FRACTIONATED SPACE ARCHITECTURES: A VISION FOR RESPONSIVE SPACE*

O. Brown**
Defense Advanced Research Projects Agency

P. Eremenko†
Booz Allen Hamilton

We propose a definition for responsive space that encompasses the speed with which a space system – broadly defined – can be made to react to various forms of uncertainty, ranging from geopolitical operational requirements to technical failures to fluctuations in the acquisition funding stream. We note that the ever-larger monolithic spacecraft of today are notoriously unresponsive. We then suggest a novel architectural paradigm, which we call fractionated spacecraft, whereby a satellite is decomposed into a set of similar or dissimilar component modules which interact wirelessly while in cluster orbits. A perfunctory survey of enabling technologies and an overview of the objectives of the forthcoming System F6 initiative at DARPA is provided. Given our more formal definition of responsiveness and this new proposed architecture, we conclude that spacecraft fractionation results in responsiveness across all possible scales of spacecraft size, including very large spacecraft systems that are only made possible by fractionation.

THE PROBLEM

Responsive Space

What is responsive space? Conventional wisdom suggests that it is the ability to quickly develop and launch orbital payloads. We disagree with this narrow view. Although shortening the development and launch timelines is one instantiation of the solution, we understand the broader definition of responsive space as this:

Responsive space is the capability of space systems to respond rapidly to uncertainty.

This broadens the solution space; it permits us to consider alternate – and undoubtedly complementary – means of enabling responsiveness across a wide

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** Program Manager, Tactical Technology Office. E-mail: owen.brown@darpa.mil.
† Associate, Defense Business Segment. E-mail: eremenko_paul@bah.com.

range of systems, large and small. The conventional view of responsive space is predicated on one manifestation of uncertainty: that of a combatant commander faced with a temporally and geographically uncertain threat. Hence, resultant efforts focus on the need for launch on demand in response to a particular tactical threat, at a specific location and on short notice. But there are other manifestations of uncertainty which vex not only the warfighter in the field, but also the acquisition official, the spacecraft designer, manufacturer, tester, and operator. Uncertainty exists throughout the entire lifecycle of a space system, and therefore the need for responsiveness is omnipresent from cradle to grave.

With this expansive notion of responsiveness in mind, we introduce a novel architecture developed by the Defense Advanced Research Projects Agency (DARPA) which we term fractionated spacecraft. This approach to spacecraft design promises to effect responsiveness not just by shrinking spacecraft development timelines and enabling launch with smaller, more tactical vehicles, but also by making the spacecraft architecture fundamentally flexible and robust. We show that this makes a satellite able to adjust to uncertainty throughout its lifecycle. DARPA's System F6 – Future Fast, Flexible, Free-Flying, Fractionated Spacecraft united by Information eXchange – is a technological and paradigmatic demonstrator of the responsive nature of fractionated satellites; the specific objectives of System F6 are discussed in later sections of this paper. But first, we turn to a brief discussion of the uncertainties faced by space systems throughout their lifecycle, and the present approaches to coping with them with the intent of identifying the potential for improved flexibility, robustness, and hence responsiveness.

Sources of Uncertainty

It is not enough for a spacecraft to deliver a given capability – it must do so with flexibility and robustness in the face of various sources of risk and opportunity.[1] As we noted above, the speed with which a space system can react or adapt to uncertainty is the measure of its responsiveness. Below we consider some of the major sources of uncertainty that arise throughout the development and operation of a typical spacecraft. Conventional methods of dealing with such uncertainties are provided.

[1] We use the terms risk and opportunity interchangeably with uncertainty. We tend to use risk to describe fluctuations in some parameter (either exogenous or endogenous to the system) that tend to lead to degradation in system performance, cost, value, schedule, or some other metric. Opportunity refers to parameter fluctuations that can produce an improvement in some metric of performance.

Technical Uncertainty: We categorize those risk sources which are endogenous to the spacecraft during operations as technical risks.[2] Examples would be a component failure, a software bug, a design flaw, or an erroneous command (if the operator is construed to be part of the spacecraft system). Such technical risks can negatively affect the capability or performance of the satellite, thereby undermining the value delivered, increase cost, or slip schedule. An example of a technical opportunity is the development of a new component capability, for instance vastly improved processor speed, that could be inserted into a system at some time after its launch.

