# 4.0 Spacecraft Payload Technology

## 4.1 Introduction

The payload mass fraction of a satellite is that portion of the satellite hardware that performs a useful function (in Air Force terms, communications, reconnaissance, surveillance, etc.). The envisioned 21st century space missions of the Air Force will require advances in four broad categories of payload:

- Spaceborne sensors
- Communications
- Onboard processing
- Weapons

This chapter describes the current status, future Air Force capability needs, and anticipated commercial advances in each of these payload areas, and provides recommendations for an Air Force technology investment strategy.

## 4.2 Applications of Spaceborne Sensors

Space, as the ultimate high ground, provides a global vantage point for detecting, characterizing, and monitoring targets at and near ground level as well as in space. However, of the many signal modalities (e.g., acoustic, chemical, etc.) that can provide useful information on targets and hostile activity, only electromagnetic radiation can be detected from space. Thus space-based sensor suites will consist of coherent or incoherent electromagnetic wave detectors and arrays of detectors. Specific applications for ground and atmospheric sensing from space include detection and imaging of military activity and assets (including hidden, camouflaged, or subsurface assets), missile warning, detection of weapons fabrication (including nuclear, chemical, and biological weapons), and battle damage assessment. Atmospheric sensing to detect airborne chemical and biological components and to profile atmospheric phenomena such as wind and clouds are also potentially important functions of space-based assets. Other roles include the detection, reconnaissance, and deterrence of hostile space assets, protection of friendly space assets, and the application of force from space. Weather observation, global weather and associated prediction, and the effect of solar activity on the environment in space and its consequences to space systems will continue to be of great interest to the Air Force.

Each application area drives somewhat different performance parameters. The result is requirements that span the electromagnetic spectrum, and include both active and passive approaches. Sensor technologies vary greatly across the electromagnetic spectrum, which can be divided into:

- Microwave and other radio frequencies (RF)
- Infrared (IR)
- Visible
- Ultraviolet (UV)

Historically, active sensors in the RF regime have been termed radar, while active sensors in the IR, Visible, and UV have been termed lidar or ladar. In principal, there is no difference between the operation of active sensors in any wavelength band. Sensor system performance depends not only on sensors, but also on focal-plane technologies, image processing, cryogenic coolers, and optical systems. Needed technology advances in these areas are also discussed in this section.

Over the past decade, the Ballistic Missile Defense Office (BMDO) has been the primary source of funding for sensor development and has been responsible for many of the advances in the visible, IR, and RF regimes. However, this support has been drastically curtailed in recent years, as BMDO's charter has evolved to focus on ground-based systems. The commercial, scientific, and other defense sectors have relied heavily on this funding source in the past and are now facing the prospect of losing this leverage. While some areas with commercial applications will be picked up by industry, many of the performance drivers for defense applications are more difficult and demanding than those for commercial markets. In addition, market forces do not provide incentives for industry to underwrite long-lead-time, high-risk technology developments that lead to breakthroughs in performance, and the science agencies that co-fund these efforts are also experiencing funding cutbacks. Thus DoD funding will continue be required to support high-risk/high-payoff and military-specific sensor technologies. As the arm of the US military with primary responsibility for space, the Air Force must expect to assume the lead in the support of spaceborne sensor development for military applications as they did before the formation of SDIO (BMDO).

## 4.3 Requirements for Spaceborne Sensors

One of the DoD-unique capabilities is the detection of hostile targets whose position is typically not known in advance, which requires the detection of signatures of small-extent targets within wide fields of view (FOVs). Looking to the future, the ever decreasing size of lethal packages will exacerbate this challenge—significant threats can be brought to bear without massive mobilization of troops or stockpiling of physical assets. The detection of small cross-section targets in a wide FOV is best accomplished with high-efficiency, large-format staring arrays. Scanned systems can cover the same ground area with a smaller array, but only if the detection efficiency is comparably higher, since the dwell time at a given location is shorter. Note that the target can be illuminated by natural sources (e.g., the sun) or by active sources from the satellite (e.g., radar or ladar).

Another challenge for space-based surveillance and reconnaissance is the low contrast presented by many military assets with respect to background, especially when enemy assets are consciously hidden, camouflaged, or placed under foliage or below ground. This drives the DoD to seek more subtle target signatures using an expanded set of measurement parameters, and to fuse information from a variety of different measurement sources (including airborne and in-situ platforms). This translates into a need for detector arrays across wider spectral ranges, and the use of hyperspectral imaging systems (e.g., imaging systems that also provide more than 100 bands of spectral information) operating across this expanded range. For the foreseeable future, Air Force requirements for hyperspectral sensing and data fusion will exceed those in the commercial sector, requiring continued government investment in these areas. Another powerful approach for detecting low-contrast targets is active sensing. Control of the illuminating source properties (wavelength, phase, and modulation or pulse length) provides additional parameter spaces that aid in target discrimination.

The return of information for military applications is typically more time critical than for most commercial uses. On-demand global knowledge can be achieved only through the deployment of multiple, distributed space platforms. Distributed assets also offer inherent advantages for survivability. Providing this capability at an affordable cost will place stringent constraints on the cost of individual sensor platforms, driving towards significant miniaturization of space sensor systems.

Another important application of spaceborne sensors is in the control of space. This includes the detection, reconnaissance, and negation of hostile space assets, including ballistic missiles, and the protection of friendly space assets, including the sensor platform itself. Sensor requirements for the detection of ballistic missiles depend on where in its trajectory a target is to be detected. During boost phase, the hot effluents render missiles detectable in the visible or near-mid IR, and sensor requirements are similar to those for any small object to be spotted in a wide FOV, as discussed above. Once into cruise phase, detection and tracking of the missile become much more challenging. For space objects in the Earth’s shadow, the challenge is to observe a cool or cold object against a dark, cold background, requiring large, sensitive, highly uniform arrays in the long-wavelength IR and beyond operating at very low temperatures. Coast-phase ballistic missiles may also be accompanied by a swarm of decoys, creating additional clutter in the image, and placing even more demanding requirements on sensitivity, uniformity, and sophisticated signal processing.

The application of force from space can take the form of kinetic or beamed weapons. In either case, targets must be identified, weapons aimed or guided, and battle damage assessed. High-precision delivery of kinetic weapons to target will require on-board guidance systems based on either the Global Positioning System (GPS) or optical sensors. Requirements for optical sensor systems are similar to those discussed for ground surveillance and reconnaissance, with the additional need for very rapid response times.

The Sensors Panel has addressed the issue of the global weather observation and the associated sensor development. From a warfighter’s perspective, it is necessary to be able to predict weather patterns in the local area up to two weeks ahead. To be able to do this on a global scale, it is necessary to reduce the current cell sizes and develop modeling and simulation technologies that model and predict the weather. Visible and IR sensors recommended in this section of the report will adequately cover these requirements. It will be necessary to develop light weight passive microwave sounders that extend to beyond 200 gigaHertz (GHz).

Solar activity has the potential for degrading the performance of spacecraft by disrupting communications and by causing upsets in unhardened electronics on a spacecraft. Solar storms can cause communication outages in the high-frequency (HF) through ultra-high-frequency (UHF) bands and can cause disruptions at lower frequencies. As DoD’s reliance on commercial communication increases, characterizing the solar environment and developing the necessary tools to predict the consequences on terrestrial and space communications will continue to be a demanding technology development area.

## 4.4 Visible Sensors

One of the earliest military uses of space technology was conducted with visible sensors. Reconnaissance satellites placed high-resolution cameras in space to take photographs of regions of intelligence interest. Although digital image technology has supplanted sending film back from space, the concept of observations in the visible wavelength bands has essentially remained the same.

