6.0 Sensor Technology

6.1 Introduction and Technology Overview

This section reviews the sensor technology areas that we feel will be crucial for the Air Force in the coming decades. We focus on areas where we expect substantial change from current Air Force system practice; areas where we expect evolutionary improvements are discussed more briefly when they are discussed at all. We discuss the current status of the technologies, what developments we can expect from commercial efforts, and what the Air Force should do to assure that its needs will be met.

There are two sources for the technology areas we consider. One is the technology needed for the sensor system concepts presented in Section 5 or mentioned in Section 4. A summary is presented in Table 6-1. There are several themes that emerge from the table. One is the importance of small sensors for a variety of phenomenologies. This is for two reasons: to fit the sensors on UAVs or small (low cost) satellites that can provide continual coverage and to allow sensors that must be close to the regions being investigated to be implanted in a small covert, package. Section 6.2.1 discusses technology for MEMS and Section 6.2.7 discusses miniature sensors for detecting chemical and biological warfare agents. One feature that these sensors have in common is the use of fabrication techniques derived from the microelectronics industry and on chip placement. This offers the likelihood of low cost and the ability to integrate easily into digital signal processing systems. Section 6.2.6 discusses sensor concepts and technology for implanting the sensors and communicating with them in a covert fashion. Section 6.2.10 discusses the related idea of implanting tags, which can be detected remotely to enable the Air Force to track key targets.

There are also needs for improvements in the RF and EO sensors that have traditionally been the core of the Air Forces sensory capability. These components are discussed in Sections 6.2.2 and 6.2.3. Many of the technologies discussed in these sections concern apertures for these sensors. These apertures are frequently expensive and difficult to manufacture; requirements will get stiffer as more functionality must be packed onto smaller platforms and as signature reduction constrains designs. The aperture technologies we discuss are ways to meet these challenges in an affordable way.

The sensors described in these sections discuss the basic sensor technologies. The need for rapidly sorting through the data generated by the sensor to find targets, or at least regions, of interest forms another major theme. This is a key problem today. We already generate more imagery than can be analyzed by human interpreters. The proposals to increase the coverage of sensors will exacerbate this problem. There are two general techniques that can aid the target identification process. One approach utilizes image processing techniques to do the ID; this is discussed in Section 6.2.5 for the particular case of military vehicles including mobile missile launchers. The other approach is to add other dimensions to the data, like multiple spectral bands or vibration. This is discussed in Section 6.2.8. A fundamental shortcoming in this area is the lack of global understanding of the recognition processes. This comes both from the lack of a fundamental theory and from the lack of experience with practical military systems. The Air Force should field systems that are partial solutions to current problems to gain experience in the use of ATR systems, and should pursue a focused research effort to develop the fundamental theory, parallel to detection and estimation theory. This will enable the system designer, for example, to trade among different phenomenologies and resolutions. The provision of historical context also improves our ability to exploit data. The technology for doing this is discussed in the Information Application Panel Volume.

The other source for important technology is related to areas where commercial advances will offer opportunities for the Air Force either to do something that cannot be done now, or to reduce the cost of things that are done now. The principal source of commercial advances is the microelectronics industry. Many of the technology opportunities are the technologies identified in Table 6-1. One important additional area is to exploit the rapid advances in computer speed. This enables one to substitute processing for expensive sensor components. Several examples of this are described in Section 6.2.4. An example of an important future sensor concept that illustrates this opportunity is "relaxed-optical-tolerance imaging." In the next several decades, the Air Force will have an increased need for fine resolution optical imaging of targets and scenes on a global basis. Acquiring such imagery on demand for any place on the globe will be challenging, but essential, given the increasing mobility of enemy threats and terrorists, and the rapid pace with which events can unfold. The need for these capabilities implies the need for a very large number of space-based optical platforms with each having a large aperture to provide fine resolution. Using current technology, a space-based optical system with a large aperture would be very heavy to insure structural integrity and rigidity. It would also be expensive and cumbersome to fabricate and deploy. A solution to the current technology shortfall is to relax optical tolerances (thereby reducing weight) on the primary mirror and recover the loss with post detection processing. For example, the primary collector could be a non-rigid (floppy) monolithic or segmented or sparse device involving a very thin mylar surface stretched over skeleton structure. The large aberrations associated with this system would then be overcome with post-detection processing involving algorithms such as *phase-diverse speckle imaging* or *multiframe blind deconvolution*. These algorithms all involve a large number of computations that require on the order of tera-operations for a single million pixel image. The use of new algorithms and advancements in computer technology will allow the development of more affordable and improved imaging systems such as this.

Another area where commercial technology offers the Air Force significant opportunity for increased affordability is in the area of inertial sensing and geolocation. Micromachined inertial sensors and small GPS receivers offer significant affordability improvements to the Air Force. This is discussed in Section 6.2.9.

In addition to the sensor technologies discussed in Section 6.2, Table 6-1 identifies other technology needed for the sensor concepts we identified. Many of these are addressed by other panels of the *New World Vistas* study.

Table 6-1. Summary of Sensor Systems and Sensor Technology

Sensor System	Sensor Concept	Sensor Technology	Other Technology
Target Reporter UAV	ESM	Rapid data exploitation/ target recognition	Information distribution Long duration platform
	SAR	Lightweight antennas, multifrequency apertures Rapid data exploitation/target recognition	
	MTI	Adaptive high power multichannel arrays Higher resolution receivers SAR based moving target imaging	High performance computer Improved sensor cross-cueing Improved high bandwidth comm
	UGS	Small sensors, covert communications	UGS delivery
Integrated Array of Distributed Microsensors	Numerous sensors	Microsensors Low power covert datalinks	Batteries Information distribution Mobile micromachine platforms
Underground Target Surveillance	Remote spectroscopic sensor (DIAL, Passive)	On chip tunable filter Automated analysis	
	Seismic/RF tomography	Small seismic sensors HF aperture Covert communications Signal processing	Implantation batteries
	SPOT SAR	Rapid data exploitation	Information distribution
	UGS Array	Microsensors: Chem/Bio, ESM, optics, acoustics	Small mobile platforms
	TAGS	Covert communications	Implantation
All condition concealed target	Wide area surveillance	Lightweight RF aperture High bandwidth	Platforms
	CCD Penetrating radar	HF components, aperture, rapid data exploitation	Information distribution
	ESM/SIGINT	RDE/ATR	
	Imaging EO	Rapid data exploitation/ATR Advanced focal planes	
Weather Surveillance	Passive IR	FPAs (Wide band, multispectral)	Meteorology
	Passive microsensor	Wideband (1-200 Ghz) aperture, synthetic aperture radiometry	
	LIDAR	Laser sources/packaging	
	Radar	20-100 GHz apertures	
	Modular integrated multi-EO	Optical phased array wideband fiberoptics IR clutter processor Advanced FPAs	
	Enhanced Active/Passive spectral sensing	Advanced Focal Planes On-chip tunable filters Tunable Lasers	
	Supply chain tagging	Tagging Materials	Implantation
	Multispectral EO/IR for wide area	Very high spectral response Uniformity in FPAs	Tunable lasers Tunable filters
	Low cost 3-D laser radars	APD arrays Modulated corner cube	
	High resolution SAR	A/D, modules, apertures	
Boost Phase Intercept	High power aperture UHF airborne radar	Lightweight aperture TR modules	
	Optical tracker for ABL	Advanced focal planes	
	Continuous surveillance SAR	TR modules	Launch costs, solar panels, information distribution
	Seismic radar	Miniature seismic sensor	
	FOPEN radar	Low frequency aperture TR modules	
	Multispectral imaging	Multispectral arrays (uncooled)	
	Building implantable sensors	Miniature seismic acoustic, RF sensors	Implantation
Self-diagnosing Aircraft	Engine monitors	Small spectroscopes Small acoustic sensors	
	Structural monitors	Acoustic transducers (Eddy current)	Propagation models
	RF/EO analog electronic	Calibration patterns	Machine reasoning
	BIT/FIT		
	Engine boresiting robots	Machine vision Miniature EO comps	Miniature robotic locomotion

6.2 Technology Areas

6.2.1 MEMS and Nanofabrication

Following in the footsteps of the microelectronics revolution, the emerging MEMS technologies offer the next step in on-chip integration. By integrating mechanical, optical, and other functions along with microelectronics, MEMS enables the next phase of system miniaturization in which transducers, actuators, control electronics and signal processing can all reside on a single chip. MEMS are fabricated using similar lithography and etching techniques developed for the micro-electronics industry, modified to create mechanical and optical structures as well as electronic devices. To date, this new technology has been pioneered in silicon, where direction-specific etches are already well known. Eventual development in other materials systems will permit integration of more diverse components and functionality's. The full range of military applications of this emerging technology is hard to predict, but will include such diverse areas as microsensors for in-situ surveillance and reconnaissance, embedded sensors for autonomous vehicle and aircraft systems, microactuators for adaptive and precision alignment of imaging systems, and microjets for turbulence control over airframes.

Micromachined Transducers

Physical sensors are likely to be some of the first applications of emerging MEMS technologies. New transducer technologies, such as those based on electronic tunneling, micromachined balances and capacitive plates, and chemically induced electronic and acoustic property changes, offer significant performance advantages in terms of signal/noise versus sensor size. In many cases, they also offer enhanced dynamic range, and are considerably more robust than their conventional counterparts. Micromechanical-transducer-based sensors also offer the potential of extended ranges of operating conditions, including wide thermal swings, high radiation environments, and high and low pressures. Thus they are appropriate for a wide range of environments. Finally, since MEMS, like micro-electronics, is based on a mass-producible fabrication technology, the price for such systems can ultimately be very low.

Tunnel sensors are based on the quantum mechanical tunneling current that flows between a tip placed within a few Å of a surface so that the electronic wavefunctions overlap significantly. Since the wavefunction tails fall off exponentially over distances on the scale of Å, this current is extremely sensitive to the relative position of the two surfaces—changes on the order of 1/100 Å can be detected. This transducer can be used as a sensor for any phenomenon that can be transformed into a change in relative displacement. To date, accelerometers, hydrophones, magnetometers, non-contact current sensors, and broadband, uncooled infrared detectors have been demonstrated.

Microactuators

Microlithography can be used to fabricate mechanical actuators that will be the basis for miniaturized guidance and control systems for autonomous vehicles and for the precision control of the position, pointing and shape of optical surfaces. For example, gyros with drift below 1°/hr are envisioned that can be used for autonomous satellite navigation. The need to lower the mass of future space systems can be met with deployable optics, but only in combination with microtechnologies able to maintain a precision surface conformation to retain the desired imaging capability.

Micro Optics

As the resolution achievable with nanolithography attains the scale of optical wavelengths, this area is also having a major impact on optics and optical systems. The fabrication of surfaces with submicron feature sizes enables controlled, efficient diffraction of light. Applications include holographic optical elements such as on-chip focusing optics, gratings for diode lasers and wavelength-division multiplexing, and nm-scale Ronchi rulings for high resolution interferometry. On-chip optics is important for emerging smart-focal-plane imagers, in which part of the detector surface is sacrificed for signal processing functions. By focusing the light only on the active portion of the pixels, the sacrificed quantum efficiency can be returned. On-chip optics is also a fundamental element of optical imager processing. Lithography on the nm scale is also required for the fabrication of high-frequency receiver components, phased-array antennas and chip-level photonic devices. For example, single-frequency diode lasers offer new approaches for active spectroscopy valuable in determining the nature of air-carried chemical species, or to profile atmospheric winds.

Microchemical Sensors

Microchemical sensors can be fabricated using a variety of chemically sensitive surface effects, such as changes in SAW frequencies (devices) and changes in the resistivity detected in chemical field effect transistors (chem-FETs). These devices can discriminate between different chemicals, especially when deployed in arrays with a range of device parameters. A variety of fiber-optic approaches are also possible including the sensing of degradation of thin film reflectors at the end of the fibers, and effects on internal reflection from the fiber surface and internal reflecting gratings. By the turn of the century, it may be possible to manufacture an entire mass spectrometer, including sample manipulation, vacuum electronics, electrostatic imaging, and species identification intelligence, on a single chip. A variety of thermodynamic parameters such as pressure, temperature, and vector wind velocity can also be measured with these on-chip technologies.

Applications

These types of miniature sensors enable new scenarios in surveillance and reconnaissance. Producible in very large numbers and requiring very little power, these sensors are ideal for “spraying” or flying in mini UAVs over potentially hostile areas to detect signature chemical species, to return visible (or other wavelength range) images of the area, and to detect activity above ground, underground or underwater. The deployment of many sensors is, in itself, an excellent strategy for survivability. Combining on-chip sensors, controllers, signal processing and transmitters results in a complete system for autonomous detection and warning. Fully autonomous satellite stationkeeping and constellation configuration maintenance are also feasible with on-chip gyros, accelerometers and GPS receivers.

Development Strategy

MEMS is advancing rapidly in the commercial sector, and many of the desired functionalities for military applications may be developed by industry. However, the USAF needs to monitor the development and be prepared to support the adaptation to military-unique applications. In many cases, the need for on-demand global knowledge, and the desire to remove military personnel from harm's way, drives performance specs in sensitivity, resolution and signature discrimination well beyond those being addressed by the commercial market.

6.2.2 EO Components

Introduction

As EO sensors play an ever expanding and increasingly important role in the Air Force's missions, the development of advanced electro-optics components becomes increasingly critical as the key enabler for the systems. Indeed, the development of new sensor capabilities is often paced by the availability of EO components, and, for foreseeable advanced systems, this is even more likely to be the case. The importance is especially apparent when it is realized that the role of EO components has expanded from primarily a sensing/detecting function to include using EO for target designation, communication, control, probing, and potentially signal processing. This section examines the status and future for Focal Plane Arrays, Laser Radars and Filters, Space Fed Optical Phased Array, T/R Module Based Optical Phased Array and On-Chip Tunable Sources.

Advances in focal plane arrays over the last few years have been dramatic. Large format (> 4,000,000 pixels), high density silicon-based visible sensors are readily available. Platinum silicide (PtSi), indium antimonide (InSb), and mercury cadmium telluride (HgCdTe) arrays for the 2 to 5 micron spectral region are becoming available in arrays sized up to 1024 by 1024 pixels. HgCdTe arrays of up to 480 by 640 pixels for 8 to 12 micron spectral region are being demonstrated in laboratories. Uncooled 240 by 320 arrays for 8 to 12 micron sensing are commercially available. Major technical challenges of HgCdTe material uniformity, size (> 24 cm^2) and uniformity have largely been met. Advances in read out integrated circuit (ROIC) technology have increased the frame rate, noise and MTF performance of focal planes. Efforts continue to shrink pixel size, to increase sensitivity of IR arrays at stressing signal levels, and to improve the producibility and reduce costs. In addition 128 by 128 HgCdTe arrays sensitive to two spectral bands simultaneously have been demonstrated in laboratories. These developments are supporting Air Force FLIRs, missile seekers, IRST, Threat Warning and Surveillance requirements.

