# STRUCTURAL DYNAMICS EXPERIMENTS ON ESA SPACE LAUNCHERS

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SAPIENZA UNIVERSITÀ DI ROMA

IOMAC2027 OMA LECTURE SERIES

April 09th, 2026

# Agenda

1. Motivations
2. Theoretical Background on OMA approaches
3. OMA on ARIANE Launch Vehicle
4. OMA on VEGA P80 Motor
5. OMA on REXUS36 Sounding Rocket
6. Concluding Remarks



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# 1. Motivations



- Topics at glance

  - The development of OMA methods allows estimating the modal parameters of a structural system by using **vibration responses only**
  - The OMA methodologies are of great importance from the industrial point of view **permitting to evaluate the behavior** of a structure **under its operative conditions**
  - The **dynamic identification of a Launch Vehicle** structure under its actual operative conditions is of great importance for **launcher industry**

    - Updating numerical models of the structure and for improving the design
    - High operative costs for the experimental acquisition also in ground testing
    - Reducing the time-to-market in the developing phase

# 1. Motivations



- Main advantages from Output-Only analysis
  - Operational Modal Analysis for time-varying systems
  - Root locus estimate and Time-Tracking of the modal parameters
  - Accuracy evaluation of the numerical prediction and model updating
  - Identification of (possible) harmonic interactions due to combustion dynamics
  - Validation of the sensor placement methodologies using time-dependent mode shapes
  - Evaluation of the effects of dynamic range of measurements in the modal parameter estimate and tracking
  - Estimate rocket performances by integrating numerical simulations
- Validation of the developed methodology
  - Numerical analyses
  - Firing test
  - Flight tests



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# 2. Theoretical Background ...



## Natural Input Modal Analysis


NIMA



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# 2. Theoretical Background ...

## Natural Input Modal Analysis: N.I.M.A.



Hilbert Transform Method (HTM)

Frequency Domain Decomposition (FDD)


Stochastic Modal Appropriation (SMA)

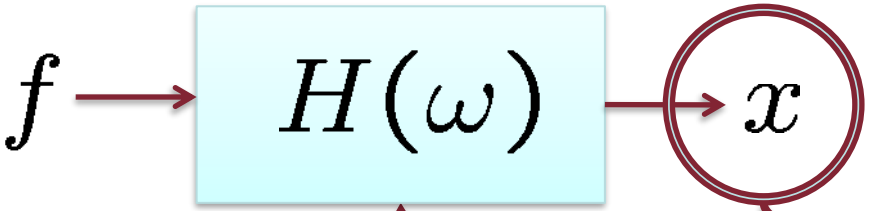
*Ready to be implemented*

Stochastic Subspace Identification (SSI)

Time & Frequency domain

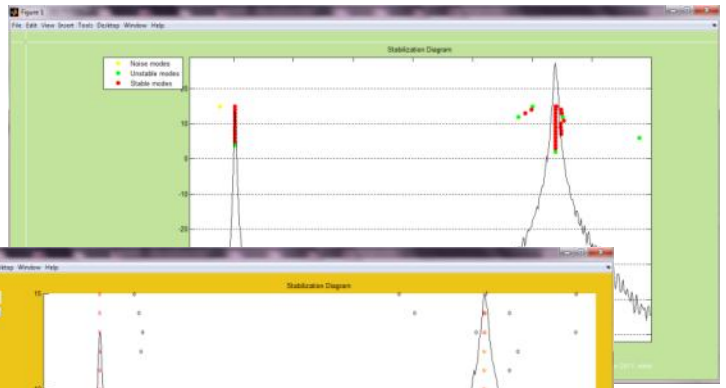
# 2. Theoretical Background ...



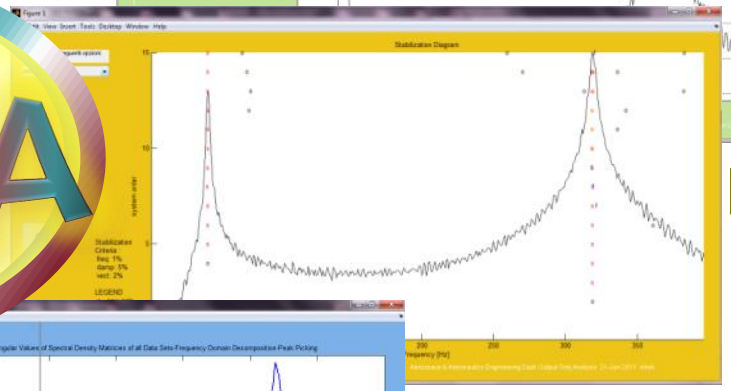




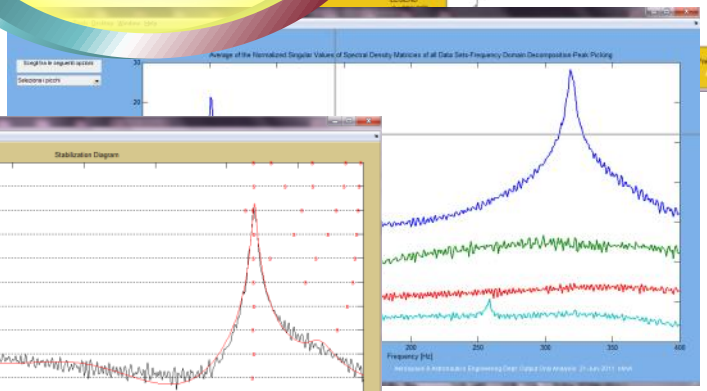
Multiple Approaches
Single Software



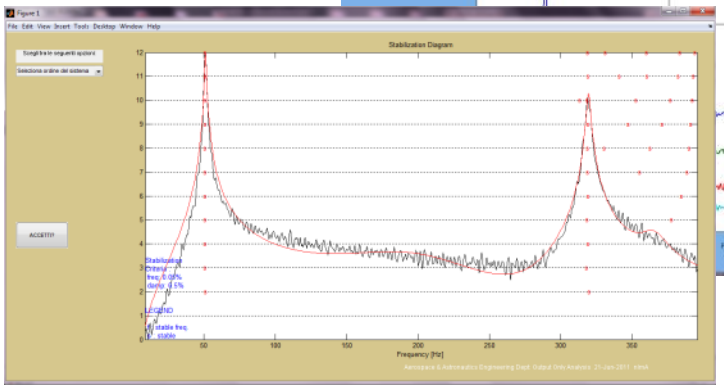
BR



f-SSI



FDD



HTM



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# 2. Theoretical Background ...



NIMA

$$f \rightarrow H(\omega) \rightarrow x$$

and also

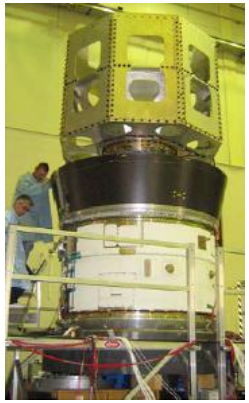
Natural Frequencies

Damping Ratios

Normal Modes

Mode scaling

Harmonic removal





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## Accuracy of the estimates: some remarks

- From the mathematical point of view the **dynamics** of a system is **defined by its poles** (state matrix eigenvalues) $\lambda_n$
- The **OMA techniques provide** estimates of the system dynamics by identifying the **natural frequencies** $f_n$ and **damping ratios** $\zeta_n$
- Once natural frequencies and damping ratios are estimated the poles of the system are identified

$$\lambda_n = \lambda_{R_n} + j\lambda_{I_n}$$
$$\zeta_n := -\frac{\lambda_{R_n}}{\lambda_{I_n}}$$
$$\lambda_{n_I} := \omega_n = 2\pi f_n$$

- If the poles (in general complex) are written in the complex plane in module and phase

$$\begin{aligned} |\lambda_n| &= \omega_n\sqrt{1+\zeta_n^2} \cong \omega_n \\ \angle\lambda_n &= \frac{\pi}{2} + \text{arctang}(\zeta_n) \cong \frac{\pi}{2} + \zeta_n \end{aligned}$$

- By introducing the uncertainties associated to the estimate quantities $\Delta\zeta_n$ and $\Delta f_n$

$$\begin{aligned} \Delta|\lambda_n| &\cong 2\pi\Delta f_n = O(1) \\ \Delta\angle\lambda_n &\cong \Delta\zeta_n = O(10^{-2}) \end{aligned}$$

- The **system poles** are practically identified within the **uncertainties associated to the natural frequencies**
- **The system dynamics is identified by the uncertainties associated to its natural frequencies**



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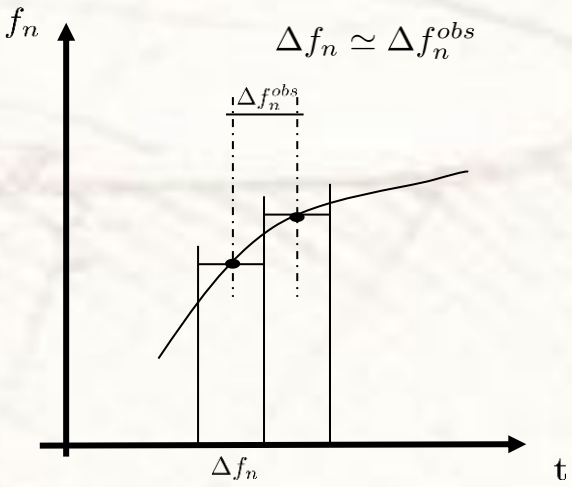
# 2. Theoretical Background ...

## A criterion of applicability for time-varying systems

- The **OMA hypotheses** require a l**inear time-independent system excited by a white noise**
- If the system is characterized by **time-dependent dynamic** properties, the analysis can be carried out by splitting the whole observation time **into sub-intervals** where the **system dynamical features** can be considered as **time-independent**
- The **system dynamics** is **identified by the natural frequencies uncertainties:** the presented criterion is based on the frequencies




- The frequency is identified within an error associated to the frequency resolution $\Delta f_n$
- The frequency can be represented by a reference value plus its time-variation in the observation-window

$$f_n = \check{f}_n + \Delta_{obs} f_n$$

- To apply the OMA methods and thus consider the system as time-invariant, it must hold

$$\Delta_{obs} f_n \leq \Delta f_n = 1/\Delta t$$

$$\text{with} \quad \Delta_{obs} f_n = \dot{f}_n \Delta t \quad \dot{f}_n = max_I \left[ \dot{f}(t) \right] \quad t \in [t_I, t_I + \Delta t]$$

- Thus, the applicability criterion, linking frequency resolution and time-variation, is obtained: $\Delta t \leq \sqrt{\frac{1}{\dot{f}_n}}$

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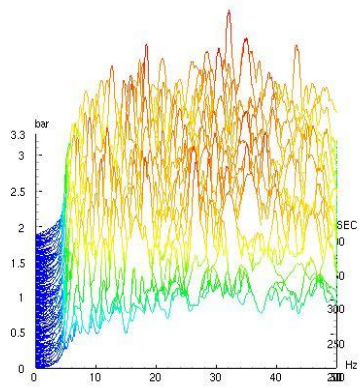
# 3. OMA on ARIANE Launch Vehicle



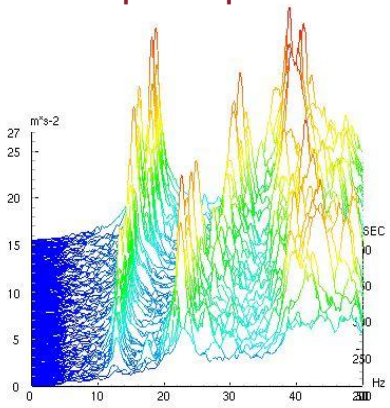
**Signal data characterization**

- ❑ Flight phase where the system is excited by a supposed white noise
- ❑ The responses are recorded in correspondence of 4 locations left intentionally unknown.
- ❑ Three different experimental cases (corresponding to the same flight phase) have been recorded and analyzed: Flight#1, Flight#2, Flight#3
- ❑ Target modes around 10/20Hz and 30/40Hz
- ❑ The analysis is performed in the time-window [200s-500s]
- ❑ For the given signal data 30 intervals $I_i$, $i=1,\ldots,30$, of 10 seconds are considered (compromise between frequency resolution and supposed frequency time-variation)
- ❑ Frequency resolution 0.1*Hz* and Nyquist frequency of 227.27*Hz*

**Excitation Spectra**

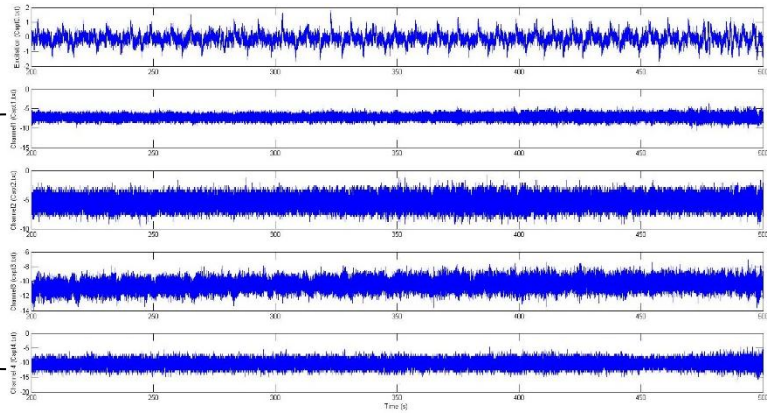



**Response Spectra**




**Excitation**

**Channels**





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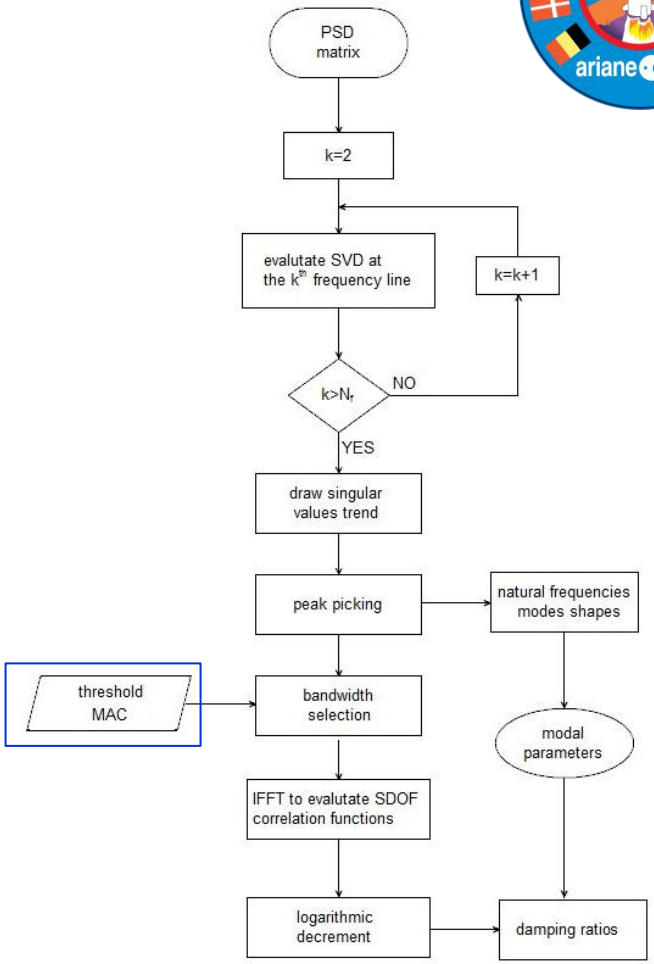
**FDD numerical procedure**

- ❑ Computation of the PDS matrix $\forall \omega_k$
- ❑ Evaluation of the SVD of the PSD matrix
- ❑ The natural frequencies $f_n$ obtained from the Singular Values trend
- ❑ The damping ratios $\zeta_n$ are obtained from the logarithmic decrement

**Analysis parameters in the estimation procedure:**

- Threshold MAC=0.9




FDD flow diagram of NIMA code



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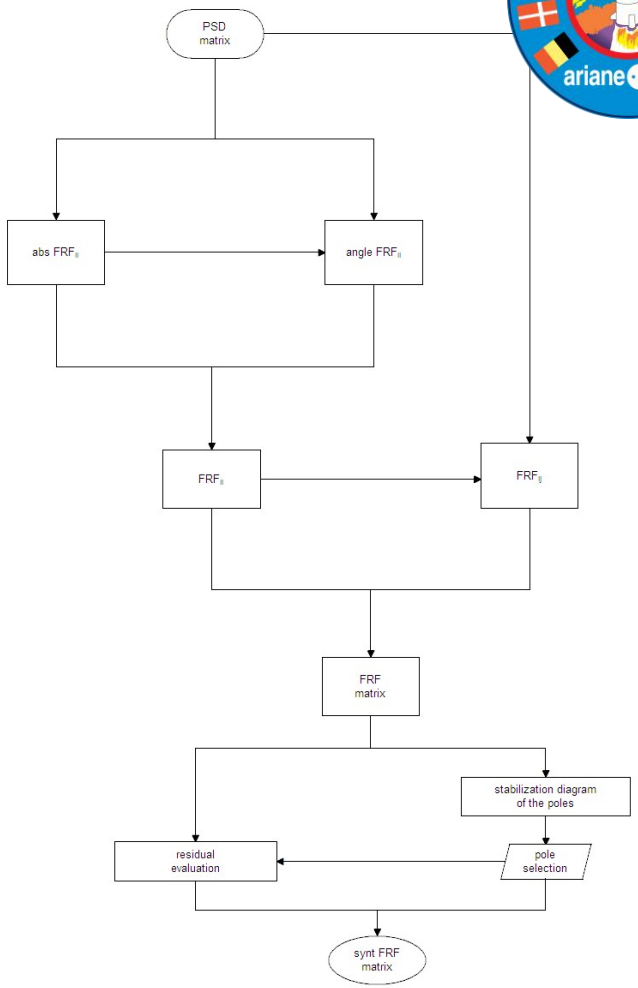
**HTM numerical procedure**

- ❑ Computation of the PDS matrix
- ❑ Evaluation of the FRF via the Hilbert Transform of the PSD matrix
- ❑ The system poles ($f_n$ and $\zeta_n$) are identified via stabilization diagram



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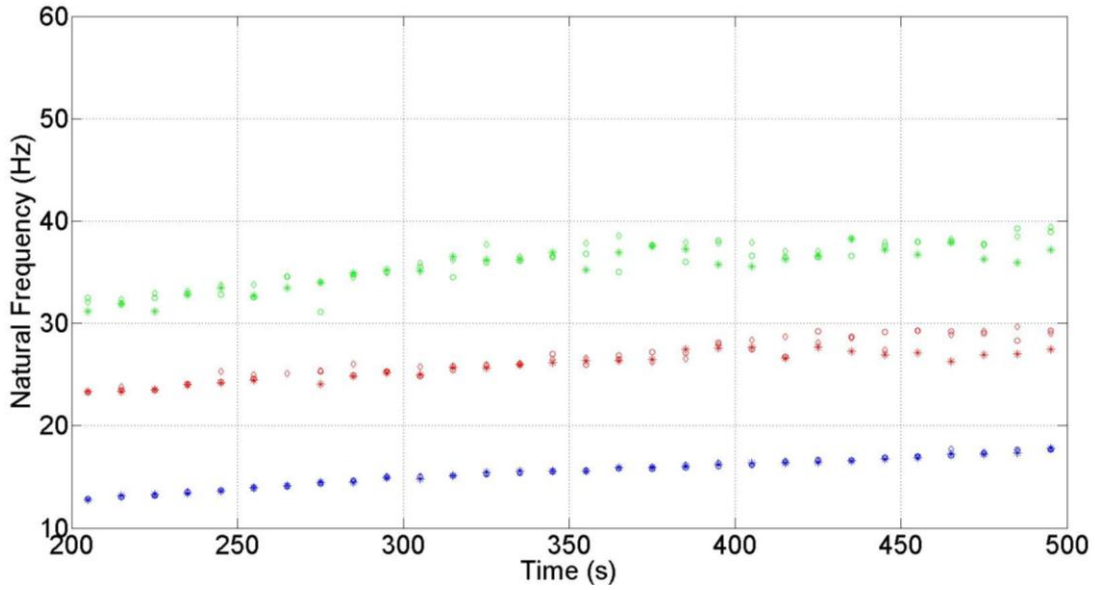
# 3. OMA on ARIANE Launch Vehicle

## Identified natural frequencies using FDD




- 1st Mode, Flight1
- 2nd Mode, Flight1
- 3rd Mode, Flight1
- 1st Mode, Flight2
- 2nd Mode, Flight2
- 3rd Mode, Flight2
- 1st Mode, Flight3
- 2nd Mode, Flight3
- 3rd Mode, Flight3

- **For all the flights the natural frequencies have been identified**
- **For all the flights the time-varying trend of natural frequencies have been tracked**
- The identified natural frequencies in different flights (for the same mode and same time) differ for a max of about 5 Hz
- The difference between the estimates among different flight increases with the mode order



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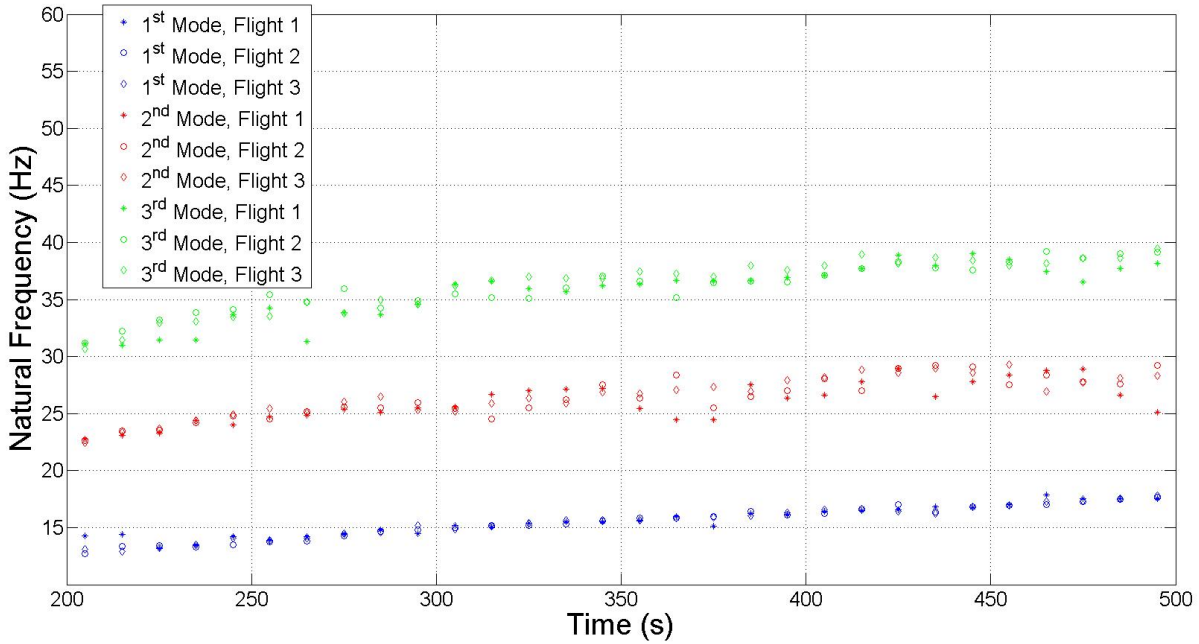
# 3. OMA on ARIANE Launch Vehicle

## Identified natural frequencies using HTM

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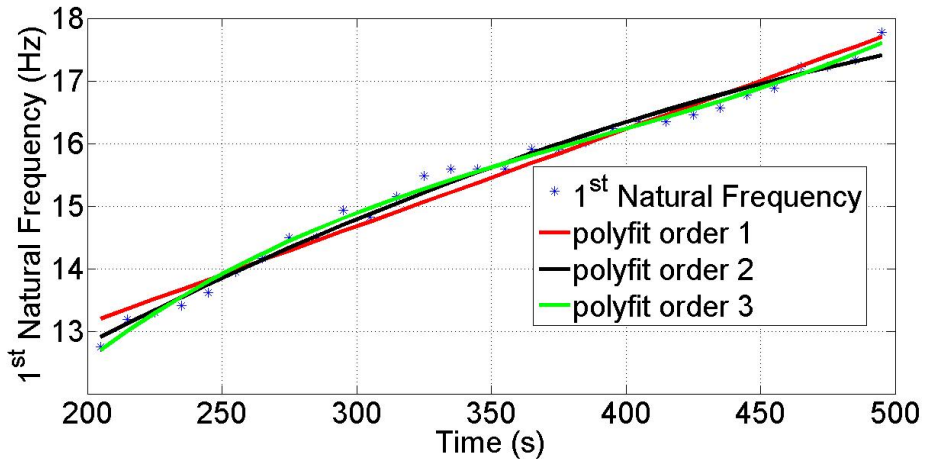
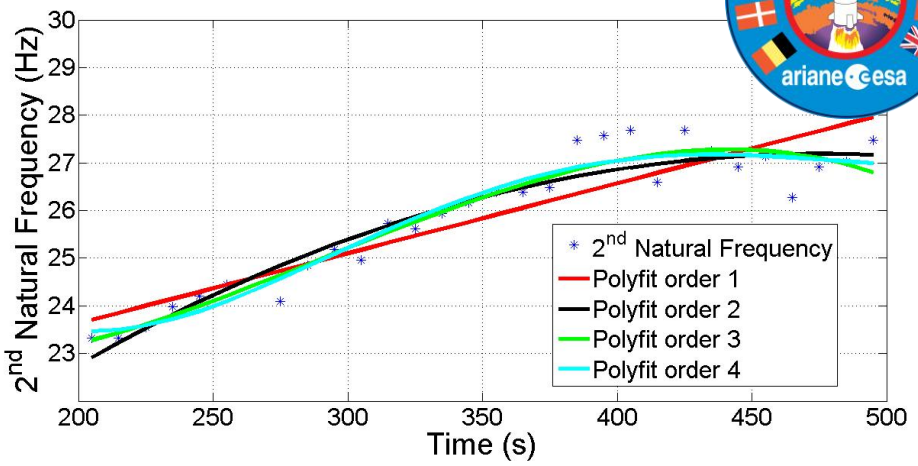
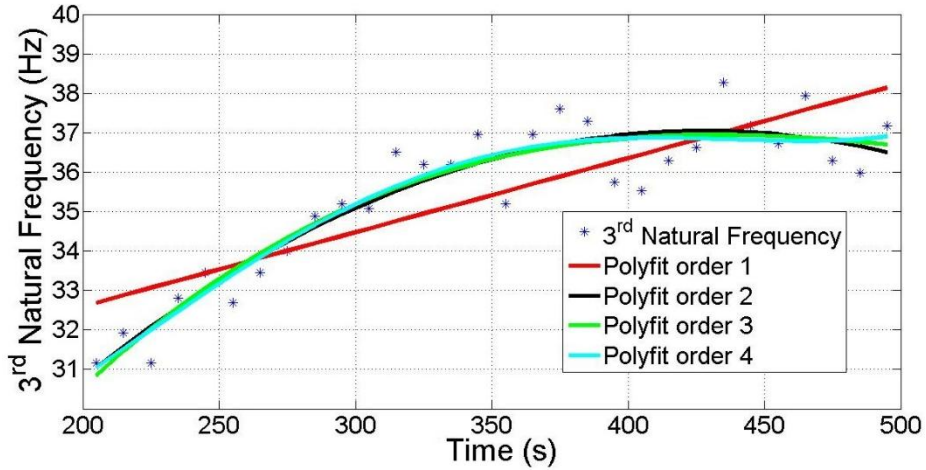
# 3. OMA on ARIANE Launch Vehicle