### 4.4.1 The State of the Art in Visible Sensors

In the visible range, charge coupled device (CCD) arrays have achieved close to 100% quantum efficiency with excellent readout noise characteristics, in arrays attaining 4k x 4k pixels that can be tiled to create mosaics of even larger effective area. Although this technology currently exists, the entire user community, including DoD and the commercial and scientific sectors, has benefited from extensive DoD investment in this area. With reduced investment from BMDO anticipated in the future, there is considerable concern that the existing infrastructure may erode. Thus continued DoD investment in this area will be required to sustain even the existing capability.

### 4.4.2 Technologies for Evolutionary Change in Visible Sensors

The performance of CCD arrays is continuing to improve, with development efforts focused primarily on the reduction of readout noise at high readout rates for low signal levels. This capability advance is driven primarily by military surveillance needs. Given the relatively high price of CCD technology, there is limited interest from the consumer market. Within the broader sensor community, there is significant motivation to search for less expensive approaches to achieve large-format, high-efficiency arrays. Array technologies such as the active pixel sensor (APS) that can be manufactured on any standard microelectronics fabrication line are thus of interest to the DoD, since they can reduce the cost of future sensor systems. As an inexpensive technology for commercial electronic camera applications, there is significant industry interest in this area, and the Air Force should watch the development of this technology and adapt it to larger array formats as required. Since the APS architecture utilizes part of the device surface for electronic processing, that portion of the focal plane is necessarily dead. To return full quantum efficiency, and reduce signal processing complexities in target location and identification, defense applications may require the implementation of emerging on-chip microlens array technology that can focus the light on the active portion of each pixel.

## 4.5 Infrared Sensors

Infrared sensors offer the possibility of obtaining valuable information about an adversary's assets—a broken-down armored vehicle and an operating one may look very similar in the visible, but they have vastly different IR signatures. It is especially important to have high-efficiency IR sensors to detect low-contrast objects against the cold background of space.

### 4.5.1 The State of the Art in Infrared Sensors

Outside the visible range, commercial interest is less significant, and large sensitive arrays are either very expensive or do not exist at all. In the near-to-mid IR, platinum silicide Schottky arrays have served as the standard for large-format arrays, available as highly uniform pixel arrays in the 1k x 1k range. However, they do not have high quantum efficiency, and recently indium antinimide (InSb) arrays have replaced them in some applications.

In the long-wavelength infrared (LWIR), the DoD has invested heavily over the last decades in mercury cadmium telluride (MCT) arrays, which represent the current state of the art in terms of sensitivity in the 3-12 μm region. However, this is an inherently difficult material system to work in, and current pixel array size is limited to about 640 x 480. The uniformity for these devices also remains relatively poor, especially at the longer wavelengths.

At wavelengths beyond 15 μm, silicon impurity band conduction (IBC) detectors currently offer the best available sensitivity. To date, array formats are limited to 256 x 256. This technology relies on the growth of ultra-pure bulk silicon, and extensions to larger formats may not be possible for the foreseeable future.

### 4.5.2 Technologies for Evolutionary Change in Infrared Sensors

Various approaches are being pursued to improve array size and performance in the near-to-mid IR. Modifications to Schottky devices, including spike doping and the incorporation of other silicides, have been shown to extend the response across the mid-IR range. However, the sensitivity of these devices remains relatively low. Meanwhile advances in InSb and indium gallium arsenide (InGaAs) arrays look promising, and large-format arrays with high sensitivity and good uniformity may be available soon in these materials.

Work is also continuing in MCT, albeit at a somewhat reduced level. Given the very large investment in this system to date that has resulted in superb sensitivity, efforts to solve the uniformity limitations through new materials growth techniques seem well focused. Any new LWIR technology must be compared to anticipated MCT characteristics for a realistic assessment of its potential. One of the most promising new technologies emerging over the next few years is the silicon- and gallium-arsenide-based quantum well infrared photodetector (QWIP) technology. QWIPs offer large-format IR arrays operating out to 15 μm and beyond (i.e., beyond the practicable range of MCT). Array formats as large as 256 x 256 with a spectral peak as long as 15 μm have already been demonstrated, and array sizes exceeding MCT at all wavelengths are expected within a year or two. In comparison to MCT, QWIP technologies also offer superior uniformity and are expected to achieve greater D* values when operated at very low temperatures. They are also much easier to fabricate, which should make them much less expensive. QWIP technology offers another valuable capability—because the spectral response bands can be made fairly narrow, it is possible to achieve simultaneous imaging in multiple spectral bands by stacking multiple layers of stepped spectral response. This effectively provides three-dimensional, hyperspectral data in a staring mode. Since there is limited commercial market for cooled LWIR arrays, and because this is a key capability for future space surveillance needs, the DoD should continue to develop QWIP technology and explore its potential for a broad range of defense applications.

To exploit the full capability of QWIP technology for detecting weak or low-contrast signals, low-temperature readout electronics will also be required. Standard complementary metal oxide semiconductor (CMOS) readout electronics freeze out at temperatures below about 60 K. Thermally isolating the sensors from the electronics is cumbersome at best, and precludes the use of large two-dimensional imaging arrays. Gallium-arsenide and germanium-based electronics are emerging that can meet this need. As there are few, if any, commercial drivers for low-temperature imaging arrays; the DoD will need to support the development of low-temperature focal-plane electronics.

Ultimately, intrinsic detectors offer important advantages for imaging of fast-moving, dim space objects, due to their inherently higher quantum efficiencies. Intrinsic technologies under study to achieve high quantum efficiencies at very long wavelengths include new low-bandgap materials and novel, artificially structured superlattice materials. The former will require significant investment in new optoelectronic materials systems, possibly comparable to the MCT investment. Artificial superlattice structures offer the potential to achieve the desired capabilities in more tractable materials systems, but will require significant development in the control of atomic-scale deposition of strained-layer structures. The maturity of these approaches is still quite low, and with limited commercial drivers, these technologies will require extended support from the DoD community to achieve the desired capabilities.

In general, the detection of weak or low-contrast IR signals beyond a few microns requires active cooling of the detector to reduce the dark current noise below signal levels. To date there has been little commercial incentive for the development of such coolers, and DoD investment will need to be continued. High-resolution imaging also requires very accurate and stable pointing. Mechanical coolers present a particular challenge in this regard, and vibration-free coolers or active vibration suppression technologies remain an exclusive requirement of the government. Candidate vibration-free technologies include sorption refrigerators and high-speed turbo-Brayton systems. Both have demonstrated technical feasibility in the laboratory, but require further engineering development and life testing for flight viability.

## 4.6 Ultraviolet Sensors

An ultraviolet detection capability is valuable for missile warning, especially for high-altitude and through-cloud tracking. UV imaging is also valuable in discriminating the hard body from the plume in boost-phase ballistic missile negation.

### 4.6.1 The State of the Art in Ultraviolet Sensors

Most state-of-the-art detectors for the UV region depend on photoemission from special cathodes such as cesium iodide (CsI) and cesium telluride (CsTe). These are incorporated into photomultipliers used at the input of microchannel plate (MCP) imaging intensifiers at the focal plane, with readout following visible wavelength imaging of the multiplied photoelectrons from the MCP with a conventional visible-light-sensitive CCD. Both one- and two-dimensional arrays are used. The quantum efficiency for the photocathode itself is in the range of 10-20%.

