MODEL VALIDATION FRAMEWORK FOR LAUNCHERS: POST-FLIGHT PERFORMANCE ANALYSIS

Juan Antonio Béjar-Romero[(1)], Tiago Coutinho de Almeida[(1)], Emanuele di Sotto[(1)] and Celia Yabar[(2)]

[(1)] GMV, Isaac Newton 11 P.T.M., Tres Cantos, 28760 Madrid, Spain; Tel. +34 918072100
jabejar@gmv.com, tmilhano@gmv.com, edisotto@gmv.com,
[2)] European Space Agency, The Netherlands, celia.yabar.valles@esa.int

ABSTRACT

The launchers GNC performance is strictly depending upon the knowledge of the system properties and its evolution throughout the flight. The GNC design and verification integrates mathematical models derived at sub-system level to predict system level behaviour. Their improvement is a key task through the development and validation of a new launch vehicle. Hence the exploitation of flight data shall be maximized in order to reduce at minimum the lack of accuracy in the mathematical models. It is clear that the exploitation of in-flight data during qualification flights in order to improve the launch vehicle models plays a key role in the tuning of the GNC system algorithms and architecture for future flights.

This paper presents the Model Validation Framework for Launchers which is a set of tools and algorithms for the determination and validation of accurate mathematical models and parameters based on pre-, in- and post-flight measurement data.

The Model Validation Framework for Launchers is made up of the following components:

- Measurement Pre-processing component in charge of preparing the flight measurements in order to be used by the Trajectory Reconstruction and Parameter Estimation components.
- Trajectory Reconstruction component in charge of computing the launch vehicle trajectory using the pre-processed flight measurements.
- Parameter Estimation component in charge of characterizing the selected launch vehicle models based on flight measurements, after pre-processing, and vehicle states based on a-priori postulated models.
- Model Validation component in charge of confirming the correctness, accuracy, adequacy and applicability of the identified models with their corresponding estimated parameters.

The target application of the Model Validation Framework for Launchers in this activity has been the VEGA Flight Programme Software Alternative (FPSA).

Index Terms— Trajectory Reconstruction, Measurement Pre-processing, System Identification.

1. INTRODUCTION

During the process of verification and validation of a Launcher GNC system several mathematical models are defined at subsystem level. These mathematical models assume a considerable number of parameters whose variability drastically affects the GNC performance and stability.

The main objective of the Model Validation Framework for Launchers is to develop and integrate a set of SW tools that implement those techniques that allow exploiting all the valuable data collected during first flights, and, through a typical post-flight analysis approach (including trajectory reconstruction and system identification), to characterize all those parameters that influence the GNC system performance.

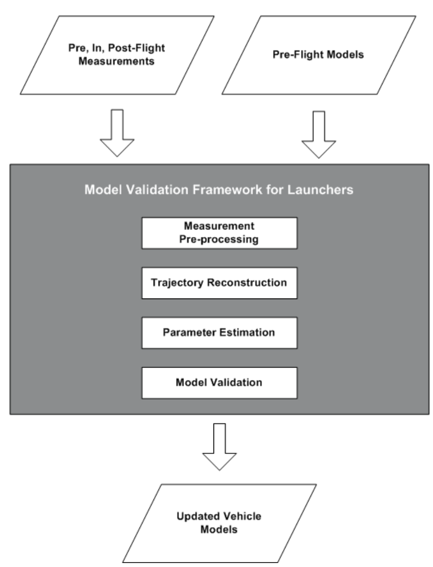

Figure 1 Model Validation Framework for Launchers

This paper is organized as follows. Section 2 introduces the Model Validation Framework, MVF, architecture with a description of the different SW elements and the data used in the frame of the determination and validation of the proposed vehicle models. The results obtained by the MVF are presented in section 3. Finally, conclusions and recommendation for future developments are given in section 4.

