5.0 Space Application Issues

5.1 Space Launch in the 21st Century

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5.1.1 Introduction

In order to access space it is necessary to have a launch vehicle capable of propelling the spacecraft out of the atmosphere into space and providing sufficient velocity to achieve orbit. This was initially accomplished by using rockets largely derived from the ballistic missiles of the 1950s. NASA as part of the Apollo lunar program developed the Saturn launch vehicle which was the largest launch vehicle developed by the US. Subsequent to the Apollo program NASA developed the Shuttle, a two stage reusable manned vehicle that after re-entry lands aerodynamically like an airplane.

All of these vehicles utilize dated technology and operationally are labor intensive, expensive to procure and operate, and require an inordinate amount of time to prepare for launch. As a result of these deficiencies there have been a number of efforts to define a replacement vehicle for the expendable launch fleet. These efforts include the Advanced Launch System, the National Launch Vehicle, and the Spacelifter. The failure of these efforts to gain acceptance is attributable to the lack of consensus among the nation’s space organizations and the fact these programs required a very large investment which is hard to justify in tight military budgets and other demanding national priorities.

Because of the Air Force emphasis on normalizing space and being able to operate in a militarily responsive manner, the growing obsolescence of the launch vehicle fleet and the high cost of operations, a number of studies have been conducted recently. These studies include the Space Launch Modernization Study (1994), a large effort carried out by the Air Force to explore future launch vehicle options. The most notable outcome of this study is the Evolutionary Expendable Launch Vehicle program which is presently in the RFP stage. A companion study was the SAB Space Launch Ad Hoc Study (1994) which addressed the technology issues relative to achieving future launch vehicles. NASA addressed the future launch vehicle needs of the agency in the NASA Access to Space Study (1995). Also during this period the Office of Science and Technology Policy put forth the OSTP National Space Policy (1994) assigning DoD the lead roll in the improvement and evolution of the current ELV fleet and NASA the lead for improving the Space Shuttle System and the technology development for reusable launch vehicles.

The New World Vistas Space Applications panel focused on the longer time frame and did not re-address the areas covered by these studies. The emphasis was put on defining future possibilities for the Air Force to gain access to space and understanding what key technologies might be enabling.

5.1.2 The Launch Vehicle Environment

The characteristics of current US space launch vehicles is shown in plate 1. The Titan, Atlas, and Delta launch vehicles were derived from ballistic missiles. The Titan II launch vehicle is a missile that has been slightly modified and refurbished, where as the Titan IV shares only some of the original technology but is a completely redesigned launch vehicle. It suffers from having many configurations resulting from tailoring to the payloads and specific missions in order to achieve maximum performance.

The Delta has evolved through many configurations and today is probably the most dependable of the launch vehicles having not had a failure of the most recent configuration. The Atlas also comes in many configurations, and the Atlas-Centaur system has had two failures resulting in the lowest reliability of .86. All these vehicles require substantial on pad time to assemble and check out the vehicle, ranging from 50 days for the Atlas to 110 days for the Titan IV. The call up time, that is the time to assemble and check out the vehicle at the launch base, ranges from 90 days for the Titan II to 180 days for the Titan IV. The Delta requiring some 98 days and the Atlas which is shipped assembled at the factory is ready to go to the pad after receiving inspection. The logistic for all these vehicles are primarily contractor supplied.

The Air Force would like the on pad time to be no more than 3 days and have the payloads shipped ready to launch as encapsulated payloads that conform to standard interfaces. They would like to be able to carry out the launch operations with blue suit crews requiring the minimum of contractor support. These are all achievable objectives attainable with today’s technology.

A more constraining characteristic of today’s launch vehicles is their high cost which has hampered full utilization of space. The price of current launch systems is shown in plate 2. The word price is used instead of cost in that foreign launch vehicles are directly subsidized by their governments and thus do not reflect the true cost. Typically the cost per pound for US launch vehicles is on the order of 4500 $/lb to LEO, 10,000 $/lb to GTO, and 14,000 $/lb to GEO. As a result of the foreign pricing strategies and the trade policies, US launch vehicles capture only about 30% of the commercial market, Ariane (French) about 50%, and the remainder is divided between the Russians and the Chinese.

The typical breakdown of space launch cost is shown in plate 3. As can be seen the engines constitute the largest single item of costs and thus technology that reduces engine cost has the most leverage. On the other hand if one considers truly reusable systems then most of the cost can be avoided except the refurbishment and flight operations cost which to some extent are amenable to automation and modern data processing techniques.

The Shuttle, the only manned access to space the United States has, was initially configured in 1972 and had its first flight in April 1981. The program was originally sold on the basis that it would reduce launch costs and even more dramatic cost avoidance could be realized in that satellites could be recovered and refurbished for reuse. These economic arguments were based on a very large mission model that reflected all the speculative thinking of the time. Because of these strong arguments with Congress indicating the lower cost of Shuttle launches and the NASA policy to offer flights at a fraction of the actual costs, DoD manifested most of its payloads onto the Shuttle. After the Challenger disaster on flight 25, the future of the Shuttle changed. It was thoroughly re-examined and many design and procedural changes were introduced to improve the safety of the vehicle. Also the decision was made to essentially limit Shuttle flights to those flights where manned applications were involved.

Today DoD has switched all its payloads off the Shuttle in favor of the Titan IV. Shuttle operations are disappointingly expensive being on the order of $485 million per flight based on 7 launches per year. Much of this cost is the result of the extensive refurbishment required between flights. As a result of their experience with the Shuttle, the DoD and Intelligence Community are reluctant to be tied to a manned vehicle, particularly one owned and operated by another agency. There is also a strong National concern over being dependent on a single launch vehicle.

In order to transfer from Low Earth Orbit (LEO) to higher orbits including Geosynchronous orbits and escape transfers, upper stages are used with the various boosters and the Shuttle. The primary stage used with the Shuttle is the IUS because its solid rocket motors are judged to be safe for use in the orbiter bay. The IUS is a sophisticated stage with multiple redundancy in its avionics and while it is highly reliable it is also a costly stage to use. The most powerful stage is the Centaur liquid hydrogen/ oxygen stage that was initially scheduled for use with the Shuttle until the Challenger accident. Subsequent to that event, liquid hydrogen/ oxygen was determined to be an unacceptable safety risk with the Shuttle.

The Centaur is used with the Titan IV to achieve Synchronous and high energy orbits. The Delta and the Titan use a number of solid and storable liquid stages. A common practice is to provide the stage with the booster to burn into the transfer orbit but then have the spacecraft provide the final apogee kick motor. These stages and in particular the Centaur represent a substantial fraction of the space access cost, so it is also important to address how in the future these costs can be substantially reduced.

5.1.3 Immediate Future Plans

The DoD is moving ahead with the Evolutionary ELV concept that is to replace the existing ELV fleet with a single family of Expendable Launch Vehicles with common subsystems, and is to achieve high reliability, low cost and improved operability. This current plan provides the IOC for the MLV capability in the fall of 2002 and the IOC for the HLV early in 2005. The critical technologies include reduced cost main propulsion, fault tolerant avionics, electromechanical actuators to replace the present hydraulic ones, onboard vehicle health management and advanced guidance, control and navigation system, aluminum/lithium alloy tank assemblies and automated launch operations. If the Evolutionary Launch Vehicle program is continued to its completion, it undoubtedly will be the expendable launch vehicle for a minimum of the next twenty to thirty years.

NASA is pursuing the technology of a Single Stage To Orbit (SSTO) reusable vehicle. They have released three, fifteen month study contracts to assess the feasibility of achieving a practical SSTO. These contracts call for developing a full-scale conceptual design as well as developing a subscale SSTO that can demonstrate the feasibility of the concept. In parallel they are developing the critical technologies which include advanced thermal protection systems, aluminum-lithium tanks, composite structures and hydrogen tank, tripropellant propulsion and lightweight engines.

While design studies show that with current propulsion and the new lightweight structures it is possible to achieve a SSTO with practical lift capability, the key issue is whether the technology can support true reusability, that is, refly with the minimum of servicing and not require recertification in the manner the Shuttle does. We are talking about thousands of flights not hundreds before major overhaul.. If this can be truly achieved, then the cost of space access could be reduced well below a thousand dollars a pound. This would rapidly accelerate the commercial development of space and reduce the cost of a major portion of the military space program, in that the MLV class payloads probably would be launched on the SSTO because of their compatibility with the volume constraints.

NASA's approach to the SSTO is a partnership with industry where the vehicles would be operated by industry and they would also share in the non recurring development costs. In this scenario one can envision the Air Force using the SSTO for routine MLV launches, large expendables for the heavier payloads and having a reserve expendable capability for reconstituting orbital constellations during time of war.

A key item that will have to be developed is the orbital transfer stage in that most military satellites are in orbits higher than LEO. If this stage is expendable it will add appreciably to the cost of operations. On the other hand if this stage returns to the SSTO and is recovered and returned to earth it may provide for lower cost operations if the infrastructure to support the recovery is not too costly of an investment. Electric ion, plasma, and solar thermal engines are technologies of today that can be applied to the orbital transfer problem, however their low thrust levels equate to long transfer times and thus are applicable only to certain scenarios. In all likelihood LOX/ LH_2 technology will continue to be applicable to most of the military orbital transfer operations.

5.1.4 Launch Vehicles of the More Distant Future

Ultimately hybrid air breathing/rocket transatmospheric space vehicles will come to age. This type of vehicle can provide routine access to space at reduced cost, increased operational flexibility both on the ground and in flight, and high reliability. Many of these attributes stem from the airplane characteristics of this vehicle, such as lifting body, air breathing propulsion, horizontal takeoff and landing, and so forth. The single stage to orbit airbreather/rocket combination is an airplane that goes into orbit and as such can be expected to accrue many of the desirable operational characteristics associated with contemporary high-performance aircraft.

The reference vehicle used in the NASA Access to Space Study has a baseline propulsion system derived from that being developed by the National Aerospace Plane (NASP) Program. The reference vehicle uses a special low speed propulsion mode, ramjets, and supersonic combustion ramjets (scramjets) for primary propulsion along with LO_2/LH_2 rocket augmentation in the low and high speed regimes of the ascent trajectory. These vehicles are typically large vehicles, this particular reference vehicle has a gross lift-off mass of approximately 900,000 pounds and a dry mass of approximately 240,000 pounds. The payload bay has a usable volume of 15x15x30 feet, and the payload capability is 52,000 pounds into 100 nautical mile orbit at 28.5 degrees inclination.

Transatmospheric vehicles will be far more than spacelifters, they will be capable of carrying surveillance and strike missions anywhere on the globe in times measured in a few hours or less. These vehicles will be expensive and few in number, but their capabilities will make them a vital part of the future Air Force global reach, global power capability.

The future of the transatmospheric vehicle lies with the enabling technologies which span material sciences including both metals and composites, new propulsion systems including linear rockets, variable Mach number ramjets, and scramjets, advanced passive and active thermal systems and high speed computational capabilities needed to control and configure the vehicle.

Considering the scope and the needed progression of these technologies, a practical and operational useful transatmospheric vehicle is probably beyond the time frame of this New World Vistas Study.

5.2 Use of Commercial Capability

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5.2.1 Background

The current explosive growth of commercial digital systems for broadband communications, information and entertainment signals a rapidly increasing gap between these commercial systems capabilities and that of our military and intelligence communications and information systems. The development of these systems in the context of a business and consumer-driven market(high volume/ low unit price) ensures widespread global access and use to these capabilities. For example, the Chinese will have all 26 provincial capitals, except Lhasa in Tibet, tied into a fiberoptic, digitally switched broadband network with Hong Kong, Singapore and Thailand by the end of this year. Even in developing countries, the investment in telecommunications will exceed $ 300 B over the next 5 years in phone lines for 90 million new subscribers. These numbers do not reflect the growing wireless investments by developing countries, leapfrogging the investment in the conventional hardwired information infrastructure.

Universal access to low cost computing power (not the $1500 artificial price structures being maintained by PC manufacturers) will be delivered by the video game industry. For example, Nintendo has released a 20Mhz, 32 bit RISC-based machine, 3D graphics, stereo sound, 2 displays and controller for $199[1]!!

In parallel to this remarkable revolution in information technologies , space missions are also becoming more fiscally appealing to the commercial sector. Industry leaders have begun to step forward and actively increase their pursuit of commercial space systems. Many foreign nations and companies are reaching to space just as quickly and with growing success. There has been a resultant increase in the amount of high resolution imagery, worldwide “cellular-type” communications, and commercial space-lift capabilities that are granting access to space for more and more nations. “Commercial Space” is simultaneously coming of age with “Information Warfare”[2]. The relationships between the two will have a profound effect on all future conflicts and will require innovations in the way we procure, operate and exploit space systems.

5.2.2 The “Dark Side” of the Global Revolution

Most observers view the communications/ information revolution as a positive trend, insuring greater worldwide communications connectivity and real-time access to disparate information sources, improving business efficiencies and improving human quality of life.

However, those charged with our national defense must also consider the threats implicit in this new age. In the near term, it is clear that the relative benefits of this revolution will fall disproportionately upon our enemies in that; access to worldwide advanced communications, computer processing and information and surveillance systems, previously denied due to the barriers of high entry costs or infrastructure deficiencies, will be assured. For example, in the recent capture of the Cali drug cartel leadership, it was discovered that the Cali counterintelligence computers had penetrated the International telephone switching networks and were monitoring Federal Drug enforcement activities, such as wiretaps, against them. Without the burden of the

DoD acquisition processes and the Federal Acquisitions Regulations (FAR), our enemies can acquire the state of the art while the DoD fields information and communications systems that are outmoded by several commercial generations.

5.2.3 The Future the Level Playing Field

By the end of this decade, consumer broadband communications channels, desktop supercomputing power, processing software and widespread information sources (imagery, GPS,...) will be ubiquitous:

- Computing Power: Teraflops on the desktop
- Worldwide Broadband Communications/Information -Direct Broadcast Satellites
  - Communications Constellations (Iridium, GPS, ...)
  - Imaging Satellites (Eyeglass, ...)
  - Wireless Communications (28Ghz,..)
  - FiberOptic Communications
- Worldwide, real-time access to information: Imagery, GPS,...

The irony of this emerging threat is that many of these advanced multisensor and communications capabilities were initially developed and financed by the DoD. As the cartoon character Pogo once mused, “We have met the enemy - and he is us!”

Now, because of the development of commercial market appetite the private sector investments, estimated for 1994 at over $1 Trillion, the DoD’s ability to maintain an incremental technology advantage by means of capital spending. The government is now a small user, rather than a market driver.

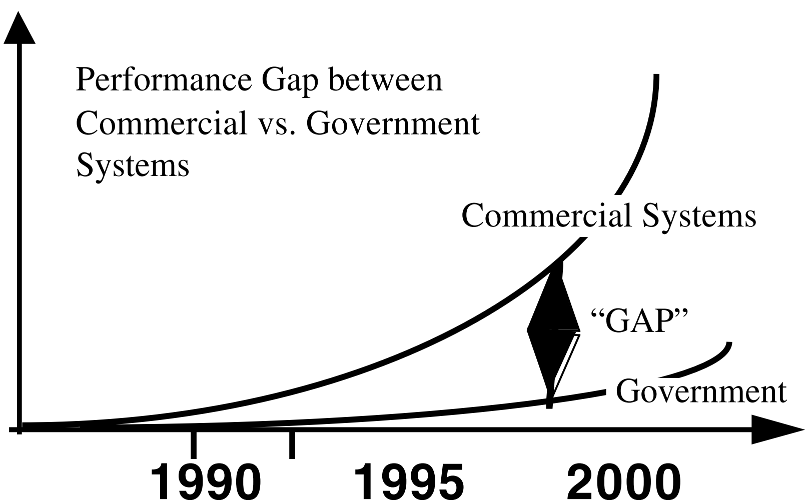

Figure 5.2.1. The Growing Performance Gap Between Government and Commercial Communications Systems

A rough graphical representation of the problem the DoD faces is shown below: The graph compares “system performance” (e.g. communications satellite bandwidth) as a function of time (years). The graph (Figure 5.2.1 The Growing Performance Gap Between Government and Commercial Communications Systems) shows the lead by the government systems has been overtaken by the commercial systems.

The sense that one should make of this representation is that there is a substantial and increasing performance gap between the commercial information systems (e.g. Direct Broadcast Satellite, etc.) and the government- developed SATCOM architectures. This reflects the large and growing disparity in commercial and DoD investments.

5.2.4 Appllications to US Military Space Systems

To support the military, as a whole, we need to consider first, the ability of commercial systems to reduce the overall cost of maintaining a minimum force level. Second, we need to consider applications of commercial systems to peacekeeping and limited regional conflicts, primarily in the reduction of deployment costs. Finally, we need to look at commercial systems from the other side and examine the drawbacks of these systems in there added value to potential adversaries and how this degrades from their overall utility.

There are a variety of potential benefits to the US military resulting from the increased development and deployment of commercial space systems. As highlighted in Table 5.2.1, these can range from a decrease in future military space system development costs, providing opportunities to share missions or to hitch along as a secondary payload, to maintain a strong US industrial base to support space systems, and to increase the ability to train and exercise our troops.

The US military should thus expect to benefit from the commercial industry’s profit-driven thrusts to reduce costs and streamline development costs for their space systems. The Air Force should focus on becoming a better customer by learning from industry as they “strip the fat” off the years of increasing space costs. If “faster, better, cheaper” is possible, the commercial sector will find a way to make it happen.

As a side benefit of the commercial space industry, the US will be able to retain its technology leadership and the skills, facilities and tools in these times of reduce budgets. Many aerospace companies have greatly reduced or eliminated in response to government cutbacks. With proper planning, the commercial space initiatives can allow for the US to retain a formidable Technology Reserve similar to the Military Reserve that can be called up rapidly in times of need.

The large number of commercial space launches and satellites planned for the next ten years will provide an opportunity to fly secondary payloads both as operational systems, or more possibly, to demonstrate new space technologies. The large cost of conducting space experiments has limited the Labs and others to space-qualify and demonstrate new technologies. The technology back-log for items “almost-ready” is growing as fewer and fewer opportunities arise. Even with ideas such as STEP, Mighti-Sats, ISTF, and others, SPOs and other space agencies are reluctant to infuse new, unproven technologies in their designs. Use the commercial launches as opportunities to demonstrate new/ready technologies might be a large cost savings both in terms of reducing space demonstration costs and in enabling new technologies for operational systems.

Table 5.2.1 - Benefits of Commercial Space Development to US Military

Potential Cost Benefit	**Description**
Reduced Space System Development Costs	Improved Manufacturing Techniques and Facilities Streamlined Practices - Trim-The-Fat Profit-Oriented Approaches Standardized Products (Busses, Interfaces, Launch Vehicles) Cheaper, Production-Line Units
Increased Availability and Capability Of Commercial Equipment, Tools And Techniques	Reduce Need For Government To Develop Specialized Tools Consumer Demands Will Require User-Friendly SW And Hardware Cross-Training With Other Disciplines -- Reduce Need For Specialized Training
Reduced R&D Expenses	Commercial Need To Reduce Costs And Increase Capability Industry Will Fund Research In Key Areas - Spacelift, Bus Technologies, Communications and E/O Payloads Military Spending Can Be Focused On Military Technologies, Payloads And Applications Number of Launches Provides Increased Opportunities for Labs To Space Demonstrate Technologies as Secondary Payloads
Retain Technology Reserve	Keep Facilities, Tools, And Skills Active Training And Cross-Breeding Of Lessons Learned Keep Ranges Active
Increased Readiness Of Military Personnel	Embedded Skills As Part Of Pervasive Knowledge-Base Increased Availability Of Training Centers Better Training Materials, Educators and Facilities Training On Real-Systems Will Become More Common

5.2.5 Working with Commercial Industry

One of the largest areas of opportunity for cost savings will result in the sharing of research and development costs. The high costs traditionally associated with space technologies has generally limited their advancement through government-sponsored projects or IR&D studies. With the increased drive to maximize the profitability of commercial space systems, industries will be more willing to invest their own dollars in R&D activities. The opportunity for the US Government to share or be a “secondary benefactor” will increase as commercial space grows. How can this be accomplished? It is clear that to fully realize the potential DoD and industry must change their behaviors and do business in new ways.

For example, the DoD cannot invest in emulating, replicating or maintaining the worldwide commercial broadband backbone but must invest in *value-added functionality* to lift the DoD above the commercial curve. Invest in building the fastest car not in building the race track. As seen from Figure 5.2.2 the DoD investment in systems for which the commercial market is in the lead (e.g. information systems) should lie in value-added functionality not in systems replication (catch-up).

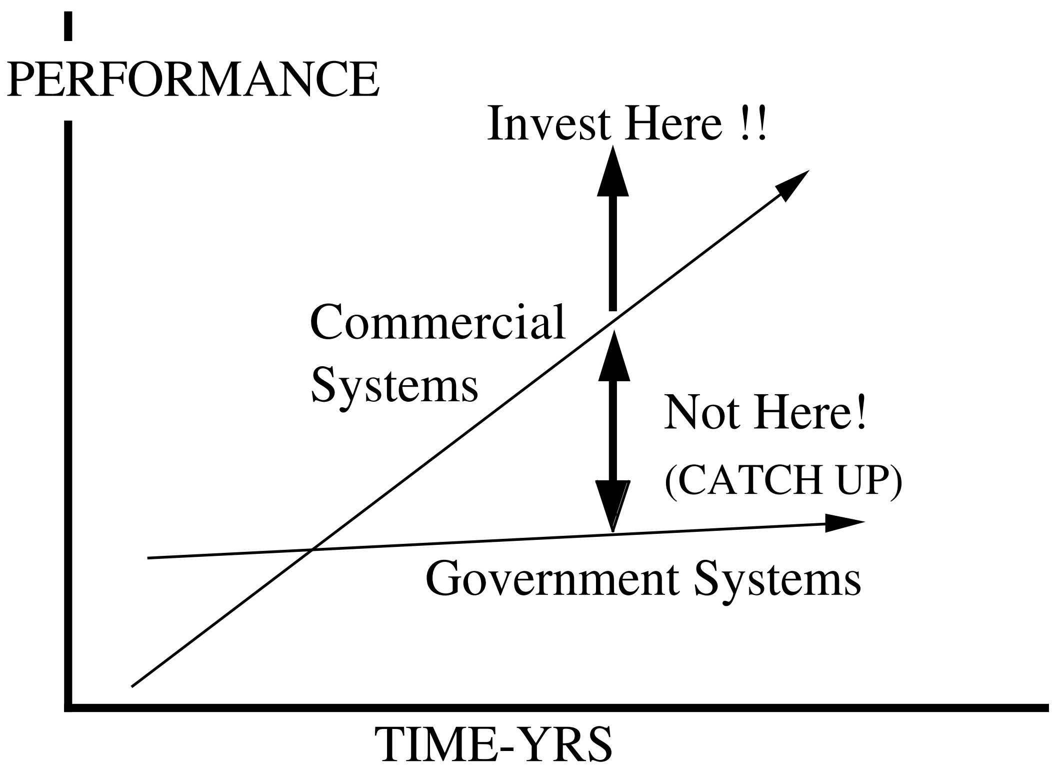

Figure 5.2.2.

