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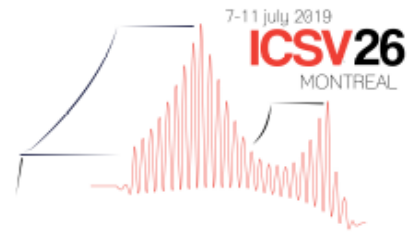
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# FULL SCALE ACOUSTIC SOURCE IDENTIFICATION ON VEGA LAUNCH PAD AT LIFT-OFF

Frédéric Mortain *and* Franck Cléro

*DAAA, ONERA, Université Paris-Saclay, F92322, Châtillon, France*

*email: [franck.clero@onera.fr](mailto:franck.clero@onera.fr)*

David Palmieri

*ESA-ESRIN, Frascati, Italy*

During lift-off, space launchers are submitted to high acoustic levels which can be dramatic for the payload inside the fairing. The present study aimed at improving the acoustic environment of VEGA (Vettore Europeo di Generazione Avanzata) launcher thanks to microphone array analysis. Two years ago, in 2015, a first analysis of this type has provided recommendations for launch pad evolutions in order to reduce the acoustic loads on the fairing. Based on these results, openings on the launch table were covered. We present here new measurement and analysis performed after this change. In Kourou, French Guyana, the time signals measured on a circular array during launcher lift-off are used to identify the acoustic sources on the launch pad, in terms of location and magnitude, thanks to deconvolution method. As for the first campaign, three source scanning plans are defined: two horizontal ones (at the level of the jet deflector and on the table) and a vertical one including the launcher. The overall results provide the evolution with time of acoustic sources on VEGA launch pad for all frequencies of interest. These are then used to extrapolate the acoustic levels to the fairing. Thanks to launch pad change, the acoustic levels are shown to be reduced by 2 dB, for the frequencies of interest and the source localization confirms strong reduction of the sources radiated from the table.

Keywords: aeroacoustics, launcher, microphone array, full scale

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## 1. Introduction

During lift-off of a space launcher, environment is so severe that it can damage the payload inside the fairing. To prevent any dramatic issues, launcher specifications are defined to set maximum levels that have to be supported by the payload in terms of acoustic, vibrations, accelerations, temperature, pressure ... These values depend on the launcher design (size, overall power, architecture) and the launch pad configuration. They are at prime interest in a strong competitiveness context to put satellites into orbit: the harder the specifications are, the more robust have to be the payload, increasing its design constraints, the weight and the overall cost from design to the beginning of its exploitation.

Noise is critical during the first seconds of the lift-off, when high level acoustic waves are generated: the Mach waves directly from the supersonic nozzle jet, reflecting on the launch pad and coming back toward the launcher; the noise caused by the impingement of this supersonic jet on the launch table; the mixing noise from the jets coming out from the flame trenches.

The optimization of the acoustic environment has often been based on small scale tests as it was the case for Ariane 5 [1], VEGA [2, 3] and future launcher Ariane 6 [4]. After several flights of Ariane 5, the flame trench cover length was extended to reduce the acoustic loads: again the optimal length was defined thanks to small scale tests [5].

Today, with the development of advanced measurement techniques, it is possible to investigate the improvement of acoustic environment directly at scale 1 during the lift-off.

During VV05 (5<sup>th</sup> flight of VEGA launcher) in Kourou, in June 2015, microphone array measurement was performed on behalf of ESA. The circular array was installed on a lightning pylon, approximately at the payload fairing level, and oriented toward the exhaust duct. ONERA was in charge of the acoustic post-treatment and analysis in order to identify the acoustic sources on the launch pad during lift-off.

Quantitative results highlighted two main source areas: (i) from the launch table, attributed to openings from which the noise produced below the table comes out; (ii) from the duct attributed to noise produced below the launch table that comes out by the duct, including possible reflections on the sloping part of the duct floor [6]. On the basis of the acoustic maps, covering of the table and/or the flame trenches was simulated to assess their impact on the acoustic loads on the fairing and to choose the best trade-off between acoustic efficiency and launch pad changes (time and cost).