Future developments in Focal Plane Arrays should focus on large format (> 2,000,000 pixels), high density (< 20 microns square) arrays for enhancing performance in FLIR sensitivity, enabling strap-down seekers, increasing coverage for IRST and Threat Warning and enabling multifunction, common aperture EO systems. Multispectral FPAs which collect simultaneous images from two or more bands will support the trend to better target identification, clutter rejection, or background suppression that is desirable for smart and/or autonomous weapons systems. Monolithic implementations for uncooled sensors with improved sensitivity attained by the use of thin film sensing material and improved thermal isolation with smaller cells can expand the effectiveness for Air Force missions. Quantum well and strained layer superlattice arrays may offer advantages in some niche applications and considerable development is required for these technologies to become competitive with existing technologies. The potential payoff versus current technologies should be seriously assessed. ROIC technology should concentrate on high speed readout rates (> 500 frames per second), increased charge storage density, increased cell density (i.e., tighter design rules), reduced noise and improved linearity. Techniques for uniformity correction of high sensitivity FPAs which will decrease the output data rate (perhaps by fovial processing or windowing), reduce the dynamic range, maintain the signal correctability, and possibly implement on-chip ADC. Combinations of these functions or others which will accommodate improved system effectiveness may lead to “smart FPAs.” The requirement for multimode systems should be assessed and a determination made whether to develop an IR/mmW sensitive array. FPA developments will enable more sophisticated FC, NAV, and weapons systems over the next 10 years.

Laser Radar has applications to multiple Air Force missions. Among these are target recognition, three-dimensional imaging, wind sensing, gas cloud sensing, wire detection, some cloud penetration capability, terrain following/terrain avoidance/obstacle avoidance and FC support. Significant advantages are offered by the capability to control the probing source and by using its interaction with various objects to gain discrimination information. However, increased power lasers are required to approach the capabilities of microwave radar. Wavelength tunable lasers could offer advantages in target recognition.

Future developments should concentrate on low repetition rate laser radars for designators, and target ID wavelength tunability needs to be developed at the proper power levels to enhance performance and target discrimination. The development of full three-dimensional imaging laser radar seekers could improve all-weather precision strike for high performance missiles.

A major breakthrough would be the implementation of the “conformal,” multimission optical system that would perform A/A and A/G target ID and detection, laser communication, missile warning, and IR missile countermeasures. Such a system could be implemented using a space fed optical phased array in each aperture module. Future versions of a multifunction concept could use a T/R module based phased array concept. This project has many very challenging developments because of the requirement to fabricate components and modules which operate at optical wavelength dimensions instead of microwave dimensions. The development of such a system would take many years but could potentially provide revolutionary capabilities in an affordable subsystem. In order to possibly achieve this capability, a number of 6.1 and 6.2 efforts are proposed for the near term.

On-Chip Tunable Sources and Filters are of great importance to multiprocessor interconnect, phased-array radar, multisensor fusion and information distribution applications. Miniaturized high power tunable lasers are currently limited by the availability of intracavity tuning and high power optical pumps. Semiconductor diode lasers can ultimately provide the pump, and several tuning techniques are under investigation but have not reached the maturity level needed. Development of these technologies is key to increase data transfer, provide self-healing control networks, increase computational capability, and code signals for security. This area can leverage heavily off of commercial developments, but the Air Force must invest to meet RF signal generation, high power generation and military temperature requirements.

Wavelength tunable active and passive EO devices are critical to the exploitation of the wavelength “dimension.” Increasing the dimensionality of our sensing space is one of the more promising new sensor concepts, as discussed in Section 6.2.8.

It is recommended that the Air Force structure a program in this area to align requirements with commercial developments and to address requirements peculiar to military applications.

Additional efforts in control system developments for multichannel processors and packaging are proposed. Continued 6.1 efforts to develop new materials for compact lasers must be pursued.

Electro-optics components will continue to be integral to Air Force systems and key developments are needed to advance the capabilities of future systems.

6.2.2.1 Focal Plane Arrays

Summary of Current Focal Plane Array Performance

Current focal plane array technology includes numerous high spatial resolution off-the-shelf devices for the UV through LWIR wavelength range. In general, visible device technology is more mature than that found in the IR. This is related to the fact that near-optimal visible-light and near-IR detectors can be fabricated from silicon, using many of the methods already developed for conventional integrated circuit manufacturing. The optical detector array and readout circuitry are usually fabricated all in one piece, resulting in a “monolithic” image sensor. UV sensitive devices are typically made by coating a visible-light FPA with a fluorescent coating. In the visible, state-of-the-art focal plane arrays will soon be available with as many as 25 million pixels, arranged in 5000 by 5000 format on 12-micron centers; pixel sizes down to 6.8 microns can be obtained in certain other devices.

In the IR, many different detector materials have been developed to serve different wavelength ranges and mission requirements. Each material requires different exotic processing techniques to produce a detector array, and most often these arrays must be attached to separate silicon readout circuits using special assembly techniques that result in a sandwich or “hybrid” image sensor. The need to separately develop these specialized material processing and assembly techniques and the lack of a commercially driven technology base has resulted in slower maturation of IR devices.

In the SWIR and MWIR (1 to 5 microns wavelength), state-of-the-art devices include monolithic arrays of PtSi, and hybrid arrays of InSb and HgCdTe. Platinum silicide arrays are now commercially available with 640 by 480 elements, arranged on 24-micron centers; devices with up to 1040 by 1040 elements on 17-micron centers have also be reported. Indium antimonide arrays with over 1 million elements, in a 1024 by 1024 format on 27-micron centers, and HgCdTe arrays, with 1024 by 1024 pixels, are now undergoing laboratory testing.

In the LWIR (8 to 12 microns) and beyond, detector types include long-wave mercury cadmium telluride and extrinsic silicon. Mercury cadmium telluride devices are available in 256 by 256 format on approximately 40-micron centers, with up to 640 by 480 devices under research. Extrinsic silicon devices that respond in the wavelength range 2 to 28 microns will soon be available in a 320 by 240 format, on 50-micron centers.

Incremental Improvement of Basic FPA Performance

Given the current state of the art in focal plane arrays, let us now consider the directions that new focal plane array developments are taking. One may classify FPA properties and their improvements in many ways. In our approach, we will first discuss FPA properties that directly influence the conversion of light to an electrical signal. Improvements that enhance system operational performance will be addressed in the next section.

The most basic function of a focal plane array is to sample the optical image that is focused on it. To perform ideally, the focal plane array must convert all light put on it into an electrical signal, and it must pass this signal to the outside world with no added noise. This aspect of its operation is broadly referred to as its sensitivity. Additionally, the focal plane array output from each detector must minimize coupling of signals between neighboring pixels. This aspect of performance is usually summarized by the FPA's modulation transfer function (MTF).

The sensitivity of any focal plane array is related to several properties—detector quantum efficiency, including optical transmittances, detector dark current, readout noise, and detector fill factor. In the visible, incremental sensitivity improvements continue to be made through improvements in each of these areas. Special techniques include the use of back-side illumination, special optical coatings, and tin-oxide gate structures to optimize quantum efficiency, MPP operation to lessen dark current, and buried-channel readout amplifiers to lessen readout noise. In the infrared, key detector materials are undergoing constant refinement to improve sensitivity. Quantum efficiency gains have been secured in PtSi through refinement of the wafer preparation and platinum deposition processes, and the addition of Fabry-Perot microstructures to the detectors. Notable advances have been made in other materials to reduce detector 1/f noise and dark currents through improved materials purity and processing techniques. Microscopic lens arrays to increase effective detector fill factor have also been discussed.

Modulation transfer function of a focal plane array is influenced both by the detector array electro-optical properties and the electronic readout circuit. To optimize MTF, each specific FPA design must control the optical crosstalk present at the detector and the electrical crosstalk introduced by the electronic readout structure. Current designs in the visible control MTF by maintaining excellent charge-transfer efficiency and by using tightly-confined collecting wells at the point where the optical-to-electrical conversion process takes place. MTF in hybrid IR FPA designs can be dominated by electrical crosstalk occurring in the CCD readout electronics, but has been overcome by the use of CMOS readouts. In these designs, some additional improvements have occurred through the use of higher-bandwidth readout electronics. Optical crosstalk in current IR FPAs is rather poor—as high as 5 percent between nearest neighbors for backside illuminated hybrids, but improves to ≤1 percent for the frontside illuminated hybrids.

Incremental Improvement of FPA Operational Performance

When one considers the inter-relationship between the FPA and overall system operational performance, it becomes obvious that a number of FPA properties (beyond those that define its sensitivity and MTF) must be taken into account. These properties include the pixel dimensions, spacing, and overall number, readout rate, uniformity and linearity of response, dynamic range, operating temperature and cooling method, price, and defect numbers and type. In this section, we will comment on several examples of the incremental technology gains being made in these aspects of FPA design and performance.

One of the most important themes in this area of focal plane development has had to do with the layout of the FPA itself. The goal has been to produce larger arrays of pixels with smaller interpixel spacing, while maintaining large active areas and low defect rates. The achievement of these goals has been hampered in visible-device production by microlithography line-width limits, silicon wafer size limits, and cleanliness standards. In IR FPA development, similar technological limits exist for the silicon readout circuits. Additional technology limits in the IR have to do with large-scale growth of IR detector materials, and differential thermal expansion limits that apply to the hybrid structures employed here. Incremental improvement in HgCdTe material size (> 24 cm^2), microcircuit fabrication techniques, moving to larger wafer fabrication sizes, and using interconnect (vs. bump bond) and special assembly techniques in the IR devices have largely overcome the limits on total pixel count.

Another area of incremental improvement has been in the area of readout rate. Here, higher overall readout rates are being secured through the use of special device architectures that feature multiple readout lines, each operating near the speed limit that earlier devices have employed on single readout lines. Another strategy in visible-light FPAs involves splitting the image field into two parts and then reading each of these out over multiple output taps. Internal pipelining has been recently employed in IR devices to overcome slow internal settling times, and hence an increase in readout rate has been obtained.

Dynamic range improvements in the MWIR have been secured in recent designs through use of specialized high-voltage VLSI processing, high capacitance density structures, and special integrating circuits for the readout structures, thus permitting very long integration times and large full-well signals.

In addition to the price advantages gained with better microcircuit fabrication yields, there has been significant interest in raising the operating temperature of IR detectors. The costs associated with cooling IR detector arrays are severe, and raising operating temperature would do much to reduce IR detector purchase and operating costs. A notable achievement in this area has been the recent release of a MWIR HgCdTe FPA that will operate with a simple thermoelectric cooler. This makes it a clear choice over LN2-cooled InSb arrays in applications where a shorter cutoff wavelength is acceptable. In addition, advances in linear drive closed cycle cryocoolers have increased reliability and reduced costs.

Finally, there has also been much interest, at least at a concept level, in on-focal-plane processing, sometimes referred to as a “smart pixel approach.” Smart pixel concepts include on-chip ADC, adaptive response NUC, morphological signal processing, thresholding of detector outputs, and logarithmic signal compression. Although these approaches are attractive at the concept level, they will tend to add power dissipation at the FPA, and must be evaluated in the context of an overall cooling budget for the detector assembly. Related to these concepts MEMS that may eventually fuse conventional image-sensing operations with other types of sensing capability.

“Break-through” Focal Plane Array Technology

Certain problems in the fabrication of FPAs have not yielded to incremental engineering solutions. This has prompted new research, aimed at creating entirely new classes of FPA devices. Perhaps the most important problems of this type have been in infrared FPAs and have to do with the unreasonably high costs associated with making defect-free devices and the unreasonably high costs associated with cooling.

In answer to the cooling issue, two new technologies have been created—micro-machined silicon bolometer arrays, and ferroelectric FPAs. Technology demonstration projects have shown that reasonable sensitivity and MTF can be achieved with both technologies in large image formats. These devices operate in the LWIR, with complete camera costs of under $10,000. The

FPA operates near room temperature, in contrast to typical LWIR detectors that operate at liquid nitrogen temperature and below (Figure 6-1). These FPAs appear to have tremendous potential for low-sensitivity, volume production applications. Although available signature strengths are weaker in the MWIR, it seems likely that at least some class of Air Force problems here might benefit from uncooled FPAs, particularly for threatwarning applications. In HgCdTe, array structures that sense MWIR and LWIR images simultaneously in spatially congruent arrays have been demonstrated in laboratories up to 128 by 128 arrays with sensitivity and uniformity approaching single color devices. Advances in linear cryogenics coolers have increased the mean time between failures (MTBF) to > 4000 hours and greatly improved efficiency and size for tactical applications. These techniques could be applied to strategic needs with efforts focused on increasing lifetime.

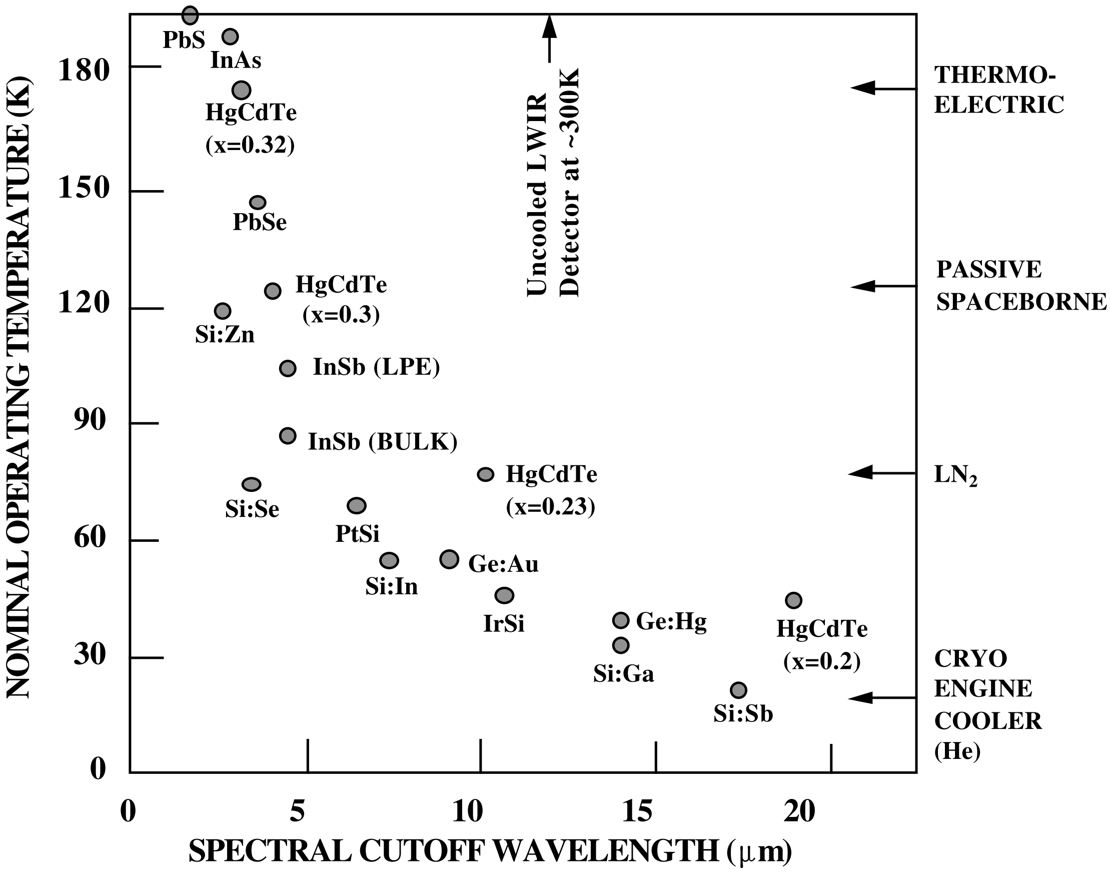


Figure 6-1. Conventional Photodetector Operating Temperature Versus Wavelength

In answer to the producibility problem, another line of research has resulted in a special class of detector that is fabricated with molecular-beam epitaxy (MBE). These detectors operate on quantum-confinement principles, with modest QE in the LWIR. Although cooling requirements are more severe than existing LWIR detectors, this approach is thought to offer very good detector uniformity and yield, even at very large array sizes. This yield enhancement, relative to conventional LWIR materials, may provide substantial affordability gains. This approach also offers the possibility of electronic bandwidth control, where a variable electrical bias will be used to control the center wavelength of the detector's optical response (Figure 6-2). Alternatively, the center wavelength for each pixel may be set individually at the time the device is manufactured. These possibilities suggest that specialized FPAs could be constructed to provide multispectral image output.