This imperative was a major conclusion of the Carnegie Commission report:

- Secretary of Defense, William Perry, summarizing the Carnegie Commission report on the future of the Defense Industrial base argues for a “merger” of the commercial industrial and defense industrial bases. The US is the only industrialized nation with a separate commercial and defense industrial base. We cannot afford this luxury in a financial sense, but more critically, in information technologies, the current defense base is years behind US commercial industry in technology and commercial practice. To better define the impetus for commercial/DoD interactions, consider the following :

What is a commercial company?

A working definition: A ***commercial*** company is one which can ignore the DoD market and still remain financially viable. The focus of a commercial companies is the fight for customers in the global commercial market. This excludes most of coterie currently surrounding the DoD program offices and includes most of the Fortune 500.

Why Should the DoD work with Commercial Companies?

Only in specific markets should the DoD work with commercial companies; information technologies is such a market—the ballistic missile market, for example, is not. The unfortunate fact is that the global commercial markets is far outpacing the investment and capabilities of DoD, as outlined above. The DoD must have access to commercial development as a baseline for its investment to obtain incremental advantage over the enemy.

Why should a commercial company work with the DoD?

This dynamic is misunderstood and not recognized. The answer is not profit. In addition, the Draconian procurement and accounting systems placed upon commercial companies is a severe disincentive. However, US commercial companies will work in a meaningful way with the DoD for the following reason:

Marketing Risk Mitigation

Major corporations take the process of parsing their R&D $$ investment into various product development options with great care and trepidation. Placing this corporate "seed corn" in the wrong places, in the development of the wrong products or services, can put the entire corporation at risk of failure. This process is not an exact science; consider the history of Wang, DEC an d IBM.

To mitigate this risk, corporate management look outside their walls to the customer base for affirmation of their R&D investment directions—the exercise referred to as "marketing". The DoD represents an attractive test market for new development ideas, because:

- *DoD requirements that are typically ahead of the rest of the commercial market. DoD systems must go faster, farther, be more stable, robust, ...etc.*
- *The DoD has the capabilities to test concepts-it is a vast, responsive test bed for new development ideas*
- *The DoD pays its way--it brings development $$ with its participation*

Thus the DoD represents a very attractive test market for exercising the viability of commercial development ideas, thereby minimizing the corporate risk. This does not mean that commercial companies view the DoD as the ultimate customer, even if the development is successful. The DoD, in general, represents a small customer base with a very difficult purchasing interface.

The benefit of this relationship, however, does not fall only to the commercial developer. Several of the commercial R&D developments which the DoD is exercising will be useful to give the DoD added capability. As a co-development partner, the DoD can influence modifications of the commercial development direction to give the DoD capabilities over the commercial implementation; for example, by development of a specific interface which is interoperable with DoD systems. *These DoD-specific modifications can be implemented at low cost, or no addition cost, if done early in the co-development cycle. Attempting to change COTS products to DoD specific needs is a lengthy, expensive process.*

5.2.6 Conclusions

In summary, there are many direct and secondary benefits to the US military that will results from commercial space system development. In addition to the retention of key resources in a technology reserve, the pooling of research dollars will insure that the US maintains technological leadership in space.

In order to reach this new world, the DoD must change the way it does business with commercial developers. New relationships must built around greater personal interaction of DoD and industry partners early in the development cycle.

References
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5.3 International Space Developments

Donald Lewis

5.3.1 Introduction

The increasing worldwide availability of space technology and services applicable to military space systems portends a future in which military access to space is affordable, broad, and brokered through many global institutions. This places a burden on the authors of national space policy and the architects of national security space systems to acknowledge and accommodate the internationalization of space as it affects US military advantage from the exploitation of space. The purpose of this paper is to describe the current and likely global environment for proliferation of space technology and its applications, and the resulting pervasive access to space available to support foreign militaries. This effort is little more than a quick view to the future. More robust and insightful examination of the projected evolution of international commercial and military space should be undertaken by responsible organizations. Consistent with the limitations of this effort, this paper concludes, not with specific prescriptions but rather with the highlighting of several key considerations for those involved in establishing national space policy and architectures.

This paper was written at the request of the US Air Force Scientific Advisory Board's Space Applications Panel following a briefing on the same subject by the author in June 1995. It captures the principal messages of that presentation without the classified substantiating examples and evidence provided in that briefing. This effort was sponsored by the Air Force Materiel Command's Space and Missile Systems Center, Developmental Planning Directorate (SMC/XR) with many valuable and substantive contributions made by Col. Robert Preston, SMC/XRT.

5.3.2 Some Issues and the Players

The issues involved in this paper's topic are not new, but have become more pressing as the country's national security infrastructure truly transitions away from the Cold War paradigms and planning for new futures is initiated. The issues arising from the internationalization of space are but just a part of the many developments that will affect the outcome of those planning activities. Among the many observations made by the author while studying the topic, the following four seemed key to capturing the essence of those issues.

First is the broad global distribution, or internationalization, of space technology stimulated through various means of technology transfer. As discussed in the following section, classic technology transfer through export is only one of several mechanisms that have contributed to a global understanding and exploitation of space technology and its applications. As a result, space technology has become virtually a global commodity with many commercial sources.

The second observation is that there are increasing global opportunities to gain access to space to support commercial as well as national security objectives. Approximately seven countries can currently launch satellites, some twenty own satellites, and at least eighteen have the ability to construct satellites (and even more manufacture satellite components). There are some fifteen consortia and joint ventures currently flying satellites. Due to the global nature of the services provided by communications, navigation and weather satellite programs, every country in the world has access to space. Furthermore, virtually every country has, to some degree or another, taken advantage of that access; be it for commercial or national security purposes.

The third observation is that there is increasing evidence of growing influence and military utility of both domestic and international commercial space services and applications in comparison with those of many dedicated military space systems. Already international commercial communications satellites have more capacity, offer more extensive service options and utilize more advanced communications protocols than military satellite systems. Demands for service to mobile users and for efficient use of limited spectrum are creating commercial communications systems with the robustness and resiliency to interference appropriate for military command and control. The growth in this particular commercial sector is driven by profit opportunities in the yet-to-be saturated global market for communications. The commercial sector also provides significant enhancements to GPS navigation services, and several commercial remote sensing satellite programs are under development that will exploit untapped international markets for space-based imagery. In general, it is the agility of the international commercial sector to assimilate technology in response to changing market conditions, far exceeding that of traditional military space, which poses significant challenges and opportunities for US planners.

The last observation is that there is an ever increasing assimilation of space-based applications by foreign military commands. Countless authors have pointed out how the Gulf War demonstrated to the world the value of space support to military operations. In fact, over the last decade there has been a slow, but steady, incorporation of space-based support functions into militaries throughout the world. The Gulf War has only accelerated that evolution through the demonstration of the efficacy of space in a real, modern war fighting environment. Furthermore, there has almost certainly been a recognition on the part of various foreign states that the US has become dependent on space to support critical war fighting capabilities. Thus, the vulnerability of US space assets to foreign compromise has been increased through a broader global understanding of the value of space to military support. This increased threat is not limited to US space assets but all international programs.

The preceding observations lead to the postulation of a number of potential consequences that may result from the global proliferation and application of space technology. There are certainly others, but those listed here serve to illustrate the environment which US national security space policy must accommodate.

Enhancement of conventional foreign military forces.

Increase in foreign space forces.

Increased threats to US and allied space forces.

Complex technical and institutional interrelationships between the providers and users of international space services.

Decrease in US space industry market influence.

The force multiplier effect provided by space has only just become apparent to the foreign military strategist, particularly with the demonstrations provided by the Gulf War. The potential for enhancement of conventional fighting units through the application of satellite communications, navigation and weather services is not lost among most military commanders. The degree to which such enhancement is realized throughout the world is dependent upon many factors and circumstances. Virtually every military is resource limited and thus forced to make weapon and infrastructure expenditure decisions that maximize their perception of force enhancement in the context of their expected war fighting environments. As the effective cost of space support to the war fighter declines relative to other force enhancement alternatives, more foreign militaries will incorporate space-derived support into their military doctrine and operations. In addition, they may do so with substantially shorter development cycles in systems, tactics, and doctrine and with surprising applications of space to their militaries. They will have arrived at useful space capability without having to re-trace the development steps that US and Russian militaries took. They will be able to buy from commercial suppliers of services and systems, unencumbered by political and institutional “baggage” and attachment to past investments and old ways of doing business.

In the near-term, the functional areas most likely to see dramatic cost reductions due to market forces (primarily as a result of commercial competition) are satellite communications, weather and navigation. Remote sensing will follow as its nascent commercial sector matures. Extensive utilization of intelligence (other than remote sensing imagery) and early warning support from space will lag due to their almost purely military nature, thus requiring dedicated national security funding.

As some foreign warfighters become more reliant on space for force enhancement, more dedicated foreign space forces will be created. These organizations have the responsibility for the acquisition, operation and protection of military space support elements. Current examples include Russia, China and France, each which has well-established military space organizations. Other nations will create similar organizations once they have bought into and come to rely on space as a significant element of their national security. Although there appears to be a global trend toward commercial suppliers of space services, foreign space forces will necessarily be driven to establishing protective doctrine for those support elements that have become critical to their military force structure; except where commercial suppliers are able to assure them of robust, reliable service. The need to ensure the availability and functionality of space support elements will cause such organizations to seek survivable services, alternate sources of support, and defensive countermeasures.

It is not a large conceptual leap to go from a defensive posture to considering developing offensive measures with respect an adversary’s space assets, particularly where they are clearly identifiable targets, distinct from commercial utilities. The increasing pervasive understanding of the value of space to the war fighter (and to national well being in general) necessarily leads to more opportunities for potential adversaries to recognize the value in degradation and denial of such. The increase in threats to US and allied space assets comes not only from this broader potential understanding of the reliance of space (for targeting purposes), but also on the proliferation of the underlying technology to perform counter space activities.

In discussing the implications of the fourth consequence, that of complex international relationships, it is important to consider the nature of the players in the international environment. The early days of space saw only those few countries that could afford the high costs of space develop national space programs. The requisite government involvement essentially limited the missions to military and scientific for many years. The first commercial endeavors were highly subsidized by national governments and a few consortiums of national governments (for example, Intelsat). Thus, the majority of space programs were developed or sponsored by individual national governments. Today, although many space programs are aligned on a sovereign state basis, there are many other owner/operator groupings that are indicative of the future spectrum of players.

There is a decreasing proportion of space programs owned by individual national governments. As the international business environment creates increasingly complex financial and ownership relationships it is only natural for such complex interrelationships to be extended to the ownership and operation of commercial space systems. Furthermore, as more countries attempt to reduce their cost of access to space for scientific and military purposes there is the potential for joint ventures for non-commercial purposes both long and short term. The European Space Agency, ESA, is probably the largest single example of a foreign joint venture in that regard. From another perspective, dual-use programs such as the French Telecom and Spanish Hispasat communications satellite programs inherently offer the potential for extremely complex mixing of commercial and military interests. Some of the current and potential future categories of players in the international space environment include: sovereign states, state consortia, commercial consortia, commercial enterprises, allied coalitions, and criminal organizations

There are some interesting potential consequences of this roster of players. Consider a time of crisis or conflict during which the determination of satellite ownership becomes necessary. That may be extremely difficult in cases involving joint ventures since such organizational constructs may cross several national borders. Further, if the objective is to get the owner(s) to deny service or access to an adversary, it may prove impossible when the ownership is multinational or highly fragmented. However, difficulties in determining ownership may pale in contrast to determining the user clientele of such systems.

For example, it may become impossible in an increasing number of circumstances to sort out allied and adversarial use of communication satellites from US use. This becomes critical when precise targeting information may be required for exploitation and service takeover and denial. However, it may be difficult to garner sufficient legal recourse for the preemptory takeover of some space services due to the interrelationships between commercial and government ownership, again with substantial potential for cross border implications.

The consideration of allied coalitions and criminal organizations as players in the international space environment is somewhat new to the space policy arena. Allied coalitions should be considered an example of short-lived relationships in which multiple users share a common military objective and more importantly share common space support elements. Integrated common operational standards for ensuring interoperability, and command and control become important issues under such circumstances.

With respect to international criminal organizations, they often have resources far greater than the government organizations that they are subverting. Their utilization of space for their various “business” purposes should be considered a given. Examples abound in the areas of satellite communications and navigation. Although their ability to purchase services globally will continue to grow, it is their increasing potential and motivation to purchase the technology to either counter military and law enforcement use of space or to purchase and operate their own programs (albeit covertly via commercial cover) which becomes more problematic. Particularly worrisome is that they will be able to purchase commercial services qualitatively superior to dedicated systems currently available to law enforcement and military agencies.

The last consequence addressed is the declining international market share held by the US space industry resulting from, among other things, more and more commercial and military buyers and sellers in the global space market. Technology obtained from export and indigenous development is increasingly available for assimilation into foreign manufacturing infrastructures. Many developing countries see involvement in space technology as an avenue for enhancing their emerging high tech industries and thus they aggressively pursue opportunities. Industrialized nations with mature space industries, once highly subsidized, now more openly and aggressively compete for international sales. The end result will be more suppliers in the international market thereby reducing the market share available to US industry. Currently the US is generally considered the supplier of choice when that choice is based on quality or technological superiority. However, the choice is often dictated by a combination of international and domestic political considerations that tend to favor other sources. This allows non-US suppliers the opportunity to gain on-orbit experience and feed back the lessons learned into improving their product quality.

In closing, the development of future US national space policy and national security space architectures must acknowledge and accommodate this larger international environment that strongly influences the efficacy of all national security space capabilities, regardless of the country in question.

5.3.3 Technology Transfer

One of the implicit consequences of the internationalization of space is the global proliferation of space technology and applications. Thus, the issue of technology transfer is a critical element that must be understood by those responsible for planning future US space policy and architectures. The purpose of technology transfer policy should not necessarily be to retard the transfer of US technology, but rather to assure that the eventual result of such inevitable transfers, whether from the US or foreign sources, maximizes the opportunities to influence the global environment consistent with US national space policy objectives.

Thus, it is important to consider this issue from a global perspective rather than being concerned only with US space technology exported abroad. Increasingly, the industrialized world is aggressively marketing its own space technology as the global market for high technology as a whole becomes broader. The French government, for example, created PROSPACE (a subsidiary of their national space agency, CNES) to actively market their national space industry's technology worldwide. Increasingly, space technology is bought and sold as a commodity rather than as advanced, novel capabilities. The maturation of much of that technology has been accelerated by the international commercial sector, a growing influential factor in technology transfer.

In recent years the control of technology export from the US has been heavily influenced by concern for regulating the proliferation of technology related to weapons of mass destruction and the incorporation of advanced technology into conventional weapons. This preoccupation with near-term, first order effects has obscured the need to carefully examine the implications of technology transfer in the larger context of evolving international capabilities and the appropriate link between control policy and national space program objectives.

There is a strong global “diffusion gradient” for technology in general and space technology in particular, given the prevailing economic opportunities. Those states (and their commercial sectors) possessing technology seek to maximize their return on investment through the sale of such technology to those that find it cheaper to buy into the club rather than develop from scratch their own indigenous capability. With many commercial concept-to-application cycle times measured in tens of months (as compared with years for traditional national space programs) and the rapid depreciation in value of older technology, it is no wonder that technology proliferation is so pervasive.

One of the consequences of the space environment becoming increasing dominated by commercial enterprise is the demand for technologies that impart competitive advantage to the owner/operators. This is currently fostering a commercial sector that is more responsive in taking advantage of technological opportunities than the traditional government-sponsored national security space institutions. The projected net result will be an increasing dominance of commercial space both in terms of gross service capacity and service performance.

Apart from the classic technology transfer that occurs when technologies in the form of goods, services or technical assistance are sold to another country, there are several other means by which technology “diffuses” across national boundaries, often with little or no monitoring or control. These range from trade off-sets between the US and favored nations to university and professional training and education. For example, as a condition-of-sale to some foreign countries, the US industry must also provide training to the recipient country on how to repair, maintain and eventually manufacture their own components and subassemblies in the future. The providing of such training and start-up of indigenous capability as a condition-of-sale has become much more prevalent in US space technology exports in the last couple of years.

Training in space technology, applications and operations is provided worldwide through universities and similar institutions and is virtually unregulated. Many thousands of students are taught the basics of space technology through countless engineering programs. Many of these programs have opportunities for students to obtain hands-on experience working on small satellite projects under the auspices of experienced aerospace industry instructors. These programs are not limited to the U. S. The University of Surrey in the United Kingdom, for example, has become a world leader in the development of small satellites through its training program. Portugal purchased its first satellite, POSAT-1, from the University of Surrey in 1993 along with on-site, hands-on training for Portuguese engineers during its construction.

The pervasiveness of space technology will continue for the future; particularly for technology supporting commercial enterprise. That technology that is more limited in its applicability to military space functions, i.e., missile warning, electronic intelligence collection, will be much less prone to wide spread availability due to lower demand. The issue at hand is to appropriately assess both the downside risks associated with global technology proliferation and the upside opportunities that may exist to provide military advantage to the US. It should be pointed out in closing on this subject, that there is no linkage between the establishment of national security space policy or architecture objectives and the control, positive or negative, on technology export from the US or elsewhere.

The concept of negative control of technology transfer is fairly clear; restrict the flow through various institutional mechanisms. In recent time, this approach has been less and less effective. The concept of positive control over technology transfer is much more innovative and charts new ground in global influence. Influence is one of the primary purposes of positive technology control. Conceptually it ranges from diplomatic initiatives to control foreign access to space by encouraging institutional outcomes favorable to the US military and commercial interests to striving to dominate the international space services market place through aggressive marketing. Influence can be achieved through direct economic means; lower prices and subsidization of expensive services ("freebies") and through technological means; adoption of US hardware and software standards and specifications and licensing stipulations; and through policy impacts on regulatory risk and opportunity perception by investors. The key to achieving positive technology proliferation control is linking the need for influence and its manifestations back to national space policy and to planning for US civil, commercial and military systems.

5.3.4 International Access to Space

The purpose of this section is to outline, at best, the vast, growing domain of international space services and applications and the opportunities for foreign military utilization. There are no new revelations suggested here, but rather a picture that portends the continued prevalence of military space throughout the world. For more authoritative and quantitative assessments there are a number of market surveys and forecasts depicting the future market potential for space technology and applications that can be consulted. Consistent with the previous two sections of this paper, the message is that the space planner should not only be concerned with the negative aspects of the foreign military exploitation of space but also the opportunities that may be present for ensuring superior US access to space.

The basic functional areas listed below are used here only to serve as a means for organizing the following discussion of commercial and military space applications. The sections that follow briefly describe some of the more interesting facets of international access to these functional areas. A more comprehensive treatment of this topic with pertinent examples can be obtained in classified forums.

5.3.4.1 Navigation

Space-based navigation has become one of the principal examples of a military support service evolving into a broad, global commercial application. The geolocation service provided by GPS has become a virtual utility, available to all those that can afford the relatively inexpensive receivers. The availability of such receivers world-wide has made it possible for essentially every foreign military to obtain them, resources permitting; the resources required having become nearly negligible. The Gulf War and other regional conflicts have highlighted the intrinsic value of accurate, personal navigation support to the war fighter. The Russian GLONASS system is a similar space-based navigation service that, although it has not caught on in popularity, has also contributed to the broad understanding of the military value of space-supported navigation services.

The effectiveness of the commercial sector in rapidly exploiting the economic opportunities in space services is exemplified by the growth in geolocation applications and associated enhancements. For example, Selective Availability, a secure means for providing higher accuracy

GPS geolocation capability to US military users, has effectively become circumvented through the international commercial marketing of differential GPS services. This is an example of how the commercial sector, driven by market opportunities and pressures, provides services equal to or exceeding those of the military sector.

Clearly one consequence of the pervasive use of GPS will be the development of special warfighting applications utilizing accurate geolocation. Of special concern are the development of precision guided munitions and high accuracy ballistic missile guidance systems. In addition, incorporation of GPS receivers on spacecraft will permit more autonomous attitude and tracking functions. Already such experimental systems are being flown by foreign space programs. This will enable access to improved remote sensing and intelligence collection products obtained through higher accuracy satellite geoposition and geolocation information.

The growing, well-known reliance on GPS for both commercial and military purposes establishes such services as potential targets. The potential threats to space-based navigation and geolocation are increasingly becoming more widely recognized. It is likely that some adversaries will give thought to degrading or denying such services; albeit with the potential for inflicting interference with their own use of those same services.

5.3.4.2 Weather

Satellite imagery of global weather patterns has been available throughout most of the world for several decades. Weather imagery data is available virtually everywhere and easily supplied and incorporated into military operations. In addition to the US programs, meteorological satellites are operated by the European Space Agency, Russia, India and Japan with China soon to follow. To facilitate global utilization of weather data for peaceful purposes, international standards have been established for common data downlink formats. More sophisticated services providing atmospheric sounding, sea states, winds and oceanographic data will become more prevalent and also probably freely available from both US and foreign programs. The foreign military commander is therefore likely to have broad access to increasingly sophisticated meteorological data from space from which to obtain significant military benefit. Like space-based navigation services, space-based meteorological services are becoming utilities with broad, global constituencies.

The sensitivity to providing weather information to ones potential adversary is exemplified by India’s encryption of weather imagery from their geosynchronous weather (and comms) satellite program, INSAT, to preclude its exploitation by Pakistan. The downside of this policy seems to be that it has precluded India from sharing their weather data with other countries and entering into the commercial market for ground receiving equipment. India is now considering broadcasting their satellite weather data in the clear; particularly since Pakistan has access to other sources of satellite weather data reducing the value of the encryption as a defensive measure.

5.3.4.3 Communications

Probably the fastest growing segment of the international space services market is communications. The evolution toward global interconnectivity has inspired consideration of novel uses of satellite systems integrated with the terrestrial communications networks. There are several important developments and trends in satellite communications support to the warfighter. A few of those are mentioned here.

One is the exploding growth in personal, remote, mobile communications capability provided in part through space networks. International mobile satellite communication has been principally limited in the past decade to INMARSAT, a large international consortium. The equipment has typically been large and suitable only for large mobile platforms such as ships and large aircraft. Recent market developments, matched with new technologies, have inspired the global offering of personal satellite communications applicable to a broad range of applications and users, including military. The potential size of the commercial market for such communications services coupled with competitive pressures will undoubtedly drive pricing down to levels that many foreign militaries can afford.

