Instar

Doing Things Right in Space Programs

This article is part of a series started in January, 2000. My intent is to share a philosophy and ideas for how to increase the chances of success in space missions while also reducing total cost. Once these articles are completed, I plan to assemble them into a book. Please send comments to me at Tom.Sarafin@instarengineering.com.

Ten Principles for Doing Things Right in Space Programs

1. **Adopt the right attitude**
2. **Invest in knowledge and understanding**
3. **Instill ownership and responsibility**
4. **Constantly seek ways to improve teamwork**
5. **Follow a sound, systems-engineering approach**
6. **Reduce total cost through good engineering**
7. **Keep everything as simple as possible**
8. **Establish an effective quality system that involves everyone**
9. **Be willing to accept risks, but only those you truly understand**
10. **Make sure everyone has enough time, resources, and freedom to do things right**

Article #18

Reduce Total Cost through Good Engineering, Part 2

Goals for the RASCAL Payload Interface

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In the previous article in this series, I referred to a new launch system being developed by DARPA[1] for which two of the goals are to reduce severity of launch environments for payloads and to reduce indirect costs to payload organizations associated with constraints and verification processes. The launch system is called as Responsive Access, Small Cargo, and Affordable Launch (RASCAL). The following is a white paper I wrote; it was included as Section 8.2 in the RASCAL solicitation. As far as I know, this is the first time such expectations of true customer focus have been voiced in Government procurement of a launch system. We can only hope that the experiment will prove successful and set a precedent. I can think of no better example of how good, up-front engineering combined with the right attitude can reduce cost while also improving quality.

Goals for the RASCAL Payload Interface

The RASCAL launch system should be designed to make everything related to it as simple as possible for its customer, the payload organization. Much of the cost of space access is in indirect expense to payload organizations of having to make their payloads compatible with constraints and environments from the launch vehicle. While direct cost—the amount the customer must pay to the launch-system provider—is always a driver in the design of a launch vehicle (LV), indirect cost to customers is seldom a consideration. Thus, environments in particular, along with the payload verification process, are whatever they turn out to be.

Payload constraints, environments, and verification processes can be made much less stringent through thoughtful consideration during LV design. We believe launch vehicles should be designed to deliver payloads to their proper orbits not only at low direct cost but also at low indirect cost.

We are aiming to make launch analogous to ground transportation: All the customer wants to do is get a spacecraft to its operating environment. To do that, a truck takes the spacecraft to the launch site, then a launch vehicle takes the spacecraft to orbit. There is very little that a payload organization must do to ensure its spacecraft will be compatible with the truck. Air-ride trailers are designed to isolate the payload from the vibration environment, which is induced by tires running over rough pavement and potholes. If the bed of the trailer were hard-mounted to the axles, ensuring a payload would not be damaged would require a verification process similar to that used for launch, including high-level vibration testing and coupled loads analysis with configuration-unique math models.

We recognize that launch is a more complex problem than ground transportation. Nevertheless, we believe the burden on payload organizations of design and verification for the launch environment can be greatly simplified. In addition, launch environments can be made less severe. The RASCAL concept is well suited to meeting these goals, as discussed below.

This paper presents objectives, targets, and requirements related to the RASCAL/payload interface. In addition to environments, subjects include payload characteristics, physical interface, payload integration, and payload separation system. Firm requirements use the word "shall," and goals use words such as "should."

1. Payload Physical Properties

The LV should be able to accommodate payloads having the properties listed in Table 1.

[1] Defense Advanced Research Projects Agency

Table 1. Limitations on Physical Properties of RASCAL Payloads.

