Wind model for Ariane 5 ECA qualification

O. Bugnet, C. Le Fèvre*, N. Stojanovic*, J. Baudoult**, C. Sadikou**, J. Oswald**

** CNES - DLA : Centre National d'Etudes Spatiales - Direction des Lanceurs*

Rond-Point de l'Espace, 91000 Evry, France

*** CS Communication & Systemes*

22 avenue Galilée, 92350 Le Plessis Robinson, France

Abstract

The system qualification process of an expandable launcher is based on a statistical approach. As the wind is a main contributor to angle of attack which is a driving parameter for general loads and controllability, it has to be statistically correctly represented.

The wind model which was used for the Ariane 5 cryogenic upper stage configuration qualification was updated with respect to the former Ariane 5 configuration.

After the description of how this wind model has been built (combining measurements and mathematical model), we will explain its validation and its application on Ariane 5. This wind model can be used for other space vehicles launched from Kourou.

1. Introduction

The system qualification process of an expandable launcher is based on a statistical approach which objective is to get limit parameters for the launcher as precise as possible in order to verify the consistency with the specification.

The limit angle of attack is a driving parameter for the general loads and controllability in atmospheric flight. It must be calculated with a probability not to be over-passed of 99% with a level of confidence of 90% in order to reach the required reliability.

Among the scattered parameters (the thrust, the atmosphere (sound speed and atmospheric pressure), the structural mass, the centre of gravity, the wind and the aerodynamic coefficients), the wind is the only parameter that cannot be represented by a statistical law although it is the main contributor to angle of attack.

Its effect is the result of its speed and its azimuth, but there is also a "historical" or integration effect due to the gradients and the inversions of the wind direction. Therefore the winds cannot be reduced simply to macroscopic data such as speed or gradient which requires to have a representative wind profile database. The chosen methodology is the estimation of the statistical effect of the other scattered parameters for each wind profile. For one wind profile, each rate of increase induced by a scattered parameter allow to calculate the distribution function due to all scattered parameters. Then the global probability due to the effect of all the winds is obtained by integrating the probability density function of each wind.

In order to study the influence of the wind, that is the main parameter, we will focus here only on its effect on a nominal launcher, that is to say that all the other parameters are nominal.

In this paper, we will first describe the real winds database, then its validation in term of statistic parameters, and finally its validation by comparison with experience.

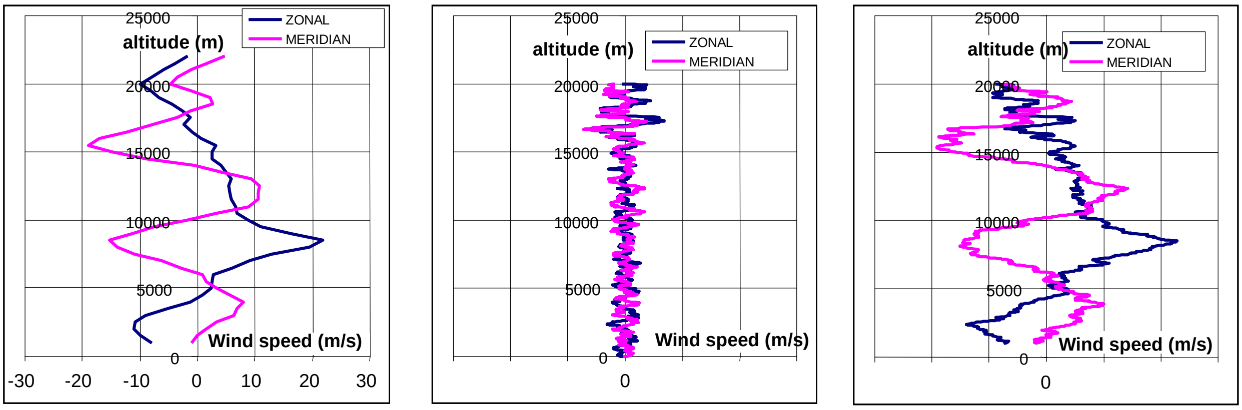
2. Building of real winds database

The real winds database is composed of hundreds of wind profiles in order to describe correctly the atmosphere in French Guyana. Each wind is built from measurement and model to give a Rebuilt Real Wind (ie Vent Reel reConstruit (VRC) in French).