### 4.6.2 Technologies for Evolutionary Change in Ultraviolet Sensors

Current DoD technology investments to achieve the desired large array formats in the UV include the development of wideband sensor materials, innovative design changes in existing large-format visible arrays (such as delta-doped CCDs), and the use of high-work-function photocathodes such as aluminum gallium nitrate (AlGaN). High-work-function photocathodes offer the potential of truly solar-blind detection without additional filters and tailorable sensitivity thresholds across the UV region of the spectrum, as well as being inherently radiation-hard. However, considerable materials development will be required before these technologies reach maturity. For the near term, modifications of existing visible array technologies will need to be implemented. Since there is little commercial push in the UV, DoD investment will need to continue.

## 4.7 Radar

Active sensing can, in principle, be carried out at any wavelength. Rather than simply gathering at wavelengths that an object reflects from the sun or emits due to its temperature, it is possible to illuminate an object with radiation and sense its return signal. The resolution in both space and time that one can achieve is determined by such fundamental parameters as the aperture size of the system and the transmitter power.

### 4.7.1 The State of the Art in Spaceborne Radar

To date, radio, microwave, and IR frequencies have the most value for defense active sensing applications. Space-based radars can be particularly powerful as all-weather, day/night detection, tracking, or imaging systems. Space radars can be implemented either in high-resolution imaging synthetic aperture radar (SAR) or low-resolution moving target indicator (MTI) mode. For SAR, the power required is a function of both the resolution and coverage, and due to on-orbit power limitations, high-resolution SAR has been implemented only in systems with relatively narrow fields of view. Broad-area MTI systems have also not been implemented in the US. Such systems would contribute significantly to the all-weather global awareness missions, but are costly with today’s technology.

### 4.7.2 Technologies for Evolutionary Change in Spaceborne Radar

In addition to on-orbit power, the keys to achieving practicable systems in the future are efficient RF modules, electronically steered phased arrays, and low-mass antenna structures. Both SAR and MTI systems require these advances, but the performance requirements for global-coverage wide-area MTI systems are even more demanding than those for SAR. Current solid-state RF transmitters achieve only about 40-45% efficiency, while a goal of 70-75% is reasonable within 5-10 years. Transmitter power is also limited by the power capability of individual solid-state devices, which can be overcome by moving to phased arrays in which the power load is distributed across the array. Phased-array technology also permits electronic beam scanning. Assuming adequate transmitter power and data handling capabilities, vertical resolution scales with the bandwidth, which can typically be extended to only approximately 10% of the carrier frequency, driving towards higher system frequencies. However, higher frequency signals are also more strongly absorbed by the atmosphere, calling for even higher transmitter powers. The receiver antennas must have large, high-precision surfaces for efficiency and accuracy. Advances in precision deployable structures and other “membrane” approaches offer great reduction in launch mass and dimensions. Since the DoD resolution and coverage requirements are more demanding than those for commercial applications, there is insufficient incentive within the commercial sector to provide the required technology development in these areas.

## 4.8 Lidar (Ladar)

Spaceborne lidars enable additional measurements of the near-ground environment such as the detection of chemical and biochemical signatures associated with weapons fabrication and height profiling of wind speed and direction. Enhanced target information can be obtained through a wider range of source wavelengths and through the analysis of the time response of signals stimulated by pulsed illumination. Short-pulse lidar can provide highly accurate target ranging, which is useful for track generation, and can even generate a range profile of a target, which is useful for target identification. Spaceborne lidars enable additional measurements of the near-ground and atmospheric environment. Using tunable, narrow-band sources, they can detect specific chemical and biochemical signatures associated with weapons manufacturing. They can also provide accurate height profiling of atmospheric parameters such as pressure, temperature, humidity, wind speed and direction, and return profile information on airborne aerosols and clouds. In general, the analysis of spectral and temporal characteristics of the returned signal can provide enhanced information over that obtained passively with solar illumination alone.

### 4.8.1 The State of the Art in Spaceborne Lidar

Airborne lidar systems have been fielded at wavelengths from the near IR (0.8 micron) to the LWIR (10.6 micron), but to date a full-up spaceborne system has not been implemented due to the large size and power requirements of current systems. The challenge for active sensing at any wavelength is the weakness of the returned signal, which must be compensated by high-power sources. Thus efficient, high-power laser sources and sensitive, discriminating detectors and arrays are critical technologies for reducing the system mass. A recent NASA shuttle experiment demonstrated some of the emerging light weighting technologies in a three-frequency, incoherent backscatter lidar measurement of cloud tops.

### 4.8.2 Technologies for Evolutionary Change in Spaceborne Lidar

Laser sources are needed across the visible and IR ranges, and extension into the UV may also be valuable in the future. Visible and near-IR diode lasers with over 80% wall-plug efficiencies have been demonstrated in the laboratory, but have yet to be fully validated in space. The fiber optics market has driven and will continue to provide incentive for the development of moderate-power near-IR diode lasers at specific fiber-optic wavelengths. However, the extension of the commercially developed capabilities to those required for space-based defense applications has been supported primarily by DoD. Defense requirements include higher powers, wider spectral ranges, and tunable, single-frequency operation. This support must be continued, as no commercial drivers are on the horizon. Low-mass optical benches and holographic reconstruction techniques can also lower the system cost by reducing the system mass. Commercial advances in these areas are not likely in the near term, and thus continued DoD investment will be required.

## 4.9 Evolutionary Technologies for Sensor System Miniaturization

Sensors for spacecraft use, whatever their wavelength of operation, become more useful as they are made smaller and lighter. The anticipated paradigm shift to clusters of small satellites to perform military global sensing tasks will provide an unprecedented incentive to miniaturize sensor systems. To date, BMDO sensor development for the Brilliant Eyes system has placed the greatest demands on the size of a space-based imaging system.

An emerging technology of great potential for miniaturizing sensor systems is microelectromechanical systems (MEMS). MEMS is the next step in the microelectronics revolution, in which multiple functions are integrated on-chip. Applications include chip-level transducers, light sources, fixed and adaptive optics, and on-chip integration of these functions with microelectronic control and processing capabilities. Some aspects of MEMS are being addressed by the commercial sector, and rapid advancement is expected. The Air Force should monitor these advances, and adapt as required. One area not as likely to see commercial focus is on-chip optics, which should be supported by the Air Force with space-based sensing and autonomous maneuvers as the requirements drivers.

Technologies that lower the power required for sensor systems can also translate directly into mass (and thus into cost) savings. For example, emerging technologies that combine sensor and processing capability on the focal plane, such as the active pixel sensor, offer orders of magnitude reduction in sensor power, simplified control electronics, and performance advantages such as agile readout capabilities, as well as the reduced cost of large arrays noted earlier. Low-power, next-generation smart sensors should be explored for Air Force benefits, and supported where commercial markets do not provide adequate development incentive. IR array technologies that do not require active cooling, such as bolometers or tunnel sensors, also lower the system power requirements, and will be valuable for long-wavelength IR spaceborne systems that do not require the highest sensitivity, and for extending the detection range across the far IR where quantum detectors do not exist.

Technologies must also be developed to reduce the mass of optics required to achieve high resolution and/or to detect weak signals. High resolution alone does not require large collection areas, and can be achieved with sparse, distributed, or synthetic apertures. In the future, distributed apertures may consist of individual spacecraft forming a coherent, configuration-controlled cluster. Such schemes will require advances in autonomy and inter-spacecraft communications links. The large collection area required for the collection of weak signals can be addressed with "membrane" structures such as deployables or inflatables, which offer large-surface-area reflectors with low mass. However, requirements for surface conformation and precision alignment drive additional technology advances. Adaptive optics can be used to correct for the less-than-perfect optical surface of such structures, and MEMS precision actuators are expected to be fundamental to both conformation and alignment control. Smart focal planes and MEMS-based high-rate adaptive zoom optics also offer important capabilities for agile automatic target recognition (ATR) and tracking. By rapidly reconfiguring the optics and/or active pixels, it will be possible to focus attention on the interesting portion of the image, and monitor it at increased speed.