Property	Limit
Mass	100 kg or less
Static envelope	1.2 m diameter by 3 m length
Mass moments of inertia	Limited only by mass and static envelope
Center of gravity (c.g.):	
Axial—distance from c.g. to interface plane	1.5 m or less
Lateral—distance from c.g. to the vector that is normal to the interface plane and that passes through the center of that interface	0.03 m or less
Fundamental frequency when rigidly mounted at LV interface:	
Axial	50 Hz or greater
Lateral	40 Hz or greater
Torsional	50 Hz or greater

Explanation:

- Mass—The mass shown is the limit for the total payload, including any needed upper stage.
- Static envelope—This is the physical space in which the payload must stay in the static, unloaded condition. The LV shall provide a dynamic envelope large enough to ensure a payload with the static envelope and fundamental frequencies given above will not make physical contact during launch with any part of the launch vehicle. The dynamic envelope should accommodate rigid-body deflections of the payload resulting from deformation of the mounting structure combined with the elastic deformation of the payload under maximum expected launch loads. We recognize that the envelope specified above is quite large for a payload limited to 100 kg, but some potential payloads may require it. Most payloads will be considerably smaller. We would like insight into the outcome of any trade studies showing the impact on the LV of accommodating such a large envelope and the effects on predicted payload accelerations.
- Mass moments of inertia—self explanatory.
- Center of gravity—These limits are arbitrary and are suggested as a starting point. If these values drive system complexity or cost, it is acceptable to derive reasonable alternatives that can be specified to payload organizations.
- Fundamental frequency—These values are also arbitrary and intended as reasonable lower limits for payloads up to 100 kg. They are suggested as a starting point for designing an LV control system and meeting the environment objectives (Sec. 4). Reasonable alternatives are acceptable.

2. Payload Interface and Integration

The physical interface between RASCAL and its payloads should be as simple as possible. Provisions should be made at the launch site to enable all payload-specific integration and testing to be done separate from the LV. The goal here is to minimize the time that any payload ties up the reusable first stage or the launch pad.

3. Separation System

The LV shall provide a payload separation system. This system should introduce negligible shock to the payload. (See Sec. 4.3, below.)

4. Payload Environments and Verification

Before trying to understand what we are asking for in the way of reduced environments and simplified verification for payloads, consider the present situation with existing launch vehicles. Most LV user's guides provide ***quasi-static loads*** (rigid-body accelerations), a spectrum of sound pressure level for acoustics, random-vibration and sinusoidal-vibration environments to be introduced at the payload's mounting interface, and a shock spectrum describing the effects from pyrotechnics used for separation.

The quasi-static loads apply only for preliminary design of the payload structure. ***Coupled loads analysis*** is typically required to provide loads for detail design and final verification. In such analysis, responses to time-varying applied loads are predicted using finite-element models (FEMs) of the LV and the payload, which have been mathematically combined, or "coupled," to form a system-level model. This analysis is required because, when a payload is hard-mounted to the LV, the system's dynamic characteristics change in a way that is unique for each payload, which means the system will respond differently to the time-varying forces during launch.

Thus, predicting structural loads for a payload is an iterative process: As the payload design is modified, it's predicted mass and dynamic characteristics change, which means the dynamics of the coupled system would change.

Coupled loads analysis is normally done by the LV organization, paid for by the payload organization as part of the cost of launch. The analysis is complicated, encompassing many load cases and accounting for many variables. Including the time spent by the payload organization in developing and checking a suitable FEM and by the LV organization in coupling and checking models, the full loads process typically takes three to nine months.

Not only is the process costly, its duration limits the number of iterations, or loads cycles. Many programs commit to a structural design after just one loads cycle; some have elected to build flight hardware before the first loads cycle is completed. As a result, payload organizations often assume a great deal of risk that the structure they build will not be able to withstand the maximum expected flight loads.

Before launch, a ***verification loads cycle*** (VLC) is normally done to confirm the payload and LV structures are adequate. Relatively large payloads, which normally have modes of vibration at frequencies low enough to interact with the LV's high-mass modes, require test-verified models for the verification loads cycle. To generate such a model, the payload organization first must conduct an expensive ***modal survey test***, individually exciting and monitoring the key modes of vibration. Because predicted loads can be quite sensitive to small changes in FEMs, the VLC often produces loads in some parts of the payload that exceed the loads used for design and test. Costly redesign and retesting results. Payload organizations try to protect against such surprises by multiplying the loads predicted from previous cycles by a model uncertainty factor. But such a factor drives payload weight, and it often is not high enough to prevent problems at VLC.