2.1 - Building of a real wind

The VRC are obtained by the superposition of Radio Soundings (RS) made in French Guyana at Rochambeau by Météo France covering a several years period and mesoscale fluctuations (see Figure 1). The validity of the

transposition from Rochambeau to CSG (Guyana's Space Center) was demonstrated by a study leaded by CNRS (French National Center of Scientific Research).
The RS are atmospheric large scale fluctuations which associated wavelengths are longer than 1000m. They come from Météo France regular sounding in French Guyana since 1991 at the frequency of two RS a day.
The mesoscale fluctuations correspond to atmospheric small scale fluctuations characterised by wavelengths between 30 and 2000m. They are induced by gravity waves and they depend essentially on the static stability of the temperature profile (see [4] for more details).
The mesoscale fluctuations are randomly built and the mathematical model has been calibrated by a dedicated balloon campaign (VEHRT = VEnt à Haute Résolution en Température = wind with high precision in temperature) managed by CNES.
No turbulent fluctuations (wavelengths lower than 30 m) are accounted in this analysis since they are not disturbing for the launcher (very low energy).



(a) (b) (c)

Figure 1 Example of VRC construction procedure :
(a) Radio Sounding profile; (b) Mesoscale profile;
(c) VRC profile obtained by the superposition of (a) and (b).

2 b - Evolution of the database

The database used since 2001 was composed of around 7600 VRC. 3800 RS measured from 1991 to 1999 superposed with 2 mesoscale profiles. This database was described in [1] and was used for A5ECA qualification.
In order to quantify margin for robustness demonstration and to improve the statistical convergence of the base, we have recently increased the number of winds in adding the RS measurements till 2005. The database grew up to around 14600 winds (7300 RS superposed with 2 mesoscale profiles).
It has been verified that the statistical characteristics of the new winds are consistent with the previous base.

2 c - Evolution of the wind characteristics along the year

In French Guyana, the wind characteristics depend strongly on the period of the year. This is mainly due to the InterTropical Convergence Zone (ITCZ). The ITCZ is the meteorological equator. Its position varies on the axis North-South along the year and gets over French Guyana twice a year. Its relative position with Guyana defines the seasons and winds characteristics in low atmosphere.

The wind speed and the wind gradient have been analysed in term of mean, standard deviation and 99% value. The significant variations of wind characteristic during the year have been confirmed but the worst period depends on the parameter (wind speed, direction, gradient…) and on altitude studied. That's why it was not possible to define a worst period applicable for all trajectories of Ariane 5 (and even less for all other launchers). Figure 2 illustrates this variation on the 99% module of the winds for the 4 main seasons.

The limit angle of attack that has to be calculated must be the limit one during the whole year. Statistical treatment with the whole year wind would lead to too weak results for the worst periods (see [3] for a discussion about the way to determine limit loads). Therefore, the duration of each period has been set to one month because it corresponds to a period which is currently used for studying aerologic phenomena.

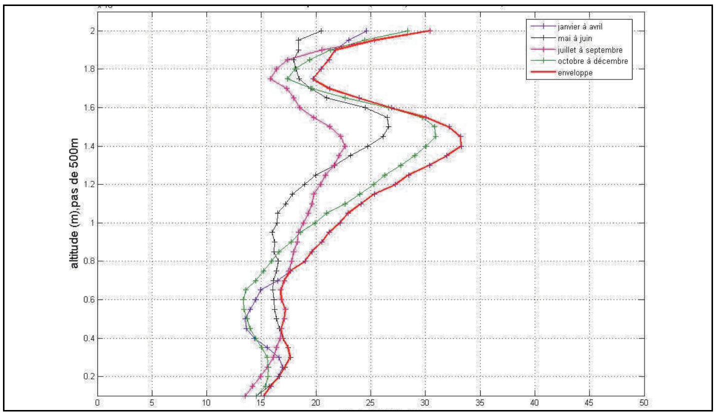


Figure 2 : maximum limit (99%) of wind speed for the four main seasons altitude (10000m) as a function of the module of the wind speed (m/s)

3. Statistical validation of the real winds database

3 a - Statistical method

As stated in the paragraph above, the statistical goal is to get limit values that is to say values at 99% (99% quantile) with a 90% level of confidence with samples of several hundreds of data. This computations should be repeated for each month, each altitude and each parameter of interest, that is several dozens times.

We first tried to fit probability distributions such as Weibull, Gumbel, Gamma. Although they for some of them performed well through statistical tests (such as Komogorov-Smirnov) ; the tail fitting was often quite poor (see figure 3). The best check being ultimately the visual one. All this was too complicated for an easy, quick and finally automatic use.

