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Operational Concepts and Payoffs for Responsive Space Systems

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OPERATIONAL CONCEPTS AND PAYOFFS FOR RESPONSIVE SPACE SYSTEMS

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ABSTRACT

The ability to rapidly emplace space assets with tailored payloads and orbits or to deliver a variety of terrestrial systems globally and at orbital speeds, providing specific operational support to a variety of military missions, would lead to revolutionary operational concepts. Three complementary elements are needed for this operationally responsive military space capability (referred to in the paper as "Responsive Space"): truly responsive and affordable launchers, highly modular and standardized satellites, and tactical reentry systems. We first consider a set of operational concepts that explore the potential roles of such systems in various military scenarios. We make preliminary estimates of size, weight, performance and cost. We then examine the technologies that make these concepts feasible in the near- to mid-term, say 5 to 10 years from the start of properly funded development programs. We show that much of the enabling technology portfolio is in hand or well along toward demonstration. The inescapable conclusion is that a military capability of genuinely revolutionary impact is not only available but essential to the realization of the kind of information-enabled operations that are at the core of Joint Vision 2020 and, indeed of military transformation in general.*

INTRODUCTION

The great and growing importance of robust space-based capabilities to military operations, from theater war to humanitarian relief, is widely acknowledged.[1,2] Traditionally, space systems have provided three broad classes of services: (1) position, navigation and timing (PNT), today using the Global Positioning System (GPS); (2) communications; and (3) sensing for intelligence, surveillance and reconnaissance (ISR); weather; and strategic warning. During roughly three decades of military space history, such systems have often been invaluable, but most have also shared the attributes of being slow, expensive, and unresponsive to the real time tactical needs of commanders and warfighters.

Since defense satellites, with few exceptions, are small in numbers and hard to replace, they tend to be large, multifunction platforms designed for long on-orbit lifetimes. When hardening against nuclear weapons is added to tolerance for the natural space environment, satellites become still more difficult and costly to develop. GPS is a rare exception to the general rule that only a few satellites of any given design will be built and at very inefficient production rates. To this must be added the cost and risk of space launch, with a ride to geosynchronous orbit (GEO) costing a sum comparable to that of the payload being launched and a typical mission running to hundreds of millions of dollars. Launch campaigns last months, even when a satellite is available in inventory. Given their rare and precious nature, defense space systems have usually been treated as national resources, with their services centrally managed to try to satisfy a demand that far exceeds the supply.

All this is the antithesis of a military capability that can be integrated into tactical operations in a theater of war or counted on for flexible, real-time support of an expeditionary operation in a contingency. Both cultural differences among the space and terrestrial communities and the inherent limitations of today's defense space systems conspire to limit their utility just as the

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evolving global security environment of the 21st century puts a premium on their potential contributions. Despite serious efforts by the organizations involved, the integration of space and terrestrial systems remains limited and uncertain, mainly taking the form of assigning space specialists to combatant units to train them in the use of space services and to facilitate requests for support that may or may not be available. No task force commander would submit to such constraints in ordering air, land and maritime forces to execute synchronized actions under a common plan. But today, it is the best that can be done with respect to space.

America and its allies and economic partners confront a threat to their collective security and prosperity for which they are ill prepared on the basis of Cold War military concepts. The new threat is global, ambiguous, endlessly surprising, and utterly contemptuous of American values of justice and human worth. Given this threat, every vision of the path to maintaining security in the decades ahead relies fundamentally on information-enabled operations. The collection, analysis, dissemination and use of information is the single most critical element of employing military assets to predict, preempt, and defeat the ever changing makeup and tactics of the new enemy. The required information infrastructure simply cannot function except as an integrated system-of-systems in which space and terrestrial nodes interact seamlessly to complement and exploit the unique capabilities of each. Yet, for all the reasons cited above, existing and planned defensive space systems fall far short of what is needed to achieve this vision.

The situation can and must change. The means to deploy space systems in greater numbers, at lower cost, and with designs that allow direct response to end users in an operational theater are rapidly emerging. The conventional wisdom about costs, timelines, and control mechanisms for space systems is out of date. In this paper, we outline the kind of new operational concepts that must be pursued and the enabling technologies that can make them real. We suggest examples of the new breed of satellites, launchers, and reentry vehicles that could be developed in the near and mid-term timeframe and offer preliminary estimates of their size, weight, functionality, and cost. We look at the state of enabling technologies to get a sense of where additional investment is needed and when they can be demonstrated to the necessary level of maturity. We conclude by placing such systems in typical operational scenarios to see how they might impact military capabilities and where the priorities should fall for their development, deployment and use.

OPERATIONAL CONCEPTS FOR RESPONSIVE SPACE

The single most glaring discrepancy between today's space and terrestrial systems can be thought of in terms of sortie rate. Space and terrestrial systems do have some similarities in this regard. As a general proposition, the aircraft, ships, armor, and other assets of a joint force have predictable abilities to generate missions at some rate and with some preparation time. To a certain extent, current operational space systems also have predictable abilities to deliver services. And in both cases, there can be competition for limited resources such as sensor platforms. However, while terrestrial systems can be rapidly deployed, assembled in formations for specific mission tasks, redirected on short notice when priorities change, and pushed to deliver bursts of activity well above their average capacity, space systems today can do none of these things. A robust tactical capability requires going to places on short notice, delivering effects, dropping off or picking up things of interest, and generally matching mission operations to immediate needs. The central thesis of this paper is that military space systems can come far closer to this kind of operational model than has so far been conceived, let alone demonstrated.

