Chapter 29:

Affordable and Responsive Space Systems

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This chapter discusses the principal issues influencing affordable and responsive space systems, and the application of low-cost, small satellites to the military and civil space domains. It establishes the proposition that small, affordable satellites will be employed mainly to extend space capabilities to regions of the "performance envelope" that large satellite systems simply cannot populate in an affordable fashion. It also discusses the technological advances that will provide opportunities to employ affordable systems in more traditional space application areas (such as strategic surveillance).

The chapter commences with discussions of the military and civilian drivers that will influence the design of responsive space systems. It describes some of the desirable characteristics of responsive and affordable systems and the capabilities that they will offer to the warfighter. It then addresses specific design approaches that lead to affordable satellite systems that can be delivered in a responsive timeframe (since the development timescales are a facet of responsiveness just as much as the launch and operations). The concluding remarks consider the high-level issues that are likely to arise as space systems become increasingly responsive, with particular emphasis on the topic of space control.

Military and Civil Drivers

The concept of responsive space has been addressed mainly in the military domain, but there are analogous drivers in the civil domain that will also support the development of such systems in the future. Indeed, applications such as monitoring water and food resources are generally treated as civilian tasks at present, but it is widely believed that as population pressures increase in the next two decades, access to clean water and fertile land will increasingly become the catalyst for conflict. As a result, the need for timely surveillance will grow, and the line between military and civil monitoring will blur.

In the military domain, since the conflict in Kuwait in 1991 (which has been described as the first space war), space has been recognized as the new high ground in military operations. The growing desire for the affordable and responsive space systems that are the subject of this chapter arises from the subsequent recognition that existing strategic space assets are relatively ill suited to supporting operational and tactical requirements.

The procurement process for traditional space systems has for many years been in a negative spiral of increased costs, aversion to risk, long development timescales, and reduced numbers of launch opportunities. This stands in stark contrast to two of the

principal drivers on the military today: reducing budgets and accelerating the tempo of operations to stay within an opponent's decision cycle.

By contrast, small satellite systems are on a positive spiral of reducing costs, pragmatic risk management, short development timescales, and frequent launch opportunities. For these reasons, they can be used to address the future needs of warfighters in diverse locations around the globe.

Other significant drivers in the military domain, all of which have implications for the design of affordable and responsive space systems, include:

- a reluctance to put the lives of military personnel (on both sides) and civilians at risk. Military interest in capabilities such as unmanned surveillance platforms and precision weapons systems, utilizing high precision surveillance capability, is therefore on the increase.
- an interest in employing network enabled technologies. The aim is to integrate the various elements of existing military capability, enhancing the efficiency of military campaigns and reducing the time for their completion. Improved communications capability, especially to mobile users, is central to this objective.
- the desire to counter enemy camouflage, concealment, and deception techniques. The nature of the threat has changed, and military targets are generally becoming harder to distinguish. There is thus a significant reluctance to rely on a single surveillance capability, and indeed, the rules of engagement typically mandate target confirmation from a second sensor prior to engagement. Enemy awareness of satellite surveillance systems also leads to concealment operations during satellite passes.
- the need for an effective Identification Friend or Foe (IFF) capability. The need to perform effective discrimination between friend and foe in a maneuver warfare environment in which the battle lines are far more fluid is a further driver for surveillance and communication systems.
- the ability to conduct operations at extended range as the capabilities of weapons systems improve. With the advent of extremely capable surface-to-air missile systems and the proliferation of long-range ballistic weapons, the challenge to perform effective surveillance of regions deep within enemy territory from which a viable threat could nevertheless arise is becoming ever more acute.
- a greater diversity of locations for potential conflict. Following the Cold War, the need for more agile forces capable of deployment to locations around the globe has increased. This includes the need to support more than one deployment in different locations on the globe at any given time.

In the civil domain, much has been written concerning the National Aeronautics and Space Administration (NASA) mantra of "faster, better, cheaper." Improving space system performance simultaneously in all these areas has proved challenging (to say the least), but they remain three of the key performance metrics for any space system. Perhaps NASA's vision has been most closely approached in the realm of small satellites, where the scale of the systems makes it possible for them to be faster and cheaper, and

where the use of modern commercial-off-the-shelf technologies has allowed them to close the performance gap on some of their larger cousins, which typically have much earlier "technology freeze dates."