In the first part of the present paper, the launch pad configuration and the changes operated after VV05 are described. New microphone array measurements were performed on 2<sup>nd</sup> August 2017 during the 10<sup>th</sup> flight of VEGA (VV10), in the same configuration as before. In a second part, the data are analysed in order to evaluate the benefits of the launch pad changes on the acoustic loads.

## 2. Launch pad configuration and measurements

The VEGA launch pad was inherited from previous ELA1 site used by Ariane 1, Ariane 2 and Ariane 3 launchers operating in early 80's, while with an all-solid propulsion system, VEGA acoustic behaviour is rather different from early Ariane launchers. In particular, the VEGA pad configuration presents open flame ducts and four openings adjacent to each side of the launch table (Figure 1). The highest acoustic levels inside the fairing measured during the first flights of VEGA launcher were in the range of 250-500 Hz frequency bands.

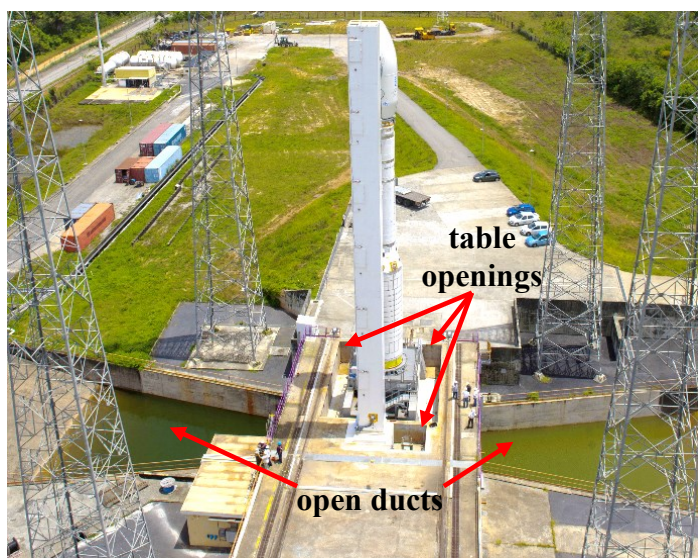


Figure 1 - VEGA launch pad

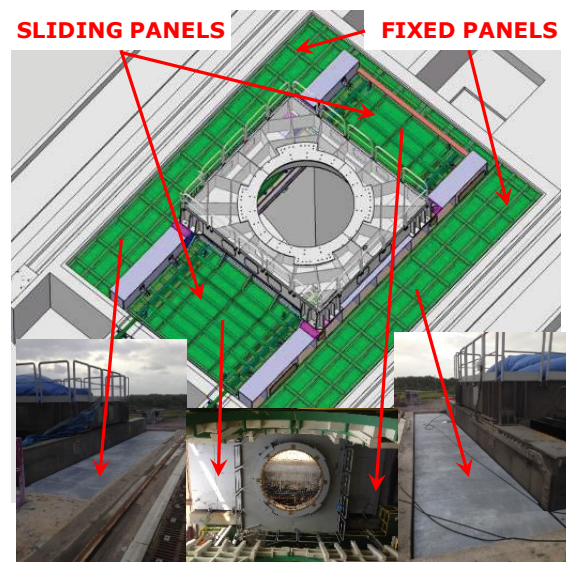


Figure 2 - Launch table covers

The data acquisition system, developed by RINA Consulting company (IT), was composed by 32 microphones with a dynamic range from 60 dB to 184 dB equally spaced along the outer circumference of a 2 meters diameter array antenna, which was installed on one of the pad anti-lightning masts (see Figure 3) at a distance of about 20 meters from the launcher nozzle. The field of view of the antenna was characterized by an opening cone of  $\pm 40^\circ$ , and the microphones acquisition frequency was 12,500 Hz.