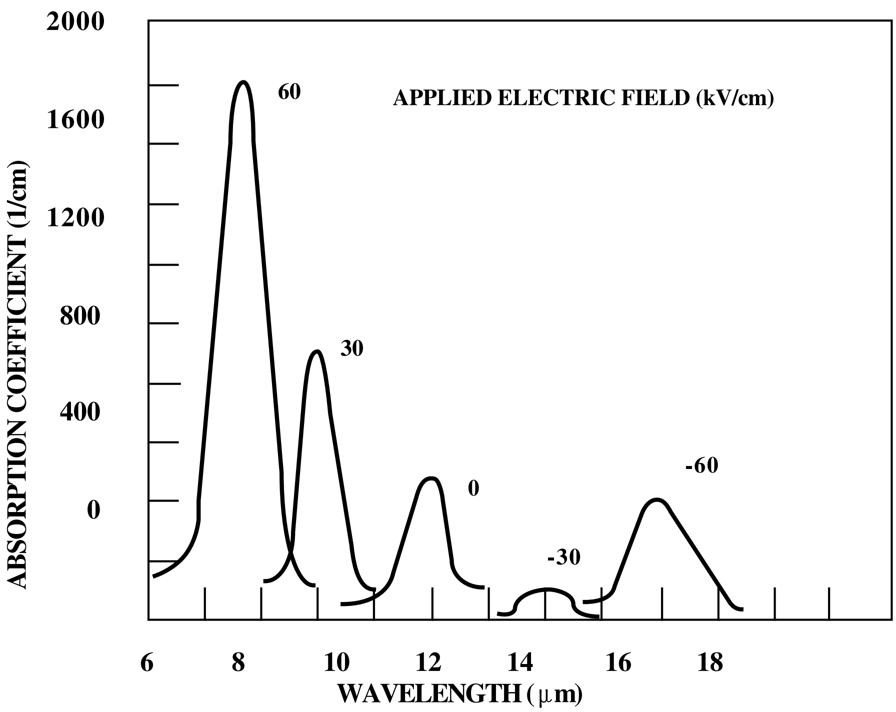


Figure 6-2. Multicolor Quantum Well Infrared Photodetectors. Center wavelength can be set by means of applied electrical bias.

FPA Technology Trends

Perhaps the most frequently used measures of FPA technology growth are the overall device pixel count, and the inter-pixel spacing, or pitch. Secondary trend metrics include readout speed, unit price, and various sensitivity and MTF measures discussed in prior sections.

For example, Figure 6-3 illustrates the growth in overall array size for silicide infrared FPAs. This chart shows that the rate of growth in these arrays is identical to that of dynamic ram memory chips, with a lag time of 5.5 years. Similar growth has been seen for other FPA types. Recently, a 256 Mbit memory chip development project was announced by IBM, Siemens and Toshiba. If this effort is successful during the next several years, it is fair to conclude that the trend in memory growth has not "rolled over" yet, and that further increases in FPA size are possible.

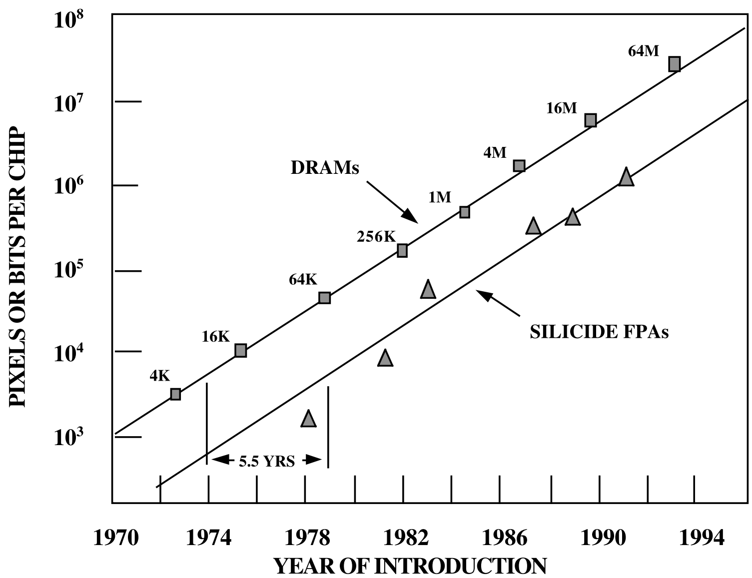


Figure 6-3. Silicide Infrared Arrays—A Comparison With Silicon Dynamic Ram Memory Devices (DRAMS)

In Figure 6-4, the trend in silicide pixel size is shown as a function of time. It is clear that the need to decrease cell size as well as the technology to do so was present up to about 1987, when active area sizes stagnated at around 520 square micrometers. At this time, this active area corresponded to a 26 by 20 micron pixel, in a 512 by 512 MWIR device. Note that the state of the art four years later had only dropped to 290 square micrometers, corresponding to a 17 by 17 micron pixel in a 1040 by 1040 device.

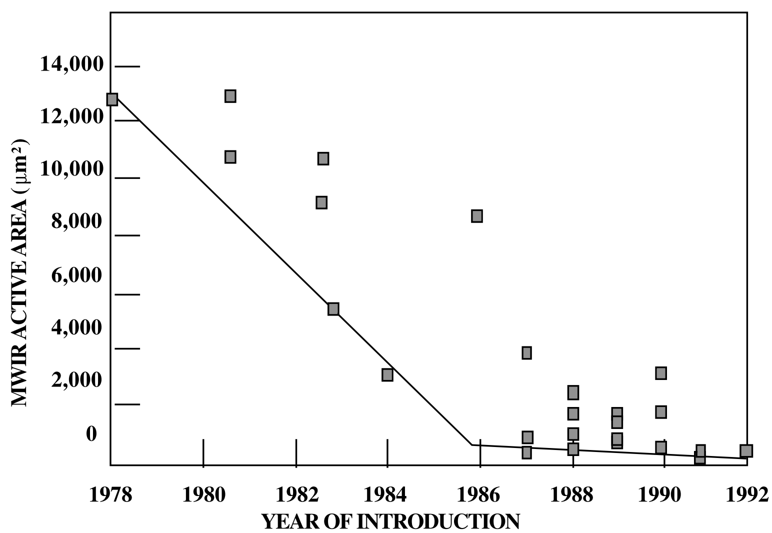


Figure 6-4. Trend in Active Area for Silicide Infrared Pixels

It is thought that this stagnation may be related to the fact that silicide FPAs have reached a size where they can map pixel-for-pixel from the sensor to a typical video monitor. Devices of this size can be fabricated with rather large (and easy to make) pixel dimensions, thus there has not been a compelling reason to reduce pixel size further. In addition, pixel sizes are approaching the diffraction limit for tactical systems.

If one considers other applications, however, it seems fairly obvious that these and other current FPAs are not well matched to the optical systems that feed them. This leaves open the possibility of aliasing, in addition to under-utilization of the spatial frequency content that can be delivered by current optical designs.

Table 6-2 illustrates this concept. For the visible, MWIR, and LWIR bands the table shows representative values for the Nyquist sampling interval demanded by various optical systems. Also shown is the state of the art in FPA pitch. Clearly, current FPA designs have not advanced to the point where they make full use of their input images. This type of FPA development is complicated by other factors besides those having to do with the layout of the device itself—the charge storage capacity for each pixel goes down with the active area, which reduces the dynamic range of the FPA.

Table 6-2. Comparison of Optical Systems and Focal Plane Array Pixel Pitch

Wavelength (microns)	Optical System F/#	Incoherent Cutoff Frequency (cy/mm)	Required Nyquist Sampling Interval (microns)	Current Device Pitch (microns)
Visible 0.5	2 8	1000 250	0.5 2.0	6.8
MWIR 4.0	2 8	125 31	4.0 16.0	17.0
LWIR 10.0	2 8	50 12	10.0 40.0	40.0

Future Air Force systems, such as high resolution reconnaissance sensors, might greatly benefit from reductions in FPA pixel size. Perhaps commercial needs will push FPA development in this direction as well.

Uniformity correction becomes more critical for all FPA approaches as the sensitivity limits are improved. The trend is to develop scene-based algorithms and increase the FPA correctibility. This is a critical effort to realize the full potential of staring arrays.

Application of Focal Plane Arrays to Key Air Force Missions

The following sub-sections summarize a few examples of specific electro-optical sensor functions that are needed to serve various Air Force missions, emphasizing why FPA technology is important and what benefits it produces.

Bomb Damage Assessment

The challenge here is not only one of sensor design but also phenomenology. How do you know when a visually damaged target is no longer able to contribute to the enemy war effort? To date, Air Force efforts involve daytime visible and nighttime imagery of the bombed target from a variety of sensors and airborne platforms. With the advent of visible and infrared focal plane technology, line scanners and cameras were developed with spatial resolution nearly comparable to that obtained with film. Because bomb damage assessment requires detailed imagery of a bombed target, focal plane advances in smaller detectors, longer focal plane arrays, and higher sensitivity through TDI have been needed and have been forthcoming.

Bomb, Missile, and Projectile Guidance

The objective is to accurately put bombs on desired targets and destroy them. The challenge lies in guiding the munition to a target that is difficult to detect in the first place or that is amid civilian structures, whose destruction is politically unacceptable. These weapons use a variety of sensors to seek out targets. There are versions that use visible light television cameras, infrared scanning sensors, laser designators, and radar imagers and more recently staring arrays.

Situational Awareness

An important mission requirement of Air Force pilots is situational awareness—to know the location, type, speed, and intention of every aircraft and missile within fifty miles of their aircraft. To accomplish this goal, historically two types of sensors have been developed—IRST sensors and MWRs. The IRST sensor strives for long-range detection in as large a forward cone, or field of regard, as possible in front of the sensor aircraft. The MWR concentrates on surface-to-air missile launches in the hemisphere below the sensor aircraft and also to some extent aircraft attacking from the rear with A/A missiles. For both sensor types, the challenge is achieving the desired sensitivity and bandwidth from the focal plane arrays and expanding the capabilities to multiple spectral regions to aid in target discrimination.

IRST Sensors

Initial IRST sensors used MWIR InSb focal plane arrays to detect hot engine parts and the hot exhaust plumes extending out behind the target aircraft's engine. Improving HgCdTe focal plane arrays for the LWIR suggested longer detection ranges than were possible in the MWIR, especially when the target aircraft was not flying in afterburner or was approaching nearly directly nose-on so that much of its engine hot parts and plume are obscured. The IRST sensor deployed on the Navy's F-14 uses a linear 256 element HgCdTe array. The IRST sensor planned for the Air Force's F-22 would have used a 480 element long by 4 TDI focal plane array of HgCdTe detectors. The use of TDI provides improved sensitivity and hence increased detection range and/or faster scans of the field of regard and/or larger possible fields of regard. Another focal plane array improvement is the availability of smaller detectors, which can be used to increase target signal-to-noise and to make more efficient signal processing techniques that extract targets from background clutter. Ideally, the target should just fill the instantaneous FOV. Failing that, the instantaneous FOV containing the target should contain as little background as possible.

Missile Warning Receiver (MWR)

MWR sensors use one or more bands in the MWIR to detect the hot exhaust plume during the launch of a surface-to-air missile and to track it during its powered flight. Earlier MWR sensors such as the AN/AAR-44 deployed on special operations C-130 aircraft used linear InSb focal plane arrays to scan the scene. With the development of two-dimensional InSb focal plane arrays in recent years, staring MWR sensors have been designed. The missile launch detection (MLD) system for the F-22 uses 128 by 128 detector arrays in staring mode. Such staring sensors can have much more sensitivity and/or image update times over their scanning counterparts. One problem posed to the staring sensor is how to cover the large field of regard required. The F-22 MLD system solves this problem with several staring sensors, each with its own FOV that is part of the total field of regard. Alternately, a single staring sensor could be scanned.

Identify Friend-or-Foe (IFF)

There have been several incidents of the accidental destruction of friendly forces in recent years. IFF is an important step in target characterization or classification. While much of it has been done between aircraft with coded radio beacons, the Navy F-14 has used a visible television sensor mounted in the F-14 chin pod. This sensor, the television camera set (TCS), has been upgraded to include a silicon 525 by 525 element focal plane array and provides the pilot an image of approaching aircraft from a range far beyond the visual range of the pilot.

Strategic and Theater Missile Defense

The Air Force and the Army have the joint mission of detecting hostile surface-to-surface launches of intercontinental ballistic missiles as well as shorter range missiles and accurately tracking their trajectory and warhead deployment so that the attacked facilities can be warned and the incoming missiles can be possibly successfully intercepted. Missile launches can be detected from space using one or more bands in the MWIR with a linear array of detectors scanned across as large a region of the earth as possible, limited by the altitude of the sensor and the number of elements in the array. Sensor concepts for this challenging mission usually require large staring (e.g,. , 1000 by 1000) LWIR focal plane arrays of HgCdTe or extrinsic silicon (Si) detectors.

Relationship to Commercial Developments and Applications

Many commercial applications require the special properties of focal plane arrays. The next several sections touch briefly on several of the more important examples of commercial FPA use.

Film Replacement Market

Kodak, Fuji, Canon and other manufacturers now produce 35mm cameras that use a visible-light CCD at what was once the film plane. These cameras provide the benefit of instant turn-around on images, digital picture format, and reasonable low-light sensitivity. Image resolution is not equivalent to that of film yet, and purchase prices are high; one would expect that the driving issues here are the need to decrease pixel size, increase pixel number, and to reduce unit prices. It would appear that the commercial push for smaller visible pixels will allow significant leverage for Air Force projects.

Industrial Inspection and Robotics Market

Large-format cameras (large number of pixels) for industrial use are now produced by Photometrics, Ltd., Sony, and others. Key considerations in the design of these cameras are image format, linearity of photoresponse, freedom from optical overload (blooming) problems, low-light-level operation, compatibility with existing computers and factory automation equipment, and reasonable purchase price.

Astronomy and Scientific Research

Astronomy has traditionally driven the development of large visible imagers. Suppliers such as TI, Thompson-CSF, SITE, and Photometrics have served this market well. It is now the case that astronomy needs in the MWIR are also impacting leading-edge FPA development, with the SBRC Aladdin project (1024 by 1024 InSb FPA) and Rockwell 1024 by 1024 SWIR HgCdTe serving as noteworthy examples.

Entertainment Industry

The home video market has been largely responsible for the low costs that now apply to moderate size (both physical dimensions and pixel count) color CCDs. Perhaps the next trend in this area will be the emergence of low-cost HDTV sensors, first to serve the broadcast marketplace, and then high-end robotics and inspection uses. Both Phillips and Kodak now offer color HDTV CCDs in 16 by 9 format, consisting of roughly 2000 by 1000 pixels that can be read out at 30 frames per second. This rapid readout, at high resolution, will doubtless permit the creation of numerous new Air Force systems without further technology investment.

Power Distribution Maintenance, Heating and Ventilating, and Combustion Engineering

One of the first commercial applications for IR FPAs was in the electric power industry, where IR cameras are used to detect "hot joints" in power distribution equipment. Of additional note are applications in heating and ventilating, where homes and commercial buildings are surveyed for areas of excess heat loss, and similar applications in power plant maintenance and combustion engineering.

Civilian Remote Sensing Programs

Numerous programs sponsored by NASA and foreign space agencies have called for specialized devices that feature large image formats, response to unique wavebands, and the ability to withstand large radiation doses. The Air Force benefit here perhaps parallels that offered by the Astronomy and Scientific Research marketplace.