## Tracking of the natural frequencies using FDD, Flight #1




- **Similar tend have been obtained for Flight#2 and Flight#3**
- **The target frequencies have globally been identified and time-tracked**
- The 2nd natural frequency has not been identified in the interval [260s. 270s] due too high uncertainties in Flight#1 and Flight#2



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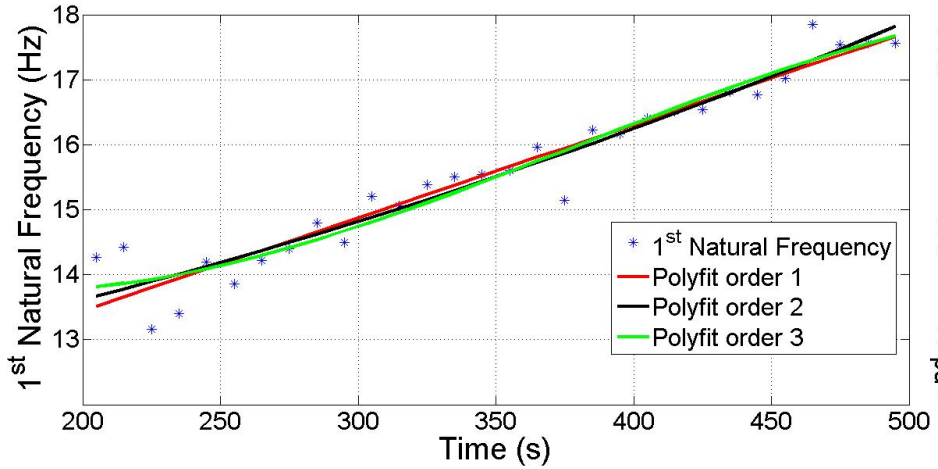
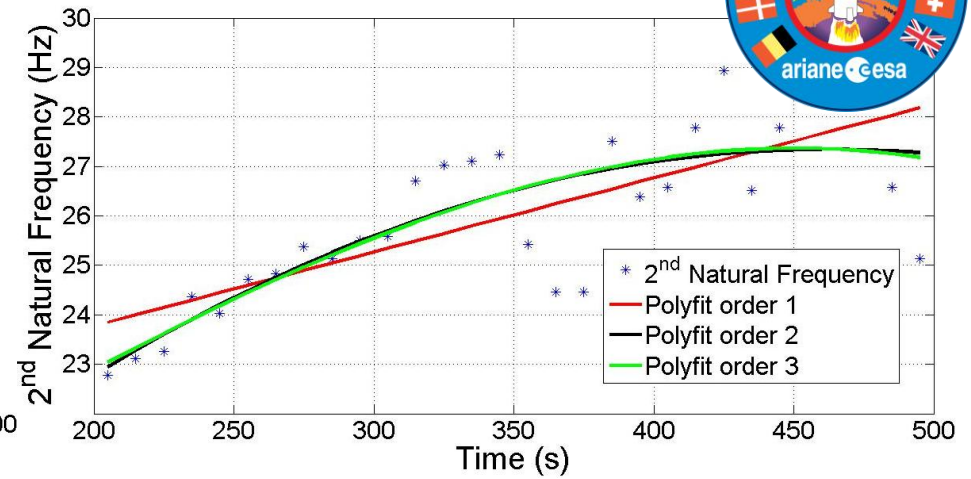
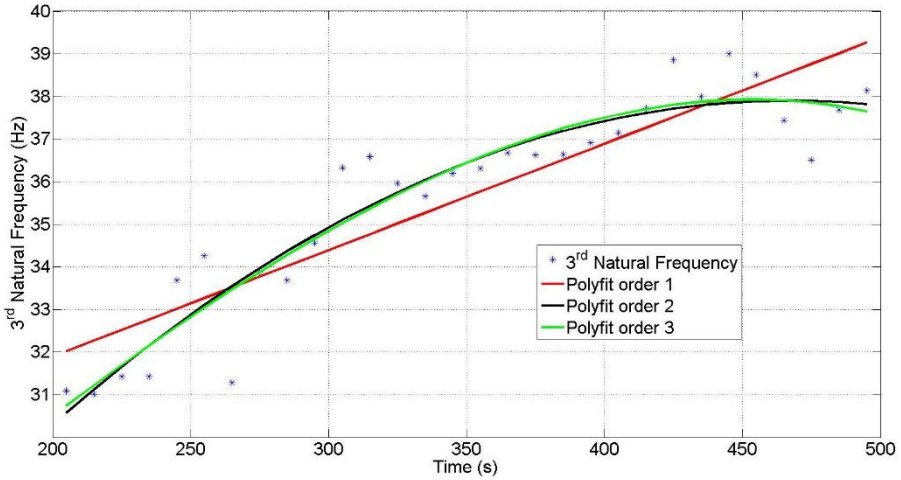
# 3. OMA on ARIANE Launch Vehicle

## Tracking of the natural frequencies using HTM, Flight #1




- **Similar trends have been obtained for Flight#2 and Flight3**
- The target frequencies have been identified and time-tracked



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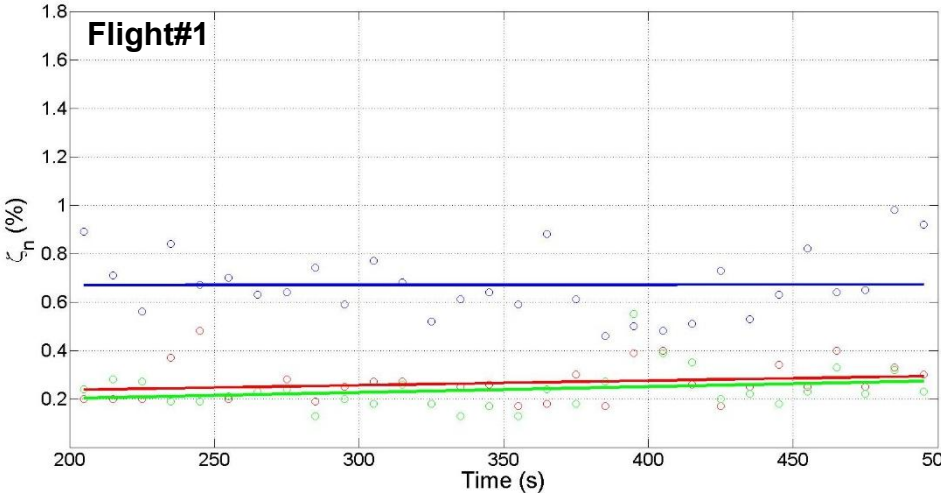
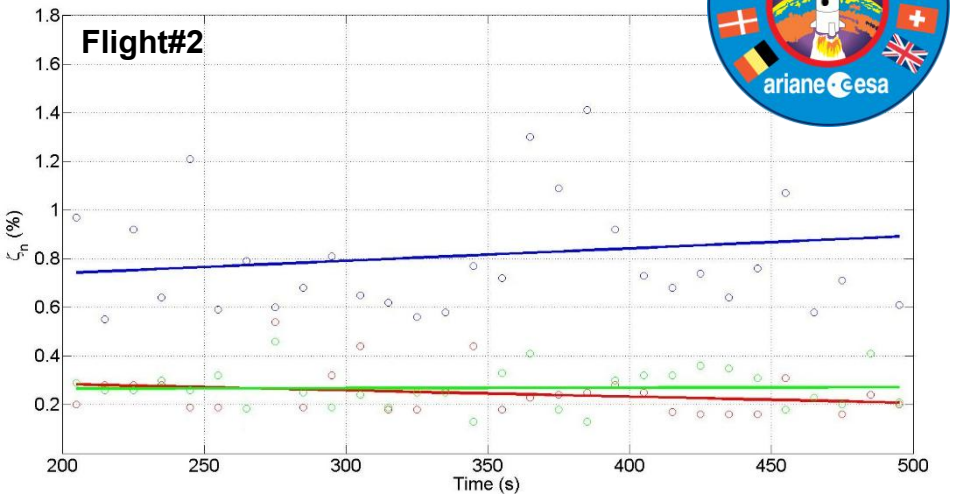
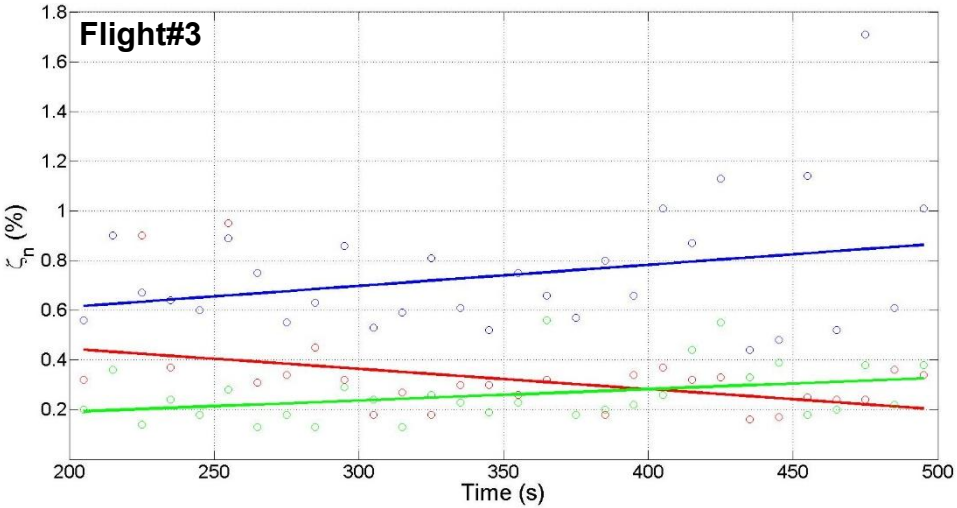
# 3. OMA on ARIANE Launch Vehicle

## Tracking of the damping ratios using FDD

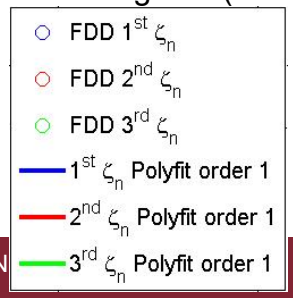



- The damping ratios have been globally identified and time-tracked
- Strongly dependent on the considered flight by considering the single value
- Similar intervals of variation

- In the interval [260s, 270s] the damping ratio are not identified for Flight#1 and Flight#2 (because are not identified the frequencies)



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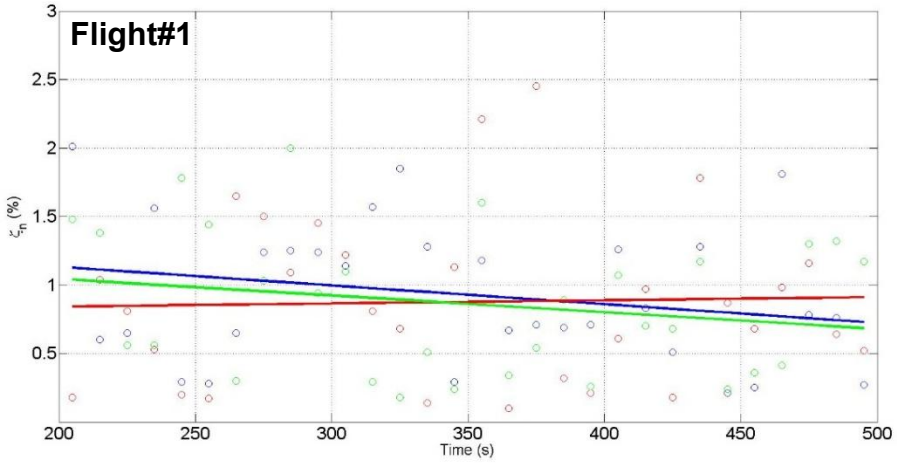
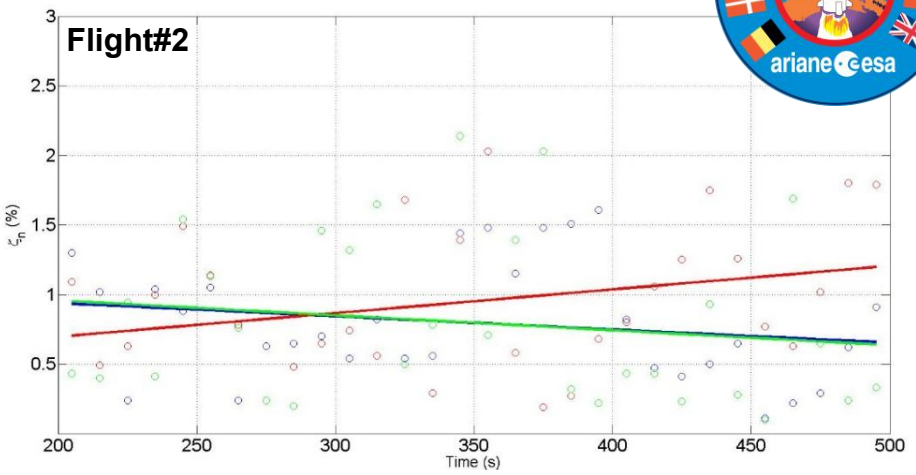
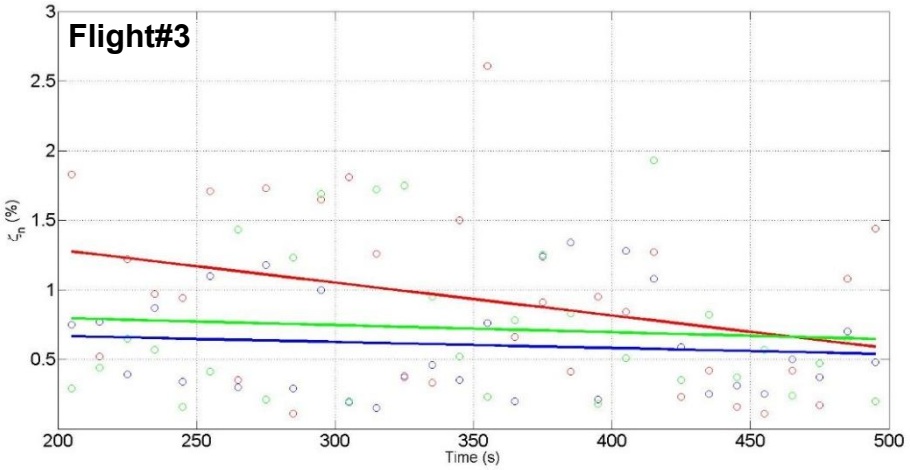
# 3. OMA on ARIANE Launch Vehicle

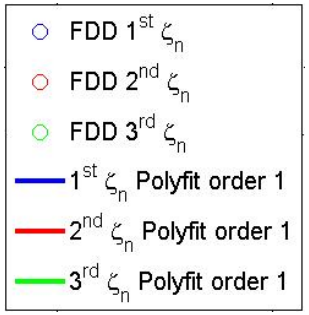
## Tracking of the damping ratios using HTM




- **The damping ratios have been identified and time-tracked**
- Strongly dependent on the considered flight by considering the single value
- Similar intervals of variation



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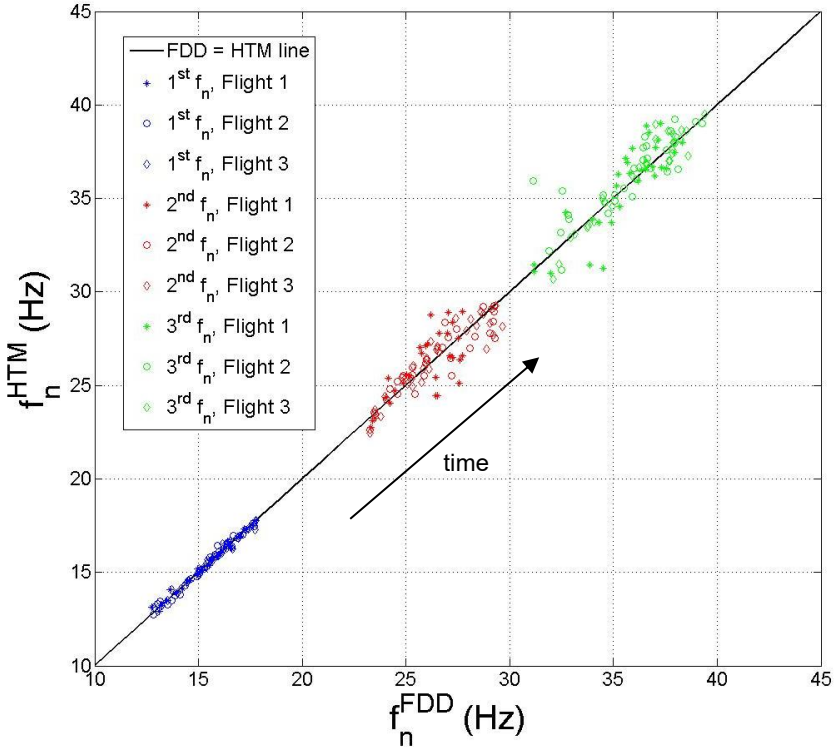
# 3. OMA on ARIANE Launch Vehicle

## HTM vs FDD natural frequencies comparison




- **The first frequency is the best identified**
- The **higher the order of the corresponding modes** the **higher the differences** within the estimates among different flights
- The largest difference among the identified frequency with FDD and HTM is around 5*Hz*



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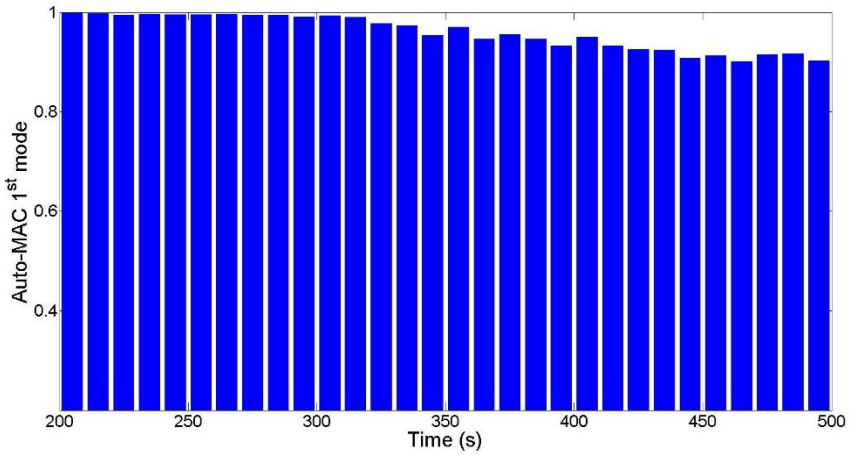
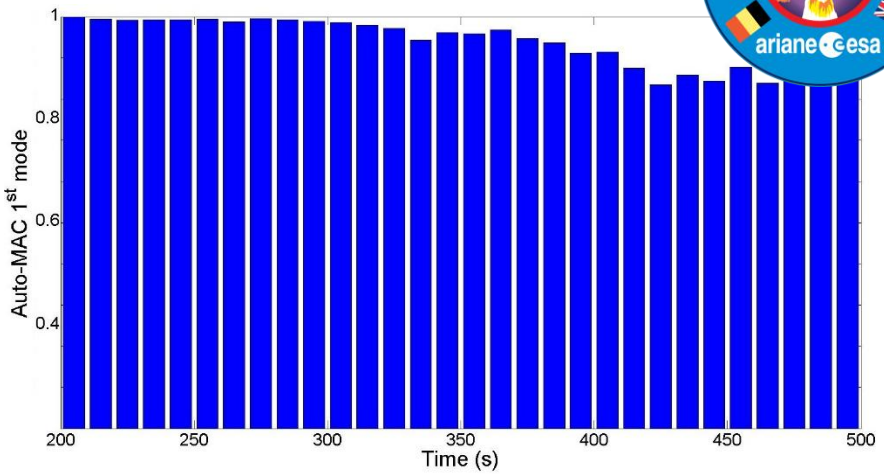
# 3. OMA on ARIANE Launch Vehicle

## Tracking of the 1st mode shape using FDD

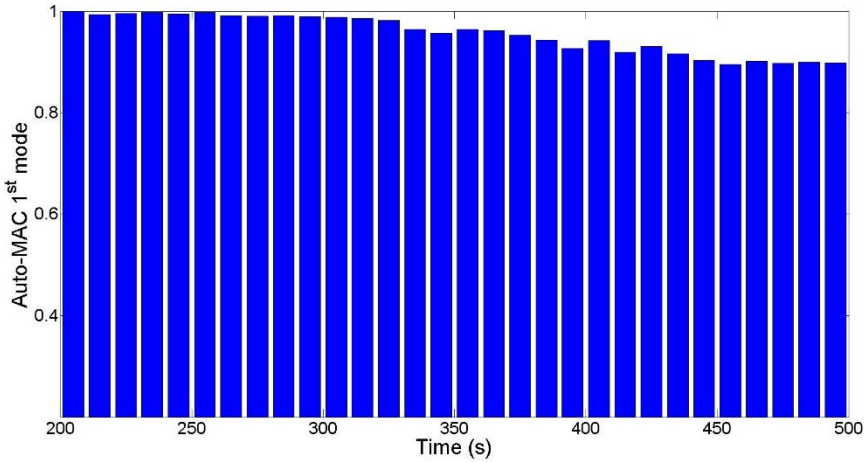
Flight#1




Flight#2




Flight#3




- The modes are compared with their estimation in the first time-interval
- 1st Mode shape tracking is consistent among the three flights



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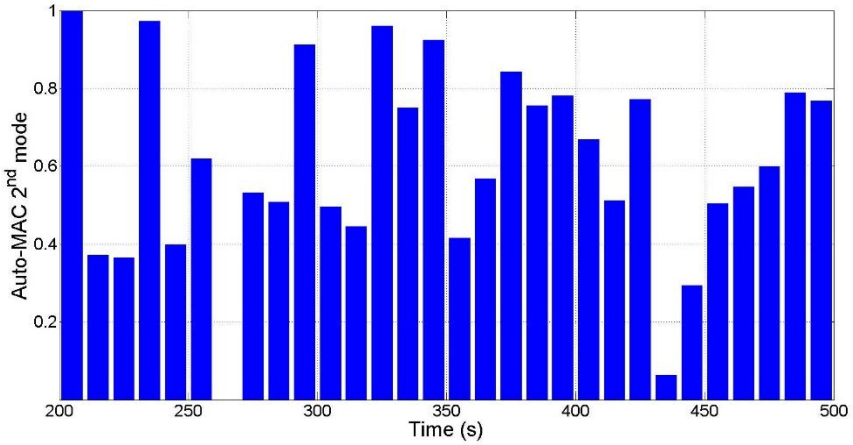
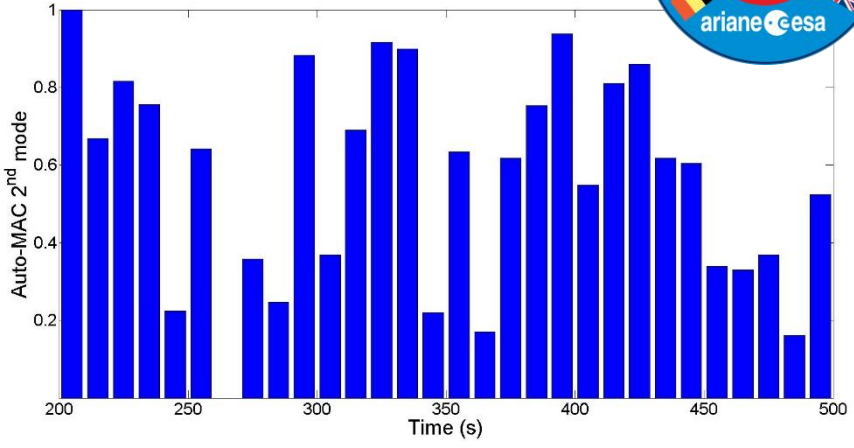
# 3. OMA on ARIANE Launch Vehicle