A consequence of growing satellite communications capacity and market demand is the increasing global competition for limited spatial and frequency spectrum resources. At geosynchronous altitudes, communications satellites are spaced apart to preclude interference with adjacent satellites. Some regions of the geosynchronous belt are saturated and diplomatic conflicts have resulted from competition for orbital slots. The frequency spectrum available for satellite communications is finite and must be allocated among the many users. This has driven the development of frequency reuse technologies to permit higher capacity within that finite spectrum resource while minimizing interference. The result is that more robust, less vulnerable communication links are becoming available.

The interesting consequence of the commercial markets' push for more efficient utilization of spectrum resources is that an increasingly dense and complex traffic environment will result. Through such concepts as packet-switched networks and agile beam forming antennas it will be difficult to identify, characterize, exploit or degrade specific users' communication links. Tighter spot beams, smaller, mobile terminals, and inherently more jam-resistant spread spectrum waveforms are already making commercial satellite communications less vulnerable. A virtual sanctuary may, in fact, be created for adversarial communications.

5.3.4.4 Remote Sensing and Intelligence

Remote sensing from space is an application that has been exploited in both the civil and military sectors for many years. There has been a slow, but steady growth in both sectors to provide increased resolution imagery. Low resolution imagery (30 m GSD) has been widely available from the Landsat program for many years as well as from Soviet earth resources programs. Even Landsat's combination of low resolution and infrequent revisit provides opponents with visibility into theater level troop movements (brigade level and higher), particularly with its multiple spectral bands. For example, General Schwarzkopf's famous "Hail Mary" flanking maneuver in the Gulf War was visible in a timely way in freely available Landsat imagery.

During the last decade several new international programs were launched to provide low and medium resolution imagery; primarily for earth resources purposes. For example, India started their IRS program in 1991 producing multispectral 36 m GSD imagery and the French SPOT program has provided 10 m GSD resolution since 1986. There are now several more sophisticated follow-ons to those programs as well as a new emerging international industry that proposes to provide high resolution imagery on the order of 1 m GSD within the next couple of years. As multispectral imagery of similar quality becomes more widely available, camouflage, concealment, and deception will become more difficult. As multiple commercial sources become available, revisit opportunities will increase and responsiveness will improve. As commercial Geographic Information Systems software becomes more widely available and competitive, fusion of multiple source information will be commonplace and easy. All such capability being actively marketed by the international commercial sector.

International remote sensing programs are not limited to visible and infrared wavelengths. JERS, ERS and ALMAZ are three synthetic aperture radar programs that have flown or are currently flying which provide worldwide commercial access to synthetic aperture radar imagery. As the all-weather, day-night imaging capability of radar becomes more widely appreciated and the resolution provided by commercial systems improved, it is expected that space-based radar products will become an important adjunct to visible wavelength imagery in foreign militaries.

With the global availability of satellite imagery available from numerous sources there is clearly a broad, increasing awareness of space-based imagery applications. The utility of once classified military imagery systems is seen in the recently released US reconnaissance photographs and those on sale from similar Russian reconnaissance programs. Again, the Gulf War probably provided the single most important boost to the emerging commercial satellite imagery industry. The success of the French SPOT satellite program in providing high quality, reliable imagery services to coalition forces was a lesson many took home following the end of the conflict. For example, SPOT now actively markets to the world the broad military support utility of their imagery from reconnaissance to target characterization and infiltration route planning, among other things.

There have been several comprehensive studies performed recently on the impact of widely available satellite imagery. Virtually all of those studies conclude that imagery from commercial sources as well as military programs will be available to the US, its allies and its adversaries. If the imagery is not available from the US, there will be sufficient supply available from foreign sources to accommodate many foreign military requirements. Performance issues such as timeliness, coverage area, downlink options and resolution will be dealt with by the competitive forces in the commercial market place. More foreign militaries are expected to take advantage of commercially supplied imagery as competitive forces result in lower prices and more useful products.

5.3.4.5 Early Warning

The slow, but steady proliferation of ballistic missile technology and programs has raised interest in several countries in the ability to detect of missile attacks. Currently only the US and Russia possess space-borne missile early warning systems, but other countries are anticipated over the next couple of decades to seek similar capability. This may stimulated by the desire to be less dependent upon US supplied and controlled data such as during the Gulf War. The Western European Union, for example, has expressed interest in obtaining the capability to detect missile launches from the Middle East and North Africa aimed at Europe. France, in particular, continues to show much interest in having such capability. The high costs associated with such systems will probably drive most serious players into cooperative arrangements rather than outright purchase.

5.3.4.6 Space Forces Support

The space forces support function, addresses among other things the command and control of domestic military space elements and surveillance of foreign space programs. It is an area of increasing world-wide capability as commercial space systems become owned and operated by a number of countries. Some countries, like France, have developed global command, control and tracking networks allowing them to communicate with their satellites over broad areas for command and data downlink purposes. Such a capability provides flexibility to support military operations over broad areas as well.

As the commercial sector increases its participation in space on a global level, it will probably find that it requires global control capability. The high costs of large, geographically distributed ground segment networks will probably preclude most countries from developing them on their own. More likely will be coalitions and joint ventures to share costs. Or, with the spread of global interconnectivity (via space and terrestrial links) and such technologies as autonomous spacecraft navigation and control, new paradigms of global space command and control may result.

The technology and concept of operations are fairly common throughout the international arena thus providing easy insight into satellite operations by those interested. This, of course, helps to provide the understanding necessary by those adversaries that might choose to develop space countermeasures.

Space object surveillance and identification (SOSI) capabilities are prolific throughout the world. In addition to those countries possessing their own dedicated infrastructure of tracking radars and optical sites for SOSI, there is a growing capability within the amateur astronomy and similar non-government entities to perform SOSI. There are several studies that have explored the threat implications of such capability with respect to supporting various counterspace activities. The fact that such interest abounds worldwide, the ability to disseminate tracking data global via the Internet and the electronic and optical technologies are available to support such SOSI activities is further strong evidence of the international availability and pervasiveness of advanced space-related technology.

5.3.5 Implications for Space System Architects

OK, so what? Space technology has become pervasive globally, an increasing number of countries have embraced the utility of space for military operations and technology transfer is driven by a multitude of market factors; *this is not new news*. At this point the reader is reminded of the intent of this paper. It is to highlight for the authors of national space policy and the architects of future US national security space systems some important issues concerning the evolution of a space market environment of truly worldwide proportions. To that end, the following sequence of key conclusions is presented. This sequence is not in and of itself significant, but rather just a convenient means for stimulating discussion.

1. The diffusion of space technology and related applications worldwide will continue unabated between friends and foes alike.

2. This has lead to and will continue to foster a more pervasive global understanding and exploitation of the commercial and military utility of space.

3. Aiding in this process is a maturing commercial sector which provides services via space and which has the ability to respond more quickly to changes in market demand and profitability than traditional military space programs.

4. The industrial infrastructure supporting this international commercial sector is starting to put more emphasis on providing more commercial capacity and capability on orbit rather than supporting similar dedicated military space systems.

5. The increasingly complex business and financial interrelationships seen throughout the global markets will continue to incorporate space-supported services into multinational enterprises while they foster the perspective that space is nothing more than a means to a business end.

6. These complex interrelationships will pose significant challenges during times of crisis and conflict when the parties involved may be inextricably linked together in a *defacto* international space architecture.

7. There will be increasing opportunities for foreign warfighters to obtain support from the international commercial space services sector as well as from new, dedicated foreign military space capabilities.

8. There will be new players and their relationships to US sovereign interests may not be singular and stable over the planning horizons currently under consideration.

9. The potential is increasing for all international space systems to become targets as reliance on space services increases and enabling technology for counterspace activities becomes more widely available.

What does this mean for the policy makers and space architects? It means that their consideration of the future must not only acknowledge the internationalization of space as postulated here, but also to seek to exploit the opportunities and appropriately respond to the various implied threats.

This paper concludes here not with specific prescriptions, but with some suggested guidelines for conducting the planning activities.

1. Constantly monitor the global development and utilization of space technology and directly inject the resulting intelligence into the policy and architectural functions.

2. Establish a link between the development of space policy (e.g., export control, regulatory controls, spectrum allocation) and the development of strategies for implementation of national space program objectives.

3. Carefully consider the near and long-term consequences of US and foreign institutional barriers to US industry participation in international space technology and services markets.

4. Exploit through international cooperative arrangements opportunities to influence space support to the warfighters; foreign and domestic.

5. Seek up front to understand and accommodate the ramifications and threats posed by reliance on complex international (and domestic) institutional relationships providing

critical national security space services.

6. Establish metrics and definitions for measuring and characterizing US superiority in national security space vis-à-vis that of the rest of the world.

The internationalization of space provides both opportunities and risks to US global superiority in space. The risks far outweigh the opportunities unless actions are taken to truly exploit the opportunities to mitigate or eliminate the risks.

5.4 Survivability of Space Systems

Gregory Canavan and Betsy Pimentel

5.4.1 Introduction

The survivability of space systems has been a concern for several decades. It might be expected that the end of the cold war could reduce these concerns; however, the changing international order and the diffusion of capable new technologies could make it even more of a concern in the coming decades. During the Cold War, strategic and intelligence satellites were essential in maintaining the balance, so both sides were reluctant to overtly interfere with the space assets of the other lest such actions escalate unpredictably. In that environment, modest augmentation of propulsion and hardening appeared adequate for perceived threats. Some satellites such as those for Strategic Defense and MILSATCOM aspired to higher levels of survivability, but they were the exceptions rather than the rule. Moreover, their survivability measures were only partially implemented, and are largely inappropriate for the emerging threats discussed below.

In the coming decades, there will continue to be a spectrum of threats reaching from electromagnetic interference and jamming to material or laser attacks. The former will remain important and measures to deal with them must continue to be developed. They are not, however, discussed extensively here, for two reasons. The first is that radio frequency interference is likely to remain an area of active probing between the major powers, and it is a very technology intensive field. In the process of developing techniques for remaining competitive with each other in this area, the major powers. should develop technologies that should keep them far ahead of second or third world powers. Thus, rather than looking back to the threats of the past or examining the incremental development of conventional electromagnetic threats, the material below looks ahead to the less understood challenges of next few decades.

These new threats are, for lack of a standard nomenclature, characterized broadly as interceptors and lasers. Interceptors are guided or self-guiding rockets with kill package payloads that will generally be nonnuclear. Such interceptors have been in development for decades. They should gain significant additional capability over the next few decades due to the diffusion of the technologies developed in the last decade for missile defense. Lasers are directed energy weapons that produce lethal beams of light. Lasers are of international interest for fusion, industrial, and research applications, which has lead to their worldwide availability. Interceptors and lasers are first discussed separately and then compared to assess their relative maturity and the difficulty of developing countermeasures to one or both of them.

5.4.2 Interceptors

Interceptor technology was given considerable impetus by missile defense programs of last decade, which improved the performance and efficiency of rockets, the sensitivity of homing focal planes, the accuracy of hit to kill packages, and the range, sensitivity, and portability of cueing and auxiliary sensors. Quite efficient rockets and kill packages have now been developed and tested through the efforts of a large number of laboratories and contractors. In the current funding situation, those technologies could be more widely available without too much delay. That assessment also holds for radars and infrared sensors, which also have a wide range of legitimate international commercial applications. Any rocket with theater or international capability or interceptor with adequate sensors to intercept intercontinental, regional, or theater missile will also have some capability against satellites. A theater missile with a 1,000 km range on an optimal trajectory with a 250 km apogee needs a burnout velocity of ≈ 3 km/s. Fired straight up, it should reach an altitude of ≈ 500 km, which would give it significant coverage against satellites in low Earth orbit (LEO). Later, with improvements in boosters, sensor, and guidance, such interceptors could threaten satellites in medium Earth orbit (MEO) and later those in geo-synchronous Earth orbit (GEO).

A key element of an interceptor-based system is its search or cueing sensor. Such sensors have shown recent progress in terms of technologies that are capable of dissemination. It should be possible to cue interceptors with individual or internetted radars of the quality likely to be in commerce. It should also be possible to cue interceptors from repeated observations over many orbits of satellites that maneuver little. Some satellite signature reduction is possible, but it is difficult for satellites that are observed over long periods of time from many different angles. For satellites that do maneuver, visible or IR telescopic search or passive occultation could suffice for detection and track. In addition to the significant progress in those areas made in recent years by the DoD, the university astronomical community has made significant advances and adaptations of these technologies, which could widely disseminate search technologies with significant capability against even objects with significantly reduced signatures. Long, lightweight tethers can be used to connect decoys, spares or other mass to an active spacecraft. The resulting ensemble would function as a survivability aid, which could degrade some ASAT systems, particularly those of third world nations or rogue groups. This concept is described further in the classified annex.

The rest of the intercept would be much like that for missile defense, for which these technologies were intended. In particular, the handover to onboard sensors for hit to kill would follow the pattern of Strategic Defense, for which these on board homing sensors are developed. The key technologies are now widely available, because they have a range of uses. Both the early PtSi and the improved InSb mid-wavelength infrared focal planes have commercial as well as astronomical applications, and blown down long-wavelength infrared focal planes that are fully capable of intercepts of cold targets are available from commercial sources. Even the lidars needed for accurate ranging in the end game are now available from a number of laboratory and commercial sources.

The availability of rockets, search, and homing sensors do not appear to be a problem for the attacker. The microprocessors required to control the intercepts are available in any modern personal computer. And the algorithms and programming required to do so are open, available, and modest. The main problem would be the expense and difficulty of integrating them. The cueing sensors might cost ≈ $10M; facilities and manpower might add a like amount, for total fixed costs of $20-30M. Current theater rockets cost on the order of $0.1M; improved rockets for this purpose might cost between that and $1M. The on-board sensors might add another $1M, for total variable costs of $2-3M per engagement. If this facility launched 10 interceptors, its fixed and variable costs would be about equal and the total cost per launch would be about $4-6M/interceptor. Such an interceptor would have a cost effectiveness ratio of about $1B/$5M = 200:1 against a $1B satellite. And given the role that such large, capable satellites play in current assessments of developments in remote theaters, the value of negating them could be much larger than just the numerical value of this cost effectiveness ratio.

As to the difficulty of integration, search sensors of this quality are routinely manned by third world personnel; similar rockets were used effectively by poorly trained personnel in the Gulf War; the launch facilities are standard; the on-board sensors and electronics could be maintained by typical electronic technicians; and the programming is at the university undergraduate level. Thus, availability of components, cost, and integration do not appear to be a significant hurdle to the development of the level of capability discussed above.

The interceptors discussed above should be able to detect, track, and hit non-maneuvering targets. And it is unlikely that a large, flimsy satellite could out maneuver an interceptor designed to intercept theater missiles capable of executing 5-10 g maneuvers in the end game. If the interceptor does hit such a satellite, the collision would probably be fatal to the satellite. It is just about possible to shield a satellite against objects with an areal density, i.e., density times length, of 0.1 to 1 g/cm^2, and these interceptors could have areal densities 100 to 1,000 times that. Given penetration, the probability of hitting and destroying a mission-critical system is also high. Thus, interceptors based on the current levels of technology should have significant margin for the destruction of non-maneuvering or even maneuvering satellites. Against such a threat, satellites must be able to avoid being hit at all, or they cannot be considered survivable.

A brief word is in order on self defense, which is often invoked as a possible means of improving survivability. In its simplest form, the satellite, when attacked, would send a small rocket ahead to hit the attacker. But the attacking kill package could detect its release, and send out some decoys that could confuse and negate the self defense missile. Thus, the assessment of the effectiveness of self defense hinges on the relative masses of the self-defense rocket and the decoys. The following section discusses that comparison and finds self defense to be of marginal value to the satellite.

5.4.3 Decoys

For satellites with limited maneuver capability, an obvious countermeasure to kinetic interceptors is the release of decoys when under attack. That both increases the number of potential targets the interceptor has to consider and forces it to include more sophisticated sensors for their discrimination. Against entry-level interceptor with unitary payloads, the deployment of decoys need not be stressing. The decoys would only need to remain credible during last few minutes of approach, when they were closest to the interceptor and most susceptible to examination by its sensors. Hence, the decoys could ideally be quite light—possibly inflatable. They would primarily need to roughly match the satellite’s overall emissivity-area, although in time attention should also be paid to the visible and infrared.

Deploying even simple decoys takes some mass. In strategic defense studies it was often found that an adequate thermal midcourse decoy for a 300 kg reentry vehicle (RV) could weigh about 1 to 10% as much, or ≈ 3 to 30 kg. An example shows the difficulty involved in achieving adequate leverage. Ten decoys would reduce the probability of the satellite being killed to ≈ 10%, if they worked perfectly. But even at 10 kg per decoy, the low end of the range above, the expected mass loss for a 1 ton satellite that is attacked by a single weapon is ≈ 10% probability of destruction x 1 ton lost if destroyed + 10 decoys x 10 kg/decoy ≈ 200 kg. That is much less than the 1 ton loss it would surely experience if the decoys were not deployed, but it is still greater than the ≈ 100 kg kill package mass of a near-term interceptor. Moreover, the satellite is in orbit while the attacker is on a sounding trajectory, so there is another factor of about 4 in favor of the attacker. Thus, overall this engagement factors the attacker by about a factor of 4 x 200/100 = 8:1.

Increasing the number of decoys would not be of value. 20 decoys would give a loss of ≈ 5% probability destruction x 1 ton loss + 20 decoys x 10 kg/decoy ≈ 250 kg. Reducing the decoy's mass below 1% does not appear credible. Reducing the satellite's mass does have some value. A 100 kg satellite with 10 decoys would have an expected loss of ≈ 10% probability of destruction x 100 kg loss + 10 decoys x 1 kg/decoy ≈ 20 kg, which gives an overall exchange ratio on the order of unity.

It is useful to codify these calculations of the exchange ratio, E, which is the ratio of the masses expended by the attacker to that extended by the satellite. The mass expended by the attacker is P, the interceptor payload mass. The mass expended by the satellite is $\approx M/n + nC$, where M is the satellite mass, n is the number of decoys, and C is the mass of a decoy. Thus, the exchange ratio is $E = kP/(M/n + nC)$, where $k \approx 1/4$ is the attacker's advantage due to his sub orbital trajectory. While the attacker's mass is fixed, the defender's can be minimized by the choice $n = \sqrt{(M/C)}$. For $C = fM$, $n = 1/\sqrt{f}$. For f = 1%, the optimum number of decoys is 10, as shown in the examples above. For that choice the defender's expected mass loss is $2\sqrt{(MC)} = 2M\sqrt{f}$, and the exchange ratio is $kP/2M\sqrt{f}$. Thus, the principal means of increasing survivability are decreasing mass and f. A 100 kg satellite with 1% decoys roughly breaks even. A 30 kg satellite with 0.1% decoys would have about and order of magnitude margin.

While the examples and derivations above indicate that small satellites could have some effectiveness against current interceptor threats, it should not be forgotten that it could also be possible to significantly reduce the mass of the interceptor kill package, and perhaps to improve their discrimination capability in the process. It is not clear that decoys is a winning game, it is only clear that it is more viable than the survivability of large satellites, which scale in the opposite direction and leave much of a constellation's essential capability concentrated in a single satellite.

5.4.4 Fragment Warheads

Fragment warheads add some complications to the above discussion that are worth noting briefly. The first is the simplification of intercepts with fragment warheads. The discussion above assumed that adequate hit to kill technology was available. That seems a reasonable assumption, but it is not essential. Even in hit to kill systems it is conventional to use lethality enhancers in terms of pellets or wire meshes extending some distance out from the interceptor to increase its geometric coverage. Such devices would also be applicable in attacks on satellites. Moreover, since the satellites can maneuver less and are more vulnerable, the nets could be spread much more widely. Indeed, a 100 kg kill package could spread centimeter pellets over an area 100 m across, which could eliminate all of the decoys and satellites in that area.

This leads to the second point: fragment warheads make this attack a game. Spreading the threat cloud widely covers more area, but might permit the satellite to slip through. Thus, the defender must optimally choose the thickness of the shielding on the satellite and the attacker must optimally choose the size of the threat cloud separately but in concert. The result is a penalty for survival that is roughly proportional to $MP^{1/5}/L^{2/5}$, where M and P are as above and L is the warning distance the satellite has to maneuver. For a 100 kg kill package and L = 10 km, this penalty would only be few percent of the satellite mass-divided about 60% for maneuver and 40% for hardening. If the attacker could reduce the distance to maneuver to a fraction of a kilometer, the penalty would increase to a significant fraction of the mass of the satellite.

5.4.5 Attrition

Attrition attacks are variant on the discussion above, which assumed that the attacker needed to negate the satellite on some given pass overhead. If the attack could be made at a time of the attacker's choosing, that adds an additional dimension to the defense's problem. Some measures--particularly maneuver and decoys--are most effective if initiated at the first sign of launch. That makes those defenses susceptible to false alarms. If the attacker made a convincing show, but did not launch the interceptor, the satellite could be misled into expending mass for fuel and decoys as if it were attacked. While it could afford a few such maneuvers, in time its fuel and decoys would be exhausted, which would defeat its mission. Moreover, as it approached the end of its reserves, it would be in an increasingly vulnerable and unstable mode. Since the decoy attacks could be simple, cheap, and sub-orbital, the economics of such feints should strongly favor the attacker.

Viewed from the perspective of the defense, the need for a possibly large number of attacks before exhaustion was reached could allow the defender to interdict the interceptor launch sites by other or on-board means, if available. In following this approach, however, it would still be best if the satellites had some degree of survivability on each pass so that the attacker saw an incentive for attacking them deceptively over time rather than just destroying them on their first pass.

5.4.6 Space Mines

Space mines are the limit of coorbiting antisatellites. They are mentioned here for completeness because they presented a nagging problem in the last decade that was never satisfactorily resolved. They are small satellites that are launched on optimal trajectories to gradually approach for rendezvous with large satellites, which they then track through their large signatures. They remain in trail until they are told to destroy themselves, and the target satellite in the process. Because they are much smaller than the host satellite and need only sensors adequate to track it from short range, they can be cheap and efficient. Having them nearby would effectively negate the host satellite's mission. It will probably not be possible to know whether the mine is threatening. It may not be possible to know who launched it. It is not clear that such mines would be detectable from the ground.

Here, the interest in mines is that they are a form of attack that could operate with cueing sensors comparable to those for direct ascent kinetic energy interceptors. Moreover, they are the type of small, simple payload that a country might just be able to put into space when they first gain an independent space launch capability. If they wished to quickly gain a role as a significant player in space, mines would be a logical vehicle for staking that claim.

