

## Ariane 5G Vehicle Equipment Bay (VEB) Mass Estimation

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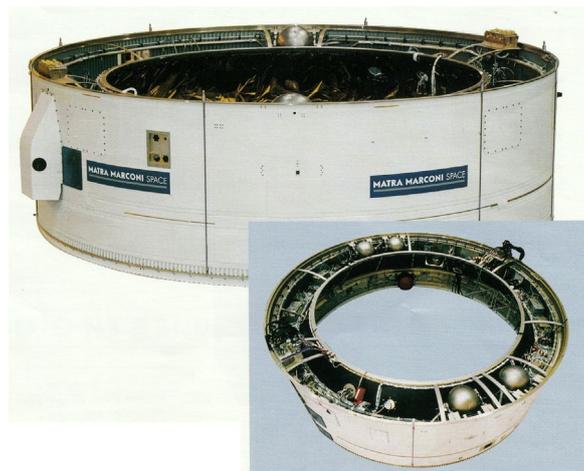
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# Ariane 5G Vehicle Equipment Bay (VEB) Mass Estimation

By B.T.C. Zandbergen

June 2025



## Abstract

In this work two Vehicle Equipment Bay (VEB) mass estimation models are applied to the estimation of the mass of the Ariane 5G VEB. The two models presented include a low-level (level 0) and an intermediate level (level 1) fidelity model. The low-level model provides a Most Likely Estimate (MLE) of 1118 kg compared to a "true" value in range 1430 to 1500 kg. The intermediate level model provides an MLE of 1506 kg and shows a clear improvement in the estimated mass as compared to the true mass. It is advised though to further investigate the validity of the two models used with focus on the intermediate level model as it seems better capable of providing the required accuracy.

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## Introduction

This document deals with a first mass estimation of the Vehicle Equipment Bay (VEB) of the Ariane 5G (G stands for generic) rocket for rocket design purposes. Aim is to identify a method/model that estimated the mass of the Ariane 5G VEB with an accuracy better (or error smaller) than  $\pm 15\text{-}30\%$ . This is considered of importance for performing proper rocket concept design.

All rockets require next to a structures, propulsion and payload system various other systems that ensure a proper flight and/or operation of the rocket. These systems include:

1. Electrical subsystem for powering the:
2. Guidance, Navigation, and Control (GNC) system: To guide, navigate and control the rocket flight.
3. Communications system for communicating with ground.
4. Flight safety system for ensuring a safe flight. This system may include a destruct system

Of these, the systems mentioned under 2 and 3 are sometimes referred to as the avionics system.

In most rockets the equipment associated to performing these functions is spread out over the rocket, but for some rockets (part of) this equipment is collected in a separate structural bay. This bay is what is referred to as vehicle equipment bay. In literature, it may also be referred to as instrument bay or instrument unit or module. It essentially is a structural element that houses (most) of the 4 above listed systems. For other rockets, these systems are more integrally to the rocket and specifically the upper stage.

For the estimation of the mass of such a VEB various methods can be used, which vary from (semi-) empirical to more rigorous theory-based relationships. The various methods used lead to different fidelity levels, i.e. different levels of estimation accuracy and design detail. Here we will only apply two methods, which represent fidelity levels 0 (the item is considered a single element and estimation is performed using mainly parametric and/or historical estimation methods) and 1 (item is split up in some of its major components with estimation methods where needed adapted to account for different technology choices and scaling). The zero level models tend to be good for rough order of magnitude estimations, whereas level 1 models allow for higher accuracy (within  $\pm 15\text{-}30\%$ ). Some more background on fidelity levels can be obtained from [Robinson].

In this work, a simple level 0 model is derived using available VEB mass data for various rockets including Ariane 5G VEB. The resulting model is like an earlier relation published in [Zandbergen] for rocket vehicle preliminary design purposes and essentially consists of a single relationship with total launch vehicle dry mass as the independent parameter.

The level 1 model is an existing model derived from literature. In this model different relations are used to compute the mass of the structure and the different vehicle subsystems included to form an VEB.

