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CALLISTO – ENHANCEMENT OF WIND ALTITUDE DATABASE AT CSG

Jean Desmariaux [1,*] – B. Mazellier [1,*] – J. Servais[1,*] – L. David[1,*] - E. Bourgeois [1,*] - <T. Bigot [,3] - - F. Duffourg [2,*]

[1] *CNES, 52 rue Jacques Hillairet 75612 Paris Cedex France*
[2] *CNES, Centre Spatial Guyanais, BP 726, 97387 Kourou Cedex*
[3] *Medysys, 8 bis boulevard Dubreuil 91400 Orsay France*

jean.desmariaux@cnes.fr *, benoit.mazellier@cnes.fr * , julien.servais@cnes.fr *, louis.david@cnes.fr *,
benjamin.carpentier@cnes.fr , thomas.bigot@cnes.fr , fanny.duffourg@cnes.fr

Abstract
The CALLISTO vehicle is a flight demonstrator for future core stages of reusable launchers and their technologies. The program involves three countries and their space agencies: CNES for France, DLR for Germany and JAXA for Japan. The first tests will be conducted in 2024 from the CSG, Europe's Spaceport for commercial launches. The challenge is to develop, all along the project, the skills of the partners for the Vehicle design, the Ground Segment set up and the operations for Vehicle recover after flight and reuse.

In this framework, the ability to simulate wind conditions all along vehicle flight path is a critical feature, especially for "low" altitude and "high" altitude conditions as well that are usually not as critical for operational vehicles, compared to the case of VTVL vehicle such as CALLISTO. This legacy ranking of critical altitude layers practically led to limitations in the current wind database, such as non-continuity of wind profile (no "end-to-end") over the whole altitude range, as well as limited wavelength content. Those have to be revisited in the frame of the CALLISTO project in order to enable a representative and time consistent modelling of wind conditions, and subsequently simulation of culmination and landing flight phases for which Vehicle flight control capability against wind can be challenging. This paper deals with work performed by CNES to enhance the current wind database and validate the developed features.

First, an overview of legacy wind models is given with emphasis on data sources & limitations; then, improvements performed in the frame of CALLISTO project are presented, which are based on a hybrid approach involving both numerical wind models and in-situ wind measurements. Performance in terms of wind data statistics are shown. Finally, comparison between legacy and advanced model relying on standard GNC simulations outputs is shown, contributing to validation of the CALLISTO wind database.

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1. Introduction

The CALLISTO vehicle is a flight demonstrator for future reusable launcher stages and their technologies. The program involves three countries and their space organizations: CNES for France, DLR for Germany and JAXA for Japan. The first tests will be conducted in 2024 from the CSG, Europe's Spaceport for commercial launches. The challenge is to develop, all along the project, the skills of the partners. This know-how includes Products and Vehicle design, Ground Segment set up, and post-flight operations for Vehicle recovery then reuse. Figure 1 gives some key numbers of the CALLISTO project:

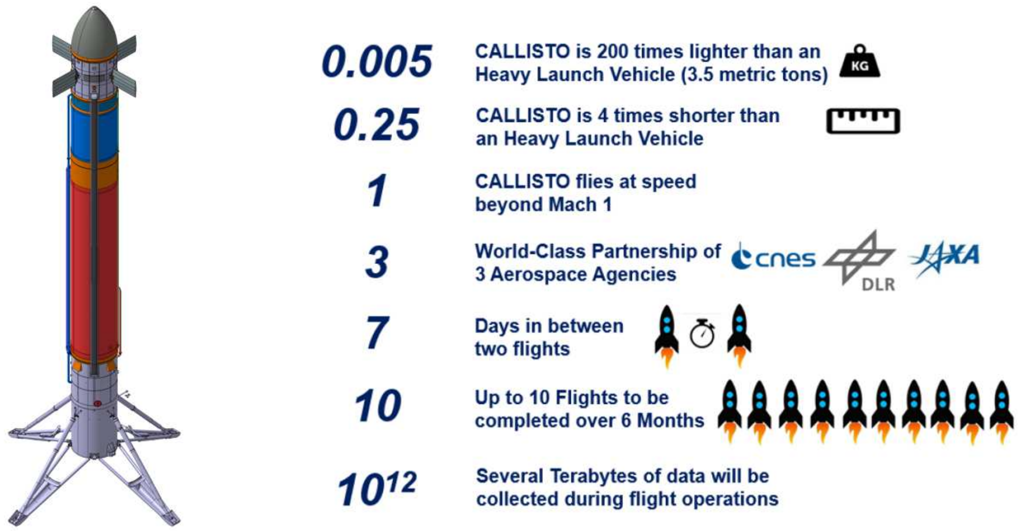

Figure 1: CALLISTO by numbers

Recovering a VTVL Vehicle at CSG Spaceport offers new technical & operational challenges compared to standard ELV design & operations, especially regarding in-flight wind management.