## Tracking of the 2nd mode shape using FDD

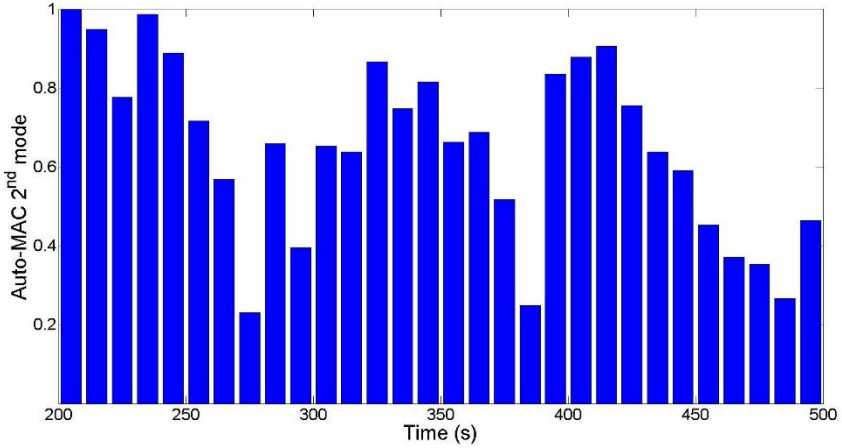
**Flight#1**




**Flight#2**




**Flight#3**

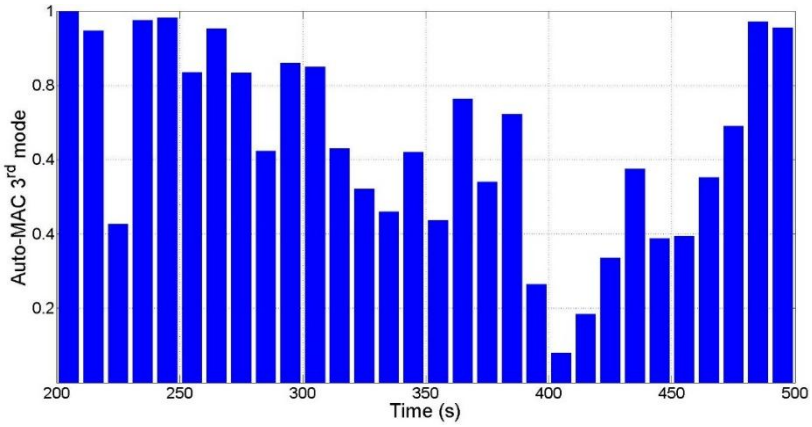



- The modes are compared with their estimation in the first time-interval
- 2nd Mode shape tracking is more difficult with respect the first even if the trend are consistent among the different flights (In Flight#1 and Flight#2 is not identified being not identified the frequencies)
- Not in all the time-intervals it has been possible estimate the modal parameters

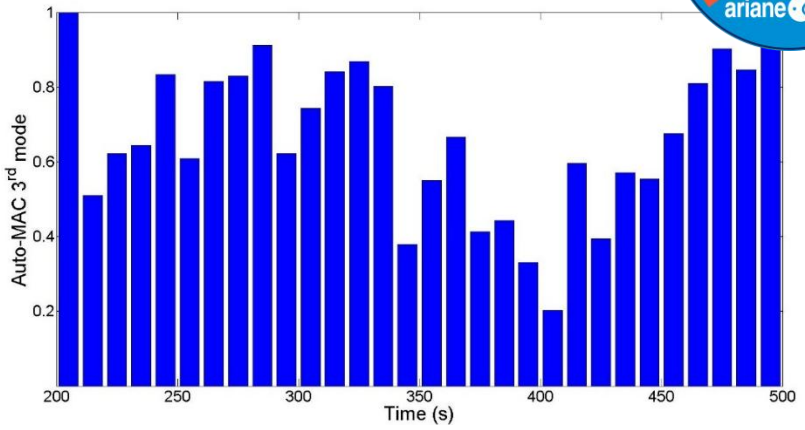
# 3. OMA on ARIANE Launch Vehicle

## Tracking of the 3rd mode shape using FDD

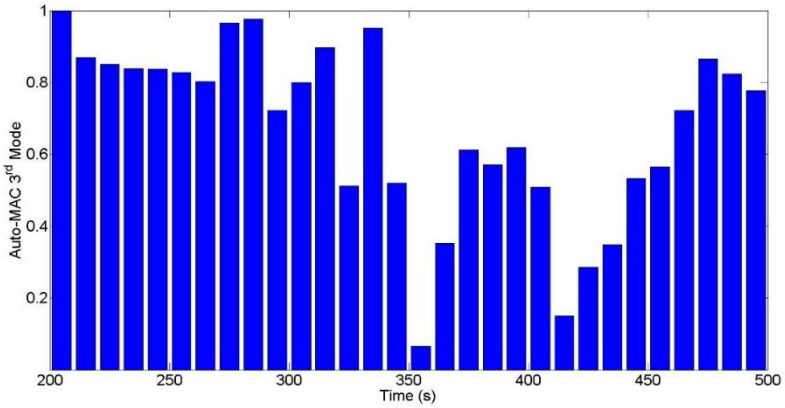
**Flight#1**




**Flight#2**




**Flight#3**




- The modes are compared with their estimation in the first time-interval
- 3nd Mode shape tracking is the most difficult with respect the first even if the trend are similar among the different flights
- Not in all the time-intervals it has been possible estimate the modal parameters



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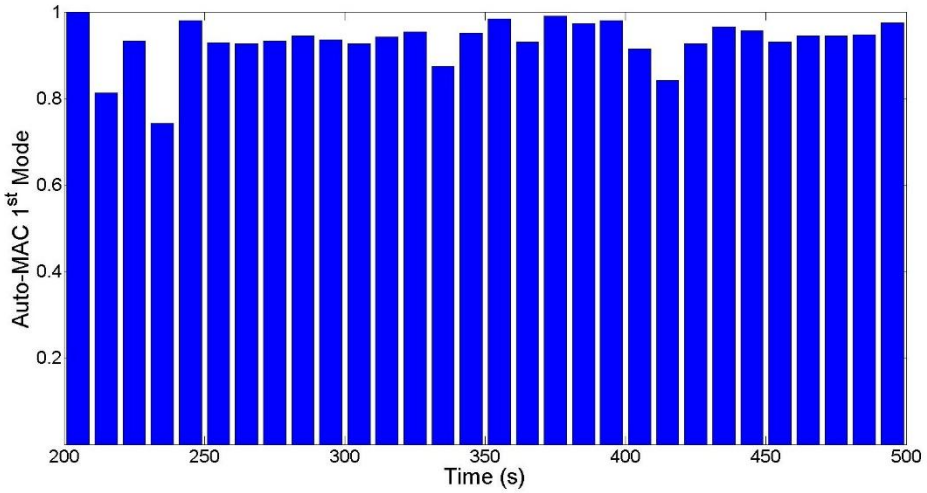
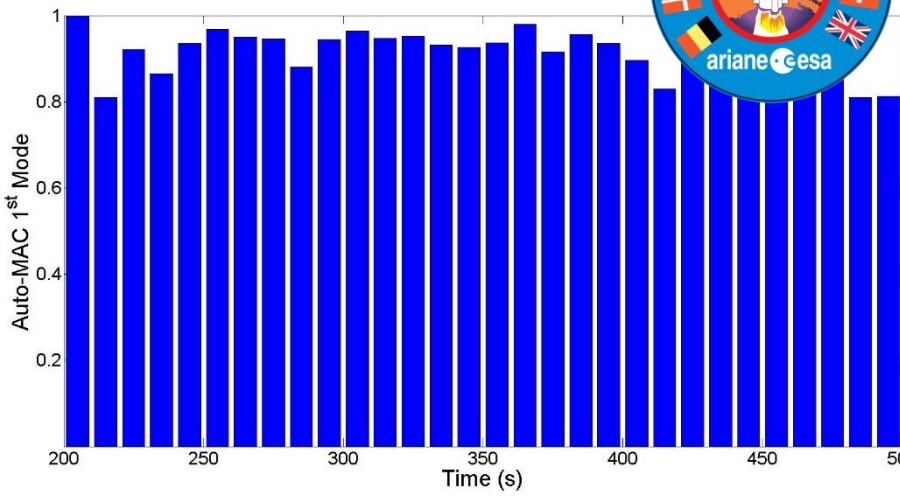
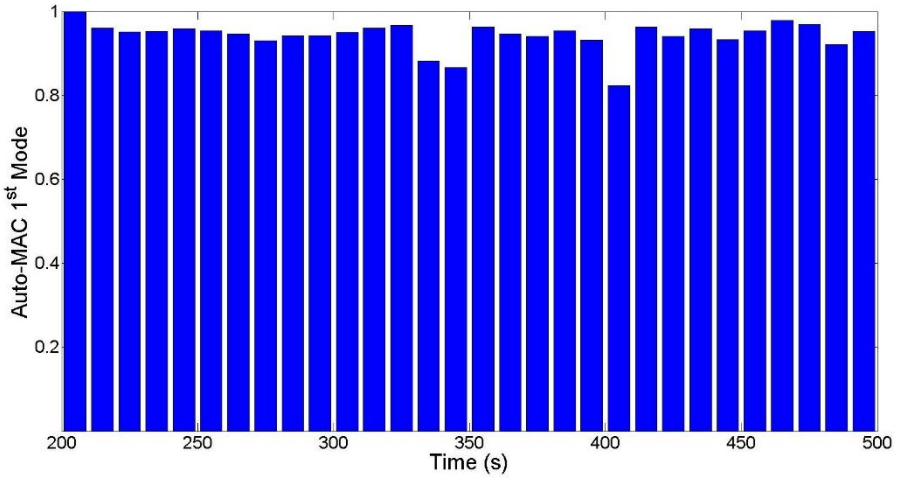
# 3. OMA on ARIANE Launch Vehicle

## Tracking of the 1st mode shape using HTM




- The modes are compared with their estimation in the first time-interval
- **1st Mode shape tracking is consistent among the three flights**



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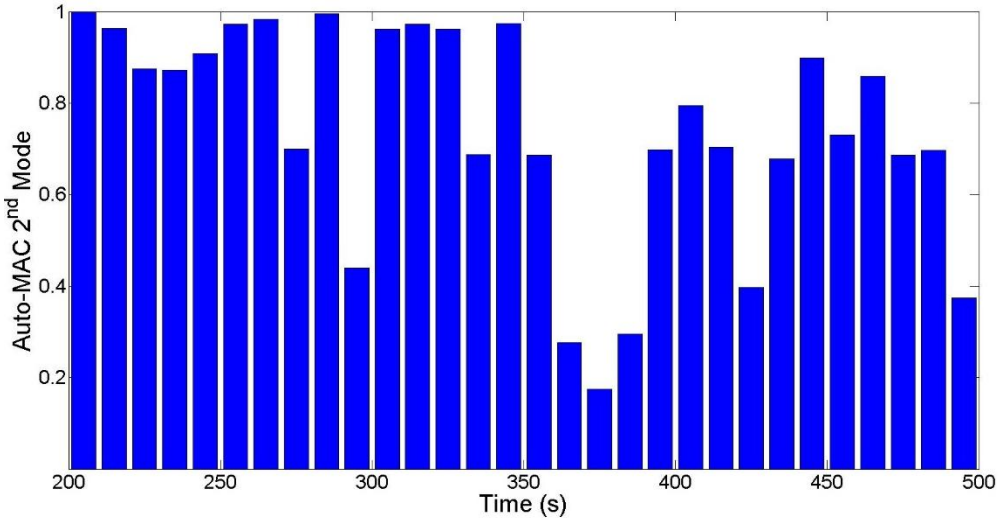
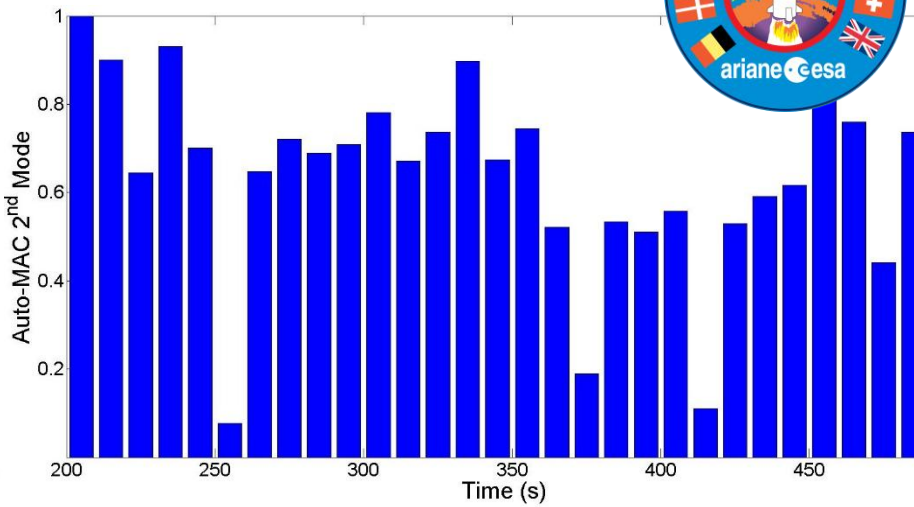
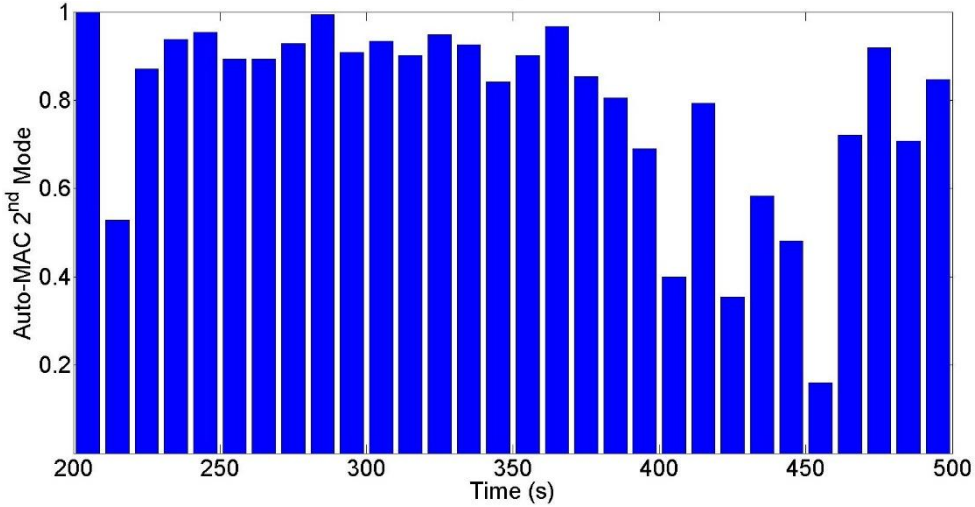
# 3. OMA on ARIANE Launch Vehicle

## Tracking of the 2nd mode shape using HTM




- The modes are compared with their estimation in the first time-interval
- **2nd Mode shape tracking is more difficult** with respect the first **even if the trend are consistent among the different flights**



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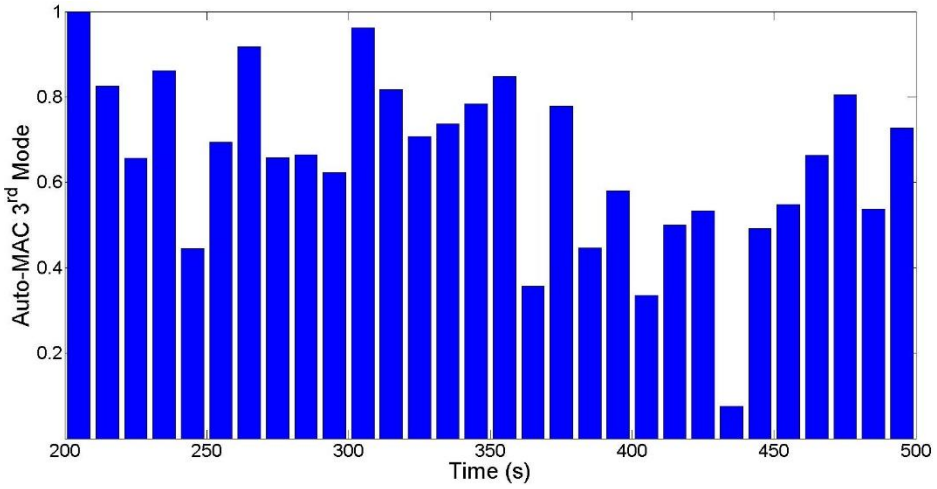
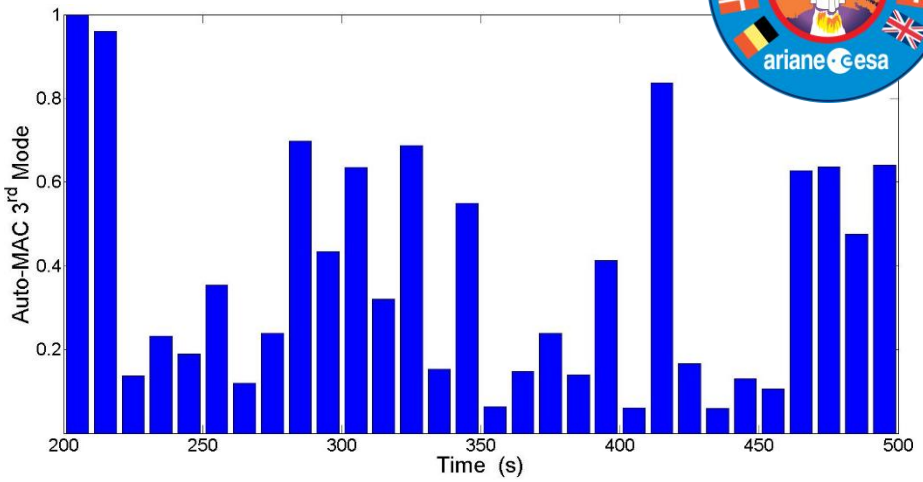
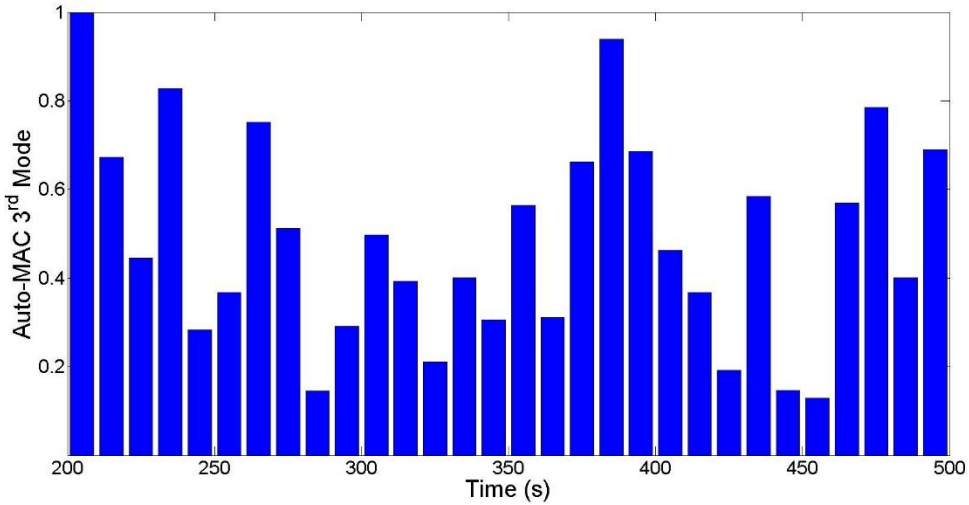
# 3. OMA on ARIANE Launch Vehicle

## Tracking of the 3rd mode shape using HTM




- The modes are compared with their estimation in the first time-interval
- **3rd Mode shape tracking is the most difficult**
- **The dispersion of the estimates suggest a lack of samples for this method**



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# Agenda

1. Motivations
2. Theoretical Background on OMA approaches
3. OMA on ARIANE Launch Vehicle
4. OMA on VEGA P80 Motor
5. OMA on REXUS36 Sounding Rocket
6. Concluding Remarks



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# 4. OMA on VEGA LV's P80 Motor



Vega is a four-stage vehicle mainly based on solid propulsion, with a high level of integration within the Ariane LV family.


| | |
|---|---|
| Height [m] | 30.152 |
| Maximum diameter [m] | 3.005 |
| Fairing diameter [m] | 2.600 |
| Mass at Lift-off [kg] | 136.811 |
| Reference mission performance [kg] | 1500 |



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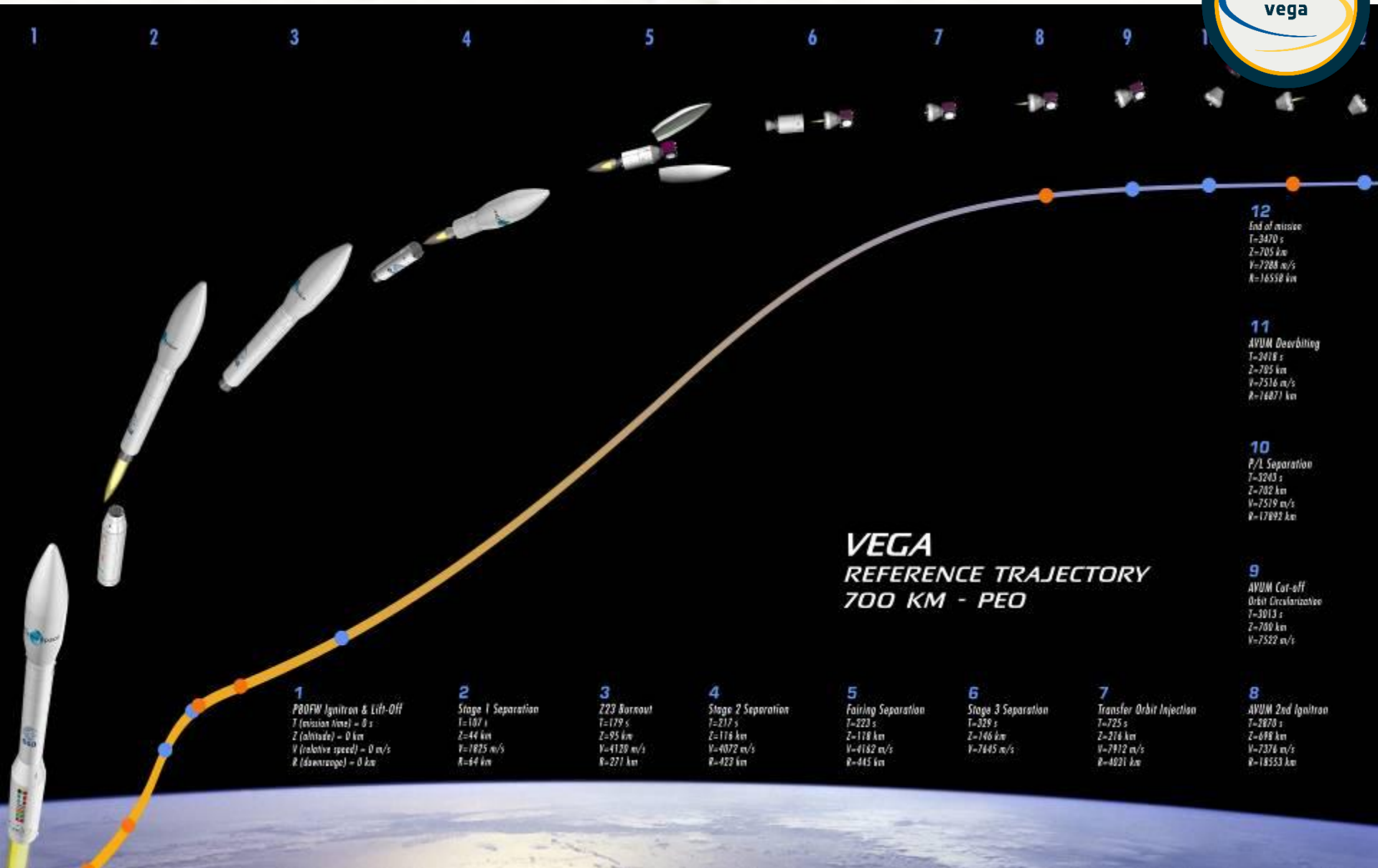
# 4. OMA on VEGA LV's P80 Motor