Both models will be applied to the case of estimating the mass of the A5G VEB. In a final chapter, we will present the results and discuss the applicability of the models.

## Background on Ariane 5G VEB

The Ariane 5G VEB holds most of the necessary avionics, flight controls (including the safety system) and electrical systems to navigate, control the rocket flight and to ensure a safe flight. This VEB, see Figure 1 is located on top of the lower core stage and carries on top the upper stage with the payload, payload adapter, and the fairing. It essentially is a cylindrical shaped bay 1.56 m high and about 5.4 m in diameter that interfaces with the payload fairing. It also interfaces with the upper stage through a composite truncated inner cone 0.87 m high. The diameter of this cone at the truncated top is 3.97 m. Some detailed pictures/photos of the VEB and the various equipment carried by the VEB are shown found in Figure 2.

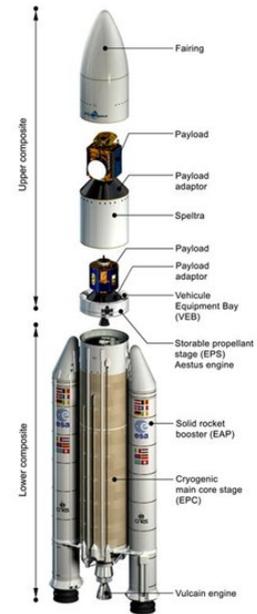


Figure 1: Schematic of A5G launch vehicle (courtesy ESA)