## 4.10 Revolutionary Technologies for Satellite Clusters

The development of low-cost, single-function satellites offers new horizons for space applications when the satellites operate cooperatively either in clusters (local formations of satellites) or in constellations (satellites distributed both within an orbital plane and over a set of orbital planes). The vision of what can be achieved from space is no longer bound by what an individual satellite can accomplish. Rather, the functionality is spread over a number of cooperating satellites. Further, these distributed systems of satellites allow the possibility of selective upgrading as new capabilities become available in satellite technology.

The analysis in the Space Applications Panel report shows that while distributed systems do not provide a cost effective answer for all applications, there are many applications for which small sensors on many satellites scale very well and give cost-effective solutions. As an example, passive scanning imagers on dedicated satellites or communication constellations scale very well indeed. In addition, distributed systems have distinct advantages in survivability. This results from the distribution of capability over all the components. Individual satellites, once found and tracked, can be easily destroyed from the ground by high energy lasers or by kinetic kill vehicles. Distributed systems will degrade in proportion to the number of satellites lost. The flexible and proper interconnection of the rest will make the overall system intrinsically survivable. Thus the Space Applications Panel report finds that advances in computers, sensors, and materials will permit establishment of large constellations of interlinked satellites, whose integrated output will give global, real-time coverage. Reducing range to target and constellation altitude reduces satellite size and cost of coverage. The advantages of such systems have already been embraced by the commercial space industry. The Space Applications Panel report makes the following recommendations:

- The Air Force should create a road map that recognizes that the twin realities of inexpensive, single-sensor small satellites and distributed processing and communications will enable a significant advance in reconnaissance, surveillance and battle awareness
- The Air Force should begin development of a suite of small satellites to complement the evolving national sensors for timely battle field reconnaissance
- The Air Force should focus, where appropriate, on hybridized, distributed architectures, employing on-board processing, storage, and cross-linking now being incorporated in commercial distributed space system designs

The development of Global Awareness will require an array of collectors with all weather sensing. For example, frequent revisit SAR of mid to low latitudes with one meter resolution could be achieved by a small constellation of low-inclination, low-altitude small satellites. These would provide all-weather, day/night observation capability. In addition, one-meter mid-wavelength infrared, two-meter long-wavelength infrared, and two-meter multispectral data could be provided by a constellation of single-purpose small satellites. The Sensors Panel recommends the possible use of bistatic SAR in which a microwave illuminator is placed in a synchronous orbit with lower orbiting receivers or airborne receivers is an interesting alternative and describes a low-cost space-based surveillance concept involving the use of approximately 10 to 20 low-earth-orbiting satellites for SAR coverage of a theater.

One of the revolutionary effects of the technologies that enable clusters of cooperating satellites will be the ability to flexibly form extremely large (in wavelengths) coherent apertures in space for sensing, communications and weapons. The development path to clusters begins with systems of interconnected, cooperating satellites such as Iridium or Teledesic whose constellations will distribute functions across their orbiting networks to provide global communications. The applications path to coherent clusters of satellites goes through sparse distributed aperture sensing satellites. The mission need driving the technology is the need to continuously sense the target and background environment in an area of interest. To provide continuous viewing opportunity over arbitrary spots on the globe requires constellations on the order of a hundred satellites (depending on the viewing angle constraints) at altitudes on the order of a thousand kilometers. At altitudes on the order of ten thousand kilometers the number of apertures shrinks to the order of ten to twenty. At geostationary altitude the number of apertures reduces to the order of three to ten depending on the need for high latitude coverage. For imaging applications the aperture dimension required to maintain resolution scales directly with the distance to the target. However, the aperture may need to be only sparsely filled where the energy received is not the limit, e.g., with illumination from the sun. At low altitudes a monolithic aperture may be reasonable. At moderate altitudes a sparse, distributed aperture on a deployable structure may provide equivalent performance. At higher altitudes, a cluster of cooperating satellites flying in formation can form the aperture dimensions required without the weight and cost penalty of a satellite subtending the entire aperture. The requirement on the cluster elements is to maintain autonomously relative positioning, attitude, and communication among the elements of sufficient quality to allow the aggregate to maintain phase coherence over the aperture. The distributed system then becomes a constellation of clusters.

The same technologies for clusters of cooperating satellites for passive sensing will enable revolutionary change in active systems for sensing, communications, and weapons. For active apertures for sensors, communications or weapons the aperture may be thinned but not sparse to the degree that the power (and waste heat) radiated per element is too high. Instead of a relatively small number of cooperating elements in a cluster, these applications will drive towards large numbers of identical cooperating (perhaps docked) elements that permit significant economies of scale in manufacturing and flexibility in launch. An example application of this approach is an alternative path to the frugal Global Precision Optical Weapon (GPOW) space-based laser. Rather than large monolithic flexible optics directing the beam from a single large laser powered by 10% efficient solar-to-chemical energy collection/storage and 25% efficient laser conversion, a clustered approach would employ phased diode lasers (like the Fotofighter concept) with 50 to 90% efficient laser conversion and 20% to 30% solar electric energy collection. This approach can also be applied to the generation of very intense RF beams from a set of separate elements on different satellites with the precision station keeping to enable all elements to radiate coherently. Such an intense RF beam could be used to overcome local jamming or to burn out sensitive electronics.

Thus, revolutionary capabilities will be enabled by the use of distributed systems and the Air Force must invest in the technologies for clusters and constellations of cooperating satellites (e.g., high-precision stationkeeping, autonomous satellite operations, very high performance communication links, distributed processing, and signal processing for sparse apertures).

## 4.11 Applications of Spaceborne Communications

Communications are vital to United States defense posture and operations. It is essential to providing the Air Force with an assured, on-demand, real-time virtual global presence and a mechanism for the delivery of Knowledge on Demand. To achieve this affordably, full use must be made of commercial communications assets and technology while at the same time recognizing and investing in those technologies that are necessary to meet DoD-unique needs even in a hostile environment.

The combined DoD and commercial assets must provide world-wide connectivity, allowing instant contact between CONUS and rapidly developing theater operations. Connectivity must be provided for timely high-data-rate information collection, relay, and dissemination to the war fighter at all command levels. Connectivity within the theater between many disparate communications systems must be established to make use of the investment in legacy systems until they are replaced by new communications systems with connectivity built in. There is a paradigm shift occurring in communications from dedicated, circuit-switched connectivity to packetized, access-on-demand connectivity for both voice and data; this is most apparent in the commercial world in the adoption of asynchronous transfer mode (ATM) communications, but it is clear that packetized communication networks should also be used by the military to maximize traffic that can be handled by available transmission circuits of all kinds, satellite and ground-based.

In designing a DoD communications architecture, it is necessary to recognize critical differences between commercial and military needs. Military communications must have the ability to prioritize traffic to provide assured, timely transmission of mission-critical information. This means that some core, protected capacity must be provided that is robust to circuit outages from either technical problems or intentional disruption. Less-critical traffic, which is the bulk of the communications load, can be moved over commercial or commercial-like systems. Military end-users are frequently at mobile sites or where access to fixed communications assets is not available. These users are frequently in-theater, and have the highest demand for time-urgent, mission-critical communications connectivity (but not for capacity) even under direct attack by an enemy. These differences drive the technology needs for military communications systems and therefore the investments that must be made to provide service not available or adaptable from commercial systems.

