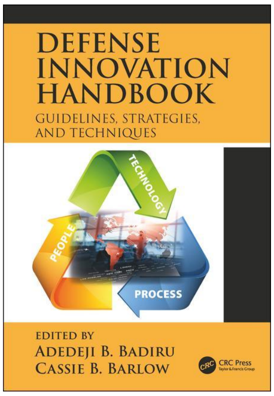

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Guidelines, Strategies, and Techniques

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chapter twenty

Innovation dynamics in the defense space sector

Zoe Szajnfarber, Matthew Richards, and Annalisa Weigel

Contents

Introduction

DESPITE a rich legacy of delivering impressive technology, government space acquisitions are frequently characterized by schedule slips and cost overruns (e.g., AEHF, JWST, SBIRS-High, GPS III) (GAO, 2007, 2016). In recent years, in an effort to address these problems, multiple blue ribbon panels have been convened. Bringing to bear the members' vast experience, working in the current acquisition paradigm of large monolithic spacecraft, their recommendations, spanning a host of technology development, requirements management, and national space policy issues, emphasize a "back-to-basics" philosophy (e.g., maturing payload technologies outside of acquisition programs) summarized in Figure 20.1. However, the sharp contrast between the pace of change in the commercial space industry and the maturity which characterizes traditional satellite providers necessitates a more

		Rumsfeld (2001)	NDIA (2003)	Young (2003)	GAO (2006)	DAPA (2006)	NRC (2008)	Munson (2015)
technology	Restore funding for testing space technologies	X			X			
	Maintain U.S. technological lead in space	X						
	Keep R&D separate from systems acquisition				X		X	X
	Identify technology for rapid exploitation and control					X		
management	Establish Presidential and NSC space advisory groups	X						
	Integrate defense and intelligence space activities	X						
	Improve front-end systems engineering (req's=resources)		X	X	X	X	X	X
	Budget programs to most probable (80/20) cost			X				X
	Evaluate contractor cost credibility in source selections			X				X
	Conduct independent program assessments at MDA's			X				X
	Do not allow requirements creep			X	X	X	X	
	Match PM tenure with delivery of a product			X	X	X	X	X
	Pursue incremental increases in capability				X			X
	Withold contractor award fees when goals not met				X			X
	Establish a stable program funding account					X		X
	Structure development to achieve IOC within 3-7 years						X	
policy	Recognize space as top national security priority	X						
	Deter and defend against hostile acts in space	X						
	End practice of appointing only flight-rated space leadership	X						X
	Incentivize government career paths in acquisitions	X	X	X		X	X	X
	Improve workforce technical competence	X		X	X	X	X	X
	Compete acquisitions only when in best interest of gov't			X				X
	Develop integrated strategy for R&D and acquisitions				X		X	X
	Encourage LSI to compete major subsystems					X		

Figure 20.1 Key findings from recent studies. (From Rumsfeld, D. et al., Report of the commission to assess United States national security space management and organization, Washington, DC, 2001; NDIA, *Top Five Systems Engineering Issues in Defense Industry*, National Defense Industrial Association, Arlington, VA, 2003; Young, T. et al., Report of the defense science board/air force scientific advisory board joint task force on acquisition of national security space programs, Office of the Undersecretary of Defense for Acquisition, Technology, and Logistics, Washington, DC, 2003; GAO, *Defense Space Acquisitions: Too Early to Determine If Recent Changes Will Resolve Persistent Fragmentation in Management and Oversight*, GAO-16-529R, Washington, DC, 2016; DAPA, Defense acquisition performance assessment: Defense acquisition performance assessment project, Report for the Deputy Secretary of Defense, Washington, DC, 2006; NRC, *Pre-Milestone A and Early-Phase System Engineering: A Retrospective and Benefits for Future Air Force Acquisition*, National Academy Press, Washington, DC, 2008; Munson, A., *Why Can't We Get Acquisition Right?* Potomac Institute for Policy Studies, Arlington, VA, 2016.)

fundamental look at how the current government acquisition paradigm can be evolved to fully leverage these structural shifts in the industry.

The operationally responsive space (ORS) paradigm pursues a fundamentally different approach to spacecraft design and operation (Cebrowski & Raymond, 2005). Rather than emphasizing the delivery of long-lived, global, high-performance space capabilities, ORS missions envision pursuing short-term space capabilities tailored for specific operational scenarios. Broadly, this trend is enabled by the halving of launch costs, satellite component miniaturization, and distributed computing. Although ORS solutions will sacrifice performance on traditional measures of effectiveness with employment of smaller

Table 20.1 Distinguishing ORS from "Big Space"

Characteristic	"Big Space"	ORS
Historical Context	Cold War	Acquisitions crisis; fragilities inherent in integral, long-life designs
Original Beneficiary	White House	Theater combatant commander
Programmatic Drivers	Performance	Cost, schedule
Payloads	Customized, satisfy multiple missions	Off-the-shelf; single-mission focus
Design Life	10+ years	1+ year(s)
Risk Tolerance	Risk averse	Risk tolerant

satellites and commercial-off-the-shelf (COTS) technology, ORS offers large improvements in schedule performance as well as an opportunity to customize capability for emergent mission requirements.[1] Table 20.1 summarizes the characteristics which distinguish the ORS concept from the current "Big Space" paradigm.

In order to assess the ability of the ORS paradigm to complement and enhance the space acquisition enterprise, this paper proposes a framework of space sector innovation challenges, which serve as a common basis for comparison. Fundamentally, the goal of defense space acquisition is to facilitate the meeting of the Joint Combatant Commanders emerging needs. This requires technological innovation; be it by generating a wholly new capability, or reducing the resources required to achieve an existing capability (e.g., making the system cheaper or lighter). Encouraging innovation (i.e., generating new capabilities to meet these unmet needs) is a difficult problem in general and characteristics of the defense space sector make it harder still; the monopsony-oligopoly market structure and complexities of the product and associated operating environment limit the ways in which natural market dynamics can drive change. Nonetheless, given that (i) innovation is an implicit requirement of defense space acquisition and (ii) there is an extensive literature and theory on innovation in traditional markets, this paper seeks to answer the following question: What are the implications of the intrinsic characteristics of the space sector (i.e., monopsony-oligopoly market structure, extremely complex robust products) on how innovation can and should be encouraged in the defence space context?

