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ACOUSTIC FIELD PREDICTION DURING THE LAUNCH OF ROCKETS.

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Resumen
En este trabajo se presenta un estudio desarrollado con el objeto de predecir el ruido generado en el lanzamiento de cohetes espaciales. El modelo, de carácter semiempírico, utiliza como datos las características físicas y geométricas del chorro de gases que impulsa el cohete, el cual actúa como fuente primaria de ruido. El modelo está basado en el propuesto originalmente por Eldred en 1971 y sus posteriores modificaciones, al que este estudio aporta nuevas expresiones para la estimación de la potencia acústica de las fuentes de ruido. Para validar la predicción en un caso particular, se ha considerado el lanzamiento del cohete VEGA de la Agencia Espacial Europea, desde la plataforma de lanzamiento ubicada en Kourou, en la Guayana Francesa. Usando como referencia datos experimentales registrados durante un lanzamiento, el estudio constata que el modelo semiempírico predice el campo acústico generado durante el lanzamiento con gran precisión, especialmente en las bajas y medias frecuencias, que son las de mayor interés desde el punto de vista del impacto que este ruido tiene sobre el cohete y su carga.

Palabras clave: cohetes, ruido, predicción, ESA.

Abstract
This work presents the prediction of noise generated during the launch of space rockets. A semi-empirical model was applied, using as input data the physical and geometric characteristics of the jet of gases propelled by the rocket, which acts as the primary source of noise. The model is based on the one originally proposed by Eldred back in 1971 and its subsequent modifications. We expanded the model with expressions for the estimation of the acoustic power of noise sources. To validate the prediction in a particular case, we have considered the launch of the VEGA rocket from European Space Agency, at the launchpad located in Kourou (French Guiana). Using as reference experimental data recorded during a launch, the study confirms that the semi-empirical model predicts the acoustic field generated during the launch with great precision, especially in the low and medium frequencies, which are the most interesting from the point of view of impact that this noise has on the rocket and its load.

Keywords: rocket, noise, prediction, ESA.

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1 Introducción

The prediction of the noise generated by the motor of a space rocket is still a complex operation that depends on many actors. Due to this, some simplifications must be made and experimental measures are used to fit the models. Predictive models are therefore semi-empirical, using experimental settings together with parameters of the engine and the launch pad. The first prediction models were defined by Peter A. Franken [1] where one of the main objectives was to predict the noise level inside the rocket. A few years later, Potter and Crocker [2] made another prediction model to account for launch pad deflectors and rockets with multiple engines grouped together. Eldred in 1971 [3] analyzed these and other works that also tried to predict noise and proposed one of the most consistent models in the prediction of noise at the time of the rocket launch. Eldred made an analysis of dozens of experimental measurements of noise in space rocket launches, thus finding relationships between the parameters of the engine and its position on the launch pad, and the pressure levels and spectra obtained at different points in space. Later, authors such as Sutherland [4], Plotkin [5,6], Varnier [7] or Haynes [8] incorporated a series of modifications to the model based on the results obtained with the measurements made in different launches. These modifications consisted considering the length of the source distribution, and the acoustic behavior of the rocket jet such as the acoustic efficiency or the spectral correction.

In this work, the the noise generated in the launch of space rockets is predicted and its experimental validation presented. A validated prediction model is useful for many applications such as the prediction of excessive levels for the environment or for the design of vibration and acoustic load control systems both on the launch pad, on the rocket itself, or on its load.

2 Distributed Source Method (DSM)

The acoustic model presented in this study to describe the behavior of the rocket is the one proposed by Eldred [3]. In this semi-empirical model, the main acoustic source, which corresponds to the jet of gases produced by the rocket, is modeled by means of a distribution of point acoustic sources (DSM or Distributed Source Method). The emission spectrum of each source is modified according the characteristics of the rocket and engine, the jet, and its position on the launch pad.

In Figure 1 the rocket and the set of acoustic sources distributed along the jet are schematically presented, as well as the variables of the model. The axis of the jet is defined by two different linear sections: the section located from the exit of the rocket nozzle to the deflector (whose length is x_1) and the section located in the zone of the jet after impacting the deflector. The angle α is formed by the second section of the jet axis and the horizontal projection of the deflector and is related to the angle θ defined for each point source from the line between the source and the nozzle and the axis of the jet.

