Doing Things Right in Space Programs

Article #2

Understanding the Problem

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I've heard it said that a good manager can manage any project, regardless of the industry. I believe that is not true. You have to understand the business you are in, and you have to understand it intimately, including the key technical aspects. Why have so many management strategies and fads come and gone in the space industry with no apparent effects? Is it because we're all boneheads, or is it perhaps because we've tried to adopt strategies that work for most commercial businesses without modifying them for the unique aspects of the space industry? Clearly we must understand our business and the problem we are trying to solve.

What makes space missions so hard? Why are space programs so costly and so prone to failure? Table 2-1 lists some key reasons.

Table 2-1. Why Space Missions are So Costly and Difficult.

- A space program requires the development and operation of a complex system.
- Space and launch vehicles must withstand many harsh environments, which are variable and hard to predict.
- Design and verification are heavily dependent on analysis.
- Despite many variables and uncertainties, we must keep flight hardware lightweight.
- Production is low-volume.
- If something fails during or after launch, we usually can't fix it.
- The space-mission customer has a huge stake in success.

Let's examine these reasons:

Complex system—A spacecraft is a complex system that must function almost autonomously. The launch system is also complex, as is the system for operating the spacecraft. These systems must work together as a higher-level system. Many things could go wrong, only one of which could cause the mission to fail

One measure of the complexity of a system is number of people involved in developing and integrating it. More people mean more interfaces and more chances of miscommunication and human error. Anything we can do to simplify the system or otherwise reduce the number of needed people involved would reduce cost.

Of the reasons listed in Table 1-1, this one is not unique to the space industry. Successfully and efficiently developing any complex system requires a systematic development process that includes

- identifying system objectives and key requirements
- defining alternative system concepts and using trade studies to select the best one
- flowing requirements down to system elements
- doing low-cost development tests to acquire information needed to design things that will work
- doing analysis to make designs efficient and dependable
- coordinating interfaces between system elements
- developing manufacturing processes that will provide products that meet design requirements
- ensuring quality of procured materials and products
- testing at incremental levels of assembly to identify problems as soon as we can
- and, finally, testing at the system level to confirm the interfaces.

We need these elements regardless of whether we're developing a satellite, a launch vehicle, or an automated baggage handling system for Denver International Airport.

Systems engineering, the art of planning and integrating the above, weakens as we dilute its meaning by referring to it when we're actually talking about some specialized part of product development. For example, consider requirements definition. Someone who joins a program to write requirements and then leaves to do the same for another is a specialist. Being a specialist is the opposite of what systems engineering is all about. We learn to develop effective requirements by, after trying to do so, staying onboard to participate in the full systems engineering process and live with the problems we cause, just as we learn to develop good designs by seeing products through development and test.

Harsh environments that are variable and hard to predict—During production, test, transport, and storage, space vehicles must withstand all the environments here on Earth that most products from other industries experience. Then we expose them to launch and space. These two environments are each comprised of many diverse subenvironments, each of which requires analysis and testing, first to quantify it and then to assess its effects. Launch and space environments are not only harsh, they are also widely variable and hard to predict. They are not easily accessible: we must launch something to measure them. Over the years, we've improved our understanding of the space environment immensely, but it remains problematic. On most of the programs I've supported, launch has been even more so.

We have difficulty both in quantifying the launch environment and in predicting how flight structures vibrate in response to it. Low-frequency vibration stresses the main structures of the launch vehicle (LV) and its payload, while high-frequency vibration stresses the materials in vehicle components, down to the electrical leads. Source excitation varies not only with the LV configuration but also from motor to motor of the same design, launch-site to launch-site (yes, the surrounding structures do affect how the LV vibrates), and day to day, considering variation in winds and other atmospheric conditions.

Without a sound appreciation of the variation involved, we might find ourselves developing unwarranted confidence in a launch-vehicle design based on three or four successful launches. We might chastise or ignore a diligent engineer who has uncovered an error or oversight in the structural analysis or testing and is trying to alert us to a potential problem that is actually legitimate.

As an example, consider the possibility of a gust of wind during the LV's ascent, which would add significantly to the structural loads in the LV and its payload. Current practice is to account for possible gusts in the loads analysis with assumed pressure magnitude, rate of change, and shape (how pressure varies over LV length). In 28 launches of the Titan IV as of the time of this writing, no vehicle has experienced a gust nearly as severe as those assumed for design or upper-atmosphere winds approaching a statistical 3-σ case. Similar findings apply for other launch vehicles, as well. Perhaps our analysis is too conservative, but, regardless, we are wrong to conclude a launch or space vehicle is "proven" simply because it has worked in the past.

In our quest to reduce cost, it's fair to challenge the data driving us to design for wind gusts: just how likely are they, anyway? Recent research indicates that gusts of wind like those we experience on the ground—and like those assumed in the launch loads analysis—do not occur in the upper atmosphere. We can break down the wind up there into a steady, predictable air pressure and a random, unpredictable pressure, which we call *turbulence*. Our present approach to assessing the effects of turbulence through an assumed, quantified gust is simply an attempt to bound a problem we don't fully understand. As we learn more, we can drive out more of the conservatism and thus safely reduce the weight and cost of our flight structures.

Even if we could predict the launch environment with reasonable accuracy, we would still have difficulty predicting how the product we are developing will respond to it. If you mount something (payload) on a vibrating machine (LV), the manner in which the combined system vibrates depends on how the two structures interact, or couple, which in turn depends on their structural modes of vibration. Of course, during design we can only predict these modes.