Most small payloads of the RASCAL class have natural frequencies above the range of concern for dynamic coupling, so test-verified models of such payloads are usually not required. However, given the capability and cost of most existing LVs, a RASCAL-class payload is not the only payload. Instead, it's included as a secondary payload for a launch of a much larger payload, or it's one of many small payloads. In either case, the system-level configuration is unique and thus requires a VLC. So the predicted loads even for a small payload can increase after that payload has been designed, built, and tested.

RASCAL is intended for small payloads only. It's reasonable to assume that, for payloads with relatively high natural frequencies, RASCAL can be designed to ensure payload-unique coupled loads analysis is not needed. In other words, if time-varying forces are made less severe through engine design, or if a loads-isolating mounting system is developed, quasi-static loads at reasonably low levels should be sufficient for design and verification of payload structures.

We are challenging would-be contractors to design a launch system that will provide a soft, predictable ride for payloads. The objectives listed below apply the full time the payload is attached to any part (stage) of the launch vehicle:

- Reduce structural loading from the levels that are typical of other launch vehicles for small payloads. This includes loading to the primary structure and also the high-frequency vibration and shock that is potentially damaging to electronics, valves, and other small components.
- Make loads more predictable and insensitive to the payload design itself. If this objective is met, dynamic coupling between payload and launch vehicle will be either nonexistent or insignificant, and thus coupled loads analysis will not be needed.
- Simplify payload design and verification for launch environments.

Launch environments for the payload should be fully enveloped by the following environments to be specified by the LV organization:

- Quasi-static loads (translational accelerations only; see Sec. 4.1)
- Acceleration power spectral density (PSD) for random vibration, applicable only to small components of the payload, such as electronics modules, not to the payload's primary structure (see Sec. 4.2)
- A spectrum of sound pressure level (should be at insignificant levels for most payloads; see Sec. 4.2)
- A time history of cabin pressure
- Temperature extremes (should be insignificant for most payloads)

Not all of these environments need be specified, but no additional environments should be needed to envelop the effects on the payload from launch. We expect RASCAL to be designed to provide negligible shock to the payload. Shock testing is difficult and expensive for payloads, and the effects of shock cannot be predicted reliably enough to support payload design. "Shockless" separation systems, such as those that do not use explosives, are in use in the space industry and should be investigated so that negligible shock is introduced to the payload.

All mention below of "maximum expected" environments, loads, or stresses refer to levels for which there is no more than 1% probability of exceeding, at 50% statistical confidence.

4.1 Quasi-Static Loads

Table 2 provides quasi-static accelerations that are typical for relatively large payloads aboard several existing launch vehicles. As payload mass drops, though, expected loading for payloads of existing LVs increases as a result of vibration. The energy in a vibrating launch vehicle is limited, so low-mass payloads accelerate more than high-mass ones when hard-mounted to the vibrating launch vehicle.

Table 2. Payload Rigid-Body Accelerations for Existing Launch Vehicles. Units: g. These loads are intended for preliminary design only. Angular accelerations may also apply. (Source: launch-vehicle user's guides)

Direction	Atlas II	Delta (all)	Space Shuttle	Titan IV
Axial	6.0	6.3	3.2	6.0
Lateral	2.0	2.0	2.5	2.5

Figure 1 shows JPL's empirically derived mass/acceleration curves, which indicate this trend. From this chart, we can see that a 50-kg payload (RASCAL class) might have up to about 17-g peak acceleration during launch on the Space Shuttle. Such acceleration would be from the combined effects of quasi-static LV acceleration, transient loading, and random vibration.