2. Legacy Wind data base

Being an operational spaceport since decades, CSG capability to acquire and record wind data base has developed all along history of operating European Launch Vehicles. CSG includes in particular a devoted Weather Station located inside its perimeter which is operating all weather related means & skills, including:

- Ground Wind prediction,
- Altitude Wind prediction,
- Thunderstorm prediction.

Figure 2 provides an aerial view of part of CSG and location of its Weather Station.

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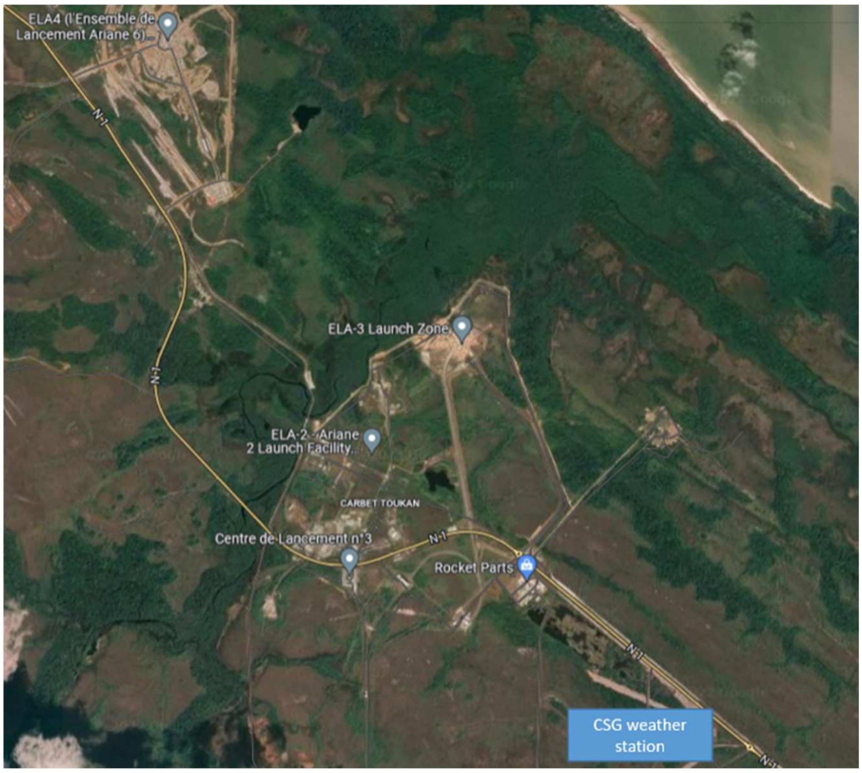

Figure 2: aerial view of CSG (part of) and location of its Weather Station (Google Earth)

In order to retrieve relevant altitude wind data, standard sounding balloons are released from the weather station. Historically, two class of balloons were used from CSG:

- Jimsphere, which are passive means whose position is retrieved through dedicated radar measurements performed from ground,
- GNSS balloons, which broadcast their position all along their ascent flight through airborne GNSS receiver

Lately, Jimsphere were removed from operational baseline and Weather station now only relies on GNSS balloons.

Figure 3: Standard Jimpshere (NASA illustration on left) & GNSS (right) balloon wind measurement means.

Defining a relevant wind data base for launch vehicle design & operations requires extensive data collection over years in order to build a representative dataset, consistent with system requirements, such as reliability & availability as well

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as with weather time constants which can significantly vary over years and period of the year as well. Typical altitudes that are relevant to CSG launch vehicle operations ranges from 0km to ca 30km.
Then, CSG undertook both:

- Extensive wind measurement campaigns, in particular (such as VEHRT campaign, see [3]) which spread over 1973-90s period
- Regular wind measurement for each operational vehicle launch campaign; standard procedure relies on several wind balloon releases, ahead and after flight, so as to provide input to pre & post flight diagnoses such as flight safety and post-flight data analysis.