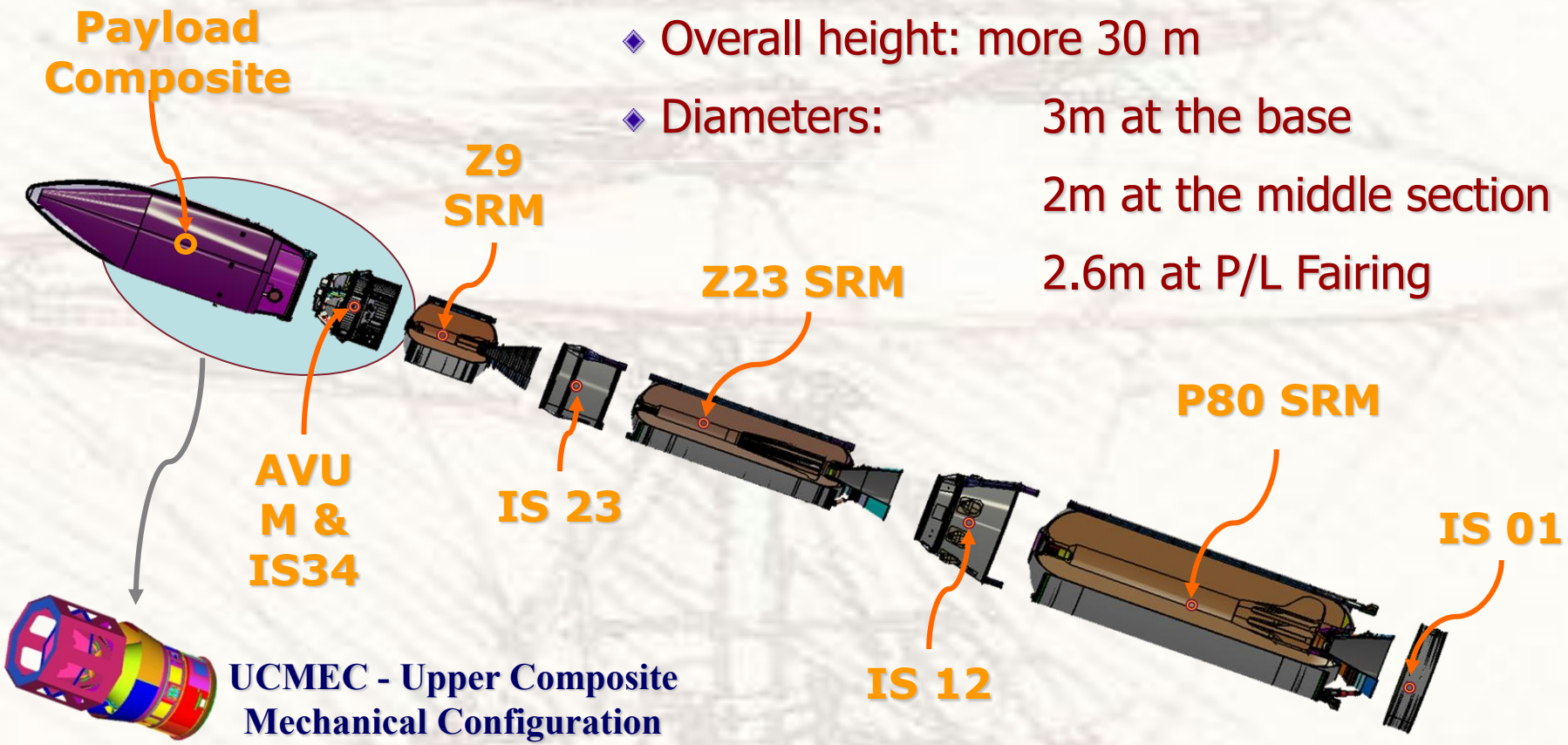




# 4. OMA on VEGA LV's P80 Motor



- Axis symmetric body
  - Weight at launch w/o payload: 137 t
  - Overall height: more 30 m
  - Diameters: 3m at the base
    2m at the middle section
    2.6m at P/L Fairing



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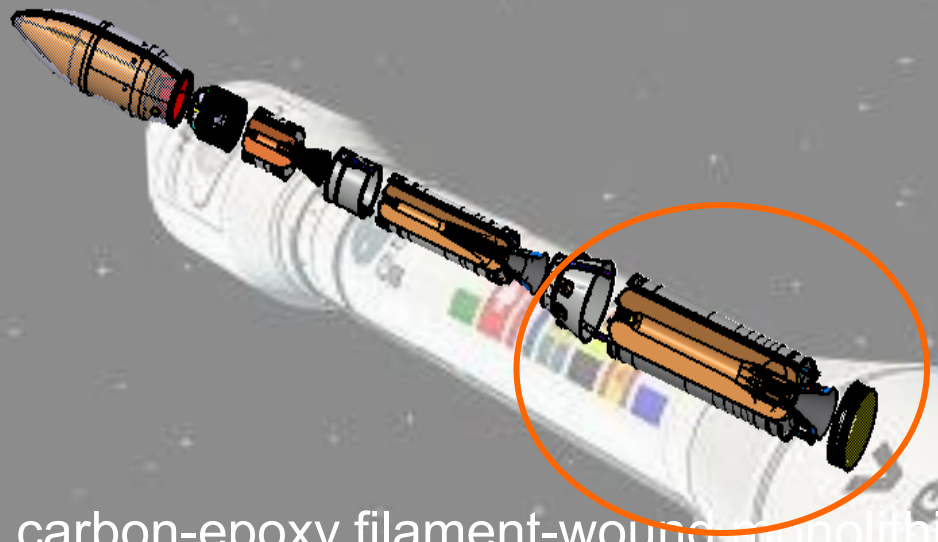
# 4. OMA on VEGA LV's P80 Motor





| | |
|---|---|
| Length [m] | 11 |
| Max diameter [m] | 3. |
| Mass at Lift-off [kg] | 97 131 |
| Burn time [s] | 106.8 |
| Total Impulse [KN s] | 242 721 |

carbon-epoxy filament-wound monolithic case

# 4. OMA on VEGA LV's P80 Motor



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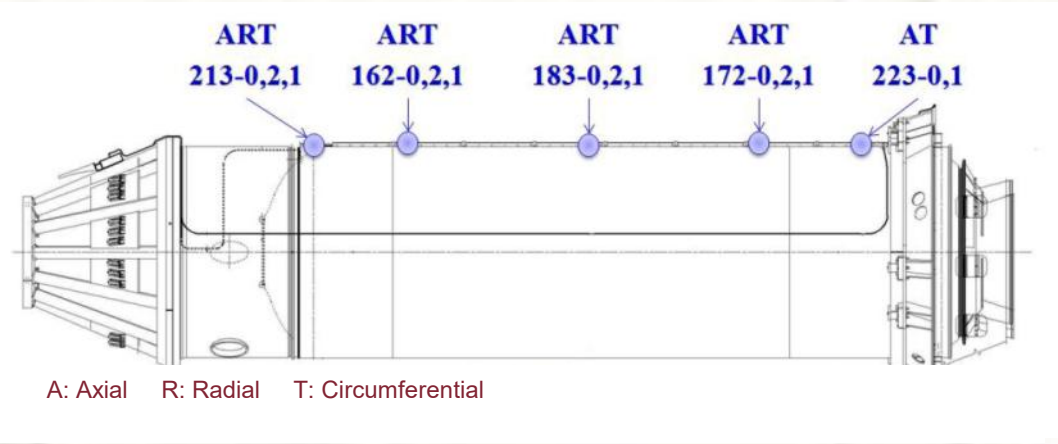
# 4. OMA on VEGA LV's P80 Motor



## Setup




Generatrix G04

| | |
|---|---|
| Sample frequency | 2500 Hz |
| Record time | 144 s |
| Number of samples | 359 870 |

| | |
|---|---|
| Slot | 30 |
| Time | 3.3 s |
| Samples | $2^{13}$=8192 |



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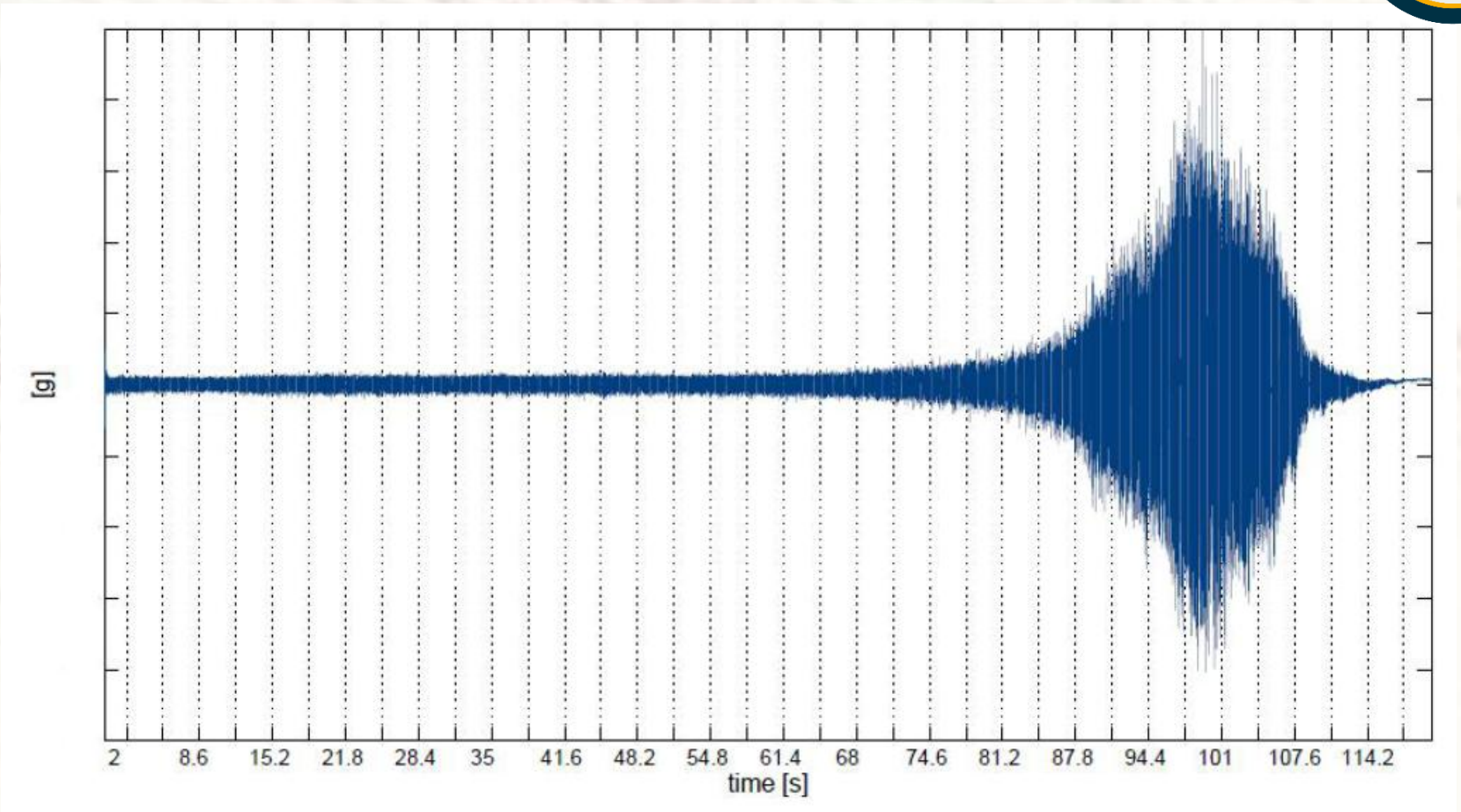
# 4. OMA on VEGA LV's P80 Motor



## Accelerometer time responses



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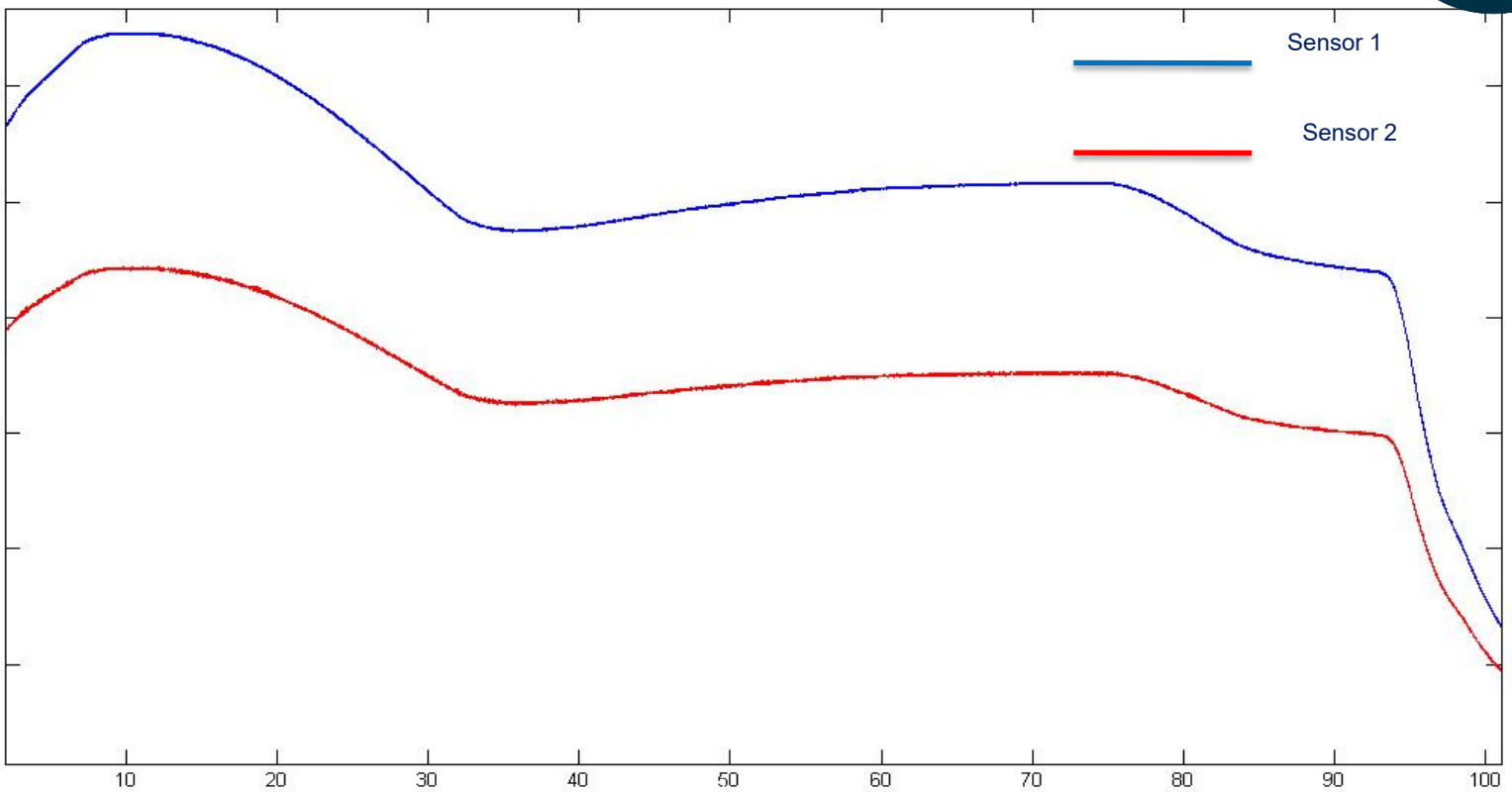
# 4. OMA on VEGA LV's P80 Motor



## Strain gauge time responses



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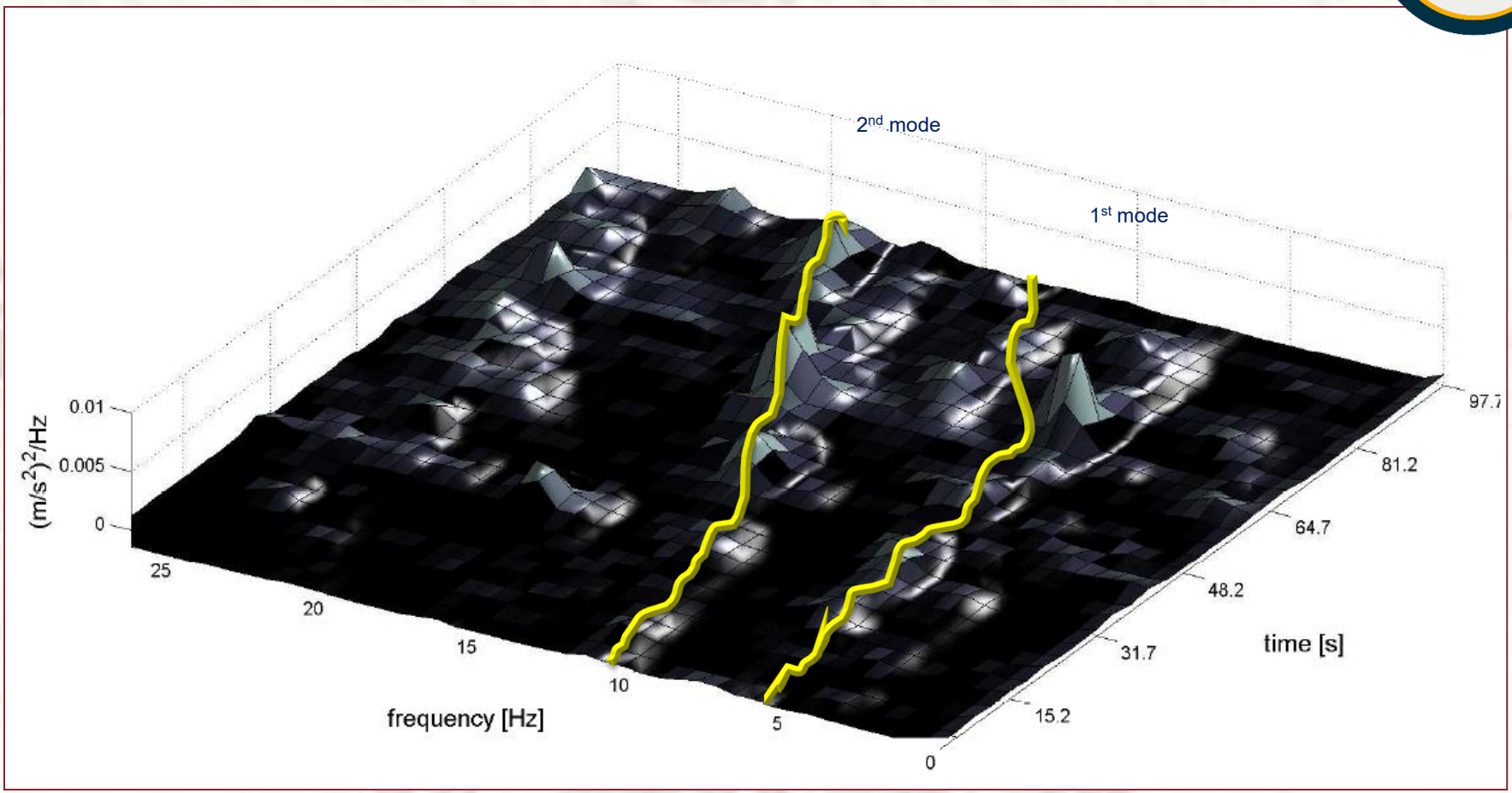
# 4. OMA on VEGA LV's P80 Motor



## Natural Frequency tracking



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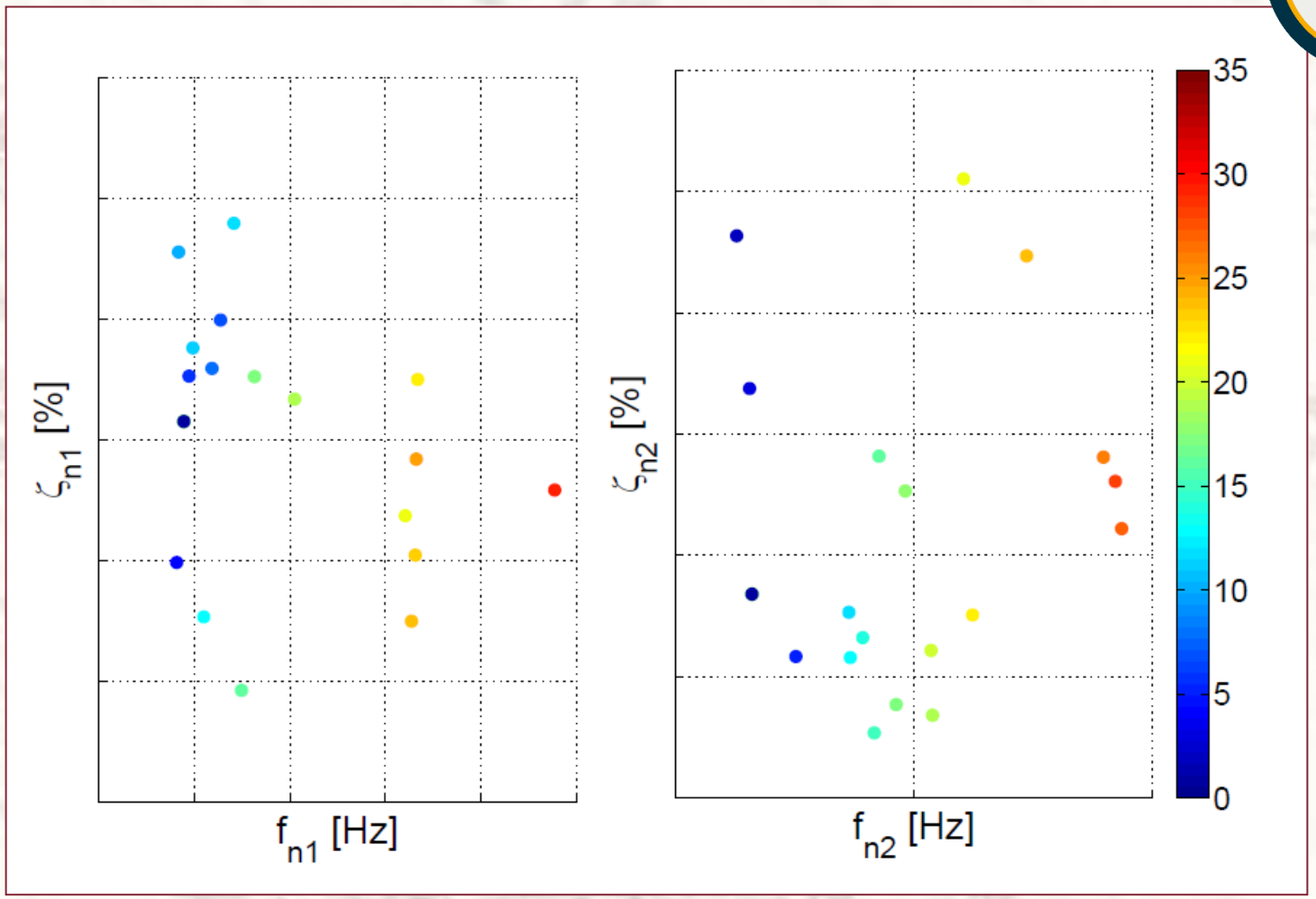
# 4. OMA on VEGA LV's P80 Motor



## Root locus



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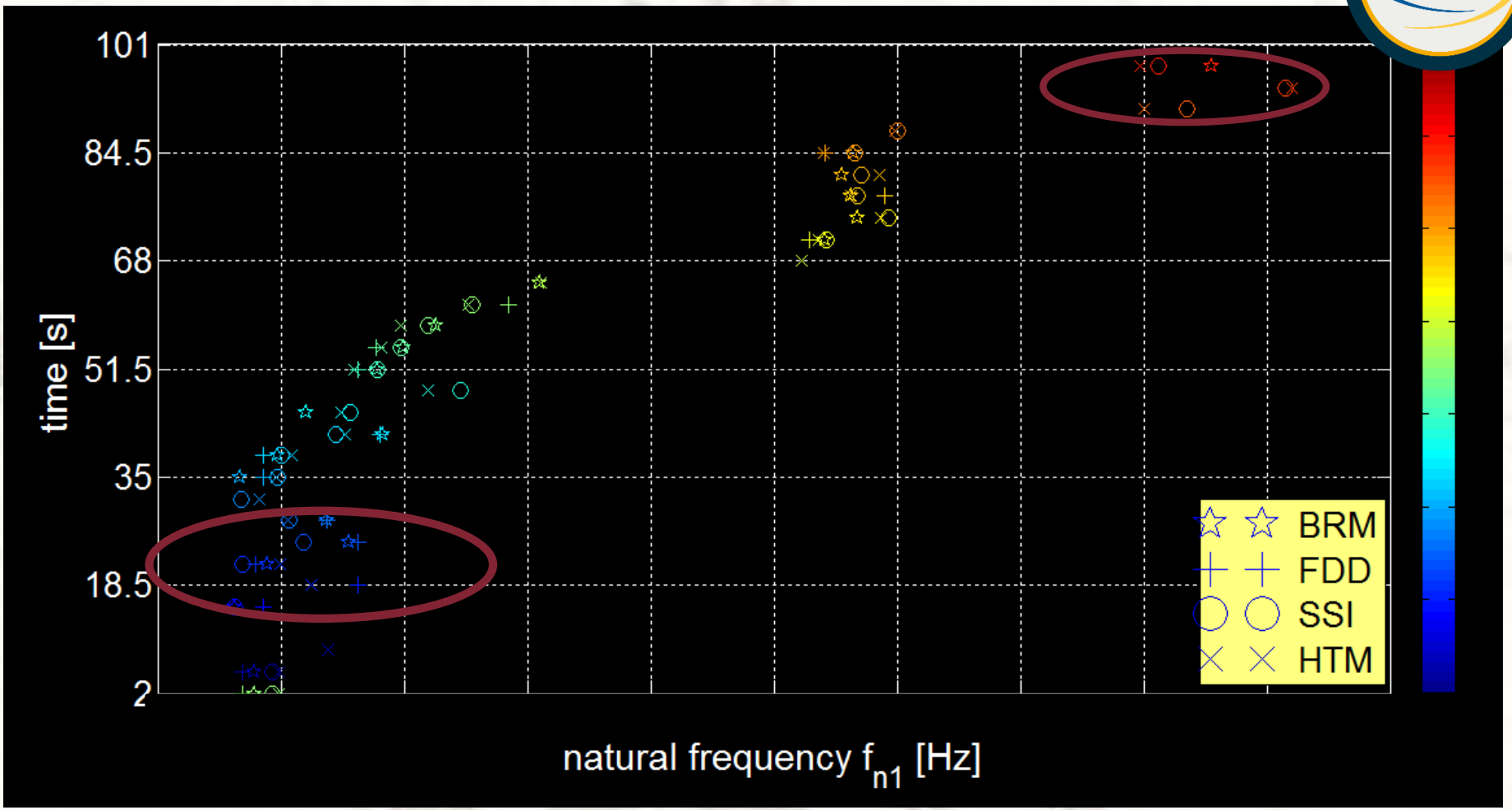
# 4. OMA on VEGA LV's P80 Motor