Space sector innovation challenges: Nature, approach, and potential

In order to understand the implication of intrinsic characteristics of the space market for how spacecraft innovation can and should be encouraged, three steps were taken: First, strategic mechanisms proposed in the innovation dynamics and strategy literatures were

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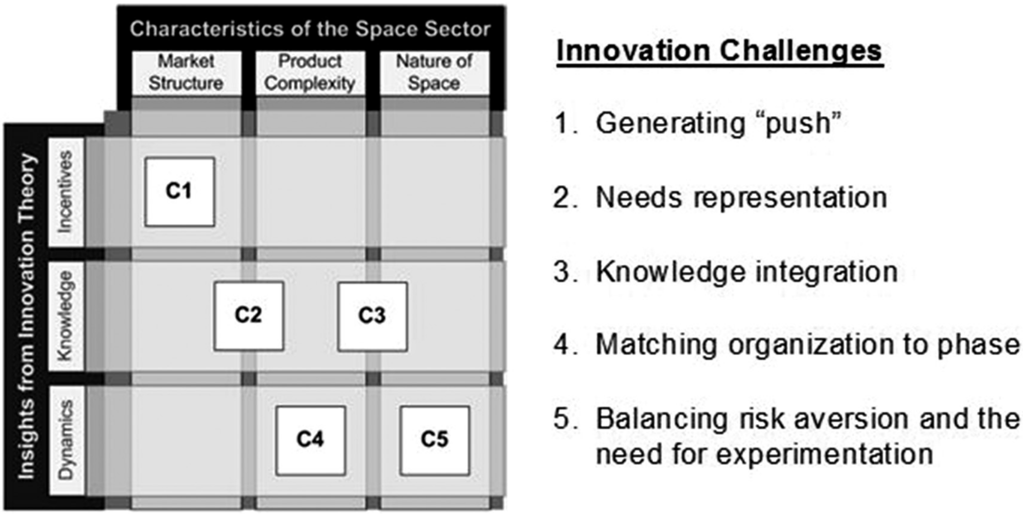
[1] The fundamental idea of ORS is to trade off the reliability, longevity, and performance achieved by satellites under the "Big Space" paradigm—the currently accepted way of conceptualizing, specifying, developing, and operating space systems—for the speed, responsiveness, and customization which may be achieved by architectures that incorporate elements such as small, modular spacecraft and low-cost, commercial launch vehicles (GAO, 2006). In addition to obtaining capability on-orbit quickly, ORS attributes include tactical control and assured access.



Innovation Challenges

1. Generating "push"
2. Needs representation
3. Knowledge integration
4. Matching organization to phase
5. Balancing risk aversion and the need for experimentation

Figure 20.2 Conceptual outline of analysis approach.

reviewed and categorized; Second, unique characteristics of the space acquisition context which could potentially limit the applicability of theories developed in other contexts, were synthesized; Finally, the interactions of the first set of mechanisms with the second set of constraints were qualitatively assessed. The results of the analysis are captured in Figure 20.2.

The rows of the matrix capture the synthesized categories of insights from the innovation dynamics and strategy literature.[2] Starting from Schumpeter's basic supposition that long term economic growth can only be sustained through the entry of innovative entrepreneurs and the necessary value destruction of established (monopolistic) companies (Schumpeter, 1934), much of the business literature on innovation dynamics, developed over the subsequent eighty years, has addressed the question of why successful firms fail to traverse the discontinuity imposed by radical innovations. There are three complimentary ideas. One school of thought, epitomized by the Teece (1986) profit model, argues that innovation happens most effectively when the innovator profits from his efforts. It follows

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[2] In order to focus this survey on the work that is most relevant to evolving management of innovation in government space, two related scoping decisions were made. First, literature focusing on commercialization and diffusion were de-emphasized. Although definitions of innovation typically combine the concepts of new and implemented, and in traditional markets, implemented is synonymous with commercialized (i.e., bringing an invention to market), in the space context, "implemented" means being integrated into, and flown on, a flight system. The fact that a flight system is often the only one of its kind, never to be mass produced or marketed, does not change the fact that the invention has been useful—the standard that differentiates an invention from an innovation. This is consistent with the way the term is used in the defense context (c.f., Sherwin and Isenson, 1967; Rosen, 1994; Grissom, 2004). Second, this framework relies strongly on innovation models developed pre-IT revolution and global networks of innovation. This is because the firms of that era are more representative of the defense space enterprise of today, than the modern innovation contexts analyzed in more modern studies. Given the national security context and the secrecy (i.e., open collaboration and information exchange across borders and industries is explicitly prohibited), their insights do not capture a realistic goal for the evolution of acquisition (this point is elaborated on in the section on space characteristics, in the body of this paper).

that established firms—who continue to profit from previous innovations if the status quo is maintained—will use their market power to resist competence destroying change (Stigler, 1971). We call this class of innovation mechanism "incentives." Another perspective is that incumbent firms don't fail to traverse discontinuous change because of a lack of capability; rather, it is because they remain focused on the needs of their core/mainstream customer until it is too late (Christensen, 2003). Further, even when a firm does recognize the need to address a new market base, there are multiple types of competence that can be destroyed by even seemingly small changes (Henderson & Clark, 1990). We call this class of mechanisms "knowledge." Finally, as articulated by Schumpeter, and supported by later empirical work (Utterback, 1994), the cycle of establishment and destruction is natural in a healthy market, and should be harnessed but not interfered with. We call this class of mechanism natural "dynamics."

Similarly, the columns of the matrix categorize intrinsic characteristics of the space sector as (a) market structure, (b) market complexity, and (c) nature of space. Firstly, the space "Market Structure" is relatively unique in that it is effectively a monopsony (single buyer) oligopoly (few sellers) contract market, which has implications for how transactions occur (Adams & Adams, 1972; Peck & Scherer, 1962). Secondly, spacecraft embody significant "Product Complexity." Each subsystem is itself a complex system; many disciplines, and many organizations are involved in each new acquisition; and multiple different levels of maturity exist simultaneously in any given system. While this characteristic is not unique to spacecraft, it has important implications for how maturity can be conceived (Sauser et al., 2008). Third, the "Nature of Space" has implications of its own. Space is a harsh, remote environment, with implications for system characteristics like survivability, serviceability etc. Space acquisitions represent an enormous public expenditure, bringing in questions of accountability and significant media attention. Further, as a strategic asset, space systems and their components are subject to stringent security protocols (e.g., ITAR, reduced communication across boundaries) and significant risk aversion.