Law Enforcement and Automotive Industry

It is believed that research on automotive applications for night vision has been conducted for at least 10 years. It is clear that low cost and reliable operation, in a reasonable TV-like format, are the primary requirements for the FPAs for these systems. Manufacturability gains in uncooled FPA systems obtained in these projects will directly benefit future Air Force purchase prices. However, for increased sensitivity, additional work is required.

Summary of Commercial Applications

Table 6-3 summarizes the key areas in which commercial activities appear to be influencing the development of FPAs.

Table 6-3. Summary of Commercial Development Activities

	Focal Plane Array Attribute or Metric								
Commercial Application	**Large No. of Pixels**	**Small Pixels**	**Video Readout Rates & Higher**	**Multi-spectral Capability**	**Linearity**	**High Dynamic Range**	**Uniformity**	**Blooming Control**	**Low Cost**
Film Replacement	X	X				X	X	X	X
Industrial Inspection	X				X	X	X	X	
Astronomy	X				X	X	X		
Entertainment	X		X						X
Therography			X						X
Civilian Remote Sensing	X			X	X	X	X	X	
Law Enforce-ment/ Auto.			X						X
Air Force Leverage	X		in visible band		X	X	X	X	in some FPA, such as PtSi & uncooled

Affordability Impact

The development of large, multispectral staring focal plane arrays will have a dramatic impact on weapon systems affordability. By utilizing an integrated multifunction sensor suite (e.g., NAV, F/C, targeting, IRST,...) future aircraft can be developed that are multimission and multirole, providing for significant life cycle cost savings during A/C volume production. In addition, an integrated multifunction sensor suite will significantly reduce the sensor life cycle costs by eliminating the need for multiple, independent sensors. Recent studies under the JAST program have shown that life cycle cost savings on the order of 6x are achievable with this approach.

The use of uncooled sensor technology dramatically reduces the cost of imaging systems through the elimination of costly ternary semiconductor detectors and their ancillary cooling systems. The broad spectral capability of the uncooled detector can also make a significant impact on total systems cost. A single, relatively low-cost detector can be utilized to cover all radiation bands of interest.

Advances in FPA performance will continue to offer efficiency improvements in several applications. One example is digital photography. The widespread use of “film replacement” CCDs in camera systems should offer the Air Force more rapid decision-making capability, lower personnel costs, and savings in material costs, in comparison to current film-based systems.

Other efficiency savings accrue from the inherently digital nature of most FPA-based systems. As conventional photographic systems are replaced by FPAs, the costs associated with operations such as document scanning, transmission, and archiving of negatives will go away entirely. Reproduction of digital images should also offer cost advantages over traditional methods.

Tremendous reliability improvements can be secured through use of FPA-based staring systems, in contrast to earlier-generation scanning imaging systems, owing mainly to their non-mechanical nature. Reliability problems in current FPA technology exist mainly in the LWIR, where it is difficult to establish long-lasting electro-mechanical bonds between detector arrays and their silicon readout structures. Recent results with via-interconnected (vs. bump-bonded) arrays at Texas Instruments (TI) indicate size limits may have been overcome. This may in part be solved through the use of uncooled FPAs in lower-sensitivity applications.

Another reliability issue for MWIR and LWIR systems has to do with the mechanical cryocoolers that are used to stabilize the FPA at its proper operating temperature. This problem may also in part be solved through the use of uncooled FPAs.

Recommended Development Plan

In general, the Air Force development plan for FPAs should be marked by a series of additional studies, accompanied by specific demonstration projects, with enough flexibility built in advance to take advantage of yet unknown FPA technology break-throughs. An overview of the recommended process is:

- Define and prioritize FPA needs, relative to an agreed-upon list of specific AF missions requirements and related, supporting capabilities.
- Analyze these FPA needs and delineate physical versus technological limits.
- Analyze technological hurdles—the steps that are thought to be needed to overcome them, costs, and payoff potential for the commercial sector.
- Establish a series of time-lines and intermediate goals for the solution of these technology problems.
- Identify other government organizations that share similar technology needs and time lines and obtain funding commitments.
- Define and fund demonstration projects (hardware systems and field trials) that will make use of the new FPA capability.

Based on the information presented in prior sections, a number of meaningful and achievable FPA technology goals can be set. Over the next 10 years, our studies suggest that the Air Force should commit to a FPA development program that takes advantage of both technology breakthroughs (uncooled arrays and quantum well devices) and incremental improvement paths. Suggested milestones include the following:

- Demonstrate a 2000 by 2000 MWIR FPA (may be achieved commercially, without AF).
- Demonstrate a 1000 by 1000 LWIR FPA.

- Reduce pixel sizes:
  - Visible: 3.5 micron square (may require entirely new approach beyond CCD technology)
  - MWIR: 10 micron square
  - LWIR: 20 micron square
- Demonstrate 1,000 frames per second in all bands (Visible, MWIR, LWIR) in 640 by 480 format or greater for specific problems that require classification of high-speed targets and signatures (may already be available in visible).
- Demonstrate specialized FPAs for IR multispectral applications. Example approaches include:
  - Multilayer HgCdTe with layers tuned to the specific bands for simultaneous 2 or 3 color band imaging sensing.
  - Fixed-tuned filters on-chip, plus electronic band-selection (a device that can provide ~6 simultaneous exposures in specified bands, from a larger set of 40 to 100 MWIR or LWIR bands, at reasonable spatial resolution).
  - A tunable filter approach (a device that contains a large array of continuously tunable detectors; typically, the device would output, say, 6 user-specified bands over 6 readout cycles, and then repeat the process).
- Demonstrate low cost, lightweight, low volume cryogenic coolers.
- Investigate and develop the use of enhanced sensitivity (i.e., improved thermal isolation and increased thin film thermal sensitivity in monolithic structures) and uncooled technology for cost savings in a specific MWIR application.

6.2.2.2 Laser Radar

Introduction

Laser radar has many important applications such as wind velocity measurements, material identification, target ranging and tracking, terrain following/terrain avoidance, and target detection. Laser radar can also aid in target recognition by:

- High range resolution imaging
- Two-dimensional imaging (angle/angle), where the laser is used as an illuminator for a TV type imager
- Three-dimensional imaging
- Target vibration/motion measurement
- Target reflectivity at various wavelengths
- Target polarization response and target speckle characteristics

In addition, gas cloud, or material identification, can be accomplished by differences in reflectivity or emission as a function of wavelength. DIAL is one technique. Materials can be identified, whether in a gas, liquid or solid form. Shorter wavelength lasers can also cause fluorescence, another material identification possibility. Laser radar can be used to accurately assess aircraft velocity and to look for obstacles. Terrain following (TF), terrain avoidance (TA), and obstacle avoidance (OA) are some of the more interesting laser radar applications for low altitude flight.

Solid state, wavelength tunable lasers are important for all of these applications and will be available in the future (see Directed Energy Panel Volume).

From a safety point of view, it is desirable that we use laser wavelengths beyond 1.4 μm, or below about 0.35 μm. The worst safety hazard from a laser comes from focused light that burns the retina. Above 1.4 μm absorption in the eye becomes significant enough that light does not reach the retina. There is a small UV window below 0.35 μm in which the eye absorbs light, but the light is transmitted through the atmosphere. At long wavelengths, absorption is very rapid and occurs at the surface of the eye.

Description of Applications

Wind sensing by laser radar is useful for many Air Force applications. These include targeting with guns and unguided munitions, as well as dropping munitions. Other applications include safety of flight applications such as detecting microbursts near airports, and detecting vortices from other aircraft. Aircraft velocity can be measured with a very small, very short range laser radar. Upcoming turbulence can be detected and the aircraft can compensate for turbulence before reaching it. This not only creates a smooth ride, but greatly extends the lifetime of the aircraft wings. These are commercial applications, which can create a large enough market to drive down laser radar prices. Vortex detection at an airport means closer spacing is allowed among the aircraft and that can mean large savings in fuel for commercial carriers. For wind sensing, a 2 μm laser radar is a likely candidate. This could consist of Holmium pumped by laser diode. Laser diode systems will become available without the need to pump another solid state material. Coherent systems are needed for most applications, since Doppler velocity is desired.

Another “soft target” for Air Force laser radar is a gas cloud. DIAL can be used to identify materials and can be used in the counter-proliferation thrust. This can also have commercial applications in pollution monitoring. It can also identify poisonous gases or could be used to detect telltale signs of a target. If a diesel generator is near a target, its exhaust might be detected. If certain chemical substances are given off by a target, they could be detected. These gas cloud detection schemes can also be applied to determining the material characteristics of target surfaces. Another benefit of a wavelength tunable laser radar is that certain wavelengths may transmit better through obscurants. For example, 1.5 μm will be greatly attenuated by fog, oil, and smoke, but 3.5 mm laser radar radiation will penetrate it easily.

Surface smoothness of an object can influence the polarization of the returned signal. If radiation is reflected off of a smooth surface, a major difference in the return polarization will result. That is, one polarization will be reflected more than the other component of polarization.

Rough surfaces will tend to have diffuse scattering, and both polarizations will be returned, no matter what illumination is used. Therefore, polarization can be a factor in determining target surface smoothness. Speckle statistics can also be influenced by target surface roughness. This is a complex area meriting further investigation.

For low altitude flight, wires can be a real hazard. Laser radar is an ideal method to detect such wires. Microwave sensors are at a real disadvantage for the same reason that they penetrate weather. The wavelength of the radiation is large compared to one wire dimension, so major scattering often does not occur. FLIRs will see wires under some conditions, but generally only at short range. Control of the illuminator is very helpful for the laser radar. Wires are thin enough that at most ranges the thickness of a wire does fill the detector in angle space. This means a degradation in signal to noise compared to a filled pixel. With control of the laser illumination, sufficient signal to noise can be generated at operational ranges under most weather conditions.

Relationship to Key Air Force Missions

Laser radar can accomplish many critical Air Force functions, as discussed above. These include target recognition, target detection, wind profiling for air drop, safety of flight, and as a FC adjunct sensor, and TF/ TA/ OA. Target recognition can even be accomplished in some cases with partial target obscuration. A wavelength tunable laser radar will have an improved probability of target recognition with obscured targets.

Relationship to Commercial Developments

Laser radar is a likely safety-of-flight sensor for commercial aircraft. It can detect microbursts at a landing and therefore can be a great safely adjunct. It can also detect vortices near an airport. This can allow better spacing of aircraft on landings and take off. Weather prediction can be aided using global laser radar systems, probably on satellites. Laser radars may be used in the future for collision avoidance in automobiles by placing them in the front of cars to detect approaching obstacles. High speed rail advocates have looked at laser radar for obstacle detection. Small obstacles on the track could derail a train. Some of these obstacles are too small to be reliably detected by microwave radar. One concept has the laser light transmitted through fibers placed along the rail lines. This allows bending around corners, and over hills.

Recommended Development Plan

Low rep rate laser radar needs to be developed that can conduct the designator function, as well as identify targets. Then wavelength tuneability needs to be inserted into the system, eventually in both coherent and incoherent laser radar form. Work needs to be done over the next ten years at a rate of about $1.5 M per year. A specific effort is required above the tech base to address target recognition. Another specific effort is required to develop a short range three-dimensional imaging laser radar seeker for all-weather precision strike (in conjunction with a high G missile). Each of these are efforts a few years in duration. The estimates of required funding are $3M per year for the combat ID system and $4M per year for the inexpensive, packaged seeker.

6.2.2.3 Space Fed Optical Phased Array Technology

Description of Technology

Optical sensors currently are burdened with heavy and complex gimbals. Optical phased arrays are an enabling new technology that makes possible simple, affordable, lightweight, optical sensors having very precise stabilization, random-access pointing, programmable multiple simultaneous beams, and dynamic focus/defocus capability. These arrays are space fed. An optical beam is transmitted through the phase shifter array, or is reflected from the array, and a phase profile is imposed on the beam. The optical phase shifters consist of electrically addressable liquid crystal gratings. Low voltage (less than 10 volts) is used to address these phase shifters. Since large-angle phased array beam steering requires phase shifter spacings on the order of a wavelength, addressing issues make one-dimensional arrays much more feasible than two-dimensional arrays. Crossed one-dimensional phased arrays can deflect a beam in both dimensions. Optical phased arrays with apertures on the order of 4 cm by 4 cm have been fabricated for steering green, red, and 1.06 μm radiation. Much larger apertures are feasible. Steering efficiencies of 57 percent at about 4 degrees and 85 percent at about 2 degrees have been achieved with switching times on the order of a few msec. Microsecond agile switching times are feasible. Optical phased arrays using liquid crystal phase shifters are becoming available. Because of the grating nature of the devices, they are ideal for steering monochromatic laser radar beams. These devices will greatly simplify beam stabilization as well as pointing, resulting in a much lower cost for high performance, stabilized optical sensors. Dynamic focus/defocus has also been shown, as well as multiple beam fanouts. Both new capabilities will simplify optical design and allow new sensor concepts to be implemented in a practical manner. Concepts have been developed to apply optical phased array technology to laser radars and to their passive acquisition sensors. A potential near-term application of phased array technology in passive acquisition sensors is microscanning. Large angle scanning of passive acquisition sensors can be accomplished using optical phased arrays if the spectral bandwidth is restricted. If these passive sensors employ high quantum efficiency detectors, then the sensitivity will be similar to state-of-the art scanning sensors. Use of optical phased arrays will enhance the development of active sensors and dramatically reduced their mechanical complexity. Dramatic cost savings for high performance laser radars will occur as optical phased array technology becomes available. Performance increases will be possible through the use of random access pointing anywhere in the FOV, simple fine stabilization, dynamic focus/defocus control, and beam fanout capabilities. Future growth areas include an adaptive optics layer for laser wavefront correction and atmospheric compensation, and for optical pattern recognition enhancement utilizing phase templates on either the transmit and/or the received beam.

Relationship to Key Air Force Missions

Optical phased array technology will have a dramatic impact on Air Force and commercial optical systems of the future. This will be a performance impact and an affordability impact. From a performance point of view, optical phased arrays will allow precise random access pointing of optical systems without undue mechanical complexity. It will be possible to point to about one part in one hundred of a diffraction limited spot size. It also should be possible to use an adaptive optics layer for correction of optical errors both in the system and in the atmosphere. Also, the fact that a single beam can be split into arrays of multiple beams will allows a number of new systems applications. Optical phased array apertures will allow the cost of high performance electro-optical systems to approach the cost of low or moderate performance systems.

Relationship to Commercial Developments/Applications

Commercial and Air Force display technology is similar to the liquid crystal based optical phased array technology. It should be possible to leverage off of this large commercial market. In addition, there are commercial beam steering applications. For example, there are telephone applications involving switching between fibers in a cable. With the multiple addressing approach, it should be possible to have a single beam in and then choose different sets of fibers to receive the signal. Also, commercial communications activities for satellites may use optical communications. This is a method to steer the beams from satellite to satellite.

Impact on Affordability

Cost should eventually be close to the cost of display technology. This means less than $1000 per large area device. Surface smoothness will be required in the near term that is more severe than that required by display technology. Later, however, an adaptive optics layer should alleviate that requirement. The device will not have to be flat because an adaptive optics layer will effectively remove any surface variation. Currently, highly precise gimbals are by far the biggest cost item in high performance EO sensors. Optical phased array technology should change that. This will greatly expand the affordability of EO systems as sensors, communication, or countermeasure devices.