Natural frequency shift of the 1st mode:



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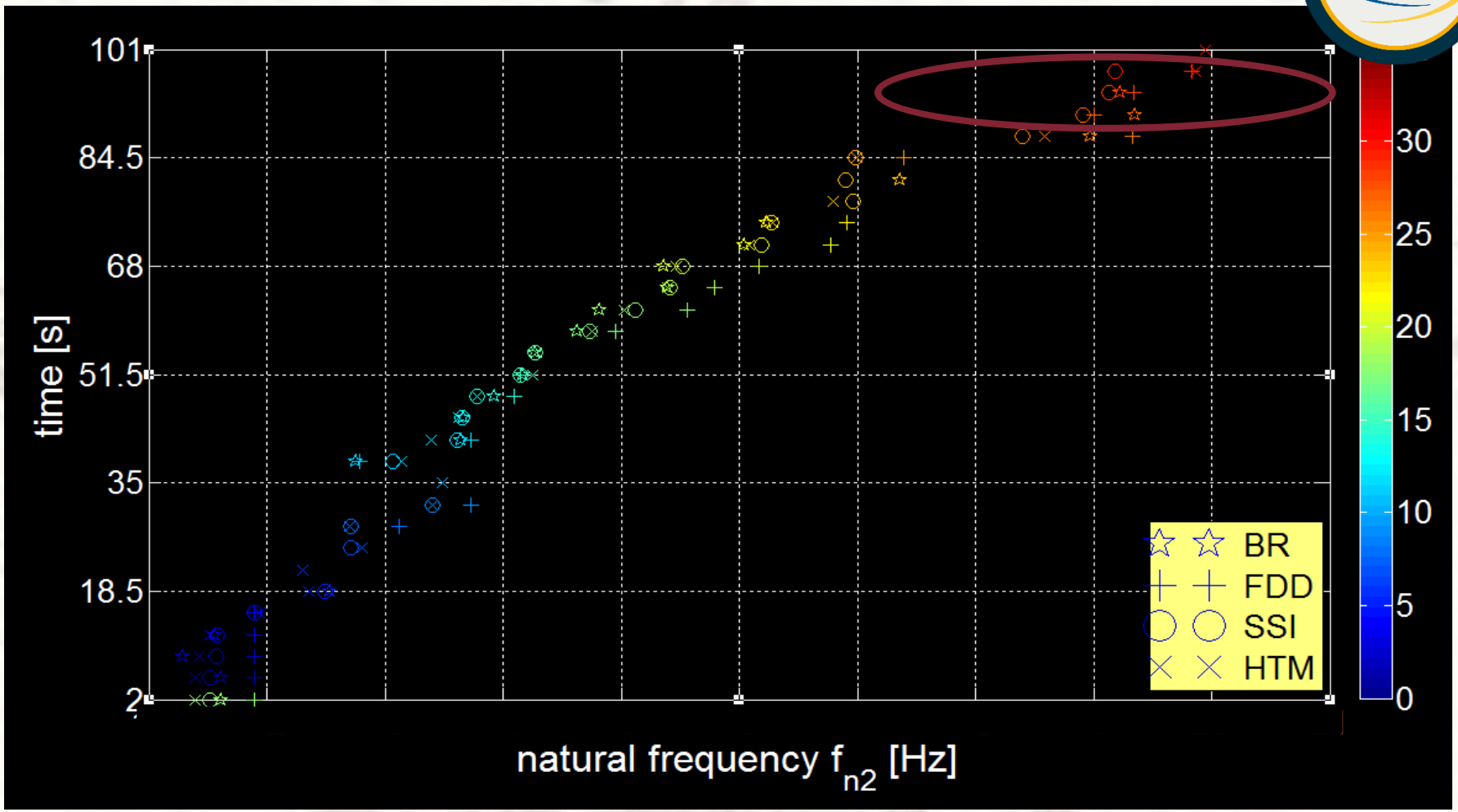
# 4. OMA on VEGA LV's P80 Motor



Natural frequency shift of the 2nd mode:



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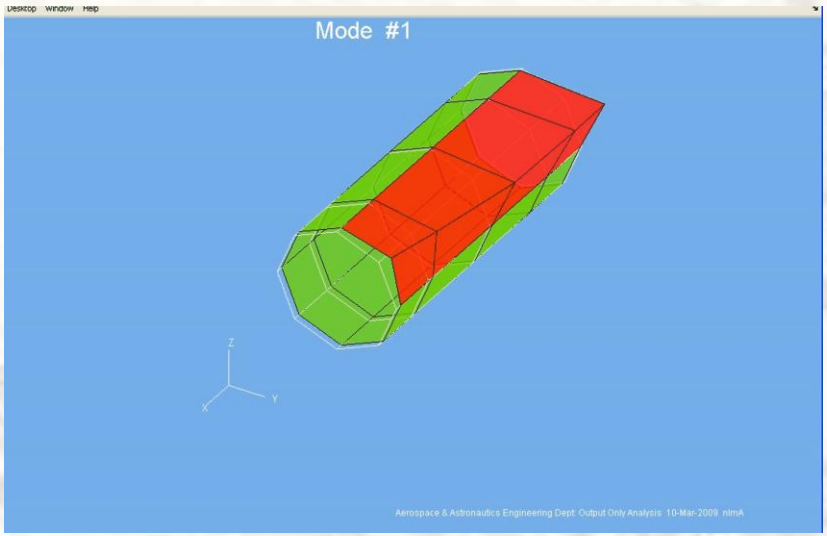
# 4. OMA on VEGA LV's P80 Motor



Lateral Mode




Axial Mode


During the firing test the natural frequencies increase:

- of 138% for the lateral mode
- of 79% for the axial mode



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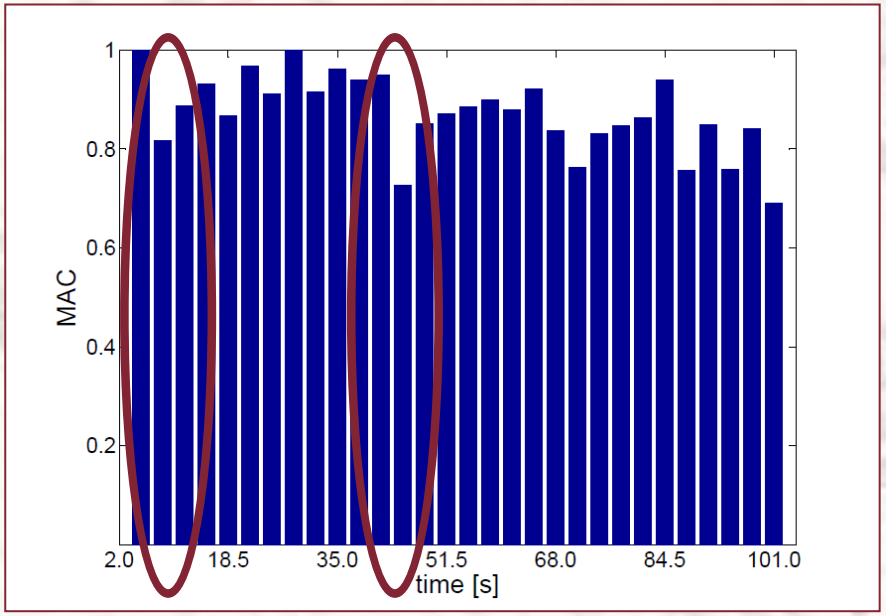
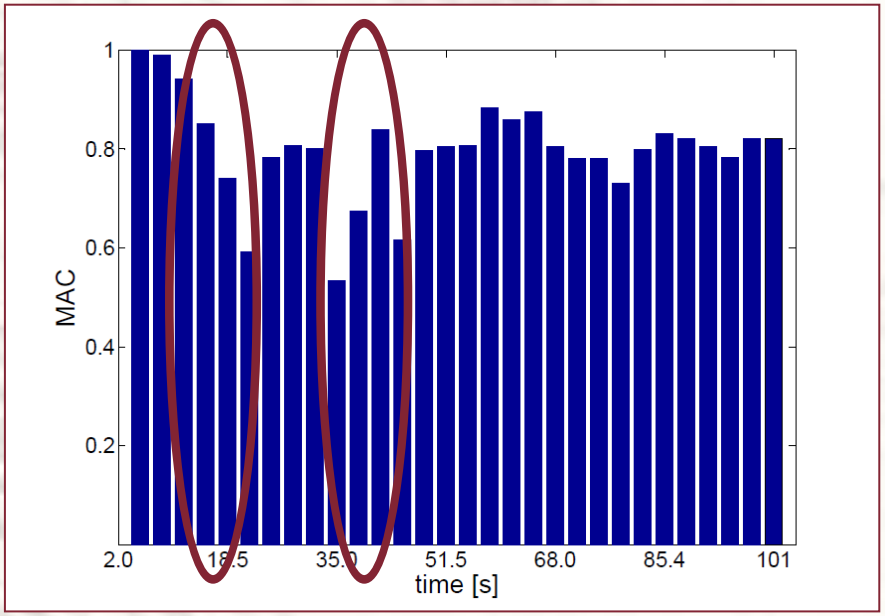
# 4. OMA on VEGA LV's P80 Motor



Mode shape variation:




Lateral Mode



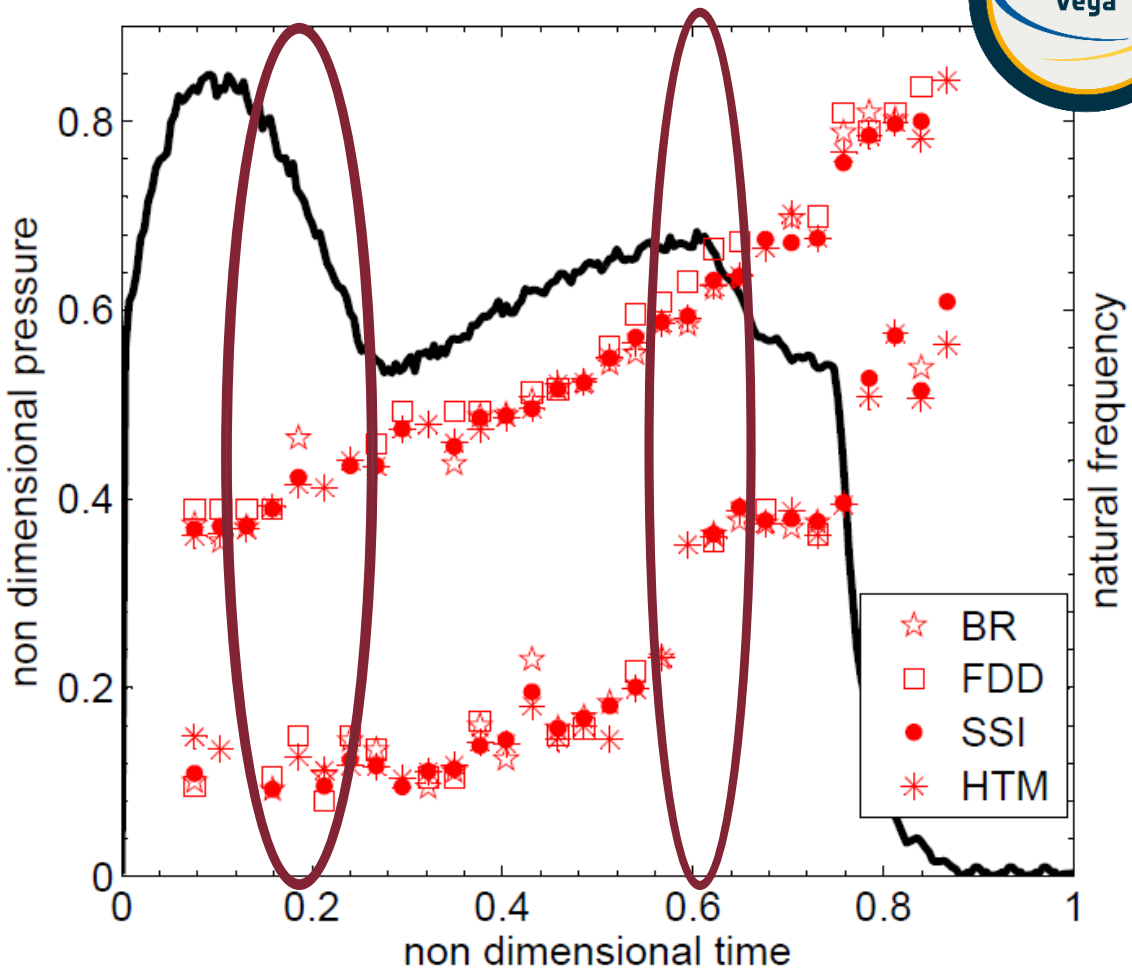

Axial Mode

# 4. OMA on VEGA LV's P80 Motor



Time evolution:

- head-end pressure
- natural frequencies

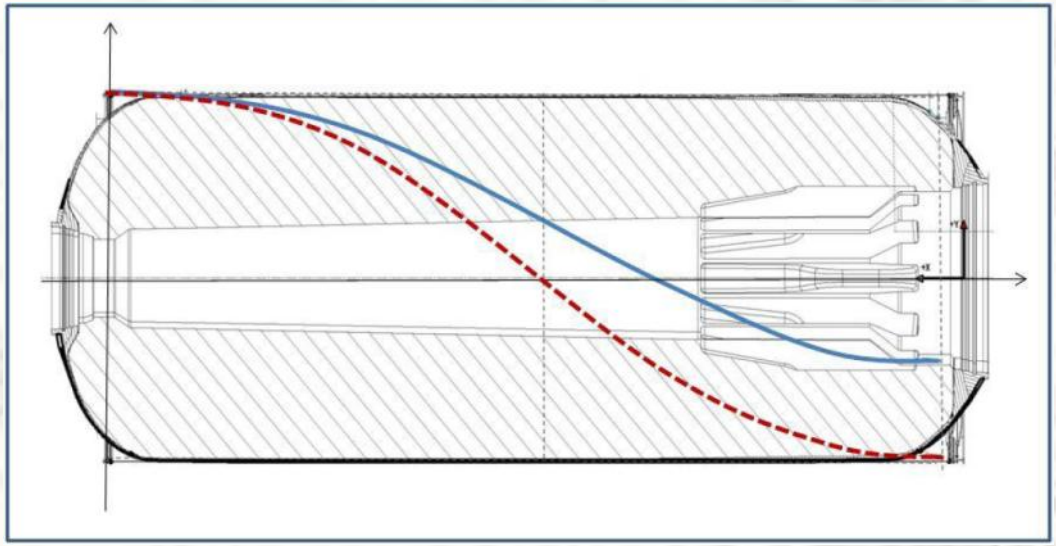


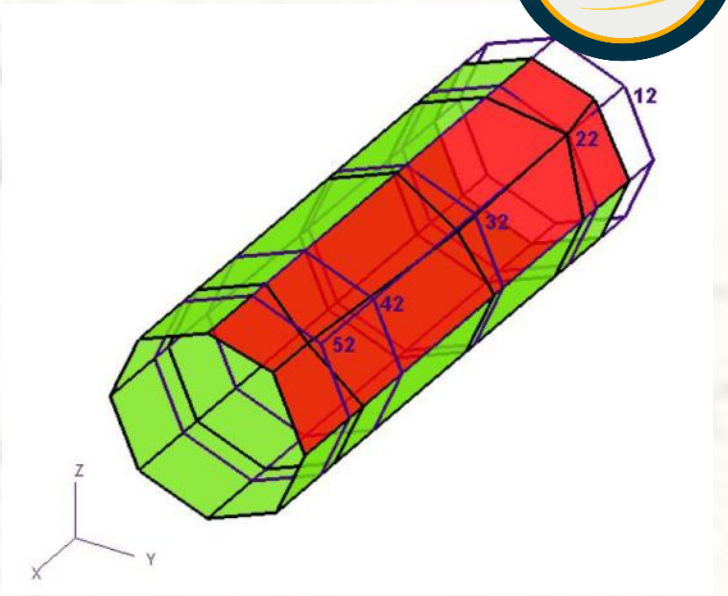

E. Cavallini, B. Favini, M. Di Giacinto, SRM Q1D Unsteady Internal Ballistic Simulation Using 3D Grain Burnback, Space Propulsion, San Sebastian, ES (2010)

# 4. OMA on VEGA LV's P80 Motor



1st Acustic Mode of the combustion chamber → Operational






| Bouffée | B0 | B1 | B2 | B3 |
|---|---|---|---|---|
| frequency $[Hz]$ | $50.30 - 51.50$ | $51.50 - 51.90$ | $53.70 - 55.00$ | $55.10 - 55.90$ |
| damping ratio $[\%]$ | $0.04 - 1.00$ | $0.04 - 0.80$ | $0.03 - 1.30$ | $0.60 - 1.60$ |

F. Mastroddi, G. Coppotelli, G.M. Polli, C. Di Trapani, Vibro-Acoustic Response Analysis to Pressure Oscillations in a Solid Rocket Motor - Comparison with the Experimental Fire-Test Data, Aerotecnica Missili e Spazio, ISSN 0365-7442, (2007)

# Agenda

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# 5. OMA on REXUS36 Sounding Rocket






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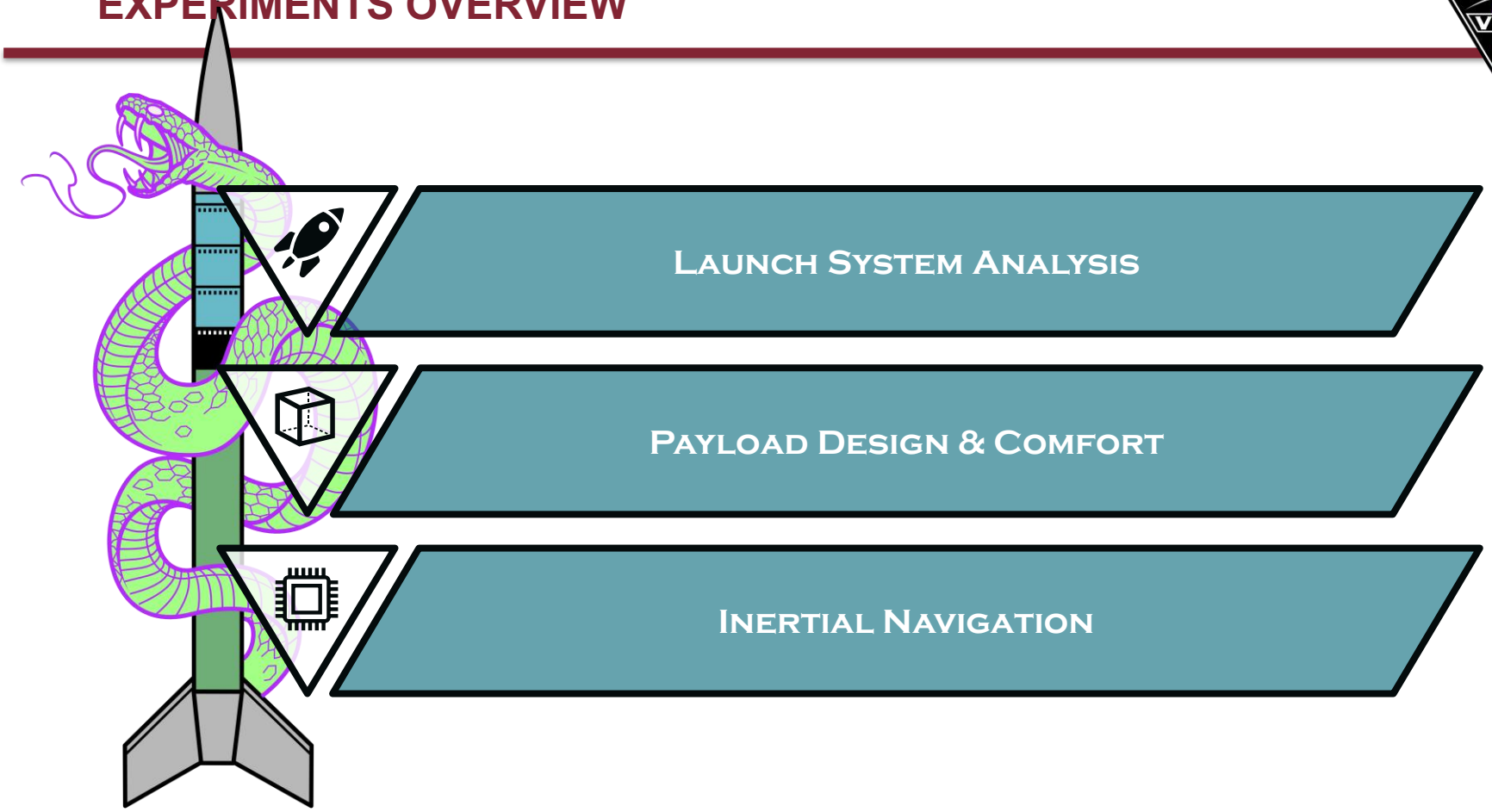
# 5. OMA on REXUS36 Sounding Rocket

## EXPERIMENTS OVERVIEW



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# 5. OMA on REXUS36 Sounding Rocket



## MAIN SPONSORS

SIEMENS

PCB PIEZOTRONICS
AN AMPHENOL COMPANY

RMIT UNIVERSITY

ROMA CAPITALE



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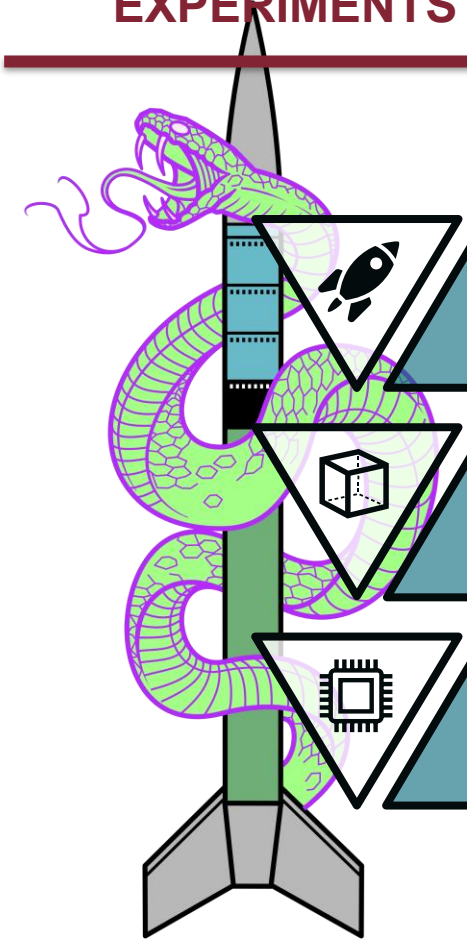
# 5. OMA on REXUS36 Sounding Rocket

## EXPERIMENTS OVERVIEW



To **measure** the **time variation** of the **modal properties** of the *launch vehicle* during the whole flight.

To **assess** how **different materials** and **junctions** impact a *CubeSat's structural response* and *payload insulation* during launch vibrations, while **evaluating** operational performance under **minor controlled damage**.

To **test** and **validate** the **performance** of **real-time Inertial Navigation Systems** for *launch vehicles*, and to study the benefits of multiple distributed sensors and their optimal location along the launch vehicle.