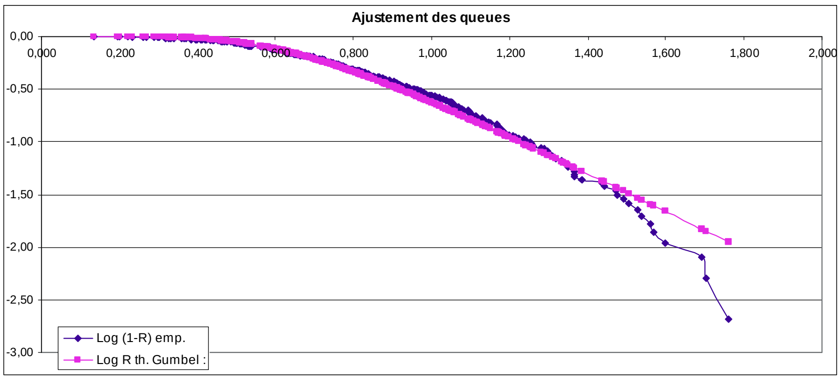


Figure 3 : an example of poor fitting for the tail with a Gumbel distribution (log scale).

We therefore choose to use distribution-free methods (so called non-parametric methods). The most popular and very intuitive one is to compute the 99% quantile by a linear interpolation formula in the sample ; that is to interpolate between the 2 points of the sample that frame the (N x 99%)-th point of the sample (where N is the size of the sample). This method is asymptotically convergent ; but poorly as it uses only two points in the sample. It is called in this document the interpolation method.

We then decided to try a distribution-free method with the property of using more information in the sample. We found a barycentric method (Harrel-Davis quantile estimator called in this document HDQE) built on the order statistics theory, as follows :

$$q_\alpha = \sum_{i=1}^{N} A_{N,i}.X_i$$
$$\text{where} \quad X_i = i-th \quad \text{point} \quad \text{of} \quad \text{the} \quad \text{sample}$$
$$\text{and} \quad A_{N,i} = \left[B_{i/N}(N\alpha+1, N(1-\alpha)) - B_{(i-1)/N}(N\alpha+1, N(1-\alpha))\right]$$
$$\text{with} \quad B_m(r,s) = \int_0^m t^{r-1}.(1-t)^{s-1}dt \Big/ \int_0^1 t^{r-1}.(1-t)^{s-1}dt$$
$$(non-complete \quad \text{Bêta} \quad function)$$

One can see that the whole X_i of the sample are used and that the sum of the $A_{N,I}$ coefficient equal 1.

We made a kind of numerical qualification of this method through Monte Carlo simulation, which concluded that with sample of a least 300 points, the method has a better convergence than the interpolation one ; that is with a fewer standard deviation. It has to be noticed that the gain, although existing, is not great as one can expected regarding the complexity of the formula.

Finally, in this study, regarding the computation of the 90% confidence interval, we used resampling techniques by redoing several times the quantile estimation, so as to have the distribution of the 99% quantile.

3 b - Statistical convergence of the Radio Sounding measurement of one month

In order to estimate if the number of RS of one month is sufficient to represent the limit wind and to compute the limit angle of attack, we quantified the effect of the number of wind, working with RS only (in order not to be perturbed by mesoscale profiles, the convergence of the mesoscale profiles is treated paragraph 3c). We use the whole database as a reference point with the hypothesis that there are enough RS in order to have a converged value at 99%.
For the wind speed and for the gradient of 1 km, we compared the limit values calculated with different number of winds (each wind being randomly chosen in the whole database). To be independent of the sample, we performed the calculation 1000 times and evaluated the value corresponding to a level of confidence of 90%.
The comparison of the winds (paragraph 4a) is limited to speed and gradient. The comparison in term of angle of attack allows to validate the effect of the winds on the launcher (including integration effects and inversion effects) but also the whole simulation (control law, simulator, …). That is why we also performed the same comparison in term of angle of attack with Ariane 5 simulations.
The result of the analysis of the winds was the same as that of the angle of attack. We found that, for 600 winds (number corresponding to one month), a margin between 5 and 10% (depending on altitude, axis, etc…) must be taken in order to assure dimensioning values taking into account the level of confidence (see figure 4, for the result of one sample). In other words, this margin covers the risk to underestimate the limit angle of attack because of non-sufficient statistical convergence. In figure 4, the negative values are used to define the margin because they correspond to the risk to under-estimate the reference value.