Recommended Development Plan

We recommend developing a 10 cm diameter device capable of steering both active and passive (3 to 5 μm) radiation. Response time of the device should be under 1 msec. The device should include a telescope and beam steering should occur over angles > 5 degrees, with efficiencies > 75 percent. As a goal, we suggest steering efficiencies of > 50 percent at 55 degrees. This will allow steering to the corner of a 90 degree by 60 degree field of regard. This device should then be placed in an EO system and tested. Sensor and countermeasure tests should be conducted. It is estimated this is a 3-year development effort, requiring about $5M, a rate of about $2M per year. This will develop a robust steering capability at the 10 cm aperture size. If tests are successful, a follow-on 20 cm device should be fabricated with the same efficiency goals. Eventual steering efficiencies should rival microwave phased arrays. A separate 6.2 effort of about $500K per year should be sponsored to investigate some of the more difficult aspects of the technology, including broadband beam steering and steering at rates > 10 kHz. This 6.2 effort should be a 5- to 10-year effort.

6.2.2.4 T/R Module Based Optical Phased Array

Introduction

Space fed optical phased array technology has been demonstrated over reasonable size devices, and has potential for relatively near term system application. From a graceful degradation point of view, there are attractions to the T/R module based implementation of optical phased arrays. Also power scaling on such an implementation should in theory be easier than with a monolithic source and space fed optical phased arrays. Scaling T/R module based phased array technology to optical wavelengths is however *very* challenging. This section will specify some of the challenges that must be overcome so that this technology can become reality.

Description of Technology

While complete azimuth and elevation coverage is desirable, something less, such as a 60 degree elevation coverage is quite useful. This depends on tactics employed by the warfighter. These are the same constraints in the multifunction, modular EO systems described in Section 5.2.6. Functions of this system include laser designation, covert high bandwidth communication, target detection (both A/A and A/G), target ID (both A/A and A/G), missile warning, and IRCM (possibly either smart jamming or sensor damage). If designing for a six-module system, then each module must cover a 60 degree by 60 degree solid angle. A four-aperture system requires 90 degree coverage in azimuth. Elevation coverage, as stated earlier, really depends on tactics and must be worked with the warfighter. Even in a four-module system, a 60 degree elevation coverage could be assumed. This elevation coverage implies designation capability will be lost briefly when the pilot turns sharply to return home after releasing laser guided ordinance, but as soon as the aircraft approaches level flight designation capability returns. The laser guided ordinance should be able to coast for the brief turning period. Limited elevation coverage also means that the pilot will not see a missile attack from the top or bottom of the aircraft. These are not high probability attack aspects.

There are two distinctly different problems to be considered. One is for the passive sensors and the other is for the active sensors. Unless true time delay is implemented, broadband optical beam steering is difficult. Most passive EO sensors are broadband. A large blur, occurs therefore, at the focal plane if a phased array is used to steer the broadband radiation. There are some approaches that may mitigate this problem, but the steering of broadband optical energy by imposing a phase shift is fundamentally more difficult than steering narrow linewidth optical radiation. A multifunction optical system must address both problems, at least at the system level. One approach would be to detect the radiation at each module, without ever transmitting the radiation to an optical focus. There would be no focal plane in the system, and the Fourier transform would be taken after detection. For a T/R module base optical phased array concept, the passive sensor mode is the proper choice. Digital deconvolution of multispectral data is a potentially promising approach to be used with a focal plane based concept.

Steering active radiation requires T/R modules on the order of the size of the wavelength to be steered. A general rule of thumb is modules that are at half wavelength spacings. Some microwave radar phased arrays go even farther because from an oblique angle the effective T/R module size appears to be reduced. If wavelengths from 0.5 μm to 5 μm are considered, then T/R module sizes from 0.25 μm to 2.5 μm are required. If the field of regard (steer over a smaller angle) is restricted, then the larger modules are acceptable, but more modules are required for complete coverage. From a sizing point of view, we should consider designing modules that are one or two microns on a side. Current detector array technology tends to be at a 25 to 50 mm pitch. Surface emitting diode array technology must be restricted to the vertical surface emitters if micron size optical pitches are to be realized. Addressing this development will also be very challenging.

Relationship to Key Air Force Missions

A graceful degradation, conformal system with no moving parts that can do A/A and A/G target detection and ID, covert laser communication, and missile warning and can counter IR missiles would have great impact on Air Force missions.

Recommended Development Plan

Much of the technology required to implement this plan is in the 6.1 stage. There are, however, a number of very interesting 6.1 technologies to be worked as part of the development of this technology. At this time, there does not appear to be any work attempting to place phase shifters on the end of vertical surface emitting diode laser arrays and then steer the output beam. Including an optical receiver in a vertical surface emitting diode array is another challenging technology. This might be done either by using the actual laser diode in a receive mode, or by attempting to have a separate detector in the same unit cell. Fundamental work to attempt single devices that can be laser transmitters and laser detectors, even on a large individual diode, would be very valuable. Building T/R modules in a small array of maybe 10 by 10 or 100 by 100 and steering them initially over a small angle will be a challenge, but it is a necessary step in the process. Initial T/R module size could be increased above the micron level size to conduct feasibility experiments. The associated passive sensor concept is another challenging technical area, independent of the laser receiver challenge. The method of blending the passive and active sensor concepts together needs to be addressed. The multifunction concept requires additional basic work. A wavelength tunable active system needs an OPO on the output of each vertical surface emitting diode. Making an array of OPO diode lasers is another required development. A small team of people (5 or 6 researchers) and on the order of $1M per year should be considered for this effort.

6.2.2.5 On Chip Tunable Sources and Filters

Technology Description

On chip tunable optical sources and filters are of great importance to multiprocessor interconnect, phased-array radar, multisensor fusion and information distribution applications. Tuning ranges cover broadband for wavelength multiplexed signal processing applications to narrow-band for optical RF applications. High-power, broadband tunable solid-state laser sources such as the Ti:sapphire, Cr:LiSAF, Forsterite, Cr:YAG and Co:MgF_2 cover wavelengths ranging from the near to the far infrared. The difficulty with miniaturization of these laser systems is the need for intracavity tuning elements and high-power optical pump sources. However, miniaturized, narrow-band tunable (on the order of a few to hundreds of gigahertz in optical frequency) versions of these lasers are in the early stages of development. The difficulty with the size reduction technology is the ability to achieve output powers approaching more than the few milliwatts required for long distance signal transport in guided wave systems, such as is required in field antenna remoting, as well as short distance signal transport in freespace systems, such as is required in laser radar and tracking systems.

The ability to achieve solid-state narrow-band tunable microcavity lasers is a direct result of the capability of producing very high-power semiconductor diode lasers, which are used as the optical pump sources for the solid state lasers and eliminate the need for bulky flashlamp pumped systems. Dielectric mirrors can then be directly deposited on the laser crystal to form the cavity and the size of the overall laser reduced to less than 1 cm^3. Narrow-band tuning elements can be incorporated into this small volume. Tuning is achieved by acoustical, thermal, or mechanical techniques. Acoustical, or acousto-optic, tuning is the fastest of these techniques with speeds approaching nanosecond time-constants. However, acousto-optic tuning requires high-voltage sources and is limited to tuning rages on the order of a few GHz of optical frequency. Thermal tuning is the simplest and most robust approach and can achieve tuning ranges of 100 GHz; however, it is limited by tuning time-constants on the order of seconds to milliseconds. Mechanical, or electro-mechanical, tuning is based on electrostatically deformable mirror elements. These elements are capable of tens of GHz tuning ranges with applied voltages of a few tens of volts. However, these elements are difficult to fabricate and have tuning time-constants on the order of microseconds.

Alternatively, broadband wavelength tuning has been readily achieved in both semiconductor and glass-doped substrate waveguides. Broadband wavelength tuning ranges of 2 to 50 nm using thermal or current injection control have been demonstrated using branching and distributed feedback structures. Digitally tunable semiconductor laser arrays are also available. Modulation/tuning rates for these lasers approach multi-GHz speeds since they rely on current injection. A key parameter for these integrated laser sources is their side-mode suppression ratio (SMSR). SMSRs on the order of 20 dB or better are required for dense wavelength division multiplexed (WDM) applications. These lasers are of great importance for wavelength conversion operations. Predominately, these lasers have been limited to the wavelength region of established semiconductor laser technology, such as 850, 980, 1300 and 1550 nm regions. With the advent of doped glasses, GaN and related large bandgap materials as well as nanoparticle structures, windows in the visible to ultraviolet should become available in the near future.

Tunable filters have evolved from bulk optical techniques similar to dispersive gratings and interferometric components such as Fabry-Perot cavities. These filters have been brought down to the scale of the microcavity lasers using state-of-the-art photolithographic, microfabrication and micropackaging procedures. These filters include acousto-optic tunable filters in lithium niobate, high-finesses fiber Fabry-Perot filters, distributed Bragg reflectors in optical fiber or substrate waveguides and waveguide grating routers. All of these optical filters are typically for use in the broadband, that is, optical wavelength separable, spectrum of light. Typical performance parameters include: tunable wavelength range (2 to 50 nm), bandpass bandwidth (0.1 to 2 nm), free spectral range, channel crosstalk (-20 to -30 dB), and tuning speed (ms to ns). Tunable filtering in the narrowband, gigahertz RF domain is usually accomplished by first optically heterodyning the incoming laser signal with a coherent local oscillator and then using standard RF electronic techniques to recover the information.

Relationship to Key Air Force Missions

Tunable filters and sources are a basic technology required in many high-performance and/or high-priority missions. The ability to optically tune both filter and source, either in the optical wavelength domain or the RF frequency domain, creates a functional element that can be used for both point-to-point and in generalized local or wide area communications network environments. Tunability permits the system designer to incorporate WDM into system design.

Tightly controlled wavelength registration permits the system designer to use coherent detection for multi-gigahertz RF throughput on individual wavelengths.

The ability to integrate these devices (filter and source) on a chip will have a tremendous impact on system design. It means that the system designer can use WDM and coherent detection capabilities, both powerful interconnection technologies, as a basic architectural tool at the lowest level of design in high performance systems.

Tunable sources and detectors for optical interconnects will permit greater flexibility and performance in system design, while integrated, on-chip components significantly reduce system weight and allow for mass production, reducing component costs. The development of this technology will provide:

- Increased data transfer rates and hence overall system throughput.
- Systems that are more reliable by permitting alternate routing (self healing) and wavelength re-use.
- Real-time computational intensive systems, especially those dealing with multiple threats.
- More secure systems by using multiple wavelengths for coding enhancement and transmission path separation.

Tunable sources and filters combined with optical fiber cable technology will significantly reduce system weight and increase performance due to its immunity to electromagnetic interference capability. Such characteristics, combined with the freedom of optical tuning, will find significant uses in the following Air Force programs:

- F-22 network control of Avionics system
- Radar antenna remoting and networking
- Optical Steering of Phased Array Radars
- Bandwidth enhancement of Rivet Joint aircraft for multiple threat environments
- AWACS Upgrade
- J-Stars (performance upgrade)
- Sensor fusion systems and massively parallel processing as will be needed in virtual reality systems for training and readiness

Relationship to Commercial Development

There is great commercial benefit for this technology. The integrated semiconductor technology for tunable sources and filters is driven primarily by the telecommunications industry in their quest to develop very high density and very high speed interconnects that take advantage of the promised terahertz capacity of optical fibers. This is evidenced by the proliferation of publications on the components listed in the description of technology section above. The requirements of commercial industry are for broadly tunable sources and filters for local and wide area distribution interconnects for data transfer environments that include traditional circuit switching of telephone services as well as very bursty traffic associated with packet switching such as is encountered on the Internet.

As commercial services grow, such as cellular phone service, video on demand and home educational services, the impact on integration, cost and reliability will also grow. However, these corporations are not investigating the military requirements for RF signal generation, high optical power generation, temperature range and stability. Thus, the Air Force must continue to participate in this technology to extend the performance of commercially developed components.

Impact on Affordability

Leveraging on commercially developed tunable semiconductor technology for WDM systems is very cost effective and will produce the most reliable components.

Leveraging on commercially developed tunable solid state technology for narrowband optical RF technology for coherent communications is not an option as the commercial industry has only a small interest in this area.

Recommended Development Plan

A key opportunity is available to leverage off the current developments of commercial industry. It is, therefore, recommended that the Air Force identify the key performance requirements of their systems and match them with the performance of currently available commercial components and then investigate the potential for extending the technological performance of these components into the military requirement domain.

Beyond these component developments, efforts in control system development for improved optical frequency stability and registration are required to maintain system-wide compatibility of multiple channel processors and users.

Also, continued efforts in packaging to improve temperature range performance and reliability are required to meet military performance.

On the basic 6.1 level, development of new materials in the area of nanoparticles and polymers to create compact, microstructure lasers that are lightweight and operate in wavelength regions not currently covered by viable semiconductor alloys would be of great interest to the Air Force.

6.2.3 RF Apertures, Components, and A/Ds

The current vision for next generation tactical airborne architectures applies broadband phased arrays shared between radar, electronic support measures, ECM, and communications functions to minimize the number of antennas on an aircraft, thus reducing overall weight, volume, and cost. This concept also provides enhanced performance by making an active electronically scanned aperture available for all these functions. A broadband multifunction array provides the system’s flexibility needed for selection of the optimum frequency, power level, radiation beam shape, beam update rate, and so forth, based on specific modes and the mission environment. An operational mission applying shared aperture technology is illustrated conceptually in Figure 6-5.

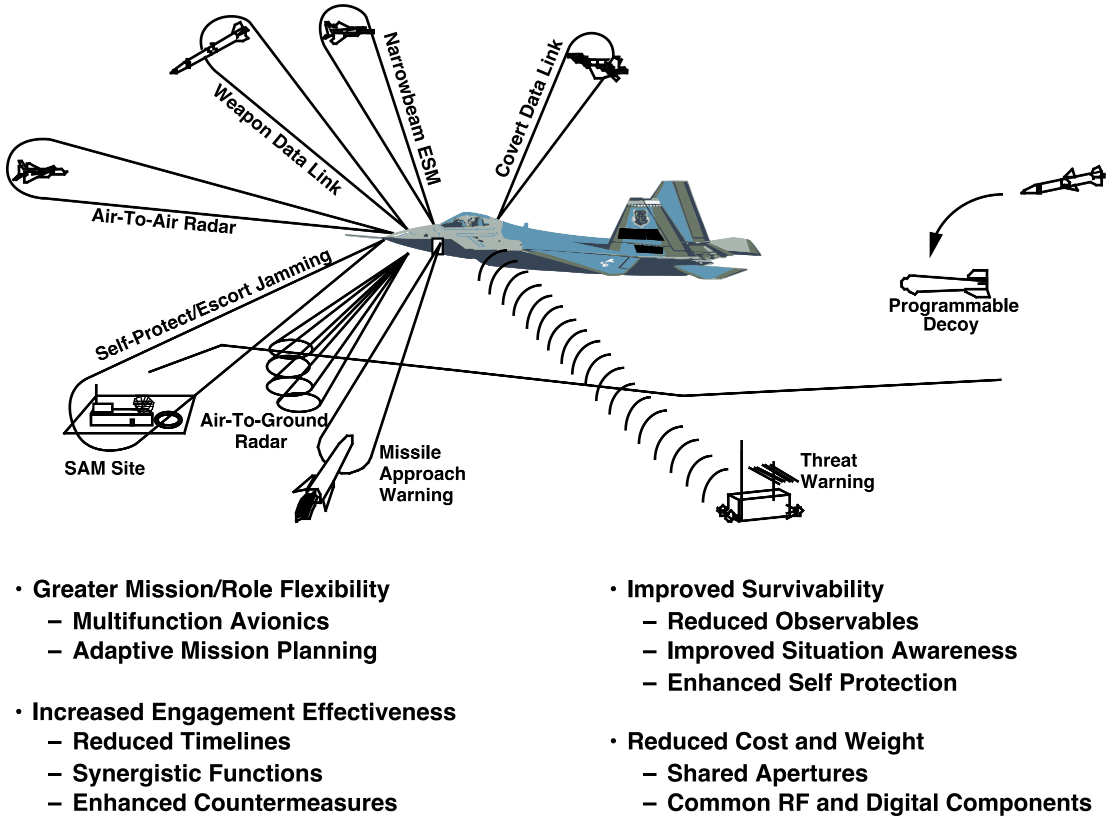


Figure 6-5. Integrated Multifunction System Benefits

In the future, system sensor suites will employ thin conformal antenna structures incorporated in the aerodynamic surfaces (smart skins) of advanced airborne platforms. The structures will provide multifunction aperture operation and will contain an array of high density microwave/millimeter-wave “tile” modules using monolithic GaAs and InP circuit technology. Conformal arrays will become practical in a low observable format with the realization of the promise offered by advances in high power density heterojunction bipolar transistor (HBT) integrated circuits. With proper R&D focus, electrical, thermal, and mechanical interface technologies can be developed to move from today’s planar microwave module topology to the three-dimensional structures of tomorrow’s “tile” architecture.