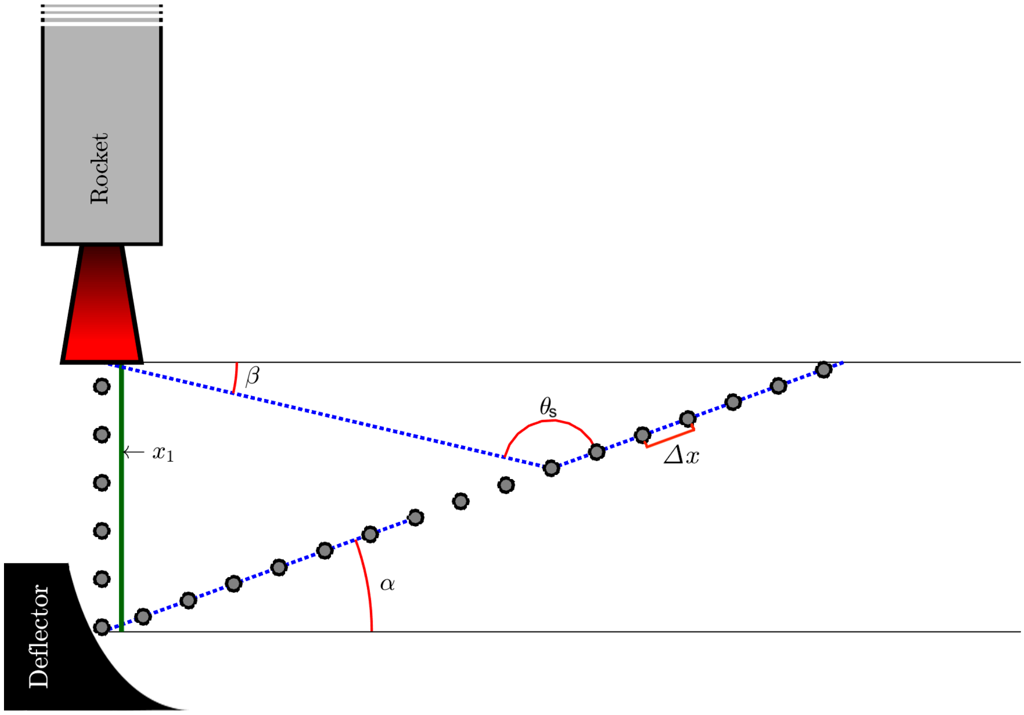


Figure 1 – Scheme of the Distributed Source Method (DSM) developed by Eldred (1971).

Once the geometric variables are defined in the rocket-platform configuration, the acoustic parameters of the model can be calculated for each source from specific parameters of the rocket motor. Thus, the global acoustic power (W_{OA}), is defined by the expression

$$W_{\mathrm{OA}} = \frac{\eta}{2} F U_e, \tag{1}$$

where F is the thrust force of the motor in Newtons, U_e is the exit velocity of the gases in m/s and η is the efficiency calculated by means of the expression proposed by Sutherland [4] and modified by Casalino and Barbarino [9], given by

$$\eta = K(\gamma_e/\gamma_0)(c_e/c_0)^3(c_e/U_e)^2, \tag{2}$$

where c_0 is the speed of sound in air in m/s, $c_e = \sqrt{\gamma_e R_s T_e}$ is the speed of sound in the exhaust jet in m/s, R_s is the exhaust gas constant, T_e is the temperature of the gas exit in Kelvin, γ_0 is the adiabatic expansion coefficient of the air, γ_e the adiabatic expansion coefficient of the exit gases, and K is a dimensionless variable that is specific for each rocket and that is adjusted experimentally from the emission sound pressure measurements.

The total length of the source distribution is calculated from the potential nucleus length (x_t), which is determined using the expression defined by Varnier [7]

$$x_t = 1.75\,(1 + 0.38\,M_e)^2\,d_e\,, \tag{3}$$

where $M_e = U_e/c_e$ is the Mach number of the flue gases in the nozzle and d_e is the diameter of the nozzle in meters.

The acoustic model consists of replacing the rocket jet with a discrete distribution of N point acoustic sources along the rocket axis. The distance between the sources (Δx) is obtained by

$$\Delta x = \frac{x_m}{N}, \tag{4}$$

where $x_m = M \cdot x_t$ y M is a dimensionless variable that fits the total length of the source distribution. In [7] M = 1.5 is proposed, which is the position of maximum acoustic power.