Current conventional capability to address risks associated with on orbit operations is very constrained. On orbit degradations and failures can sometimes be addressed through software patches or novel operations.[3] Systematic architectural solutions to repair and/or replace failed or degraded systems onboard spacecraft are rare, and can be found on only one spacecraft, the Hubble Space Telescope. Hubble servicing missions using the Space Shuttle and trained astronaut crews require extensive planning and training, and consequently are not responsive. DARPA's Orbital Express (OE) program is intended to demonstrate the capabilities of unmanned robotic servicing, thus providing a new method to responsively address technical risk (without risk to humans). A second means to address technical risk in a rapid manner is through the use of on-orbit spares. Currently though, the overwhelming majority of space systems address operational risk through prevention and redundancy, i.e., quality and reliability. This has led to unintended consequences, especially for large spacecraft. Since failure is not acceptable, reliability is addressed by a high degree of redundancy. The impact is to make an already complex engineering system even larger and more complex. Quality control focuses on rigorous inspections and lengthy testing programs. With the exception of the on-orbit servicing architecture offered by OE and the maintenance of expensive on-orbit spares, none of the aforementioned methods of addressing technical risk offers the potential for responsiveness.

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[2] The distinction between such endogenous failures and exogenous environmental factors is admittedly blurry. For instance an internal component generally fails only due to some external stimulus. We loosely categorize those failures which occur under nominal environmental conditions as endogenous, and those triggered by unusual environmental variations as exogenous. This categorization, however, is of no importance to our argument. Also, note that we are not referring to technical risk during the development phase – the risk that an unproven technology will not come to fruition. We associate such risk with requirements uncertainty.

[3] An example includes utilization of the low data rate antenna together with advanced data processing techniques for science return on the Galileo spacecraft after the high gain antenna failed to deploy (see http://www2.jpl.nasa.gov/galileo/anomaly.html). Another example is that of GOES-10, which was flipped upside down to enable its solar array to rotate in the opposite direction, after it was found the array become stuck while commanded to rotate in the intended direction (see http://goes.gsfc.nasa.gov/text/goeskstatus.html).

Environmental Uncertainty: Variations beyond some nominal range in the environmental conditions during spacecraft operations, including temperature, radiation levels, space object impact, etc., would constitute environmental risks. Analogously to technical risks, environmental risk factors can adversely affect the capability or performance of the spacecraft, potentially reducing the value it delivers. It is difficult to proffer environmental uncertainties which provide opportunity.[4]

The conventional methods to address environmental uncertainties are very similar to those for technical uncertainties as described, i.e., through prevention and redundancy. Prevention is mainly handled by large design margins, especially in radiation hardness. Again, these preventative and design techniques offer little recourse if damage or failure due to environmental factors does occur. Only an on-orbit servicing architecture can truly react to such risks quickly.

Launch Uncertainty: Although launch failure risk itself can be seen as composed of various factors which may be endogenous or exogenous to the launch vehicle system, from the spacecraft perspective they can all be aggregated into the uncertainty in reaching the desired orbit. Failure to do so can have an adverse effect on the satellite value stream (as well as schedule and cost, if a replacement must be launched). An example of launch vehicle uncertainty resulting in opportunity is the market introduction of a new launch vehicle that could be utilized to diversify risk or enable more responsive launch.

The current method of dealing with launch vehicle risk is once again mainly by prevention, with intensive mission success programs. Commercial operators also address launch risk by purchasing insurance, which typically runs 10% to 20% of spacecraft value. Military missions, although self-insured in an economic sense, frequently necessitate the availability of a rather expensive on the ground "spare" to ensure mission success in the event of a launch failure.

Should failure occur – and it does – the costs are extreme, both in terms of money and underserved markets. In the case of DOD or civil losses, failure results in lost capability or lost science. The time to recover from such catastrophe, especially for large spacecraft, is substantial. Opportunities brought on by the introduction of new launch vehicles are limited, being available only if that vehicle has the capacity to launch a current design. Altogether, responsiveness to launch risk in today's space system can be seen to be poor.

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[4] An aerospace example of an environmental opportunity would be atmospheric thermals, which can be exploited by birds or glider pilots to increase endurance.