Mines are quite awkward to negate. They are hard to detect from the ground--even from space, unless all satellites are provided capable search sensors. It is not possible to use normal maneuvers to loose them, as their smaller size and simpler mission enables them to follow maneuvers closely. Eliminating them would appear to require a search set and self-defense means on each satellite or a roving inspection capability. Either would represent a significant cost and loss of flexibility. If it could not be assured that the mines were nonnuclear, these means of disinfectant might not be viable at all.

5.4.7 Overall Assessment of Interceptors

Kinetic kill interceptors have been a significant concern for several decades. While the previous systems were of limited capability, the development and diffusion of improved cueing, missile, homing, and lethality enhancement over the last decade has significantly extended the capability available to potential attackers for modest investment. Given good information on trajectories, the combinations of technologies in commerce should be capable of hitting most satellites. Give that they did, hardening would appear to be of marginal value at best. Very light and capable decoys could provide some margin, but only for small, light, and cheap satellites. For large satellites, the only defensive measures with much leverage would appear to be the denial of trajectory information through signature reduction, deception, the use of other objects for cover, etc. While these measures appear difficult, the alternative would be moving these satellites out of low Earth orbit.

5.4.8 Lasers

Lasers differ in that they both move and track targets with the speed of light, which negates the effectiveness of target maneuver. Moreover, they send up only photons, which can enter space with little penalty. That tends to give the attacker a great mass and cost advantage. There are two pain types of high power lasers. They are described separately here, because they have distinctly different modes of interaction, which lead to significantly different effects and countermeasures. Continuous wave (CW) lasers run continuously for many seconds. They interact by depositing heat on their targets, which they kill by cutting structural members or melting internal components. Pulsed lasers deliver their energy in short bursts of energy, typically milliseconds to microseconds long. Its deposition vaporizes and blows off material. The recoil produces impulse on the target, which can blow holes in surfaces and break structural elements. Thus, the kill mechanisms are closer to those of kinetic energy interceptors.

Lasers have not been a serious threat to date because the lasers have been too large and expensive and because their beams have been spread out widely by the atmosphere. Recent technical developments have removed both of those constraints. Pulsed lasers can now be scaled to the MJ level, which is adequate for lethal applications, for a few $M with several different technologies. Even more important than the advances in laser technology are the advances in active optics. An uncorrected beam propagating upward through the atmosphere develops a spread of about 2 arcsec (10 microradian), which is set by the atmospheric “seeing” at good sites. In propagating to a satellite to a satellite at a range of 1,000 km, the beam then spreads to a diameter of $\approx 10^{-5}$ rad x 10^{6} m $\approx$ 10 m. For a MW laser, that would produce a power density of $\approx$ 10 kW/m^2, which is only a few times the flux from sunlight. It is possible to shield against such fluxes simply and passively. Such power levels do not represent a serious threat. It is possible to produce much higher power lasers, but nonlinear effects in propagation through the atmosphere further distort the beam and actually reduce the received power. There are special problems with sensors, but they can be protected or covered. Thus, large lasers with uncorrected beams do not appear to pose a serious threat to even lightly hardened satellites.

The situation is quite different for corrected beams. Active optical systems sense the density distortions that cause phase errors and cancel them with conjugate motions of deformable mirrors.. That restores the diffraction limited beam divergence of $\lambda/D \approx 10^{-6}$ m /1 m $\approx 10^{-6}$ rad ($\approx$ 0.2 arcsec). Thus, the beam diameter at 1,000 km is $\approx 10^{-6}$ rad x 10^{6} m $\approx$ 1 m, so the power density is $\approx$ MW/m^2, which cannot be countermeasured passively. Such fluxes would kill in a few seconds. The energy density from a MJ pulse is $\approx$ MJ/m^2, which is also far above the threshold for enhanced coupling and shock production. It would be difficult to shield against the pulsed laser, which would deliver energy at a rate of about 10^{12} W/m^2--about a billion suns. Such fluences would kill in microseconds.

The technical requirement for producing such a weapon are not great. The main need is an active mirror with about as many corrector elements across it as there are atmospheric coherence lengths across the primary aperture. For a 1 m aperture and 10 cm coherence (good seeing), that would require a mirror with $\approx$ (1 m / 10 cm)^2 $\approx$ 100 actuators. It would also require a low power laser for atmospheric sensing. Such mirrors and probe lasers are being provided to U.S. and foreign astronomers for legitimate scientific projects. The astronomical community has already adapted and is making improvements to both key technologies. An awkward aspect of pulsed lasers is that they could be very difficult to find. Even using current technology, the active region of a MJ laser could be on the order of 4-5 m in diameter, and the energy storage and optics region might be only a few times larger. Thus, a MJ laser could fit in a garage-sized building, whose only distinguishing features could be a sliding roof panel and a modest power supply. This lack of large, visible signatures could make it difficult to interdict the laser should other defensive means fail.

Corrected lasers track without penalty, so they negate the effectiveness of maneuver. Decoys are also ineffective against lasers, since laser pulses could be generated for $\approx$ \$1,000 per shot, which is much less than the launch cost of decoys weighing as little as a few kg. The laser should have an adequate shot rate and engagement time to irradiate many decoys and watch them deflate, leaving the target in view. It might be possible to shield against certain levels of attack by CW lasers by exhausting hydrogen, but the amounts required are very large and could be quickly exhausted. Against pulsed lasers, it should be possible to use shock shields or sacrificial layers to decouple energy deposition from the surface of the satellite. That could reduce material removal, so attrition would be less by one measure. However, even with decoupling, significant shocks would be produced, which could break reinforced mechanical structures. Pulsed lasers produce typical coupling coefficients of C $\approx$ 10 dyne-sec/J, so a MJ pulse would produce $\approx$ 10 dyne-sec/J x MJ $\approx$ 10 Mdyne-sec, which would produce a relative velocity of $\approx$ 100 m/s between irradiated and non irradiated parts of a satellite. That would cause the irradiated material to blow in and turn into fragments, which would be difficult to accommodate.

Even if it was possible to block bulk damage of the satellite, it would still be necessary to guard against sensor kill. Focal planes are particularly vulnerable. In a short pulse, a fluence of 100 J/cm^2 might damage a single detector. That is a significant flux, but an optical system with a 10 cm aperture would magnify the incident radiation by a factor of $\approx 10^{8}$, so an input fluence of $\approx 10^{-6}$ J/cm^2 could damage focal plane. Moreover, with that much leverage, even the energy that blooms over onto adjacent detectors due to scattering in the optics could damage them too. Even if the transfer function of the optics was good enough to provide factor of 2 isolation for every additional detector separation, several hundred detectors could be affected. Such damage would negate the primary mission of an imaging sensor. It would not be acceptable. Means to overcome it are needed. There are some ideas in the form of very fast acting shutters, which would detect the incident radiation and shut off before unacceptable levels of light were transmitted. Such protection might be possible for CW lasers, for which the damage accumulates over many seconds. It is much more difficult against pulsed lasers, which would require isolation to build up from low levels to a factor of 10^6 or more rejection in microseconds. That should be possible with semiconductor electro-optical switches, but is not available.

The comments above have concentrated on lasers for specificity, but they apply to other related electromagnetic threats such as microwave weapons as lesser included threats. Microwave weapons have undisturbed propagation, so active correction is not an issue. However, the do require arrays that are larger by the ratio of their wavelength--about a factor of a million than lasers--to achieve the same spot size and flux on target. That translates into football field sized transmitters. Microwave weapons also have the advantage of coupling in through various electrical cracks in devices, which can give efficient coupling. Conversely, those leaks can be shielded against through known, developed means. Overall, microwave weapons have many of the advantages of lasers coupled with very large, visible, and expensive transmitters. Other such concepts such as electron and particle beams are too immature by comparison to even be assessed on the same footing.

Overall, laser threats appear to be significant, near term, and difficult to address. The key technologies needed to make lasers very large and effective have been placed in civil scientific, commercial, and international hands. It would be difficult to recall them. Lasers make maneuver and decoys ineffective, and they make hardening very difficult. Satellites would be unable to make more than a few passes over large lasers before exhausting their countermeasures. Thus, in that time some other means of dealing with the transmitter must be sought. Unfortunately, given the small size and limited observables of even large pulsed lasers, it is not clear that there would be a proper basis for effective interdiction.

5.4.9 Distributed Systems

A number of observations above have indicated the advantages of distributed systems in promoting survivability. This section collects those arguments together. Distributed constellations have advantages in scaling and performance that are discussed elsewhere. Their survivability is of particular interest here. It results from the distribution of the capability of the constellation about equally over each of its components. In such a configuration, the degradation of the capability of the constellation would be reduced only in proportion to the number of satellites lost. The flexible and proper interconnection of the rest could make the overall system intrinsically survivable. In most applications, the loss of one satellite would not even be felt for several days. Moreover, lost elements could be replaced quickly on demand with modest launchers. A somewhat different aspect of their scaling is the potential synergism with civil and commercial satellites, whose integration through add on sensors could increase the number of satellites in the constellation even further. A final point having to do with the defensive capability of distributed systems is that if the satellites were required to use space-based assets to achieve survivability of the constellation, distributed systems would distribute the needed defensive and offensive systems directly over the threats to themselves and others.

5.4.10 Space Control

There is a fundamental connection between the narrow technical issue of survivability and the overall policy of space control. Control of space requires that we have freedom of action to accomplish our objectives (military, civil or commercial) and the ability to deny similar freedom of action to potential adversaries. The 1989 National Space Policy reaffirmed U.S. goals in space of deterring or defending against enemy attack; assuring that hostile forces cannot prevent our use of space; negating hostile space systems; and enhancing United States and Allied operations. For the DoD to maintain enduring space systems implies an integrated combination of antisatellite, survivability and surveillance. The Air Force has developed this into a doctrine including surveillance, protection, prevention, and negation.

This discussion requires the Air Force to be able to remain in and move freely and forcefully in space to do essential missions. To do that, Air Force systems must be survivable. According to the discussion above, that is not likely to be the case over the coming decades. Moreover, space control also requires the Air Force to be able to deny such free access to hostile powers. By the converse of the analysis above, logically, the Air Force should be developing advanced interceptors and lasers capable of denying access. It is not. Thus, both in terms of the positive survivability the Air Force should be developing to perform specified functions and in terms of the offensive anti-survivability capability it should be developing to exploit weaknesses of hostile powers, there is a growing gap between the positive policy and doctrinal statements that should guide development and the actual and likely course of events.

5.4.11 Summary

Satellites previously received a free ride, which was an exception to the usual military rule of seeking and exploiting the opponent’s weaknesses. That resulted from satellites unique value in maintaining a stabilizing flow of information during the cold war. In the post cold war era, these arguments are less compelling, and the new threats from lesser nations, which are not so inhibited and which now have access to comparable levels of technology, are gaining in importance. Interference with launch, command signals, and communication will continue, but the new element is the threat from the advanced technologies disseminated by the missile defense activities of last decade.

The primary threats are advanced interceptors and lasers. Interceptors have benefited from development and dissemination of the needed cueing sensors, rockets, homing sensors, and kill packages. Non-maneuvering satellites would not survive against them; even maneuvering satellites would be marginal. For survivability, satellites would need good, light decoys; even then exchange ratios are only favorable for small satellites. Exchange ratios are also marginal against fragmenting warheads, which largely eliminate effectiveness of decoys. Attrition attacks are possible even at lower levels of technology. Space mines that efficiently co-orbit with the prey satellite are elegant, simple, and anonymous. They could be constructed with a modest level of technology. They were a nuisance threat of the last decade that could be just within the grasp of new space powers in the next decade. In the most favorable situation, satellites could use countermeasures to make some number of passes over the threat, which would give some time for it to be interdicted by other means. Overall, advanced interceptors appear to be a threat that could be deployed within the next decade on the basis of released technology.

Lasers track and kill at the speed of light, which negates decoys and maneuver. Large energies are now available cheaply. Active optics, which are now widely available, makes the transmission of near perfect beams to space possible. The fluxes and fluences that can be delivered to low Earth orbit by such lasers are apparently too high to shield against. Such lasers could exhaust a satellite's countermeasures in single overhead pass. The issue of sensor kill looks somewhat worse. The only straightforward countermeasure is a large extension of electro-optical isolation technology. Thus, lasers are an awkward threat. They appear to be a low priced system with few observables--either for development or use. The timelines for their appearance could be about the same as that for interceptor technology.

Over next few decades satellites will probably become more valuable in assessing a more complicated world situation, but at the same time they will probably be stripped of their historical political protection. They will need active measures to survive and function. The only physical measures developed thus far are modest levels of hardening and maneuver. It does not appear possible to harden against either the kinetic energy interceptors or the energy delivery rates possible with lasers. It does not appear feasible to use maneuver alone against interceptors or to use it at all against lasers. Decoys play a role, but they are not particularly effective for large satellites, fragments, or attrition attacks and they are completely ineffective against lasers. Thus, a new generation of countermeasures appear to be needed. None have been suggested.

Against interceptors, large satellites may be able to use decoys and maneuver to survive long enough for the interdiction of the launchers. Small satellites can use decoys more effectively, and can be lost without catastrophically degrading the performance of the whole system. Against lasers, either would have to use enough shielding to avoid bulk damage, enough isolation to avoid sensor damage, and enough auxiliary assets to locate the transmitter for interdiction by on- or off-board means.

It is difficult to say which of these threats is the more difficult. Against interceptors, satellites need decoys and maneuver; and shielding is ineffective. Against lasers, satellites need shielding and protection; and maneuver and decoys are ineffective. For effectiveness against likely threats that combine the two, satellites would appear to need protection against both sets of attacks--and to need them in about a decade. They would also need the means to locate and interdict launchers or transmitters with quite low observables in less than a day. Two positive notes are that it is still possible that effective protection might be implemented with a fraction of a satellite's mass, and that the means of achieving both survivability and interdiction might develop from attempts to provide global real-time surveillance, communications, and strike through distributed systems.

5.5 Distributed Space Systems

Gregory Canavan, David Thompson, and Ivan Bekey

5.5.1 Introduction

Rapid progress in a number of new technologies—computers, sensors, materials, etc.—have made large constellations of satellites with good sensors affordable. This paper explores the new applications that these developments make possible and the technologies that are available to support them. Alternative architectures involve distributed systems of constellations with many satellites, each of which has modest sensor and communication capability, whose integration gives the whole constellation global, real-time coverage. Such constellations can also have advantages in scaling, performance, cost, and survivability. The next section discusses the essential features of their scaling that determine when they do. The following section describes the new defensive applications such scaling makes possible. It is followed by a discussion of the appropriate sensors, their status, and the platforms on which they might be mounted. The paper concludes with rough estimates of the timelines and resources for development and a summary of the prospects for their integration with other defense, civil, and commercial activities.

5.5.2 Alternative Architecture System Scaling

The advantages of alternative architectures of distributed systems result from the reduced ranges from the satellites to their targets and to each other. This scaling is discussed in detail in the Appendix; the principal results are discussed and simply illustrated here.

Passive, scanning, sensors of a given resolution require a sensor of diameter, D, which is proportional to the range to its target, r. Thus, for a given level of technology, the sensor's volume increases roughly as the cube of its range, and its cost increases proportionally. If the sensor is responsible for targets out to a cross-track swath W, the number of satellites, N, required to achieve a revisit time T, is inversely proportional to W and hence range. Thus, the total cost of the constellation, which is proportional to the product of the cost per sensor and the number of satellites, varies as the square of the range to the target. That means there is about a factor of 4 advantage for deploying twice the number of satellites at half the range.

More careful analysis shows that such satellites should be operated as low in altitude as possible with a swath about 1.5 times their altitude. There is some latitude about this optimum. Increasing T would decrease cost—at the price of less timely data. Degrading resolution would decrease cost—at the price of a disproportionate degradation of the value of the data. Increasing T or degrading resolution would be the final steps in cost reduction. These optimizations are insensitive to the costs for the focal planes and supporting computers, which are fixed. However, those costs are significant, and should be controlled, lest they upset the proper balancing of aperture and constellation size. At high resolution, aperture costs dominate those for focal planes and computation, although scanning sensors might require excessive array sizes and bandwidths for whole-Earth coverage.

Active sensors such as lidars, radars, and SARs offer less advantage for distribution. The product of their power, P, and aperture, A, generally scales as the fourth power of range, which suggests strong benefit for operating at small r. However, P and A can be optimized separately to minimize total cost, which is the sum of the costs for P and A. That is minimized by the choice

A proportional to P, which gives a power-aperture product PA proportional to the square of P, so that the cost per sensor only increases as the square of range. Active sensors should be deployed as low as possible; their cost has a shallow minimum at a swath twice the altitude. Thus, there is less of a penalty for operating active systems away from optimum separations. Active systems operate at about 30% greater range than passive systems because optimizing both P and A allows them to do so with less penalty in sensor cost.

Communication satellites have quite different scaling in distributed operation. While they would not normally be used in a scanning mode—apart from store and forward systems—their scaling in a scanning mode can be discussed simply. The key issue is the link margin between the satellites and ground stations. If the satellite has aperture area A, the power density at range r is proportional to PA and the signal received by an aperture A there is proportional to PA^2. Since P and A can be optimized separately, their cost is proportional to P, while PA^2 scales as the cube of P, so the cost per channel scales as $r^{2/3}$, for which the optimal range is large enough for Earth curvature to be important. Long-haul communications satellites do not distribute favorably.

An exception is the growing area of distributed communication directly from satellites to user handsets and pagers, for which the key link is from the handset to the satellite. That is limited by the power that is allowed and the antenna gain that will be tolerated. The former is set at ≈ 3 Watt by the FCC; the latter is dictated by customers, who do not care to point high-gain antennas at satellites. Thus, rather than the high gain of long-haul systems, personal handsets have little gain, so the received signal is proportional to A, the cost per satellite scales as r^2, and their scaling is much like that of the other active systems discussed above, i.e., their optimum swath is about twice their altitude, and the penalty for operating with wider swaths is modest.

Staring sensors must observe most of the surface of the Earth at all times, which changes the basis of constellation sizing from coverage within a given revisit time to complete coverage at all times. If each satellite is responsible for staring continuously at an area » W^2 below it, the number of satellites required is inversely proportional to W^2. If the cost per sensor scales as the cube of range, as above, the constellation cost scales as the cube of the range divided by the square of the W, which is minimized by reducing r to about the constellation altitude and operating at the minimum altitude possible. There, costs have a shallow minimum about a minimum at an optimal swath of about three times the constellation altitude. Thus, the advantage of operating staring, passive systems in a distributed mode is about equivalent to operating active systems in a scanning mode.

For other staring sensors, distributed operation is less advantageous. Active sensors costs scale as r^2, so their constellation cost scales as r^2/W^2, which does not favor operation at shorter ranges. Direct satellite communication from handsets scales as r^2, which also does not favor operation at shorter ranges, although distribution may be preferred for voice delay and engineering considerations. Long-haul communication systems scale as $r^{2/3}$, which favors operation at maximum range. Thus, whether or not distributed operation is appropriate for a given mission depends on the detailed scaling of the sensors proposed.

Space based kinetic energy systems scale quite differently. To reach their targets during the time T allowed by missile burnout, warning cycles, target movement, etc., kinetic energy systems' velocity, V, must be such that VT = r, where r is the distance to target. If complete coverage is required, the number of vehicles required is inversely proportional the square of range or inversely proportional the square of VT. While T is determined by the application, V can be varied. However, higher V costs more in launch mass and volume. The optimization of kinetic energy systems is a tradeoff between the cost per interceptor and the number of interceptors. For a range of missions, the optimal velocity is on the order of 6 to 8 km/s, which with a roughly 4 kg kill package implies a 40-60 kg space vehicle. Such vehicles could arguably be produced for roughly $1M each. Is so, with 100-200 s warning, a constellation of ≈ 1,000 systems for single coverage would cost about $1B.

A distinguishing feature of kinetic energy systems, whether used for defensive or offensive purposes, is that they are distributed directly over the threat, which generally gives them the minimum response time possible. That has different impacts for defensive and offensive applications. For defensive applications, this very fast response time permits space-based systems to address missiles in boost, when they are most vulnerable and before they can deploy decoys or multiple munitions. For offensive applications, fast response would permit delivery of munitions in minutes rather than hours, which could be important in blocking or disrupting highly structured operations or attacks until other means could be brought to bear. In such applications, highly accurate delivery of $1M munitions from space could be quite cost effective relative to other interim means of blocking such operations.

Related considerations. The sections above have discussed the advantages for distributed systems that follow directly from the scaling of their sensors and platforms. Other considerations arise from their low-altitude operation. An obvious one is the greater drag satellites experiences at lower orbits. Although satellites at 300 km altitude would experience an order of magnitude more drag than one at 500 km, with proper design and modest makeup propulsion, it should be possible to achieve lifetimes of 2-4 years. That possibility is not unique to small satellites; it could be used to advantage by large satellites as well. However, at present, only a few do.

Such lifetimes would be short compared to those of most current satellites, but not too short to be useful. Moreover, they are matched to doubling times of computer and focal plane technology. Thus, distributed satellites could be maintained in operation for a few years and then allowed to decay at about the point at which they became technologically obsolescent. Of course, these options for more rapid turnover of technology are not unique to small satellites either; they could be used to advantage by large satellites as well. However, to date, only small satellites have taken advantage of them.

A related issue is the large data rates and transmission bandwidths required for the scanning and staring sensors discussed above, which would far exceed the capacity of current flight computers and transmitters. However, the much larger on-board computers are now available could be used to compress the data from improved instruments into the available bandwiths. This is not an intrinsic advantage of distributed systems; however, they have been the quickest to introduce the current level of technology. This would appear to be an area in which both small and large satellites could benefit from more aggressive deployment.

Many applications require revisit times of minutes or hours, which in turn require constellations of 30-100 satellites. For such constellations to be affordable, the satellites in them must be small and inexpensive. A cost goal of $1B for 30 satellites would give ≈ $30M per satellite, which is far below industry standards. However, a number of commercial enterprises, such as Motorola's IRIDIUM are now in the process of producing such satellites in even greater numbers with roughly those cost goals through industry factory line procedures. Those cost goals also imply a cost goal of ≈ \$10M for the sensors for distributed systems, which is also stringent. But the individual Clementine sensors were built for significantly less than that, and current developments in visible and infrared focal planes for imaging systems indicate that such a goal is not unreasonable. The cost of active systems is not as well known, since they have had less development for space. But lidar, SAR, and radar sensors have each been developed extensively for special applications, and each is capable of efficient scaling to small payloads. Thus, they too could contribute from distributed systems.