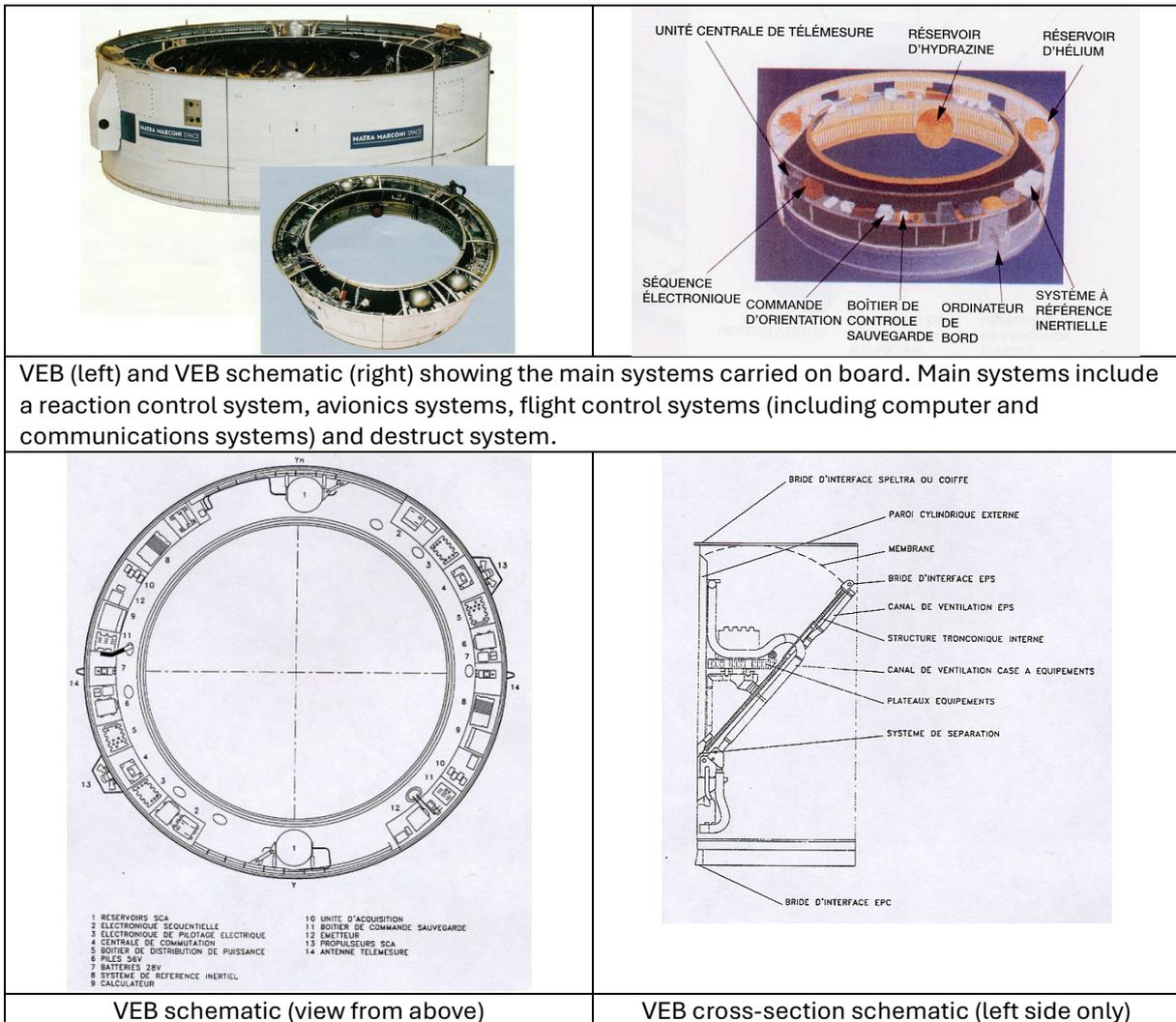


Figure 2: VEB details [CAPCOM]

According to [ESA], the VEB autonomously orchestrates, from start to end, all the systems required to control a flight such as engine ignition, separation of the boosters, the upper stage, and operation and release of the individual payloads. Calculations are made by on-board computers and implemented by dedicated electronic systems. The computers act on information provided by the inertial guidance units. The inertial reference system is the key to flight control and composed of accelerometers, plus gyroscopes and their electronic units. Another major function of the VEB was to send back a steady stream of information to the ground stations to allow the diagnostic of the launcher during its mission. This is handled by the telemetry system

One other feature of the VEB is an independent attitude control system that directs the launcher throughout its propulsion phases to reach the orbit for which it is programmed. This attitude control system puts the launcher on its roll axis during the propulsion phase, after separation of the solid rocket boosters, and ensured the 3-axes orientation of the satellites upon separation after extinction of the EPS stage. The system uses 70 kg of hydrazine stored in two 38-litre tanks that feed two sets of three thruster modules.

It is important to realize that all equipment in the VEB is duplicated. This is one of the many aspects of basic launcher design that ensures the reliability of Ariane 5 launchers. This duplication also includes the attitude control system jets and the telemetry antennae on the external surface of the VEB.

Some typical data of the Ariane 5G VEB are provided in Table 1.

| Characteristic              | Value                      |
|-----------------------------|----------------------------|
| Type                        | A                          |
| Mass at launch              | 1500 kg                    |
| Dry mass                    | 1430 kg                    |
| External cylinder           |                            |
| Material                    | Aluminium alloy            |
| External Diameter           | 5.43 (bottom)/5.46 m (top) |
| Height                      | 1560 mm                    |
| Truncated conical interface |                            |
| Material                    | Composite                  |
| Diameter at top             | 3.97 m                     |
| Base diameter               | 5.40 m                     |
| Height                      | 0.87 m                     |
| Slant height                | 1.13 m                     |
| # of RCS tanks              | 2 to 6                     |
| Operational life            | 115 min                    |

*Table 1: Ariane 5G VEB characteristics*

The external cylinder consists of two smaller cylinders on top of each other and separated by a ring containing a separation system. The two cylinders are from machined aluminium panels with integral stringers riveted between them and to the interface rings. The internal cone is CFRP sandwich made from co-cured sectors assembled by bonding and riveting and bonded and riveted to the rings.

For further reading on the Ariane 5G VEB, see the excellent web page from Capcom Espace on Ariane 5 [Capcom].