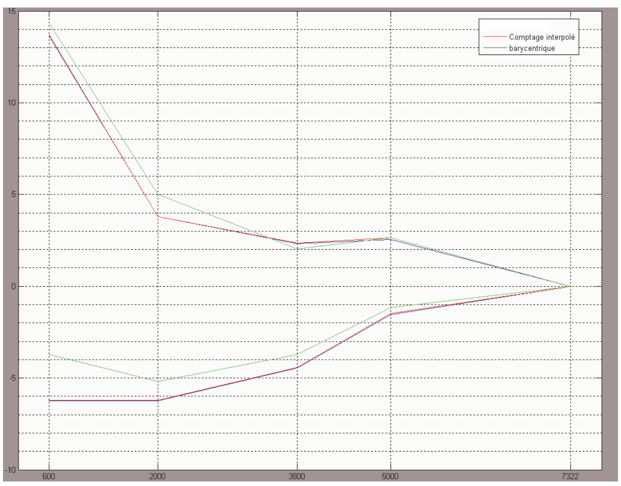


Figure 4 : Maximal difference (in %) with the reference value (7322 winds) in term of limit angle of attack as a function of number of winds for both statistical methods

The best statistical method is the HDQE, but the interpolation one increased of some percent only the margin to be taken.
To confirm the convergence, we also verified the stability of the results by shifting the month definitions of some days. We calculated the limit values for each month beginning the first of each calendar month and selected the maximum on the year. The results with a shift of 1, 2 or 3 weeks are, of course, different for each month (we changed one fourth of the winds) but equivalent for the envelop on the year.

The convergence of the database was demonstrated by this stability and by the fact that the margin to add in order to ensure the level of confidence is rather low and would not decrease a lot if we increase the number of wind in a month. We considered then that the number of winds for each month is sufficient to represent the monthly winds in French Guyana.

3 c - Number of mesoscale profiles to use

We put also into question the best number of mesoscale profiles to combine with RS. For one month, we increased the number of mesoscale profiles until 56. With that number of combination, wind speed, gradient and angle of attack calculated for Ariane 5 are stable in term of number of combination for both statistical methods.

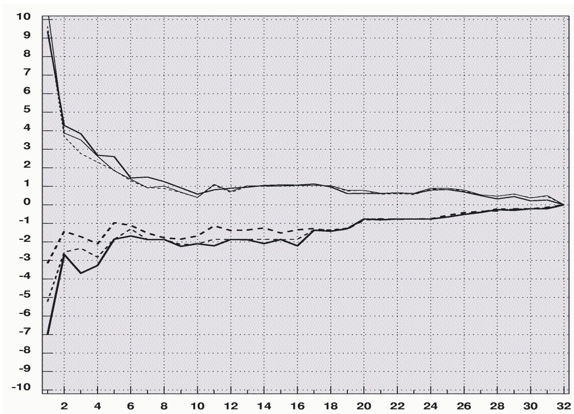


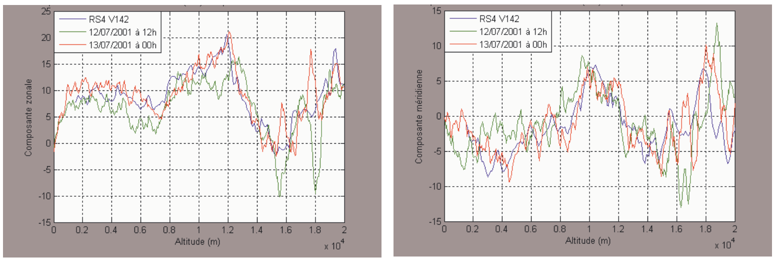
Figure 5 : Maximal difference (in %) with the reference value (32 mesoscale profiles)
in term of limit angle of attack as a function of number of mesoscale profiles

The figure 5 shows that 2 combinations are necessary and sufficient to guarantee a good precision with a little margin. We calculated the margin to take for 90% of level of confidence with a large number (1000) of sample of 2 mesoscale profiles. We obtain margins between 3 and 5%. This result is almost the same for both statistical methods, HDQE being slightly better.