Demand Uncertainty: Here we refer to the demand for the capability or service provided by the spacecraft during its operational life. Demand fluctuations can occur due to a variety of factors including a change in user constituency, competing providers of the same service, or obsolescence. Demand volatility impacts the value delivered by the spacecraft. Initial demand below the full capacity of the spacecraft design can be categorized as demand risk, while increases in demand (above the full capacity of the spacecraft design) can be construed as demand opportunities. Quick reaction to demand uncertainty in today's space system architectures is currently viewed as the "niche" application of responsive space. Specifically, responsive space is seen as a response to threats that will appear at currently unknown place sometime in the future. In other more conventional (i.e., not responsive) spacecraft architectures, demand uncertainties are not addressed in a rapid manner. If a sufficient increase in demand is experienced, additional spacecraft are developed and deployed in timelines that are not particularly quick. Demand risk is accepted as just that – risk, with no current systematic way provided to first test markets before rolling out full capability.

Requirements Uncertainty: Risk related to uncertainty in requirements comes in two forms. First, there is risk due to changing requirements during a design cycle. Requirement changes throughout the development of a spacecraft can necessitate design changes with associated cost, schedule, and value penalties. Second, there is risk due to requirements causing coupled interactions between payloads and/or bus elements. This is especially true with large spacecraft where multiple requirements create a systems engineering nightmare. For example, take a spacecraft with two sensors. One stares, with very rigid pointing requirements. The second sensor rotates. Dynamic interaction between the two sensors, as well as a large spacecraft bus structure susceptible to thermal distortions, creates a difficult engineering problem. There is no systematic approach currently in use for addressing requirements risk. Requirements uncertainty can lead to opportunity. For instance, if a space system has sufficient flexibility to test and demonstrate a new capability, a new requirement can be created to fund future operational systems with that capability.

Funding Stream Uncertainty: Due to competing program budget priorities, the available funding for the development of a particular system, can fluctuate in a quasi-random manner due to innumerable factors. Funding stream risk can be, and frequently is, fatal to many systems since most space systems are deeply integrated and their performance not easily scalable (especially in the downward direction). Funding stream opportunities could occur if a program is given high prioritization and therefore more funding. Given the "craft" nature of the space industry today, programs are in reality hard-pressed to effectively and efficiently

capitalize by offering more capability per unit time. In other words, the "production line" is hard to speed up, because it does not effectively exist.

As described above, currently no systematic means for addressing uncertainty from all sources and throughout all phases of conventional spacecraft development and operations is employed. Today's space systems are thus limited in their responsiveness. This is true for all sizes of spacecraft, but especially so for large spacecraft. Why is this so? The short answer is because the problem of identifying and designing for responsiveness to a multitude of sources of uncertainty is intractably complicated and expensive. The history of various complex engineered systems has been marred by the phenomenon of cost-complexity death spirals. Spacecraft have been no exception. Whereas in principle the complexity and the cost of an engineering system should scale roughly in proportion to the system's capability, in practice this is almost never the case. The assured delivery of the capability necessitates making the system flexible and robust to various uncertainties. The array of uncertainties and failure modes itself grows with the system's complexity, and the mechanisms (the most common being design margins and redundancy) to address these potential failure modes add to it, with the resultant effect of making overall system complexity grow exponentially. The system's cost follows suit.

While engineers are trained to mitigate many sources of uncertainty in system design through redundancy, and while acquisition officials attempt to compensate for other sources through stringent contracting oversight and insurance, there is no cogent architectural framework for identifying and quantifying risk and opportunity sources and implementing optimal strategies for addressing either.

Today's spacecraft are designed for requirements. A more responsive solution is to design spacecraft for uncertainty.

The requirements-centric paradigm, together with a minimum-cost acquisition mindset has had negative consequences, having led system architects and decision-makers to reach the erroneous conclusion that the answer to cost growth is greater capability and/or increased lifetimes.[5] Consequently, longer lifetimes, more transponders per satellite, and multi-functional payloads have all been touted as panacea for the rising cost problem. Unsurprisingly, longer lifetimes have levied additional requirements in the face of system obsolescence, additional capability has led to bigger satellites posing commensurately harder

[5] See, e.g., Saleh, J., "Flawed metrics*: satellite cost per transponder and cost per operational day (*for guiding design decisions)," *IEEE Transactions on Aerospace and Electronic Systems* (accepted), 2006.

integration, testing, and launch problems, and multi-functional payloads have imposed the most stringent payload pointing and isolation environments across the entire system. The consequence, unsurprisingly, has been further cost growth and *less responsiveness* to the various forms of uncertainty.