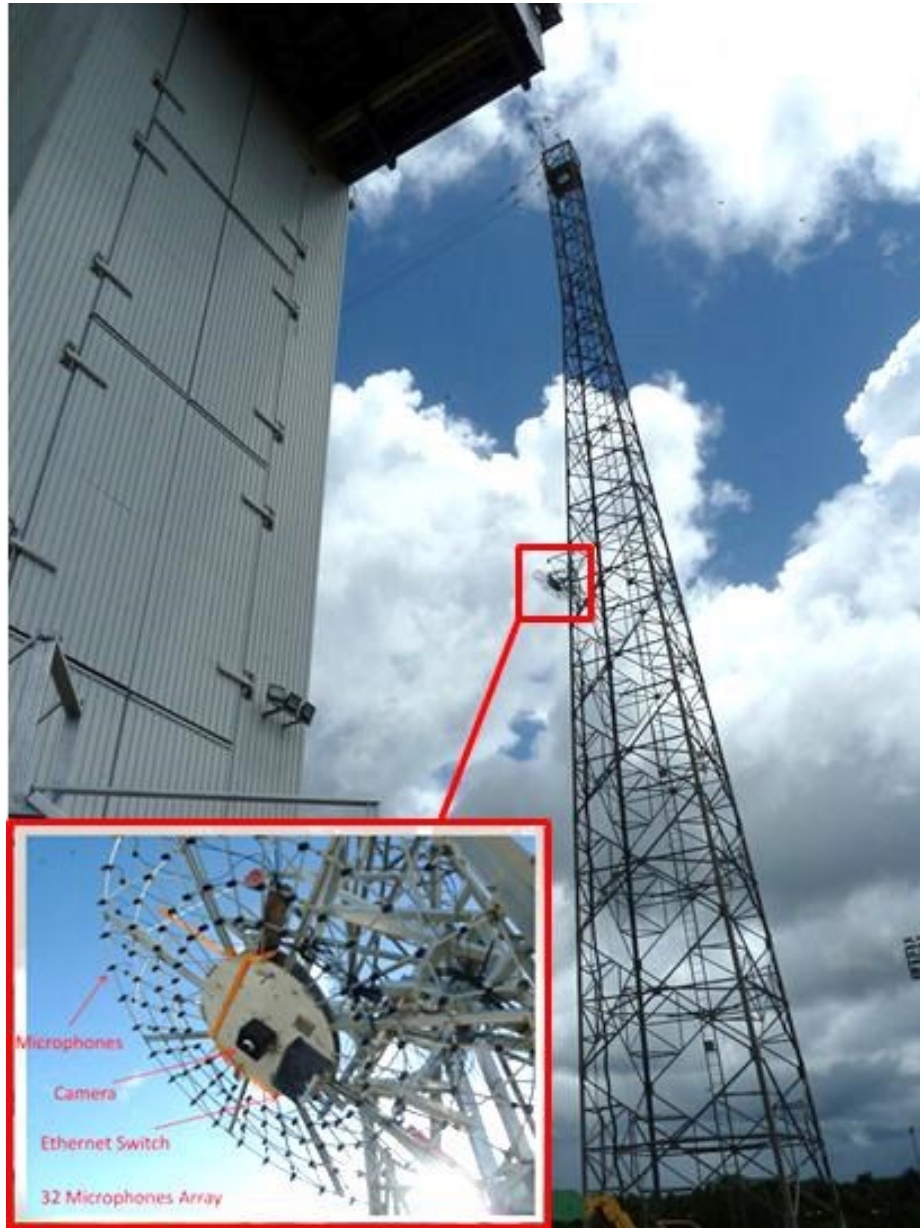


Figure 3 – Microphone array on the anti-lightning mast

Each microphone was connected by a 100 meters length coaxial cable to a National Instruments PXI acquisition unit, equipped with two analogue input cards of 16 channels each. The acquisition unit was housed inside a shelter close to the mast base in order to protect it from the lift-off environment.

The microphones were installed on the antenna 2 days before launch and were equipped with specific rain-protection caps. The acquisition unit was synchronised during the chronology in order to start automatically the data recording some seconds before lift-off.



Based on the results of acoustic measures, a first set of modifications to be introduced on the launch pad was identified in the coverage of the existing openings around the launch table (Figure 2). This choice was driven by the predicted significant acoustic attenuation and the simple/low cost implementation. The covering structures were realised by specific & acoustically insulating sandwich plates, composed by steel outer sheets and a mineral wool internal core. This design allowed to guarantee a good acoustic attenuation while keeping a relatively low weight of the plates, in order to ease the transportation and installation on-site.