4. Validation of the new database by comparison with experience

4 a - Validation of the database by comparison with winds measured

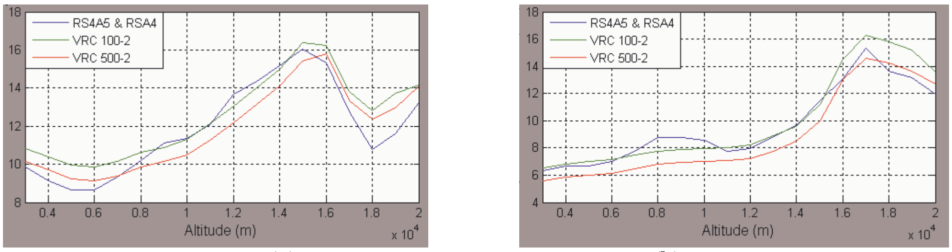
We explained at paragraph 2.1 that each VRC is built from a RS measured at Rochambeau (around 100 km from Centre Spatial Guyanais or CSG), at 0h TU or 12h TU, with wavelength higher than 500 m extended to 30 m with mesoscale. Those three characteristics are the differences with the wind that will be met by the launcher.
To verify the validity of the model, we compared it with the winds measured after each flight. Those winds are measured at CSG, at hours of flights and with wavelength higher than 200-450 m for Ariane 4 and Ariane 5 measurements with Totex balloon (called RS4). As the model of winds contain wavelength till 30 m, we filtered those winds in order to be consistent with the wavelength of the measured one. There are only 125 winds measured after flight as RS4, this low number induces an error on the comparison (lack of convergence).
Firstly, we compared qualitatively the wind measured after each flight with the VRC built from RS measured just before and just after it (see the example figure 6). The winds are well correlated and the differences between Rochambeau and CSG winds are of the same order of magnitude as the differences between both Rochambeau winds.



(a) (b)

Figure 6 : comparison of one wind measured at CSG with both winds before and after at Rochambeau zonal (a) and meridian (b) wind speed (m/s) vs altitude (10000m)

Secondly, we checked that the extreme values of wind measured after flights rarely overpassed the limit values of wind characteristics.
Thirdly, we compared the mean of the 125 winds with the mean given by the model in term of wind speed and gradient (Figure 7). As the precision of the 125 is between 200 m and 450 m, we filtered the winds of the model at 100 m and 500 m.



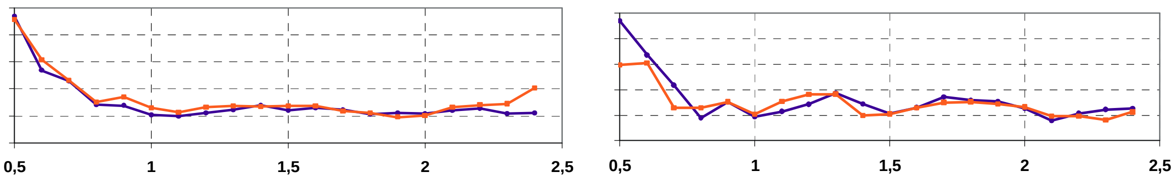
(a) (b)

Figure 7 : comparison of the mean of the 125 winds measured at CSG with mean of the model filtered at 100 m and 500 m in term of wind speed (m/s) (a) and gradient of 1 km (m/s/1000m) (b) vs altitude (10000m)

Despite the slight higher values of the CSG winds at few altitude, mainly due to the low number of wind analysed, we considered that the model of the VRC is consistent with measurements and so that it is validated.

4 b - Angle of attack

The 27 flights of Ariane 5 that were launched at the beginning of this study correspond to different configurations of the launcher (new upper stage vs former one, height of the fairing, masses of the satellites, trajectories…). So as not to disturb the results by those differences in studying angle of attack, we carried out two steps.
Firstly, we calculated the angles of attack with the 27 winds measured just after the flights with one configuration of the simulator (A5ECA GTO), we will call them “angle of attack calculated with observed winds” or more simply pseudo-real angle of attack. We compared them to the angle of attack observed by the launcher, wind by wind. The comparison is illustrated figure 8 with the means and the standard deviations. The differences are small and allow to conclude that the simulation is valid, and that the effect of the configuration is statistically low. That is to say that it is acceptable to perform the analysis with only one configuration of launcher and to extrapolate to generic conclusion.



(a) (b)

Figure 8 : mean (a) and standard deviation (b) of the pseudo-real angles of attack (in orange) compared to those of the observed one (in blue) (vs Mach number)

Secondly, we calculated the angles of attack from 27 winds chosen randomly from the database (consistent with the periods corresponding to flights). We performed these 27 simulations 1000 times. For each range of 1 km in altitude or for each range of 0.1 Mach number, we obtained a statistical repartition function. For each range, we have then the probability that the set of the 27 pseudo-real angles of attack had occurred, according to our model (see the example figure 9). This analysis was performed for the mean and the standard deviation (27 flights being not sufficient to have a precise 99% value) and for each range of 1 km in altitude.