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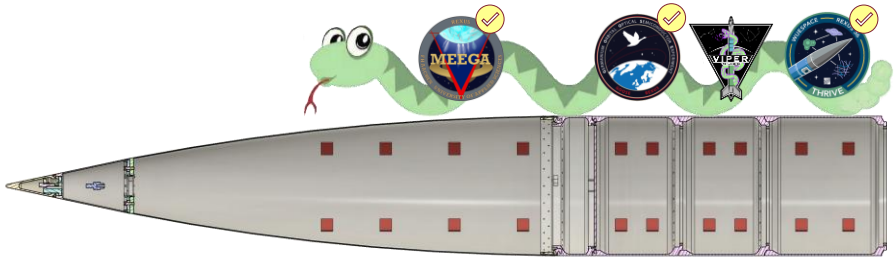
# 5. OMA on REXUS36 Sounding Rocket

## TIME VARIATION OF THE LAUNCHER MODAL PROPERTIES

### EXPERIMENT COMPONENTS



SCADAS XS


X 11 ACCELEROMETERS



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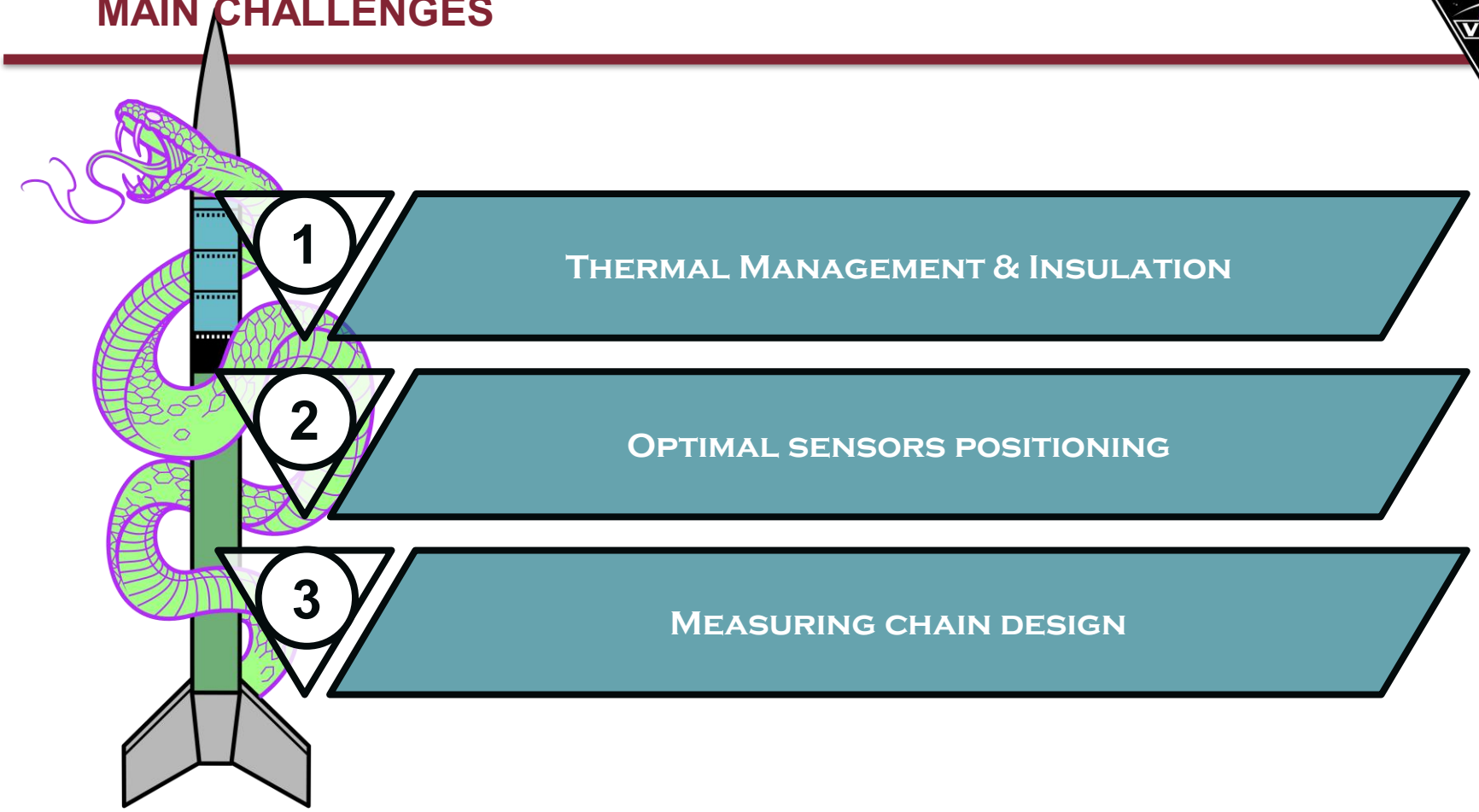
# 5. OMA on REXUS36 Sounding Rocket

## MAIN CHALLENGES



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## THERMAL MANAGEMENT & INSULATION

### ACCELEROMETERS MOUNTING CHALLENGE

Thermal design for the VIPER experiment is mainly focused on the **launcher mounted sensors**, as they will experience the **highest temperature changes** given by the **conductive heat transfer** of the **launcher structure**

| Component | Name | Operating Temp (° C) | | Nosecone Placement |
|---|---|---|---|---|
| | | Min | Max | |
| Rocket Structure Accelerometers | PCB Electronics ICP352C22 | -54 | 121 | Yes |

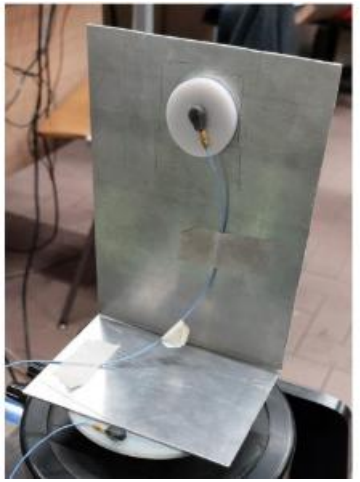
**NOSECONE OUTSIDE TEMPERATURE UP TO 200 C°**

**The temperature outside is higher than the maximum operating temperature of the accelerometers, thus a thermal insulation device Is required.**

**High** external **temperature**

**Exceeds sensor limits**

**Thermal insulation required**





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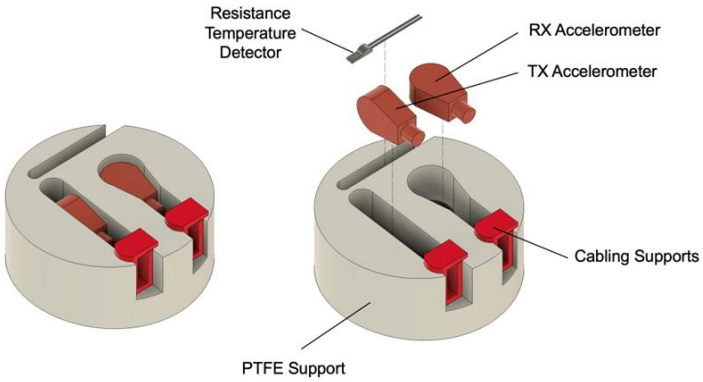
## THERMAL MANAGEMENT & INSULATION

### DESIGN

**To choose the material and thickness of the insulation layer different choices were taken into account. Important features to take into account are:**

| | MATERIAL | |
|---|---|---|
| | PEEK | PTFE |
| DENSITY | 1.3 - 1.32 | 2.1 - 2.2 |
| YOUNG MODULUS | 3.3 - 4.0 | 0.5 |
| GLASS-TRANSITION TEMPERATURE | 143 | 100 |
| THERMAL CONDUCTIVITY | 0.25 | 0.25 |




- **Thermal insulation was bonded to the module inner wall using 3M™ VHB™ F9473PC high-temperature adhesive tape.**
- **Performance was validated through testing with a PTFE support plate, integrating an RTD sensor for temperature monitoring.**
- **A 1D transient thermal analysis was conducted to define the required insulation thickness, ensuring temperatures remain within sensor operating limits.**



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## THERMAL MANAGEMENT & INSULATION

### TESTING

**Thermal and vibro-thermal on the PTFE supports shown their viability as insulation material. On the other hand, the glass-transition temperature was considered too low for the mission, therefore PEEK was chosen.**

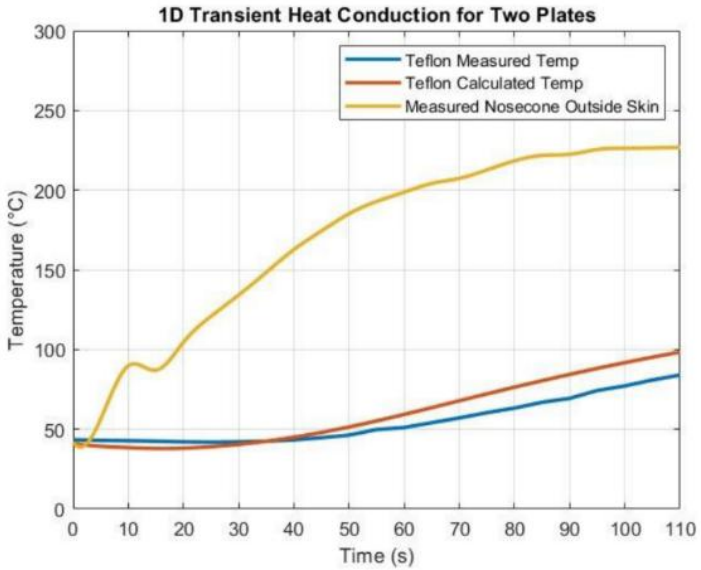



*Figure 10 - Thermo-Vibrational Test Temperature Profile*

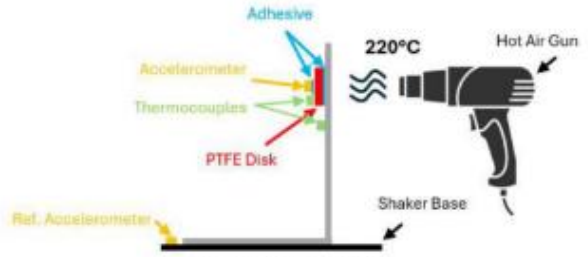
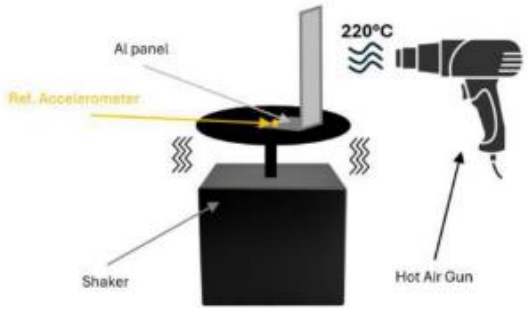



*Figure 5 - Test Configuration 3*



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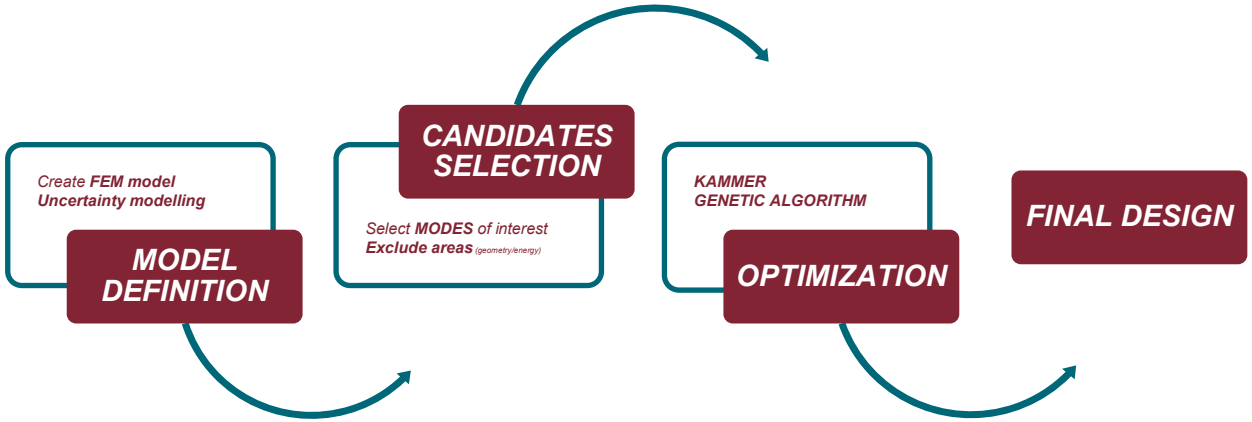
## OPTIMAL SENSOR POSITIONING

### OBJECTIVES

- ✓ **Maximize information** content
- ✓ Achieve **robust** and **reliable** sensor **placement**
- ✓ **Mitigate noise** and modeling **uncertainties**




***KAMMER:*** *quicker, low computational cost, easy to implement, limited flexibility in handling complex geometrical constraints*
***GENETIC ALGORITHM:*** *strong constraint-handling capabilities, global search, suitable for complex layouts*

# 5. OMA on REXUS36 Sounding Rocket

## OPTIMAL SENSOR POSITIONING

**DATA PRE-PROCESSING:** *Nodes to be excluded*

**Reduce** the **initial population** of candidate sensor locations → **GPKE** to **discard points close** to **modal nodes**

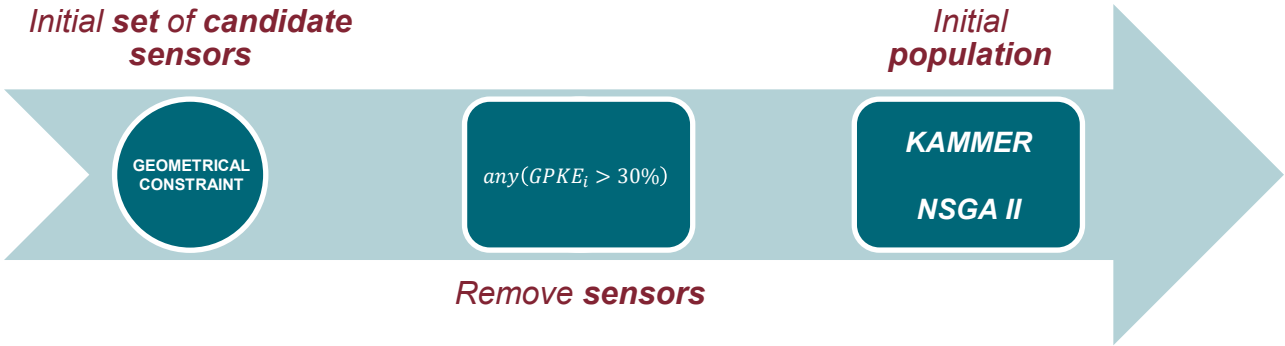
**LOW SIGNAL-TO-NOISE RATIO**

### G.P.K.E. *(Grid Point Kinetic Energy)*

$$GPKE = \Phi_{pq} \sum_{s=1}^{N} M_{ps} \Phi_{sq}$$

→ *kinetic energy of a given mode shape associated with a specific degree of freedom*

*momentum associated with a given modal shape*



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## OPTIMAL SENSOR POSITIONING

**KAMMER METHOD:** *Mathematical Foundation* ❶

**Assumption (HP)**: **Normal modes linearly independent**

At least ***m*** **independent measurements points** required to identify ***m*** **modes**

$$\underline{u_s} = \underline{\underline{\Phi}}\,\underline{q}$$

$\underline{u_s}$ : ***measured*** *structural* ***displacements***

$\underline{\underline{\Phi}}$ : ***mode shapes*** *evaluated* ***at sensor locations***

$\underline{\hat{q}}$ : ***modal coordinates*** *to estimate*

$$\underbrace{\begin{bmatrix} \Phi_{11} & \cdots & \Phi_{1m} \\ \vdots & \ddots & \vdots \\ \Phi_{n1} & \cdots & \Phi_{nm} \end{bmatrix}}_{\textbf{\textit{M modes}}} \Bigg\} \textbf{\textit{N nodes}}$$

*Is it* **BEST APPROACH** *even with measurement* **NOISE***?*

It is possible to invert the relationship, but **the matrix $\underline{\underline{\Phi}}$ can be non square**.. *Least Square Estimator*

$$\underline{\hat{q}} = \underbrace{\left[\underline{\underline{\Phi}}^T\underline{\underline{\Phi}}\right]^{-1}\underline{\underline{\Phi}}^T}\,\underline{u_s}$$

**PSEUDO-INVERSE**

**Why the pseudo-inverse?**

Sensor placement gives $\underline{\underline{\Phi}} \in \mathbb{R}^{N\,x\,M}$, which is generally **rectangular**



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## OPTIMAL SENSOR POSITIONING

**KAMMER METHOD:** *Mathematical Foundation* ❷

Let us now **consider** the **structural (linear) case**:

$$\underline{u_s} = \underline{\underline{\Phi}}\,\underline{q} + \underline{N} = \underline{H(q)} + \underline{N}$$

$\underline{N}$ → **NOISE**

$\underline{H(q)}$ → **MEASUREMENT PROCESS**

In the **linear structural case**, the **measurement operator** is $\underline{H(q)} = \underline{\underline{\Phi}}\,\underline{q}$, so $\underline{\underline{J}} = \underline{\underline{\Phi}}$.

$\underline{\underline{J}}$ → **JACOBIAN**

For an **efficient** (*minimum-variance unbiased*) **estimator**, the **error covariance** is:

$$\underline{\underline{P}} = E\left[\left(\underline{q} - \underline{\hat{q}}\right)\left(\underline{q} - \underline{\hat{q}}\right)^T\right] = \left[\underline{\underline{J}}^T \underline{\underline{\Sigma}}\,\underline{\underline{J}}\right]^{-1} = \left[\underline{\underline{\Phi}}^T \left(\psi_0{}^2\right)^{-1} \underline{\underline{\Phi}}\right]^{-1} = \frac{1}{F.I.}$$

$\underline{\underline{P}}$ → *It is related to the **FISHER INFORMATION MATRIX***

$\underline{\underline{\Sigma}}$ → **Noise spectral density**

$\frac{1}{F.I.}$ → **Amount** of **information carried** by the **data**

**Goal**: **to minimize/maximize** the **variance** of the **estimator**/ the **Fisher Information Matrix**



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## OPTIMAL SENSOR POSITIONING

**KAMMER METHOD:** *Mathematical Foundation* ❸

$$\underline{\underline{P}} = F.I.^{-1}$$

To optimize sensor placement, a **scalar measure** of the **Fisher Information Matrix** is required

A common choice is the **determinant**, leading to the following procedure:

1. Compute the **eigenvectors** of $\underline{\underline{\Phi}}^T \underline{\underline{\Phi}}$ which coincide with $\underline{\underline{\Phi}}$ (*orthogonal modes for* $H_p$).

2. The **matrix** $\underline{\underline{\Phi}} \left[\underline{\underline{\Phi}}^T \underline{\underline{\Phi}}\right]^{-1} \underline{\underline{\Phi}}^T$ **quantifies** the **contribution** of each sensor location to the matrix **rank**

   ( $\underline{\underline{\Phi}}[F.I.]^{-1}\underline{\underline{\Phi}}^T$ *Projection)*

3. Iteratively **remove** the **sensor locations contributing** the **least** to the **Fisher Information**, yielding the optimal sensor configuration for a given number of sensors $N$.


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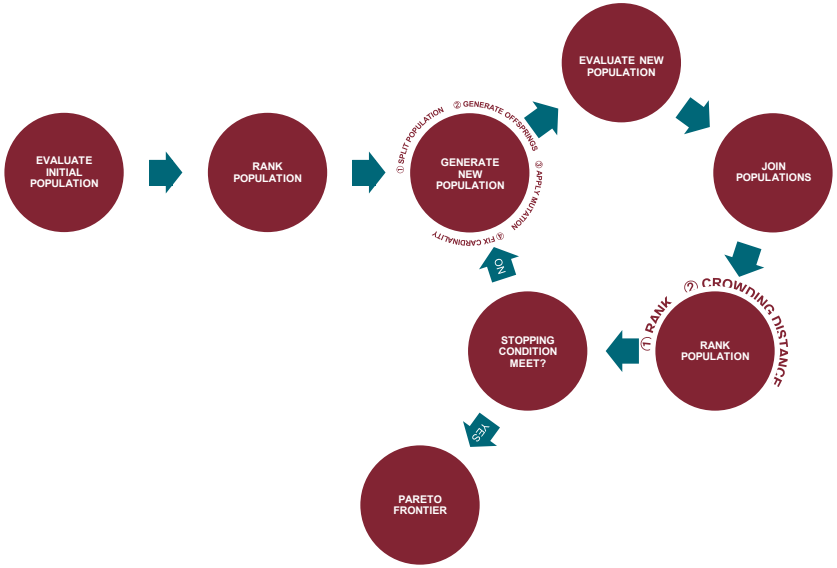
## OPTIMAL SENSOR POSITIONING

### GENETIC ALGORITHM

To better **explore** the **space** of **possible sensor configurations**
This approach exploits **mutation** and **crossover operators** to efficiently explore the design space




**Sensor configurations** are **encoded using a binary mask**, where **1** denotes an **active sensor** and **0** an **inactive one**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## OPTIMAL SENSOR POSITIONING

RANK POPULATION

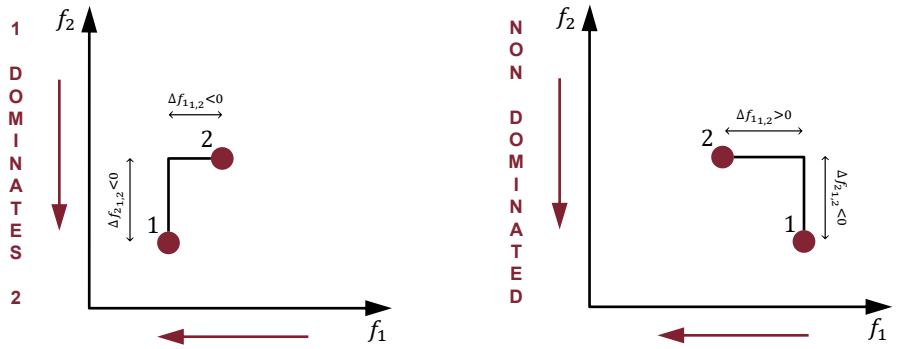
**GENETIC ALGORITHM:** *Ranking and Selection*

**Ranking** is **assigned based** on the concept of **dominance**

A **solution** is said to **dominate** another if it **performs** at least **as well** in **all objectives** and **strictly better** in **at least one objective**

A solution belongs to the **Pareto front** *(RANK 1)* if it is **not dominated by any other solution** in the design space

**Solutions dominated** by one or more **Pareto-optimal solutions** are assigned **higher ranks**. If a **solution** is **dominated** by **at least one solutions of rank $n$**, it is assigned **rank $n+1$**



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## OPTIMAL SENSOR POSITIONING

**GENETIC ALGORITHM:** *Crossover/Mutation*

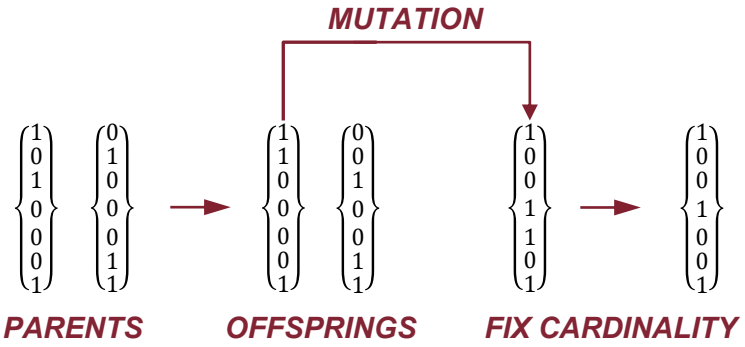
GENERATE NEW POPULATION

Once the **population** is **ranked**, it is randomly **split into two groups**

Each individual in **one group is paired with** an individual from **the other** group
The **paired individuals** are **combined to generate** two **offspring** with different genetic compositions (**crossover**)

**Mutation is** then **applied** to the offspring *(randomly **change** a/more gene/**genes**)*

To ensure that the **number of active sensors** remains **fixed**, **any excess sensors** are randomly **removed** (**fixed cardinality** constraint).




**N° SENSORS = 3**



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## OPTIMAL SENSOR POSITIONING

**GENETIC ALGORITHM:** *Joining Populations and Ranking*

GENERATE NEW POPULATION

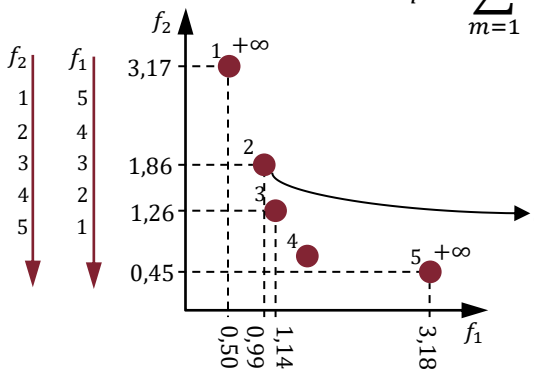
The **two populations** are **joined** and **ranked based on rank** and **crowding distance**

The **crowding distance** ensures **diversity among solutions** along the front and is **used** to **rank individuals within the same rank**.