Responsive Satellites. The first element in many Responsive Space operational concepts involves the ability to rapidly prepare for launch satellites that have specific functions required by a given mission or scenario. A simple but useful framework is suggested in Table 1, which groups satellites according to function, size and orbit, with three classes in each dimension. For simplicity, geosynchronous and highly elliptical orbits are treated as a single category since both tend to be used for similar satellites. The size categories, admittedly somewhat imprecise, are:

- Micro/SmallSATs – 10s of kg to 100 kg, 10s of W prime power.
- MediumSATs – 100 to 1000 kg; 100s of W prime power.
- LargeSATs – greater than 1000 kg; 1000s of W to 10s of kW prime power.

Table 1. *Examples of Military Satellites by Function, Size and Orbit.*

	LEO	MEO	GEO/Elliptical
PNT			
Small	Aux Payload	N/A	N/A
Medium	N/A	GPS	N/A
Large	N/A	N/A	N/A
Communications			
Small	Relay	N/A	N/A
Medium	Network Node/Interface	Network Node/Interface	N/A
Large	N/A	N/A	Global COMSAT
ISR			
Small	Passive EO/MSI/HSI	N/A	N/A
Medium	Ladar/Lidar	N/A	N/A
Large	SBR	SBR	Strategic ISR, Weather

Although not rigorous, the table shows representative satellite types in various weight classes and orbits. GEO and elliptical orbits are of most interest for large satellites performing missions like warning, intelligence collection, weather observation, and global communications. MEO orbits, with the radiation hazard of the Van Allen belts, are used today by the GPS constellation. However, as further discussed in a later section, this orbit may have attractive features for satellites which interface terrestrial user equipment to advanced global communications satellites in GEO. There are also possible space-based radar (SBR) configurations that use MEO orbits, e.g., for the illuminators used in a bistatic mode.

At least initially, it appears that LEO constellations are most interesting in a Responsive Space context. This is the leading candidate for both SBR and electro-optical (EO) sensors, including active laser radar (Ladar/Lidar) systems. LEO also provides the shortest range for low power user terminals that need to access space communications networks. LEO satellites with other primary missions could host a variety of auxiliary payloads such as extensions to the GPS constellation or communication relays.

Interesting operational concepts emerge from consideration of the ability to rapidly emplace satellites in the various niches of Table 1. The first of these involves simply prompt replacement of existing satellites following premature failure or the results of hostile action. As space grows in importance in military operations, such an ability would mitigate the risk that an important service could be lost or denied. A fully responsive satellite concept also includes designing the satellite and ground environment for first revolution operability.

Other concepts involve deploying specific new spaceborne assets in response to a particular mission or contingency. An example which has recently arisen in connection with unmanned aerial vehicle (UAV) operations in Afghanistan is the need to quickly provide sensor data links in remote, infrastructure-poor locations. Responsive space would make it possible to deploy relay satellites with the right payloads to interface to legacy terminals on such airbreathing platforms and in a constellation tailored to optimize coverage over the area of responsibility (AOR). These considerations are further developed later in this paper.

Operationally Responsive Spacelift. Responsive space operations depend upon fast, affordable launch as fundamentally as tactical air operations need a runway. The proper scale for judging the timeliness of space lift is that of the operational situation being supported. We can illustrate this point with two simple examples. First, suppose that an operation is underway which relies heavily on a set of space assets for direct support of tactical missions and that one or more of these are lost or degraded. If the failed satellites can be replaced in less than 24 hours, the impact will be a disruption of operational tempo, but only in a worst case such as communications outage at the critical point of a battle would it rise to catastrophic levels. If, as is the case today, a replacement can only be launched after weeks or months of preparation, the commander will be forced to find a terrestrial backup for the functions in question, fundamentally change plans, or accept increased risk of losses or even failure. Few commanders will be willing to commit critical functions to space systems if this risk is significant. It is also worth bearing in mind that responsive launch would have great value to civil and commercial space systems by enabling the capture of time-sensitive phenomena.

A second, perhaps more probable, example involves support to a short notice force deployment. An Air Expeditionary Force today is tasked to pack up, deploy to a forward operating location, and begin operations in 72 hours or less, and special units expect to deploy on even shorter timelines. The optimum approach to providing information services in such an operation is an integrated blend of space and terrestrial assets. The airbreathing platforms will move on a schedule similar to the main force; for example, a Global Hawk UAV can establish an initial orbit in 24 to 48 hours anywhere on earth if maintained in the necessary alert posture. A major part of the space component can be expected to consist of satellites already in place. However, providing full sensor, communications, and PNT support simultaneously and continuously over the globe is an expensive proposition. If the launch element of a Responsive Space force could loft supplementary satellites on the same timeline as that of the deploying force, and selectively augment these assets depending on the evolving nature of the operation, a more cost effective and operationally satisfactory solution would be possible. In short, operationally responsive spacelift means launching multiple payloads within one to a few days of a deployment order, compared to today's capacity to launch one or two with a delay of many months.

Tactical Reentry Vehicles. Schemes for using missiles to deliver non-nuclear payloads have been around for many years. If, instead, the concept is to use space assets to achieve the effect of very fast transport of a wide range of payloads, a much broader array of operational concepts emerges. Perhaps the outstanding example of this is the Common Aero Vehicle (CAV) that has been investigated by the Space Vehicles Directorate of the Air Force Research Laboratory. This is not just a ballistic missile with a less devastating warhead. Instead, it involves a reentry vehicle that could be sent world-wide on short notice by a responsive launch system to deliver a variety of effects such as dropping precision guided munitions or launching a small reconnaissance UAV, as well as one or more small relay satellites to provide a downlink path for prompt delivery of collected information. As a contributor to an overall strategy based on effects-based operations, such a system would be a powerful extension of current capabilities.