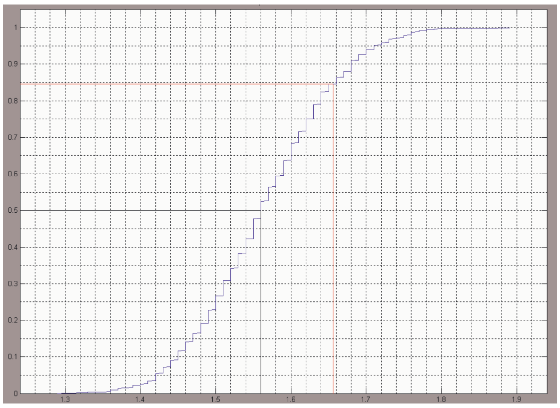
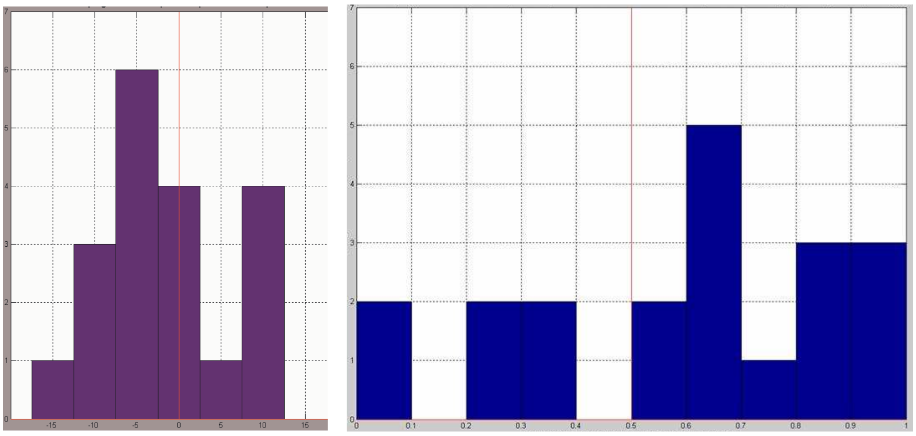


Figure 9 : example of a repartition function (blue) of the mean angle of attack and comparison with observation (red)
Probability vs angle of attack for one range of altitude

The results for all the ranges of altitude are represented figure 10 for the mean of the 27 samples. Figure 10-a illustrates the repartition of the ranges in term of difference with the median of the model. Figure 10-b illustrates the same result but in term of range of probability. It shows that the model fits with a good level of confidence with observation :

- in terms of difference with the median :
    - the distribution is symmetric about 0,
    - the maximal differences are low in term of angle of attack (around 15%),
    - the highest density is close to 0,
- in terms of probability :
    - there are no extreme values in term of probability (all the values are inside the range [0.01 ; 0.99]),
    - there is an equirepartition.

For the standard deviation, the result is a bit more dispersed but also consistent.



(a) (b)

Figure 10 : repartition of the ranges of altitude in term of distance between the mean pseudo-real angle of attack and the median of the mean of the model in % (a) and in term of probability according to the model (b)

These results confirmed that the model of winds fits correctly with experience.

5. Application to Ariane 5 ECA

The former paragraph described a new database, with a new statistical method. This new model has been used for A5ECA to be compared with qualification loop. The result corresponded to what was expected. The increase of the number of winds smoothed the curves of angle of attack as a function of altitude, so this curve decreased were there were peaks and increased were there were holes.
Finally, the local small increase are covered by margins and the qualification was confirmed. The use of this new database improved the robustness of the qualification of the launcher.

6. Conclusion

The real winds database has been enriched in order to improve the statistical model of the French Guyana's atmosphere. This model was validated in terms of winds and in term of angle of attack on Ariane 5 (effect of the winds). Validation of the statistical representativeness of the wind database was achieved by introducing small factor to guarantee the required 90% level of confidence. Then a second validation was achieved by comparing the statistical prediction of the model with the data of the first 27 Ariane 5 flights :

- The measured winds after the flights are statistically consistent with the model.
- The angles of attack in flight are also statistically consistent with simulated data obtained with the wind database.

The qualification of Ariane 5 was confirmed with the new wind database that improved the robustness of the qualification of Ariane 5.

The new database can be used for new trajectories or delta qualification of Ariane 5 if necessary, but also for other spacecrafts launched from French Guyana like Soyuz and Vega.

References

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