2. MVF ARCHITECTURE

The following components and elements are included in the Model Validation Framework in order to be used for pre-, in- and post-flight analyses of the models related to GNC performances of a Launch Vehicle, LV:

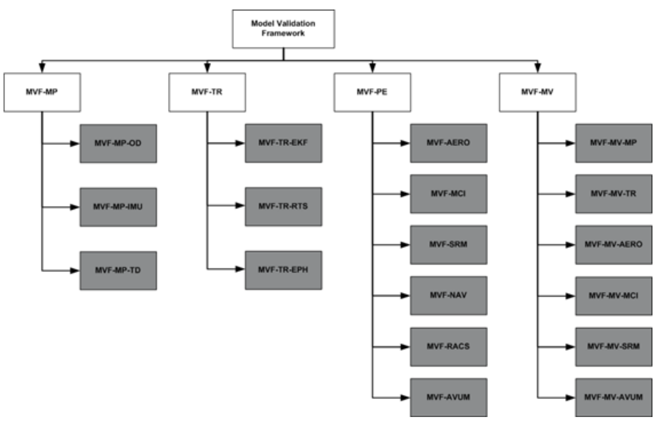

Figure 2 Model Validation Framework for Launchers

The flight analysis is based on the following data:

- IMU measurements available at 25 Hz from the Digital Message 22.
- TVC deflection commands available at 25 Hz from Digital Message 22.
- RCT commands available at 25 Hz from Digital Message 1.
- Simulated radar measurements from tracking stations available at 1 Hz.
- Simulated combustion chamber pressure measurements available at 25 Hz.
- A-priori LV models, e.g. aerodynamic database.
- Environment models, e.g. Kourou Atmospheric model.

The following lines provide a description of the different elements available in the MVF.

2.1. Measurement Pre-processing component

This component, MVF-MP, implements a set of filters, corrections and time tagging techniques to the input measurements to prepare the input data for the rest of the MVF components. The following elements are identified in the frame of the measurement pre-processing step:

MVF-MP-OD. Outlier detection element. To detect and substitute outliers in the IMU velocity increment and attitude quaternion measurements.

MVF-MP-IMU. IMU measurement pre-processing. To derive the flight time history of the non-gravitational velocity increments, acceleration, attitude, angular rate and angular acceleration to be used by the rest of MVF components.

MVF-MP-TD. Tracking data pre-processing. To provide a relative time stamp w.r.t. a common reference time, i.e. transition to flight mode of the IMU, to the tracking measurements in order to be used in the LV trajectory reconstruction.

2.2. Trajectory reconstruction component

This component, MVF-TR, implements the reconstruction of the evolution of the LV position and velocity along the flight based on pre-processed IMU measurements and tracking measurements. The following elements are identified in the frame of the trajectory reconstruction step:

MVF-TR-EKF. Extended Kalman filter element. To estimate the LV position and velocity using an Extended Kalman Filter, EKF.

MVF-TR-RTS. RTS smoother element. To perform an optimal smoothing of the estimated trajectory provided by the EKF using a Rauch-Tung-Striebel, RTS, smoothing filter.

MVF-TR-EPH. Ephemeris element. To generate the LV ephemeris file with the position and velocity time history during the LV flight to be used by the rest of MVF SW elements.

2.3. Parameter estimation component

This component, MVF-PR, implements a set of estimation algorithms to reconstruct and characterize a set of LV models. The following elements are identified in the frame of the parameter estimation step:

MVF-AERO. Aerodynamic Parameter Estimation component. To estimate aerodynamic variables and aerodynamic force and moment coefficients.

MVF-MCI. MCI Estimation component. To reconstruct the evolution LV MCI properties based on pre-processed IMU measurements and reconstructed mass flow rates of the different propulsive phases.

MVF-SRM. Solid Rocket Motor component. To characterize the LV Solid Rocket Motors in terms of throat area evolution, characteristic velocity efficiency and thruster coefficient efficiency.

MVF-NAV. Navigation component. To characterize the IMU performance parameters based on a set of IMU measurements.

MVF-RACS. RACS Estimation component. To reconstruct the RACS forces and torques based on RCT model.

MVF-AVUM. AVUM Reconstruction component. To characterize the AVUM main engine actuations in terms of specific impulse and mass flow rate.