Perhaps an even more sinister byproduct of rising system complexity is fragility. Fragility is the tendency of complex systems to exhibit "emergent" – i.e., un-modeled – failure modes, usually due to an unanticipated component interaction leading to a highly improbable but catastrophic sequence of events. Whereas a complex system can be made robust by anticipating uncertainty and designing for it, fragility tends to rear its ugly head in the most robust, scrupulously designed, and meticulously tested of systems. One need only look to the *Apollo 13, Challenger*, or *Columbia* accidents for examples.

Is this cost-complexity death spiral in spacecraft avoidable? Is uncertainty (and fragility) a manageable phenomena? Can satellites of all sizes be designed "ground up" with uncertainty in mind? We believe the answer is answer to all of these questions is a resounding "yes." Prerequisite, however, is a transformation from the gargantuan monolithic spacecraft of today to distributed networks of small fractionated spacecraft components.

THE RESPONSIVE SOLUTION

The Concept of Free Flying Fractionation

A new space system engineering architecture is now introduced which in fact provides a means to design for uncertainty. This concept is that of free flying fractionation. We use "fractionation" as a term of art to describe the decomposition of a system into distinct modules which, once "assembled" on orbit, deliver the capability of the original monolithic system. Previous and existing concepts exist which envision "lego block," "plug-and-play," and other such architectures which would enable fractionation. We depart from this path with a novel notion: fractionation can be more elegantly enabled by free flying fractionated modules in cluster orbits. The elements – or nodes – of the fractionated network are connected wirelessly. This wireless network in a sense creates a "virtual satellite."[6] So consider, for example, a conventional spacecraft with a fully wireless spacecraft bus (power and data). All "boxes" are not

[6] Note that this concept stands in contrast to formation flying concepts devised to create large arrays using homogeneous (versus heterogeneous) elements (e.g., TechSat21, Terrestrial Planet Finder). Such concepts require very precise formation control, generally to synthesize an effective payload aperture. Although the fractionated spacecraft concept could indeed be used to create large arrays, that is not the driving purpose of fractionation. Rather, flexibility and responsiveness are the primary objectives.

connected by structure, but rather are in free flight. Now, to rapidly replace a failed box, for instance (an example of responsiveness to technical uncertainty), a new replacement box needs to be launched into this cluster and commanded to "log" itself into the network. No complicated rendezvous, docking, or robotic servicing is needed.

One can conceive the fractionation trade space as being defined by three high-level metrics. First, the heterogeneous degree of fractionation is the number of functionally dissimilar modules into which a system is decomposed. Thus, for instance, a spacecraft with a separate payload, telemetry and communications (T&C), and computation and data handling (C&DH) modules would be fractionated into three heterogeneous modules. Second, the homogeneous degree of fractionation reflects the number of identical modules of a particular type. One could envision a spacecraft whose effective capability would be delivered by a handful of smaller, but otherwise similarly functional modules. Or more interestingly, a heterogeneously fractionated spacecraft as described in the example above, with multiple homogeneous C&DH modules, for instance. And the third top-level dimension of fractionation is the type of connectivity among the modules.[7] The modules could be connected by data links, for instance. Or they could also remotely determine and exchange attitude and position information. Similarly they could transmit power among themselves, or even remotely effect forces and torques.[8] A more detailed discussion of the key technical enablers for this fractionated architecture now follows.

Data Sharing

Data exchange is the most basic form of connectivity among the modules of a fractionated spacecraft. It simply involves replacing the data bus of the monolithic spacecraft with a series of wireless data links among the several modules of the fractionated one. Data exchange alone would permit the heterogeneous fractionation of at least T&C, C&DH, and payload modules. Not unlike the inter-satellite crosslinks used by Iridium and TDRSS, data exchange poses little in the way of technological challenge. A variety of technologies fall

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[7] Obviously there is no attempt to make these three "metrics" truly independent, orthogonal axes spanning a trade space in a rigorous sense. For instance the type of inter-module connectivity would be closely related to the heterogeneous degree of fractionation since power exchange would presumably imply a separate power module (or multitude thereof), etc.