Among the principal civil drivers for responsive and affordable satellites systems are:

- the push for newsworthiness. Despite the proliferation of satellites among many new space players in recent years, it is still comparatively rare to see satellite images in the news media. The reason is that the typical 2- to 3-day life of a news story represents a significant timeliness challenge to large space systems, where the access times to the region of interest are usually long, and the need for comparatively high-resolution imagery has until recently precluded the use of constellations of small satellites.
- the goal of disaster mitigation. Some forms of natural disaster, such as hurricanes, can be tracked by existing space assets, but there are many others, such as earthquakes and floods, where timely access to warning data would be of extreme utility to the people attempting to respond to the crisis. As our understanding of the physical processes behind earthquakes improves, it may even be possible to use constellations of responsive spacecraft to move from disaster monitoring to disaster mitigation.
- data continuity. Although the military has requirements for multiple surveillance data sets to perform short-term change detection, the need for data continuity in the civil domain is crucial to the maintenance of a wide variety of monitoring services. At the current time, for example, the Landsat community of users who are exploiting that system for long-term environmental modeling faces a potential data gap as the on-orbit assets reach the end of their lives. Here the driver is to find an affordable way to maintain access to data over long periods of time, but there is also a need to replace assets in a timely fashion should one of the existing sensors fail unexpectedly. Another element of responsiveness is the desire to monitor some phenomena at specific times of day or during particular seasons. With a limited number of space assets available, such monitoring becomes something of a statistical lottery. By contrast, responsive constellations provide sufficient collection opportunities to overcome the vagaries of the weather.
- integrity and reliability. As we rely increasingly on space assets in a variety of subtle ways—for example, mobile phone networks and national power grids use the precision timing signal provided by global positioning systems (GPS) for switching coordination—it is important that our space systems can monitor their own state of health and respond accordingly if one of the elements in the system becomes unavailable for some reason. However, these high levels of integrity and reliability quickly become cost drivers unless significant levels of autonomy are included in the system.

Characteristics of Responsive and Affordable Space Systems

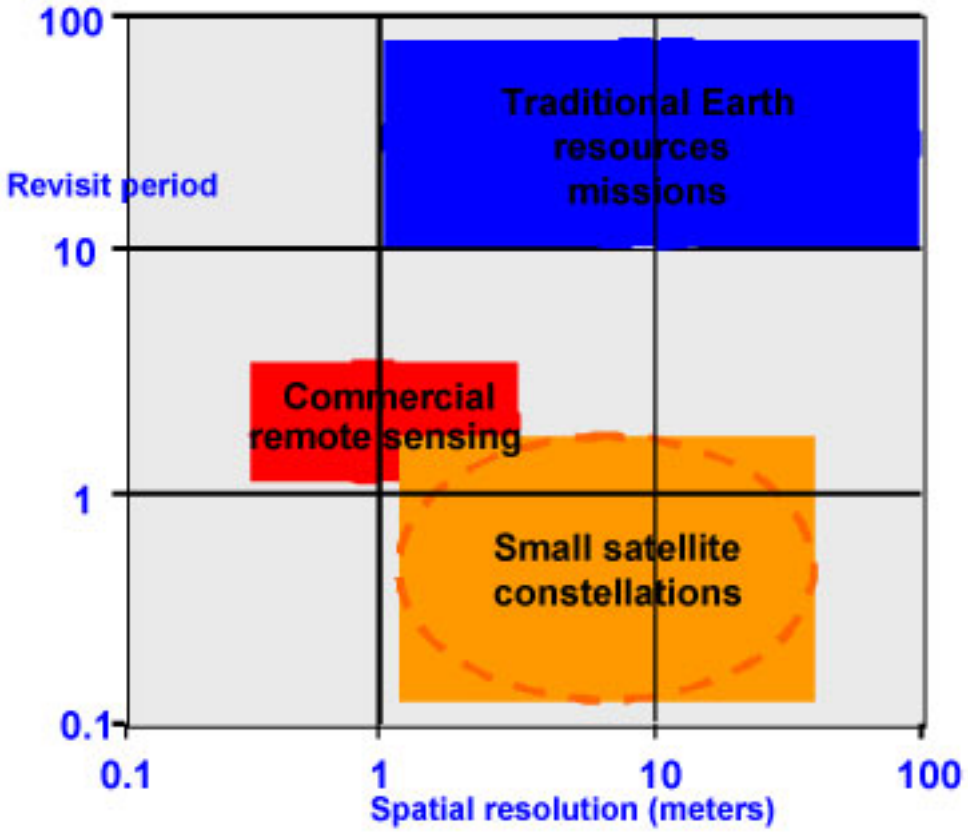
There is a pressing need to keep the costs associated with space systems to a minimum. The budgets available to the military have decreased in real terms since the end of the