CANDIDATE RESPONSIVE SPACE SYSTEMS

The possible satellite, launcher and reentry systems that might be incorporated in a Responsive Space force are too varied to deal with in this summary paper. Nevertheless, it is suggestive to look at a few examples in terms of their inherent feasibility and the maturity of the technologies needed to implement them.

Characteristics of Responsive Satellites. Table 2 addresses a hypothetical SmallSAT carrying a payload such as a UAV data downlink relay or a passive EO imager. Typical rules of thumb have been used to estimate the major system elements.^{3}

Table 2. *Preliminary SmallSAT Estimate*.

Component	*Estimated Weight*	*Estimated Power*
Satellite bus & systems	200 kg	650 W
Prime power	12 kg	1 kW
Payload & apertures	150 kg lbs	120 W
TOTALS	362 kg	1 kW

Using a rough cost estimating relationship of \$40k to \$60k per kg, such a satellite might cost in the range of \$15 – 20M. Producing the system or its major components in quantities of dozens at an efficient production rate could easily reduce this by a third, based on the kinds of learning curves and economies of scale that are often assumed in the aerospace industry. A reasonable planning figure for a constellation of 36 satellites, providing continuous coverage over a given AOR, would then be on the order of \$300 – 500M, which is of the order of the cost of a single large satellite using typical current design assumptions.

Another factor in making such satellites less expensive and more responsive involves their design lifetime. Mainstream defense satellites today are designed to survive in the natural space environment for perhaps 7 to 15 years, consistent with the model of few, very expensive assets and long lead times for launch. Much attention is paid to monitoring satellite health and predicting failures far enough in advance to get replacements into orbit to ensure on-orbit spares and maintain continuity of system function. In addition to the component cost and structural weight penalties associated with hardening electronics to the required levels, long-lived satellites need a lot of maneuvering and station-keeping fuel, which can constitute a significant fraction of the launch weight. If the model changes to one where satellites are much less costly and can be launched quickly at need, it's likely that one to three years would be a perfectly satisfactory lifetime, allowing largely commercial electronics to be used, especially if emerging techniques of "hardening by design" are used instead of requiring high intrinsic radiation tolerance. Weight savings in fuel for the shorter period would also be substantial.

One final important element of the Responsive Satellite concept is that of modular, tailorable payloads.[4,5] We assume that the satellite bus provides housekeeping functions such as telemetry, tracking and control (TT&C); vehicle pointing; orbit maintenance; prime and regulated power; and basic payload control and monitoring. The concept requires a very well defined and standardized interface between the bus and the payload, covering:

- Mechanical interface and mass properties .
- Mechanical, acoustical, and thermal environment, especially during launch.
- Provisions for on-orbit deployment of payload structures.
- Bus-provided pointing, tracking and orbit maintenance.
- Electrical power.
- Command and status data interface.
- Timing.
- Payload data interface, if the transceiver is provided by the bus.

Next comes a set of modular payload elements designed to be mixed and matched as appropriate to a given mission. These might include communications transponders, sensors, and information processing units, including data and signal processors, interface electronics such as analog-to-digital converters, and data storage. A high data rate transceiver to support payload traffic could be treated as either a payload module or a bus subsystem. It's likely that the most difficult part of the payload design task will involve the apertures, either antennas for communications and RF sensors or optical apertures for EO payloads. Figure 1 sketches the modular payload idea and shows the interface between the bus, with a relatively low speed TT&C local area network (LAN) and the payload, with a higher performance interconnect. The payload data transceiver is shown here as a standard payload module, rather than as a bus subsystem.

While SmallSATs are the obvious place to begin implementing Responsive Satellites, nothing precludes applying the ideas of modular payloads and rapid emplacement to the larger categories. A unitary, monostatic space based radar system has been estimated to use an X-band active electronically scanned antenna (AESA) of about 15 m^2 dimension with a total satellite weight of about 4,000 kg.[6] A Ladar payload with a sufficiently powerful laser transmitter for modes like synthetic aperture radar (SAR) would probably fall in the medium weight category of Table 1. Given the family of responsive launchers described next in this paper, such systems could be built for inventory and launched on demand to create, supplement, or replenish a constellation. As size increases, the idea of modular payloads, perhaps placing smaller secondary payload modules on board with a larger primary payload, becomes progresssively easier. The Responsive Satellite concept is pervasive and potentially covers the full range of military space systems.

A Family of Responsive Launch Vehicles. Despite the attention given to fully reusable launch systems as the path to dramatically lowering the cost of getting to orbit, the most mature and demonstrated opportunity for the near and mid-term is the Scorpius® family of expendable launchers from Microcosm, Inc. We will use the characteristics of Scorpius® as a template for this element of a Responsive Space capability.