## 4.12 Requirements for Spaceborne Communications

Satellites are a particularly useful platform for communications payloads. Their primary advantage is connectivity over long ranges (particularly oceans) and to users not connected to other long-haul circuits (e.g., mobile users). Today, the primary use of commercial satellite communications is long-haul point-to-point trunking among large, fixed ground sites. These circuits can be (and are) used (leased) to provide bulk connectivity for the military. This practice should be continued and expanded as much as possible, along with use of other commercial long-haul circuits (e.g., fiber). New commercial satellite services are providing connectivity to end users; examples include Iridium, Direct Broadcast Service (DBS) TV, and INMARSAT. These systems can be used by the military where prudent, but their limitations (in assured availability and robust connectivity) should be recognized. However, the technology that has been developed for these new systems is available for inclusion in DoD-specific satellite communications systems; such systems using available technology could be bought outright by DoD or their use acquired through leasing service on orbit (as has been done with LEASAT). Only when technology that is not in the commercial domain is required is development and procurement of satellite systems by traditional government contract warranted. Satellites that provide the core, protected capacity (such as MILSTAR) are examples; satellites that collect intelligence information and relay it are other examples. The complete architecture for military ground and space communications must include service for both core/protected needs and routine support needs, making use of appropriate types of circuits for each need and allowing traffic to flow among the various circuit providers seamlessly.

In summary, commercial communications (satellite and terrestrial) can provide much of needed military communications for:

- Data, voice, and image transmission among fixed sites in CONUS and world-wide
- Routine traffic among some mobile users (ships, aircraft, vehicles)

However, military-specific communications requirements will need military-specific solutions for:

- Timely relay and dissemination of high-volume intelligence information from sensors to warfighters
- Robustness against interference (jamming) and tampering (information warfare) on critical circuits
- Instant establishment of volume service in remote areas, particularly to forces on the move

## 4.13 Spaceborne Communications Technologies

Historically, communications with satellites have been provided by RF links. There is room for significant improvement in this technology area, although moving into the optical band of the electromagnetic spectrum offers considerable advantages to the military user, especially as requirements for bandwidth increase.

### 4.13.1 The State of the Art in Spaceborne Communications

Today's military satellite communications are provided by three DoD dedicated satellite systems plus much leased commercial point-to-point trunking. These three systems (in increasing robustness of service) are ultra-high-frequency (UHF) service (provided by FLTSAT and leased UHF satellites) for simple, low-rate, low capacity mobile terminals; super-high-frequency (SHF) service (provided by DSCS) for high-volume, long-haul trunking from large, fixed terminals and for modest sized terminals on ships and in ground forces at higher echelons; and extra-high-frequency (EHF) service (provided by MILSTAR and its FLTSAT EHF Package precursors) for low-volume, highly protected service to Single Integrated Operations Plan (SIOP) forces and other highly valued platforms, including mobile users on ships and aircraft.

The UHF system is highly desired by mobile users and is extremely useful, but is grossly oversubscribed in times of stress; it is also very vulnerable to interference from even small sources. This frequency band is very desirable to mobile users because the terminals and (particularly) antennas are small. There has been a large investment in military UHF satellite communications terminals that work at the allocated frequencies within the military UHF band. All Navy ships are so equipped, many Army terminals exist, and most large Air Force planes have UHF satellite communications capability. The technology for UHF transponder satellite service is well known by industry. This class of service is available through leasing of service from industry. A similar class of service will be offered by commercial carriers through low-altitude constellations operating around 1 GHz. The DoD should determine the suitability of these commercial services as an eventual replacement for current UHF military satellite communications systems. Issues to be evaluated include transmission costs, acquisition of new terminals to replace current inventory, and guaranteed world-wide service.

The DSCS system (operating in the allocated military band at 7/8 GHz) is used mainly for trunking of high-volume data between CONUS and overseas sites through large, fixed terminals which have protection against jamming through bandspreading and commanded antenna pattern control (although lower data rates may be necessary under jamming). DSCS is also used to provide communications to Navy ships for $C^3$ and for general traffic; this is the Navy's only current assured satellite communications connectivity. DSCS is also used by the Army through transportable terminals for connectivity at higher echelons between the Army Mobile Subscriber Equipment (MSE) in-theater trunking system and CONUS. A significant investment has been made in SHF terminals by these users. Some more-mobile Army terminals are starting to be employed at lower echelons to maintain connectivity between elements that are not within the line-of-sight required by the MSE equipment, but rapid transport to theater is a problem (inadequate airlift) and ability to keep up with rapidly maneuvering mechanized forces is a serious shortcoming. Future use of the SHF band by the military is appropriate to take advantage of the ground infrastructure investment (terminals) and the frequency allocations owned by the military.

Assured frequency allocation is a major issue in military satellite communications. (It should be noted that the SHF allocation is only 500 megaHertz (MHz) wide and individual transponders on DSCS are narrower than that, limiting the maximum data rate for some users to far less than desired.) Since the only DoD-specific technology on DSCS is secure telemetry, tracking, and control (TT&C) and reconfigurable multi-beam antenna systems, it seems likely that such future services could be provided by spacecraft acquired through commercial-like contracts. Alternatively, service could be provided through commercial satellites operating in the commercial bands of 4/6 GHz and/or 11/13 GHz, although antenna discrimination adjusted in real time to fit a battlefield situation will not likely be available this way. Substantial numbers of new military terminals will have to be procured to operate at these frequencies. The Army is currently developing the STAR-T tri-band terminal for the Ground Mobile Forces that will operate at both commercial bands as well as the military SHF band. Use of commercial satellites for war fighting situations will require transponder assignments by the satellite owners and use approvals of the country involved; this may present some delicate political issues that impact on the military need for assured access to communications.

MILSTAR is just coming online and represents a quantum leap in assured, anti-jam (AJ) service to highly valued platforms. Although initially designed for SIOP forces, it is able to provide any small, mobile EHF (44 GHz uplink, 20 GHz downlink) terminal with very high-quality, extremely AJ service. A current drawback is limited capacity per terminal of 9600 bps. This capacity problem is being addressed in the MILSTAR II spacecraft, which will be launched in the next few years; protected capacity of up to 1.5 Mbps per terminal will be available. The Navy and the Army have made substantial commitments to procurement of MILSTAR terminals; the smaller antennas of the EHF terminals (vs. SHF) are an advantage to both of these user communities from platform installation and mobility considerations and do not require sacrifice of AJ capability. MILSTAR satellite communications technology is uniquely DoD; it includes the most aggressive use of on-board signal processing for AJ and for demand-assigned, circuit-switched routing (but not packet routing). MILSTAR uses on-board processing for jamming protection through frequency-hopping/dehopping and through antenna pattern shaping (but not yet for real-time adaptive jammer nulling). Future acquisition of this class of service should be done through the regular DoD procurement process because of these unique technologies for jamming protection that are not of interest to the commercial world.

In comparing future communications needs with current capabilities, clearly there are service deficiencies:

- The ability to quickly provide very robust (AJ) service to small terminals that can be carried and operated on the move by forces is extremely limited.
- Very high-rate (many gigabits per second or Gbps) relay of intelligence data is not available through any current system, particularly from airborne platforms or sensor spacecraft. There is current interest in the use of commercial DBS technology to provide about 22 megabits per second (Mbps) for relay of intelligence data from a central injection station to tactical users in a theater of operations using low-cost derivatives of the commercial DBS TV terminal. There is an architectural issue in this concept, in that this data could also be relayed through existing military communication satellites and terminals. Also, this DBS capability does not address the needs for very high-rate (many Gbps) intelligence data relay from sensors to analysis sites.