Cold War, but at the same time, the number of military tasks that satellites are able to support has grown significantly, to the point where effective military operations are now infeasible without the surveillance, communications, navigation, and meteorological capabilities provided from space. In the civil domain, it is becoming increasingly common for commercial organizations rather than governmental institutions to commission constellations of satellites. In the commercial domain, there is always a focus on providing a return to investors in the shortest possible time. In order to be responsive, future space systems will thus need to provide significantly greater capacity to meet this increasing demand. However, it is simply not feasible to proliferate large satellite systems to achieve this; the costs and timescales are prohibitive. It is thus axiomatic that to be affordable and responsive, future responsive space systems must be designed around constellations and clusters of small satellites.

This process of evolution to multiple satellite systems has already begun. Examples in the surveillance domain include the international Disaster Monitoring Constellation (DMC) and the forthcoming RapidEye constellation, both of which comprise five satellites in Sun-synchronous orbits. Even more numerous in terms of satellites are the low Earth orbit (LEO) communication constellations, such as Orbcomm and Iridium; these are clearly starting to enter the realm of mass production, where the costs of the initial design can be amortized through the production of multiple platforms, thereby enhancing the affordability of the system as whole. The broad coverage offered by these systems leads to some of the most interesting possibilities for the future, with every likelihood that space systems will be used to support individual users/operators equipped with network-enabled Blackberry-class terminals (discussed in more detail below).

Figure 29–1 illustrates the regions of the surveillance performance envelope that are occupied by different classes of satellite. Satellites for traditional Earth resources missions, such as Landsat and Spot, are large and expensive, are launched infrequently, and have 2-week orbital revisit cycles. It is a measure of the increasing capability of small satellites (which employ far more modern detector technology) that similar resolutions can now be achieved with much smaller and cheaper space hardware. Uniquely, as a result of the lower costs associated with small satellites, they can be proliferated in constellations, such as DMC and RapidEye. As a result of having five satellites, these constellations offer daily global imaging capability, moving their performance envelope significantly lower in the diagram. By contrast, existing military satellites are located somewhere to the left of the red region representing the capabilities of commercial remote sensing satellites such as Quickbird and Ikonos.

Figure 29–1. Revisit Period versus Spatial Resolution for Imaging Surveillance Satellites



In the future, the operational and tactical requirements that drive the design of responsive satellite systems will be located near the bottom of the 1-meter (m) resolution line on this diagram; that is, the spatial resolutions required will be less exacting than for strategic intelligence assessments, but the data will need to be delivered in near real time. It is apparent that the journey from the existing capabilities to this target location on the diagram is far shorter, and hence far more feasible, for small satellites.

This is just one example of the need for different metrics to measure the performance of responsive satellite systems. The increasing need to conduct operations at extended range means that area coverage rate, rather than spatial resolution, will be one of the primary performance metrics. The 600-square-kilometer (km) images generated by the wide area cameras on the first-generation DMC satellites are approximately 10 times the size of a comparable resolution Landsat image and take just 80 seconds to collect, rather than the weeks demanded by the Landsat orbit cycle. The pan-sharpened multispectral data available from the second-generation DMC satellites are arguably the best quality (4 m resolution) per dollar (a total mission cost of less than $20 million) of any satellite ever launched.

The next generation of small surveillance satellites will offer even more interesting tradeoffs between resolution and area coverage by exploiting the agility of small satellite platforms. Because large satellites frequently have deployed appendages, such as solar

arrays and antennas, settling time is required following maneuvers to allow the highest resolution imagery to be collected. By contrast, small satellites have relatively few dynamic modes and hence can be pitched and rolled to collect multiple images of a specific theater in a given pass. In consequence, 2–2.5 m resolution imagery over regions covering 60 km^2 will be available before the end of the decade.

For affordable space systems, the value-for-money metric is also of crucial importance. This metric is typically assessed by comparing the spatial resolution of the imagery provided by the system with the costs incurred in building and launching the satellite. It is also conventional to extend this performance metric to consider the value provided by the system as the total number of images at a given resolution over the satellite lifetime. This is a valid calculation, but it can be seen that attempting to maximize this particular measure of the value can sometimes come into opposition with the need for affordability and responsiveness. The value provided from a satellite in this case clearly increases if the lifetime is extended (since the satellite will have the opportunity to collect more imagery), but the costs associated with extending the satellite's lifetime (higher specification components, additional functional redundancy of the satellite hardware, far more extensive and time-consuming testing programs) can start to compromise the goal of affordability; that is, the value of the system increases, but the value for money is not necessarily enhanced because the costs also rise. The need for a more sophisticated approach becomes more apparent when the temporal aspects of the problem are considered—a complex satellite with a long design lifetime is a concept that stands in direct contrast to the responsiveness that is increasingly desired. As will be discussed, there are distinct advantages to designing "responsive" satellites with a 5- to 7-year lifetime.