**Boundary solutions** of each rank are assigned an **infinite crowding distance**.

The **remaining solutions** are **ranked** according to the **crowding distance**, **computed** after **sorting** the **solutions with respect to each objective**:

$$CD_p = \sum_{m=1}^{M} \frac{f_m(p_m^+) - f_m(p_m^-)}{f_m^{MAX} - f_m^{MIN}}$$




$$CD_2 = \frac{3{,}17 - 1{,}26}{3{,}17 - 0{,}45} + \frac{1{,}14 - 0{,}50}{3{,}18 - 0{,}50} = 0{,}94$$

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## OPTIMAL SENSOR POSITIONING

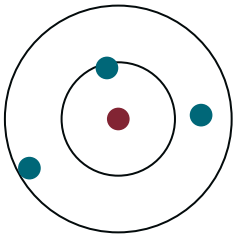
OBJECTIVE FUNCTIONS

### GENETIC ALGORITHM: *Objective Functions* ❶

① **MAC** *(Modal Assurance Criterion)* $\xrightarrow{\text{IDEAL}} \underline{I}$

$$MAC = \frac{\left|\underline{\varphi_i}^T \underline{\varphi_j}\right|^2}{\left(\underline{\varphi_i}^T \underline{\varphi_i}\right)\left(\underline{\varphi_j}^T \underline{\varphi_j}\right)} \Longrightarrow f_1 = \sqrt{\frac{1}{m(m-1)} \sum_{i=1}^{M} \sum_{j=1}^{M} MAC_{ij}^2 \; (i \neq j)}$$

② **ROBUSTNESS***



**SENSOR LOCATION**

**MIS-PLACED SENSOR LOCATION** → $\Delta MAC$

*50 analysis* → $f_2 = \max \Delta f_1$

***FEM uncertainties**: 5 analysis conducted for each of the 10 different models



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## OPTIMAL SENSOR POSITIONING

OBJECTIVE FUNCTIONS

### GENETIC ALGORITHM: *Objective Functions* ❷

*Objective function*: **MAC** for mass-varying systems

*fuel consumption*

11 mass models considered
$(\Delta m = 29\ kg\ of\ propellant) \rightarrow radial\ burning$

**MAC** *evaluated for* ***each model***

*The* **MAC** *is* ***integrated over time*** *using the* ***trapezoidal rule***

**MINIMIZE**

$$\sum_{i=1}^{11} \frac{\left(f_1^i + f_1^{i+1}\right)}{2} \Delta t$$

$\Delta t$ *time span defined by fuel consumption*

**Fuel consumption** *defines the* ***duration*** *of* ***each mass*** *configuration*



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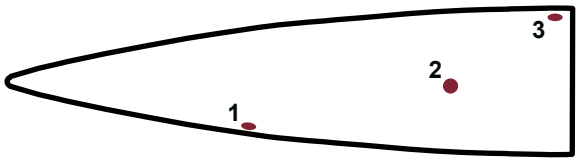
## OPTIMAL SENSOR POSITIONING

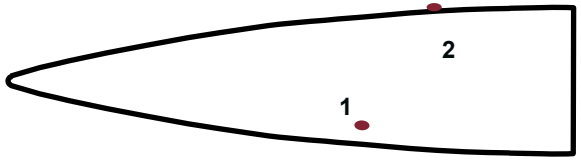
**GENETIC ALGORITHM:** *Constraint Functions*

CONCTRAINT FUNCTIONS

① **MAXIMUM 2 measument point inside the nosecone** *(limited number of pins)*

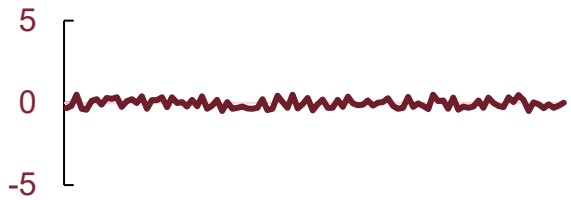



***NOT FEASIBLE***

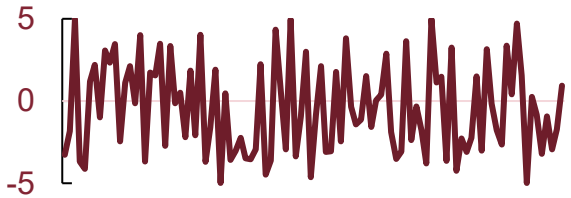



***FEASIBLE***

② **NO LOW ENERGY POINTS*** *+ at least 4 high−energy measurement points for each mode*




***AVOID***




***PREFER***

***FEM uncertainties**: 5 analysis conducted for each of the 10 different models



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# 5. OMA on REXUS36 Sounding Rocket

## OPTIMAL SENSOR POSITIONING

### REXUS ROCKET

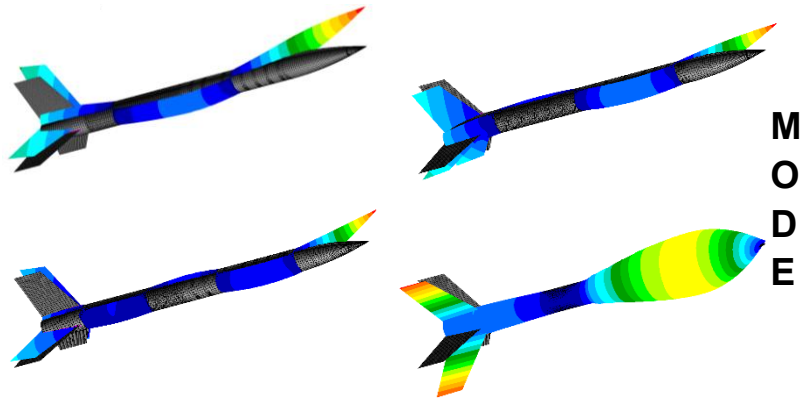
The ***REXUS*** **rocket** is a **small sounding rocket**, approximately 6 meters long


**FEM model** → generated on the information provided in:

- **REXUS/BEXUS User Manual**
- **assumptions** (**previous launch campaigns**)
- typical **reference values**

**FE model** → **compute** the **structural mode shapes** *(S.P.O.)*

**ESSENTIAL ACCURATE MODE SHAPES REQUIRED**





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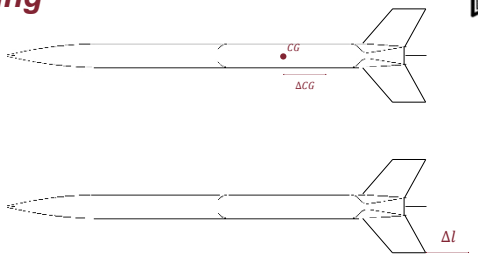
## OPTIMAL SENSOR POSITIONING

DEALING WITH UNCERTAINTIES

**REXUS ROCKET:** ***uncertainties modeling***




① **Motor mass distribution** is **uncertain**
**Internal balancing weight position** is **unknown**

② **Mass** and **center-of-mass locations** of the **Recovery Module**, **Service Module**, and **Motor YoYo Adapter** are **unknown**

Previous launch campaigns → $\mu$ and $\sigma$

③ **Material properties** → $YOUNG\ MODULUS\ (500\ MPa)$
$DENSITY\ \left(0.20\ {}^{g}/_{cm^3}\right)$
$POISSON\ RATIO\ (0.03)$

***11 different randomly evaluated configurations for 11 mass cases (fuel consumption)***



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## OPTIMAL SENSOR POSITIONING

**REXUS ROCKET:** ***sensor position optimization results (KAMMER)***

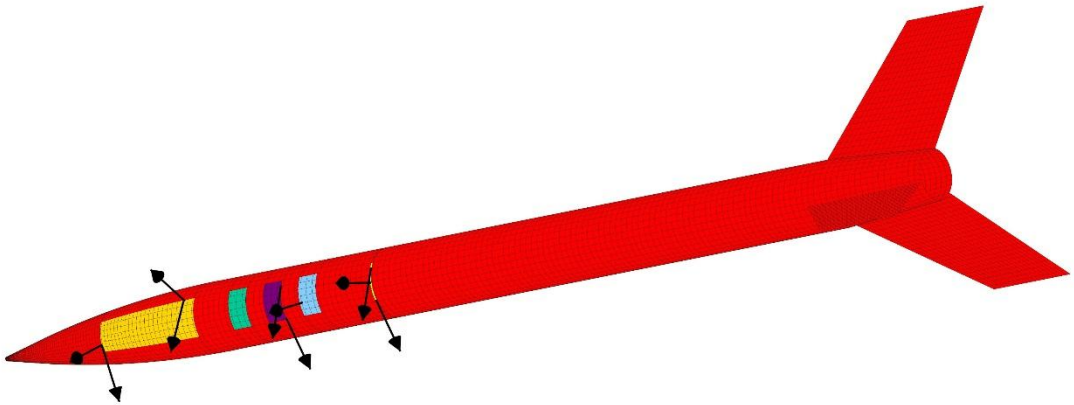
For each mass case, the **optimal sensor configuration** is **identified**

↓

**Optimal configuration** minimizes the **time-integrated offMAC** $(f1)$

**MINIMIZE**

$$\sum_{i=1}^{11} \frac{\left(f_1^i + f_1^{i+1}\right)}{2} \Delta t \longrightarrow f_1 = \sqrt{\frac{1}{m(m-1)} \sum_{i=1}^{M} \sum_{j=1}^{M} MAC_{ij}^2 \, (i \neq j)}$$



***OPTIMAL SENSOR PLACEMENT***



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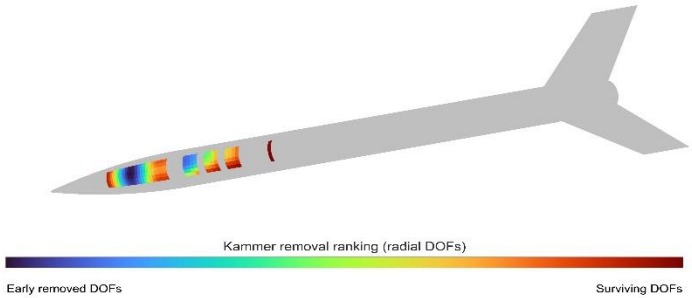
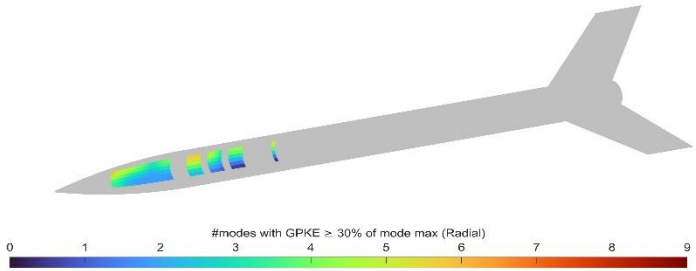
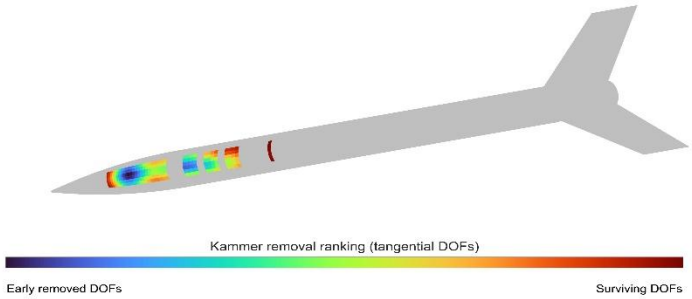
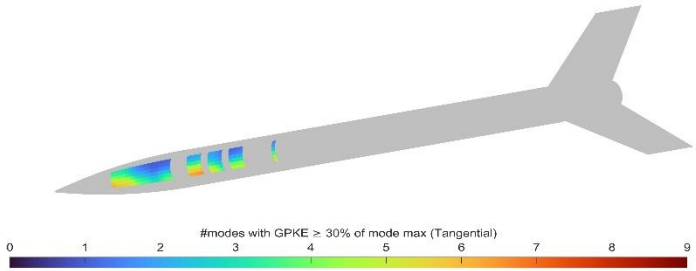
## OPTIMAL SENSOR POSITIONING

**RESULTS: *Kammer***



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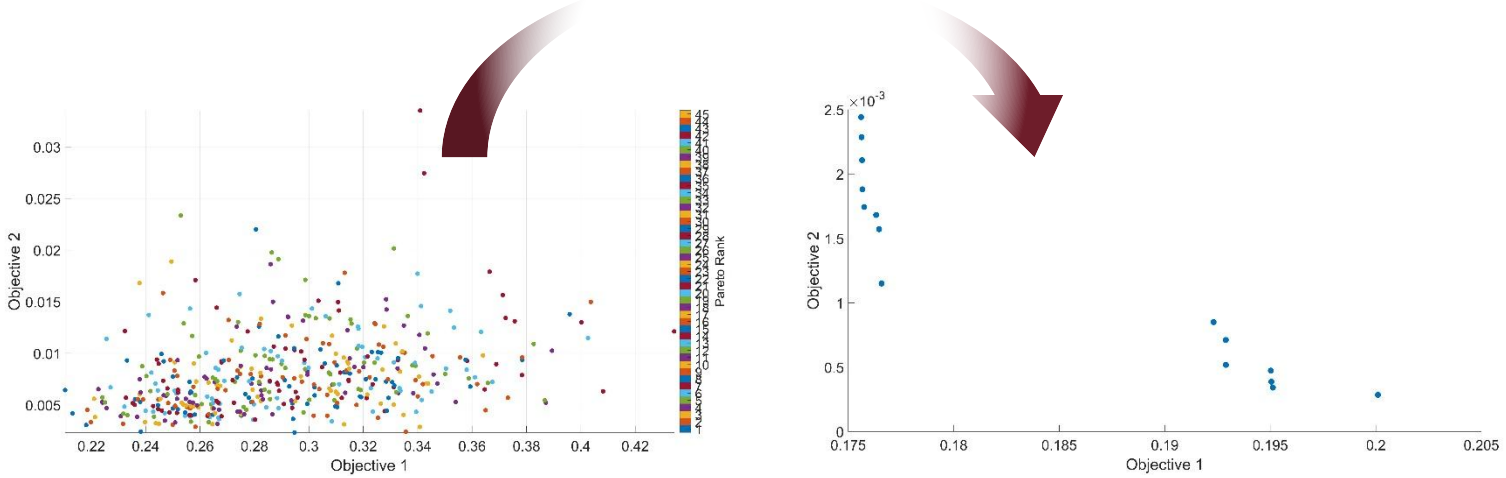
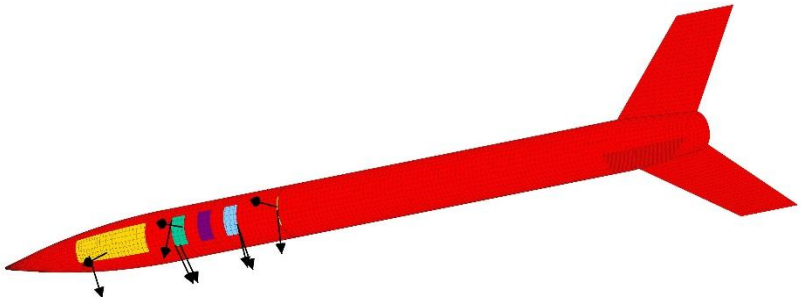
## OPTIMAL SENSOR POSITIONING

### RESULTS: *NSGA II*





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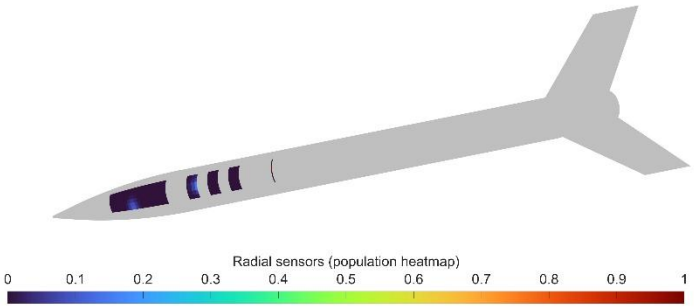
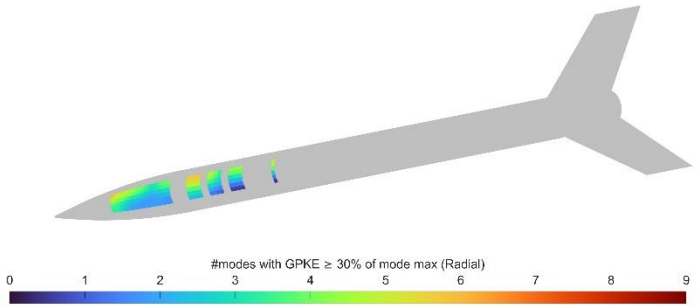
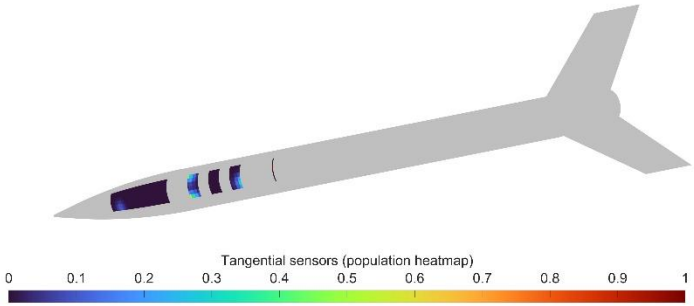
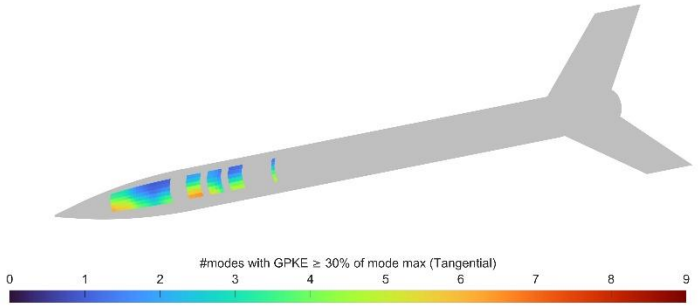
## OPTIMAL SENSOR POSITIONING

**RESULTS: *NSGA II***



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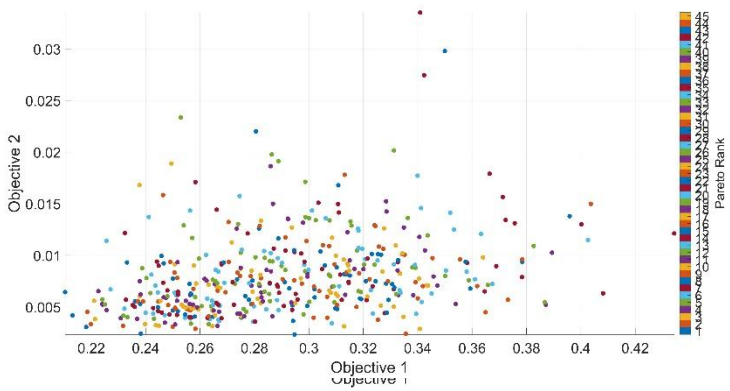
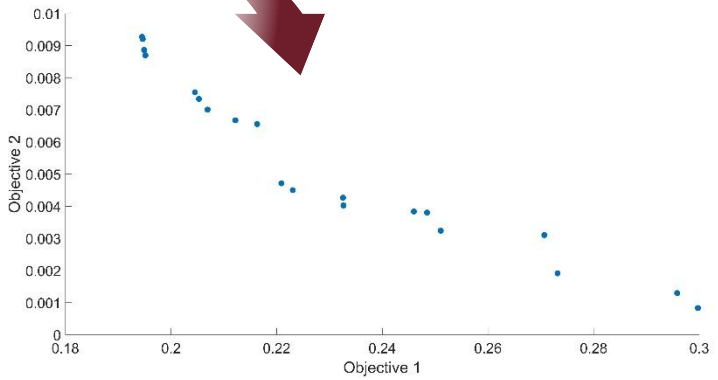
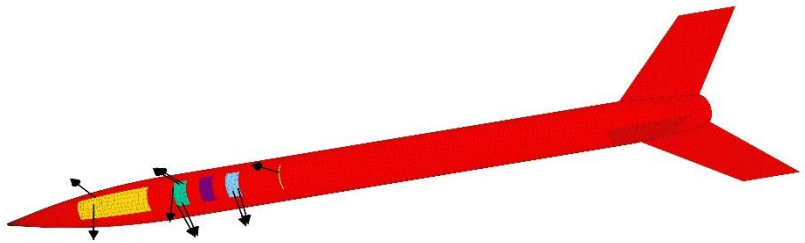
# 5. OMA on REXUS36 Sounding Rocket

## OPTIMAL SENSOR POSITIONING

**RESULTS: *NSGA II with uncertainties***





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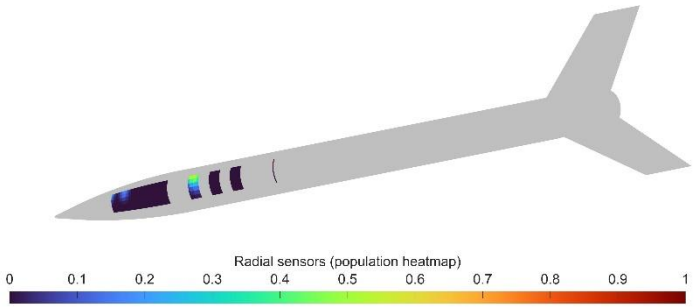
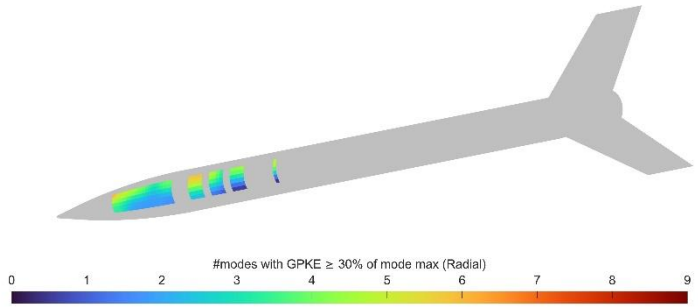
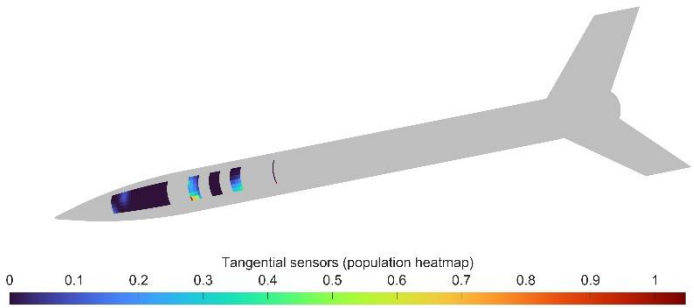
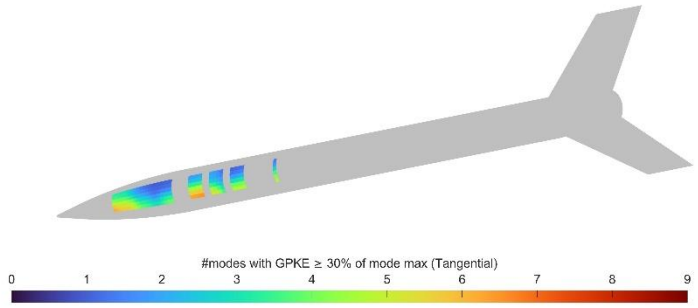
## OPTIMAL SENSOR POSITIONING

### RESULTS: NSGA II with uncertainties





IOMAC2027 OMA Lectures: STRUCTURAL DYNAMICS EXPERIMENTS ON ESA SPACE LAUNCHERS

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# 5. OMA on REXUS36 Sounding Rocket

## OPTIMAL SENSOR POSITIONING

METRICS

**RESULT:comparison**

① ***M.A.C.*** $MAC = \frac{\left|\underline{\varphi_i}^T \underline{\varphi_j}\right|^2}{\left(\underline{\varphi_i}^T \underline{\varphi_i}\right)\left(\underline{\varphi_j}^T \underline{\varphi_j}\right)} \Rightarrow f = \sqrt{\frac{1}{m(m-1)}\sum_{i=1}^{M}\sum_{j=1}^{M} MAC_{ij}^2 \,(i \neq j)} \Rightarrow \sum_{i=1}^{11} \frac{\left(f_1^i + f_1^{i+1}\right)}{2}\Delta t$

② ***G.P.K.E.*** $\Rightarrow g = \min_j\left(mean_i\left(\frac{GPKE_{i,j}}{\max_i(GPKE_{i,j})}\right)\right)$

③ $N_{sensors}$***(NOSECONE)-2*** *(≤ 2 allowed)*

④ $N_{sensors}$ ***(G.P.K.E. < 30%)*** *(Sensors below energy threshold)*

⑤ $max(\Delta①)$

⑥ $N_{MODES}$ with fewer than 4 sensors exceeding the G.P.K.E. threshold (30%), accounting for uncertainties

| | ① | ② | ③ | ④ | ⑤ | ⑥ | ΔT |
|---|---|---|---|---|---|---|---|
| KAMMER | 0.2294 | 0.1907 | 1 | 7 | 0.0059 | 1 | 1.7 s |
| NSGA II | 0.1756 | 0.2256 | 0 | 0 | 0.0098 | 1 | 1717 s |
| NSGA II *with uncertainties* | 0.1945 | 0.2164 | 0 | 0 | 0.0093 | 0 | 3054 s |



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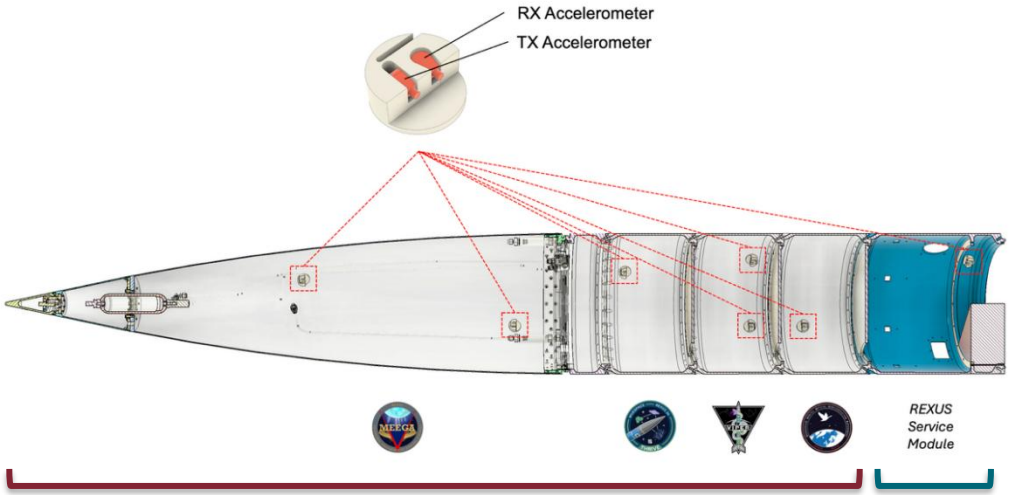
# 5. OMA on REXUS36 Sounding Rocket

## OPTIMAL SENSOR POSITIONING

**RESULT: optimal configuration**




*x8 in different REXUS teams modules*


*x2 in the REXUS Service Module*



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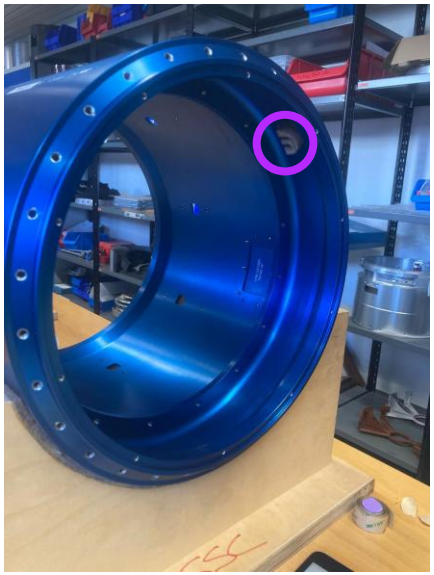
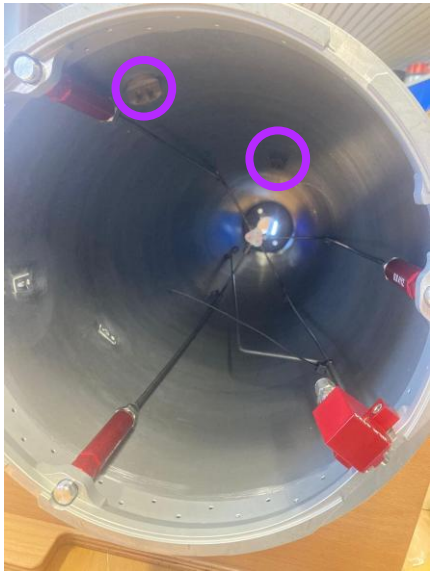
## OPTIMAL SENSOR POSITIONING