After defining the rows and columns, the interactions of each of these innovation mechanisms and space sector characteristics were examined in detail, leading to the identification of five fundamental challenges for innovation in the space sector. Specifically: (1) generating bottom-up push in a predominantly top-down acquisition process, (2) representing the needs of a disaggregated buyer, (3) integrating fragmented sell-side knowledge from the top-down, (4) matching the innovation environment to the stage of development, and (5) balancing risk aversion and the need for experimentation. The discussion, in the sections that follow, is structured around these five challenges. In the remainder of the paper, the nature of the challenge is first explained in terms of the impact of characteristics of the space sector on the ability of mechanisms capable of encouraging innovation in *traditional* markets to function. Second, the current acquisition system is examined to determine how and to what extent it overcomes each of these challenges. Third, the ORS paradigm is evaluated to determine how, and the extent to which, its philosophies can be applied to improve the broader spacecraft innovation process.

The challenge of generating "bottom-up" push in a predominantly top-down acquisition process

Taking a classical economic view of innovation, market transactions are thought to be the fundamental driver of innovation. In a competitive market, both the consumer's needs and the supplier's capabilities are revealed through the mechanism of price (Adams & Adams, 1972). Innovation occurs (i.e., unmet needs are met) over time, through the continuous interaction of market pull and capabilities push (Rothwell & Zegveld, 1994). However, the market for spacecraft is neither competitive on the buy-, nor sell-side, and this holds important implications for innovation. Firstly, a monopsony market is discrete and specific since the market only exists when the buyer wants to buy, and as a result, user needs must be specified explicitly since there is no aggregate buyer behavior out on the open market from which they can be inferred. Further, in the stable oligopoly that exists on the space sector sell-side, there is little incentive for contractors to invest in innovation on their own; they tend to innovate in response to government requests.

In the traditional market conception (as illustrated in Figure 10.2), transactions can occur in one of two ways. Products are either sold by a third party retailer in a store, in which case prices are relatively standardized (i.e., every person will be charged the same amount for a given capability). Or, more customized products (i.e., a new roof for a home) and the labor associated with their installation are contracted directly with the supplier. Even in this case, enough sufficiently similar transactions occur to establish a market price. For the most part, buyers are limited to whatever is currently available on the market; however, the state-of-the-art is constantly changing to meet new needs. For example, if you decided to replace an iPod that was bought three years ago, in today's market you would expect to be faced with a different set of better model choices. Although you personally hadn't continued to reveal your preferences through ongoing purchases, the other millions of consumers had. Thus, as long as your values align with those of the general market, the continuous market feedback process will have driven innovation to create a next generation iPod model that better suits your needs.

Where in the traditional case, buyers are limited to what's available on the market, in the space sector, the government is the whole market; if the government doesn't buy it, it won't be sold. As a result, the buyer's needs and preferences must be revealed explicitly, thereby dictating what should be produced. Further, while a monopsony buy-side does not preclude price-competition among sellers (Adams & Adams, 1972), the earlier iPod example should give an intuitive understanding of why the incentives for such competition are weak. Specifically, the market growth potential is limited by the needs of the government, the profit margins are relatively small compared to commercial industries[3] and the barriers to entry are high as significant complementary assets and specialized knowledge are required for satellite manufacturing. These factors all contribute to the sell-side oligopoly that exists in the government space sector, resulting in the suppression of bottom-up capability development.

Extent to which the current Department of Defense structure resolves the issue

In order to generate the necessary technology "push," the Department of Defense (DoD) acquisition process employs a two-tiered organizational structure focused on (1) research and development and (2) formal acquisition programs. Initial technology development within the DoD is conducted by the Service Laboratories (e.g., Air Force Research Laboratory, Naval Research Laboratory, Army Research Laboratory) and several science and technology (S&T) organizations such as the Air Force Office of Scientific Research, the Office of Naval Research, and the Defense Advanced Research Projects Agency (DARPA). These latter S&T organizations are focused primarily[4] on a research-level investigation of

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[3] The risk level for profit on government contracts varies with the type of contract vehicle used; more risk for firm-fixed-price contracts, less risk for cost-plus contracts. In the past, the government has often, but not exclusively, used cost-plus contracts for satellite procurement. But in the future, the government is expected to move to greater use of firm-fixed-price contracts for satellites.

[4] DARPA may also fund Advanced Technology Demonstrations.

basic physics and phenomenology. As these S&T organizations demonstrate concept feasibility, technologies are transferred to the Service Laboratories for further development, maturation, and demonstration of capability. Once these innovation organizations mature concepts to the point where they can be realistically assessed for cost, schedule, and performance contributions to a given set of program requirements, they may be considered as part of the Joint Capabilities and Integration Development System (JCIDS).

Figure 20.3 takes a highly simplified view of the acquisition process to illustrate how the two-tiered process generates the necessary push, despite its top-down structure. In Figure 20.3, capability-push is denoted with hashed arrows and need-pull with solid arrows. Nominally, the formal part of the acquisition process matches user needs with relatively mature technologies to drive system-level innovation as dictated by the innovation theory. However, that pool of capabilities is not being created and marketed by the supply-side as would be the case in a traditional market. The lead on technology development efforts is still primarily the domain of the government, albeit a separate branch (both organizationally and culturally). The lab structure, as described earlier, contributes in two main ways: they conduct fundamental research in areas that may one day be of use to the Joint Combatant Commanders, and they fund technology development contracts and studies. Although these contracts tend to be less specific than formal acquisitions, they follow the same general pattern; the customer identifies a need and puts out a request for comment, based on the response a more formal request for proposals is released, leading to a contractual relationship.

As a result, rather than the confluence of pull-push forces which drive innovation in a traditional market, the space drive is characterized by a coordinated pull-push-pull. One key disadvantage of this approach to top-down capability generation is that it creates a situation where much of the investment in product development for space applications originates from the government (Sherwin & Isenson, 1967). Also, while this system does technically create the required push, it is a fundamentally different push force than the independently supply-side initiated one described in the traditional market. The implication of this difference will be discussed in the sections that follow.

The potential improvements offered by operationally responsive space

Operationally Responsive Space has been defined broadly by the Department of Defense as "assured space power focused on timely satisfaction of Joint Force Commanders'

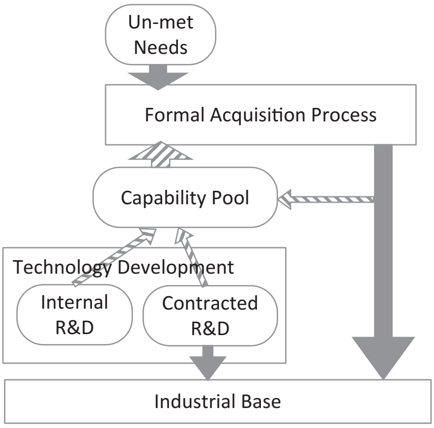

Figure 20.3 Capability generation in the acquisition process.

needs…while also maintaining the ability to address other users' needs for improving the responsiveness of space capabilities to meet national security requirements (DoD, 2007)." The purpose of ORS is to reduce the time constants associated with space system acquisition, design, and operation. ORS intends to enable rapid responses to changes in space capabilities by supplementing them quickly when they are lost, with lesser but still useful capabilities. In terms of the structure described in Figure 20.3, ORS is typically grouped into the category of technology development; however its functions really span both the roles of technology development and spacecraft acquisition. This has two key implications with respect to issue 1 (i.e., that the monopsony-oligopoly market structure enforces a top-down acquisition process).