## VEB level 0 mass estimate

The level zero estimate is based on known (reported) VEB mass data for several (N=11) launch vehicles (see appendix) in relation to the dry mass of the full rocket:

|  |  |     |
|--|--|-----|
|  | $M_{VEB} [kg] = 0.402 \times (M_{dry} [kg])^{0.696}$ | (1) |
|--|--|-----|

This relation was found to have an R-squared ( $R^2$ ) value of 0.64 and a relative standard error<sup>1</sup> (RSE) of  $\pm 49\%$ . A plot of the relation in relation to the actual data can be found in Figure 3.

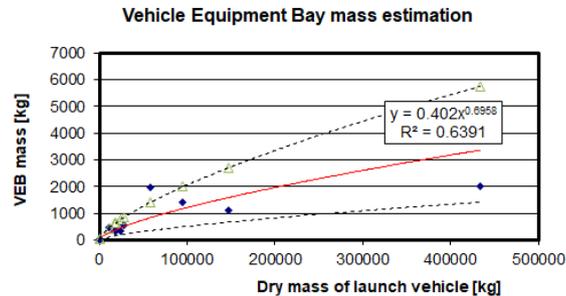


Figure 3: VEB mass estimation relationship (best fit curve) based on total launch vehicle dry mass (N=9); dotted lines show a  $\pm 1RSE$  region about the most likely estimate (the regression curve)

Data shows that there is quite an uncertainty in the estimate when comparing the estimated mass data with the “true” data. When studying the data given in appendix, we find that for Ariane 44 L some VEB mass is provided. However, from [LVC], we learn that this mass is valid for all versions of Ariane 4. This then would rule out any such relationship. Same follows if we compare the mass of the instrumentation unit of Saturn V and Saturn 1B. They also have about the same mass, but dry mass and total mass at lift off are completely different. Hence, this relationship should be used with lots of caution.

Applying this relationship to determining the VEB mass of Ariane 5G with a dry mass of Ariane 5G of 88790 kg (is sum of dry mass of 2 solid rocket boosters, lower core stage, upper core stage, and VEB as given in [LVC]), it follows.

$$M_{VEB} [kg] = 0.402 \times (88790 [kg])^{0.696} = 1118 \text{ kg}$$

Given the RSE of  $\pm 52\%$ , this estimate has quite some uncertainty. It follows that, with a probability of  $65\%^2$ , the real value is within the mass range of 537-1699 kg. Hence, there is still plenty of room for improvement. Additionally, it is noted that the above method only works in case the dry mass of the complete rocket is known beforehand. For design purposes, this is generally not the case and hence other methods may be needed.

## VEB level 1 mass estimate

The level 1 mass estimation of the A5G VEB has been largely based on the method presented by [Castellini] but has been adapted/extended using relationships taken from [Rohrschneider] and

---

<sup>1</sup> RSE or RRSE is a Relative Residual Standard Error that is defined as the root mean squared relative deviation from predictions, adjusted by degrees of freedom. It is a relative measure in regression analysis to assess the accuracy of a model's predictions. Lower RSE (or better RRSE) values indicate a better model fit, with a value of zero signifying perfect. *When you build  $\pm RRSE$  bands around the regression curve, this local relative error scaling lets you interpret the bands as a percentage range around your predicted values. **RRSE in this sense should not be seen as an error metric but rather a metric for residual design flexibility** — the degree to which an dependent variable can vary beyond what is captured by the independent variable alone.*

<sup>2</sup> This assumes that the error in the estimation is normally distributed, and that the variance does not vary with the value of the independent variable.

[Jentzsch]. The method as described in [Cassini] makes a distinction between the structure of the VEB itself and the subsystems housed by the VEB.