The essential principle of Scorpius® is a careful examination of the elements of cost associated with launch systems and their operations and a

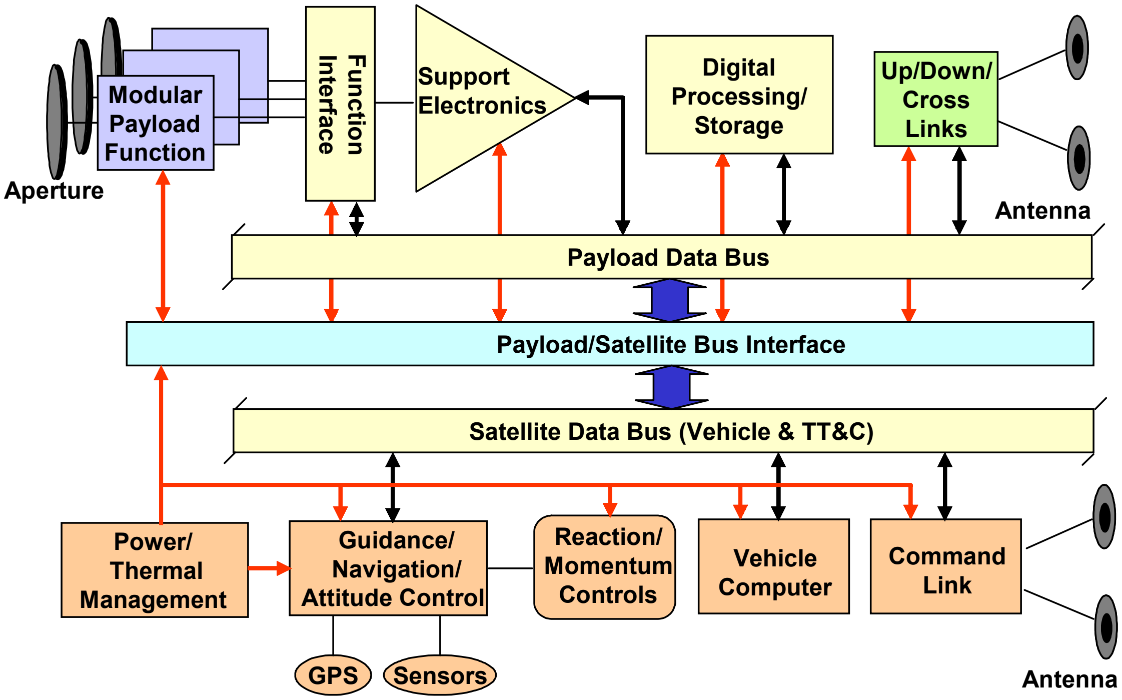


Figure 1. *Responsive Satellites Employ Modular Payloads with a Standardized Bus Interface.*

rigorous design approach based on minimizing those costs. Traditional big rockets are expensive because they are optimized purely for performance, they incorporate a large number of complex parts, and they are produced in limited quantities. Examples of design features that result in high cost are turbopumps for propellant delivery, elaborate thrust vectoring schemes, and complex electronics. Launchers based on this design philosophy achieve (relatively) high payload fractions, but show no prospect of lowering launch costs much below $5 to 10k per pound to LEO. The cost dilemma is exacerbated by economics: high launch costs mean few launch customers and few launches, which in turn lead to inefficient production and launch operations.[7] A further complicating factor is that traditional launchers require extensive infrastructure, especially when they employ exotic propellants.

The Microcosm Scorpius® team has approached the launch problem from a fundamentally different viewpoint. By tolerating lower performance (payload fraction) and exploiting breakthroughs in materials technology, the

Table 3. *Comparison of Scorpius® Launchers to Conventional Vehicles*

Launcher	Type	Weight to LEO (lbs.)	Payload Fraction	$/Launch	$/lb
Small					
Sprite (Scorpius®)	**Liquid**	**700**	**0.6%**	**$2.0M**	**$2.8k**
Pegasus	**Solid**	**1,000**	**1.7%**	**$22M**	**$22k**
Taurus	**Solid**	**3,100**	**2.0%**	**$30M**	**$9.7k**
Medium					
Delta 7920	**Mix**	**11,220**	**21.2%**	**$53M**	**$4.7k**
Exodus (Scorpius®)	**Liquid**	**15,000**	**3.6%**	**$13M**	**$0.83k**
Atlas IIAS	**Mix**	**18,500**	**3.6%**	**$99M**	**$5.3k**