In addition, Cayenne-Matoury Meteo-France station (located in the area of Cayenne Felix Eboué Airport, i.e. around 60 km east from CSG) is another source of radiosonde data for altitude winds over French Guiana. This station is part of the Météo-France radiosonde network, which releases radiosondes twice daily (at 00h UTC and 12h UTC) and resulting data being integrated in Numerical Weather Prediction models such as ARPEGE and IFS.

This constant and non-interrupted effort led to accumulation of 7000+ wind profiles that are the basis for computing the wind data base. Currently, regular wind sounding balloons do not allow access to high altitude resolution, so that post-processing and data fusion is required for deriving relevant wind profiles across all wind frequency spectrum/ wavelengths (wrt to altitude instead of time as done more classically). This is being done by analyzing separately long & mid/low frequency range (also called “meso-scale”) spectra and combining those two data sources.

Such method has been successfully applied to derive the wind data base which has been used for past and present heavy-lift ELV development and qualification.

2.1 Tracks for improved wind data base(s)

While current wind database allowed to successfully develop and operate European launch vehicles up to now, the possible introduction of launch stages getting back home brought additional issues about its validity and completeness, in particular regarding low to mid altitudes – typically in the range of 100-2000m of altitude – for which ascent flight is not so critical.

Indeed, ascent phase often features relatively low dynamic pressure at these altitudes, as well as low accuracy requirements (requirement mostly relates to proper transition from vertical flight path to gravity-turn like flight path). At the contrary, descent and landing flight phases of a VTVL vehicle feature high dynamic pressure and require high (to very high) position/velocity accuracy ahead of the critical pinpoint touchdown event at landing site.

Concentrating on wind data base themselves, it was stated that the data collection for this altitude range was lacking some frequency content, due to the fact that it was mainly derived from:

- Ground wind data (i.e. Earth boundary layer, over the first 100m above ground floor),
- Interpolation with 1-2km altitude data, which represented the altitude limit for which standard sounding balloon data is available.

Then, dedicated studies were performed in order to fill the gap between the system design needs (flight dynamics discipline especially) and the available database. Also, considering the timespan of CALLISTO project, ways to close this gap without time and budget consuming means were investigated first. This excluded in particular to perform a dedicated wind sounding campaign, and thus imposed to rely on computations and data processing.

3. Enhanced Data Base

3.1 ERA5 model and its post processing

Several detailed atmospheric models are available from meteorological and climate institutes, including:

- Weather forecast numerical tools, such as AROME and ARPEGE from Meteo-France,
- Re-analysis numerical tools such as ERA5 from European Center for Medium-Range Weather Forecasts (ECMWF)

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Distinction between prevision and re-analysis models is key. Forecast models allow to perform prediction of upcoming weather conditions over the next hours/days, considering a set of initial conditions. Hence, they are rather adapted to operational use during launch campaigns, typically for launch GO/NO GO criteria in addition to wind soundings. They run in a continuous manner and produce, for locations close to CSG Spaceport, weather forecast twice a day at fixed hours.

Re-analysis models are mathematical model used to provide data for past dates only (hence no prevision/forecast capability). Two main features need to be underlined:

a. Models are constantly fed with data coming from worldwide data gathered by measurement means.

b. Version of models are also continuously improving along progress on Weather science

Then, for a given (past) date, the quality of simulation is constantly increasing so that two simulations done at several years interval lead to different results.

Re-analysis model exhibits several features which are key for setting up a wind database consistent with requirements and limits fitting needs for launch vehicle qualification:

a. Number of wind profiles is not limited: runs of the model can be performed as much as required so as to generate the right amount of profiles,

b. Output of model is an altitude-continuous (“end-to-end”) profile from 0 m to 30 km altitude, including in particular the very low altitudes.

For the purpose of this study, the 5th generation European ReAnalysis (ERA5) from ECMWF was used.

Detailed study of ERA5 performance against past sounding balloons sourced measurements, based on legacy data (ca. 7000 radiosondes) was first performed to assess the accuracy of the numerical modelling in terms of wind velocity and wind wavelength, so as to identify which components of the model are representative of actual wind profiles. Hence, systematic treatment of wind-sounding based and model-based data was performed for relevant comparison in terms of:

- Frequency content
- Statistics (modulus, gradient, etc.)