The comparison between the measures performed on the microphone array before and after the installation of the table covers shows that a SPL reduction ranging from about 3 to 1 dB during the first 2 seconds after lift-off (when the max levels are recorded on the fairing) is achieved in the 500 Hz and all above frequency bands (Figure 4). The SPL levels are given on each octave band. On the other hand, no significant variation is observed in the 250 Hz band, while at lower frequencies a reduction is achieved only during the first second after lift-off.

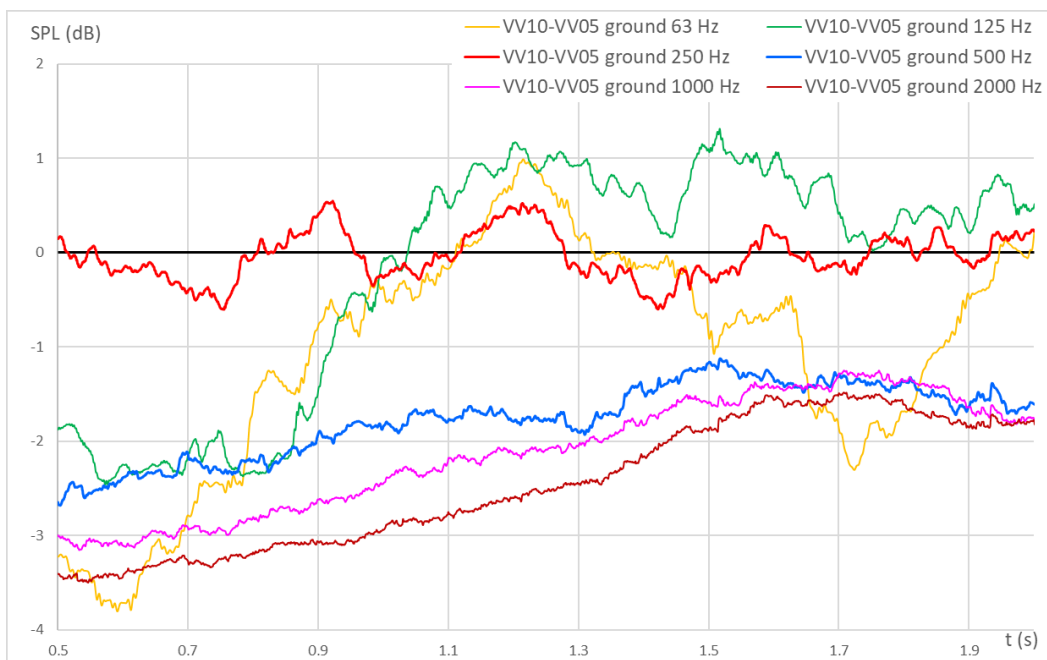


Figure 4 – Difference of acoustic measures with and without table covers for each octave band (negative values correspond to noise reduction)

### 3. Acoustic impact of launch pad changes

#### 3.1 Direct comparison on the microphone acoustic levels

Microphone array measurements implemented during VV05 and VV10 allows the evaluation of acoustic change consequently to the covering of launch table openings.

The time window of interest from 0.1 s up to 3.7 s, takes into account the time shift of 0.1 s due to the acoustic propagation from the launch table to the microphone array. At 3.7 s, the P80 nozzle exit section is approximately 41 m above the launch table (Figure 6) and the acoustic loads on the fairing can be considered as not anymore influenced by the launch table.

Due to severe environmental conditions and some acquisition issues during test, experimental data are carefully reviewed before the signal processing to detect potential anomalies that have to be accepted or rejected. This review results in 24 common exploitable microphones between VV05 and VV10 over a total of 32.