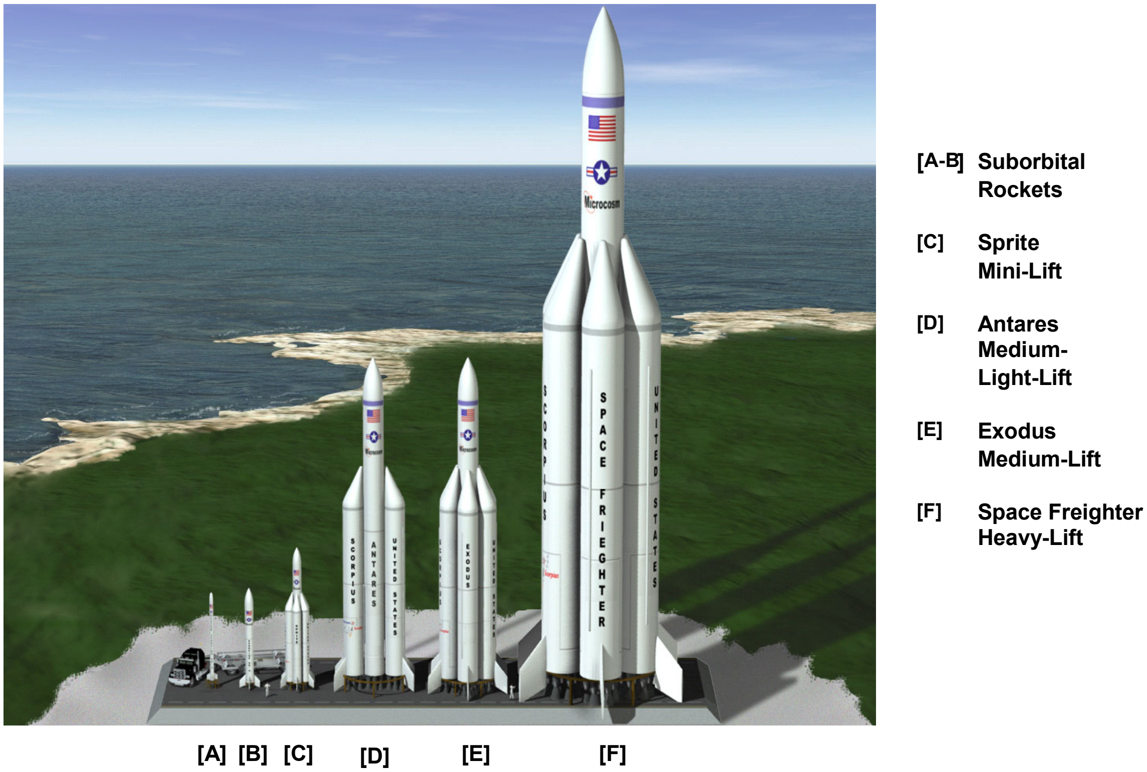


Figure 2. *The Scorpius® Launcher Family Scales to a Wide Range of Lift Capabilities.*

Scorpius® launcher family eliminates the primary cost drivers of traditional designs. Scorpius® makes extensive use of advanced composites technology and is based on reducing the total parts count, the number of unique parts, and the number of moving parts. The family is based on building up successively higher capacity launchers by adding thrust chambers, which achieves both fine-grained scaling of launch weight to match specific payloads and inherent redundancy from multiple rockets operating in parallel, and on scaling tanks, engines and the pressurization system to control costs. At the same time, the design approach leads to larger numbers of fewer individual parts and thus enables economies of scale in manufacturing. A demonstrated high performance pressurized system for propellant feed design eliminates the need for turbopumps, even for the larger thrust categories. Another important breakthrough that has been tested in initial launch demonstrations is the first successful use of an all-composite liquid oxygen tank, confirming that these materials are ready to replace more expensive metal structures.

Reduced launch mission cost introduces flexibility into planning for the deployment of a constellation. Multiple manifesting is more complicated than single payload missions, but creates options to launch multiple satellites at the lowest possible total costs. Preliminary estimates suggest that single satellite emplacement cost may be the largest cost driver in the overall constellation launch budget.

The basic soundness of the Scorpius® design has been validated in two successful suborbital launches, each of which demonstrated nominal performance. Table 3 summarizes the projected launch costs of various members of the Scorpius® family vs. comparable existing launch systems. The various models of the Evolved Expendable Launch Vehicle (EELV) systems that are now entering service employ some elements of this design approach and are projected to lower launch costs to the range of \$7k per pound to LEO[8] with a long term goal of perhaps \$4k. However, this is still well above the estimated \$500 -1,000 per pound that would be needed to make space truly affordable and bring in a broader community of users.[7] Finally, unlike traditional launchers, Scorpius is cheap enough that its launchers can be kept in inventory, the essential characteristic of responsive space systems.

In addition to intrinsic low vehicle cost, Scorpius® demonstrates a powerful approach to reduce the cost of launch infrastructure and operations. Figure 2 shows the current Scorpius® family of launchers. The use of liquid oxygen/.kerosene propellants results in very simple storage and fueling provisions. The concept of horizontal staging (concentric firing of rockets sequentially from the outside inwards) leads to vehicles that are relatively squat in configuration and thus highly stable on the pad, removing the need for gantries and other elaborate launch structures. A Scorpius® launch facility can consist of little more than a concrete pad, a tank farm, and a blockhouse. Since there is little pad refurbishment after a launch, a single pad could support several launches per day in an operational surge situation. The fact that a Scorpius® launch has been conducted from just such an austere site, and that the rocket was ready within eight hours of the arrival at the pad, confirms the feasibility of a very basic launch infrastructure.

From the Scorpius® experience, we can draw the following summary of the features of Responsive Launch systems:

- Minimum use of expensive materials.
- Non-exotic propellants.
- Minimum launch infrastructure.
- Minimum parts count and few or no moving parts.
- Simple, GPS-based vehicle navigation and control.
- Advanced composite materials and structures to reduce design and manufacturing costs.
- Multiple thrust chamber design for redundancy, fine grained performance scaling, and simplified directional control through differential throttling.
- Simple thrust termination.

Combining a launch vehicle in the Antares class from Table 3 with a satellite design like that in Table 2 would allow a full LEO constellation with militarily significant capability for communications, EO sensing, or both to be deployed for a cost on the order of half a billion dollars and subsequently updated or replenished at an annual cost of a fraction of that. Such a dramatic change in the traditional calculus of military space cost would be critical to making Responsive Space a reality.

Tactical Reentry Vehicles. The third component of Responsive Space is made up of one or more reentry vehicles that can be boosted to orbital or suborbital trajectories by responsive launchers and used to deliver a variety of payloads to terrestrial targets on timelines of one to two hours and with no restrictions associated with overflying foreign territory. Concepts like the CAV are predicated on delivering conventional precision guided munitions like the Joint Direct Attack Munition (JDAM) and do not require high precision guidance because the munitions themselves will home accurately to their preset Designated Points of Impact (DMPIs). Such reentry vehicles could be used for a variety of payloads, including small unmanned aerial vehicles (UAVs) that could carry out local reconnaissance missions based on cues about activities of interest in a particular area. The operational appeal of such systems derives from their ability to achieve a wide range of precise effects anywhere on Earth with complete surprise and within hours of the decision to proceed.