[8] It may be instructive to entertain the extrema of fractionation. One can imagine a spacecraft fractionated into microscopic components – a cloud of pixie dust of sorts – whereby the components would effect electromagnetic fields and exchange photons amongst themselves to produce an effective capability equivalent to a monolithic system. This leap of the imagination is made somewhat easier by the observation that – distilled to their quintessence – most spacecraft missions involve little more than collection of photons emitted a source, some processing of this received signal, and subsequent re-radiation of photons to an interested target.

within the tradespace, including low-power, omnidirectional, spread-spectrum links analogous to IEEE 802.11 (which relax much of the relative orientation requirement between modules and permit ad-hoc addition and removal of nodes), or the emerging ultra-wideband (UWB) technology (which can also provide centimeter-precision relative position information between transceivers). Alternatively, if power is also exchanged between modules (see *infra*), the communications signal can be modulated on top of the optical or RF power beam. The overriding concern in exchanging data wirelessly is the effective exposure of the link to external interference. While encryption can ensure that the information content of the signal is not intercepted, care must also be taken in its design to provide – to the maximum extent possible – interference-resistance capabilities. Notably, both spread-spectrum and ultra-wideband technologies provide excellent anti-interference performance.

Navigation Sharing

Navigation functionality can be fractionated into a separate module responsible for determining its position and attitude in an absolute (inertial) reference frame. It could be the only module aware of its inertial position, with the rest of the fractionated spacecraft determining its position and attitude relative to the navigation module. Synergies with data, power, and perhaps even force/torque crosslinks could be exploited to yield relative distance and orientation information with minimum additional hardware.

Power Sharing

Fractionation of power generation capability into a separate module requires its wireless dissemination throughout the rest of the virtual spacecraft. A variety of means for wireless power transmission are in the trade space, the choice among which is driven largely by inter-module distance. Preliminary studies appear to favor radio frequency transmission at distances below several hundred meters, with V- or W-band frequencies being heavily favored. Beyond inter-module distances of several kilometers, laser transmission appears preferable. If power transmission only during sunlight hours is acceptable, then solar collection and redirection (i.e., without first converting the solar energy to electricity aboard the power module) promises considerable efficiency improvements over both RF and laser transmission. Induction offers yet another option which, while conveniently omnidirectional, is only efficient (for that very reason) at extremely close ranges.

Cluster Flying

We use the term cluster flying to refer to persistently proximate orbital positioning of multiple satellite modules in passively stable, Keplerian orbits. Such orbits can be constructed by effecting a small perturbation to modules which are otherwise in co-altitude circular orbits. A small eccentricity change can create a co-orbiting cluster in the plane created by radial and in-track relative motion, while an eccentricity perturbation would create motion in the radial and cross-track plane.[9] Such orbits are called halo orbits and permit a cluster of arbitrary size to be stationkept with only second-order ΔV expenditures to compensate for differential force and third-body effects.

We are careful to distinguish between our notion of cluster flying and the more commonly discussed concept of formation flying. As will be readily apparent from the subsequent discussion, fractionated architectures do not generally require precise maintenance of relative module attitude or position, but only their determination with sufficient accuracy to enable pointing of power transmission links. Thus, relative drift of the modules due to higher-order orbital disturbances is perfectly acceptable so long as relative distances and orientations do not exceed the ranges supportable by the cross-links, and so long as collision avoidance can be ensured. This alleviates the technical challenges of the relative stationkeeping problem, and instead simplifies to a rather moderately difficult question of relative navigation.

Sharing Forces & Torques

Currently on the technological horizon is the fractionation of propulsion and stationkeeping. Remote forces and torques can be effected from a designated propulsion module to the rest of the fractionated cluster. A viable approach appears to be electromagnetics, as demonstrated in a terrestrial laboratory by Miller et al.[10] Each module is equipped with three orthogonal electromagnetic coils which, when energized, can create an effective magnetic dipole in arbitrary orientation. The interaction of a pair of such dipoles produces torques and moments (which can be reacted with a reaction wheel if the desire is to induce motion in only one of the modules) that can be used for stationkeeping or cluster reconfiguration purposes.