A direct comparison can be made on the signals measured by the microphones. The same tendency is observed on all microphones: the levels are globally reduced as shown on Figure 5; the maximum level is obtained when the engine jet is in front of the microphone array. In the spectral domain, on the first third octave bands, levels are reduced by 0.6 dB at 250 Hz, by about 2 dB at 500 Hz and by about 3 dB at 800 Hz. These first results have to be confirmed by the indirect estimation of the acoustic level on the fairing thanks to the analysis of the overall microphone array data.

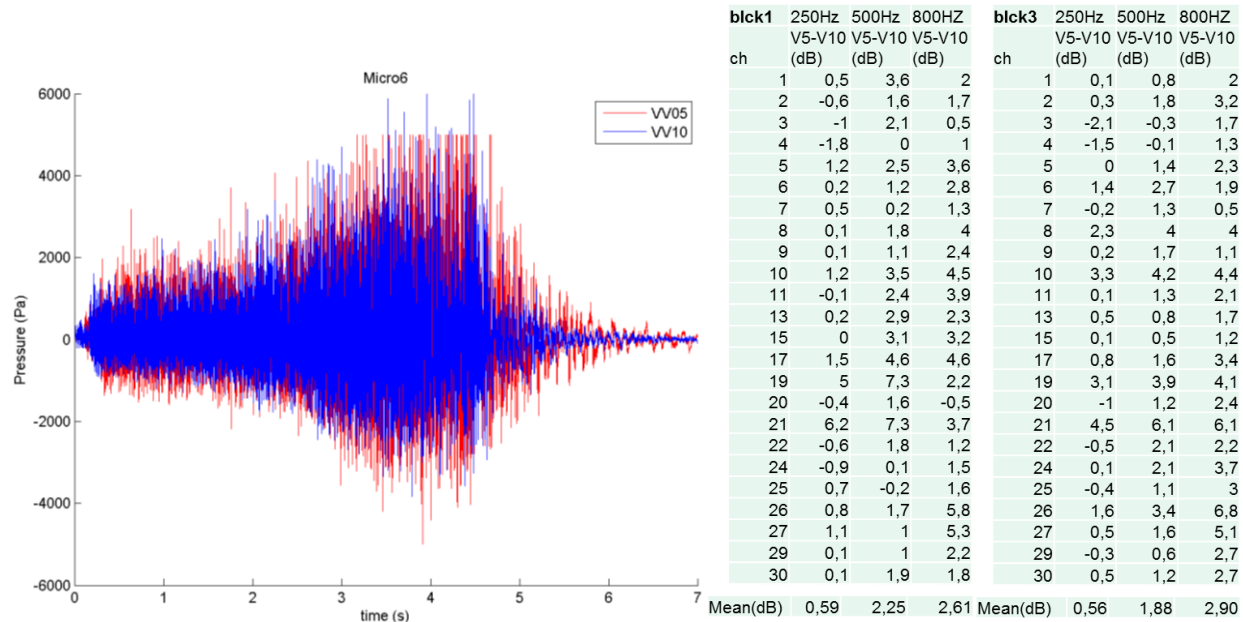


Figure 5 – Direct comparison on the microphone signals between VV05 and VV10 on the left, time signal; on the right, difference between the sound pressure level at 0 m and 2 m (blk3)

### 3.2 Acoustic source maps

As shown in Figure 6, each of the 24 non-stationary signals are first split into 9 blocks of 400 ms. For each block, signals are Fourier transformed to estimate the Cross Spectral Density (CSD) matrices according to the periodogram method with 50 non-overlapping averages sub-blocks of 8 ms Hanning windowed.