ENABLING TECHNOLOGIES

Most of the technologies and many of the products required for Responsive Space systems exist or are in development. We list some representative examples in this section.

Responsive Satellite Technologies. A variety of small satellite buses has been designed by companies such as MicroSat. These would require only the definition and implementation of the standard payload interface described earlier and appropriate sizing of their power systems to provide suitable vehicles for at least an initial family of Responsive Satellites.

Modular payloads could also be built using demonstrated technologies. Communication transponders draw on a mature industrial product base, and would benefit from the reduced range and power required in LEO. One always challenging area is high performance, light weight RF apertures. Innovative designs from companies like EMS Technologies show that such products are available for fixed pattern, switched beam, and beam forming antennas suitable for compact communications payloads. Several kinds of passive EO sensors have been flown on SmallSATs. The major challenge is to provide the required aperture diameter for high resolution imagery, but once again a relatively low orbit makes the problem easier. At larger satellite sizes, both radar and ladar active sensors have been successfully operated in LEO. Onboard processors like those developed in the Advanced Onboard Processor program have evolved through several generations and can provide the necessary data and signal processing.[9]

Two areas where further technology progress is needed to support the full range of desirable Responsive Satellite systems are memory and analog to digital converters (ADCs).[9] Familiar silicon static random access memory (SRAM) is unlikely to achieve the power efficiency (bits per watt) needed for the relatively large data storage needs of some systems. However, a variety of very dense and energy efficient technologies that also have the advantage of being nonvolatile show great promise.[10] Also, since many compact payload designs seek to maximize the functionality that is implemented digitally, faster ADCs than current technology will support would be very helpful. The most promising approaches use optical (photonic) techniques, but the desired levels of resolution and sample rate will not be available for some time, based on current programs and funding.

Responsive Launcher Technologies. The description given earlier of the Scorpius® family gives convincing proof that the technology portfolio needed is available and has been demonstrated. The remaining need is to fund development and launch of orbital launchers such as Sprite to complete the proof of the feasibility of this concept.

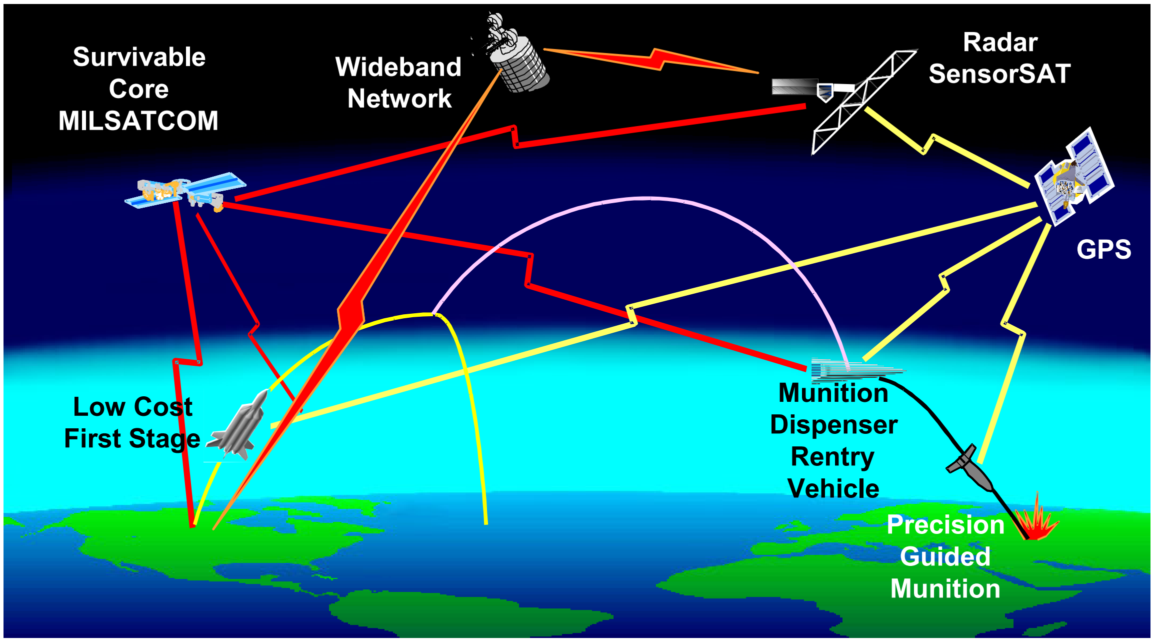
Tactical Reentry Vehicle Technologies. Because they transfer much of the complexity to the payloads that are delivered, concepts like CAV do not create a need for radically new technologies. As with launchers, the primary need is to design and demonstrate test vehicles to show that the materials, guidance, and dispensing mechanisms are mature and ready for operational systems.

PAYOFFS FROM RESPONSIVE SPACE

We now turn to the operational significance of the kinds of new military space capabilities discussed in the preceding sections. We will briefly consider four scenarios that suggest the kinds of payoffs Responsive Space could deliver.