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[9] Wertz, J.R., *Mission Geometry; Orbit and Constellation Design and Management*, pp. 519-525, Microcosm Press (2001); Bekey, I., *Advanced Space System Concepts and Technologies*, pp. 19-20, The Aerospace Press (2003).

[10] Kong, E., Kwon, D., et al., "Electromagnetic Formation Flight for Multisatellite Arrays," *Journal of Spacecraft and Rockets*, vol. 41, no. 4, pp. 659-666 (2004).

FRACTIONATION AND RESPONSIVENESS

The fractionated architecture may, at first blush, appear overly complex, massive, and expensive. But, because of its flexibility and robustness, it is responsive. With this flexibility to rapidly adapt to uncertainty comes great value. Subsequent work by the authors will address in more detail econometric tools which can indeed provide a monetary valuation of this flexibility, which in many instances more than compensates for the additional costs resultant from fractionation. Examples are now provided, in light of previous discussions, to illustrate the responsiveness of a fractionated system to the main forms of space system uncertainty.

Technical Uncertainty: The fractionated architecture allows space systems, large and small, to address technical uncertainty in a rapid manner. Technical risk, brought about because of the possibility of component failure, is reduced because of the inherent simplified mechanism of component replacement. Replacement at box, and possibly even the chip level is greatly simplified by the nature of the fractionated systems wireless architecture. As previously described, the virtual nature of the fractionated spacecraft enables component replacement to take place without the need for complex robotic servicing – rather a new component is flown into and becomes part of an ad-hoc wireless network. Technical opportunity is likewise exploited. The fractionated system can make it possible to take advantage, for example, of Moore's Law on a given spacecraft. A separate, fractionated, processor element, can be designed into a fractionated network. This element is then easily and rapidly replaced every 2 to 3 years as processor speeds double.

Environmental Uncertainty: The risks of environmental uncertainty can be addressed responsively, in much the same way as technical uncertainty is mitigated by fractionation. The fractionated network also addresses environmental risk in a second way – by target spreading. Specifically, the risk of collision with micrometeoroids or space junk will no longer be a risk to the entire space vehicle. Rather, only a given fractionated node is at risk, and it is (relatively) inexpensively and responsively replaceable.

Launch Uncertainty: Fractionated systems allow launch vehicle risk to be addressed in a unique way. By launching the elements of a fractionated system on different launches, risk is diversified: thus, not all eggs are placed in one basket. In other words, an entire investment is not lost due to a single launch failure. Brown[11] considers this problem in more detail and finds that in order to

[11] Brown, O., "Reducing Risk of Large Scale Space Systems Using a Modular Architecture," *Space Systems Engineering and Risk Management Symposium*, Manhattan Beach, CA (2004).

get a 99.9% probability of a successful on-orbit operational capability, using reasonable launch cost and fractionation "mass penalty" assumptions, the expected launch costs are nearly a factor of two lower for the fractionated system than for the monolith. Since such elements of a fractionated network are smaller and less complex, reacting to launch failure takes less time. Considering launch opportunities, the smaller the elements of a fractionated architecture, the greater the number of possible launch vehicles available for launch. It is interesting to note that a fractionated architecture allows space systems to be constructed that are so large that no launch vehicles exist today which could place a comparable monolithic system into orbit.

Demand Uncertainty: Fractionated architectures allow both demand risk and opportunity to be addressed quickly by the strategy of incremental deployment. The decision of how much capability should be designed into a spacecraft is not one that needs to be made years in advance of its launch. Instead, it is something that can be adjusted throughout the lifetime of the spacecraft by deploying additional modules. Thus, for instance, one could envision deploying an initial communications capability in the form of a power module, a T&C module, a C&DH module, and a handful of transponder payload modules. The decision to deploy additional transponder payloads could therefore be deferred until an initial operating capability is attained and the actual demand can be assessed. Individual transponder payload modules would allow for much finer "tuning" of on-orbit capacity to match demand than the double-or-nothing option available to the operator of a single large monolithic system.[12] deWeck et al.[13] have quantitatively shown that such incremental, scalable deployment can significantly impact the business case for commercial LEO communications systems. The result is generally applicable, however.