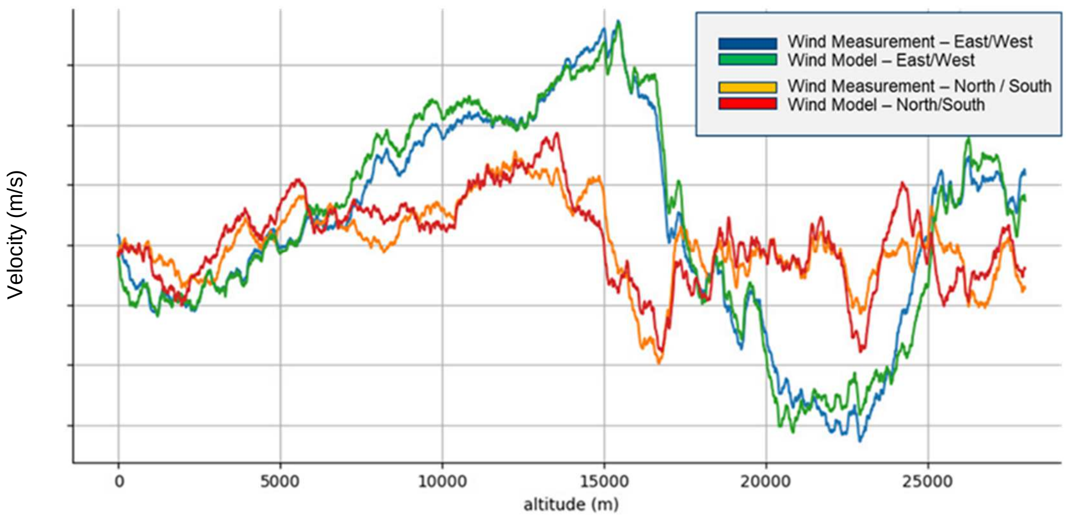

Figure 4: Example of comparison between model-based and measurement based wind profile at similar date and hour

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Numerical models cannot represent all wavelengths so that, in the same manner as for the measurement-based wind data base, additional information has to be added to derive a relevant profile. This has been done by analysing CSG meso-scale model frequencies versus model-based frequencies. Then, recombination/blending between the two sources has been carefully completed and wavelength combination is figured below.

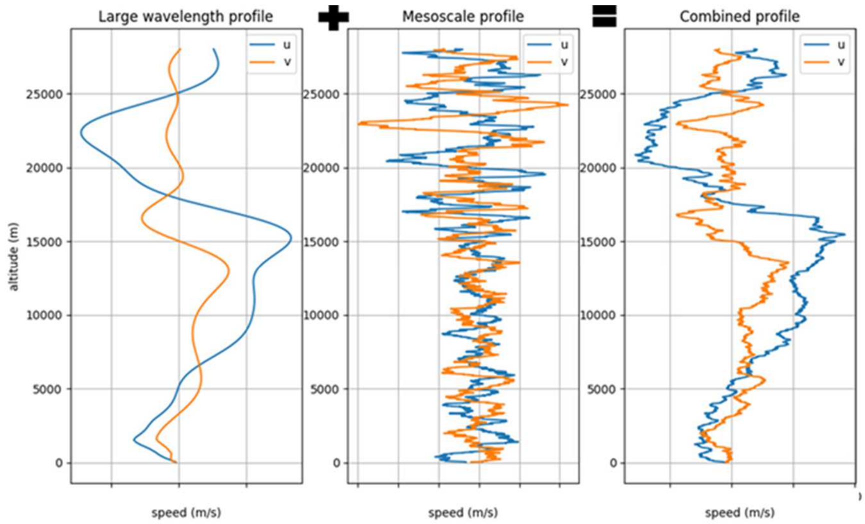

Figure 5: Combination of Wind Wavelength components

3.2 Statistics against legacy wind database

Enhanced wind database have been compared to legacy database for altitudes ranges where legacy database features a large number of wind profiles. Results of such comparison in terms of wind shear and modulus is provided in Table 1, showing good agreement in terms of statistics:

Altitude range	**Parameter**	**Discrepancy**
1-3km	Wind speed	Up to ±1%
	Wind shear	Up to +17%
4-15km	Wind speed	Up to +11%
	Wind shear	Between -5% and +13%
16-27km	Wind speed	Up to +15%
	Wind shear	Between -10% and +15%

Table 1: Comparison of 99% wind statistics between databases coming from updated wind model and legacy wind model (negative percentage means that updated wind model is less severe than legacy wind model)

Low altitude statistics exhibit quite some differences between the two data sources, which was anticipated due to historical lack of wind content in this altitude range.