The continued and rapid advancement of digital technology, combined with GSPS clock rate, 8 bit and greater ADC, will allow earlier (closer to the system front end) digitization of the signal originating from each system sensing element. For example, the sensing element could be the individual radiating elements of a phased array aperture. Early digitization and high speed preprocessing can facilitate the implementation of pulse compression, multiple simultaneous beam formation, and digital I and Q channels prior to the normal coherent digital processing performed by today's advanced electronics systems. Higher performance, lower cost systems will result and will provide increased flexibility inherent in software based architectures.

Each of the above technology areas will be discussed in the following sections.

6.2.3.1 Broadband Integrated Multifunction Shared Apertures

Technology Description

Over a number of years, avionics systems have been evolving toward more integrated "open" architectures. Today's typical weapon system has integrated multifunction displays and controls and in some cases, such as the F-22 aircraft, a common processor for all sensor functions. The next logical step is to integrate the "front-ends" (apertures and support electronics) of avionics systems so multiple functions can share common resources. AESA technology has progressed to the point where it is now feasible to produce integrated multifunction apertures (IMAs) that will perform all RF functions (radar, EW, and CNI) across broad portions of the microwave frequency spectrum. For example, the RF spectrum from 500 MHz to 18 GHz, which is typically used by airborne weapon systems, can conceivably be covered by three multifunction apertures: 500 MHz to 2 GHz, 2 GHz to 6 GHz, and 6 GHz to 18 GHz. These apertures would perform all of the RF functions that fall within their operating band.

An IMA that covers the high band, 6 to 18 GHz, is the most challenging but also offers the highest potential for dramatic life-cycle-cost savings. Based on recent studies, a high band IMA that could be used in future applications such as JAST and retrofit applications on existing aircraft such as the F-15 or F-16 might have the following general characteristics:

- Open architecture with multiple independently scanned beams for simultaneous, interleaved functions
- High power, high efficiency radar operation across all of X-band
- Low noise, high gain ESM across the full 6 to 18 GHz band
- Lower power ECM and CNI functions across critical portions of the 6 to 18 GHz band

This aperture could be constructed from a set of common building blocks (T/R modules, high density power supplies, and beam steering computer) and would be tailorable to particular applications. Tailorable characteristics could include aperture size, array grid shape and size, number of subarrays (independent beams), and polarization. With this degree of tailorability, a common aperture approach could cover applications from conventional aircraft with very little RF functionality to low observable aircraft with high degrees of RF functionality. The open architecture design would allow higher performing technology (such as higher power, higher efficiency, wider bandwidth, etc.) insertion as it became available, thus mitigating technology obsolescence.

A key part of the IMA concept is a "smart" resource manager that can adaptively allocate aperture and "back-end" resources to meet critical mission timelines. Previous studies and simulations have shown this resource manager can be "rule based." Control of assets at millisecond time increments provides adequate control for most timeline requirements.

Relationship to Key Air Force Missions

Air Force missions require a broad spectrum of RF functionality. High efficiency radar is usually a driving requirement, but passive RF for threat warning and precision targeting can be essential for certain missions. Some missions would be benefited by on-board ECM for self-protection or escort support for other aircraft. Also, the capability for covert communication at the higher microwave frequencies could provide improved mission effectiveness. A common multifunction aperture that can synergistically provide all of these capabilities would potentially be of great benefit to the Air Force.

In the past, primarily because of federated avionics architectures, expanding existing RF functionality was deemed to be unaffordable. This has led to the current emphasis on low observable platforms with limited RF functionality and as much off-board support as possible. It was envisioned that this was the only way to achieve affordability. In particular, on-board ECM was generally not seriously considered because of its perceived high cost. Recent studies have shown, however, that on-board ECM capability can reduce low observability requirements, which are a major aircraft cost driver. There is also the question of the ability or desire to maintain very low levels of observability after the first few days of a war. Assuming that multimode radar and ESM are required, a multifunction shared aperture approach can also provide additional ECM functionality, and the attendant survivability benefits, at very little increase in cost.

Relationship to Commercial Developments and/or Applications

The broadband Monolithic Microwave Integrated Circuits (MMICs) and low cost manufacturing processes required for a multifunction aperture are also being proposed for other DoD and commercial applications. Multibeam AESA antennas for commercial communication satellites and gateways are strong candidates for low cost technology insertions. It is unlikely, however, that commercial applications will require the multifunctionality needed for Air Force missions.

Affordability

Recent studies have shown that, depending on the degree of functionality required, life-cycle-cost saving for JAST avionics over 20 years can be as much as $5B to $12B through the application of common IMAs. The larger savings is for aircraft that require full RF functionality (radar, ESM, ECM, and CNI) and spherical (all aspect) coverage for threat warning and self-protect jamming functions. Studies have shown that to implement such a system, using today’s technology, would require about 32 apertures and a large complement of support electronics (transmitters, low noise receivers, etc.). Equivalent functionality and coverage using IMAs would require only 8 apertures and, since transmit and receive functions are inherent in AESA apertures, the supporting electronics would be greatly reduced. If the requirement for on-board ECM is eliminated, the savings would still be a dramatic $5B. In addition, further savings would result from the reduced cost of aircraft installation due to fewer apertures and less support electronics, and the attendant lower weight.

The above savings are for JAST aircraft only. If the common building block approach, described above, were applied to future AESA upgrades such as the F-15 and F-16, the Air Force could realize additional savings in areas of:

- Reduced development cost (common building blocks would apply to multiple applications).
- Reduced acquisition cost due to increased manufacturing volume of common components.
- Reduced upgrade cost due to inherent growth capability.
- Reduced maintenance cost due to increased reliability of AESA apertures.
- Reduced logistics cost (common support equipment, training, etc.).

In addition to the Air Force, other service components could realize substantial savings from use of common aperture building blocks. An upgraded F-18, for example, will have similar aperture requirements to the F-15 and F-16. Bombers, ships, national assets, ground installations, and even future submarines are considering the potential benefits of multifunction shared apertures.

Recommended Development Plan

The basic technology exists to develop broadband IMAs, but it has not been demonstrated. Current aircraft that employ electronically scanned array antennas use bandpass radome concepts to reduce their RCS outside of the typically narrowband radar operation. This concept will not work for IMAs where broadband operation is required to realize the full benefits of multifunction shared apertures. Future developments should therefore concentrate on building and demonstrating an integrated aircraft “forebody,” consisting of a low observable, broadband (6 to 18 GHz), multifunction aperture and “clear” radome, that could be applied to JAST and other future/retrofit aircraft needs. Development of a robust resource manager to allocate system resources as needed to meet critical mission timelines should be an inherent part of this plan. The integrated forebody, along with “back-end” test assets and the resource manager, need to be demonstrated first in a rooftop environment and eventually in a test-bed aircraft to fully prove the multifunction, shared aperture concepts.

A strawman program plan and ROM cost to implement the plan for the 6 to 18 GHz IMA are as follows:

Phase I: Concept Definition Study	6 Months	$1 to $2M
Phase II: Integrated Forebody D&D	33 Months	$40 to $60M
- Develop Aperature, Radome, and Resource Manager		
- Integrated Forebody Demo		
Phase III: Rooftop and Flight Test	33 Months[4]	$20 to $30M
- Modify Existing “Back-end”		
- Rooftop and Flight Demo		

4. Phase III starts 12 months after Phase II and extends 12 months beynd the end of Phase II (total duration of Phases I through III is 51 months)

If funding allows, IMAs covering the other frequency bands (500 MHz to 2 GHz and 2 to 6 GHz) could be developed and demonstrated in parallel programs with the 6 to 18 GHz IMA. The development risk for these apertures, however, is much less than the 6 to 18 GHz aperture and could be delayed and incorporated in an EMD program.

6.2.3.2 MMICs for RF Aperture-Multifunction Shared Aperture, Broadband

Technology Description

MMICs are used for various applications in the microwave frequency domain from around 1 GHz to 60 GHz and above. Typical uses are as active components in the form of amplifiers (low noise and power), oscillators (stabilized and voltage tuned), and control elements (switches, limiters and phase shifters) and passive components such as couplers, power splitters and combiners. MMICs are fabricated using Gallium Arsenide (GaAs) semiconductor technology and are now being used in a variety of military and commercial programs.

AESAs for the BMDO Ground Based Radar (GBR), several classified Service and Agency applications, and the F-22 fighter aircraft are now under development. These radar arrays use GaAs MMICs to construct a T/R function (module) that drives individual radiating elements of the radar array. Although the MIMIC program has demonstrated an impressive advancement in capability, future defense system developments will require, for example in the power amplifier area, increased power outputs from today's 5 to 10 watts/MMIC to the range of 20 to 30 watts/MMIC at X-band. Enhanced operating efficiencies, greater than 40 percent, will be required in order to reduce array size and improve performance. Figures 6-6 and 6-7 show the power and efficiency trends that can be expected over the next 10 years for X- and K_a-band devices if R&D funding is made available. Multifunction wideband RF system architectures are supportable by AESAs technologies and as such can provide radar, electronic support measures, and communication functions in a single aperture. Large reductions in weight, volume, and complexity can then be realized over the multiple apertures used on our current airborne platforms.

Technological advances are needed in several areas to support future mission roles and reduce acquisition costs of AESAs. MMIC processing facilities will need to convert to 150 mm diameter wafers from the 75 mm and 100 mm wafers presently used. Considerable advancement in GaAs processes and processing technology is required to provide MMICs with high yields at the increased levels of complexity and performance that have been projected to meet future system needs. High density microwave packaging will be required to reduce array size and weight. Advanced microwave device structures and microwave semiconductor materials are needed to provide higher output powers at greater efficiency than the present GaAs devices. Multifunction MMICs with RF, digital, and analog functions on a single chip will be needed to provide increased weapons system capability at an affordable cost.

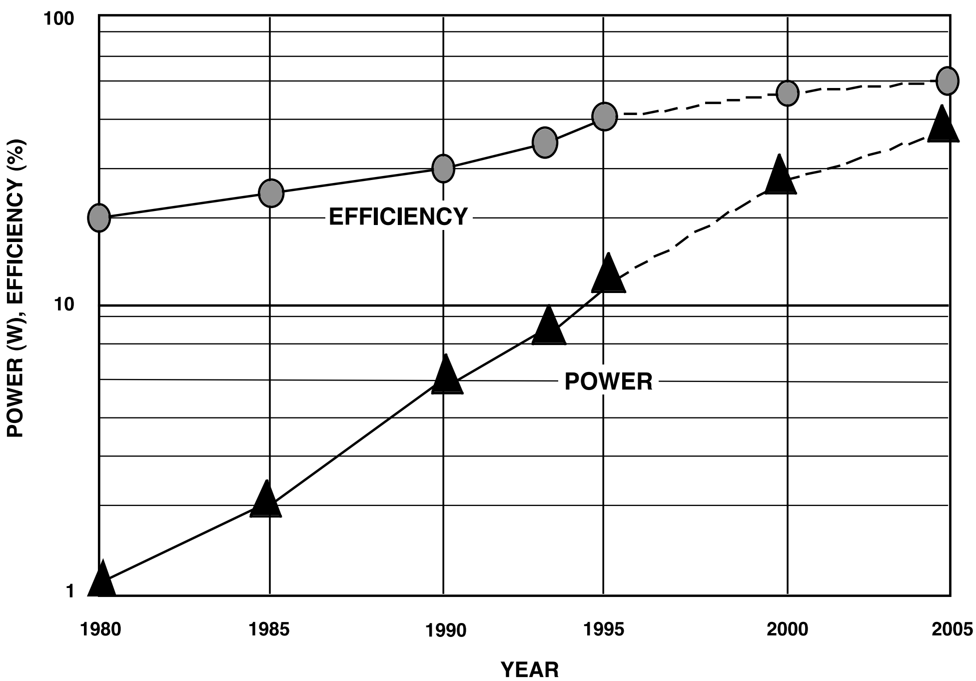


Figure 6-6. X-Band Power Amplifer Performance

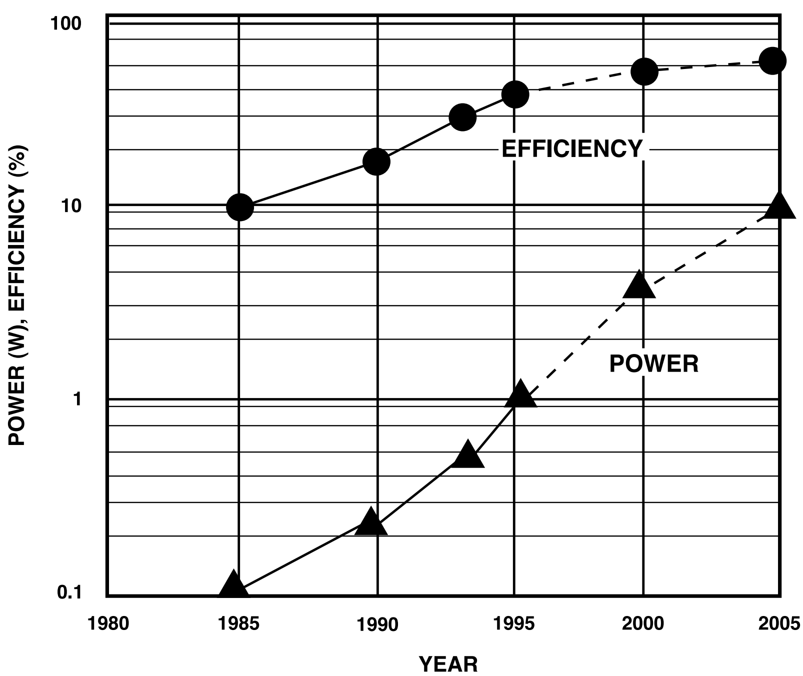


Figure 6-7. K_a-Band Power Amplifier Performance

Relationship to Key Air Force Missions

The Air Force is currently funding developments for AESAs for future A/A and A/G missions. These technology development activities directly support the F-22 program. The technology is playing an increasingly important role in the arena of towed and expendable decoys and A/A missiles that must seek and destroy stealthy targets. The development of small compact phased array systems based upon enhanced performance from MMICs and high density packaging will eventually lead to smart skins (conformal array) systems capable of providing full sector situation awareness on aircraft platforms. Compact millimeter-wave communications arrays will be enabled and will allow continuous information flow to and from high dynamic airborne platforms via MILSTAR satellites.