First, by shifting to a greater reliance on standardized satellite buses and payload modules, ORS envisions lowering the barriers to entry for satellite suppliers by defining a potential future market for unarticulated products around common interfaces. If this *plug-and-play* market is successful it may generate more bottom-up initiative from the space industrial base and provide avenues for small, innovative companies to enter the DoD market. This process will be encouraged through a model of seed-funding rather than development contracts.[5] Where the historical lab structure, to a first order approximation, specifies a need and pays for the development required to meet it, the seed-funding model would allocate funding to firms in the early stages of a promising development. Conceptually, the difference between these two approaches is significant; the latter has the potential to reach non-traditional space firms and leverage bottom-up initiative, where the former perpetuates the traditional pull-push-pull. It remains to be seen whether the practical difference will be significant.

Secondly, the emphasis on rapid development cycles might create a more continuous innovation environment. One of the problems with the discrete nature of a monopsony market, as discussed earlier, is that it limits the opportunities for new capabilities to be "needed," while at the same time placing a high premium on major inter-generational improvements. Both of these factors serve to limit the incentives for bottom-up initiative. What the ORS paradigm may change (from the point of view of generating real push) is to create a more frequent market for incremental improvements. If there is a clear opportunity to capture the value of taking the functionality of a spacecraft beyond the specification, contractors may be more inclined to take the initiative.

The challenge of representing the needs of a disaggregated buyer

The necessity for a top-down process as described previously could theoretically foster ideal conditions for innovation because a knowledgeable buyer could: (1) decrease information asymmetries in the transactions by eliminating the need for suppliers to infer the future preferences of potential buyers; and (2) encourage investment in R&D by specifying sufficiently advanced needs that can only be solved through radical innovation. However in practice, the specialized knowledge required to drive change is fragmented across the space market structure, limiting the effectiveness of both 1 and 2 above. This section explains why knowledge fragmentation on the buy-side limits the efficiency of needs specification; the next section addresses how sell-side fragmentation exacerbates the challenge of integrating bottom-up push with top-down pull.

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[5] As reported in an interview conducted by the authors with Dr. Adang, representing the recently stood up ORS office (2-26-08 1:00-2:30 EST).

The situation where sellers only make what buyers want, but can't currently get, could be an ideal environment for innovation. Where the business strategy literature emphasizes the importance of downstream aspects of the innovation process[6] (Bhide, 2008), in the space market, nearly everything that is developed is adopted. Similarly, on the upstream side, Von Hippel argues (as for e.g., in Ref. (Thomke & Hippel, 2004; von Hippel, 1988)) for increased emphasis on capturing lead user innovation. The idea is that people who actually use the product will be more likely to find its limits and potential extensions than engineers in a lab environment. In the DoD context, where the buying function nominally includes both use and needs specification, one might expect lead user innovation to be captured naturally. However, when the monopsonist buyer is as complex as the US government, incorporating multiple disaggregated interests, the assumption that the buyer knows what it needs is not always accurate.

As shown in Figure 20.4, in the traditional market conception, buyers are a relatively homogenous group of individuals or firms acting in their own interests. They determine what to buy based on an internal evaluation of their relative wants, budget and what is available on the market. However, in the government acquisition context, this evaluation is made among several independent organizations, based on presumed capabilities. Specifically, while the nature of the monopsony buyers' interests (i.e., those of the Department of Defense as a whole) is not dissimilar to that of the traditional buyer, in practice, having the interests disaggregated across organizational boundaries makes a

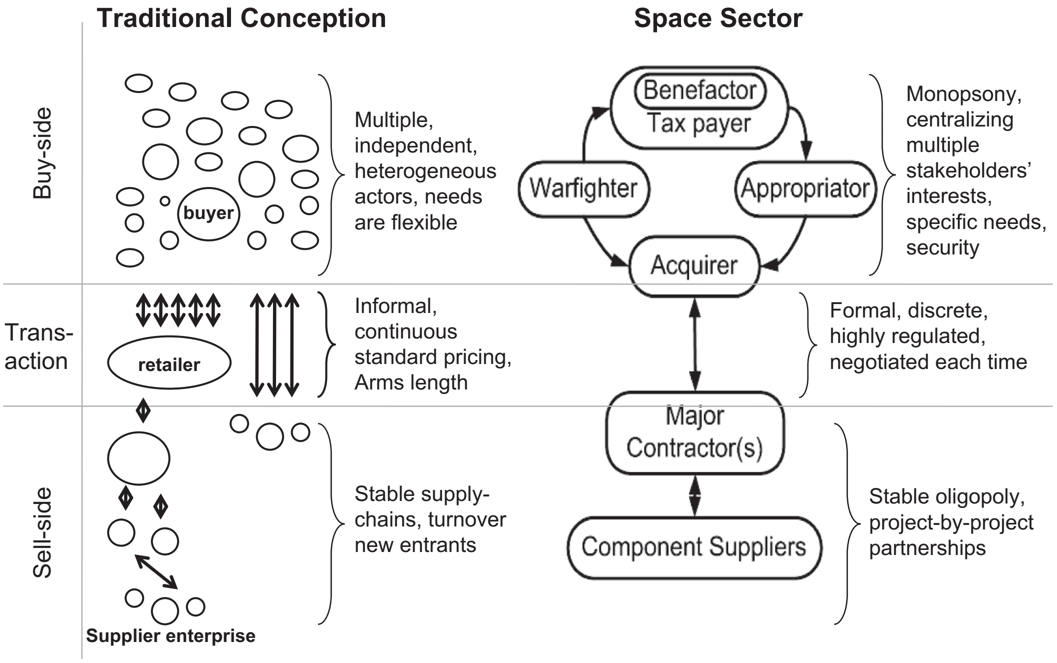

Figure 20.4 How the space market is different.