## VEB structure

To estimate the mass of the VEB bay structure, we will use a relationship developed by Castellini for an interstage/tank section or front/aft skirt. This relationship uses the assumption that the mass of the section is proportional to the surface area (S) of the section and depends on the section diameter (D). The relation taken from the work of [Rohrschneider] and adapted in accordance with [Castellini] reads:

|  |     |
|--|-----|
| $M_{VEB\ bay} = K_{SM} \times K_1 \times S \times (3.208 * D)^{K_2}$ | (2) |
|--|-----|

Here  $K_{SM}$  is a corrective factor for the material used (1 for classical Al-alloy based structures, 0.9 for Al-Li based structures and 0.7 for advanced composite based structures), D is stage diameter, S is surface area of front skirt<sup>3</sup> and  $K_1$  and  $K_2$  are constants that depend on the stage number, according to:

- Stage 1 elements including stage 1-2 interstage:  $K_1 = 7.7165$ ;  $K_2 = 0.4856$
- Stage 2 elements including stage 2-3 interstage:  $K_1 = 5.5234$ ;  $K_2 = 0.5210$

The mass of the VEB is estimated by applying above relation to the metallic cylindrical section as well as to the truncated composite conical section. For the estimation, we opt for the values associated with stage 2 elements as for A5G, the upper stage (EPS) is relatively small and carries only a limited mass on top. This though may seem somewhat arbitrary and may need some further investigation in future studies.

For the Al-based cylindrical structure of height 1.56 m and 5.4 m diameter follows:

$$M_{cylinder,VEB} = 1 \times 5.5234 \times 26.5\ m^2 \times (5.4\ m \times 3.208)^{0.5210} = 646.8\ kg$$

For the composite conical part, using data from Table 1, follows:

$$M_{cone,VEB} = 0.7 \times 5.5234 \times 16.6\ m^2 \times (4.7\ m \times 3.208)^{0.5210} = 263.8\ kg$$

For simplicity, we represented the conical structure as a cylindrical structure with a diameter equal to the average of the outer VEB diameter and the top diameter of the cone, and a height if(equal to the slant range of the cone.

The correctness of our estimate was checked by comparing estimated mass of the full (cylinder + cone) structure with actual mass. It follows a mass of 910.6 kg, which should be compared with the actual structural mass of 860 kg [Gomez]. This shows a pretty good comparison with a difference of not more than 50 kg or ~6%.

It is noted that the relationship taken after [Castellini] allows for considering size and material effects on mass, but detailed material characteristics as well as details on the specific structural loads that should be withstood by the VEB remain unaccounted for. So, this still leaves room for further detailing.

---

<sup>3</sup> For a conical shaped skirt, surface area follows from average diameter times slant height.

## Avionics, electrical power, reaction control and stage separation charge(s)

Like in the work of [Castellini], the mass of the avionics system (AVS) and electrical power system (EPS) are estimated using two linear MERs. The mass of the reaction control system (RCS) and the stage separation system (SSEP) are estimated based on relations adapted from [Rohrschneider].

### Avionics

For avionics, the MER uses as independent variable the vehicle body external surface  $S_{body}$ .

|  |   |     |
|--|---|-----|
|  | $M_{AVS}(kg) = K_{RL} \times (246.76 + 1.3183 \times S_{body}(m^2)) \times (1 - TRF_{AVS})$ | (3) |
|--|---|-----|

Where KRL is a factor with values of 0.7, 1.0 and 1.3 depending on the type of redundancy applied (no redundancy, critical components only, or full redundancy).  $TRF_{AVS}$  is taken equal to 0.75 to account for the advances made in on board electronics since the Shuttle technology. For the EPC stage follows assuming full redundancy:

$$M_{AVS}[kg] = 1.3 \times (246.76 + 1.3183 \times \pi \times 5.4 \times 23.7 [m^2]) \times (1 - 0.75) = 252.1 kg$$

### Electric power system

The electric power system (EPS) of Ariane 5G VEB consists mostly of batteries plus power leads and power distribution system). The mass of this system, the mass is estimated using a relationship from ref 1 of the work of [Rohrschneider], but adapted for use of SI units:

|  |   |     |
|--|---|-----|
|  | $M_{EPS} = 2.18E - 5 \times T_{vac,gimbal}[N] + 0.1835 \times M_{AVS}[kg] \times (1 - TRF_{eps})$ | (4) |
|--|---|-----|

Where  $TRF_{eps}$  is taken equal to 0.18 in accordance with [Rohrschneider]. For the EPC stage with a vacuum thrust of 1140 kN and an avionics mass of 252.1 kg follows:

$$M_{EPS} = (2.18E - 5 \times 1140E3[N] + 0.1835 \times 252.1 [kg]) \times (1 - 0.18) = 62.3 kg$$

It is noted that battery mass not only depends on power levels, but also on the duration of the mission. Ariane 5G VEB had only a limited duration. Later versions showed a much longer operational life of up to 6 hours. This is expected to affect the mass of the EPS. For now, this effect is neglected.