Survivability is another key consideration, although all of the factors are not analyzed. Some points, however, are obvious. Since the capability of the constellation is distributed about equally over each of its components, their proper interconnection could make the system intrinsically more survivable, in that the loss of one element would not be catastrophic, and would not even be felt for several days. Moreover, elements that were lost could be replaced on demand by modest launchers. A related point is the potential synergism between distributed systems and civil and commercial applications. The small size of the sensors for distributed systems could make it possible to use them as add-on payloads to commercial and communication satellites, which would further increase the number of the satellites and further increase the survivability of their constellation. That complementarity would not be possible with the large sensors from unitary satellites.

5.5.3 Defense Applications

Defense applications for distributed constellations include missions ranging from missile warning to communications. Some are unique to distributed systems; others are shared with smaller constellations. This section primarily discusses the applications; the next section discusses the application of distributed systems to them and why it would or would not be effective. Some of the applications are shown in Fig. 1, which indicates the rough spatial resolution and temporal revisit time required for a number of defense missions, together with those for a few representative civil and commercial applications.

Defense applications generally lie to the lower left part of the figure, at demanding spatial and temporal resolutions. Missile warning and watching is at the lower corner. Technical assessments are along the left side, where the required spatial resolution is high but longer times may be available to achieve it. Global surveillance—and its component damage, chemical, and biological assessments—start on the lower border at revisit times of tens of minutes. Meteorological applications lie at the lower right, at modest spatial but demanding temporal resolutions. Agricultural, crop maturity, and disease applications lie to the upper right at modest space and time resolutions. Climate change studies lie at still lower space and time resolution. Civil applications have significant overlap with each other as well as with the traffic, disaster control, and some military applications—particularly at intermediate space and time resolutions.

Missile warning is a well established mission. Watching the missile's bus for decoys and weapons is just the most demanding form of it. The current system is based on radars and short wavelength infrared sensors on satellites at GEO altitudes. The satellites are capable, although based on decades-old technology, using linear arrays of detectors with large pixels to produce adequate signal to noise ratios that are adequate against large current strategic missiles. They now integrate the outputs of several satellites to obtain range information, which improves track accuracy. They also have a useful capability against the much smaller signatures of theater missiles, against which their main weaknesses are the delays between revisits, which causes them to miss transient events and to take tens of seconds to give warnings and establish tracks.

In adding advanced detector arrays to improve detection, discrimination, and track, distributed systems are probably the preferred because of their ability to increase signal by decreasing altitude and decrease pixel size and detector count simultaneously by diving the search area between a number of sensors and satellites—so long as these improved focal planes could be introduced without giving up range information, which would be a step backwards in terms of tactical and strategic utility. The laser and radar rangers discussed below could provide that information for distributed systems. They progressed slowly for several decades, but have now reached about the right level of development. Staring systems should have modest but real advantages in this application when deployed at low altitudes and comparable fields of view.

Much of the pressure for a shift to distributed, staring systems comes from increased concern with theater threats. However, threats is single theaters might be addressed more cheaply by additional AWACS aircraft, which are individually expensive and redundant, but which do not encounter space-based systems' absenteeism, i.e., the geometrical fact that most of the constellation is somewhere else over the globe at any given time. For simultaneous threats in multiple theaters, absenteeism is automatically reduced and distributed space-based systems could become economically competitive due to their lower unit cost. Distributed space systems would also benefit from their survivability, which could be significantly greater than that of aircraft with active sensors that must continually radiate to be effective. In the longer term, distributed space-based radars for all-weather search, detection, and track would be a natural adjunct to other space-based sensors as well as to AWACs. With this combination, it should be possible to detect, track, perform threat assessment, and direct intercepts from space.

Several emerging applications require technology and systems closely related to that for missile warning. Distributed systems can use smaller pixels for better spatial and spectral resolution, which is difficult to achieve with large satellites at GEO. Such resolution could be valuable in detecting and tracking aircraft and cruise missiles, which are likely to become an increasing fraction of the threat in coming decades as ballistic missile defenses shift the threat to other delivery means. In this period, the U.S. could also face serious, competent competition for the control of space. In it, smaller, more numerous, non-GEO satellites would have distinct advantages. Hardening would be simpler. Maneuver would be less costly. Decoys and self-defense would be simpler and more efficient. And from the systems perspective, the loss of one satellite would be less damaging and easier to remedy. All of these defensive capabilities will be essential in protecting the satellites' long enough to perform their warning and assessment mission, which will become more important in this period.

Global surveillance will gain in importance as more countries gain access to modern weapons to press their grievances with neighbors and as weapons of mass destruction and their carriers proliferate to more theaters and countries. Current systems are capable of daily reconnaissance of small, fixed areas, but lack the prompt, synoptic coverage needed for assessing emerging threats, attacks, or occupations. Interim use of Landsat and Spot helped fill that lack in the Gulf War, but assets with prompt, global coverage dedicated to this task are needed. The characteristics of the needed systems have largely been defined in the section on scaling. The optimal solutions are generally distributed systems, because of the difficulty of producing the required resolutions from high altitudes or long ranges. It appears feasible to produce appropriate constellations of either scanning sensors with resolutions of meters and revisit times of hours or staring sensors with finer resolution and near-instantaneous access to all points below. Each has significant advantages over current systems; scanning systems' advantages are particularly great for applications that admit their somewhat longer response times. The cameras, computers, compression, and transmission capabilities required appear to be within current capabilities; they have significant and useful commonalties with those for distributed missile warning.

An interesting extension of these concepts is the coupling of visible or infrared staring arrays with large-scale, on-board signal processing to perform moving target detection on board the satellite. The cameras are modest compared to current flight units; the computation rates are roughly what current flight computers can supply; and the resolution required is roughly what current mid-wavelength infrared focal planes can provide. Adequate algorithms are known and tested. Combining these elements would provide a capability to detect and track moving targets from orbit. If so, the satellite would only need to transmit the track—not the whole sequence of scenes—back to the ground for discrimination, which would make much more efficient use of target designation assets. Alternatively, if the satellite was equipped with a kinetic energy projectile, it or its neighbor might prosecute the attack itself.

Such surveillance systems could perform certain missions that are not addressed at all today, whose importance is increasing. One is the detection and track of mobile missile launchers and relocatable missiles, which move with impunity today during the long intervals between the known times of overhead observation. Frequent observations from distributed systems would largely remove the effectiveness such systems. The timely, selective dissemination of modest-resolution information from such distributed sensors could be a very effective means of maintaining prompt coordination of activities with allies.

Damage assessment concentrates on higher spatial resolution of limited areas that have just been attacked in order to evaluate whether the attack has achieved its objectives. Assessments of threats and damage typically require spatial resolutions of a few to a few tens of meters and revisit times of minutes to hours. These requirements are shifting towards more demanding levels, but they can be achieved by high-quality sensors on large constellations. Distributed systems would be well suited to performing damage assessment of strategic or conventional engagements because of their timely coverage, which is essential in planning follow up operations. Ideally, damage assessment would be available in tens of minutes, while delivery platforms were still in the area, although cycle times of hours can support follow up sorties. Current systems support a roughly daily cycle. The effectiveness of damage assessment would be greatly enhanced by the addition of active lasers or radars, which add depth resolution to remove the ambiguities involved in interpreting post-strike passive imagery today.

Detection of chemical and biological weapons is a related application that could take advantage of recent developments in active sensors. Lasers and detectors are now deployed in truck or aircraft mobile units for the detection of bulk aerosols. It appears possible to develop units using more precise fluorescence and DIAL measurements for the identification of specific chemical and biological agents that could be packaged in distributed satellites—in part because of their shorter ranges to targets. These sensors would represent both a global warning system for the introduction of such agents and a safe means of tracking their dissemination. As noted earlier, there is significant benefit from deploying such sensors on distributed satellites, particularly for operation in a scanning mode.

Weather measurements are currently infrequent, incomplete, and poorly resolved. Passive scanning sensors could make a significant improvement in measurements of cloud cover. Active scanning sensors including lidars and radars would have a significant advantage in measuring detailed cloud compositions and distributions and wind patterns at all altitudes in an adequately timely fashion. The sensors for making such measurements should be sufficiently small, light, and efficient to be added on to commercial satellites.

Meteorological measurements also require revisit times of minutes to hours and spatial resolutions of tens to hundreds of meters. Active sensors required for improved measurements of cloud tops, bottoms, and structure for military planning and could also improve climate change and engineering measurements. Previously, cloud measurement requirements were limited to much coarser spatial resolutions. However, both military and scientific investigators now want spatial scales of about 10 m to address critical kinematic, exchange, and thermodynamic processes. These requirements—and those for surface ecological process—could become even more demanding over the next decade. Similarly, agriculture would like roughly 30 m resolution to check soil moisture, and few meter resolution for crop stresses. By this standard, Landsat has adequate spatial resolution for agriculture, but its utility is compromised by its 16 day revisit time and limited spectral resolution. Distributed systems appear ideal to address both needs.

Distributed communication links are possible with distributed systems. At a minimum, commercial communication systems will make several thousand voice-quality circuits available in the area of conflict. They could do much more. They could solve the current dilemma of the “last mile” distribution which results from the fact that high-bandwidth fibers can efficiently carry information to a central point in the theater, but not to the ultimate, distributed users of that information. Direct handset to satellite communication systems could provide needed two-way communication to both complete in-theater distribution and complement the one-way flow of direct broadcasting systems.

Distributed communications systems could do quite a bit more than that. For a constellation of a few hundred satellites, a few tens of satellites could be in sight at any given moment. Thus, they could transmit their signals with the appropriate delays to form a coherent communication array with high gain in any selected direction. That, together with their low altitude, would make it possible for the satellites to burn through jamming and provide clear communication to besieged or covert groups. A variant on this concept is the use of the constellation for the delivery of distributed, survivable precision global positioning in theaters. Alternatively, their coherent, directed, intense signal could be used for precision jamming of the opponent’s communications. Another alternative is the use of high-gain coherent distributed networks for selective, sensitive electronic intelligence.

The high capacity available when current microwave cross links are replaced with laser cross links in about a decade should make possible the delivery of near-real-time, high-quality information from the whole theater and globe to war fighters. It should also make possible real-time, high-margin communication links from remote satellites and sensors to operators who can discriminate the targets in these signals. As sensor resolutions and communication bandwidths grow, this could emerge as the best way to remotely project man into the battlefield. The high capacity cross links would be common to both distributed and central systems, but only the distributed systems could take full advantage of them in this manner.

An emerging, but unconventional, alternative is the use of massive, compact processors on board satellites, not just as bulk filters, but as thinking machines that can filter out noise by extensions of the moving target indication algorithms discussed above. With that capability they could identify targets, impose priorities, and prosecute the attack themselves. This is a little discussed possibility, but most of the key pieces were developed in the strategic defense program of the last decade. The main element now lacking is sensors that can look down and find targets in strong clutter, and as noted above, rapid progress is being made on such sensors.

Space surveillance is now performed from the ground with radars and telescopes. Distributed systems in space could maintain a more timely and complete survey of active satellites, debris, and the natural environment. Indeed, that mission could largely be accomplished as a part time function or by a small visible sensors added on to each of the platforms described above. The proposed adjunct mission of planetary defense has somewhat more demanding requirements, which cannot be fully satisfied by sensors on the ground. For them, space basing is natural and apparently cost effective. It could also be executed as an auxiliary mission of space surveillance distributed systems, although the sensors required would be a significant extension of their primary sensors. For these missions, there is a natural match between the SSTO and other initiatives to reduce cost to orbit, which is the essential feature in delivering on the cost performance estimated above.

Defensive and offensive operations from space are possible with response times of a matter of minutes. Distributed systems are appropriate hosts for brilliant kinetic munitions of either defensive or offensive orientation. The essential tradeoff is the number of interceptors against the velocity increment of each. These tradeoffs are relatively insensitive to application, and lead to modest numbers of affordable systems for most. Once deployed, these platforms would also be available for satellite self defense or space control, for which they appear ideally suited. An interesting alternative use is the correlation of the many occultations their transmissions would experience with ground receiver arrays to detect stealth satellites.

5.5.4 Related Applications

Related applications for distributed constellations include synergisms with other military, scientific, civil, and commercial space operations. As noted above, in the Gulf War, Landsat proved to be a useful source of interim synoptic multispectral data for coarse surveillance and targeting. Such cooperation could continue in the future. Not only Landsat, but also AVHRR, weather, and civil monitoring assets could be used to augment military assessments. Conversely, suitably desensitized information from distributed constellations could provide valuable information to civil agencies, which lack prompt information on land and water use, weather aloft, and pollution dispersion. There is a sound basis for a healthy scientific and programmatic exchange.

That basis is particularly clear in the areas of agriculture, environment, and the ecology, in which detailed information is now available on a global basis only on intervals of weeks (with reporting delays of months) of data with tens of meters resolution and only a few spectral bands. Any of the active or passive sensors discussed above would enhance by several orders of magnitude the amount of information available to civilian scientists for the assessment of degradations of the environment or ecology and to commercial investigators for the assessment of domestic and global crop health and production.

A specific example is the Earth Observing System (EOS), which is a $10B set of experiments to sample the impact of man's activities on the environment. It could provide useful background, surface, and meteorological data to the military. In return, distributed systems could provide measurements of temperature, water, and winds aloft, which EOS has been unable to measure from its large, high altitude satellites. The same is true of burgeoning efforts at climate engineering, which needs even more timely data that only distributed systems could provide. Finally, there is the possibility of harnessing the simpler, affordable technology of Clementine-like defense missions to deep-space missions of other agencies and countries. In all cooperation with other fields, agencies, and countries appears to be a very fruitful and natural aspect of the development of distributed systems.

5.5.5 Distributed Sensors

Distributed sensors include both passive imagers and active sensors throughout the electromagnetic spectrum. This section discusses their relevance to the applications discussed in the previous section and their scaling advantages relative to small constellations. It also discusses the relative maturities of the various sensors that are now or soon will be available. Figure 2 overlays on the straight black lines of Fig. 1 the capabilities of various distributed radar, microwave, infrared, visible, and laser sensors to address the requirements discussed in the previous section. The capabilities shown are those of small sensors that could be deployed on light satellites for incremental payloads of roughly 100 kg, 1 cubic meter, and 100 Watt, although a number of the sensors—particularly the passive visible and infrared imagers—are now available for an order of magnitude less than that.

Missile (bus) warning is perhaps the most demanding in space and time resolution. Satellites and focal planes now exist to do this from low altitude. They would do so in a staring mode, which would reduce their leverage, but they would still have a significant advantage over performing the missions with larger satellites from longer range. However, as noted above, they would need to derive range information. If that could not be done from stereo viewing, which was not assumed in the above analysis, they would require active sensors for ranging. There would not be any advantage in deploying such active sensors by themselves in a distributed, staring mode. But they would have great benefit in improving the tracks from the passive sensors, so there would be a positive benefit in deploying both large focal planes and active rangers on distributed, low-altitude platforms. An additional benefit of distributed systems for missile defense is that they connect well with the distributed space based interceptor concepts that have been found appropriate for missile defense against a determined enemy because of their greater survivability and modular deployment and interaction. They could be a natural element of such defenses, should serious missile defenses again be found appropriate.

Global surveillance was perhaps the original stimulus for work of distributed systems and remains its most likely early beneficiary of it. That is because the requirement for global, prompt, medium resolution is precisely what current visible and infrared sensors are best suited to provide. Visible sensors provide the high resolution needed for target identification; they could also be used in registering the larger pixels from infrared sensors for data enhancement. It should be possible to obtain roughly one meter resolution from small satellites. There are both commercial and military programs under way to do so. Infrared sensors can provide few meter resolution for night, hot, and moving target detection and damage assessment. They could also provide wide-area multispectral images of suspected deployments in vegetation.

Both the visible and infrared sensors could be deployed on small satellites as scanning sensors. If so, they would have a very significant advantage over larger, higher systems in providing similar resolution and coverage. If deployed in a staring mode (or equivalently with a requirement for coverage everywhere, all the time), their leverage would be reduced, but they would still appear to have more than a factor of two advantage over larger systems.

Damage assessment uses higher spatial resolution of limited areas that have just been attacked to evaluate whether the attack was successful. Small satellites can do that, too. There is no intrinsic limit to the resolution or registration that small satellites can provide. Current systems are working towards one meter from satellites that weigh a few hundred kilograms. The scaling of distributed systems for this application is as discussed above for global surveillance. In a scanning mode, they have high leverage; in a staring mode they have less but still significant leverage. There is, however, one additional point. The value of distributed systems for damage assessment would be greatly enhanced by the addition of ranging sensors, which could eliminate ambiguities in interpreting passive images. By themselves, active sensors would have modest leverage as scanners; none as staring sensors. But deployed in conjunction with visible and infrared sensors of either type, they would add significant value to the combination, and should be included.

Small SARs could also provide rapid revisits with meter resolution, which would be adequate for some military damage assessment and tactical intelligence. More importantly, it would provide such coverage in all cloud and weather conditions. As shown in Fig. 2, they could cover much of the very important medium resolution region. Like other active systems, SARs have modest leverage as scanners, not as starers. However, their normal sidelooking and spotlight modes of operation both scale and scanners, so they should have adequate leverage in either. Any when deployed in conjunction with any of the sensors described above, SARs should have great benefit because of their ability to do precision measurements in weather.

Detection of chemical and biological weapons is particularly suited to distributed systems. It is very difficult to detect chemical and biological weapons with passive remote sensing systems and it is dangerous and manpower intensive to search for them from the ground. Lasers and lidars are the sensors of choice, in that they can sense from long distances, identify specific chemical species precisely, and minimize exposure to personnel in the process. Lasers are essential for host of applications such as damage assessment, chemical and biological weapon detection and tracking, and cloud coverage measurements. They also have metric capabilities that are well suited to the measurement of structured, transient phenomenon in civil and commercial applications. Lidars have been developed extensively for back scatter and aerosol measurements; sensors for DIAL measurements are in development and on track for the allowable weights and powers for distributed deployment.

The scaling of lasers for this purpose is quite positive. The time lines for chemical attacks are such that revisit times of a half an hour or so are generally acceptable. Thus, the lasers can be deployed in a scanning mode, which means that they have significant leverage for being deployed in distributed systems. If the time lines were such that they had to be deployed in a staring mode, they would have no leverage. However, if they were deployed as an adjunct sensor for missile warning or surveillance, they would add enough value to justify their inclusion as a staring system for chemical detection as well.

Weather is a very important but often overlooked aspect of military operations—until they actually have to be executed. Distributed systems could add to both the timeliness and resolution of weather information. The lower right of Fig. 2 shows the possible contributions from real aperture radar arrays for 10-100 m resolution of weather and threat clouds with » hour revisit times. Such resolutions would also be adequate for the detection of some military targets, the assessment of cloud cover, disaster control, and the assessment of vegetation. Such radars have recently been reduced in size and power to appropriate levels for distributed applications, in which their radiating arrays and mechanical issues would be greatly reduced.

Radars do not obviously scale well for distribution. They are active and hence scale as r^2. They are also capable area search sensors, in which their number scales as $1/r^2$ for applications such as aircraft or cruise missile search. Thus, their total cost is independent of r, and there is no benefit for distribution. For that reason, previous studies have looked at very large systems, hoping for economies of scale, which have not emerged. Alternatively, it could be recognized that with a satellite coming over every half hour it is possible to have each one observe the aircraft and to make an estimate of its plan. If so, the number of satellites scales as 1/r, the total cost is proportional to r, and there is a strong benefit for distribution. That would just require a different way of looking at the problem.

Microwave sounders have also been developed extensively. Deployed on distributed constellations, they would be much more effective, and could provide detailed cloud and water profiles rather than just integral measurements. While active, they naturally operate in a down-looking mode, which is effectively scanning, so their leverage is generally high enough to justify inclusion, even if they weren't very small. But the real reason for deploying them on small satellites is that from very low altitudes they can do much finer vertical resolution of clouds, and from very many satellites they can essentially to tomography of the clouds.

Distributed communication links are possible with distributed systems, although as noted above, they do not necessarily scale well. The earliest impact of distributed communications in theaters is likely to be the addition of a large number of voice quality circuits. The second could be the solution of the "last mile" problem, which both fiber lines and long-haul satellite systems have. If it was possible to inject the signals from these long-haul systems into distributed satellites, they could redistribute it rather efficiency—using idle bandwidth. As noted above, distributed communication systems scale as r^2. As area communication nodes their number must scale as $1/r^2$. Thus, their total cost is independent of r, and there is no benefit for distribution. However, if the communication systems have already been built for service of non-hostile theaters, they are essentially free for the price of a mobile gateway to inject the signals into them. For that reason, distributed communications in theater appears very advantageous.

Space surveillance does not appear on Figs. 1 and 2, but it does underpin each of the applications, in that space surveillance keeps track of the myriad threats to the satellites that provide the services indicated. Moreover, distributed space systems could maintain a more timely and complete survey of active satellites, debris, and the natural environment. The low Earth orbit threat could be largely tracked as a part time function or with small visible add on sensors. It is difficult to perform a useful cost-benefit estimate, but given the cost and manpower requirements of the current radar and GEODSS systems, it seems quite plausible that could be a viable option. For the objects in synchronous orbit, larger sensors would be needed. They would require some additional development and deployment, but given the increasing value of objects there, the effort seems justified. Such sensors would also support the proposed mission of planetary defense, which has still more demanding requirements.

Defensive and offensive operations from space are attractive because of the possibility of response times of minutes. That distributed kinetic energy is the preferred mode for strategic missile defense was established in the last decade. There are now strong arguments that it may be preferred for theater missile defense as well. The notion of offensive operations from space are newer. While they are unfamiliar, and hence opposed by some, they do have certain advantages. The first is timeliness. A few kilograms delivered at 7 km/s in a few minutes is probably worth a few megatons delivered a few days later. The second is accuracy. It now appears that projectiles from space can take advantage of the same suite of sensors as other precision munitions to strike within meters. The third is cost. It appears possible to deliver such a round from space for a cost on the order of a million dollars. If so, that is competitive with other means of interdiction. for reaction times from minutes on the order of tens of minutes, distributed deployment is both appropriate and effective to other basing modes.

5.5.6 Technology Status

The status of sensor technology is roughly represented by the visible and infrared cameras developed by Lawrence Livermore National Laboratory for missile defense applications and for Clementine’s mapping of the Moon. Those earlier applications used roughly 400 x 400 detector silicon visible and 128 x 128 detector platinum silicide infrared array focal plane arrays with few to few tens of centimeter optics. A few years later, the current systems can use megapixel silicon and indium antimonide arrays for roughly the same costs. These sensors typically weigh on the order of a kilogram, consume a few watts of power—including their coolers, and produce images with few to few tens of meter resolution, which is more than adequate for applications discussed above.