4. Assessment by Guidance & Control Simulations

Among users of wind data for Vehicle in-flight operations is the guidance and control discipline, which does simulate the Vehicle in-flight dynamics according to (i) Vehicle own properties (e.g. Mass, Thrust), (ii) its flight control systems (e.g. thrust vectoring) and (iii) its external environment such as wind.

Monte Carlo simulations featuring serval thousands of wind were run in order to derive the behaviour of a given Vehicle against the updated wind database. Two vehicles were simulated against each of the two databases:

- Ariane 5,
- CALLISTO.

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Those two Vehicles feature some large differences:

- Vehicle properties (Ariane 5 is hundred times heavier than CALLISTO),
- Flight control strategy.

So that their in-flight closed-loop behaviour is quite different as well. Hence, the wind data that will be relevant for assessing vehicle performance may differ from one vehicle to another, so that coverage of updated database against the legacy one is better validated through these two vehicle simulations.

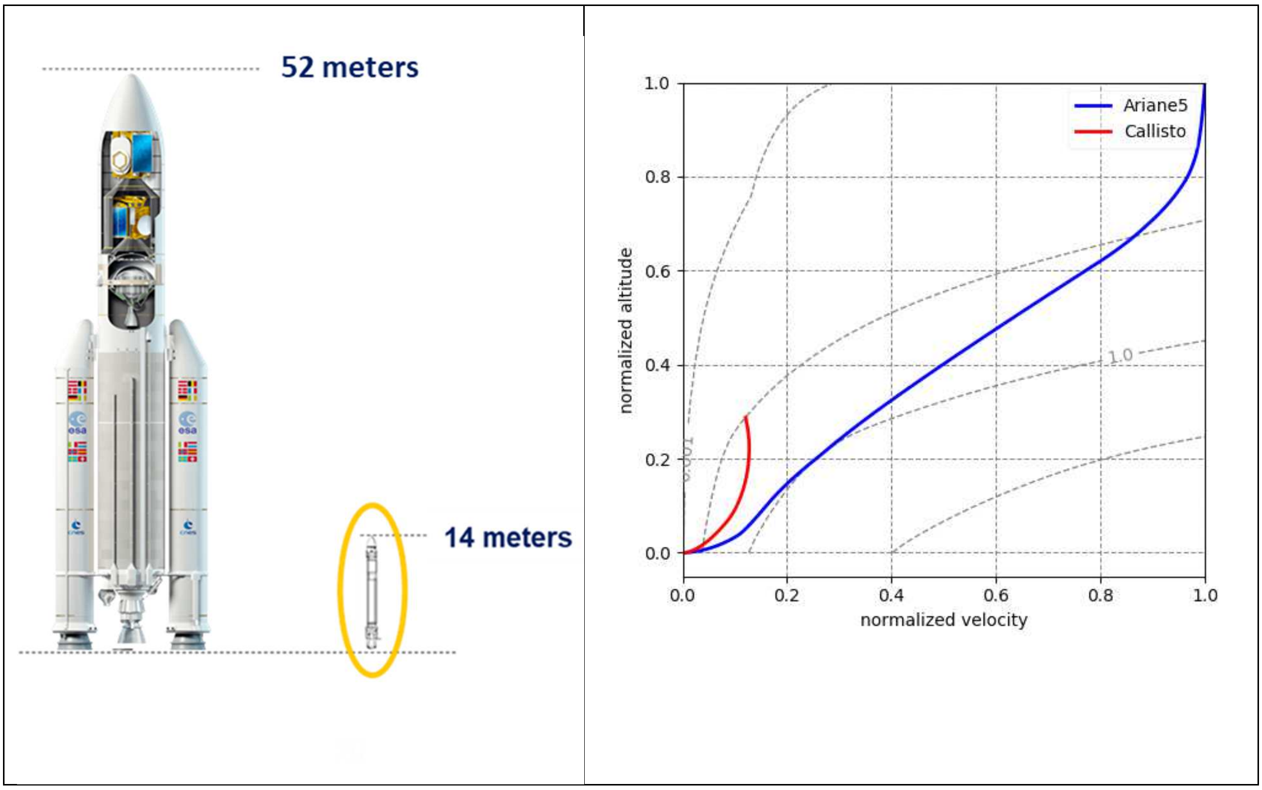

Figure 6: Differences in between Ariane 5 & CALLISTO: Size (left) – Altitude/Downrange for ascent phase (right)

Results in terms of several standard performance parameters are presented:

- On Figure 7: “Q.Alpha” metrics (combination of local dynamic pressure & angle of attack) which relates to wind-induced mechanical (quasi-static) loads applied to Vehicle,
- On Figure 8:: (engine) thrust gimballing (for CALLISTO only), which refers to orientation of the thrust wrt the Vehicle longitudinal axis, and that is used for generating control torque around vehicle CoG.