To solve these DoD-specific problems and to provide these services using lower-weight and lower-power (and hence lower-cost) satellites will require technology investments by the DoD.

### 4.13.2 Technologies for Evolutionary Change in Spaceborne Communications

The Air Force should invest in those satellite communications technologies unavailable in the commercial sector that are critical for military-specific, core communications services; other technologies and services can be adapted from commercial practice. From the foregoing discussion these critical technologies are:

- Antenna systems that efficiently direct downlink power to users (even at unplanned locations) and reject jamming on the uplinks by use of multi-beam, real-time adaptive antenna patterns
- Very high-rate (many gigabits per second) communications for sensor data relay and dissemination among spacecraft, airplanes, and ground sites; optical communications is the method of choice
- Onboard processing for jamming protection that despreads and demodulates uplink signals and routes them to appropriate downlinks, providing interconnection of disparate users (including packet communications)

The present state of practice for advanced antenna arrays is to use global spot multibeam routing and switching. However, recent advances on antenna arrays have provided limited adaptive beam forming. Based on the present development, a 3 Gbps data throughput rate should be achievable on satellites before the end of the century. It will be necessary to continue shifting the RF communication band to a higher frequency with wider bandwidth to obtain increased data rates. Therefore, it is essential to continue to develop the electronics required to send telemetry at a higher operating frequency.

The use of *real-time adaptive* beam patterns on up-link and down-link on communications satellites has been very limited. Today, commercial satellites have multiple beams, but they are usually fixed in anticipation of a particular orbital location and an intended customer base. For military communications, neither of these is likely since the theater of operations is scenario-dependent. The ability to create multiple narrow-beam downlinks allows the satellite transmitter power to be directed only to the intended users, as well as permitting frequency re-use (important in the crowded spectrum allocations). Both factors result in increased capacity through the satellite. The ability to create multiple narrow-beam uplinks provides high receiving gain that in turn allows either smaller earth terminals to close the link or higher data rates to be transmitted. Substantial reductions in ground terminal costs will result. More importantly, narrow-beam uplinks can be used to reject interfering sources (jammers) out-of-beam, and, through combining of multiple beams, to reject jamming sources *within* a beamwidth. The ability to do such real-time adaptive antenna beam formation to create very deep, narrow nulls anywhere within the field of view of the satellite over the very wide bandwidths necessary for AJ modulation is not something that the commercial sector will develop (commercial users are interested in out-of-beam signal reduction for frequency re-use, a much easier problem); the technology for this military capability must be developed through Air Force investment. This technology is necessary to meet the military requirement for robust, AJ service (particularly for mobile users with modest size terminals) in remote areas with little warning. The beginning of the application of this technology has been seen in MILSTAR, but substantial improvements in performance and in reduction of weight and cost are certain with continued investment. The specific technologies in which the Air Force must invest include:

- Use of optical phase control and combining to maximize nulling depth over bandwidths consistent with AJ spreading (GHz) while minimizing system weight
- Use of optical phase shifting to drive each element in a phased array antenna through a fiber, to avoid heavy ferrite phase shifters, heavy waveguide feeds, and difficult integration problems

For a fixed operating frequency, as both range and desired data rates for communication increase, one is faced with increased transmitter and antenna sizes as well as limits on allocated frequency bands. It is for these reasons that historically satellite communications have pushed to ever higher frequencies, where the same size antenna concentrates the transmitted energy into a narrower beam and where wider frequency allocations are available. Frequencies now in use go as high as 60 GHz, and expansion to the 95 GHz band should be pursued for the future. But even at these millimeter wave frequencies, multi-Gbps data rates require unreasonably large and heavy equipment over geostationary ranges. It is for this reason that optical communications systems have generated so much interest.

Optical frequencies offer the ability to communicate at very high data rates (many Gbps) over long ranges (crosslink at synchronous orbit or from aircraft to synchronous orbit) using small apertures (10 inch telescope) and low laser power (a few watts). Bandwidth for these high data rates is not available easily in conventional RF bands, and RF antennas would be considerably larger than optical telescopes, leading to weight and integration problems on spacecraft and aircraft. The extremely narrow optical beamwidths utilized (a few microradians) require special techniques for acquisition and tracking. These problems have been the primary stumbling block to use of laser communications in the past, along with reliability of the laser sources. However, continued investment by the Air Force will result in the ability to successfully field such systems after the year 2000, when the next generation of military communications satellites must be procured, and will be essential to relay of the volume of sensor traffic that will appear due to global surveillance developments. Optical links will also have application to uplinking data from airborne sensors, in addition to spaceborne sensors, to high-orbit relay spacecraft; the small optical link can be more easily integrated on an aircraft. (For example, the Tier 2+ unmanned air vehicle (UAV) will utilize a four-foot diameter satellite antenna to uplink its SAR and electro-optical (EO) sensor data even at modest data rates; the integration of this antenna had a major impact on airframe design.) The technology for optical links of this nature will not be developed by the commercial sector because the data-rates and required optical beamwidths needed are considerably more difficult to implement than the short-range, modest-rate optical crosslinks that may be used by some of the proposed commercial distributed-satellite offerings; the Air Force must make this technology investment. Specifically, the optical communications technologies in which the Air Force must invest include:

- Long-life, diffraction-limited, multi-watt laser sources
- Efficient multi-Gbps modulation techniques with forward error-correcting codes
- Efficient, near-quantum-limited optical demodulators
- High-bandwidth steering mirrors for acquisition and tracking
- Wavelength-division multiplexing techniques that efficiently combine several-watt laser transmitters operating at different laser wavelengths (as opposed to lossy combiners that suffice for commercial fiber systems)

On-board signal processing is essential to provide full AJ capability when uplink signals are spread over very wide bandwidths, as they are in the MILSTAR system. Once uplink signals are de-spread and channel assignments de-randomized, the ability to demodulate an uplink transmission into digital data and route it to an appropriate downlink will provide efficient utilization of satellite resources (in particular, downlink power) to allow volume service into remote areas for theater operations. Processing will be used again on the downlink to form a time-domain multiplexed (TDM) data stream of all traffic with randomized time slot assignments after which frequency-spreading will be applied; both operations are needed to provide downlink jamming protection. The on-board processing that is necessary to implement AJ is not the same as on-board processing for message routing alone that is being planned by some of the commercial satellite services such as Iridium.

As antenna systems become more capable, the benefits of on-board demodulation/ remodulation will increase. Not only will downlink resources be utilized more efficiently by routing to only the appropriate downlink beam, but the modulation format change possible in the satellite will be able to be used to interconnect disparate ground-based terminals. On-board processing may also be used to establish a packetized data network through the satellite. By reading headers on packets, it will be possible to dynamically switch data to the appropriate downlink beam, the appropriate modulation format, and the appropriate data rate for the intended recipient. This will allow the satellite resources to be allocated on a packet-by-packet basis, rather than, for example, the circuit-switched paradigm used by current-generation MILSTAR, resulting in a greatly increased communications efficiency. This capability will be a necessary part of the current efforts in digitization of the battlefield. Such on-board signal processing will become possible with the increased capability of specialized digital processing chips that will be developed over the next decade by the commercial market. However, Air Force investment to adapt the use of these chips to the satellite communications is required. The Air Force must also take the lead in the adaptation of commercial network and signaling protocols to address the robustness needs of core services while providing transparent flow of data through multiple network nodes, whether they are in space or on the ground.