Relationship to Commercial Developments

Current commercial developments are in ground-based and satellite telecommunications with emerging applications in personal communications services, cellular telephones, and satellite-to-air relay communications. The Air Force applications require much higher performance in terms of bandwidth, output power, and operating frequency than the commercial uses. Although commercial MMIC and packaging developments will benefit in a significant way from the R&D activities and enhanced processing and manufacturing capabilities, commercial investments will be required to tailor the technology to specific large scale, cost-driven opportunities. Emerging systems applications such as higher frequency, broadband, wireless local area networks, personal communications services, satellite-to-air communications, and a variety of satellite based telecommunications services will take several years to be fully deployed and become operational.

Affordability Impact

The development of higher performance microwave devices will reduce parts count and simplify the assembly of T/R modules and high density microwave packages. This will allow a system of comparable performance to be procured for a lower cost or a system with increased performance to be procured for a more affordable cost. From a commercialization perspective, manufacturing experience, based upon traditional learning curves and ongoing cycle time reduction efforts, shows that large volume production of MMICs for commercial and military applications will lead to lower costs. Statistical quality control is more effectively instituted and production variations are minimized with large production bases.

Recommended Development Plan

Processing improvements continue to be needed to increase the yield, reliability and quality of MMICs. Expanding applications in military and commercial systems require further concentration upon cost reduction efforts, such as converting to 100 mm diameter wafers for present uses and eventually to 150 mm diameter wafers for future large volume manufacturing. Device and modeling developments are also needed to increase power output and efficiency of power devices and to further reduce the number of active devices used in AESAs. Continued emphasis on reliability studies is needed to assure dependable performance and to achieve longer operating lifetimes of MMICs.

New microwave semiconductor materials such as indium phosphide, silicon carbide, diamond, and so forth, must be researched and developed to provide the best power amplifier MMIC performance consistent with the needs of the next generation systems.

Advanced epitaxial deposition techniques must be developed to decrease the cycle time for the higher manufacturing rates forecast for future production programs. Production lithography processes for sub-micron device structures suitable for high rate production are also needed to support the advanced microwave device developmental efforts.

Continuing developments are needed to support microwave packages with high density multilayer microwave circuit boards and multichip, multilayer modules. Packaging technology efforts must continue to focus on the small footprint (less than a quarter of a wavelength on a side) T/R module tile architecture that is essential for conformal array implementation. Composites suitable for microwave packages are needed for hermeticity, minimum weight, and effective heat dissipation of power sources.

MMIC technology is currently viewed as a maturing industry that has demonstrated the potential for satisfying the Air Force requirements for future airborne platforms. A considerable tech-base capability has been demonstrated in all the development areas outlined above and is amenable for full development of efficient production processes to achieve the manufacturing rates needed by the Air Force. Even though the MMIC industry is viewed as maturing, many areas requiring an advanced R&D focus have been highlighted above.

6.2.3.3 Analog to Digital Converters

Technology Description

Over the last two decades, the rapid evolution of digital integrated circuit technologies has led to ever more sophisticated signal processing systems. These systems operate on a wide variety of “natural” or continuous-time signals, which include, but are not limited to, speech, medical imaging, sonar, radar, EW, instrumentation, consumer electronics and telecommunications. One of the keys to the success of these systems has been the impressive advances in the development of the ADCs that convert the continuous-time stimuli to discrete-time, binary-coded form. The large number of signal types has led to a diverse selection of data converters in terms of architectures used, bits of resolution achieved, and sampling rates employed.

Despite the variety in data converter systems, their performances can be summarized in a relatively few charts. One is shown in Figure 6-8, where ADC resolution (as stated by the manufacturer) in bits is plotted against sampling rate, f_{samp}. Over 100 converters, including experimental integrated circuits (ICs) and commercially available parts, are represented in the graph. One performance limitation that emerges from the plot indicates that approximately one bit of resolution is lost for every doubling of the sampling (clock) rate (indicated by the line on the graph). As technologies advance, the line moves slowly upward but the slope remains about the same. The -1 bit/octave slope can be explained in terms of aperture jitter, which is the uncertainty in time in which the amplitude of the input signal voltage is sampled (captured). Another limitation evident in Figure 6-9 is that the highest sampling rate attained so far is a few giga samples per second (GSPS). This limit is related to the ability of the comparator(s) to transition from sample-to-hold (regeneration time constant) mode and/or to transition from

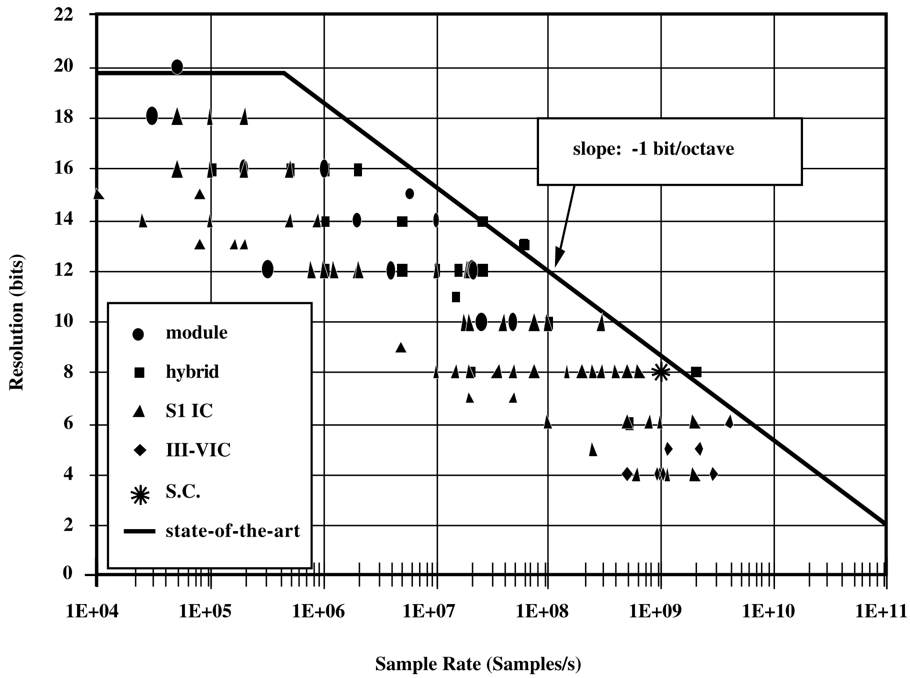


Figure 6-8. Survey of Analog-to-Digital Converters

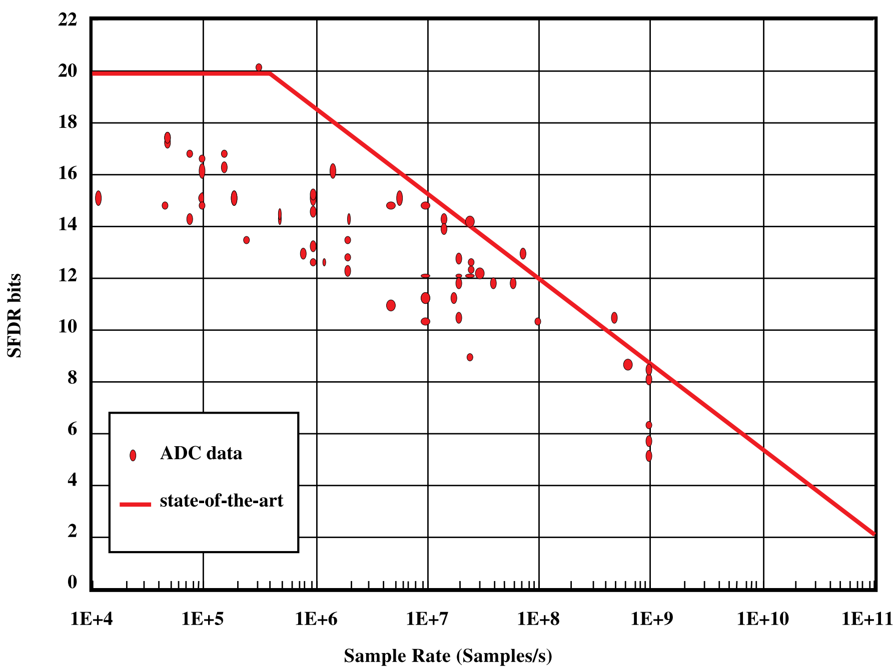


Figure 6-9. Spur-Free Dynamic Range Expressed as Effective Number of Bits

hold-to-sample (track recovery time) mode and still make an unambiguous decision regarding the relative amplitude of the input voltage. This can be directly related to the performance of the device technology used to fabricate the ADC, in terms of the unity-current-gain frequency, f_T, and/or device parasitics. At lower sampling rates, the maximum resolution appears to be limited by white noise found/generated at the ADC input stages.

A/D Converter Characterization

There are a number of ways in which to measure and compare A/D converter performances. Primarily we are interested in determining the resolution in bits for a given sampling rate, and, in an increasing number of applications, the power consumption is also important. Resolution can be determined both quasistatically and dynamically: quasistatic measures include, but are not limited to, differential nonlinearity (DNL) and integral nonlinearity (INL), while dynamical measures include signal-to-noise ratio (SNR), spurious-free dynamic range (SFDR) and noise power ratio (NPR). These last three quantities are determined from a spectral analysis (usually in the form of an FFT) performed on a sequence of A/D converters' output samples. The most significant figures of merit are probably SNR and SFDR because (1) the dynamic performance is most important for high-speed applications, (2) SNR and SFDR data provide a more accurate, yet general, indication of A/D converters' performance than the stated-number-of-bits used in Figure 6-1, and (3) SNR and SFDR have been universally accepted as performance measures.

SNR is defined as the ratio of the rms signal amplitude to the integral of the noise spectrum over the frequency band of interest (we will use the full Nyquist range, 0 to $f_{samp}/2$). The SNR in dB can be related to an effective number of bits, which we will refer to as SNR bits, by

$$\text{SNR bits} = (\text{SNR (dB)} - 1.76) / 6.02$$

Similarly, an effective number of bits associated with SFDR can be expressed as

$$\text{SFDR bits} = \text{SFDR (dBc)} / 6$$

where the SFDR is defined as the ratio of the signal amplitude to the largest component (not the signal) of the frequency spectrum within the band of interest (again 0 to $f_{samp}/2$).

Performance Limitations

In order to determine the performance limits quantitatively, it is necessary to replot the data of Figure 6-8 according to the effective resolution as determined from either SFDR or SNR. Figure 6-9 shows the results using reported SFDR values (where available). A comparison of Figures 6-8 and 6-9 indicates that, when the population is taken as a whole, the effective resolution expressed as SFDR bits appears to be roughly the same as the stated resolution (number of output leads). However, this is somewhat misleading because the variation in the quantity (stated bits - SFDR bits) for any given converter is ~0 ± 3 bits—a wide variation.

A similar graph can be constructed for SNR bits versus sample rate and is shown in Figure 6-10. A comparison with Figure 6-8 shows that, in general, the number of SNR bits is approximately 2 bits lower than the number of stated bits. This conclusion is supported by looking at individual A/D converters. The results of Figures 6-9 and 6-10 clearly show that relying only on the stated number of bits can be very misleading when evaluating performance.

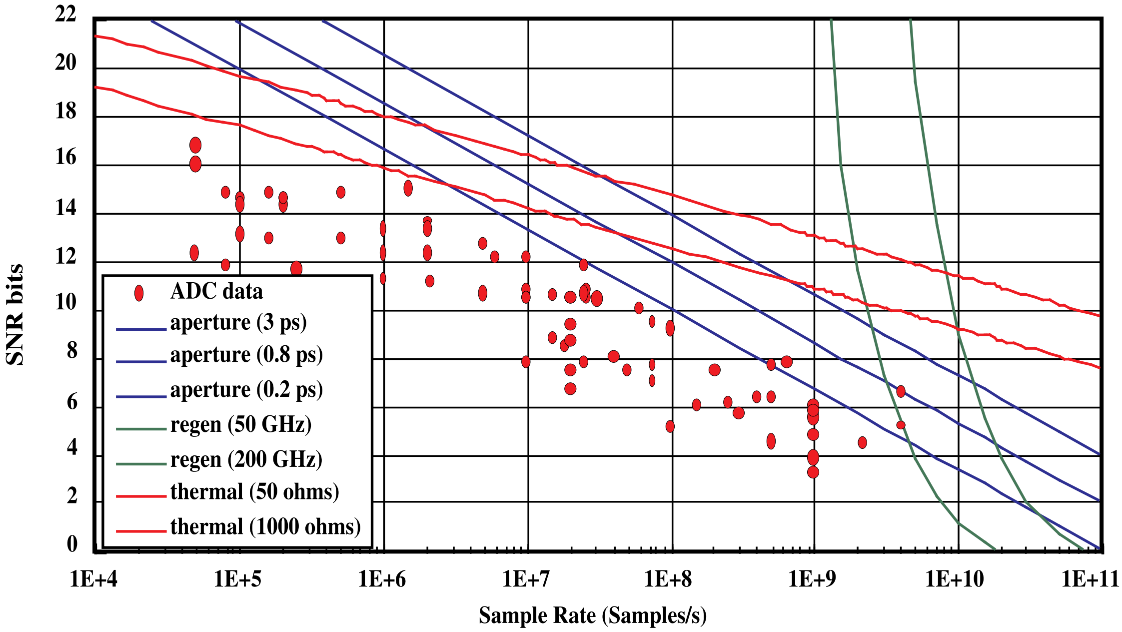


Figure 6-10. Signal-to-Noise Ratio Expressed as Effective Number of Bits

An examination of global performance limitations of the A/D converters indicates that the current state of the art is limited by (1) white noise roughly equivalent to the thermal noise associated with a 1kΩ resistor for low (1 MSPS) sampling rates; (2) aperture jitter of 1 to 3 ps for a large sampling frequency range (1 MSPS to 4 GSPS); and (3) regeneration time constant corresponding to an f_T value of 50 GHz at the highest sampling rates. The aperture uncertainty effect gives rise to the -1 bit/octave slope and is the dominant limit because the range of affected f_{samp} values is so large.

To advance beyond present capabilities will require designs that achieve less than 1 ps of jitter and/or technologies that perform better than 50 GHz. There are reported HBT technologies that have achieved device performances in the range $160 \leq f_T \leq 190$ GHz; hence, one can envision an eventual increase in sampling rates of a factor of three or four beyond today's 4 GSPS.

A/D Converters Performance Over Time

It is revealing to examine the progress made in A/D converters' performances during recent years. It is evident from the graphs that little progress has been made over the last six years. Some reasons for this stagnation may be: (1) a technological (if not fundamental) aperture jitter barrier of 1 ps; (2) much of the recent research has been aimed at monolithic and, therefore, efficient A/D converters; (3) a recent and general de-emphasis on research and development; and (4) few application drivers.

Architectures

Current A/D converters are designed using a variety of architectures ranging from parallel (flash) which is the fastest, through integrating which is perhaps the most accurate but also the slowest. Most of the converters have been fabricated in some form of Si technology, while a few have been realized in GaAs-based and in InP-based technologies.

The flash architecture utilizes 2^{b-1} comparators, all of which sample the analog input voltage simultaneously and, therefore, this type of converter is inherently fast. The parallelism of this architecture has a significant drawback when high resolution conversion is desired, namely, the number of comparators grows exponentially with b. In addition, the separation (ΔV_{ref}) of adjacent reference voltages grows smaller exponentially. The consequences are: very large ICs, high power dissipation, difficulty in matching components, and the increasingly large input capacitance reduces analog input bandwidth. Most flash converters available today have < 8-bit resolution.