The need for greater accuracy to support precision-guided long-range weapons systems means that future responsive satellite systems also need to emphasize geolocation accuracy among their design criteria. In part, this can be achieved by improved orbit knowledge (on-board GPS receivers already deliver better orbit determinations than ground-based radars). In addition, the use of enhanced star cameras will permit attitude determinations to very high precision on the next generation of small satellites. These missions should thus be capable of providing geolocation values of better than 50 m without the need for ground control points. The agility of this generation of small satellites will also permit the collection of in-pass stereo data to further improve the quality of the geospatial information available from the system. A direct comparison with large satellite design helps to emphasize this point. Most large satellites cannot collect in-pass stereo because they have large deployed antennas and solar panels, which are excited into dynamic modes by any maneuvering of the satellite. Hence, pitching a large satellite at the angular rates necessary to achieve a suitable stereo pair would lead to unacceptable perturbations of the sensor and seriously degraded image quality. One solution to this problem has been implemented on Spot 5, where the satellite carries two cameras, one pointed forward and one pointed aft, so that the satellite can collect two images without changing its attitude. Clearly, though, a small, agile satellite that can capture two images using a single camera makes a significant saving relative to this approach.

Improving Future System Responsiveness

The responsiveness of future systems can be improved in a number of ways, some of which are enumerated below.

Orbital heights and inclinations. The satellite system can be designed to operate at a greater variety of orbital heights and inclinations. This has the advantage that, upon launch, an orbit can be chosen that maximizes the coverage of a particular theater of interest, wherever it is located on the globe. The increase in the number of passes per day potentially compensates for the reduction in the satellite's duty cycle that may result from having less than optimal power generation conditions. (However, note that an operational duty cycle as low as 2 percent per orbit will still be sufficient to provide coverage of most theaters of interest.) As the sizes of militarily relevant satellites reduce, it becomes increasingly feasible to envisage a flexible concept of operations in which the satellite is able to perform on-orbit maneuvers to establish a repeating ground trace. The advantage of such an orbital maneuver for a surveillance satellite is that the imaging geometry generally can be duplicated on successive days, with the result that relatively straightforward (and hence timely) change-detection algorithms can be applied to extract the relevant military information from the raw data.

It is also interesting to consider the extent to which lower orbits (traditionally avoided by long-lived satellites since the propellant loads become prohibitive) can be exploited by satellite systems that have shorter design lives. This potential extension into the near space domain can offer higher resolutions (the sensor is closer to a target at nadir); improved sensitivity/signal to noise ratios (for the same reason); and, surprisingly, greater area coverage rates (for a sensor with a maximum slant range of operation, the instantaneously accessible region on the surface of the Earth actually increases if the satellite flies at a lower altitude).

Time of operation. The system can be designed to operate at different local times of day. Many surveillance systems are constrained by lighting or power considerations to operate in specific orbits, from which they provide coverage at particular times of day. This not only limits the operational flexibility of allied commanders, but also introduces a degree of predictability that an opponent can exploit to avoid being detected. The agility of small optical surveillance satellites can be exploited in the form of a pitching motion that reduces the effective ground speed of the satellite's sensor, as demonstrated by the current TopSat mission. The effect of this pitching motion is that more light enters the camera, producing a better quality image. It follows, therefore, that by increasing the pitching rate, more ground-motion compensation is possible. Enough light can then be collected to generate usable imagery even when the satellite is comparatively close to the terminator. Optical surveillance is thus freed from its traditional time slots either side of local noon and (with some caveats) is also freed from its traditional dependence (in the West at least) on Sun-synchronous orbits. Orbits that are not Sun-synchronous will pass over specific locations on the ground at different times of day. This lack of predictability in terms of orbital pass times will make it more difficult for an opponent to implement concealment measures, a difficulty that will be compounded as satellites become smaller

and thus more difficult to track. Again, the agility of small satellites can be seen to be delivering capabilities that large satellites would find it extremely difficult to match.