2.4. Model validation component

This component, MVF-MV, is made up by a set elements to analyze the results of the LV trajectory and model reconstruction steps. The following elements are identified in the frame of the model validation step:

MVF-MV-MP. Measurement pre-processing validation element. To compare the pre-processed measurements w.r.t. in-flight estimates available via digital messages.

MVF-MV-TR. Trajectory reconstruction validation element. To compare the reconstructed trajectory w.r.t. the LV trajectory available via digital messages and to analyze the covariance matrix time history and residuals of processed tracking data measurement.

MVF-MV-AERO. Aerodynamic estimates validation element. To validate the aerodynamic estimates based on pre-defined validation thresholds, reference profiles and evolution of measurement residuals and relative standard deviations of the estimates.

MVF-MV-MCI. MCI validation element. To analyze the reconstructed MCI properties.

MVF-MV-SRM. SRM validation element. To analyze the reconstructed SRM model.

MVF-MV-AVUM. AVUM validation element. To validate the reconstructed mass flow rate and estimated specific impulse of the AVUM main engine in the different actuations.

3. MVF RESULTS

This section introduces the results obtained by the MVF based on the in-flight measurements simulated by VEGA High Fidelity Simulator and provided in the frame of the contract 4000108350/13/NL/MH between ESA and GMV.

3.1. Trajectory reconstruction

The reconstruction of the LV trajectory represents a cornerstone of the flight analysis activities because the reconstructed state is used as input data by different reconstruction and estimation processes that are implemented in the framework.

Two different areas are identified in order to reconstruct the LV state. First, the rotational state, this is the attitude, angular rate and acceleration. Second, the translational state considering the evolution of the position, velocity and non-gravitational acceleration vectors along the flight.

The reconstruction of the rotational state takes into account the following steps:

- Filtering of IMU attitude measurements in order to detect and substitute possible outliers in the complete data set.
- Smoothing of attitude measurements in order to reduce the impact of the quantization step and suppress high frequency noise.
- Computing the angular rate from the smoothed attitude data by numerical differentiation.
- Computing the angular acceleration from the angular rate by a second numerical differentiation.

The smoothing and numerical differentiation schemes can be configured by means of suitable configuration parameter files.

Table 1 contains the errors of the reconstructed LV attitude w.r.t. reference data along the complete LV flight.

	Maximum Error (deg)	Minimum Error (deg)
Rz	1.360e-01	-2.850e-01
Ry	4.10e-02	-2.480e-01
Rx	3.70e-02	-8.90e-02

Table 1 Errors of Reconstructed LV Attitude

Table 2 contains the errors of the reconstructed LV angular rate w.r.t. reference data along the complete LV flight.

	Maximum Error (deg/s)	Minimum Error (deg/s)
Rz	4.290e-01	-4.230e-01
Ry	3.750e-01	-3.130e-01
Rx	2.360e-01	--3.860e-01

Table 2 Errors of Reconstructed LV Angular Rate

The reconstruction of the LV rotational state is based on IMU attitude measurements, quaternions. The availability of angular rate measurements shall be explored in order to improve the reconstruction of the angular rate and acceleration.

The reconstruction of the LV translational state is based on two different types of measurements. First, the IMU velocity measurements, expressed in Inertial Navigation reference frame and in IMU Accelerometer reference frame, and second, the tracking measurements, i.e. range, azimuth and elevation angles from ground stations.

The reconstruction of the translational state takes into account the following steps:

- Filtering of IMU velocity measurements in order to detect and substitute possible outliers in the complete data set.
- Smoothing of velocity measurements in order to reduce the impact of the quantization step and suppress high frequency noise.
- Processing the smoothed velocity measurements expressed in Inertial Navigation reference frame to derive the non-gravitational velocity increments to be used in the propagation algorithms of the translational state reconstruction.
- Processing the smoothed velocity measurements expressed in LV Body Fixed reference frame to derive the non-gravitational acceleration vector.
- Reconstruction of the evolution of position and velocity vectors by means of an Extended Kalman Filter process that takes advantage of the tracking data to complement the inertial propagation based on IMU velocity measurements, [1]. Once this estimated trajectory is available, a Rauch-Tung-Striebel smoother is applied in order to improve the estimated trajectory, [2].