For convenience in the analytical description of the model, a continuous variable (x) is used to describe the position of each source, even though it is a discrete variable. Thus, x is the distance between the nozzle and each source in the continuous path along the axis jet from the nozzle along the two linear sections that define the axis of the jet. Once the number of sources and the distance between the nozzle and each of these (x) have been fixed, the normalized acoustic power ($\overline{W_S}$) is calculated for each source S with the Eq. (5). In the analysis carried out by Eldred of different experimental measures, the relationship shown in Fig. 2 was obtained, this curve, in linear, can be approximated by the expression proposed by this study, given by

$$\overline{W_S} = x_t \frac{W(x)}{W_{OA}} = x_t \frac{\left(\frac{x}{x_t}\right)^{1.42}}{103 + \left(\frac{x}{x_t}\right)^{6.51}}, \tag{5}$$

where $W(x)$ is the acoustic power at position x of each source. In Fig. 2 it can be seen that the maximum emission corresponds to the value M = 1.5 as proposed by Varnier in [7].

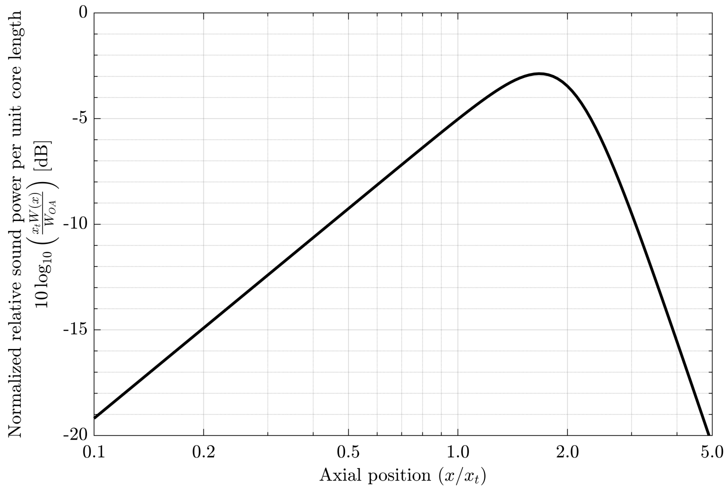


Figure 2 – Normalized relative sound power per unit core length along the axis of the jet.

The acoustic power per frequency band ($W_{S,b}$) for each source S is determined by fitting experimental measurements of the normalized relative sound power level and the axial modified Strouhal number $s_t' = f_b x c_e / U_e c_0$, where f_b is the frequency band b, as shown in Fig. 3.

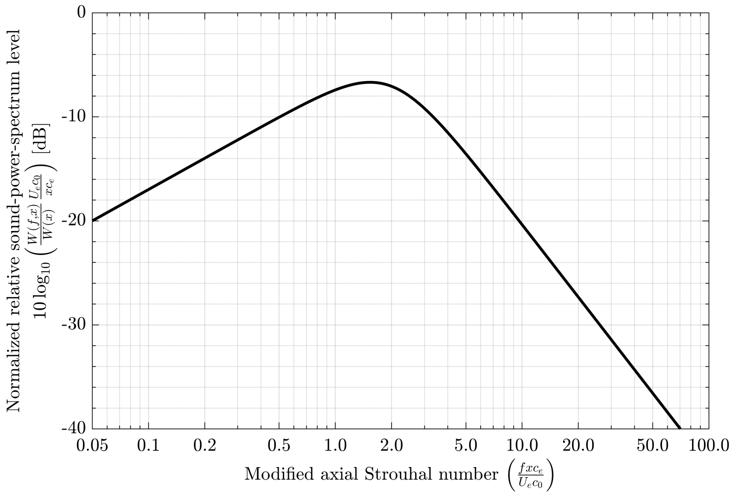


Figure 3 – Normalized relative sound power-spectrum level along the axis of the jet related to the modified axial Strouhal number.