Adding intersatellite links. Current LEO communications systems include Iridium, which is equipped with intersatellite links (ISLs) to expedite the delivery of messages within the system. Iridium allows communications with much smaller mobile terminals on the ground, but it is also possible to envisage using systems of this sort to communicate with other satellites in LEO. In the near future, satellites equipped with ISLs are anticipated to be permanently in contact with their control stations for the purposes of receiving thin-route command data. Some existing LEO surveillance assets are equipped with complex low Earth/geosynchronous orbit links via broadband data relay satellites to allow them to return their data in near real time. At present, the data volumes that can be supported by the LEO communications networks are insufficient to allow imagery data to be passed in a responsive timeframe, but future data delivery concepts, such as the Cascade satellite program, may allow this.

Onboard processing. Exploiting the rapid development of miniaturized, high-capacity terrestrial processors, small satellites are increasingly able to outperform their much larger cousins in terms of onboard processing. As an example, the 6.5-kilogram Snap-1 nanosatellite launched in 2000 had twice the processing capability of the entire 8-ton Envisat platform that was launched in 2003. This ability to exploit novel technologies means that small satellites will increasingly be able to preprocess their data and return their information at a much reduced data rate, either via the LEO communications networks or to transportable, in-theater command and data reception terminals.

In-theater control. Placing the command authority in the theater of operations will significantly improve the responsiveness of the system to the commander's needs. Networking such capabilities through a network-centric architecture has already been demonstrated by the Virtual Mission Operations Centre experiment, in which a router carried by the United Kingdom's DMC satellite was used to create an in-orbit point of presence on the Internet that is able to respond to requests for imagery data from the satellite's memory. At present, the logistical impact of in-theater payload control and data reception is that a 2.5-meter-diameter tracking dish needs to be fielded, alongside a vehicle equipped with the processing capabilities to turn the raw data into exploitable imagery. The United Kingdom's TopSat mission has already demonstrated the feasibility of in-theater data reception direct from the satellite on the same pass that the imagery was collected. Future experiments are planned with TopSat that will additionally demonstrate the ability to command the satellite on the same pass as the planned imagery collection, with the result that the tasking, collection, and processing elements of the imagery intelligence process can be completed in less than 15 minutes.

In the future, technological developments—including greater satellite power generation capacities achieved through improved solar cell design, better use of satellite power resources through the employment of intelligent, steerable antennas, improved on-board processing, enhanced coding schemes, and improved ground terminal designs derived from mobile phone technologies—will significantly reduce the logistical impact on the

ground stations, to the extent that a relatively noncooperative handset, potentially comparable to an Iridium mobile phone, will be all that is required to interact effectively with the space segment. These technical improvements should also help to address one of the other military drivers discussed earlier: the need for more effective IFF capabilities to protect troops at all levels of command, some of which would otherwise find it difficult to carry terminals with adequate performance to interact reliably with a satellite.

Sensor diversification . The speed with which a target of interest will be detected and discriminated from friendly forces will depend on the range of sensors that can be brought to bear on the task. In the past, the lack of coordination between different sensor systems (imagery and signals intelligence, for example) has made the fusion of their data difficult, if not impossible. In the future, responsive constellations of multiple satellites will greatly enhance the number of opportunities to collect collocated, contemporaneous surveillance data, and so address the problems posed by camouflage, concealment, and deception, and IFF. This may be implemented on multicapability missions (such as TACSAT–2) or on cooperative constellations of satellites with single sensing systems. The range of fusion techniques that can be applied will be further enhanced by the variety of surveillance modes on offer from future sensors. Hyperspectral imagers and synthetic aperture radar (SAR) instruments are responsive in the sense that they can vary their number of sensing bands, spatial resolutions, and surveillance footprints in order to tailor their collection to the intelligence task at hand. The compact hyperspectral imaging spectrometer instrument carried by the Proba satellite has already demonstrated some of this flexibility in the hyperspectral arena, and multimode, multi-polarimetric SAR collection is the objective of the United Kingdom's proposed AstroSAR satellite.

Clearly, this move toward active sensing using small satellite radars will progressively escape the constraints of lighting conditions and cloud cover, which will forever limit the responsiveness of optical surveillance assets. However, the performance of an optical sensing system depends in no small part on the extent to which it can be provided with cueing information about cloud cover. In a sparse network consisting of just a few surveillance assets, only limited near-real-time information is available to target the collection through the gaps in the cloud cover. A more densely populated constellation of satellites potentially can be used much more efficiently if the data from one satellite can be exploited in a timely fashion to update the commanding for the next asset that will make a pass over the theater of interest.