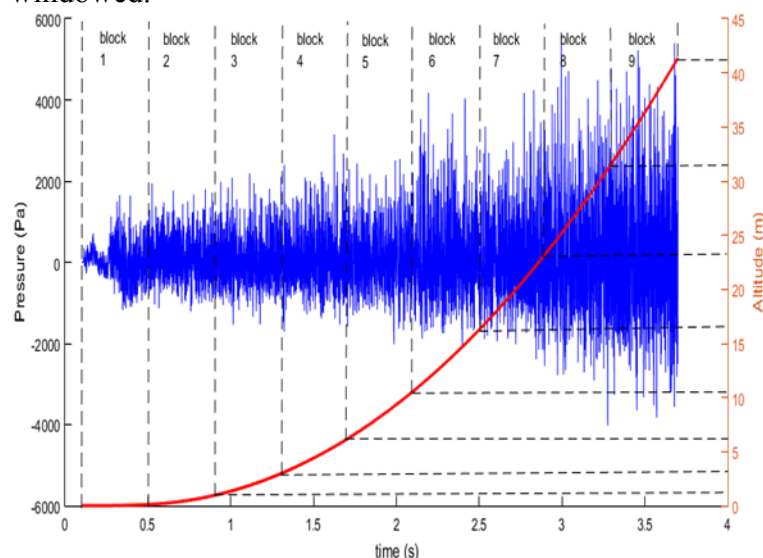


Figure 6 : evolution of altitude with time; time blocks definition

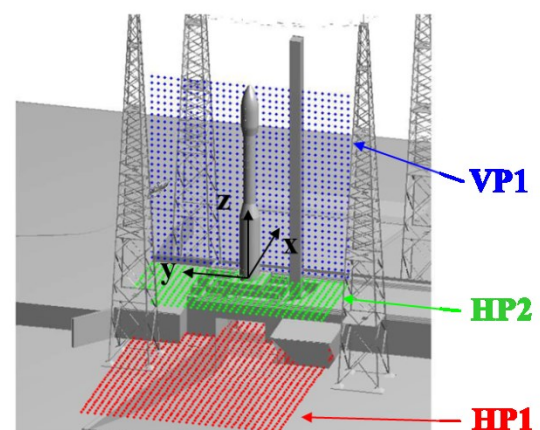


Figure 7 : Scanning plans

Source identification methods need to define a set of scanning points which is expected to include the location of the physical sources, including sources induced by reflection and diffraction effects of the acoustic field by solid boundaries. During VV05 lift-off, 3 source scanning plans were defined, shown in Figure 7; the same plans are used for VV10 post-processing: HP1 for the flame trench; HP2 for the table; VP1 for the engine jet. The number of sources by plan is 1271, 403 and 1240 respectively on HP1, HP2 and VP1. The origin of the coordinate axis is located at the center of the P80 nozzle exit section when the VEGA launcher is at rest, the X axis is in line with the flame trenches and oriented towards the East, the Y axis towards the North, and the Z axis towards the sky.

The estimation of all acoustic sources on each block was then performed by an improved technique with respect to the classical beamforming method already used in 2004 to process the results of VEGA acoustic tests on a 1/20<sup>th</sup> scale mock-up [7].

On the contrary of this latter method which only allows to locate the main sources, the method preceded here provides the location and the magnitude of the source thanks to the deconvolution method developed by ONERA [8], referred as DMS, as is based on the well-known DAMAS method proposed by the NASA [9] in 2006. It relies on the same mathematical model but integrates a more efficient minimization algorithm designed for large-scale constrained optimization problems, and a regularization scheme that is intended to provide a good trade-off between accuracy and robustness.

Dealing with random signals, acoustic maps display Power Spectral Densities (PSD) in dB using the reference level  $4.10^{-10}$  Pa<sup>2</sup>/Hz. Frequencies vary from 125 Hz up to 1875 Hz with a regular frequency step of 125 Hz which results from the spectral analysis previously mentioned. To make comparisons easier between each DMS maps, a constant level range of 30 dB is used and it is also indicated for each plan the *OverPlanSPL* value defined as the square of the RMS value over the plan (1).

$$(1) \text{OPSPL} = 10\log(\sum_{ik} p_{ik}^2) + 94$$

With  $ik$  corresponding to the point source and  $p_{ik}$  is the estimated acoustic pressure level. Even if it does not correspond to a physical data, this value provides the contribution of each plan to the overall radiated noise.