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[6] For example, Bhidé argues that innovation depends as much on the user's willingness, and ability, to adopt new products and technologies, as the development of those products and technologies themselves.

significant difference. Rather than making an internally consistent determination of preferences, acquisition agents must integrate the inputs of needs (as expressed by the warfighters who use the system and possess the best understanding of how different systems will affect them operationally), budgetary constraints (as imposed by Congress which appropriates the funds and has the best appreciation for how spending in one sector will affect the overall national purse) and technical feasibility (as inferred from industry studies, in-house experts and through the contracting process). This creates a principal agent problem and complicates the needs representation process significantly. The key implication is that the ability of the space buyer to drive the radical innovation expected of spacecraft acquisitions is limited by incomplete architectural, component, operational and budgetary knowledge; all of which play an important role in driving change.

Extent to which the current Department of Defense structure resolves the issue

The short answer is that the acquisition structure does not address the knowledge disaggregation problem well. In fact, *challenge B* (i.e., needs representation) is in a sense a bi-product of the complex organizational structure that exists to resolve *challenge A* (i.e., insufficient bottom-up push). In the current DoD acquisition process, the intersection of what is possible and what is useful, is nominally identified through a series of "gap analyses" performed as part of the Joint Capabilities Integration and Development System (JCIDS). However, in practice the complexity of integrating the needs of such a disaggregated buyer as the US government leads to significant shortcomings in JCIDS' realization.

One critical aspect of prioritizing "next" acquisitions is in soliciting and integrating inputs from the operational arm of the DoD—the user warfighter. While it is relatively well accepted that a warfighter has a unique understanding of the impact of performance tradeoffs on operational utility, and should thus be consulted to help refine needs; the extent to which a warfighter can contribute to the capability generation side of the innovation process is less well understood. When von Hippel's theory of lead-user innovation[7] (von Hippel, 1986) is extended to the acquisition context, warfighters are often identified as analogous to lead users because self-preservation is the highest possible incentive to innovate (Frisbee, 2003). To date, much of the empirical research on lead-user innovation has centered on systems that are either software intensive (e.g., personal computer—Computer Aided Design software (Urban & von Hippel, 1988)). Online public access library software (Morrison et al., 2000) or personal-use expert systems (e.g., canyoning, sailplaning, boarder cross and paracyclists' equipment (Franke & Shah, 2003)). While some of the findings from these studies may generalize to government acquisition systems, key differences make the analogy suspect. Specifically, the cost of changing military systems is prohibitive,[8] warfighter culture emphasizes acceptance of the status quo and uniformity of equipment, and individual warfighters do not necessarily have the required knowledge to make substantial changes to the systems they use (particularly in the space context). Despite all these caveats, refining our understanding of lead-user innovation as it applies to complex products developed in government enterprises has the potential to lead to an improved approach to collecting and interpreting warfighter input into the acquisition process.

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[7] Which asserts that users who (1) face needs in advance of the market at-large and (2) are positioned to benefit significantly by obtaining a solution to those needs, represent an important source of innovative product concepts.

[8] Developed over multiple years and designed to last for a decade or more, transition costs measure in the billions.

The potential for improvements offered by operationally responsive space

Given the extreme specialization required to develop and manage national security space assets, a large degree of organizational decomposition is inevitable. However, ORS does show some promise in reducing the magnitude of this principle agent problem. In addition to mitigating the complexity of traditional space assets by nature of a smaller, less-capable design paradigm, the ORS approach brings the warfighter closer to the acquisition process through its simplified concept of operations. On the front end, the tactical control provided to the warfighter by ORS assets may enable the lead-user innovation discussed in the previous section. On the back-end, the direct downlink of satellite data to the warfighter (removing traditional layers of analysis) may concretize the value of alternative satellite capabilities for improved needs representation in future satellite developments. This hypothesis will need to be tested over time.

The challenge of integrating fragmented sell-side knowledge from the top-down

The existence of a top-down acquisition structure presents a unique opportunity for the monopsony buyer to take a long-term, coherent perspective on driving innovation to their benefit. However for this to happen effectively, not only does the buyer need to know what they want, they also need to know what is possible. In practice, this proves extremely difficult since the required knowledge is fragmented across the space sell-side.

The innovation literature has historically differentiated between two types of innovation: incremental and radical (see e.g., ref. (Abernathy & Clark, 1993; Anderson & Tushman, 1990)). Incremental innovations are competence-enhancing; they generate a product that is better along dimensions that are familiar within the current paradigm. Radical innovations, on the other hand, are competence-destroying; they typically take a different approach to solving the same problem. For example, building bigger communication satellites that can carry more transponders would be an incremental innovation approach to increasing capacity, while developing a new method of performing on-board calculations (e.g., use of integrated circuits over core transistors on Apollo) is a way of addressing the same problem with a radical innovation. If established suppliers are driving change, not surprisingly, there is a tendency to avoid competence-destroying change (Christensen, 2003); on the other hand, if change is driven from the top, as in the space sector, by specifying sufficiently advanced needs, radical change may be the only option, thereby legitimating the risk.

However, in more complex product systems, Henderson & Clark (1990) observed that more than one type of knowledge is required to generate radical innovation. They differentiated between component level knowledge and architectural knowledge (i.e., knowledge of the linkages between components), which leads to a two dimensional spectrum of innovation types as shown in Figure 20.5. When these categories of knowledge are mapped onto the space market structure (see Figure 20.4), they are concentrated on the sell-side and divided between system integrators and component suppliers. This means that while acquisition agents may be in a position to drive radical innovation, they may not have all the knowledge required to do so. Further, unlike in the traditional market conception, where firms tend to establish stable supply-chain relationships (which enable them to integrate both component and architectural knowledge), in the space sector, stable relationships are effectively discouraged by the project-by-project acquisition structure. This further complicates the problem of determining the feasibility of future projects.

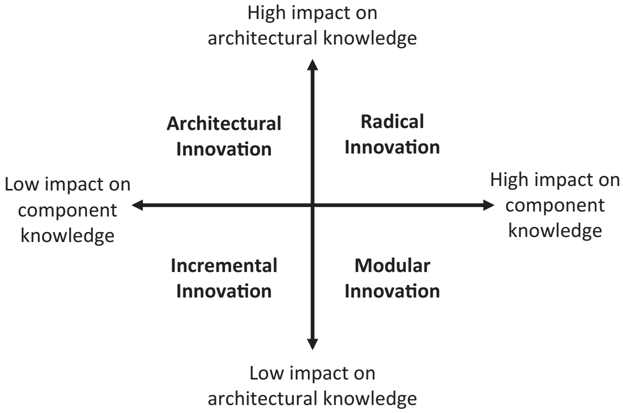

Figure 20.5 Knowledge required for innovation. (Adapted from Henderson, R. and Clark, K., *Adm. Sci. Q.*, 35, 9–30, 1990. With permission.)