## 4.14 Applications of Spaceborne Information Processing

Information processing and extraction will be critical functions in the next generation of satellites. In order to make the information gathered by a spaceborne surveillance or reconnaissance system useful to the warfighter, the Air Force needs technologies to perform two related but distinct functions:

- Storing, moving, and analyzing vast amounts of data
- Extracting knowledge from the above data set

## 4.15 Requirements for Spaceborne Information Processing

Current projections of the data being delivered from imaging satellites show that data rates greater than one terabyte per day will soon be required. Such rates will stress communication links and memory, and will be difficult to sustain in a cost-effective, secure manner. Furthermore, the sheer magnitude of the data will inhibit rapid information extraction needed in time of conflict. To be effective, on-board satellite information extraction will be required. Fortunately, a great deal of progress is being made in information processing for communication systems and computer vision by commercial and industrial laboratories at this time. The commercial sector is pioneering certain types of image processing, coding, compression, and very large scale integration (VLSI) architectures for video and telecommunication applications. The Air Force can effectively adapt much of this technology where needed as it develops in the next decade. Air Force investment will, however, be required in the area of sensor fusion as the next generation of satellites develops multidimensional sensing (radar, passive observation, hyperspectral, lidar). Furthermore, DoD should take the lead in developing with commercial industry standards for information retrieval and processing while such techniques are still in a nascent phase.

## 4.16 Spaceborne Information Processing Technologies

Information processing technologies include not only the hardware for storing and processing large amounts of data, but protocols, techniques, and algorithms as well. As the amount of information available increases, such techniques as artificial intelligence and neural networks will play an increasingly important role in fusing data into a complete picture of the battlespace and extracting knowledge from this picture for use by the warfighter.

### 4.16.1 The State of the Art in Spaceborne Information Processing

The Information Age has led to the creation of a major commercial market and research effort in information processing. The major US national labs (e.g., ATT Bell Labs, IBM) are establishing significant research efforts in information processing for data and telecommunication. There are also significant international efforts in this area (primarily in Japan) due to the large market for information transmission. The commercial information industry has pioneered data compression, improved bandwidth utilization, and established communication protocols for connecting different points on a vast network. Image compression algorithms such as JPEG and MPEG allow video data to be transmitted with reduced bandwidth. However, they have been designed to take advantage of frailties of human vision, and are not adequate for the image processing required for military applications such as target recognition. The Air Force and DoD should work with industry to develop standards for high definition image compression and processing formats so that future industry-driven developments will benefit military applications.

Other significant commercial developments include dramatic increases in computing power. Today it is possible to acquire single board processors with 250 megaflop (Mflop) performance. By 2010 it is expected that for approximately the same investment 20 gigaflop (Gflop) performance will be available that will consume approximately the same power as the processors used today. Data storage is increasing rapidly and predictably. Terabyte storage will be available in hard disk and random access memory (RAM) form for these processors. The Air Force should adapt these technologies to suit specific tasks.

### 4.16.2 Technologies for Evolutionary Change in Spaceborne Information Processing

Effective utilization of space will require on-demand knowledge extraction using sensor data in multiple dimensions. Hyperspectral data, in conjunction with SAR or optical images, will be needed, and will require significant data processing, storage, and data basing. Automatic target recognition (ATR) is a unique DoD task. While computation should be done where it makes more sense, processing of data on-board the satellite will be desired for many applications. For example, the parallel nature of optical imagery from a focal plane array can best be processed by a massively parallel processor directly connected to the array. Serializing optical imagery data for transmission to an earth station for processing introduces delays and errors and stresses communication channels. Commercial industry will continue to lead the development of advanced processing technology on the ground. The Air Force must invest in technologies to leverage commercial developments and to adapt these to the unique space environments and to invest in complementary technologies that will greatly enhance the missions of the Air Force. Technologies that are essential are:

- On-focal-plane processing, especially for the hyperspectral sensors that can operate at cryogenic temperatures
- Optical processing for processing optical signals and for processing data by means of optical computing

- Data fusion technologies that take data from multiple phenomenology sensors and fuse the data in near real time
- Neural network and artificial intelligence (AI) technologies that can do automatic pattern recognition and knowledge extraction from fused data
- Advance packaging and electronics technologies for space that can dramatically reduce power consumption, weight, and volume

There are tradeoffs on where the processing, data fusion, and knowledge extraction have to be performed. With the advent of hyperspectral sensors and the growth in active sensors such as space-based radars and synthetic aperture radars (SARs), processing requirements onboard the spacecraft will increase dramatically to more than 10 Gflops per channel of the sensor. DoD investments to leverage commercial technologies and the complementary DoD unique technologies will be essential to keep the US superiority in space assets.

The Air Force must invest in real-time data fusion. (Data fusion is described in great detail in the report of the Sensors Panel.) In terms of payloads, defense satellites are likely to evolve toward clustered sensors, mixing both passive and active observations. Observation satellites will be members of clusters that use multispectral arrays of sensors: radar, lidar, hyperspectral, imaging, and possibly others. The fusion of this data from the satellite cluster will be essential to the efficient and timely operation of information gathering from space. Intelligent analysis of data will allow satellites to focus on interesting areas, and ignore regions of inactivity, in a fashion much like a human being looks at a scene. Advances in software, especially in artificial intelligence and neural networks, will be required for this effort. Preliminary demonstrations at Lincoln Lab have demonstrated automatic target recognition of ships using current neural network technology that is as effective at identifying ships as a human operator. Commercial applications of neural nets are developing, and are likely to increase dramatically in the next 10-20 years. The Air Force should invest to adapt commercial technologies in this field to enable such demanding applications as ATR in the future.

## 4.17 Applications of Spaceborne Weapons

The ability to deploy and use weapons from space is constrained by technology and policy issues. At this time national policy restraints are the most significant barrier to such implementation. It would be imprudent to ignore technological developments that could enable such a capability in the future.

The function of a spaceborne weapon is essentially the same as a weapon on any other platform, to deliver a damaging or lethal amount of energy to a target of the warfighter’s choosing. In future conflicts, the ability to destroy or incapacitate a target in the most timely manner and with the least collateral damage possible will be at a premium. The potential global presence by a space-based system is attractive, but the long stand-off distances involved place significant demands on any weapons systems in space.

Space weapons could be targeted against terrestrial targets (Force Application) or against an opponent’s space assets (Space Control). Destruction of a given target, depending on the situation, may not be desirable. Rather, it may be preferable to temporarily disable an opponent’s capabilities for a specified period of time.

## 4.18 Design Considerations for Spaceborne Weapons

Design considerations for spaceborne weapons are driven by the requirement to place the right amount of energy at the right location to achieve the desired effect. Two technological approaches merit serious consideration for use as spaceborne weapons:

- Directed energy (RF and lasers)
- Kinetic kill

Of the two, directed energy is attractive in that it offers a range of responses. By adjusting the power density on the target, for example, the laser could modulate its impact from simply sending a message to an enemy (e.g., placing a low-power beam on an artillery crew to let them know that they are targeted) to destroying an offensive weapon such as an ICBM during its boost phase. Using directed energy to jam enemy communications or sensing systems constitutes a form of information warfare. (See the report of the Information Applications Panel for further discussions of the information warfare concept.)