A further advantage of having multiple sensors that are capable of viewing a region simultaneously is the increased possibility of novel sensing techniques. In the hyperspectral domain, for example, the power of such sensors to discriminate different materials on the ground depends in part on the ability to measure the bidirectional reflectance distribution function (BRDF), which is essentially the extent to which the color of a surface changes depending on the angle between the direction of illumination and the direction of the sensor. A small, agile satellite can potentially make a number of samples of the BRDF as it passes over a target, but these are necessarily separated somewhat in time. An even more attractive and responsive possibility is that a number of satellites with similar sensors could be trained on a given target at the same time to get an

immediate readout of its BRDF, since this would allow instantaneous measurements of the signatures of moving targets as well as static ones. It is hard to imagine large satellites that are either agile enough or cheap enough to be proliferated sufficiently to match these capabilities.

Radar satellites also offer a greater range of sensing mechanisms when used collaboratively. Traditional monostatic imagery collection can be enhanced by bistatic collection modes, and the simultaneous collection of multipolar imagery can further enhance the discrimination capabilities of the system if required. The range of different illumination angles available from a constellation reduces the impact of "radar shadows" that would otherwise affect the responsiveness of the system (since, to be useful, the imagery products need to include data on a significant percentage of the terrain below). As an example, terrain information can be generated by two radar satellites working in tandem using inverse synthetic aperture processing techniques. The digital terrain elevation data products resulting from this process must include a high percentage of the terrain in order to meet the established criteria for such products. Terrain shadowing often prohibits this level of coverage from a single imaging pass, resulting in the need for several orbital passes at different geometries in order to build up a suitable mosaic. The problem of terrain shadowing becomes even more acute in the case of moving target information (MTI) systems. In hilly terrain, the areas most likely to be shadowed are those at the bottoms of valleys. For practical reasons, most of the lines of communication (roads, railways, and rivers), and hence most of the moving targets of interest, are also at the bottoms of valleys. This statistical bias is likely to make MTI ineffective unless a constellation of assets providing a range of surveillance geometries is available.

Some of the examples discussed above assume the use of small satellites operating in widely separated constellations, where the timeliness and responsiveness of the system on a global basis will be maximized by distributing the passes of the satellites in time. Some of the later examples of simultaneous multiple-satellite coverage assume the use of formation-flying techniques, where the assets are operated in a cluster, providing contemporaneous coverage of a specific region of interest. Assuming that at least some of the satellites in a constellation operate in common orbital planes, it is possible to envisage a situation in which relatively small propulsive maneuvers could reconfigure a "constellation" into a formation-flying "cluster" over a period of time via in-plane velocity changes. This is a higher, system-level aspect of responsiveness that will allow space systems to be configured most appropriately for the military tasks at hand.

When configured as a cluster, the elements of a satellite system can operate in a comparatively independent fashion to generate data sets that can later be combined. It is, however, also possible to envisage clusters of satellites with the ability to combine their data interferometrically, and thus create a sparse aperture that could synthesize the capabilities of much larger satellites. In order to preserve the signal phase information required to achieve this, the intersatellite links would need to provide not only the relatively coarse positional information required to maintain acceptable baselines between the satellites, but also the much finer metrology necessary to measure the intersatellite separations to small fractions (perhaps 10 percent) of the operational

wavelength of the system. In the near term, this implies that such systems will be constrained to operate at radio and microwave frequencies, but the long-term ambition would be to create clusters of satellites that could avoid the expense of having to launch a satellite with a massive, deployable instrument.

In response to a future conflict scenario, the operation of a cluster of orbiting assets could be varied progressively depending on the user need. A cluster of assets operating as an interferometer over comparatively small regions on the ground (to generate high-resolution imagery, for instance) could be switched almost immediately to more independent modes covering somewhat larger regions within the same theater (for example, using the separate apertures within a cluster to collect data on a given region sequentially, rather than simultaneously, for change detection purposes), and could then be maneuvered physically around their orbit plane to change the pattern of passes over the theater to maximize the area coverage rate and timeliness of revisit. Physical reconfigurations offer the additional advantage that an opponent will find it harder to predict surveillance overflights and hence will have more difficulty implementing countersurveillance operations.

Achieving Responsive and Affordable Capabilities

To provide the most cost-effective, responsive space capabilities, there is a need to change procurement strategies to exploit terrestrial technologies, which now often exceed military capabilities. Following World War II, the Western militaries had access to the highest technology levels across a wide range of disciplines. The huge sums of research money now being invested by commercial industry in areas such as telecommunications, computing, cameras, and so forth mean that, in these areas especially, the former military supremacy is no longer the case.

Experience with small satellites suggests that some very specific techniques can be implemented to exploit novel technologies and thus increase both affordability and responsiveness.