Extent to which the current Department of Defense structure resolves the issue

Challenge C, the challenge of integrating fragmented sell-side knowledge, has been addressed differently over the history of the space age. Initially, significant in-house technical expertise was cultivated among government buyers and significant oversight spanning the entire sell-side supply-chain was common practice. The government buyer adopted the risk through cost-plus contracts, but retained design authority giving them the ability to intervene when contracts were not being executed as desired. More recently, as cost control became a primary focus, the role of system integrator has been delegated to industry contractors, with technical development subsequently delegated to subcontractors. The idea was that profit maximizing firms will allocate resources more efficiently. However in practice, the interests of industry do not always align with those of the government, limiting the effectiveness of the relationship. Coupled with the fact that the delegation of the oversight role has lead to a decrease in the technical competency of the acquisition core (NRC, 2008), this trend has exacerbated the challenge of integrating sell-side knowledge rather than helped. In fact, improving collaboration on requirements and increasing the technical competence of the acquisition core, are two of the nearly unanimously recommended remedies in the "blue ribbon" reports (see Figure 20.1).

The potential improvements offered by operationally responsive space

The ORS structure may lessen the knowledge disaggregation problem through its streamlined organization. Just as the rapid development cycles pursued by the ORS Office may strengthen the DoD industrial base by providing more opportunities for small, innovative firms, the approach might also improve the technical competency of space professionals by providing more opportunities for mid-career program managers to manage small-scale projects. As noted in a GAO report (2006), Navy and Air Force lab officials have found that the TacSat experiments have provided more hands-on and lifecycle management experience than would otherwise be possible on larger acquisition efforts.

The challenge of matching the innovation environment to the stage of development

The remaining two challenges relate to the nature of the "push" that must be generated. To this end, Utterback and Abernathy (1975, 1994) observed that the innovation process

Table 20.2 Phases of innovation process

	Fluid phase	Transitional phase	Specific phase
Innovation	Product changes/radical innovations	Major process changes, architectural innovation	Incremental innovations, improvements in quality
Product	Many different designs, customization	Less differentiation due to mass production	Heavy standardization in product design
Competitors	Many small firms, no direct competition	Many, but declining after the emergence of a dominant design	Few, classic oligopoly
Organization	Entrepreneurial, new entrants	More formal structure with task groups	Traditional hierarchical organization
Threats	Old technology, new entrants	Imitators and successful product breakthroughs	New technologies and firms bringing disrupting innovations
Process	Flexible and inefficient	More rigid, changes occur in large steps	Efficient, capital intensive and rigid

Source: Utterback, J.M., *Mastering the Dynamics of Innovation*, Harvard Business Press, Cambridge, MA, 1994.

proceeds in three phases—fluid, transitional, and specific, as shown in Table 20.2. During the fluid phase, the emphasis is on just getting the product to work. Lots of new, and very different, radical ideas are being tried. Some work, but many don't; it's a time of free experimentation. As a result of the high risk associated with this type of endeavor, the fluid phase is often carried out by entrepreneurial start-ups or single inventors working out of their garage. The goal is to prove-out the concept to the point that a larger company will buy-into the idea and facilitate its commercialization. Thus begins the transitional phase.

During the transitional phase, the emphasis is on making the invention mass producible. As a result, the product innovations tend to be architectural in nature. There may continue to be many players in the industry, but the number drops quickly after a dominant design emerges (e.g., the QWERTY keyboard set the standard for physical interfaces to computers). Where entrepreneurial organizations are best suited to the free experimentation required for the fluid phase, a more formal structure is required to standardize and commercialize the product in the transitional phase. And, once the standardization has occurred, this marks the beginning of the specific phase.

During the specific phase, the goal is to optimize the design within the framework of the dominant design. Changes tend to be incremental, reducing costs and increasing quality as the process improves. As the manufacturing process becomes increasingly specialized, investment in complementary assets leads to a market composed of few established firms with strong market positions. Unlike in the fluid and transitional phase, where the biggest threats are a lingering perception that the old way is better and losing out to competitors working in the same phase, in the specific phase, the biggest threat is complacency. There will always be entrepreneurial firms bringing in disruptive innovation; and so the cycle repeats itself.

There are very clear differences between the types of organizational environments that enable each phase of innovation. In the traditional market, different structures can easily be applied in each phase because the phases proceed relatively sequentially and distinctly. However, space products tend to integrate elements of each phase making the process harder to decouple. For example, many spacecraft are (1) fluid phase prototypes at the system level, in that they are accomplishing a task that has never previously been

Table 20.3 Phases of innovation in the acquisition system

	Technology development	Program acquisition
Innovation	Component/subsystem focus, some radical Innovation but mostly incremental	System level focus architectural innovation (major systems changes, minor component changes)
Product	Initially, as many different designs as funding allows (often few); later, heavy standardization	Two or three preliminary designs, but typically only one developed
Competitors	Few, classic oligopoly (even less for program acquisition)	
Organization	Siloed, hierarchical, but maintains research culture	Matrix organization
Threats	Resistance to change, funding cuts	Scope creep, funding cuts, political changes
Process	Less rigid, but still contract milestones	Inefficient, capital intensive, changes occur in large steps

accomplished; (2) built out of transitional components on the way to being standardized; and (3) machined using highly specialized specific phase equipment. As a result, the supporting organization incorporates elements of each phase, but is not optimized for any.

Extent to which the current Department of Defense process resolves the issue

In addition to generating the necessary capability push (as discussed in challenge 1), the “formal acquisition”/“technology development” separation has the effect of creating different innovation environments for different phases of development. These differences are highlighted in Table 20.3. For funding purposes, the capability development process is divided into seven categories; basic research (6.1), applied research (6.2), advanced technology development (6.3), demonstration and validation (6.4), engineering and manufacturing development (6.5), RDT&E management support (6.6) and operational systems development (6.7). Categories 6.1–6.3 are typically carried out in the research laboratories, while categories 6.4–6.7 are incorporated into the formal acquisition structure.

The cultures of the two tiers of acquisition are quite different, as desired. Especially for the 6.1–6.2 funds, the work is primarily contracted out to universities and research institutes or performed by in-house scientists. The nature is exploratory and the expected time frames for results relatively long (i.e., 15–20 years, although more emphasis has been put on near term focus, 5–10 years, of late (AFRL, 2009). As the concept matures (6.2–6.3) the emphasis on military usefulness increases. Projects are expected to show obviously useful areas of application; as a result, there is pressure to focus on near term development. For both the fundamental and applied research, projects may be siloed by discipline and collaboration across disciplines may be limited. On the formal acquisition side, the emphasis is obviously on immediate usefulness in the project and there is an expectation that the technology is mature and nearly ready to be implemented. The innovation at this stage primarily involves integrating the system components to accomplish a new task, although some emphasis on technical maturity persists, for example, through technology demonstrations.