Figure 8 shows the maps of PSD levels at the most critical points: at the first frequencies of interest (250, 500 Hz – note that 375 Hz has been skipped but it is similar) and at the altitude where the acoustic levels are the higher at the fairing level. At first glance, it appears that the main source comes from the flame trench. For VV10, one can notice that this source is not centred: no explanation was found for this phenomenon, neither a bad orientation of the array (an error of 30° would be necessary!), nor wind effect (it should be 50 m/s, what is not compatible with lift-off). It should be verified on future measurements. The figure also highlights the reduction on *OverPlanSPL*. At the altitude 0 m, the sources in the flame trench are similar in both flights, whereas the levels on the table are strongly reduced by 8 dB. As the cover is made of steel with soundproofing material, the acoustic attenuation increases with the frequency, reaching around 10 dB at 1 kHz. The levels on the vertical plan are also reduced due to the masking effect of the cover which prevents the acoustic sources below the table to be “seen” by the microphone array. For higher frequencies, aliasing effect is visible through rings centred on the flame trench source. As the microphone array has a bad resolution power in the direction normal to its plan, it is difficult to separate the low frequency source from the two horizontal plans, what explains the fact that trace of main source is seen on the table edge. At the altitude 1.8 m, the engine jet is above the table and is already larger than the hole which guides the jet to the flame trenches. Therefore, a part of the jet impacts the table, and the sources coming from the vertical plan and from the table are less reduced. It is interesting to notice that, as the openings on the table have been covered, the part of the jet going in the flame trenches is limited in comparison with VV05, what results is strong reduction on the sources from the trench exhaust.

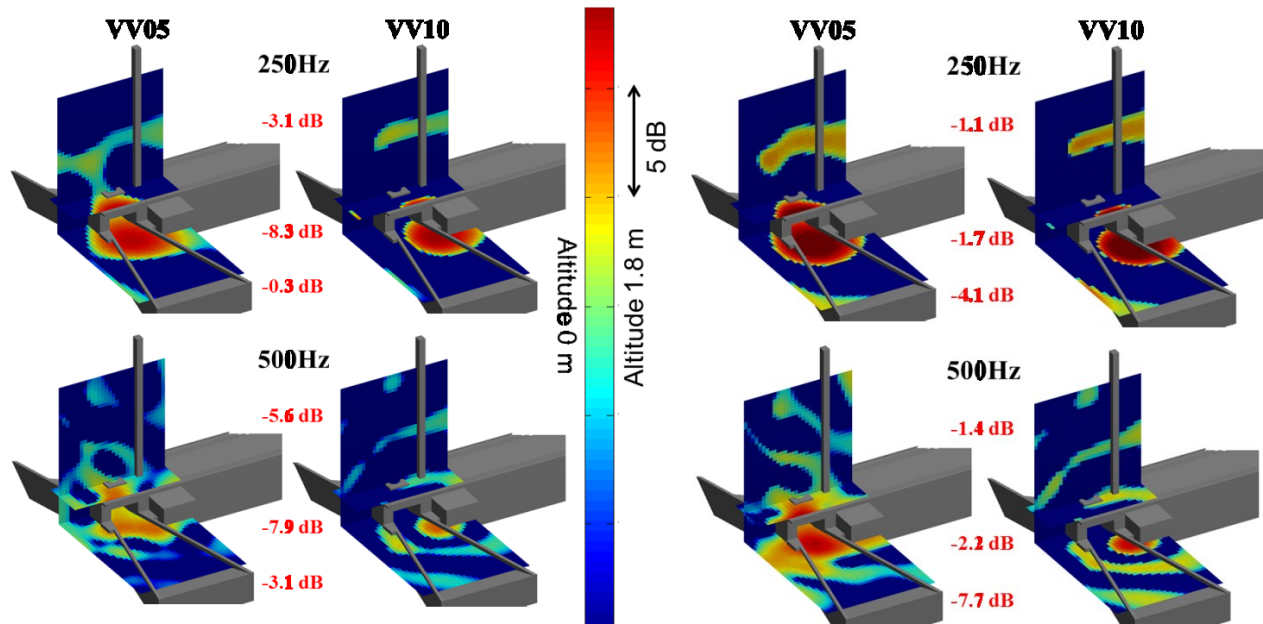


Figure 8 – Acoustic sources map and reduction on each plan at altitude 0 m (left side) and 1.8m (right side)