Requirements Uncertainty: By mechanically decoupling payloads from a space system, risk due to requirements uncertainty can be responded to more rapidly. If a requirement for a given payload changes, the impact does not ripple across the entire space system much in the same way it does for a conventional spacecraft today. The support systems of a fractionated network (e.g., power, TT&C, etc.) provide an infrastructure for multiple payloads. Those payloads can be launched and inserted into this network on different time schedules. Therefore, as long as the infrastructure is designed with sufficient margins, a delay in one payload's development need not impact another's. Likewise, since

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[12] Their comparatively small size would also enable more rapid fabrication and responsive launch either aboard a small "tactical" launch vehicle, or by piggy-backing off any upcoming launch to an appropriate orbit.

[13] deWeck, O., deNeufville, R., & Chaize, M., "Staged Deployment of Communications Satellite Constellations in Low Earth Orbit," *Journal of Aerospace Computing, Information, and Communication*, vol. 1, pp. 119-136 (2004).

each payload is mechanically and thermally isolated from all nodes, there is a much smaller probability that bus-payload or payload-payload interactions will drive difficult systems engineering problems. Requirements opportunities are available from this architecture much in the same way that demand risk is addressed – by allowing small demonstrator payloads to be operated within the network.

Funding Uncertainty: Funding risk is quickly responded to using fractionated systems by using incremental development and deployment strategies. As described, deployment can be incrementally conducted in order to address demand risk. This also of course has the effect of deferring cost to future funding cycles. In fact, cost deferral has additional effect of reducing total system cost due to the discounting of future year investments. Funding opportunities are more easily capitalized since ramping production of fractionated payloads can be accommodated more easily, since such payloads are less complicated to build as compared to entire satellite systems. Although not described in great detail in this paper, because of commonality amongst fractionated nodes, there is a potential that a production line-like manufacturing scheme can be created if fractionated architectures with a common standard are widely utilized.

Demonstration Program

The Defense Advanced Research Projects Agency (DARPA) has been studying the fractionated architecture concept and is poised to commence an initiative entitled System F6 – short for Future Fast, Flexible, Fractionated, Free-Flying Spacecraft united by Information eXchange, and incidentally a tornado of unimaginable strength on the Fujitsu scale[14] – that will mature the associated technological, architectural, and organizational advancements necessary for an on-orbit demonstration of a fractionated spacecraft. F6 will explore a rapid, multi-spiral design-build-test program structure, and will require the utilization of explicit quantitative system value models to support design decisions. We anticipate the formal start of the System F6 program at the beginning of FY2007 to culminate in an orbital demonstration in the FY2008 – FY2009 time frame. The end goal of the F6 program is to fabricate and space test a microsatellite-scale fractionated space system.

[14] F6 is also the fictitious mountain which reveals to its climbers more about themselves than they ever knew (or, perhaps, ever cared to know) in the brilliant play by Auden, W.H. & Isherwood, C., *The Ascent of F6: A Tragedy in Two Acts*, Faber & Faber (1937).

Conclusion

The quality of responding rapidly to uncertainty is the hallmark of responsive space systems. Fractionated architectures offer the flexibility to adapt to changed circumstance in real time. Traditional monolithic architectures, on the other hand, generally only allow for changes during the initial design phase. Thus, in response to each of the uncertainty factors faced by space systems, a fractionated architecture offers the post-design option of substituting a module, augmenting the system with an additional module, removing a module from the system, or porting a module from one system to another. These operations correspond to the various manifestations of system flexibility: maintainability, scalability, and reconfigurability. Equivalent changes can, of course, be effected in a monolithic system as well, but they can only be made during the initial design of the system or through complex and risky on-orbit servicing. Thus, the key distinction between a fractionated and monolithic system is that the former retains elements of design flexibility throughout the operational lifetime of the system. Since fractionated systems can exist across all sizes of space systems, responsive space need no longer be relegated to small, tactical, or niche systems. In fact, responsive space systems can potentially exist that are so large, that no launch vehicle exists today with the lift capacity to place them into orbit.