Lidars are evolving rapidly. Their power has increased and their size has decreased from the roughly 1 ton, 8 kilowatt versions built for the Gulf War to roughly 100 kg, 3 kilowatt versions for environmental assessments and 200 kg, 1 kilowatt versions for space applications. They have provided quantitative measurements of important meteorological variables, including spatially resolved Raman measurements of water vapor distribution over typical terrain and temporally and vertically resolved measurements of water vapor over tropical mixing layers. Lasers are rugged and reliable; advanced diode lasers could be developed to much higher efficiencies. Thus, they could soon be practical tools on most small satellites. There are similar developments in radars and SARs that could support the applications shown, although there are restrictions on their development.

Landsat was a useful interim solution in the Gulf War; it has a number of more capable successors. The Miniature Sensor Technology Integration (MSTI) series of satellites has the goal of developing small sensors more useful for defense. MSTI-1 flew in 1992, accumulating 100,000 MWIR background images during its longer than expected lifetime. MSTI-2 was designed to detect and track missile launches in multiple IR bands relevant to water vapor. MSTI-3 and its successors will test advanced visible and IR sensors and tracking, culminating in the flight of a lidar with an auxiliary mission of environmental and ecological disaster monitoring. A number of small satellites such as ALEXIS have demonstrated unexpected robustness in their response to deployment problems during launch that could have negated more sophisticated satellites. Their modest control requirements, short and economical fabrication schedule, and demonstrated reliability show that while light satellites can be cheaper, their performance need not be inferior to that of larger ones.

5.5.7 Platforms for Distributed Sensors

Platforms available for distributed deployment include dedicated small satellites, commercial satellites, and new communication constellations. Dedicated satellites have obvious advantages in schedule and deployment flexibility, but would cost the most, although costs might be reduced on the basis of recent missile warning and defense technology. Distributed sensors are sufficiently small to be added to most or all new or replacement satellites of commercial constellations. However, few constellations offer enough platforms to provide the close spacing distributed systems need.

An alternative deployment is on the new handset-to-satellite communication constellations, with which distributed systems have obvious synergisms. Both require continuous global coverage with modest links—and hence low altitude deployments. These communication constellations have a great deal of capacity in the form the sensors need. At any time, much of it is unused—particularly in the less-developed areas that are the focus of much of the current concern of theater operations. Small sensors could tap the power available there to gather the information and use the large unused bandwidths in underdeveloped areas to transmit it back. The combination of light add-on sensors on such satellites could provide good, timely global surveillance for little cost. Such arrangements could lead to more fruitful discussions of potential interactions of defense and non defense distributed constellations. The two could learn how to cohabit space, jointly address issues such as debris, and find accord on space surveillance. They could lead to arrangements for renting, internetting, and sharing bandwidth in peace and conflict. However, there could be resistance to such measures from both domestic sources and from consortia with foreign partners and users, which could inhibit cooperation.

5.5.8 Timelines for Distributed Systems

Timelines for evolution of distributed constellations are unclear. There is a somewhat negative impression of small satellites due to DARPA's programs, which convinced some that small satellites were intrinsically expensive and only capable of carrying inferior sensors. There was a positive, transient impact due to the Gulf War's exposure of the U.S.'s lack of a wide-area surveillance system, but that has subsided again the traditional bias towards very large, capable, and expensive systems of the type the services have traditionally preferred. Together with the continuing downward pressure on DoD and space budgets, that has led to the current situation in which there is again minimal current or planned development of distributed systems.

By contrast, the planning timelines for non-defense distributed constellations are rather aggressive. There are currently about 6 commercial consortia for distributed communication constellations which have plans to deploy significant numbers of satellites within the decade.

There are also about 4 commercial ventures to develop constellations for distributed imaging within the decade. All are using the current level of technology for their satellites, sensors, computers, and communications. The overall result is that these commercial systems are now moving faster, with better technology, than DoD systems, which could make it more difficult to achieve a working relationship with them later.

5.5.9 Summary

There are a number of applications for which small sensors on many satellites scale well. This paper has addressed that scaling analytically and applied it to find the applications for which distributed systems scale best. Some, like passive scanning imagers on dedicated satellites or communication constellations, scale very well indeed—offering a way to fill the current gap in wide-area surveillance quickly for little expenditure of funds or effort. Active sensors and communication systems scale more sensitively and depend on the coverage required. Each application has to be examined carefully to see how its costs scale in such a constellation, but there are enough applications for which the results are positive to make the area interesting for development.

Applications for distributed systems range from missile warning through global surveillance to communications, space surveillance, and control. The scaling for each has been examined and shown to be favorable through a process that derives certain principles that can be used to evaluate other proposed applications. For example, missile warning not only justifies the deployment of distributed passive imaging systems, it also justifies the deployment of active lasers that are useful for other applications such as global surveillance, damage assessment, and the detection of chemical and biological agents. Damage assessment justifies the deployment of small SARs, which are also valuable for all-weather surveillance. Weather an aircraft justify the deployment of radars and sounders which would be vulnerable and less effective on larger platforms. Kinetic energy provides both a defensive and offensive capability to the constellation. The ability to connect to long-haul communication assets enhances their potential as an in-theater distribution system.

There is a well developed store of sensors for distributed applications including passive imaging sensors and active sensors throughout the electromagnetic spectrum, whose weight, volume, power, and cost meet the requirements for effective deployment. Modest constellations can meet both the spatial resolution and revisit times required. Radars can provide wide-area coverage of weather, threat clouds, an air traffic. SAR, infrared, and visible sensors can provide high resolution assessments. And lasers can provide accurate ranging and chemical and biological threat assessment. There is an extensive data base on the development of adequate sensors for each of these applications.

While dedicated platforms would be preferred, the possibility of add on deployment on new communications offers many synergisms and opportunities for cost savings. There is a basis for DoD/civil/commercial cooperation, although civil research is in decline because of budgetary pressures, and foreign participation and bandwidth competition could inhibit cooperation with commercial ventures. The likely result is little DoD development and aggressive commercial development of distributed systems for a number of applications. If so, the DoD could be displaced from distributed constellations, denied the early global surveillance it could produce, and forced to purchase or rent such communications and surveillance services from international suppliers within the decade.

5.5.10 Enabling Technologies

Enabling technologies for distributed systems are indicated in the text above and in the appendix, but they are collected here for clarity. There are a large number of enabling technologies, this section discusses only the most important. The primary one is, of course, recent developments in the ability to cheaply and efficiently build, launch, and control small spacecraft and the sensors that go on them. A key element of this is the application of industrial methods to the production of spacecraft, such as Lockheed's fabrication of the IRIDIUM buses for Motorola, which is taking place at about 10% the cost and 1% the time of defense systems. No less important is industrial progress in minimizing the manpower required to run quite competent satellites. Further developments in each would be extremely valuable in further improving an already favorable tradeoff relative to small constellations of large satellites. In this area, further reduction of launch costs, particularly of multiple satellites, would be most helpful.

Particularly rapid progress has been made in a few key technologies. Some, like computers and materials, are well known. Without the 2-fold advance in computers every 18 months, it would not be possible to consider the level of on-board computation required to support such sophisticated sensor suites. The rapid turnover of technology, is an integral part of an alternative hierarchy of distributed systems. That also holds for the sensors themselves. Megapixel visible and infrared arrays, lasers, lidars, DIAL, radars, SARs, microwave sounders, light apertures, and space based kinetic energy have all made rapid progress. Just how much can be carried on a distributed system depends on how much progress they make in the next decade. Their quantitative development will determine just how much can be put on given satellites, and their qualitative development will determine which new missions can be addressed.

There are also some externalities that have great potential leverage. The large number of commercial communication satellite systems such as IRIDIUM planned for the next few years offer significant avenues for multiplying defense capability and bandwidth through cooperation. Another important externality that emerges as a by product of distributed systems is the greater survivability, both of the small individual platforms and of the distributed system. With adequate attention to the supporting technologies, this could become a dominant feature of distributed systems. The final point is the simple scaling of the sensors, platforms, and missions of concern in the coming decades. They simply fit together well. Distributed systems do not dominate all applications, but for those for which they do scale favorably, the mission and technology themselves give them a great deal of leverage.

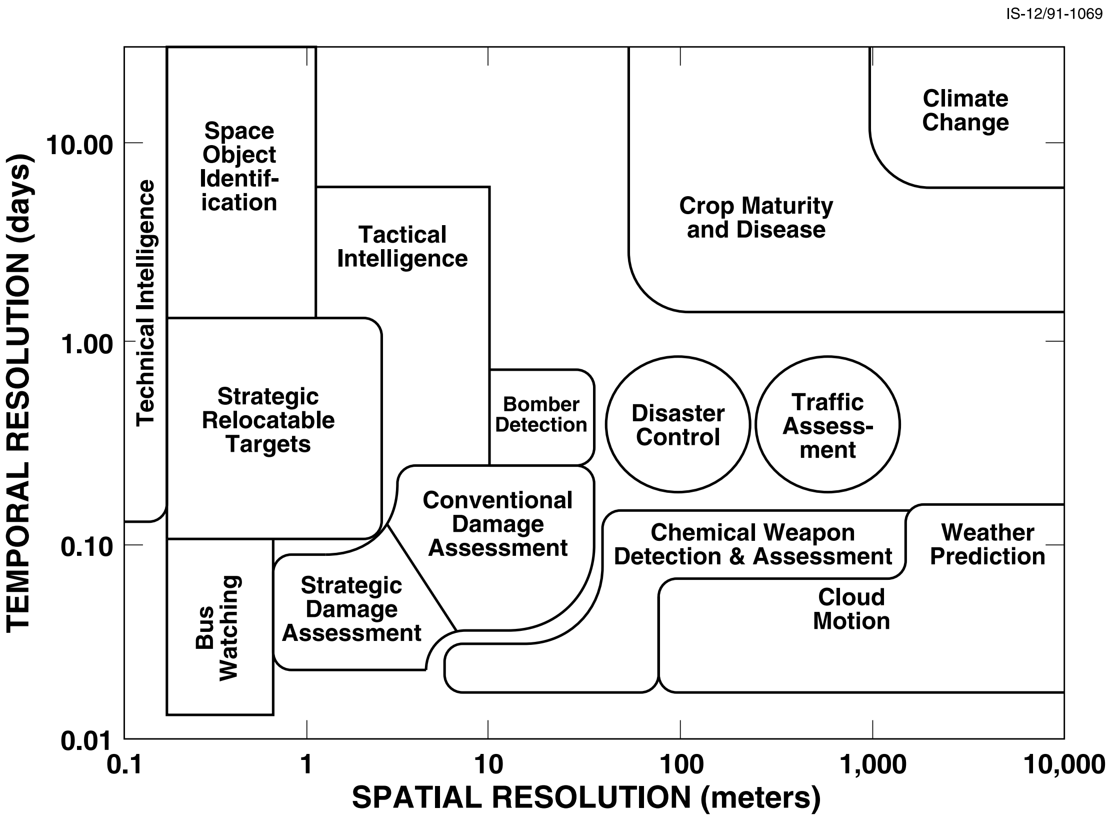

Figure 5.5 - 1 Temporal and spatial resolution required for various defense and civil remote sensing applications

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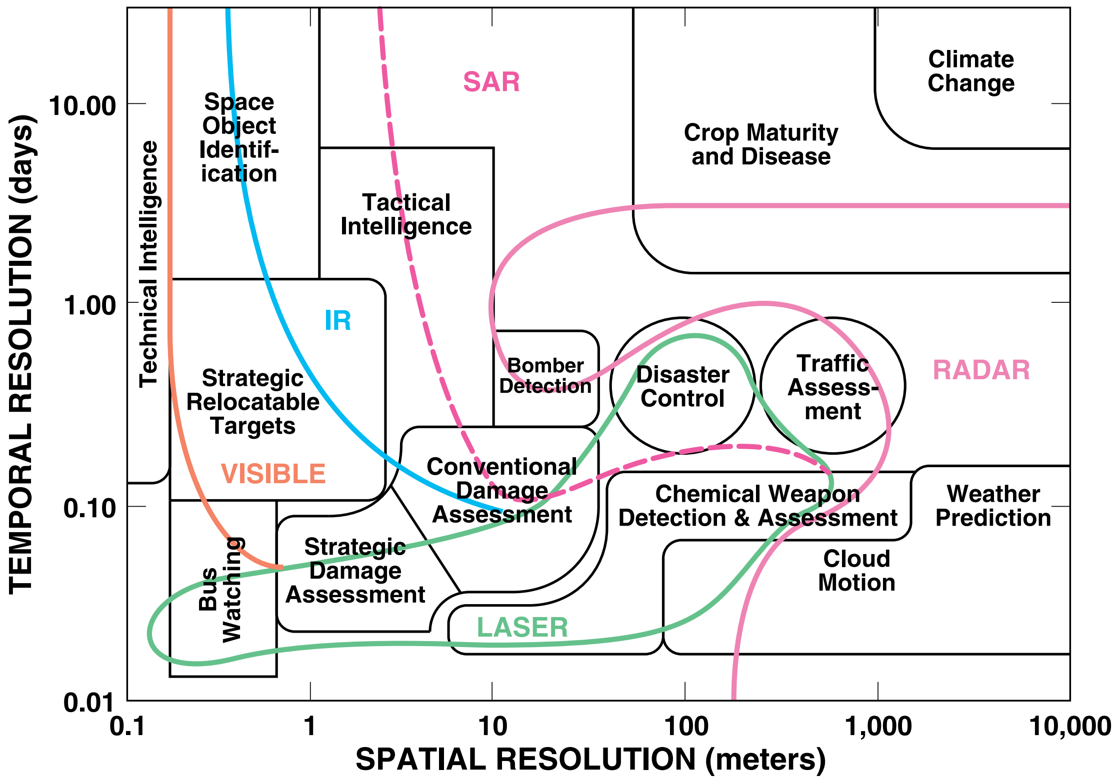

Figure 5.5 - 2 Distributed sensor capabilities for defense and civil remote sensing applications

Appendix to Section 5.5: Scaling of Distributed Systems

Distributed systems have many satellites, each with modest sensors and communication capability, whose integration gives the whole constellation global, real-time coverage. For some missions, such constellations have significant advantages in scaling, performance, and survivability. This appendix discusses the missions for which those benefits can be realized. The advantages of distributed systems result from their reduced ranges to their targets and between the satellites in their constellations.

Passive distributed sensors demonstrate the benefits that result from reducing the range to target. A sensor of diameter D operating at wavelength λ has resolution $d_{min} \approx r\lambda/D$ at range r; thus, achieving resolution d_{min} at r requires a diameter that increases with range as $D \approx r\lambda/d_{min}$. The sensor's aperture area increases as r^2, and its volume and cost increase as roughly D^3, for a given level of technology. A constellation of N satellites has a revisit time $T \propto \lambda/Nr$, so that for a given revisit time, $N \propto \lambda/r$. Multiplying the cost per sensor times the number of satellites gives a total cost $C \propto ND^3 \propto r^2$, which indicates a significant reduction in cost for operating more satellites at shorter ranges, e.g., there is an advantage of about a factor of 4 for deploying twice the number of satellites at half the range.[1]

These results can be extended to incorporate constellation altitude, which provides additional insights. From a satellite at altitude h, the range to a target at cross range y is $r = \sqrt{(h^2 + y^2)}$. If the satellite is responsible for a transverse ground swath 2W, the maximum range to its targets is $r_{max} = \sqrt{(h^2 + W^2)}$, for which a sensor operating at wavelength l must have diameter $D \approx r_{max}\lambda/d_{min}$ for resolution d_{min}. The aperture required increases with range as $(r_{max}\lambda/d_{min})^2$; its volume and cost roughly as $(r_{max}\lambda/d_{min})^3$. For a constellation of N satellites, the revisit time is $T \approx 4\pi R_e^2/2zVWN$, where R_e is the Earth's radius, V is the satellite's speed, and z is a constant (≈ 3) that depends on the extent and uniformity of coverage in latitude.[2] Inverting this relationship gives the number of satellites required to support a given revisit time

$$\mathbf{N \approx 4\pi R_e^2/2zVWT \propto 1/WT.} \qquad (1)$$

A few tens of satellites with few hundred kilometer swaths give few hour revisit times. The constellation cost is proportional to the product of the cost per sensor (and satellite) and the number of satellites, which is

$$\mathbf{C \propto (4\pi R_e^2/2zVWT)(r_{max}\lambda/d_{min})^3 \propto (h^2 + W^2)^{3/2}/WTd_{min}^3}. \qquad (2)$$

C increases as 1/T as the revisit time is decreased; it increases very rapidly as better resolution is required. For W small, C is large because N is large; for W large, C is large because the range and hence the sensors are large. C has a minimum at an intermediate value that can be found by introducing the variable $w = W/h$, the swath half width in units of constellation altitude, in terms of which Eq. (2) is

$$\mathbf{C \propto h^2(1 + w^2)^{n/2}/w} \qquad (3)$$

The total cost is minimized by reducing h to the lowest value consistent with practical operation of the constellation. The exponent n, which is 3 for the passive sensors discussed above, is generalized here to show the sensitivity of costs to the scaling of the sensor size and cost on range. Figure 1 shows the scaling of N and C on w for n = 3. N falls as 1/w from 4 at w = 0.25 to ≈ 0.5 at w = 2.3. C falls from ≈ 4.4 at w = 0.25 to ≈ 2.6 at w = 0.75, but rises again to

≈ 7 by w = 2.3. Thus, there is a factor of two penalty in cost for operating scanning passive sensors a factor of two away from the optimum swath. The minimum C can be confirmed by differentiating Eq. (3) to produce $w_{opt} = 1/\sqrt{(n - 1)}$, which for n = 3 is = $1/\sqrt{2}$, as shown.

For smaller n, w_{opt} moves to larger values, as shown in Fig. 2, which compares the costs for n = 2 and 3. By n = 2, which would be appropriate for optics that scaled as the aperture area rather than volume, the minimum in the curve moves to $w_{opt} = 1$ and its value drops from ≈ 2.6 to 2. With decreasing n, the cost curve becomes much flatter, so there is less of a penalty for operation at separations larger than optimum. However, the significant penalty for operating at swaths much smaller is altered little for smaller n.

C varies as $\sqrt{[n^n/(n-1)^{n-1}]}$, which is shown in Fig. 3. As n falls from 3 to 1.5, the optimum range increases from about 0.7 to 1.5 and the optimum cost drops from 2.6 to about 1.6. This analysis does not show that it is better in general to operate at longer or shorter ranges, only that for each sensor there is an optimal range that is set by its scaling characteristics and that the penalties for operating far from that optimal range could be a factor of two or greater. Independent of the optimization of swath width, it is advantageous to operate distributed systems as low as possible. Having done that, the swath can be optimized through a process that more restrictive for large n, less so for small. Then, increasing T would decrease cost at the price of less timely data, and degrading resolution would decrease cost, but at the price of an equivalent or disproportionate degradation of the value of the data. Increasing T or d_{min} would appear to be the final steps in attempting to reduce costs to affordable levels. If that is not possible without unacceptable degradation of performance, it may be necessary to shift to the staring sensors discussed below, which have added degrees of flexibility.

The scaling arguments above are based on range and aperture size. The number and cost of the detectors in the focal plane and the computational power to support them should also be taken into account; however, that does not change the above results. When computer and detector costs are included, the constellation cost of Eq. (2) is generalized to

$$\mathbf{C \approx N[a(W/d_{min})(V/d_{min}) + bW/d_{min} + cD^3]}, \qquad (4)$$

where a, b, and c are constants. On the right hand side, the second term is the number of detectors in the linear focal plane, W/d_{min}, times the cost per detector, b. The first term, which is proportional to the product of the number of pixels and the rate at which they are crossed, V/d_{min}, gives the computation rate required to support the focal plane. The third term gives the cost of the aperture, which is discussed above. Since the first and second terms are both proportional to W, they can be combined into $[aV/d_{min}^2 + b/d_{min}]W$. The two terms in brackets scale differently on d_{min}, which is important for studies of resolution, but for fixed d_{min} and cost parameters, their sum is a constant. Since it scales as W, and N scales as 1/W, the product of the sum and N is independent of W. Thus, its derivative with respect to W vanishes and does not affect the optimizations studied above. For passive scanning sensors, detector and computer costs add a fixed amount to the total cost, but do not affect the optimization with respect to W, which remains as shown in Figs. 1 to 3.

It is possible to estimate the rough increase in costs due to computers and focal planes. Factoring out the coefficient of the third term in Eq. (4) gives

$$\mathbf{C \propto ch^2(\lambda/d_{min})^3[(aVd_{min} + bd_{min}^2)/ch^2\lambda^3 + (1 + w^2)^{3/2}/w]}. \qquad (5)$$

The values of the cost parameters are not known precisely, but can be estimated well enough to give some guidance. A system with a 1,000 detector linear array might cost ≈ \$1K, including detectors, electronics, and integration; if so, b ≈ \$1/det. A 100 million instruction per second computer can now be flown for about \$100K, so the computational cost parameter is a ≈ \$0.001s. While the Hubble telescope cost ≈ \$100M for a few m^2 aperture, strategic defense systems proposed orbiting lightweight ≈ 10 m optics for \$100M. A geometrically intermediate cost target for aperture is c ≈ \$10M/m^3, which is given per unit volume rather than area to account for finite thickness and the greater support required for larger apertures. For these values of the cost parameters, resolution d_{min} = 10 m, a visible-near IR sensor, and h = 1,000 km, the first term in Eq.(5) is ≈ [\$0.001s x 10^4m/s x 10m + \$1/det x $(10m)^2$] / [\$10M/m^3 x $(10^6 m)^2$ x $(10^{-6}m)^3$] ≈ (100 + 100\$-m^2)/\$10 m^2 ≈ 20. Thus, for these parameters, fixed costs are significantly larger than variable costs, so any variation in fixed costs due to factors not treated here could significantly impact the optimizations above. For operation at lower altitude, this sensitivity would be further enhanced. However, fixed costs scale less strongly on resolution than the costs for aperture. If 3 m resolution was required, the cost for the focal plane would drop to about that for aperture. For 1 m resolution, the cost for computation would drop to about that for aperture, too, although scanning sensors for continuous, whole-Earth coverage might require excessive array sizes and bandwidths.

Active sensors such as lidars, radars, and SARs scale slightly differently. In general the product of their power, P, and aperture, A, scales as r^4, which suggests a stronger scaling than that of passive sensors. However, for active sensors P and A can be optimized separately to minimize cost. Sensor costs are typically the sum of the costs for P and A, which is minimized by the choice A α P, which gives PA α P^2 a (cost per sensor)^2, so the cost per sensor only increases as $\sqrt{(PA)}\ \alpha\ r^2$. Thus, the actual scaling exponent for distributed active sensors is n ≈ 2, for which cost as a function of w is shown by the bottom curve in Fig. 2. It is very broad, with a minimum at a half swath of 1 constellation altitude. While it is not appropriate to compare the costs of passive and active systems, which involve different missions and component costs, it is proper to note that active systems would operate at about 30% greater range than passive systems on average. They could do so because optimizing both P and A allows them to increase range with less penalty in sensor cost.