Modular design. A standardized approach to the design of core satellite elements such as electronics trays allows specific elements to be incorporated in the design with a minimum of overhead.

Maximize use of heritage hardware. In small satellite design, in order to keep costs down, it is generally considered good practice to ignore blank sheets of paper. It is also inadvisable to use lists of components that have been designed before. The approved approach is to use a change management process to adapt an existing design for a new mission. This approach can also be used for software to keep the launch and early orbit phase shorter.

Evolve capability using experiments. An approach that has been successfully employed over a series of satellite missions is to fly experiments in orbit to prove their viability before baselining them for operational missions. A current example is the GPS

reflectometry experiment flying on the DMC satellite, where GPS satellite signals that have been reflected into space by the ocean surface are collected by an orbiting receiver. In the process of reflection, the GPS signals are modulated by the waves. By comparing the reflected signal with the direct-path original, it is possible to derive information on the prevailing sea state.

Design for launch on any vehicle. Having a satellite design that will withstand the loads imposed by any launch vehicle avoids potential delays due to launch vehicle failures (potentially imposing a program hiatus while the problem is resolved or while the satellite is redesigned for an alternative launch platform). This approach allows design effort to be concentrated on elements of mission that are unique. Satellites will thus not be mass-optimized, but rather time- and cost-optimized.

Selecting appropriate technologies . Some terrestrial technologies are more suitable than others for exploitation in space. For example, the use of a controller area network to link the various components of a satellite can be seen as an appropriate choice when it is recalled that this technology was developed for use in the automobile industry, where the temperature and vibration environment is extreme. When considering placing a technology on a rocket and launching it into a vacuum, it is clearly desirable if it comes "pre-ruggedized."

Avoid requirements creep . The most responsive approach normally is to work with a customer in advance to agree on satellite design specifications (sometimes accepting slightly lower performance for a major discount on cost), and then sign a fixed-price contract—a major disincentive to requirements creep and contract change notices. Satellite builders have to learn to "just say no" when design modifications are mooted.

Mass produce . As in any other branch of manufacturing, there are significant cost savings to be made through mass production. In the case of the automobile industry, more than 99 percent of the prototype costs can be saved via the implementation of a mass production process. It is unrealistic to assume that figures as optimistic as this would be possible for space in the short term, but the successes of the Russian space program over an extended period would appear to be largely based on long production runs of essentially identical satellites, which kept the costs to an affordable level.

Automate. A significant component of any mission's costs is operations. This is an area where responsiveness and affordability can be competing drivers, but it remains a major advantage to take the human out of the loop wherever possible. This is only partly because computers are cheaper to employ. They are also able to perform calculations faster than human beings and, if programmed correctly, do not make the sort of errors that can add delays and costs to a program.

Conclusion

Small satellite systems now have the ability to provide affordable support in the responsive timescales associated with the operational military domain, with the result that

military planners (especially in the United States) view space as the new military high ground. As small satellites provide this operational support, they will increasingly become targets for hostile enemy action, causing space situation awareness and the control of space to move up the agenda of military priorities. Responsive satellite assets have a role to play in creating the "recognized space picture" that will underpin all military operations in the future.

Improved affordability means that military space capabilities based on small satellite systems will continue to spread to a variety of nations that have not previously had access to such systems. While these systems will not match the performance levels of large satellites in terms of spatial resolution, they will offer a degree of timeliness and responsiveness that will level the playing field to some degree.

It is likely that this expansion of capabilities will extend into the radar remote sensing domain, with the result that the National Reconnaissance Office assertion, "We own the night," will be challenged. Previously, this would have required access to a very capable launch system, as well as significant radar satellite hardware, but the change in scale of the on-orbit hardware will diversify the available launch options, and the use of commercially available terrestrial technologies that can be sourced from anywhere on the globe means that export controls are likely to prove ineffective. It is thus unrealistic to suppose that it will be possible to prevent the deployment of novel in-orbit capabilities.

Increasingly, the opportunities for satellites to collaborate in multinational constellations, such as DMC, will make the ownership of certain capabilities a more complex issue. For example, it is clear who owns each of the individual satellites in the DMC constellation, but the emergent responsiveness of the constellation as a whole is "owned" by a multinational consortium. It is not difficult to imagine circumstances where such multinational arrangements could be compromised by political considerations in the future. Increasingly, though, the advantages of such international constellations will be perceived not only by the satellite owners, but also by the other nations that benefit from their existence. (For example, although not a part of the DMC constellation, the United States was supplied with wide-area disaster relief imagery by Nigeria in the wake of Hurricane Katrina.) In this sense, satellites become a form of public good, and decisions on space control operations will need to be influenced by the potential costs associated with the denial of capability in certain circumstances. The recent proposal for a coalition operationally responsive space capability is thus widely regarded as the sharpest space idea to emerge from the United States this millennium.