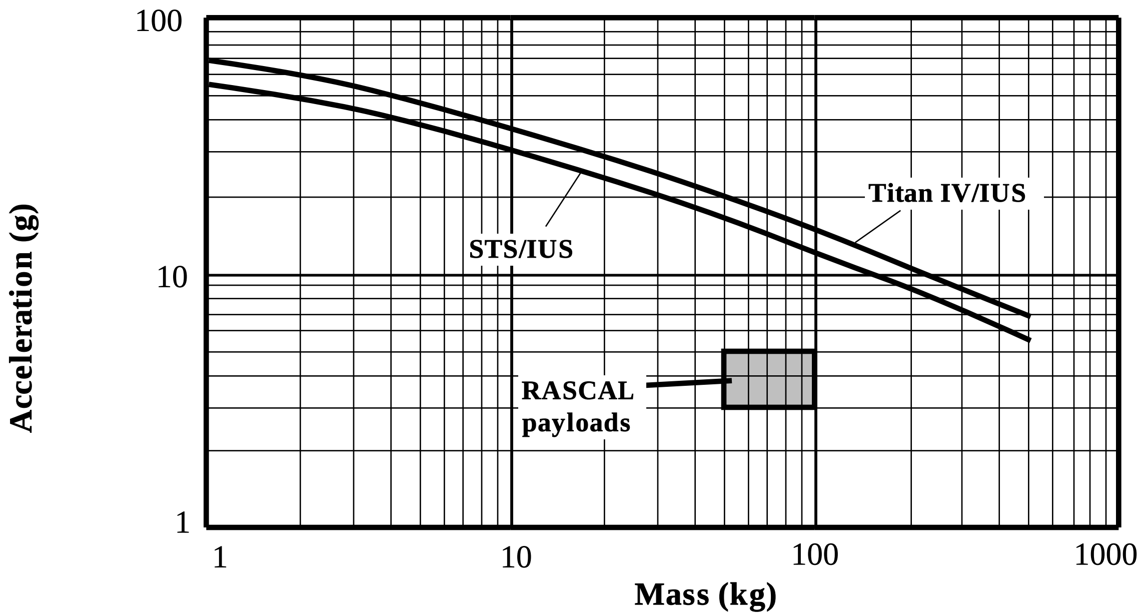

Fig. 1. Upper-Bound Payload Acceleration versus Mass. These curves are intended to represent upper bounds on acceleration, based on flight and test data. (Ref. Trubert, 1989.)

To understand how severe the specified launch environment can be for small payloads—and how complicated the structural verification process can be, even without coupled loads analysis—consider NASA/Goddard's Hitchhiker program. Shuttle payloads flying under this program typically are small, in the RASCAL class. NASA/GSFC 740-SPEC-008 [1999], the specification for Hitchhiker payloads, defines rigid-body accelerations for the payload of 11 g in each axis acting simultaneously, combined with 85 rad/s^2 angular acceleration about each axis, also acting simultaneously. Such loading is not only severe, penalizing the payload in terms of structural mass and risk, it's also difficult to assess and to duplicate in a test. According to the specification, each of the six components of acceleration can act plus or minus, so the payload organization must assess a total of 64 (2^6) load cases.

An easy way to verify structural strength for a small payload is to mount it on an electrodynamic shaker and do a sine-burst test. In such a test, the shaker introduces sinusoidal acceleration at a frequency well below the payload's natural frequencies of vibration. As a result, the payload's modes of vibration are not excited, and the payload accelerates uniformly with the shaker. Such tests are often done in each of three orthogonal axes.

For three such tests to be adequate for a Hitchhiker payload, the payload organization must analytically derive a set of three uni-axial load cases that would stress the structure at least as much as the specified set of 64 load cases. This derivation depends on the geometry of the payload structure. As an example, the FalconSat-2 program at the United States Air Force Academy concluded that, for their payload, three orthogonal cases of 25 g acceleration (including a small uncertainty factor), separately applied, would envelop the specified Hitchhiker loads. 25 g is a lot of acceleration, and designing for it leads to a heavy structure!