The curve shown in Fig. 3, can be approximated by the following function proposed in this study:

$$\frac{W(f_b,x)}{W(x)}\frac{U_e c_0}{x c_e} = \frac{1.93 s_t'}{9.63 + s_t'^{3.32}}. \tag{6}$$

In order to obtain the acoustic power for each source S, in each frequency band b, Eq. 6 must by multiplied by the term $W(x)$, which is obtained by Eq. 5 and consider the discretization including the product with the increasing distance and with the frequency bandwidth f_b as

$$W_{S,b} = W(f_b,x)\frac{U_e c_0}{x c_e}\Delta x\,\Delta f_b. \tag{7}$$

The acoustic model accounts for the specific position of each source in the spectrum. Therefore, a spectral correction ($DI_{S,b}$) is applied to each source S due to its position relative to the nozzle outlet. For this, it is necessary to obtain the angle θ in degrees of each source S (see Fig. 1), locating each source in its coordinates, taking into account the distance between the nozzle and the deflector (change of direction of the jet). In the scientific literature, there are different corrections the spectrum of each source with respect to its position, such as, for example, Eldred [3] or Plotkin and Sutherland [5]. In this work, the proposal of Plotkin and Sutherland is used given its simplicity and the validity of the results. To obtain the angle θ, the distance between the nozzle outlet and the deflector in meters (x_1), the distance between the source S and the nozzle outlet (r_s) and the angle formed by the flow of gases relative to horizontal in degrees (α):

$$\beta = \operatorname{asin}\left(\frac{x_1}{r_s} sin(90-\alpha)\right),\\ \theta_s = 180-\beta. \tag{8}$$

The spectral correction defined by Plotkin and Sutherland [2] is obtained by the expression

$$DI_{S,b} = 10\log_{10}\left(\frac{c_1\cdot[1+(cos(\theta_e))^4]}{[(1-M_{ec}\cdot\cos(\theta_e))^2+0.3\cdot M_{ec}^2]^{2.5}\cdot(1+c_2\cdot e^{-c_3\cdot\theta_e})}\right)-c_4\log_{10}(s_{t,b})-c_5, \tag{9}$$

dónde

$$\theta_e = \left(\theta_S - 9.61\log_{10}(s_{t,b}/0.0515)\right)\frac{\pi}{180},$$

$$c_1 = 0.37, c_2 = 30, c_3 = 9, c_4 = 0.698, c_5 = 1.67, M_{ec} = 0.75,$$

where $s_{t,b} = f_b d_e/U_e$ the Strouhal number for the frequency band b, θ_s the angle formed by each source S with respect to the outlet nozzle in degrees, and M_{ec} is the typical value of the Mach number of the vortex turbulent viscosity model for a heated jet. In Fig. 4 the index is shown $DI_{S,b}$ for different Strouhal numbers. It can be seen that the angle of maximum correction increases with $s_{t,b}$.

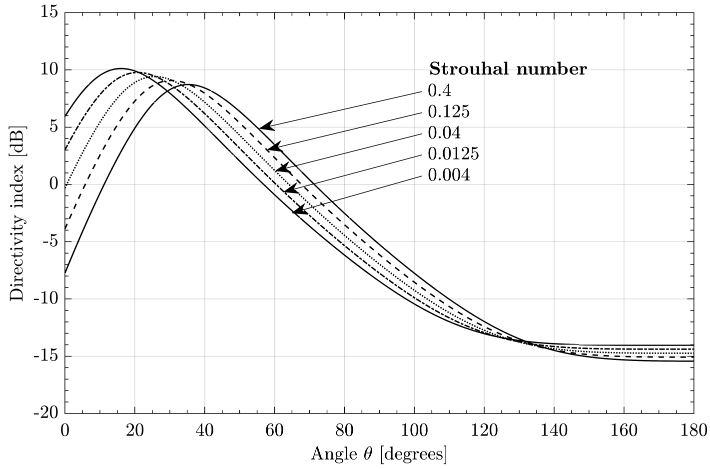


Figure 4 – Directivity index proposed by Plotkin and Sutherland (2007).

Therefore, the corrected linear acoustic power of each source S, per frequency band b is

$$W'_{S,b} = W_{S,b}\cdot 10^{DI_{S,b}/10}. \tag{10}$$

3 Comparison of the model with the experimental measurements

To validate the model, acoustic pressure measurements were obtained at the launch pad during takeoff of VEGA located at the Kourou spaceport in French Guiana (see Fig. 5).

Figure 5 – Digital image of the launch pad and VEGA rocket. ©ESA–J. Huart, 2020.