The U.S. navigation warfare strategy recognizes a similar issue by mandating that the various public good missions supported by the satellite assets will be unaffected outside the immediate theater of operations. If—as now appears likely following the successful launch of the first low-cost Galileo demonstrator satellite—the European equivalent of the GPS constellation can be implemented affordably, similar navigation warfare issues will arise.

The desire to avoid collateral damage to uninvolved civilians means that, in some senses, the objective of exercising space control will require the ability to control not the whole of space, but specifically the region of space above and adjacent to the theater of operations. Clearly, this has implications for the systems that may be used to conduct surveillance of this localized region and for the ones that may subsequently utilize this localized surveillance information to exercise space control: both are likely to require an in-theater component. If some of the surveillance assets are in-theater, adequate secure communications will be required to convey their data to the locations in home territory from which the launches of any responsive space assets would presumably be coordinated. This would probably be true even if some of the launches themselves occurred from mobile platforms located in places that would either deliver an element of surprise to the enemy or allow easier access to orbits tailored to the particular theater of operations. (In the case of the United States, for example, sea-launch platforms located close to the Equator would allow greater payload masses to be delivered to low inclination orbits than would be possible using similar launch vehicles from fixed sites within the continental United States.)

It should also be borne in mind that the space surveillance task, whether in-theater or not, is likely to become more challenging in the coming years. At present, all operational satellites are large enough to be tracked by the existing radar network, but "cubesats," with dimensions of about 10 centimeters, are already starting to push the limits of detectability. In the future, an increasing proportion of the on-orbit assets will be small responsive systems that present these sorts of problems to the tracking networks. (Incidentally, the risk here is not simply that an enemy might deploy undetectably small platforms, but also that maintaining knowledge of small responsive allied assets will become harder for the traditional sensors.) But it is not just size that is the problem. In the future, the sort of stealth technologies that have been applied to aircraft and other military platforms inevitably will also be applied to satellites, reducing their signatures and making them harder to see. Clearly, though, small, responsive satellites start out with an advantage in the stealth arena in the sense that their signatures are smaller.

The space situation awareness task will be further complicated by the proliferation of assets that are likely to be launched (in part to convey robustness through proliferation). This will be especially true in time of crisis (in a responsive, constellation-dominated future, there will simply be more satellites to detect, characterize, and track). Responsive systems also require a responsive concept of operations, a consequence of which is that satellites are likely to maneuver frequently, either to optimize their number of passes over a theater; to create specific viewing geometries; or to make it harder for enemy forces to target counterspace operations against them. In the last of these instances, it is axiomatic that such maneuvers would take place out of sight of the opposing forces, such that the satellite would make its next transit over the theater on a novel trajectory. This emphasizes the need for robust in-theater tracking capabilities, especially since there is an element of statistical uncertainty in all satellite maneuvers. A satellite's postmaneuver orbit may successfully confuse the opposition, but for its subsequent passes to be used effectively, its new orbit will need to be determined quickly by its owners, as small

timing errors can lead to large miss distances at orbital velocities close to 7.5 kilometers per second.

The opportunity cost associated with having responsive satellites on hand awaiting launch is only viable if costs are very low and launches are frequent. In the small satellite domain particularly, satellite lifetimes are short because of rapid technology evolution. Just as for personal computers, 5 years is the typical "obsolescence timeframe" for a small satellite, since at this point its performance will be superseded by new technologies. It is thus not a viable strategy to use up a significant fraction of this lifetime with the satellite hardware on the ground. A more credible approach would appear to be to design satellites with a flexible concept of operations, allowing the configuration of the constellations and clusters to be modified on-orbit in response to changing situations on the ground.

If small satellites are "the PCs of space," then the interconnection of small satellites using intersatellite links (initially exploiting the existing LEO mobile communications networks) will create a responsive and affordable "space Internet" offering a wide range of exciting possibilities and emergent capabilities. The protection of this multiply interlinked, international network could become one of the highest priorities for any space control system in the future.

The contributions that various nations make to this international network will be one dimension of the soft power projection that they will be able to exercise in this timeframe. In light of the stated aspirations of China to launch more than 100 small satellites over the next decade or so, producing affordable and responsive space systems may not be something the West chooses to do in order to create an advantage and exert influence in the future, but rather something that it needs to do simply to maintain parity.