RASCAL should be designed to ensure the maximum expected rigid-body payload accelerations, including the effects of steady-state and transient loads, are relatively low and independent of the payload's physical characteristics. Suggested targets are

- 5 g axial
- 2 g lateral

These values are reasonable when compared with the quasi-static loads shown in Table 2 for existing LVs. To ensure such accelerations envelop the state of loading for the payload structure, RASCAL must be designed to ensure the payload's high-mass modes of vibration are not significantly excited during launch. This can be accomplished through a loads-isolation mounting system, engine design, or perhaps other means.

The quasi-static loads specified to customers should cause stresses in the payload's primary structure that are at least as high as the maximum expected stresses during launch. The goal is for people to design a payload with confidence that the quasi-static loads represent a worst-case condition for its primary structure, enveloping the combined effects of actual steady-state acceleration, transient loading, and random vibration.

We are asking that rigid-body, rotational acceleration (typically in rad/s^2) not be specified because, from our experience, many developers of small payloads do not know how to assess rotational accelerations and thus ignore them. To keep things simple for payload organizations, the potential effects of any rigid-body, rotational accelerations expected to occur in flight should be included in the derivation of the quasi-static translational accelerations. Because RASCAL payloads will be relatively small, it should not be too difficult for the LV organization to identify simple load cases of rigid-body translational accelerations that would stress the payload's primary structure at least as much as the maximum expected flight loads.

Although payload organizations can deal with load cases consisting of rigid-body accelerations acting simultaneously in three orthogonal axes, it's easier to test a small payload for acceleration in each of three axes separately, as discussed above. Three load cases of single-axis accelerations can be determined to envelop launch loading, but they no doubt would overstress some areas of the structure. Some customers may prefer designing and testing their payloads to single-axis load cases, whereas others may prefer to minimize mass by designing and testing to more realistic loads. Not all customers will have the experience necessary to reduce specified three-axis load cases down to equivalent single-axis cases. Thus, we are asking the LV developer to do this for a bounding range of payload geometry and mass properties and then specify single-axis loads as an option. As a goal for ensuring a soft ride, the specified limit rigid-body acceleration should be no greater than 8 g acting in any direction.

One possible way to meet the above goals is through use of a loads-isolating mounting system for the payload. Such a system probably would require soft springs and high damping, as is the case with ground-vehicle suspension systems. If such a system is used,

- the LV control system must be designed not to respond to low-frequency, highly damped vibration of the payload moving as a rigid body on the soft springs, and
- enough clearance must be provided to ensure the payload, moving on the soft springs, does not make contact with any part of the launch vehicle.

The 1.2-m by 3-m static envelope defined in the second column of Table 1 is quite large for payloads limited to 100 kg. Most payloads under 100 kg would be considerably smaller so, by designing the LV to accommodate the larger envelope, there will be plenty of clearance to make loads isolation feasible for most payloads. It is acceptable to propose a design that effectively isolates only payloads that are smaller than the envelope defined in Table 1. It is also acceptable to require ballast for low-mass payloads to be assured of a soft ride.

4.2 Acoustics and Random Vibration

Because of the RASCAL concept, the acoustic environment for payloads should be quite low. The first stage will have air-breathing engines, which should not generate nearly as much noise as rocket engines, and the reusable vehicle should be much more aerodynamic than a typical launch vehicle. The second and third stages, which will use rocket engines, will be deployed above the atmosphere. Thus, the LV should be designed to ensure the acoustic environment is negligible for design and verification of typical payloads. The acoustic environment should still be defined, though, even if it's low, because someone could design a payload that is extremely sensitive to acoustics. The LV organization should provide guidance to customers regarding when acoustic testing should be considered.