**RESULT: sensor installation**







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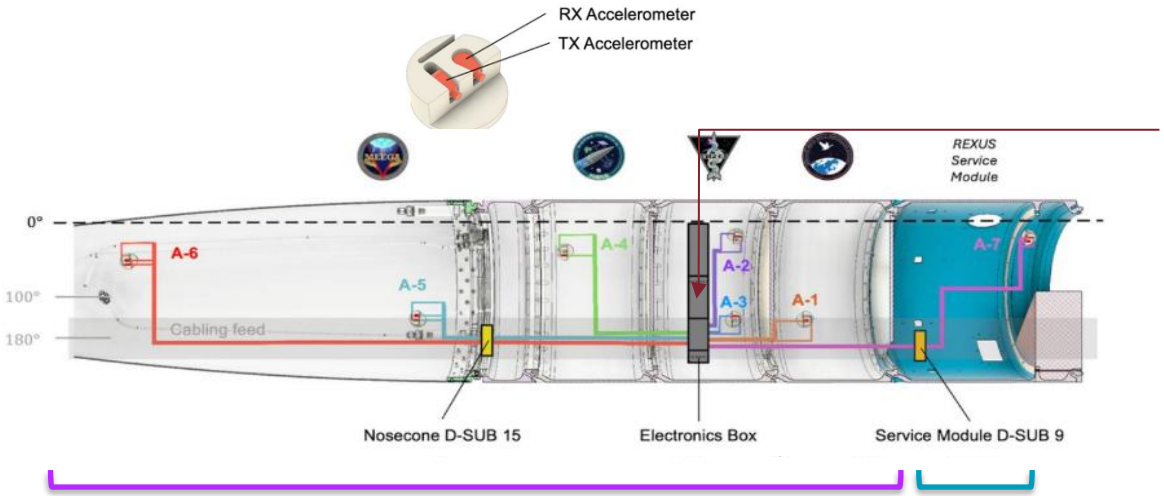
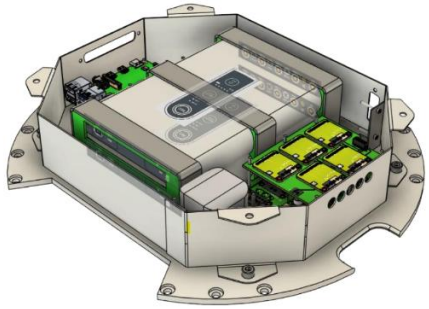
# 5. OMA on REXUS36 Sounding Rocket

## MEASURING CHAIN DESIGN



*x2 SCADAS in the electronic box in VIPER module*

*x8 in different REXUS teams' modules*

*x2 in the REXUS Service Module*

**The accelerometer will be mounted all over the payload area of the Rexus-36 launcher. The cable interfaces was carefully designed to guarantee: quick disconnection of the different modules, mounting of the accelerometers without cables already connected, nosecone ejection, minimal noise interference and optimal signal quality**



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# 5. OMA on REXUS36 Sounding Rocket

## MEASURING CHAIN DESIGN

### TESTING

**Tests aims to verify the SCADAS XS functionality under vibration levels exceeding its design specifications.**

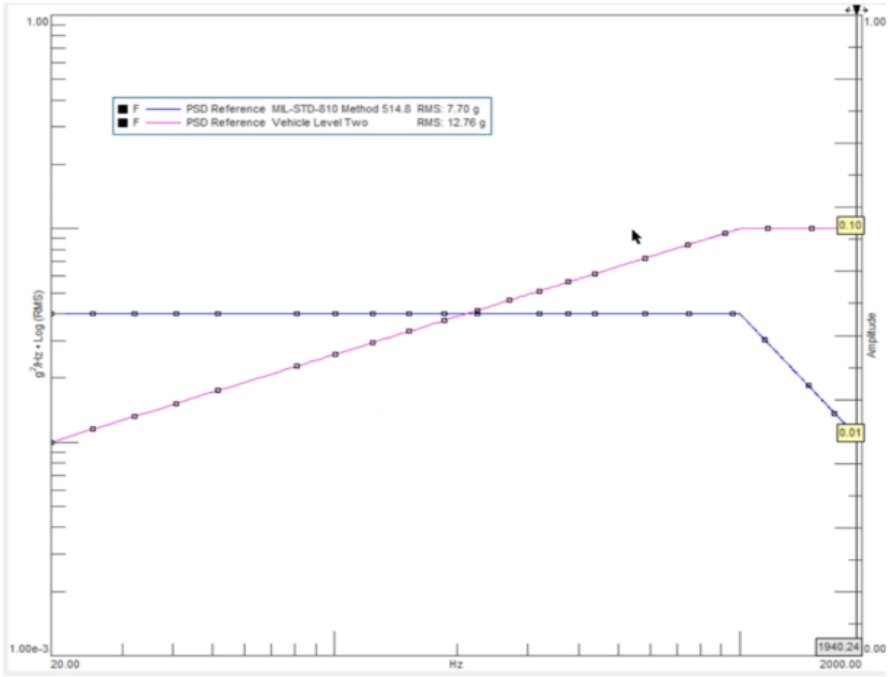


*Figure 3 – Random Vibration PSD comparison between SCADAS XS Qualification Level and RX Level 2*

**The system maintains proper functionality under vibration levels exceeding its qualification profile, while the supports effectively secure the SCADAS without structural degradation.**



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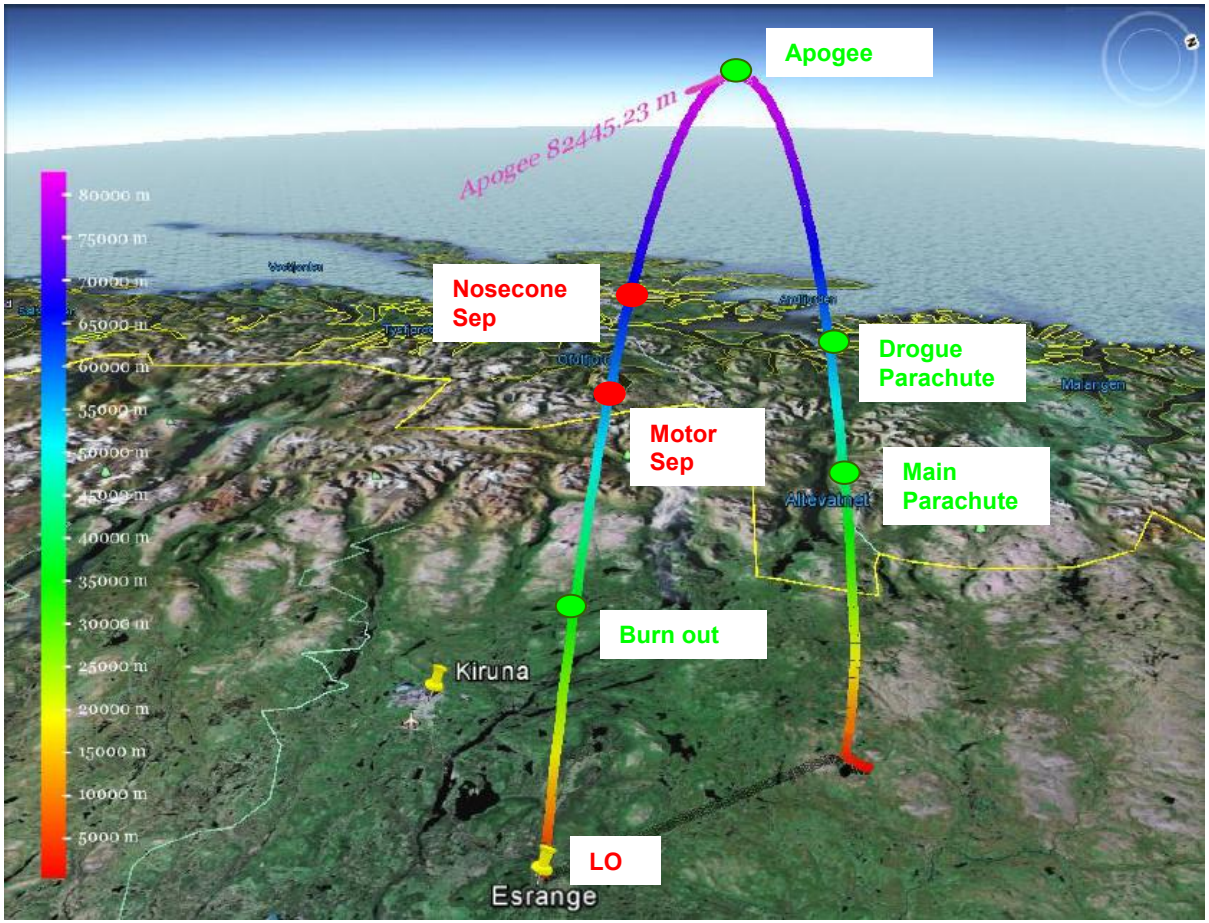
# 5. OMA on REXUS36 Sounding Rocket

## PRELIMINARY RESULTS

### FLIGHT ENVELOPE



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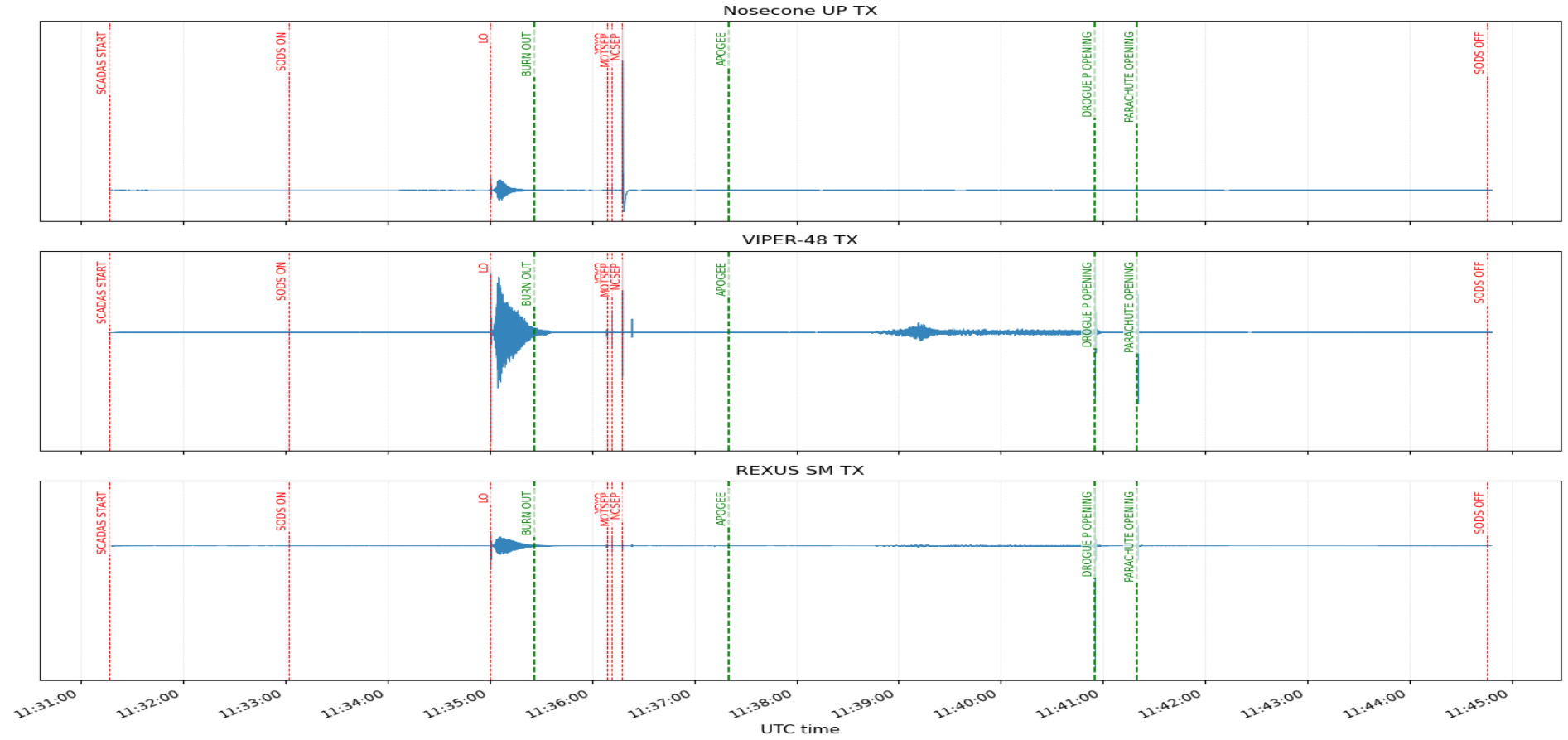
## PRELIMINARY RESULTS

### RECORDED ACQUISITIONS WITH FLIGHT'S EVENTS



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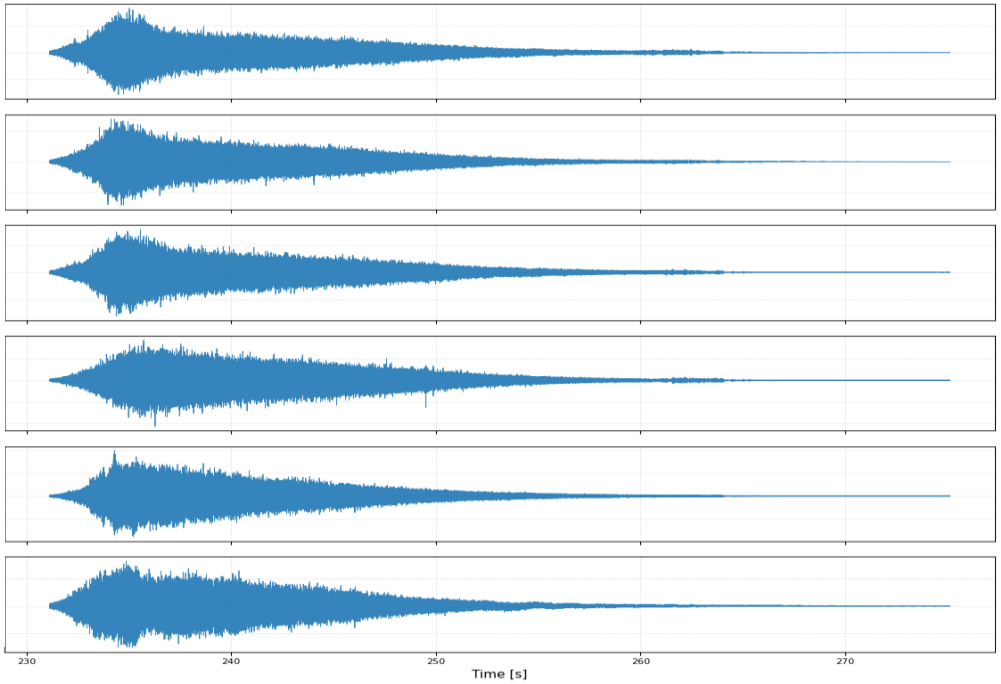
## PRELIMINARY RESULTS

### OMA ANALYSIS PARAMETERS DURING BURN OUT PHASE

- OMA method: SSI
- Number of samples: 32768
- Number of blocks for overlap: 16
- Overlap percentage: 50%
- Vandermonde order: 80
- Stabilization diagram order: 100



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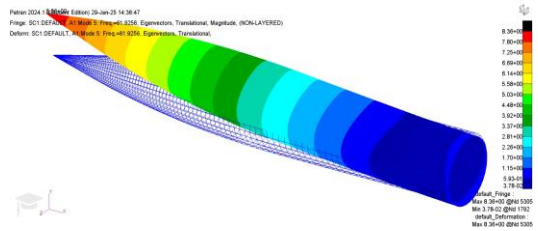
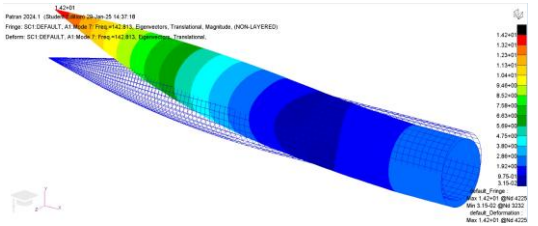
## PRELIMINARY RESULTS

### COMPARISON OF THE FIRST 3 MODE SHAPES: FEM vs OMA ANALYSIS

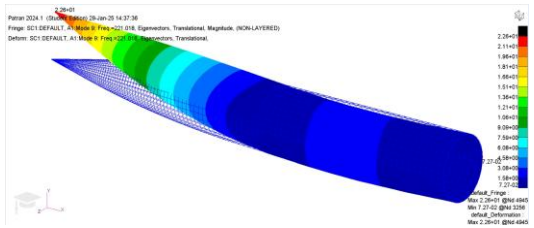
$f$ = 61.58 Hz



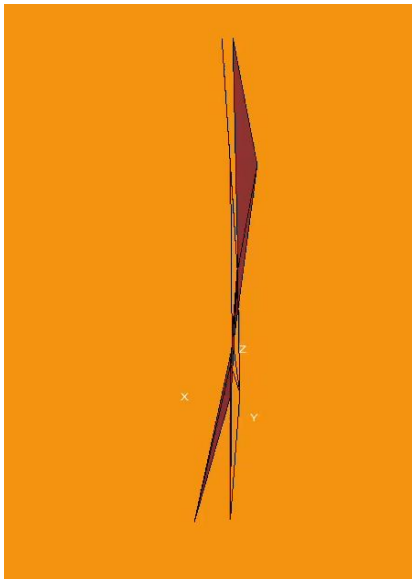
$f$ = 142.91 Hz



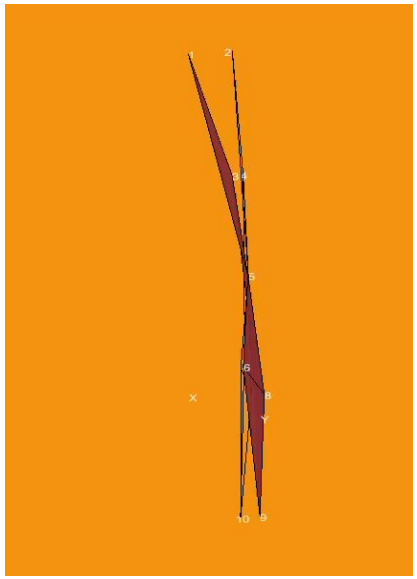
$f$ = 221.43 Hz



**f = 44,57 Hz**



**f = 114,35 Hz**



**f = 194,79 Hz**

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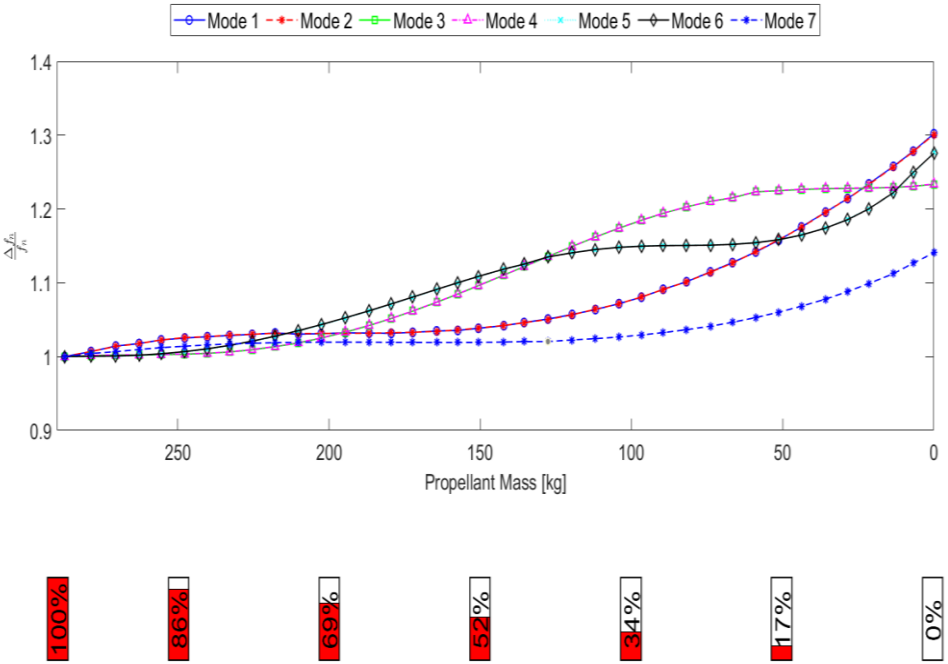
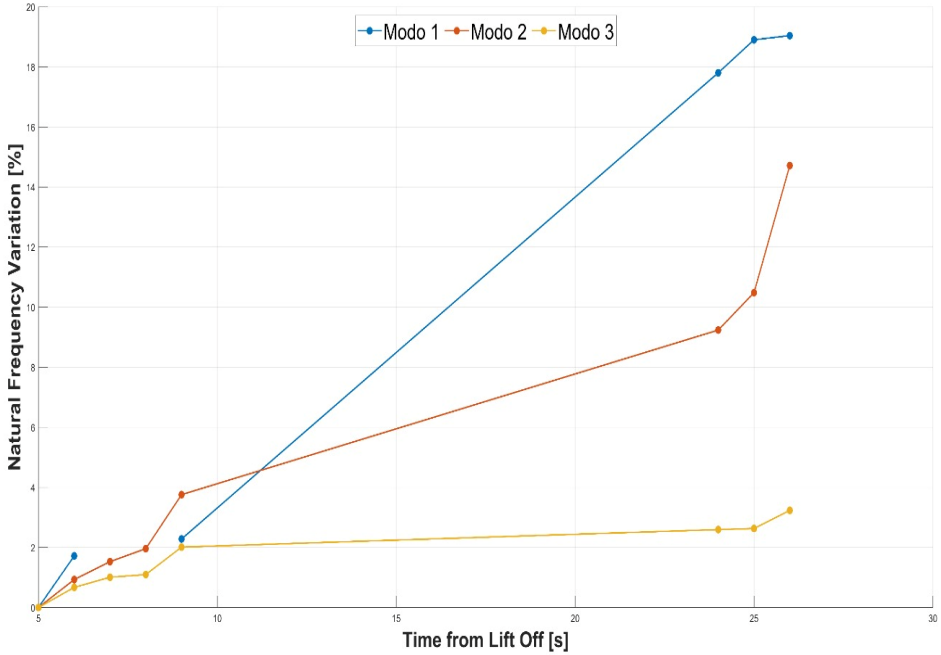
## PRELIMINARY RESULTS

### COMPARISON of NATURAL FREQUENCY VARIATION DURING BURN OUT: FEM vs OMA ANALYSIS



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# 5. OMA on REXUS36 Sounding Rocket

## FUTURE DEVELOPMENTS

**THERE IS STILL MUCH WORK TO BE DONE**

- **Implementation of pre-procesing techniques to enhance data quality for OMA analysis**
- **Application of multiple OMA methods for sensitivity assessment**
- **Further inverstigations of dynamic behaviour during :**
  1. **propulsed flight**
  2. **burn out phase**
  3. **ballistic flight**
- **Re-entry phase analysis correlated with IMU-derived velocity profiles**
- **Possible interactions with controlled systems and on board hardwares or payload**
- **OMA technologies exploitation for larger commercial launch vehicles**



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# Agenda

1. Motivations
2. Theoretical Background on OMA approaches
3. OMA on ARIANE Launch Vehicle
4. OMA on VEGA P80 Motor
5. OMA on REXUS36 Sounding Rocket
6. Concluding Remarks



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# 6. Concluding remarks



- The considered OMA methods (FDD, HTM – but also SSIs) **provide a time-tracking** of the modal properties of the considered launch system
- The system natural frequencies are time-tracked with practically **the same behavior**
- The **damping ratios** behavior seems to be **dependent** on the chosen **method** and on the **analysis parameters**. However, by considering the system poles as representative of the system dynamics the **methods give consistent results**
- The considered methods are **able to time-track the mode shapes** even if for **higher order modes are required more samples and measure points**
- It is relevant to point out that even if **the identification can fail** for same intervals within the same method, the **synergic use of the methods provides the complete tracking** of the modal properties of the studied system

# 6. Concluding remarks



- The developed **sensor placement method** reveals itself as a very **useful tool** for the test planning and for the mode shape identification phases
- **Uncertainties from OMA** analysis are **comparable** with those from the **standard EMA**, in which both the input and output signals are measurable
- The **OMA also allows** to evaluate the so-called **operational modes** due to harmonic excitations caused by the inner dynamics of the system, that the **standard experimental tests do not induce**

# Acknowledgements

The authors gratefully acknowledge the contributions of the following individuals to this presentation:

Prof. Alessandro Agneni
Prof. Luigi Balis Crema
Prof. Franco Mastroddi
Prof. Paolo Gaudenzi
Dr. Chiara Grappasonni
Prof. Cristina Riso
Dr. Marco Eugeni
Eng. Valerio Spadoni
Eng. Tommaso Pantalani

And all the VIPER student Team


# Reading list


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# THE END!



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