Rogue State with Nuclear Capability. A very serious threat would be posed by a country or terrorist group able to obtain even one or two nuclear devices and a rocket capable of lofting them into space. Recent news reports indicate that this is a plausible scenario. Analysis done over many years suggests that even a tactical weapon (say, three to five kilotons) would pump the Van Allen belts to high densities of energetic particles and degrade or destroy any non-nuclear hardened satellites in anywhere from a few seconds to a few weeks. Given the dependence

Figure 3. *A Rapid Global Strike Concept Combines Responsive Launch and Tactical Reentry Vehicles.*



of the developed world on commercial and civil space systems, this could well bring on a commercial and social disaster. Moreover, once the space environment is contaminated this way, weeks may elapse before particle densities relax to normal, meaning that replacement satellites, even if they were available, would be likely to fail also.

In this situation, Responsive Space would function as an emergency backup during the period of widespread space system outage. With relatively cheap satellites and low launch costs, a carefully chosen limited set of space services could be maintained by repeated launches of satellites with the required functions. These would probably include weather surveillance and emergency communications. While it is not feasible to restore space services fully and immediately, even limited replacement could have great military and societal benefits.

Rapid Global Strike. The US military is steadily improving its ability to deploy globally with a wide range of combat and noncombat capabilities. Even so, there will be situations in which the near-instantaneous delivery of an effect without the time and cost of moving aircraft, ships, troops and equipment would give senior leadership attractive alternative options. An obvious example would be to respond to credible intelligence about the location of a terrorist group by striking without warning and before they can move.

This scenario is supported by combining Responsive Launch with Tactical Reentry Vehicles. Figure 3, from a recent study by the Air Force Scientific Advisory Board,[11] illustrates the concept. In the example shown, a space based sensor confirms the location and identification of the target and relays the information through a high speed channel. The strike system is prepared while the decision to use it is being made and launched from a secure site to put the reentry vehicle over the target in something like 45 minutes. The payload, in this case a GPS-guided munition, is released and homes to the DMPI. Given expedited decision processes and a properly postured launch facility, the whole operation from detection to deletion of the target could take as little as a few hours.

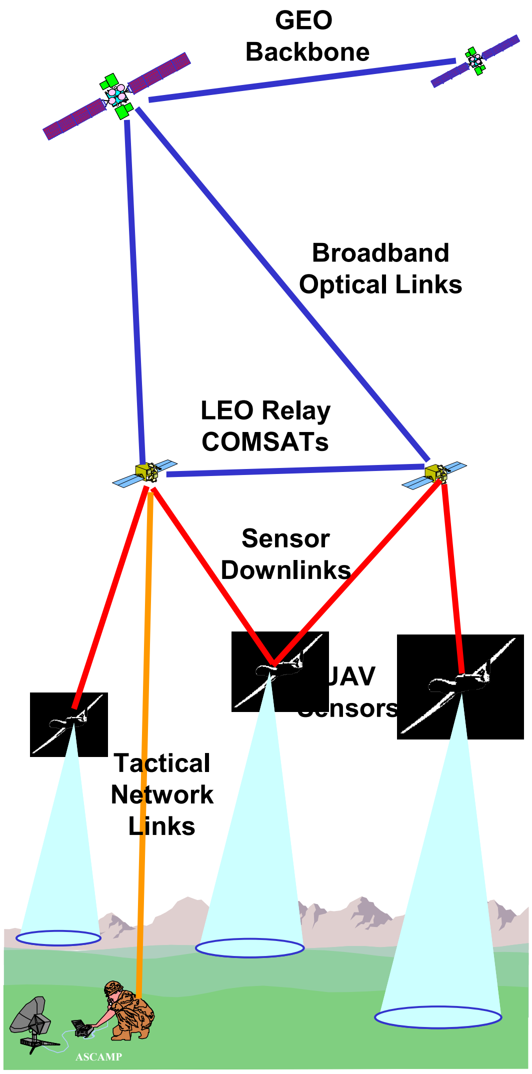


Figure 4. *LEO Responsive Satellites Offer One Way to Implement the Lower Tier of the Transformational Communications System.*

Lower Tier of the Transformational Communications System (TCS). The emerging TCS architecture is predicated on a high capacity (10 Gbps) network backbone in GEO using optical cross links, and probably optical up and down links to platforms like LEO satellites or high altitude aircraft. This "lower tier" will be responsible for providing a flexible, highly adaptive interface to the TCS for individual users, both fixed and mobile. Figure 4 summarizes the concept. This lower tier needs powerful abilities to receive and transmit traffic from and to a wide range of legacy systems that operate in many bands, use diverse waveforms and message schemes, and often have limited power and antenna gain. To reach its full potential, TCS will need to provide not only high data rate long haul communications but also such functions as gating message traffic between incompatible data links and adaptively routing messages over the best available channel.

In principle, a combination of long duration LEO COMSATs and airborne platforms that deploy as part of an operation could provide this capability. However, in many realistic situations, Responsive Space would add valuable flexibility and cost savings. Responsive Satellites could be emplaced along with or in advance of deploying aircraft, and the two sets of platforms could be optimized to provide the required communications at the lowest cost. With modular payloads, the satellites could carry specific radios and processors as needed by a particular set of supported units. Another alternative would be to put a backbone of long endurance TCS LEO nodes in orbit and supplement them with Responsive Satellites in tailored orbits to maximize coverage over the AOR. Since they would have assured clear line of sight to GEO, the satellite nodes could carry optical transceivers and route subchannels from the broadband data stream to individual users. They would also be immune to hostile air defenses.