While the acquisition system described earlier does nominally divide the spacecraft innovation process into phases, each of which has different expectations and cultures, the categories and strategies in each do not align with either the Utterback-Abernathy (1975) or Henderson-Clark (1990) model of innovation. Firstly, the research environment of the DoD technology development phase has a completely different effect on innovation than the entrepreneurial inventing environment of the fluid phase. Research is about exploration without a strong focus on how the results can be applied, while inventing is about taking what's known and making it useful. Research is collaborative, building on colleagues' insights; inventing is about competition—being the first to figure it out. Of course, inventors need research to be done, to generate new "knowns," but, it is inventors who generate the "creative destruction" at the heart of economic growth and innovation (Schumpeter, 1934). Thus, while 6.1–6.2 funds, and the laboratory structure, may generate breakthrough fundamental research, the applied value of those efforts won't be fully captured unless they get into the hands of inventors. This is the real implication of the lack of natural bottom-up push; an entrepreneurial environment is extremely difficult to manufacture and without it, innovation suffers.

The second limitation of the technology development and formal acquisition categorizations is that the former focuses primarily on developing component knowledge, leaving the dimension of architectural knowledge to the latter. This is an effective approach when the system level change is modular (Figure 20.5) as is the case with, for example, incorporating an advanced communication payload into a satellite with an otherwise standard architecture. However, when the system-level change is architecturally or radically innovative, mature component technology does not necessarily align with existing system program offices that are structured around legacy subsystem boundaries. Technology readiness needs to be defined along both the component and architectural dimensions.

The potential for improvements offered by operationally responsive space

The challenge of matching the innovation environment to the stage of product development identifies a fundamental limitation of the formal acquisition system. In the existing acquisition paradigm, the product development required to enable future missions is conceptualized as a linear progression from TRL 1-9. With this view in mind, the blue ribbon panels call for increased funding for technology testing. However, while increased funding for technology development is a needed step in the right direction, it only addresses part of the problem. It fails to appreciate the difference between architectural and component dimensions of knowledge and what that means for system level maturity. If the rest of the problem is to be addressed, there is a need for more than two organizational tiers: one for each of the three phases as well as the dimensions of component and architectural knowledge.

As discussed previously, ORS has the potential to incentivize (more) entrepreneurial contributions to space capability development and cut across the traditional tier system by emphasizing architectural innovation. By focusing on disruptive approaches to system-level integration of existing technologies (e.g., modular plug-and-play satellites), the ORS Program Office complements traditional technology development efforts focused on improving components and subsystems. The collective structure of an ORS office focused on architectural innovation and existing labs focused on technology development is well-aligned with the Henderson-Clark model of innovation in which product maturity is a function of both technology readiness and a readiness for system integration.

The independence of the ORS Program Office from existing organizations may also address other limitations of the formal acquisition system. As discussed in Frostman (2007), separation of entrepreneurial business units from mainstream business practices is important to prevent suppression of innovation. By focusing on operational experimentation for meeting existing requirements, ORS acquisitions are exempt from a traditional JCIDS approach. In addition, by emphasizing modular and flexible designs, ORS is able to rapidly integrate component-level technology innovation and may demonstrate the value of a more flexible design paradigm, for the current acquisition system. ORS platforms may also complement existing traditional space architectures by providing test beds for the on-orbit experimentation and maturation of emerging technologies outside of large scale acquisition programs—consistent with the "back to basics" philosophy.

The challenge of balancing risk aversion and the need for experimentation

Perhaps the biggest difference among the three phases is the extent to which innovation can be planned. Once a dominant design emerges (in the transitional phase) innovation can be achieved by systematically making incremental improvements along particular dimensions, but until that point, there is much less certainty about what will work. In the transitional and specific phase, increasingly formal organizational structures are put in place, and those structures facilitate the optimization aspect of the innovation process. Conversely, the fluid phase start-ups have very little in the way of formal organizational structure, in part because they are so transient. Many innovations fail to make it out of the fluid phase; in fact most successful entrepreneurs failed several times before they succeeded; and fail again many times afterwards. These are not risks that big companies typically take; it requires an undying belief in one's product that is often associated with entrepreneurs (Casson et al., 2006). As a result, society doesn't have a high expectation for the success of start-ups and it's not remarkable when they fail. This is not the case with space systems.

The critical mission areas fulfilled by government space programs and the drive for investor return in the commercial space industry, combined with the high cost of space systems, has led to an extremely risk-averse industry. Although decreasing launch costs are mitigating this to some extent, unlike in the fluid phase of traditional markets (where inventors get little attention until they succeed) space projects are highly visible (reinforcing the need to succeed the first time). However if radically different solutions are to arise, there is a need to shelter innovators from the constraining pressures of success.

Extent to which the current Department of Defense structure resolves the issue

The high cost of launching spacecraft combined with a focus on traditional strategic measures of effectiveness in the space industry (e.g., optimize cost-per-function) has driven US space architecture from an era of single-payload, short-lived spacecraft to the current state of multi-payload, long-lived systems. While this design philosophy is justified on the basis of economic arguments associated with the high initial cost of spacecraft and enabled by improvements in supporting subsystems, this design philosophy also has many negative implications. For example, noting that space system developments now take five to ten years, Brown (2007) describes how "complexity has bred fragility" in terms of unanticipated modes of failure. Such unanticipated modes of failure include an acquisitions crisis (Young et al., 2003) where development problems with an individual sensor can cripple the schedule and budget of multi-payload programs (e.g., the National Polar-Orbiting Environmental Satellite System), on-orbit failures that circumvent margin and redundancy (Leveson, 2004), and uncertain technological change.

The blue ribbon panels' recommendations (Figure 20.1) emphasize the need to conduct more technology development outside of programs of record. This will have the positive effect of sheltering high-risk developments from the public eye, but it only addresses the component level issue. As discussed earlier, system integration is, at a minimum, architectural innovation (but often radical innovation) and requires a fluid phase of free experimentation too. Without more system level technology demonstration missions, or a change in expectations regarding first-time mission success, innovation will be stifled.

The potential for improvements offered by operationally responsive space

To better balance risk aversion with the need for on-orbit experimentation, a major philosophical shift is needed in how space systems are designed and operated. In this case, "back to basics" might mean a return to the CORONA paradigm (e.g., recall that 12 launches of the revolutionary CORONA photoreconnaissance satellite were required before a successful demonstration of film capsule recovery on the 13th flight (Wheelon, 1995)). Advanced spacecraft must be sheltered from failure-is-not-an-option mentality, if the desired radical innovation is to be achieved.