Table 3 contains the errors of the estimated LV position and velocity w.r.t. reference data along the complete LV flight expressed in the North-East-Down, NED, reference frame when the EKF process is applied.

	N-axis	E-axis	D-axis
Position Error (m)	2000.0	1500.0	750.0
Velocity Error (m/s)	2.00	1.00	2.00

Table 3 Errors of Reconstructed LV Position and Velocity (EKF Results)

The following figures illustrate the evolution of the estimated, from EKF, and reconstructed, from RTS, position and velocity during the endo-atmospheric flight. It is possible to see the improvement in the reconstruction of the position vector when the RTS smoother is applied, i.e. the evolution of the position error is smoother when the RTS is applied.

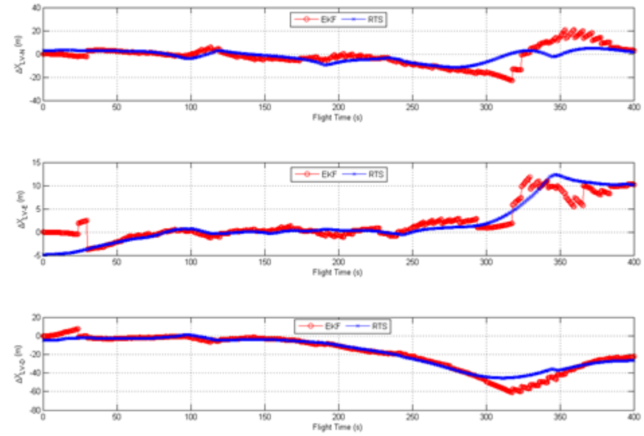

Figure 3 Evolution of Position Errors during Endo-atmospheric Flight (EKF and RTS)

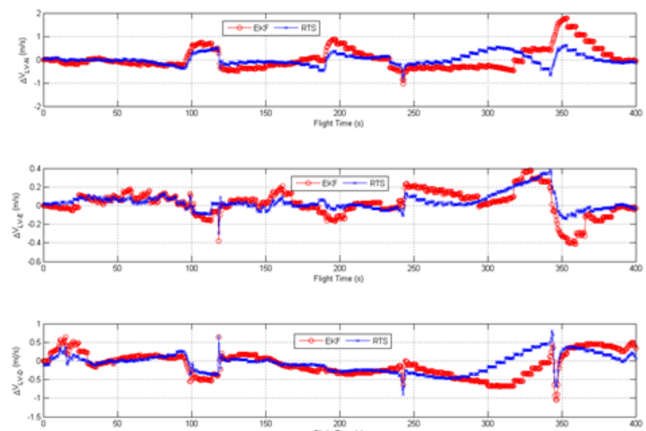

Figure 4 Evolution of Velocity Errors during Endo-atmospheric Flight (EKF and RTS)

Table 4 contains the errors of the reconstructed LV non-gravitational acceleration w.r.t. reference data along the complete LV flight expressed in the LV Body-Fixed reference frame.

	Maximum Error (m/s^2)	Minimum Error (m/s^2)
X-axis	2.00e+00	-2.80e+00
Y-axis	3.30e-01	-3.10e-01
Z-axis	2.50e-01	-3.70e-01

Table 4 Errors of Reconstructed LV Non-gravitational Acceleration (Complete Flight)

Table 5 contains the errors of the reconstructed LV non-gravitational acceleration w.r.t. reference data during the endo-atmospheric flight expressed in the LV Body-Fixed reference frame.

	Maximum Error (m/s^2)	Minimum Error (m/s^2)
X-axis	1.20e+00	-2.80e+00
Y-axis	3.30e-01	-2.50e-01
Z-axis	2.50e-01	-3.70e-01

Table 5 Errors of Reconstructed LV Non-gravitational Acceleration (Endo-Atmospheric Flight)

The reconstructed non-gravitational acceleration is a key element for the reconstruction of other variables of the LV flight or an input to characterize additional LV models. The reconstruction is based on IMU velocity measurements and the availability of acceleration measurements from IMU shall be explored in order to improve the results.