### 4.18.1 The State of the Art in Spaceborne Weapons

Most of the technologies for a kinetic kill weapon (either a projectile dropped from orbit to the surface of the earth, or an interceptor targeted against another satellite) are available today; the greatest effort would be in integrating existing technologies into a functional system.

High-energy lasers exist in laboratories and have been successfully flown in military aircraft, but tend to be large. Much work has been devoted to high energy chemical lasers, such as hydrogen fluoride (HF) at 2.9 mm, or oxygen-iodine at 1.3 mm. Chemical lasers provide tremendous energy storage, and are capable of delivering tens to hundreds of megajoules (MJ) of energy per shot. The downside of the chemical laser is that it consumes its fuel, and thus has only a limited number of shots (although projection on the HF laser show that approximately 1600 MJ of stored energy is feasible, allowing hundreds of 10-MJ shots before recharging would be required). A second downside of the chemical laser is that, given the limited choice of viable chemical laser systems, an enemy is likely to know precisely what the wavelength of the laser will be, and would be able to take passive countermeasures to reduce the optical interaction on the target.

### 4.18.2 Technologies for Evolutionary Change in Spaceborne Weapons

Although kinetic kill vehicles are possible with current technologies, capabilities of such weapons would be significantly enhanced by MEMS technologies. The energy density of matter in LEO is on the order of 20 kilojoules per gram (kJ/g), so that a tiny maneuverable vehicle has large destructive potential. Miniaturizing sensors, guidance, and propulsion would enhance the utility of kinetic kill weapons by allowing them to be used with minimal collateral damage. Another set of technologies that would allow for a high degree of autonomy for kinetic-kill vehicles would bring the concept of a smart interceptor closer to reality. Kinetic-kill vehicles could be effective whether directed at ground- or space-based targets.

For directed-energy application, evolutionary advances in electrically-powered solid state lasers (semiconductor diode or optically pumped dielectric schemes) will lead to new wavelengths and power levels. All-solid-state lasers with 10 MJ per shot will be possible in the next decade with volumes of less than 1 $m^3$. The technology for the high power laser, either chemical or solid state, should be available in the next decade. The Air Force should continue research to achieve this level of performance.

Wavefront control and correction of the laser beam are required to deliver focused energy (< 30 cm spot size) on target after propagation through a turbulent atmosphere. This can be achieved today using phase conjugation based on four-wave mixing in nonlinear optical media using the output from a single-mode laser, or by adaptive optics ("rubber mirrors"). In the future it may be possible to create an array of semiconductor lasers that could be phase-controlled for targeting. Research into phase locking of individual diode lasers is an attractive research topic for industry and academia. Further basic research will be required to determine whether phase control of large arrays of individual lasers is feasible.

Large mirror optics with diameters of approximately 20 meters will be needed to focus a laser beam to the desired spot size. This technology must be developed. NASA is working on innovative ideas such as inflatable mirrors for civil space applications. Advances and developments in this area are critical to the space-based laser weapon.

Finally, the laser and mirror must be precisely aligned and pointed for target destruction. To use a desirable f/10 optic, the laser should be approximately 100 meters from the mirror. Either a large space frame will be needed, or precision stationkeeping of the independent laser and mirror will have to be established. Advances in constellation control and precision stationkeeping will be required.

Space control activities in the coming decades will need a spectrum of weapon systems. Microwave weapons have some advantages that the Directed Energy Panel report has covered in much more detail. With commercial space technology proliferating, potential adversaries are likely to have the same space sensing, communications, and navigation capabilities as the US currently has. In this regard, information warfare technologies will be playing a critical role in the next century and microwave weapons including electronic warfare (EW) and high power microwaves can play a key role in this area.

The Air Force should invest in developing space-based information warfare technologies that have the potential for disabling and or permanently damaging the adversary's spacecraft. Some of these technologies include disposal jammers, jamming and high power radiating satellites. Technologies that will make these feasible include high efficiency RF power converters, lightweight antennas, long-life, lightweight batteries and high-efficiency power generation systems. There are a variety of tradeoffs in being able to perform these activities (e.g., space-based versus airborne platforms) and those constraints will dictate the development of these technologies.

### 4.18.3 Technologies for Revolutionary Change in Spaceborne Weapons

The toughest technological challenge for the high-energy space-based laser is power generation and energy storage. Assuming overall 50% electrical energy conversion efficiency, a 10 MJ laser would require 20 MJ of stored energy per shot. One shot of this weapon every 20 seconds would require 1 MW of power. This power could be stored on board in supercapacitors or high-energy-density flywheels. However, replenishment of this power in a timely manner would be enabled by the development of technologies for high power generation in space. As discussed in the spacecraft bus chapter, technologies in which the Air Force must invest include nuclear power, electrodynamic tethers, and laser power beaming.

A companion issue to power generation is thermal management. (Chemical lasers such as the oxygen-iodine laser can directly discharge their reactants and thus have a small effective thermal load, but they also have a limited fuel supply and are extremely expensive per shot.) The 0.5 MW of waste power generated by the operation of this hypothetical laser would need to be radiated away in order for the system to operate. Handling such large heat loadings is beyond the capability of current practice; technologies that would enable thermal management of high-power systems are as critical as power generation in those systems.

## 4.19 Recommendations for Investments in Spacecraft Payload Technologies

The Air Force should follow a carefully targeted plan of investments in spacecraft payload technologies, investing for both revolutionary and evolutionary improvements in spacecraft payload capabilities.

### 4.19.1 Revolutionary Spacecraft Payload Technologies in Which the Air Force Must Invest

Several key spacecraft payload technologies offer the possibility of a substantial increase in the exploitation of space by the Air Force, the potential impact of which is so great that the Air Force must invest now. These technologies are:

- Technologies for high power generation (greater than 100 kiloWatts) such as nuclear, laser power beaming, and electrodynamic tethers
- Technologies for clusters of cooperating satellites (e.g., high-precision stationkeeping, autonomous satellite operations, and signal processing for sparse apertures)

### 4.19.2 Evolutionary Spacecraft Payload Technologies in Which the Air Force Should Invest

The Air Force should invest for evolutionary improvements in performance or reduced life-cycle costs to its systems. The technologies that offer such benefits in the area of spacecraft payloads are:

- Sensor technologies:
  - Large, sensitive focal plane arrays and associated readout and cooler technologies for hyper - and ultraspectral sensing of small low-contrast targets and long wavelength detection against the cold background of space
  - Active sensor technologies (e.g., large lightweight antennas, high-efficiency radio frequency (RF) sources for synthetic aperture radar (SAR) and moving target indicator (MTI) radar, and high-energy lasers for lidar)
  - Microelectromechanical systems (MEMS), including on-chip optics

- Communications technologies
  - Very high rate, long-distance optical communications
  - Multi-beam adaptive nulling antennas for anti-jam communications
- Data fusion technologies, including automatic target recognition
- Space-based weapons technologies
  - Laser weapons technologies (e.g., large lightweight optics)
  - Technologies for smart interceptors (e.g., autonomous guidance, MEMS)
  - RF weapons technologies (e.g., lightweight energy storage) for electromagnetic pulse (EMP) and jamming

### 4.19.3 Commercially Led Spacecraft Payload Technologies

Another set of technologies that will allow for evolutionary change spacecraft payloads will be driven by the commercial sector. These technologies merit minimal investment by the Air Force, yet the Air Force should invest as is necessary to adapt these technologies to its needs. These technologies are:

- High-efficiency energy conversion and storage
- High-data-rate RF communications
- Information storage, retrieval, and processing technologies and protocols
- Image processing, coding, compression, and very large scale integration (VLSI) architectures
- Neural networks and artificial intelligence