What all this means is that, unless we physically mate the payload to the LV and launch the system—and do this enough times to acquire a relevant statistical database—we won't know the structural loads. Yet, to design the LV or a payload, we need a good estimate of the highest structural loads it could see. Although we can individually test pieces of the system for some key characteristics before launch, such tests typically occur late in the program, after we've already invested a great deal in the design. Thus, we depend heavily on analysis.

Heavy dependence on analysis—Dealing with environments is not the only area in which we depend on analysis. Testing is unfeasible or impossible for many aspects of a space mission. We can test pieces of the system used to ensure our spacecraft has the right trajectory, but we can't test the system itself to make sure the craft will actually land on Mars. On Earth, we must test things in one *g*, knowing the absence of gravity will cause dimensional changes, differences in how fluids flow, and other effects. We test to as low a pressure as we can affordably generate in a vacuum chamber and then react to what we learn in hopes things will work in the lower pressure in space. And, returning to the subject of launch environments, we put things on shaker tables and test them to random vibration, one axis at a time for one to three minutes, knowing the launch vehicle will actually vibrate randomly in all three directions simultaneously while also accelerating. We do what we can in test to bound the expected problems, but even the tests themselves are based on analysis.

Such dependence on analysis means an unusually high cost of discovering poor judgment, improper assumptions, or human errors. As a result, our analyses warrant greater detail and review than in most other industries.

On the other hand, if we all recognize that the traditional tests are not true requirements—that we do them in the absence of any better ideas in order to build confidence (verification)—we open many opportunities to reduce cost. Just because we've always done, say, single-axis random vibration testing does not mean a better test or better way of doing that test doesn't exist. We can challenge traditional tests responsibly, however, only by deeply understanding the problems those tests are trying to address and the benefits they provide.

Uncertainty vs. lightweight—Despite the uncertainties in environments and product responses, we must keep everything lightweight. Each kilogram of mass we add to LV hardware drives several kilograms of extra propellant and, usually, thousands of dollars of additional cost. Accordingly, we can't take the standard engineering approach of dealing with uncertainty by using high uncertainty factors or factors of safety. Instead, we must devote a great deal of time and effort acquiring and interpreting test and flight data, developing analytical forcing functions to bound that data with appropriate conservatism, confirming math models, predicting how the LV and payload structures will couple, and devising environmental tests that are minimally excessive. When we don't have the time, budget, or expertise to do these things—or otherwise avoid problems with launch loads, as I'll discuss in later articles—we invite risks we don't understand and thus should not accept.

Low-volume production—The above problems are magnified by the economics of low-volume production. When I ask my classes to name a high-volume industry, the answer is almost invariably "automobiles." When a major auto company develops a new vehicle, they plan to recover their costs over the sale of hundreds of thousands of cars. To us in the space industry, where a production quantity of one or two is not uncommon, that's a huge number. But if you ask an auto engineer, he or she might say, "We're not high volume. Soda cans … now that's high volume!"

Nonrecurring development and tooling costs become insignificant when amortized over a high build quantity. Almost anything we could do to reduce recurring costs would be worthwhile. For example, we would use statistics to learn how to control manufacturing processes so we wouldn't need to inspect hardware and so we wouldn't have to pay the price of scrapping or reworking hardware that fails inspection. The machines used to make soda cans are quite expensive, but the process itself is fast, cheap, and well controlled. You can bet the next can you drink from was not inspected and tested before it was placed in service.

In the space industry, we face the dilemma of wanting to design and build things right the first time but not being able to afford it. There are cost-effective mixes of process control vs. inspection, and analysis validation vs. testing, but they are difficult to find.

We can't fix it after launch—Norm Augustine, former head of Lockheed Martin, once compared launch to heart surgery: we have to get it right the first time. The difference is that heart surgery is a relatively simple procedure compared to a space mission. One might argue that a modern automobile is as complex as a spacecraft, but if something in your car breaks down you can get it fixed. Not only can we not repair a broken spacecraft (certain costly exceptions noted), we can't even see it to find out what's wrong.

This unique aspect of our industry greatly affects the process of developing a space or launch vehicle. *Verification*—establishing confidence that a product will work or the mission will be successful—and quality assurance, which can be considered a subset of verification, are necessarily extensive and costly.

The customer's stake—When you or I plan to purchase a new car, say a new model of a Ford Taurus, we aren't invited to the design review. But then, we don't fund the development of that Taurus, either. In some commercial space ventures, the customer has everything on the line at launch: if the system fails, the customer organization goes out of business.

Until private companies in the space industry invest their own money to fully fund the development of a space or launch vehicle to be sold for a profit (as some actually are starting to do), we must accept a unique way of treating our customers. Reducing cost by excluding our customer from design reviews or from the development of our verification plan is not a viable option. Our customer has a huge stake in success and thus has a right to be made confident that, once we launch the system, it will work. If we accept that verification means establishing confidence, we must also accept that no one deserves that confidence more than our customer.

Will trying to make our customer confident increase cost? You bet. But it's unavoidable. If our program starts off with the plan of letting contractors be solely responsible for verification of their products, that plan will change as the customer gets more and more nervous (a natural outcome of ignorance) as the launch date approaches. That's when unplanned activities and cost overruns occur. It's far better to accept the customer's role from the start and develop a plan that is acceptable to both parties.

On the other hand, customers must understand how this approach to product development can lead to cost that increases uncontrollably if the customer's representatives are unqualified or unreasonable. We must remember: verification means establishing appropriate confidence, not proof. Given many uncertainties and sources of variation, we must accept some risk of failure. And customers must remember they are hiring prime contractors for their expertise as much as anything.

Next month I'll discuss some of the common problems that arise when developing systems and components for space missions.

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.