3.2. Model reconstruction and characterization

In the frame of the LV model reconstruction and characterization results related to AVUM Main Engine and LV aerodynamic database are presented in this section.

The purpose of the AVUM Main Engine model in the MVF is the reconstruction of the mass flow rate and the characterization of the AVUM Main Engine activations during the LV flight.

The mass flow rate reconstruction and the estimation of the specific impulse is based on the minimization of the difference of the non-gravitational acceleration profile derived from the IMU velocity measurements w.r.t. the one computed based on mass flow rate and specific impulse during the steady phase of the AVUM Main Engine activation. For the rise phase, a linear fit is applied to the mass flow rate, setting to zero the mass flow rate just before the AVUM Main Engine activation and setting the mass flow rate to the value estimated during the steady phase at the end of the rise phase. For the decay phase the mass flow rate is characterized by an exponential least squares fitting that has been obtained from the mass flow rate reference values, i.e. simulating the availability of an a-priori model for the AVUM Main Engine mass flow rate during the decay phase.

The reconstruction of the AVUM Main Engine thrust profile is based on the reconstructed acceleration profile, i.e. based on estimated mass flow rate and specific impulse; and on the reconstructed mass derived from the consumed propellant mass.

Table 6 contains the errors of the estimated mass flow rate, specific impulse and LV mass for the three different activations of the AVUM Main Engine available in the simulated data.

	1st	2nd	3rd
Δm (kg/s)	-0.012	-0.019	-0.001
Δm (%)	1.52	2.38	0.12
ΔIsp (s)	5.42	8.16	0.99
ΔM (kg)	-4.07	-2.46	-0.15
ΔM (%)	0.23	0.14	0.02

Table 6 Errors of Reconstructed AVUM Main Engine

From the presented results it is possible to derive the following conclusions.

- The characterization of the AVUM main engine during the steady phase is performed by means of the estimated mass flow rate and specific impulse and provides good performances.
- The reconstruction of the mass flow rate during the rise and decay phases of the AVUM main engine activations, based on linear fit for the rise phase and based on a pseudo-a-priori model for the decay phase, provides good results in terms of reconstructed LV mass during the complete AVUM main engine activation

The purpose of the characterization of the LV aerodynamic model based on in-flight measurements is to reduce the uncertainties of the a-priori AEDB models.

This process is implemented in two steps:

- Reconstruction of aerodynamic forces and torques. They are the input data for the estimation of the aerodynamic stability and control derivatives and are computed based on the pre-processing of in-flight measurements, i.e. non-gravitational acceleration, angular rate and angular acceleration reconstructed from the IMU measurements; and reconstructed forces and moments derived from the actuation of SRM stages and RCTs.
- Parameter estimation in order to characterize the aerodynamic stability and control derivatives of the aerodynamic forces and moments coefficients around pre-selected flight regions, [3], [4], [5], [6] and [7].

The first step is implemented by the MVF element MVF-AERO-VAR when the ASCD processing mode is selected. The second step is implemented by the MVF element MVF-AERO-EST that characterizes the different aerodynamic derivatives of the proposed model.

The following structure has been considered in the characterization of the longitudinal aerodynamic force coefficient for the selected flight regions:

$$C_X = C_{X0} + C_{X\alpha} \cdot \alpha$$

The selected flight regions have been characterized by Mach numbers M_1 = 1.35 and M_2 = 2.00 that corresponds to the first SRM phase, P80 phase.

Table 7 contains the errors of the estimated aerodynamic derivatives of the longitudinal force at the selected target Mach number M_1 and M_2.

	M_1	M_2
C_{X0}	-0.760e+00	-1.50e-01
ΔC_{X0} (%)	1.10%	4.50%
$C_{X\alpha}$	2.490e+00	1.23e+02
$\Delta C_{X\alpha}$ (%)	0.90%	5.80%

Table 7 Errors of Estimated Longitudinal Aerodynamic Derivatives

From the presented results it is possible to derive the following conclusions.