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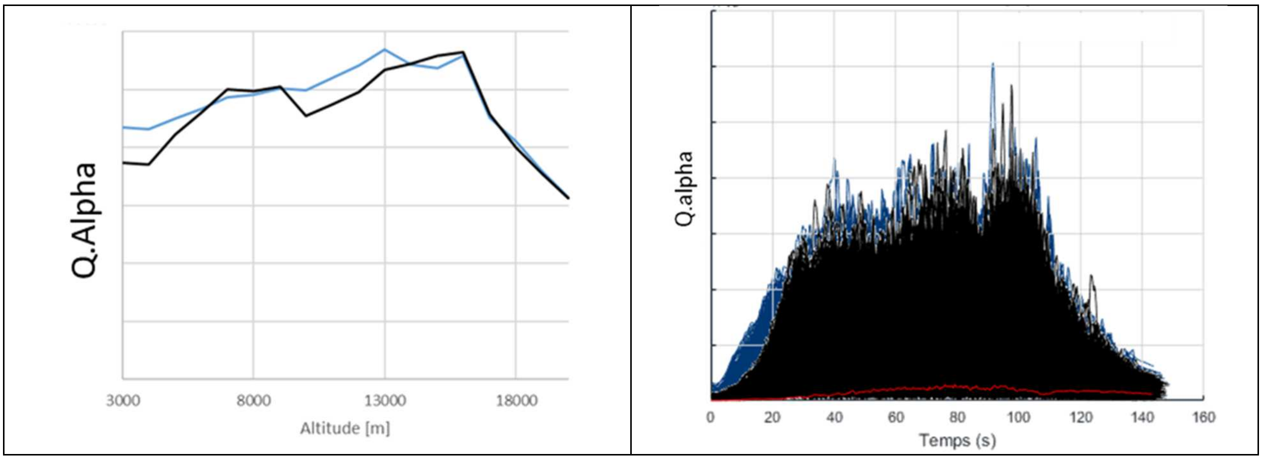

Figure 7 : Q.alpha - Ariane 5 (Left) CALLISTO (Right)

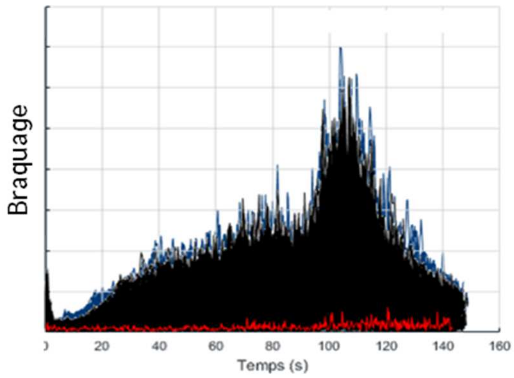

Figure 8: Gimbal angles CALLISTO

Both metrics reveals very similar behaviour for most altitude ranges, however with some differences to be highlighted. For flight period and high dynamic pressure, the update WDB features slightly increased values for both Q.Alpha and Gimbal angles, revealing that the current content of UWDB is conservative compared to LWDB. Then for low altitude, and as expected after statistical comparison of section §3.2, the UWDB generates significant increase of both metrics, and in particular Q.Alpha. This reveals that the LWDB was rather on the non conservative side for this altitude range which was however not of major importance for past (expendable) vehicle developments.
Finally, the low altitude range exhibits continuous and regular variations of vehicle state parameters, showing that the usage of ERA5 based wind profiles allows to close the gap between the 0-100m range and the 1000 – 30000m as was initially ambitioned.

5. Conclusion

The ongoing development of recoverable vehicles operated from CSG spaceport requires adapted wind database with relevant accuracy over the full 0 – 30km altitude range. This involves new engineering challenges in terms of data collection and data fusion.
A dedicated methodology involving both numerical weather models and data collection though measurement campaigns has thus been developed, and extensive work has been performed to rework and expand the available wind database. It was then tested successfully against both operational and demonstration vehicles through Guidance & Control closed-loop simulations, enabling validation of the general methodology and results. Differences wrt legacy wind database were concentrated on low altitude ranges, thus not questioning the approach used for past and current expandable heavy launch vehicle developments. Further steps will focus on validation of low-mid altitude range through comparison with additional measurements to be collected soon.

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