The measurements provided by the European Space Agency (ESA) have been made with a circular microphone antenna with 32 microphones located in a small area of 0.5 meters, 30 meters from the position of the rocket. In Fig. 6 both the normalized mean pressure level and the range of maximum and minimum values recorded by all the microphones of the antenna are shown in the entire audible spectrum and in thirds of an octave. For normalization, the maximum value of the pressure level of the average of measurements has been taken as a reference.

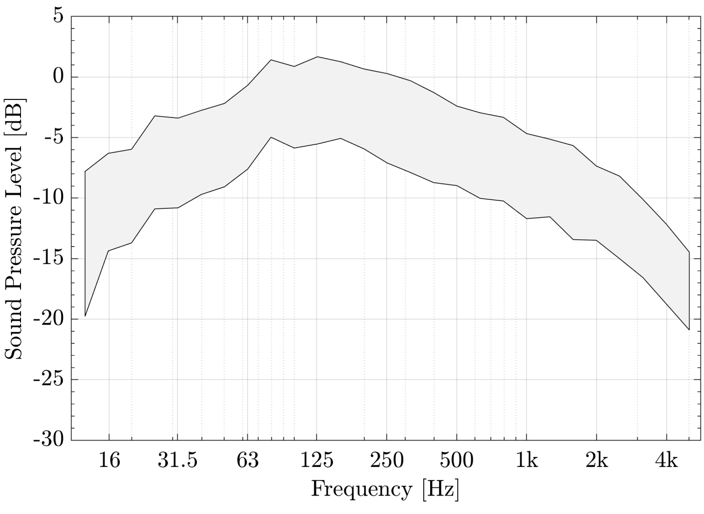


Figure 6. Normalized acoustic level pressure measured in the launch of VEGA rocket in Kourou.

The model is defined from the parameters of the rocket and the launch pad. In order to validate the model, the mean of the experimental measurements is compared with the estimate of the sound pressure level provided by the model calculated in the center of the microphonic circular antenna in which the measurements have been made.

In Fig. 7a) and Fig. 7b) the sound pressure level is shown as a function of the frequency in thirds-octave bands using the model with N = 20 sources and with N = 300 sources, respectively. It can be seen that the model fits well to the experimental measurements up to the frequency of 4 kHz. In the model with 300 sources, there is a slight increase of approximately 1 dB at high frequencies.

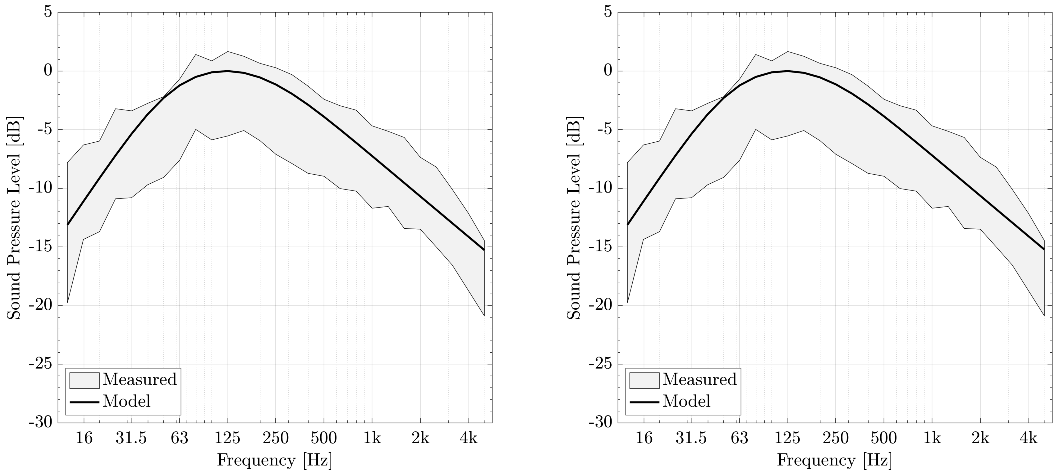
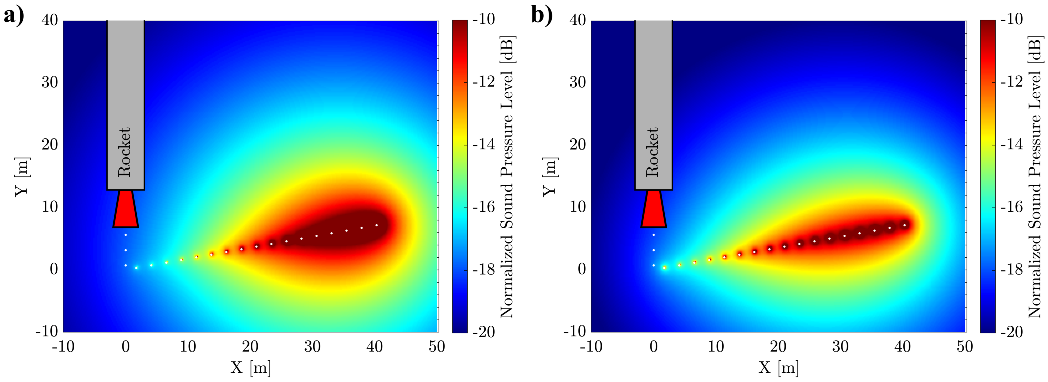