- The characterization of the LV aerodynamic model for the longitudinal force coefficient is possible during the first SRM phase.
- The characterization of the LV aerodynamic model for the normal force coefficient is not possible with the reconstructed aerodynamic forces.
- The reconstruction of the aerodynamic roll coefficient and center of pressure location is compromised by the reconstructed aerodynamic torque, i.e. reconstructed rotational state and aerodynamic forces along Y-axis and Z-axis.
- During Z23 phase several attempts to characterize the aerodynamic model have been performed, but the reconstructed aerodynamic forces and torques do not allow estimating the aerodynamic control and stability derivatives.

4. CONCLUSIONS

The following conclusions are derived from the development of the Model Validation Framework for Launchers:

- The trajectory reconstruction step provides very good estimates of the evolution of the LV position and velocity during the flight. The application of the EKF improves the trajectory reconstruction performances w.r.t. a pure inertial propagation in those regions where tracking data are available and can be processed. The application of the RTS filter to the trajectory estimated by the EKF improves the results if and only if tracking data are available.
- The rotational state reconstruction is based on IMU attitude measurements. Then in order to complete the reconstruction of the LV rotational state two numerical differentiations shall be applied to get the angular rate and angular acceleration evolution. In order to improve this reconstruction, availability of IMU angular rate measurements should be explored. These angular rate measurements will be integrated to reconstruct the LV attitude and differentiated, only once, to reconstruct the LV angular acceleration
- The reconstructed non-gravitational acceleration is a key element for the reconstruction of other variables of the LV flight or an input to characterize some LV models. It is reconstructed based on velocity measurements applying numerical differentiation. To improve the results of the reconstructed acceleration, the availability of IMU acceleration measurements should be explored.
- The characterization of the AVUM main engine during the steady phase is performed by means of the estimated mass flow rate and specific impulse and provides good performances.
- The reconstruction of the mass flow rate during the rise and decay phases of the AVUM main engine activations, based on linear fit for the rise phase and based on a pseudo-a-priori model for the decay phase, provides good results in terms of reconstructed LV mass during the complete AVUM main engine activation.
- The reconstruction of the aerodynamic force is driven by the performances of the reconstructed non-gravitational acceleration. The reconstruction of the longitudinal component for the first SRM phase in the central part of the actuation is around of 2% of relative error and has been used to analyze the estimation of longitudinal aerodynamic derivatives.
- The characterization of the LV aerodynamic model is possible for the axial force coefficient for the first SRM phase and can be improved if the pre-processing of the IMU measurements to derive the non-gravitational acceleration is improved, i.e. IMU acceleration measurements are available for the reconstruction.

10. REFERENCES

[1] Simon D. *Optimal State Estimation: Kalman, H Infinity, and Nonlinear Approaches*, John Wiley & Sons, 2006.

[2] Rauch, H.E., Tung, F., and Striebel, C.T., "Maximum Likelihood Estimation of Linear Dynamic Systems", *AIAA Journal*, Vol 3, No. 8, 1965, pp 1445 -1450.

[3] Iliff, K. W., and Taylor, L.W., "Determination of Stability Derivatives from Flight Data Using a Newton-Raphson Minimization Technique", *NASA TN D-6579*, March 1972.

[4] Balakrishnan, A. V., *Communication Theory*, McGraw Hill, New York, 1968.

[5] Kumar, K. S. P. and Sridhar, R., "On the Identification of Control Systems by the Quasi-Linearization Method", *IEEE Transactions on Automatic control*, Vol. AC-9, No. 2, 1964, pp 151-154.

[6] Marquardt, D. W., "An Algorithm for Least Squares Estimation of Nonlinear Parameters", *SIAM Journal of Applied Mathematics*, Vol. 11, No. 2, 1963, pp. 431-441.

[7] Moré, J.J., "The Levenberg-Marquardt Algorithm: Implementation and Theory", *Springer Lecture Notes in Mathematics, No. 630*, edited by G.A. Watson, Springer, Berlin, 1978, pp. 105-116.