Communication satellites have distinctly different scaling in distributed operation. While they would not normally be used in a scaling mode (apart from store and forward systems), their scaling in that mode can be discussed simply. The key issue is the link margin between the satellites and ground stations. If the satellite has a dish of diameter D and aperture area A, the power density it delivers at range r is ≈ $P/(r\lambda/D)^2 \approx PA/(r\lambda)^2$. The signal received by an aperture A at that range is proportional to PA^2/r^2. Since P and A can be optimized separately, the channel cost is proportional to P, while PA^2 scales as P^3, so the cost per channel scales as $r^{2/3}$ and the scaling exponent is n ≈ 2/3, for which the above optimization does not apply. The practical answer is to move long-haul communications satellites as far apart as is convenient, which is where Earth curvature effects modify these arguments. Long-haul communications satellites do not distribute favorably, and should be deployed much as they are at present.

An exception to this result is the active and growing area of distributed communication from satellites directly to user handsets and pagers. For such scanning systems, the key link is from the handset to the satellite, which is limited by the power that is allowed and the antenna gain that will be tolerated. The former is set at p ≈ 3 Watt by the FCC; the latter is dictated by customers, who do not care to point high-gain antennas at satellites. Thus, rather than the $(D/\lambda)^2$ gain of long-haul systems, personal handsets have essentially no gain, so the received signal reduces to ≈ pA/r^2, whose optimization involves only A. Then, the cost per satellite scales as r^2, n = 2, and the scaling of direct communication satellite systems is much like that of active systems. From Fig. 2 their optimum swath is at ≈ 1, although the penalty for operating with wider swaths is modest. Staring sensors. An interesting variant on the scaling discussed above is given by missile launch detection and other applications that require the sensors to observe most of the surface of the Earth at all times, which changes the basis of constellation sizing from scanning in a given revisit time to complete coverage at all times. If each satellite is responsible for staring continuously at an area πW^2 below it, the number of satellites required is roughly

$$\mathbf{N \approx (4\pi R_e^{\,2}/\pi W^2).} \tag{6}$$

If the cost per sensor scales as $D^3 \alpha (r_{max}\lambda/d_{min})^3$, the constellation cost is

$$\mathbf{C \; \alpha \; (h^2 + W^2)^{3/2}/W^2 \; \alpha \; h(1 + w^2)^{3/2}/w^2,} \tag{7}$$

which again shows the importance of operation at low altitude—although the advantage is linear, and hence somewhat reduced from that for scanning sensors. Figure 4 shows N and C as functions of w. N drops sharply as $1/w^2$. C increases sharply at small w due to this variation of N. C drops to a fairly sharp minimum at w ≈ 1.4, and then increases sharply, approaching the asymptotic C α w by w ≈ 2. If the exponent in Eq. (7) is generalized to n/2, the optimum w can be found by differentiation to be $\sqrt{[2/(n-2)]}$, which is $\sqrt{2}$ for n = 3, as shown. This result also shows, however, that for n less than or equal to 2, the cost does not have a minimum, and there is no benefit for distributing staring sensors within this analytic model.

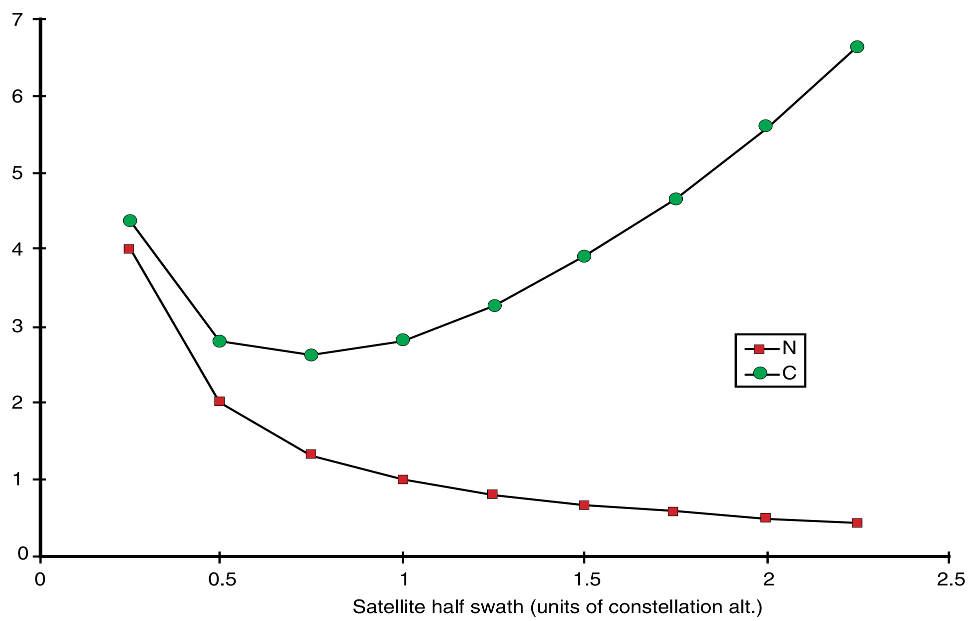

Figure 5.5 App -1

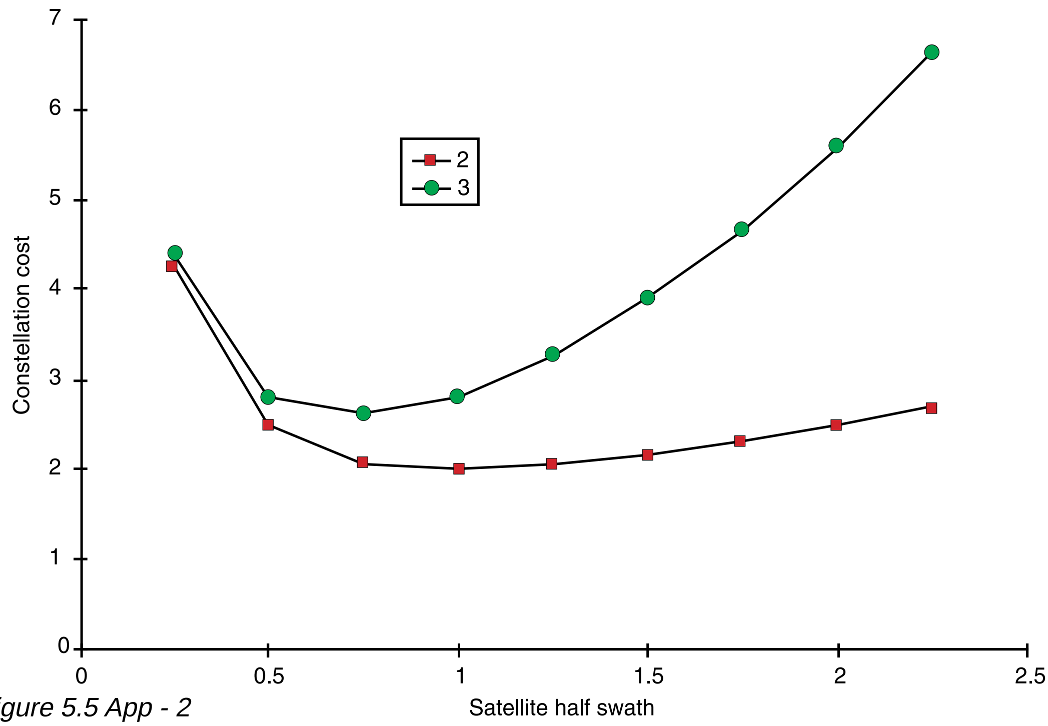

Figure 5.5 App - 2

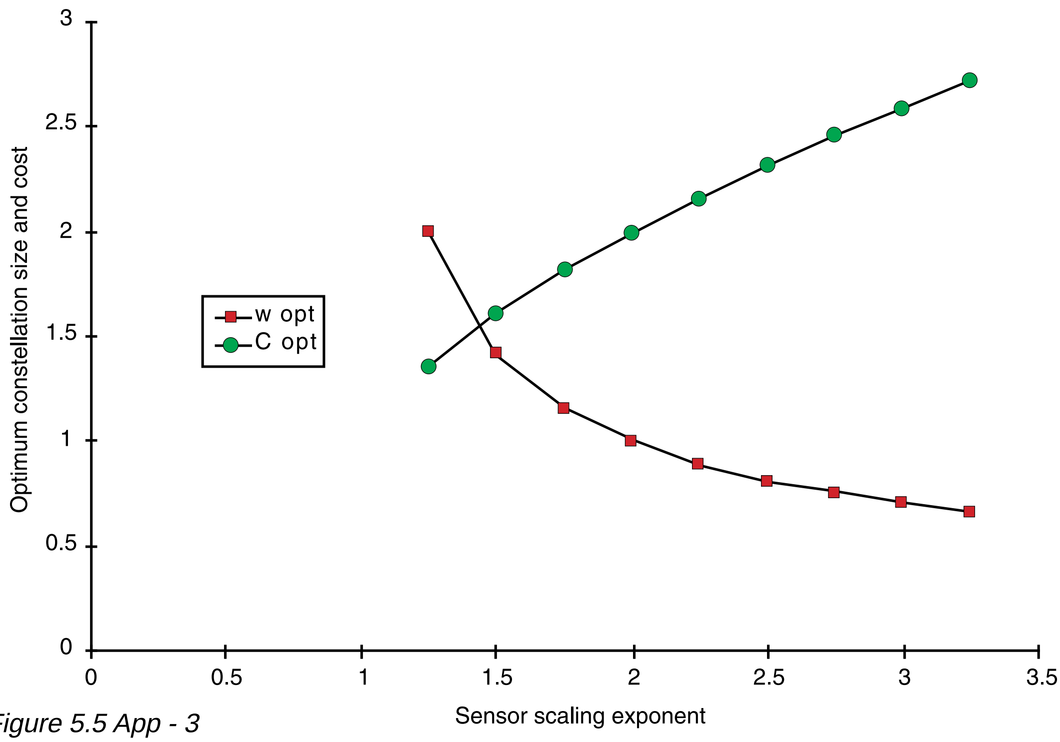

Figure 5.5 App - 3

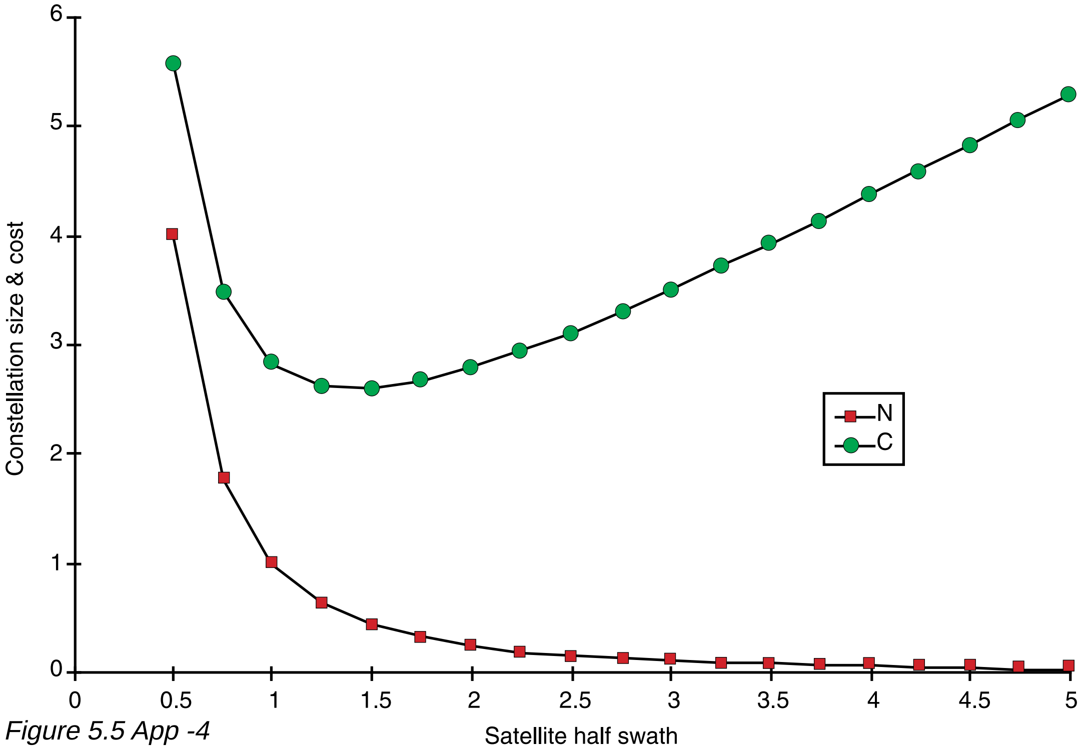

Figure 5.5 App -4

1. G. Canavan and E. Teller, "Low-Level Satellites Expand Distributed Remote Sensing, " *Signal* August 1991, pp. 99-103.
2. G. Canavan, "On Satellite Constellation Selection," Los Alamos National Laboratory report LA-12059-MS, May 1991.

5.6 The Human Role in Air Force Space Applications

Harry Wolbers

5.6.1 Introduction

Too often in system design an artificial dichotomy is created that attempts to classify systems as manned or unmanned. This especially seems to be true when referring to space applications. In reality there is no such thing as an unmanned system. Everything that is created by the system designer involves the human element in one context or another. The point at issue is to establish in every system, whether the system is controlled directly or remotely by humans, the optimal role of each human and each machine component.

It is the thesis of this paper that maintaining Global Presence, Global Power and Global Reach beyond the 2020 time period may well require the direct participation of Air Force personnel operating in space rather than relying entirely on remotely controlled systems as is now the case. The unique Air Force interests in supporting our space assets can not be abdicated to other agencies, countries, or commercial ventures. Rather, the Air Force infrastructure must be prepared, when appropriate, to directly utilize manned space capabilities to support the DoD overall space missions.

5.6.2 Historical Precedents and Past Experience

In the mid 1960's the Air Force initiated the development of a Manned Orbital Laboratory (MOL) which was to have operated in a low Earth orbit for classified missions. The program was canceled before the MOL became operational for various reasons, including budgetary, political, and the rapid parallel development of specific unmanned systems. In the years since the MOL was canceled considerable experience has been obtained in manned space systems including the Apollo Lunar Landing missions, the very successful Skylab (the Nation's first Space Station), and the Space Shuttle missions which have included the Spacelab missions and various special purpose missions such as the repair of the Hubble Space Telescope. In view of the developments of the last three decades it would seem appropriate to re-examine once again the human role in Air Force space applications.

Since the first manned spaceflight of Yuri Gagarin in Vostok 1 in 1961 (4/12/61) through the end of 1993, the former USSR had logged a cumulative crew total of 9,782 man days, 34 hours and 32 minutes in space. The U.S. had logged a cumulative crew total of 3320 man days, 6 hours and 44 minutes. Together these figures represent nearly 13,104 man days or 36 man years in space.

During this period 308 individuals, males and females, representing 25 different countries participated in one or more space missions. In these missions nearly every conceivable human task has been demonstrated as being feasible to be conducted in space provided that the necessary supporting equipment is available. Electrical and fluid systems have been repaired, large objects have been moved or replaced, and instruments have been re-calibrated and realigned. In the early 1974 Skylab missions the large food lockers (in excess of 6 cu, ft and weighing over 250 lbs) were very readily relocated in zero gravity by one crewman working alone. (A task that required four men on the ground). More recently the repair mission to the Hubble Space Telescope demonstrated the utility of human intervention to repair and upgrade free flying satellites, thereby extending indefinitely their operational lifetimes.

5.6.3 Current Trends

At least 27 different countries currently have payloads in Earth orbit. In addition to the launch vehicles utilized by the U.S. and the former Soviet Union, other players are rapidly coming on the scene. The French Ariane has had a number of successful launches and the Japanese are rapidly improving their launch vehicle capabilities. As reported in the open literature (Aviation Week and Space Technology 3/20/95) Japan is working to double the lift capacity of the new H-2 launch vehicle. The Japanese are increasing their planetary programs and have stated their intent to become a leader in Earth Observations. Some $69 million dollars (U.S. equivalent) are currently budgeted for development leading to the H-2 Orbiting Space Plane (HOPE). In addition Japan spent $496.8 million (U.S. equivalent) in 1994 and have allocated $746.8 million (U.S. equivalent) in their 1995 budget to develop the Japanese Experiment Module (JEM) which is a manned research and development facility currently planned as an element of the International Space Station (Space Station Alpha).

Other players with orbital launch capabilities include India and the Peoples Republic of China. As reported in the press (Aviation Week and Space Technology - 2/27/95) the PRC's current Five Year Plan (1995-2000) includes a Satellite to orbit the Moon in the year 2000.

Before the year 2020, Space will no longer be the sole province of the United States or Russia. The capabilities to support humans in orbit will continue to increase and through competition and technological improvements launch costs will decline. The advent of many new players will undoubtedly require that current U.S. Policy and International Treaties be revised. Given the emerging technological capabilities and the demonstrated capabilities of human involvement in the deployment, servicing, and operation of space systems, it is our belief that the Air Force would be remiss if it does not actively exploit the human resource where appropriate when developing future systems.

5.6.4 Human Capabilities

A detailed list of human capabilities applicable to space mission activities may be found in many references.[1] A listing of typical human capabilities (categorized by Sensory/Perceptual, Intellectual, and Psychomotor/Motor abilities) is presented in Table 1.

While considerable quantitative data may be found in the literature defining human sensory discrimination abilities and the fine and gross motor responses that humans are capable of making, the higher level intellectual functions such as cognition are not as precisely defined in terms that can be used directly by program managers and system engineers in the design of new systems and applications. Fortunately pertinent research programs to overcome this deficiency are now underway at the USAF Armstrong Laboratory. These programs are making significant progress in defining and describing the underlying factors key to the effective use of human intellectual capabilities in the design and operation of future Air Force systems, regardless of the physical location of the human operator of those systems.

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1. McDonnell Douglas Astronautics Company, The Human Role in Space, 5 Volumes, NAS8-36511, December 1985

For those "Intellectual" capabilities listed in Table 1 the following definitions may be helpful:

Cognition is defined as awareness, immediate discovery or rediscovery, or recognition of information in various forms. It involves comprehension or understanding. Information acted upon by the human element can be in the form of figures, symbols, semantic units, behavioral units, classes, relations, systems and transformations.

The terms cognition and perception overlap to some degree. Both perception and cognition are concerned with input information from sensory sources. Perception, however, is concerned primarily with sensory properties and with the cognition of figural units. The complete cognitive process includes operation with symbolic, semantic, and behavioral concepts as well. Perception is midway along a continuum extending from sensing at one end to thinking at the other end. It is the process of organizing and interpreting sensory inputs based upon past experience. Cognition involves a broader range of mental activity including awareness of semantic meaning and abstract concepts.

Memory is defined as information retention and storage, with some degree of availability of information in the same form in which it was committed to storage and in connection with the same cues with which it was learned. Memory is distinguished from cognition per se by the ability to recall information having once been exposed to the information. Memory storage, however, is an essential condition or determiner of cognition.

Divergent Production can be defined as the generation of new information from given information where the emphasis is on variety and quantity of output from the same source. Divergent production is related to creative imagination. In this process, items of information are retrieved from memory storage and used to generate a number of varied responses.

Convergent Production may be defined as the derivation of logical deductions or at least compelling inferences leading to a unique answer or conclusion. In convergent production the problem can be rigorously structured, and is so structured, and an answer is forthcoming without much hesitation.

Evaluation can be defined as a process of comparing a product of information with known information according to, logical criteria and making a decision concerning criteria satisfaction.

5.6.5 Human Limitations

The limits of human capabilities may be altered by both environmental and task related factors. Among the most commonly examined factors are atmospheric stresses - hostile changes in the individual's ambient breathing atmosphere. Six such stresses are identified in Table 2A. The severity of each stress is dependent upon both the intensity of the variation and the duration of the exposure. Each of the stresses indicated is capable of producing unconsciousness or death with the appropriate combination of duration and intensity.

In space operations, atmospheric stresses are generally compensated for by Environmental Control and Life Support Systems (ECLSS), either in the spacecraft or associated with the space suit during extravehicular activity. Because of this, atmospheric stresses do not commonly restrict activities, but they do add to the cost of utilizing humans in performing certain tasks.

The human also is susceptible to environmental stresses other than atmospheric and these stresses may also reach intensities that can produce injury or death. Stresses of the type indicated in Table 2B are not as easy to counteract as are the variations in atmospheric characteristics and are usually avoided by specific approaches to spacecraft design characteristics or mission operations.

The Space Adaptation Syndrome (SAS) or space motion sickness has occurred to some degree on all U.S. space flights since the days of the Mercury and Gemini Programs. In addition 49 percent of the Russian cosmonauts have reported the condition. The symptoms are generally the same as those associated with conventional motion sickness. They occur early in flight, peak at about 24 to 36 hours, but may last as long as four days.

The occurrence of SAS cannot be predicted in any given individual. Once adaptation has occurred in flight, however, and it always does, the individual is exceptionally resistant, even to challenging exposures, for the rest of the flight and for a week or more postflight.

The extent to which SAS degrades crew performance has not been measured with any accuracy or precision. There is some evidence that dedicated, well trained crew members will perform successfully despite the effects of SAS. On the other hand, some activities on previous space missions have been postponed or canceled because of SAS. Table 2C summarizes previous SAS experience on U.S. spaceflights. The SAS syndrome may mitigate to some extent the use of rapid response Trans-atmospheric Vehicles because of the critical nature of the first 24 to 48 hours in the weightlessness of space. Once adaptation to the space environment has occurred, however, longer duration missions associated with a space station or other manned and unmanned platforms have been demonstrated to be very feasible.

5.6.6 Potential Activities of Value

Human creativity and intellect, sensory and perceptual capabilities, and fine manipulative skills provide a valuable resource to draw upon in any application. While the human role in space can take many forms, it is suggested that Air Force planners seriously consider the use of humans to repair, service, and upgrade space systems. Assuming human access to space, considerable cost savings are possible by using humans to perform certain tasks in the deployment, servicing or upgrading of systems, even though operationally those systems may function as remotely controlled or monitored platforms. As an example, Skylab estimates (made in 1974 after the failure of the orbital workshop solar wing to deploy automatically) indicated that a manual deployment mode for the solar arrays would have produced a 15 percent weight savings in that system. In another NASA sponsored design study, a 25kw space platform[2] was designed to be a resource module to which unmanned pallets could be docked to receive power, cooling and other resources. This was similar in concept to the “motherboard” configuration described

2. McDonnell Douglas Astronautics Company, Alternative System Design Concept Study, NAS8-33955, July 1982

in the Air University's SPACECAST 2020 Study.[3] It was found that in the initial deployment some 15 different mechanisms including launch supports, solar array launch latches, radiator latches, antennas, etc. could be operated manually by an EVA crewman at an estimated EVA cost of $200K as compared to the development cost of $2406K required to provide automated or remotely actuated deployment mechanisms, a better than 10:1 cost savings.