Figure 7 – Maximum and mínimum values of the Sound Pressure Level measured experimentally and obtained by the model with 20 sources (left) and 300 sources (right).

The acoustic field has been calculated in an area 60 meters wide and 50 meters high in order to observe the acoustic power distributed along the jet. In Fig. 8 the levels for different frequencies of analysis are shown: 20 Hz, 80 Hz, 250 Hz and 500 Hz. The rocket has been represented schematically, although it is not considered in the model nor influences the acoustic field. The sources are represented by white dots, and the model with 20 sources has been considered.

It can be seen that the power at low frequency is mainly attributed to the area furthest from the nozzle and, as the frequency increases, the power is distributed throughout the jet, tending towards the area of the deflector and the nozzle where the speed of sound it is very high, approximately c_e= 760 m/s.



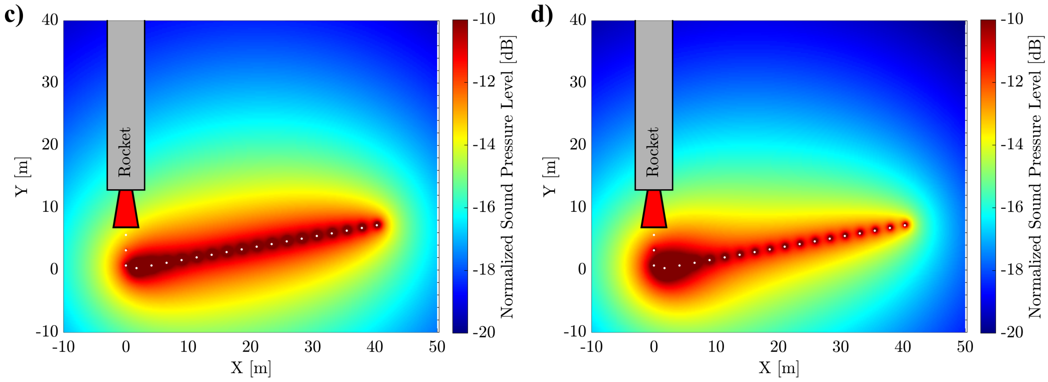


Figure 8 – Sound Pressure Level supporposed for the model with N=20 distributed sources. Frequencies shown are: a) 20 Hz, b) 80 Hz, c) 250 Hz, y d) 500 Hz.

4 Conclusions

An experimental validation of the distributed source model proposed by Eldred for the prediction of noise emitted by rockets during takeoff is presented. The model determines the power and sound spectra of each of the sources that are distributed along the axis of the rocket jet. The incoherent superposition of the joint emission of all the sources allows to obatain the sound field emitted by the rocket. Experimental measurements of the VEGA lift-off recorded on a microphone antenna have been used in order to adjust and also validate the sound emission model proposed for the rocket. The model considers that the rocket is not moving. However, once the rocket starts to rise, the conditions of the model change: the nozzle-deflector distance and the angle formed by the jet with respect to the horizontal vary. Also the distance from the reception point to the exit of the nozzle changes varying therefore the perceived level. Therefore, the signals recorded in the experiment have been processed only in the time window corresponding to the start of the engine until the moment in which the rocket begins to rise. The present model has application in the prediction of excessive levels for the environment and in the design and optimization of the vibration and the acoustic load control systems both on the launchpad, on the rocket itself, and on its load.

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