### Reaction control system

For the reaction control system (RCS), the mass is estimated using a relationship from ref. 6 as mentioned in the work of [Rohrschneider]:

|  |   |     |
|--|---|-----|
|  | $M_{RCS}[kg] = 1.26E - 2 \times M_{insert}[kg]$ | (5) |
|--|---|-----|

Using the sum of payload mass (19000 kg) and the upper stage empty mass (1250 kg), both taken from [LVC], as the inserted mass, the mass of the RCS system is:

$$M_{RCS} = 1.26E - 2 \times 20250 kg = 255.1 kg$$

It is noted that [Rohrschneider] is not clear on whether this estimate provides dry mass only or also includes RCS propellant mass. For now, we assume that propellant mass is included.

### Stage separation explosive charge

Explosive charges for stage separation are estimated using a relation taken from [Jentsch] but adapted for using SI units. The relationship expresses that the mass of the stage separation charge can be estimated based on the mass of the upper composite being separated:

$$M_{SSEP} [kg] = 8.7E - 4 \times M_{upper} [kg] \times (1 - TRF_{SSEP}) \quad (6)$$

With a total mass of the upper composite of 19000 kg + 11300 kg follows (value of  $TRF_{SSEP}$  taken from [Castellini]):

$$M_{SSEP} = 8.7E - 4 \times 30300 \text{ kg} \times (1 - 0.5) = 13.2 \text{ kg}$$

## Discussion of results

The results are summarized in Table 2. For comparison also actual values as reported in literature have been added. Comparison shows that the level 0 estimated VEB mass value is roughly 33% (of the actual value) below the true (reported) value. In contrast, the level 1 estimated VEB mass is much closer (within 5%).

| Mass elements                       | Estimated value | Actual (reported value)             |
|-------------------------------------|-----------------|-------------------------------------|
| Level 0 fidelity estimation results |                 |                                     |
| VEB total mass                      | 1188.7 kg       | 1500 kg/1430 kg (without hydrazine) |
| Level 1 fidelity estimation results |                 |                                     |
| VEB structure                       | 910.6 kg        | 860 kg                              |
| Avionics                            | 252.1 kg        | -                                   |
| EPS                                 | 62.3 kg         | -                                   |
| RCS (hydrazine included)            | 255.1 kg        | Max RCS propellant mass is 70 kg    |
| Stage separation explosive charge   | 26.4 kg         | -                                   |
| Total (summed) mass of VEB          | 1505.6 kg       | 1500 kg/1430 kg (without hydrazine) |

Table 2: Mass estimation results versus actual mass values reported in literature [CAPCOM].

All in all, the level 0 estimated VEB mass is ~21% below the actual value. Moreover, there is some doubt on whether dry mass and lift off vehicle mass are true descriptors for VEB mass. All in all, the results from this relation as well as the relation provided in [Zandbergen] should be treated with caution. In this respect, it is considered that it is better to use the RSE to provide a probable mass range for the item considered as illustrated in the foregoing.

The level 1 estimated VEB mass is more reasonable (within 0.5% of the actual value). This signifies a large improvement as compared to the level 0 based result. However, a few remarks need still to be made. The first one is that a single case is not very conclusive about how well the method is suited to also predict VEB mass of other rockets. Hence, some further checking needs to be done using still other cases. Some preliminary checking done by applying the above referred to relation for structural mass estimation on a variety of cylindrical and conical structural cylinders and comparing the estimated value with the reported value. The results are shown in Figure 4.