ORS represents a major change in mentality, shifting from a performance oriented risk-averse paradigm, to a "good enough" approach; trading some failures for cost and schedule (Richards et al., 2008). While pursuing a "good enough" approach may increase risks of individual satellite failures, the approach may actually enhance the overall resilience of space architecture. For example, in addition to obtaining capability on-orbit quickly and providing the warfighter tactical control, a key attribute of ORS is assured access. Assured access refers to the potential ability of small, tactical spacecraft to be used to partially reconstitute Air Force space mission areas (i.e., Intelligence, Surveillance, and Reconnaissance; Position, Navigation, and Timing; Communications; Environmental Sensing; Missile Warning; and Space Control) should adversaries negate existing space capabilities (Cebrowski & Raymond, 2005). If this radical shift in organizational priorities can be achieved (and the ORS economic assumptions are validated), it may allow for risks associated with on-orbit failures or losses to be mitigated architecturally rather than the customary (and costly) approaches to reliability and survivability at the satellite-level. The Iridium constellation (Garrison et al., 1997) of 66 active satellites (with a reliability requirement of only 58% for a five-year mission) exemplifies this architectural approach to risk management.[9]

Way forward

This paper set out to answer the question: What are the implications of the intrinsic characteristics of the space sector (i.e., monopsony-oligopoly market structure, extremely complex, one-of-a-kind, robust products) for how innovation can and should be encouraged in the defense space context? By structuring the analysis around root-cause challenges, derived from innovation theory, rather than the existing acquisition norms as is typically done, this work contributes to the acquisition reform discussion by providing a baseline for identifying ways that the system could be different. To this end, it identified five core challenges of generating innovation in national security space: (A) generating bottom-up push in a predominantly top-down acquisition process, (B) representing the needs of a disaggregated buyer, (C) integrating fragmented sell-side knowledge from the top-down,

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[9] These constellation level survivability features include dynamic control and routing of satellite crosslinks around unavailable nodes, on-orbit satellite spares, and the ability to control all 66 operational spacecraft from a single ground facility. For example, following the shattering of the satellite on February 10, 2009, Iridium was able to move one of its in-orbit spares into the network constellation within a month. As noted by Garrison, Pizzicaroli and Swan (1997), "…the design philosophy provides redundancy at the system level instead of the hardware configuration level. Autonomous operation and dynamic resource management and routing provide constellation failure mitigation. In effect, the traditional hardware redundancy is spread over many spacecraft".

(D) matching the innovation environment to the stage of development, and (E) balancing risk aversion and the need for experimentation.

From an innovation theory point of view, Challenge A (generating bottom-up innovation) the space market structure inhibits half of the natural competitive market innovation dynamic. As a result, until more buyers become involved in the space market,[10] any acquisition system will need a mechanism through which to ensure that new ideas continue to be infused into the acquisition system. Development contracts do accomplish this *capability development* to a certain extent, but as discussed earlier, they are limited in their ability to encourage *sell-side initiative* and the parallel and varied concept explorations it embodies. The emergence of "New Space" introduces other partial models for encouraging and leveraging sell-side initiative including COTS, seed-funding models such as Starburst Accelerator, prizes (e.g., Ansari X-Prize) and the market-independent funding associated with many of the New Space companies. The idea in each of these is to for the government to help sustain a market rather than subsidize the development of a particular technology (i.e., generate sell side initiative, not just capability development).

With regard to Challenge B (needs representation) and Challenge C (knowledge integration) the blue ribbon panels are almost unanimous in their recommendations to increase the technical competence of the acquisition core and emphasize the importance of front-end specification. However this only addresses half of the problem. No matter how many new capabilities are generated, their value will hinge on how well the original need was represented as a set of requirements. For the other half of the problem to be fully resolved, more emphasis must be given to the challenge of knowledge integration on both the buy- and sell-side. Specifically with respect to Challenge B, increased emphasis must be placed on flowing needs to requirements. This will involve a combined effort to educate users about their choices (what is possible) and help acquirers capture their needs more effectively. To this end, value-based system analysis methodologies to facilitate the process of capturing both articulated and unarticulated needs, early in the conceptual design phase, are currently being developed by researchers. Taking the value-centric perspective during conceptual design empowers stakeholders to rigorously evaluate and to compare different system requirements in the technical domain using a unifying set of attributes in the value domain (Mathieu & Weigel, 2005; Ross et al., 2004; Hanumanthrao et al., 2017). If deployed by System Program Offices, these emerging system analysis methodologies will contribute significantly to overcoming Challenge B.

Overcoming Challenge C will require more frequent interactions among contractors, integrators and the government through formal acquisitions. Where need-capability information is transferred continuously from buyers to sellers, and vice versa, in traditional markets, the transfer only happens during contracted hardware development in the space sector. As long as space acquisition continues to operate on a model of infrequent, extremely complex monoliths, the knowledge required to innovate will continue to be fragmented across the various players. Decreasing the acquisition cycle time will help both the knowledge integration problem identified in Challenge C, but also the risk aversion indentified in Challenge E.

Challenge D (matching) identifies a fundamental limitation of the current system. In the existing acquisition paradigm, the product development required to enable future missions is conceptualized as a linear progression from TRL 1-9. With this view in mind, the

[10] This has happened, to a certain extent, in the domain of communication satellites and earth imaging and may soon be the case if space tourism were to take off, but is arguably unrealistic in the near future for more advanced and military applications.

blue ribbon panels call for increased funding for technology development. However, while increased funding for technology development is a needed step in the right direction, it only addresses part of the problem. It fails to appreciate the difference between architectural and component dimensions of knowledge and what that means for system level maturity and infusion of new technologies. If the rest of the problem is to be addressed, there is a need for more than two organizational tiers—up to one for each of the three phases as well as the dimensions of component and architectural knowledge—and better coupling among them.

Similarly, the recommendations of the blue ribbon panels that pertain to Challenge E (risk shelter) emphasize a "back to basics" philosophy which keeps R&D separate from system acquisition. This would serve to shelter component development from political pressures, but do nothing at the spacecraft level. For spacecraft level development to achieve the risk shelter that is required, a major philosophical shift is needed. An ORS-like philosophy could serve that purpose.

The challenges identified in this paper are fundamental to generating innovation in the space sector; they will not be easy to overcome. The previous discussion provides some guidelines for how to approach solving the problems, but will require all stakeholders involved to come together to implement a solution.

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