Because random vibration is so closely related to acoustics, random vibration should also be a non-driver for payload structures. Random-vibration testing (and sine-vibe testing as well) should not be expected at the full spacecraft level of assembly. Doing such tests at high levels of assembly presents a difficult challenge in that, without notching or force limiting, primary structures are stressed much more severely than they will be during launch. ***Notching*** is a strategy for avoiding an overtest by reducing the input (typically acceleration power spectral density) in a frequency range corresponding to the fundamental frequency of the test article. ***Force limiting*** effectively does the same thing by controlling force introduced to the test article in addition to the shaker's acceleration. Such strategies are justified because energy is limited in a mounting structure that is randomly vibrating in response to acoustics, whereas, for an electrodynamic shaker, the energy is virtually unlimited. As a result, without notching or force limiting, a payload's high-mass natural frequencies respond much more in a base-driven test than they would in an acoustic test or during flight. Unfortunately, justifying and implementing specific levels for notching or force-limiting is costly and beyond the capability of many payload developers. Thus, most small spacecraft are subjected to unrealistically severe loading during random-vibration testing, with the result being unnecessary fatigue damage and possible failure.

The LV should be designed to ensure the maximum expected stresses in the payload's primary structure during launch will not exceed those caused by the specified quasi-static loads (Sec. 4.1). Specified random-vibration environments should apply only to smaller levels of assembly, such as electronics modules and PC boards.

Many small-spacecraft developers, though, may prefer testing for random vibration at the spacecraft level of assembly while set up to do sine-burst testing. Even at low levels of random-vibration testing, the primary structure for a relatively large assembly such as a 50-kg spacecraft can be overstressed. A relatively simple strategy for a payload developer to preclude overtest, if it can be justified, is to notch the specified environment to ensure the 3-σ response acceleration of the fundamental vibration mode does not exceed the specified quasi-static acceleration (Sec. 4.1). Rather than expect the payload organization to justify this approach, the LV organization should do so through LV design and through sensitivity analysis that covers the expected ranges of mass properties and fundamental frequencies for RASCAL payloads.

4.3 Justification for Specified Environments

When requested by DARPA or by a customer payload organization, the LV organization shall provide adequate justification (supporting analyses and test data) to show the specified environments will envelop the maximum expected launch environments for the payload. Declining to provide this information, whether based on an argument that it is proprietary or any other reason, will not be acceptable. Payload organizations have the right to become confident in the loads and environments they use for designing and testing their payloads.

References

NASA/GSFC 740-SPEC-008, 1999. "Customer Accommodations and Requirements Specification." (CARS)

Trubert, Marc. November 1, 1989. JPL D-5882. "Mass Acceleration Curve for Spacecraft Structural Design."

About the Author

Tom Sarafin has been involved in the space industry full time since 1979, at which time he graduated from The Ohio State University with a BS in civil engineering and took a job as a stress analyst at Martin Marietta Astronautics in Denver, Colorado. While at Martin, he was involved with design, analysis, verification planning, and testing on several spacecraft and launch vehicle programs. After contributing to the book *Space Mission Analysis and Design* [Larson and Wertz, editors, first edition published in 1991], he obtained management's support and funding at Martin Marietta for the development of a book on the interdisciplinary development of structures for space missions, and served as principal author and editor for 23 other authors. He left Martin Marietta in 1993 to complete this book, under the guidance of Dr. Wiley Larson at the U.S. Air Force Academy. The result of nearly four years work—*Spacecraft Structures and Mechanisms: From Concept to Launch*—was published in 1995 jointly by Microcosm, Inc., and Kluwer Academic Publishers.

In 1993, Mr. Sarafin formed his own company, Instar Engineering and Consulting, Inc. Once he finished his book, he began providing review and advice as a consultant to space programs. He also developed a short course based on his book and began teaching it throughout the industry. The course has been quite popular, and the business has grown. Now Instar offers a curriculum of courses taught by experienced engineers and continues to add to that curriculum.