LEO satellites are not stationary over the AOR, and so this concept requires both apertures that can track terrestrial nodes and users and crosslinks that support handoff between entering and exiting satellites. When combined with multiple radios and sophisticated onboard processing for message routing, security, network management, and the like, the payload would probably fall into at least a MediumSAT class. Even so, the operational flexibility they would contribute warrants some amount of complexity, especially in a balanced system-of-systems that optimizes the functions of GEO, LEO and airbreathing nodes.

Multiple UAV Downlinks. The final scenario we discuss is a variant of the preceding one. Here we explore the idea of a very specific Responsive SmallSAT to solve a particular communications problem: providing simultaneous downlinks for multiple UAVs operating in an AOR. The concept closely resembles familiar cellular phone systems in which contiguous service areas allow a user to maintain a connection on the move. In this case, a communications SmallSAT carries a switched beam antenna that creates a pattern like that sketched in Figure 5. Low antenna gain is sufficient for the individual beams to create spots of 50 nmi diameter from LEO. The satellite would keep track of which UAV data stream was coming from which spot and when the platform moved to an adjacent spot. By using a standard multiplexing method like time division multiple access (TDMA), several UAVs could share a beam while taking advantage of the high power capability of these antennas. Tracking data at a rate quite low compared to the sensor downlink would suffice to allow the satellite to sort out the traffic. If desired to minimize power consumption, only spots that are occupied or about to be would have to have their receivers active. The satellites would carry broadband transmitters to pass aggregated sensor data streams to a TCS node or other portal. They would need just enough crosslink data capacity to allow handoff between exiting and entering satellites, consisting essentially of the current pattern of UAVs. With the exception of the broadband optical link, which will be developed as part of the TCS, a satellite of this kind would use well established technologies and products from systems like Iridium. Switched beam forming antennas with the required performance and with very low loss have been demonstrated by EMS Technologies.

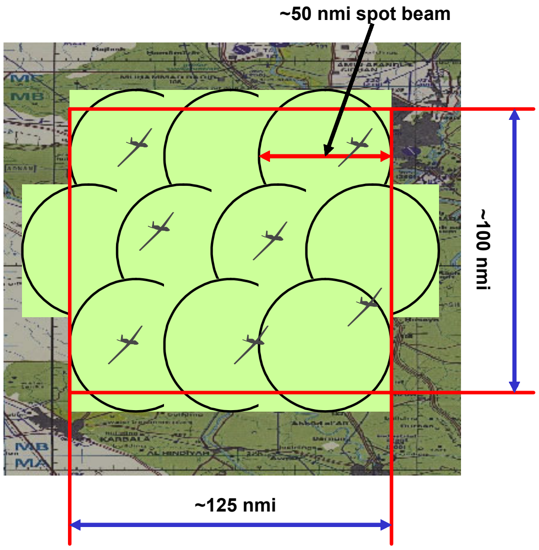


Figure 5. *A Switched Beam Antenna with TDMA Could Create a Cellular Telephone-Like Pattern for Simultaneous Connectivity to Multiple UAVs.*

As with the other scenarios, the operational payoff is the ability to rapidly and affordably put in place the infrastructure needed to support an operation. Such relays could operate with impunity over hostile territory. In a long duration surveillance mission, the economics of satellites vs. manned or unmanned communication nodes would quickly swing in favor of the space segment. The sensor data relay function could easily translate to one set of assets in a modular payload that included other capabilities. Based on the estimates performed earlier in this paper, the cost of the satellite constellation would be comparable to that of the UAV force they support.

STRATEGIES FOR RESPONSIVE SPACE SYSTEM DEVELOPMENT

We have emphasized the fact that relatively few technology developments are required to allow the design and fielding of Responsive Space systems. Thus the investment to make this a reality in the near or mid term consists mainly of specific demonstration programs to prove feasibility, refine system concepts, and find the best niches for Responsive Space in the total force structure.

Specifically, the following would have high leverage in achieving the payoffs promised by these concepts:

- Develop and launch a set of demonstration satellites that have modular payloads based on repackaging of existing products and on selective new component development.
- Convene an industry colloquium to define the modular payload to bus and bus to launch vehicle interface standards.
- Conduct the initial orbital launch demonstration of responsive launchers using the Scorpius® design approach.
- Similarly complete and launch one or more tactical reentry vehicles that are matched to high interest payloads like JDAM and compatible with the projected responsive launcher family.
- Fund selected technology developments like those identified in this paper.

SUMMARY

Responsive Space would revolutionize military operations in the 21st century. Systems can become operational in as little as five years with focused demonstrations as the key strategy.

ACRONYM LIST

ADC	Analog-to-Digital Converter
AESA	Actively Electronically Scanned Array
AOR	Area of Responsibility (Theater)
CAV	Common Aero Vehicle
COMSAT	Communications Satellite
DMPI	Designated Mean Point of Impact
EO	Electro-Optical
GEO	Geosynchronous Earth Orbit
GPS	Global Positioning System
ISR	Intelligence, Surveillance and Reconnaissance
JDAM	Joint Direct Attack Munition
Ladar	Laser Detection and Ranging (Hard Body Targets
LAN	Local Area Network
Lidar	Light Detection and Ranging (Diffuse Targets)
LEO	Low Earth Orbit
MEO	Medium Earth Orbit
PNT	Position, Navigation and Timing
RF	Radio Frequency
SATCOM	Satellite Communications
SBR	Space-Based Radar
SRAM	Static Random Access Memory
TCS	Transformation Communications System
TDMA	Time Division Multiple Access
TT&C	Telemetry, Tracking and Control
UAV	Unmanned Aerial Vehicle

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