Space crews are fully capable of performing such activities as: activate/initiate system operations; adjust/align elements; communicate information; confirm/verify procedures/ schedules/operations; connect/disconnect electrical/fluid/mechanical interfaces; correlate data; deactivate/terminate system operation; deploy/retract appendages; inspect/observe; measure physical dimensions; perform precision manipulation of objects; engage in problem solving/ decision making/data analysis; removal and replacement of modules/coverings; replacement and/or cleaning of surface coatings; transporting items from one location to another; etc.

At the present time NASA together with its international partners is developing an International Space Station (Space Station Alpha). Although this effort has been beset by many organizational changes and by budgetary and political constraints and has undergone a number of redesign efforts in the past five years, it is still scheduled to be built in orbit between 1997 and 2002 and to become fully operational at that time. It will operate at a 51.6 degree inclination in a low altitude (200-250 nmi) orbit. It will require 67 logistics missions during the building process, including 21 by the U.S. and the rest by Russia. After the Space Station becomes operational in 2002, NASA intends to phase out the current Space Shuttle and replace it with a new more efficient logistics carrier for transporting modules containing people and material to orbit. This will present an opportunity for the Air Force to consider the development of dedicated modules or work platforms providing the capabilities to remotely command, control, monitor, throughput, and preprocess data for free-flyers and other platforms, and to provide support capability for construction, assembly, and deployment of payloads. Payloads capable of maneuvering themselves within a reasonable distance of the space crews' work platform could be maintained, serviced and checked out. Payloads and satellites requiring transfer to other orbits could be integrated with a transfer stage and launched. The transfer stages could be commanded and controlled by the space crew and be either expendable or re-useable. Payloads, experimental samples, or captured samples requiring return to Earth could be demated, prepared, and stored until placed in the crew return module.

5.6.7 Man/Machine Trade Offs

The potential level of operational involvement of the human in any system falls somewhere along a continuum ranging from direct manual control or involvement at one extreme to merely monitoring systems that are self actuating, self healing, independent operations with minimal requirements for direct human intervention at the other extreme. For reference purposes several benchmarks along this continuum can be defined as summarized in Table 3.

The criteria that program managers and system engineers use to select the most cost effective approach to meet system objectives include performance, cost, and mission success probability. The decision maker must base his judgment on knowledge that a particular implementation option can or cannot meet the performance requirements in terms of such factors as force,

3. Air University, AETC USAF, SPACECAST 2020, Volume 1, June 1994

sensory discriminations, speed, and accuracy. If that option can meet the performance requirements, can it do so within the systems environmental constraints of, e.g. temperature, pressure, radiation, atmospheric constituents, mass limitations, and acceleration disturbance limits? In many cases, more than one implementation option can meet the performance requirements, and it is then necessary to examine the relative costs and the mission success probability in terms of the state of technological readiness or program confidence associated with each approach.

As experience is gained in manned space operations over the next 25 years the permanent presence of humans in space will be established. On the other hand, the competing demands on this Nation’s limited economic resources are forcing an increasing awareness of the need to maximize economic efficiency in achieving the Air Force goals and objectives in promoting Global Presence, Global Reach, and Global Power. Baring a major worldwide confrontation the current DoD budget will likely continue to shrink in purchasing power. Furthermore future DoD space assets will undoubtedly be required to operate for longer lifetimes. If these assets are designed to be maintained, serviced, and upgraded in situ, and thereby allowing new technological advances to be introduced as they become available, it can be anticipated that the operational life of those assets can be significantly increased. This represents a direct analogy to today’s environment where we find it cost effective to upgrade the systems in our current aircraft fleet even though some of the airframes themselves may be 30 years old.

In establishing the relative roles of the human in future systems cost will be a principal factor. Program planners and system designers must develop appropriate costing metrics to help in the decision process. One example of an approach to this process can be illustrated with data generated several years ago in a NASA sponsored study.[4] In the referenced study some 37 basic activities were derived from the analysis of the functions to be performed in a number of manned and remotely controlled space systems. The costs of performing these activities in manual, augmented, teleoperated, supervised, and independent modes of operation were derived, costs normalized, and nomographs prepared to define the domains wherein each man-machine node of operation would be most cost effective.

The human is limited in the number of activities that he can perform simultaneously in any given time interval and also in the number of times an activity can be repeated without fatigue setting in. These factors are key in the tradeoff decisions which must be made by the system designer in determining the mode of operation to be utilized in any given application. As an example, if an auto maker were to make a one of a kind model of a door assembly, it would be most cost effective to have that unit fabricated in the model shop with manual intensive labor. On the other hand in a production run of 500,000 or 1,000,000 door assemblies, labor costs would be so high that it would be more cost effective to invest in automated production equipment to manufacture the unit. The same reasoning applies to space systems. Even if an operation could be performed manually, if it must be repeated many times there is a cross over point where the cost of labor would dictate the use of some degree of augmentation or automation.

Figures 5.6.1, 5.6.2 and 5.6.3 are costing nomographs developed in Reference (1) to provide comparative data on the relative costs for each man-machine mode in performing from one to forty activities, from one to many thousands of times, as a function of the time (1, 10, 100

4. op. cit. (1)

minutes) required to complete the event. The relative costs of the various human/machine modes for the time intervals indicated are expressed in terms of normalized "Accounting Units". An accounting unit is defined as the cost to perform an activity one time in the manual mode.

In the man-machine modes requiring direct human involvement, the more activities that are required to accomplish a specific mission objective, the more time required and the higher the cost. In the modes where the human is more indirectly involved, the cost of resources and the supporting equipment items required to perform each activity in orbit contribute more to overall cost than does the time required to accomplish the activity. Thus, in modes requiring direct human involvement, the cost reduction due to the potential of sharing common equipment items and common resources can be a significant factor in the cost equation.

As an example of the use of these nomographs, if a particular task requires 10 different activities to be accomplished in 10 minutes or less, and will be repeated 200 times during the course of the mission, the most cost effective system design approach would most likely be to consider the use of teleoperators or other computer directed functions to perform the task. On the other hand, providing human support was available, if the task required only one activity to be performed during a ten minute interval the task would have to be repeated 100's of times before it would be cost effective to automate the process.

These examples are offered only to illustrate some of the factors involved in the design and operation of future systems. The point to be made is that as new systems are designed and old systems evolve. the Air Force must not arbitrarily abandon the human role in space to civilian agencies and to commercial entrepreneurs. In order to maintain a presence in space to serve those functions unique to our national security in a cost effective manner, manned military operations in space may be required and must be considered.

5.6.8 Conclusions

We have learned from the U.S. Space Programs to date as well as from the former Soviet Union that: (1) systems can have indefinite operational lifetimes in space if they are designed to permit the contingency of in-flight repair and maintenance; (2) structures too large to be launched intact can be constructed and assembled in orbit using the humans unique abilities; and (3) the flexibility and creative insights provided by the crew in situ significantly enhance the probability of achieving mission objectives.

The ability of the human to manually assemble delicate instruments and components and to remove protective devices such as covers , lens caps, etc., means that less rugged instruments can be used compared to those formerly required to survive the high launch-acceleration loads of unmanned launched vehicles. As a result the complex mechanisms secondary to the main purpose of the instrument will no longer need to be installed to remove peripheral protective devices or to activate and calibrate the instruments remotely. The time required to calibrate and align instruments directly can be as little as 1/40th of that required to do the same job by telemetry from a remote location. In general, physical articulation and movement constraints in teleoperated systems result in performance times that are up to ten times longer than if the same tasks could be performed by human operators.

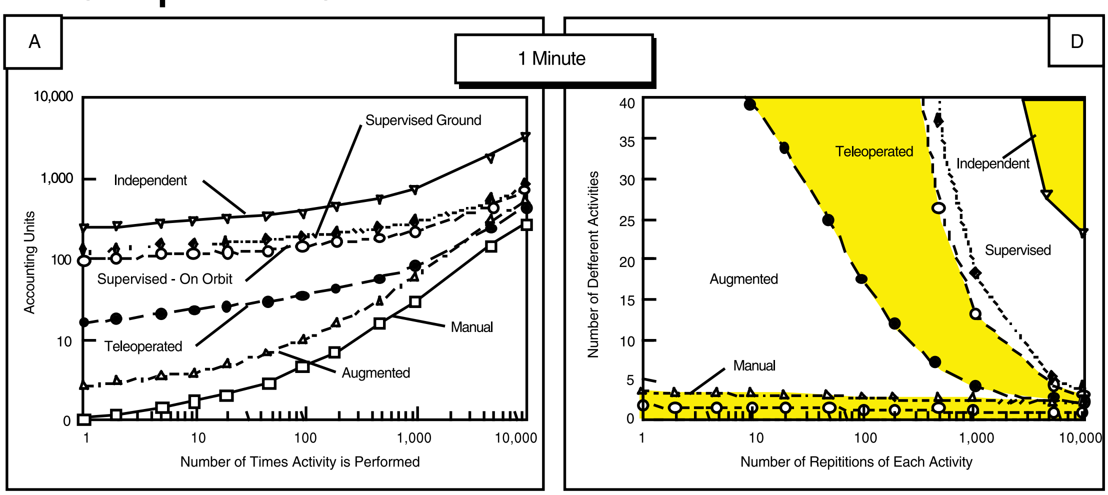
The human can abstract data from various sources and can combine multiple sensory inputs (e.g., visual, auditory. tactile) to interpret, understand, and take appropriate action, when required. In some cases the human perceptual abilities permit signals below noise levels to be detected. The human can react selectively to a large number of possible variables and can respond to dynamically changing situations. The human can operate in the absence of complete information. The human can perform a broad spectrum of manual movement patterns, from gross positioning actions to highly refined adjustments and in this sense behaves as a variable gain servo system.

For the foreseeable future, humans will continue to surpass machines in their perceptual abilities to recognize and interpret patterns of light and sound, improvise and use flexible procedures, recall relevant facts at appropriate times, reason inductively, and exercise judgment. On the other hand machines surpass humans in their ability to respond rapidly to control signals, apply great force smoothly and precisely, perform routine repetitive tasks reliably, store information and erase completely, process data deductively, compute complex relationships, and handle many different tasks at the same time.

With the advent of manned platforms in space inherent there are alternatives to potential deployment of remotely manned systems, with their operational complexity and high cost of system failure. Long-term repetitive functions, routine computations or operations, and large scale data-processing functions will be capable of being checked out, modified, and serviced by crews in orbit, just as they are now serviced in ground installations.

To date, NASA has developed many of the basic tools and techniques required to support intravehicular and extravehicular manned space operations. This available background of technology provides a point of departure for re-examining the role of the human in future Air Force applications. The Air Force infrastructure must be prepared, when appropriate, to utilize manned space capabilities in future mission applications

Comparative Costs of Alternative Man-Machine Modes

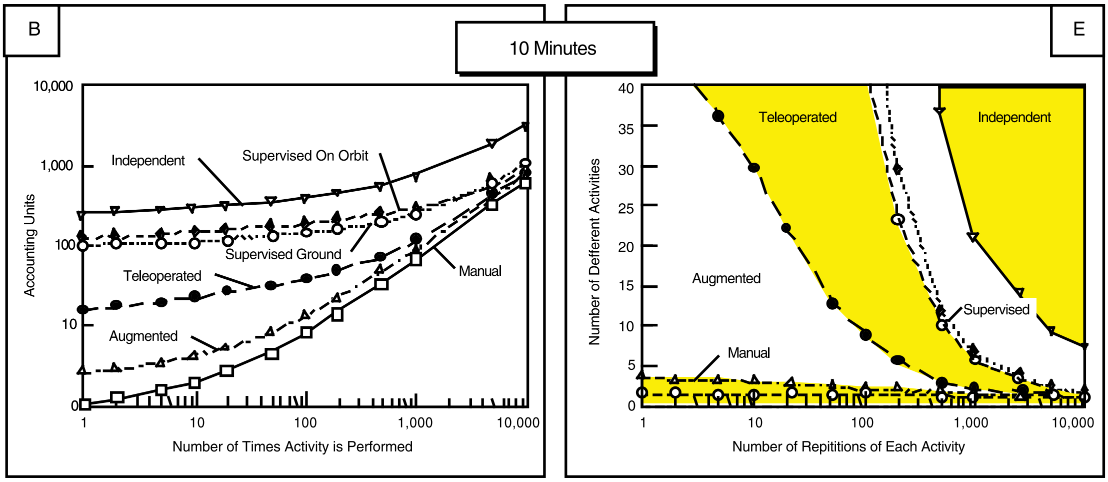


Relative Costs for Single Activity

Regions Where Modes Are Most Cost Effective When Multiple Activities Required

Figure 5.6.1

Comparative Costs of Alternative Man-Machine Modes (Cont)

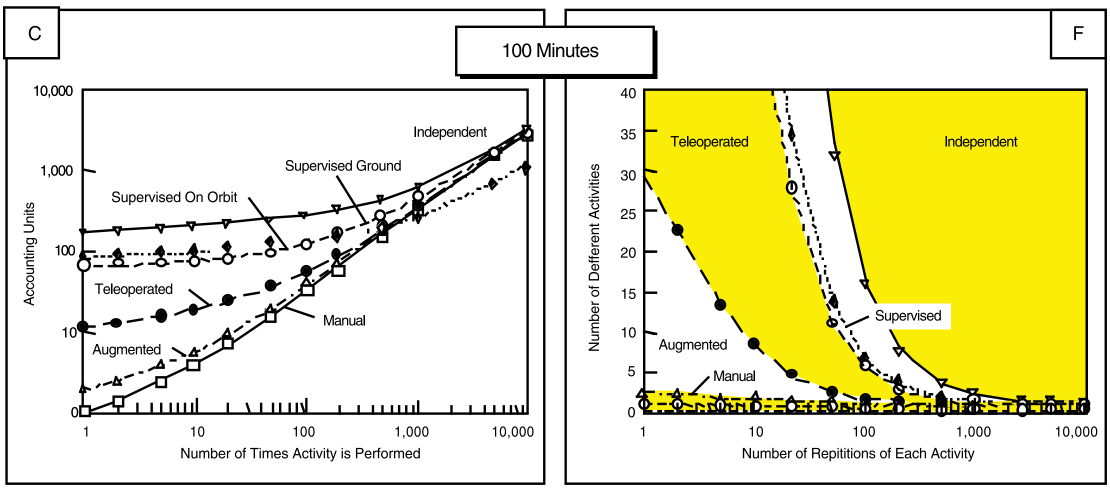


Relative Costs for Single Activity

Regions Where Modes Are Most Cost Effective When Multiple Activities Required

Figure 5.6.2

Comparative Costs of Alternative Man-Machine Modes (Cont)



Relative Costs for Single Activity

Regions Where Modes Are Most Cost Effective When Multiple Activities Required

Figure 5.6.3

Table 5.6 - 1

TYPICAL BASIC HUMAN CAPABILITIES

Sensory/Perceptual

- Visual Acuity
- Brightness Detection and Discrimination
- Color Discrimination
- Depth Perception and Discrimination
- Peripheral Visual Detection and Discrimination
- Visual Accommodation
- Detection and Discrimination of Tones
- Discrimination of Sound Intensities
- Sound Localization
- Tactile Discrimination of Shape and Texture
- Discrimination of Force Against Limb
- Discrimination of Limb Movement and Location
- Detection and Discrimination of Angular Acceleration
- Detection and Discrimination of Vibration
- Detection of Heat and Cold
- Detection and Discrimination of Odors

Intellectual

- Cognition
- Memory
- Divergent Production
- Convergent Production
- Evaluation

Psychomotor/Motor

- Production and Application of Force
- Control of Speed of Motion
- Control of Voluntary Responses
- Continuous Adjustment Control (Tracking)
- Arm/Hand/Finger Manipulation
- Body Positioning

Table 5.6 - 2

LIMITING FACTORS ON HUMAN PERFORMANCE

A. EFFECTS OF ATMOSPHERIC STRESSES

Type of Stress	Performance Degrading	Injurious or Life Threatening
Decreased Oxygen (Hypoxia)	Partial Press. Oxygen < 109 mm Hg	Partial Press. Oxygen < 73mm Hg
Increased Oxygen (Oxygen toxicity)	Partial Press. Oxygen > 400 mm Hg	Partial Press. Oxygen > 1500 mm Hg
Increased CO2 (Hypercapnia)	Partial Press. CO2 > 20 mm Hg	Partial Press. CO2 > 45mm Hg
Increased Temperature (Hyperthermia)	> 95 deg. F.	> 120 deg. F
Decreased Temperature (Hypothermia)	< 50 deg. F.	< 39 deg. F
Atmospheric Contamination (e.g. CO)	>25ppm CO	>400ppm CO

B. EFFECTS OF OTHER ENVIRONMENTAL STRESSES

Type of Stress	Performance Degrading	Injurious or Life Threatening
Vibration	0.08 g's at approx.4-8 Hz	2 g's at 3-8 Hz
Noise	80-85 dB	100-120 dB
Gz Acceleration	2 to 3 g's	5 to 6 g's
Gx Acceleration	5 to 6 g's	12 to 15 g's
Light	Complex	2.4 x 10^5 lumens/sq.ft.
Ionizing Radiation	---	>5 rads/day

Table 5.6 - 2 Continued

C. EFFECT OF SPACE ADAPTATION SYNDROME

Human Capabilities Impacted	Duration of Exposure (hours) <3	3-12	12-24	24-48	48-72	72-96	>96
Vision	None	Mod.	Mod.	Negl.	Negl.	None	None
Discrimination	None	Mod.	Mod,	Negl.	Negl.	None	None
Discrimination of Angular Accel.	Negl.	Mod.	Sig.	Sig.	Sig.	Sig.	Sig.
Cognition	None	Mod.	Sig.	Sig.	Mod.	Negl.	None
Memory	None	Negl.	Negl.	None	None	None	None
Evaluation	None	Mod.	Sig.	Mod.	Negl.	None	None
Visual-Motor Tracking	Mod.	Sig.	Sig.	Mod.	Negl.	Negl.	None
Manipulative Skills	None	Mod.	Sig.	Sig.	Mod.	Negl.	None
Body Positioning	Mod.	Sig.	Sig.	Mod.	Mod.	Negl.	None

None = (None) Negl. = (Negligible) Mod. = (Moderate) Sig. = (Significant)

Table 5.6 - 3

CATEGORIES OF HUMAN-MACHINE INTERACTION

Manual
Unaided manual activities possibly requiring the use of simple tools or restraints.

Augmented
Amplification of human sensory or motor capabilities with powered tools, exo-skeletons, sensing devices, etc.

Teleoperated
Use of remotely controlled sensors and actuators allowing the human presence to be removed from the work site: e.g., remote manipulator systems, teleoperators, telefactors, etc.

Supervised
Replacement of direct manual control of system operation with computer-directed functions although maintaining humans in supervisory control.

Independent
Self-actuating, self-healing, self-learning, independent operations dependent on automation and artificial intelligence, and minimizing the requirement for direct human intervention.

5.7 Modeling, Simulation and Analysis

Christopher Waln

Modeling, Simulation and Analysis of space capabilities and the integration of those capabilities into terrestrial operations and the overall force structure is extremely partitioned. MS&A are partitioned by classification, by mission area, by space vs. terrestrial, and by government vs. industry proprietary. This partitioning has evolved from the Cold War concepts of space systems management and space force employment. This situation is antithetical to advancing the application of space capabilities to joint warfighting.

The SDIO, through its National Test Bed, spearheaded the concept of interlinked MS&A which could be used to demonstrate technical and operational concepts well before substantial hardware investments were necessary. The concept did not deliver the envisioned benefits because of changes in national policy on missile defense. Since then, the state of the art has out-paced the National Test Facility (NTF) implementation, but the concept remains valid.

The concept was extended by Air Force Space Command (AFSPC) and Air Force Material Command (AFMC) in its "Seven Strategies for Space" to include all stakeholders in space--military, Intel, civil, and commercial. The concept was expanded to include the ability to support decision making through experiments, demonstrations, and exercises with technology, hardware, and humans in the loop. The concept, for management purposes, was named Frontier Arena and early demonstration recommendations focused on exercise support in much the same way the NTF is currently supporting joint exercises. The next level of implementation will be to provide support to DoD level space modernization decision-making by enabling warfighter in the loop assessments of alternative architectures.

Ultimately, Frontier Arena may be used to evaluate tactics, operations, and strategies involving the integration of space and terrestrial capabilities. By linking the various space and terrestrial MS&A capabilities in a shared ownership environment where each of the stakeholders can take advantage of the whole (given security and contracting limitations) the partitioning will be gradually eliminated and we will be well on our way to thinking about space as an integral element of our military forces rather than a stand-alone appliqué.

Frontier Arena or something like it is essential to maturing our thinking about space and space related terrestrial issues. Current net assessment models either assume space assets (their products actually) are universally available and have attributes undifferentiated from terrestrial assets. For example DoD level net assessment models do not distinguish the presence or absence of space based weather support; they assume perfect positioning awareness and cannot assess GPS degradation; they assume communications and "monte carlo" availability on the basis of enemy capabilities to interfere without regard to the means of communication; and early warning information is drawn from "look-up" Tables. This is not a pejorative assessment of the mode but an indicator of the immature state of our ability to fully exploit space and space assets.

Beyond Frontier Arena, virtual reality implementations offer the opportunity for political leaders and warfighters to visualize the interaction of all force elements--lethal and otherwise. Within the horizon of New World Vistas it will be possible for military officers and their civilian leaders to stand in the middle of a virtual theater and conduct digital sand-table maneuvers in multiple dimensions--space, time, and consequences. War rooms will not only contain the order of battle for the forces arrayed against one another but the other elements of national power as well. Commanders will be able to design there operations, test them, deploy the orders to the forces, and evaluate the results and required changes in one continuous intuitively visualized environment. Such a concept will put us inside our adversaries political, military, and economic turning circles for decades to come.

The Air Force plan for the joint implementation of Frontier Arena is fundamentally sound. It represents the first step on a path to command situation awareness previously only in the province of the futurist or science fiction writer. The Air Force is particularly well suited to lead such an enterprise and should commit to do so on behalf of the Department of Defense.