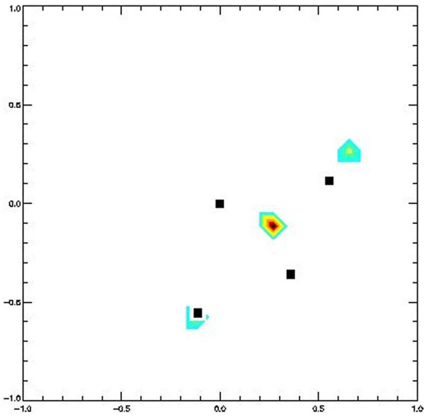
2. **J. Varnier, D. Gély, H. Foulon**, Environnement aérodynamique et acoustique d'un jet chaud et fortement supersonique, In *Premier Colloque Européen sur la Technologie des Lanceurs, Toulouse (France)*, 1999

3. **H. Foulon, D. Gély, J. Varnier, E. Zoppellari, Y. Marchesse**, MARTEL facility: simulation of space launchers aeroacoustic ambiance, In *12th European Aerospace Conference (AAAF/CEAS), Paris (France)*, 1999



(a): Conventional localization.

(b): Uncorrelated plane waves model.



(c): Reduced source number model.

Figure 6: Flight 503 – 31 Hz third octave band – t=H_0+9.2 s.