### 3.3 Extrapolation to the fairing

The maps showed in the previous section correspond to about 3000 equivalent monopole sources which can radiate and propagate acoustic waves toward the fairing in order to simulate the incident field. Because on-board microphones are flush-mounted on the wall of the payload fairing, they do not measure the incident free-field but a wall pressure field which includes diffraction effects by the fairing. These effects are taken into account in the extrapolation method that is carried out here, which is an adaptation of the approach followed in [7]: by modelling the incident field by plane waves and the VEGA launcher as an infinite rigid cylinder, it is possible to relate analytically the incident field to the wall pressure field. The PSD, and even the CSD matrix, of the wall pressure field can then be computed. Without any information about the East-side exhaust duct, a symmetry assumption between both ducts is taken, what is relevant here. Figure 9 shows the acoustic reduction obtained on a microphone located in front of the flame trench. On the left side, the reduction at the altitude 0 m on the low frequencies is confirmed even if it not as strong as on the sources from the table; this can be explained by the fact that at this altitude, most of the acoustic energy comes from the flame trench, with an angle of incidence higher than the sources from the table. Moreover, sources from the jet exhausting from the duct present lower frequency contents. Thus, for higher frequencies, the benefit from table cover is large with reduction by about 4 dB. The overall pressure level is reduced by more than 2 dB for low altitudes, which are the most critical for the acoustic loads. Logically, for higher altitude (right figure), the influence of the table decreases: the jet plume from the engine jet fully covers the launch pad and the sources are similar to the previous configuration.

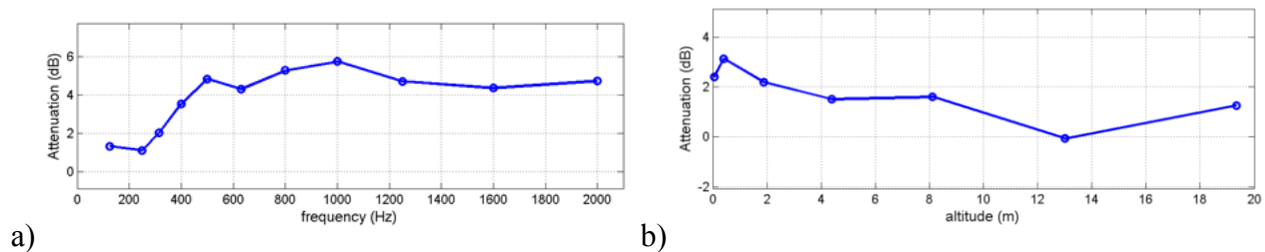


Figure 9 – Acoustic reduction on the fairing in front of the flame trench

a) SPL on third octave frequencies at altitude 0 m; b) Evolution of OASPL reduction with altitude



For even higher altitudes, one should bear mind that the acoustic level are estimated by the microphone array, which does not move, on the contrary of the launcher. Therefore, the identified sources are not adapted any more, what does not matter, the interest being for lower altitudes.

## 4. Conclusions

The present paper has pointed out the capabilities of advanced measurement techniques to improve the acoustic environment of scale one launch pad. Thanks to microphone array analysis, the location and the level of the acoustic sources, and their evolution during lift-off were determined in 2015, during VV05. Based on these results and simulations to estimate the potential of masking some areas, it was decided to cover openings present on the table. Two years later, in 2017, the table has been modified thanks to heavy steel plates filled with porous materials, with the objectives to resist to the impact of the supersonic jet exhausting from the nozzle and to reduce the noise levels at the fairing.

The same microphone array measurement was performed during VV10. The new analysis confirms a reduction of the acoustic sources from the table when the launcher is at low altitude. When it starts lifting-off, the engine jet impacts the table and tends to remove this benefit, however no amplification is noticed. A reduction of the sources in the flame trenches was also observed after the launcher leaves the table, which might be due to the additional effect of the covers preventing a part of the jet to enter in the ducts from the original openings.

The propagation of the equivalent monopole sources identified by the convolution method allows to estimate the benefit of the table change on the acoustic loads on the fairing. An average reduction by about 2 dB is obtained on the lowest altitude.

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