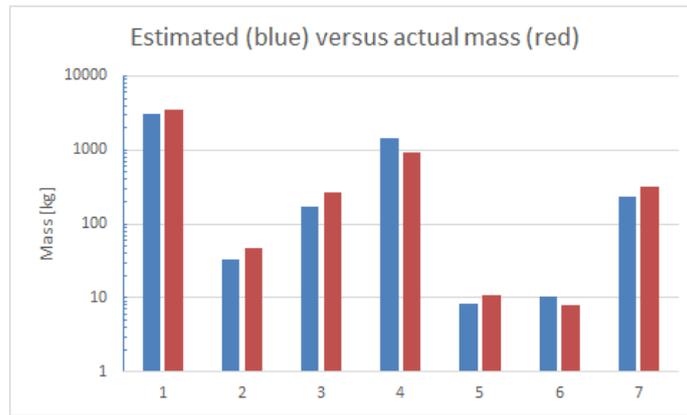


Figure 4: Estimated versus actual mass for various non-pressurized cylindrical or truncated conical structural elements

On a first look, results (N=7) look promising. However, when looking at the differences in more detail, it is found an RSE (or RRMSE) of  $\pm 33\%$ . This means, when assuming that errors are normally distributed, that with a probability of around 65% the estimated value is within  $\pm 33\%$  of the actual value or about half of the uncertainty for the level 0 model.

A second remark is that there are still various other aspects that are not accounted for in the method used that may affect the mass estimation of the VEB. Such aspects include e.g. the structural loads carried by the VEB, the exact materials used, the exact materials used and their associated properties, like mass density, tensile and compression strength, and stiffness, the operational duration of the VEB, most likely affecting EPS and RCS, and the structure needed to contain the separation charges, etc. In case, estimation accuracy is to be improved, it is advised to consider further detailing the estimation methods thereby accounting for more of the above-mentioned aspects.

A third remark is that actual values reported in literature are found to sometimes differ considerably. For the Ariane 5 VEB, this could be attributed to different versions existing of the VEB, see e.g. [Gomez] whereas in literature, it is not always clear to which version the data applies. Another reason is that it is not always clearly reported whether the reported mass value was including all the VEB subsystems or not.

A fourth and final remark is that inaccuracies may also result from that most rockets do not have a single VEB or do not have the same subsystems as part of the VEB. For instance, the RCS as part of the VEB is common for the early Ariane 5 versions, but in later versions and most notably Ariane 5 ECA, the RCS is integrated in the upper stage and not as part of the VEB. This may also explain for the large inaccuracies resulting for the level 0 VEB mass estimation model.

## Conclusions and recommendations

So, all in all, the two methods mentioned in this work provide reasonably accurate estimates, but there is little to no evidence that says this holds for all cases. Moreover, for the level 0 model there is some evidence that the relation is not correct.

Preference is given to the level 1 model, wherein the VEB structure and the instruments needed for the GNC system, EPS, RCS etc. are estimated separately as this would allow for considering that VEBs do not always have the same functions, but it would also allow for integrating these subsystems also on other elements of the vehicle.

Concluding, the level 1 estimation method has potential of being more successful in estimation of VEB mass in its entirety or for the estimation of subsystems found in an VEB. It is recommended to conduct further studies as to explore this potential in more detail. It is also recommended that a data base is developed wherein data from rocket vehicles are collected that can be used to estimate the different mass elements considered in this work as well as true mass values for validation of the level 1 estimation model.

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## Appendix A: Data used in level 0 VEB mass estimation

In table below some data has been collected related to vehicle equipment bay (VEB) mass of various rockets. Also, data are provided of launch vehicle lift-off mass and dry mass as these masses are generally considered reasonable indicators of VEB mass.

Table A-1: Launch Vehicle VEB characteristics for VEB mass estimation.

| Launch vehicle                  | Lift-off mass [kg] | Dry mass [kg] | VEB [kg] | Ref      |
|---------------------------------|--------------------|---------------|----------|----------|
| TeamX Mars Ascent Vehicle (MAV) | 261.8              | 77.4          | 4.6      | [1]      |
| EADS MAV                        | 919                | 256           | 29       | [2]      |
| Atlas Centaur                   | 137097             | 10944         | 464      | [3]      |
| Ariane 1                        | 210000             | 17800         | 320      | [4]      |
| Ariane 2                        | 219000             | 19280         | 320      | [4]      |
| Ariane 3                        | 237000             | 23880         | 320      | [4]      |
| Ariane 44L                      | 420000             | 27588         | 530      | [4]      |
| Ariane 5G                       | 746000             | 95000         | 1390     | [4]      |
| ARES 1                          | 912000             | 146460        | 1100     | [5]      |
| Saturn 1B                       | 568600             | 58570         | 1980     | [6]      |
| Saturn V                        | 3,038,500          | 433500        | 2030     | [7], [8] |

The following observations are made regarding the data reported.

1. VEB mass data are not explicitly detailed in available documentation. Data as given in table are believed to be accurate, but errors in data used cannot be excluded.
2. All Ariane 4 versions have an identical VEB mass [4]. Also, Saturn 1B and Saturn V have almost same instrument mass. This may introduce some doubts on whether vehicle dry and/or wet mass are true descriptors of VEB mass.

Refs:

|     |   |
|-----|---|
| [1] | JPL   |
| [2] | Source unknown  |
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## Appendix B: On the Use of Relative Root Squared Error (RRSE) in Engineering Regression Analysis

In the context of engineering design regression, particularly when modelling relationships such as rocket engine mass versus thrust, the Relative Root Squared Error (RRSE) provides a meaningful measure of error that captures the inherent variability in design outcomes. Unlike traditional error metrics that often assume additive noise, RRSE is computed as

$$RRSE = \left( \frac{1}{N - m} \sum_{i=1}^N \left( \frac{f(x_i)}{y_i} - 1 \right)^2 \right)^{0.5}$$

where  $y_i$  is the actual dependent variable,  $f(x_i)$  is the predicted value from the regression,  $N$  is the number of data points, and  $m$  is the number of estimated parameters.

---

### Interpretation and Practical Value

The RRSE metric inherently measures the **relative error** between actual and predicted values, enabling the construction of intuitive, percentage-based error bands around the regression curve. These bands are particularly valuable in engineering applications where output variability arises predominantly from **unmodeled design parameters** rather than random noise.

Thus, RRSE reflects not just prediction error but also the **degree of design flexibility**—the extent to which the dependent variable can vary due to design choices beyond the independent variable included in the regression. A low RRSE indicates tight control of the output by the modelled variable, while a high RRSE signifies significant residual variability attributable to other design factors.

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### Addressing Common Criticisms

- **Division by predicted value and small denominators:**  
Although normalizing errors by predicted values may amplify relative errors for small, predicted values, in engineering design data these small values typically correspond to valid physical configurations rather than numerical artifacts. Rounding or computational noise can be managed through consistent relative treatments.
- **Asymmetry of relative errors:**  
RRSE's asymmetry in penalizing over- and under-predictions aligns well with design practices that prioritize margins on one side (e.g., avoiding mass excess). This one-sided focus supports practical margin setting.
- **Sensitivity to extreme values:**  
Extreme relative deviations often represent real, legitimate design variants rather than statistical outliers and therefore should be included as informative boundary points of the design space, pending data verification.
- **Implicit multiplicative error assumption:**  
Unlike additive error models typical in statistical regression, RRSE's relative error

formulation better represents the nature of variability arising from multiplicative, design-driven effects. When multivariate regression models are used with well-chosen independent variables, RRSE can effectively quantify residual unexplained variability.

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## **Conclusion**

RRSE serves as a powerful and interpretable metric in engineering regression contexts where output variability stems primarily from design choices rather than measurement noise. By framing errors relative to predicted values, it captures the true extent of design freedom and provides intuitive, percentage-based error bands that align with engineering judgment and margin setting. While RRSE is less common in general statistical practice, its contextual advantages recommend its use and further study in engineering design analytics.