In order to overcome these problems, variations on the flash architecture have been developed that utilize relatively small numbers of comparators yet retain good speed. Examples that are capable of giga sample/s conversion rates are: the multistage, folding, and pipelined. Another approach for achieving high-speed conversion is to time-interleave two or more converters. This particular converter is “the exception that proves the rule” with respect to the overall lack of progress in improving A/D converters’ performance. Specifically this A/D converter’s system achieves 1 ps aperture jitter, but requires two hybrids, each with five LSI chips. The total P_{dis} = 40 W, which is roughly an order of magnitude larger than other contemporary converters.

An architecture that can trade speed for resolution is the combination of delta sigma modulation and digital decimation filtering. Delta sigma modulators sample the analog input signal at a rate that is many times the final (Nyquist) output rate and use feedback to suppress the quantization noise in the lower portions of the spectrum (relative to the delta sigma clock frequency). One advantage of this technique is that very few analog components are required. The challenge is that a very high speed IC technology is needed. Recently, ARPA has demonstrated an InP-based HBT (f_T = 70 GHz, f_{max} = 90 GHz) second-order DS modulator at a sampling rate in the 3.2 GSPS range and an oversampling ratio of 32 (Nyquist rate of 100 MSPS). This is the fastest DS modulator yet built.

Relationship to Key Air Force Missions

The Air Force uses A-D conversion in a wide variety of systems including radars, communications systems and electro-optic sensors in aircraft and missiles as well as in ground based systems.

Relationship to Commercial Developments

Current commercial developments are focused on communications and entertainment applications with digital radios, cellular telephones, personal communications services (PCS), digital satellite and cable TV receivers as the current leaders in anticipated demand as well as the most stressing designs. None of the commercial applications is likely to push A/D performance beyond Air Force needs in the foreseeable future.

Affordability Impact

As A/D converters become more capable, the general trend in sensor systems is to move the converter closer to the transducer and to eliminate more and more analog electronics. This trend toward early conversion from analog to digital signals has the effect of reducing the fraction of the system with historically increased costs while increasing the digital fraction, thus allowing that part to follow the declining cost curves of commercial digital processing technology.

Recommended Development Plan

The trend toward lower cost digital processing is likely to continue. Further increases in A/D converter speed and dynamic range will enable Air Force systems with full digital signal path implementations for electronic warfare and information warfare systems applications. These digital signal path systems can cost less both in life cycle terms and in acquisition costs if the development of high performance A/D technology advances fast enough to keep up with developments in digital signal processing technology.

In order to improve on the present state of the art in A/D converters performance, significant technical challenges must be met: (1) a reduction in aperture jitter to below 1 ps, (2) an increase in the maximum sampling frequency to beyond 4 GSPS, and (3) accomplishing both (1) and (2) while maintaining low power consumption, for example, < 5 W.

With respect to aperture jitter, only about one bit of overall improvement has been achieved over the last six years in both SNR and SFDR. The best effort was the time-interleaved A/D converters which achieved 1 ps aperture jitter. In addition, while significant progress has been made in achieving power-efficient A/D converters' designs, none of these efforts has gone below 2 to 3 ps of aperture jitter.

It would be timely, therefore, to investigate the basic noise mechanisms responsible for aperture jitter, and how they manifest themselves in particular A/D converters' circuits. Such an undertaking would involve examining very high performance IC technologies.

The achievement of ultrahigh sampling rates (> 4 GSPS) requires an ultrahigh speed IC technology. A particular combination of sample rate and resolution is 4 GSPS and 8-bits, and would be interesting to investigate because it "pushes the envelope" for both aperture uncertainty and sample rate (see Figures 6-10 and 6-11), and because its realization would also enable future ultrahigh-speed signal-processing systems.

Finally, a study of power-efficient A/D converters' designs would concentrate on A/D converters' architectures that minimize component/device count. In addition, scaling down of transistor sizes to reduce "per capita" power consumption would also be important.

Without appreciable efforts in these directions, it appears that very little progress will be made by the turn of the century in increasing the resolution-sampling rate product of A/D converters in general.

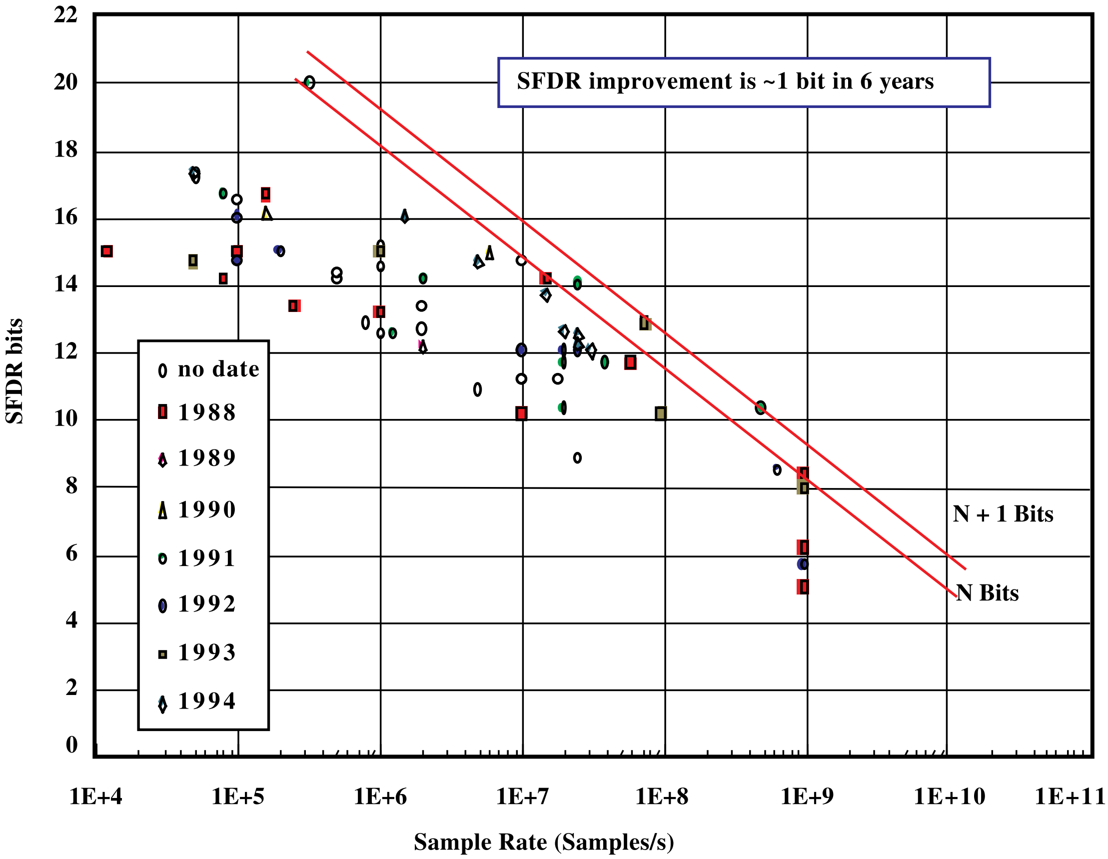


Figure 6-11. Time Development of A/D Converters With Respect to SFDR Bits

6.2.4 Enhanced and Affordable Sensing Through Signal Processing

The digital revolution has provided a common envelope of vast yet different forms of data and information providing an unprecedented ability to integrate, process and use disparate information. As stated earlier in Section 6.2.3, as A/D converters became more capable, the general trend in sensor systems is to move a sensors converter to the transducer and to eliminate more and more analog electronics. This trend toward early conversion from analog to digital signals has the effect of reducing the fraction of the system with historically increased costs while increasing the digital functions, thus allowing that part of the system to follow the declining cost curves of commercial digital processing technology.

Many of the advances in sensors that have been achieved recently and will be achieved in the future are directly related to concurrent and supporting improvements in two key areas: computer technology and signal processing algorithms. The exponential growth in computational capacity (ever increasing MIPS per pound, watt, and dollar) is well known. Also important for the advance of sensing systems, but less well publicized, are the dramatic innovations in signal and data processing algorithms, for example, efficient large array image registration and two-dimensional Fourier transforms. By exploiting these two areas, it is possible to shift some of the burden from the sensor itself to the signal/data processor to achieve more affordable and/or enhanced overall sensing systems. This opportunity is often called "trading mass for MIPS" and generally involves using processing power to compensate for inadequacies in sensing hardware.

This section contains a set of representative sensor system concepts expected to be enabled, enhanced and/or made affordable through the availability of high performance computing resources. By no means are these examples meant to be exhaustive in either their concepts or coverage. They serve only to stimulate the reader to extrapolate to the many and diverse areas expected to provide the Air Force with next generation mission capabilities beyond those of today through enhanced sensors. Put another way, the benefits and enablements of digital technology will continue because the technology itself is still enormously fluid and, therefore, its impacts are difficult to predict but will definitely be varied and global.

Reduced Tolerance Sensing

The idea that adding processing power to an otherwise insufficient sensor can bring performance to acceptable levels within cost constraints is a fundamental theme for this section. A good example of this is the human vision system. The basic sensor—the eyeball—is fraught with imperfections and inadequacies. For example, the eyes of the human visual system collect 250 million pixels of information about 20 times per second. From this massive data stream, the tremendous processing power of the human brain turns these corrupted vision signals into sharp, usable images. Further, by processing two sensors simultaneously, the brain can render not only two-dimensional vision images, but full three-dimensional in full color!

An example of an important future sensor concept that illustrates this opportunity is "relaxed-optical-tolerance imaging." In the next several decades, the Air Force will have an increased need for fine resolution optical imaging of targets and scenes on a global basis. Using current technology, a space-based optical system with a large aperture would be very heavy to insure structural integrity and rigidity. It would also be expensive and cumbersome to fabricate and deploy. A solution to the current technology shortfall is to relax optical tolerances (thereby reducing weight) on the primary mirror and recover the loss with post detection processing. For example, the primary collector could be a non-rigid (floppy) monolithic or segmented or sparse device involving a very thin mylar surface stretched over skeleton structure. The large aberrations associated with this system would then be overcome with post-detection processing involving algorithms such as *phase-diverse speckle imaging* or *multiframe blind deconvolution*. These algorithms all involve a large number of computations that require on the order of tera-operations for a single million pixel image. The use of new algorithms and advancements in computer technology will allow the development of more affordable and improved imaging systems such as this.

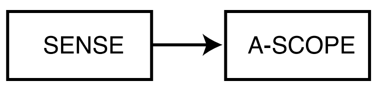
Similarly, signal processing can provide the capability to exploit SAR image data from space or airborne platforms to detect and measure subtle changes in a scene between imaging passes. This technique is often called "coherent change detection" and involves using the phase differences between two SAR images taken with antennas that are displaced either spatially or temporally to retrieve information on motion, change, or surface elevation differences within the images. Differences in phase are indicative of subtle changes between imaging cycles. For example, decorrelation in the image phase indicates changes have occurred in the scene microstructure due to surface disturbances such as might occur if a man walked across the scene. Small surface subsidences of a few mm due to clandestine underground activity can be detected using this sensing technique. These changes are usually not observable to a human viewing the scene nor can changes be seen in a conventional SAR image. This class of sensing techniques will have increasing utility in dealing with many operational tasks of interest to the Air Force in the future.

Ultimately, the goal of airborne and spaceborne imaging systems is to build up a model of the world so limited resources can be used in the most effective way. Typically, these systems are severely bottlenecked by their data rate and storage capacity. Evaluation of biological systems as a model for computer vision systems may offer some advantage or solution to add robustness and capacity to the current systems.

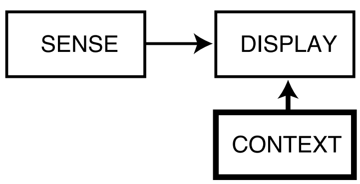
This is one aspect of affordability in sensing systems. Processing power can be traded for sensor precision—software algorithms can compensate for inadequacies in sensing hardware.

Review of Processing History

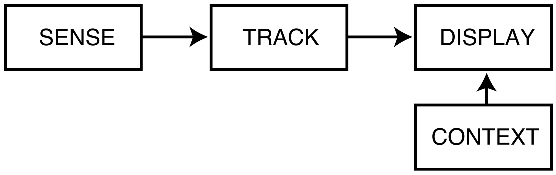
To further develop another concept of cost-performance improvement of sensing systems through enhanced signal and data processing and future algorithms and technology innovation, consider first the history of tactical sensing systems and then extend this history to future vision. Early tactical sensors used no computer processing. Radar and sonar operations, for example, involved state-of-the-art sensors that had direct analog connection to the mission operators. Tactical commanders observed the raw sensed data, drew conclusions about the military situation from these observations, and took action accordingly. The primary processor was the human brain—and it still is.



The introduction of digital computing enabled more usable display representations of sensed information by presenting the sensor outputs in tactical context. The commander’s brain had a better connection to the sensor and more information to work with. For example, an airspace surveillance radar could produce historical *smoke trails* that showed where an enemy aircraft had been and, by extrapolation, where it was going. In addition, computer-generated background displays could show enemy and friendly airspace, and annotate radar reports with pertinent information.

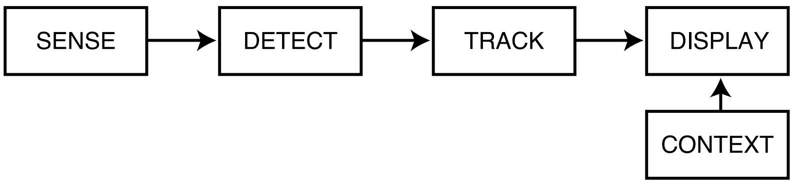


Increased processing power allowed the formation of *tracks*. More information could be extracted from the raw sensor reports by applying computer processing. In the tracking example, velocity data is extracted from position data.



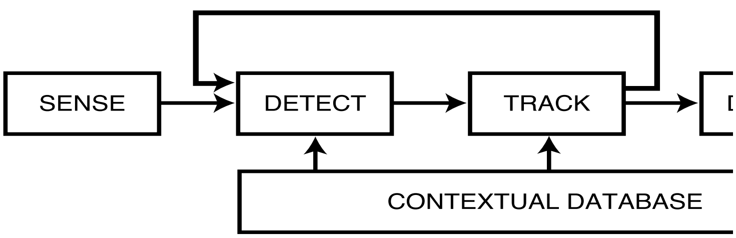
Signal Processing

Revolutionary progress was made when it became possible to digitize and process analog data at the rate it was produced. This is called real time signal processing, and it opened the door to vastly improved sensing performance while maintaining equivalent costs. A new processing step, called *detection*, was added to convert the raw analog inputs to usable sensing outputs.



Modern signal processing algorithms for detection include fast Fourier transforms, matrix inversion, clutter suppression, image formation, jammer nulling, space-time adaptive processing and CFAR processing. In most all cases, the *sophistication* of the signal processing algorithm is limited by the available signal processing throughput. In fact, space time adaptive processing poses an (essentially) arbitrarily large problem in which detection performance is directly proportional to problem size. Detection performance can be increased solely by adding processing throughput to the signal processor. Figure 6-12 depicts the flow of a generic space time adaptive algorithm and notes appropriate division between special-purpose and general-purpose computing hardware.

Other techniques, besides expanding signal processor throughput, can improve detection. These involve feedback from the tracking algorithm (known as track-before-declare) and incorporation of contextual data in the signal processing (e.g., a geographic database can provide information about land-sea boundaries that can improve overall clutter suppression performance). Arguably, as will be discussed later, future algorithm development may well be as important to advancements in affordable sensor developments as improvements in hardware processors have been to date.



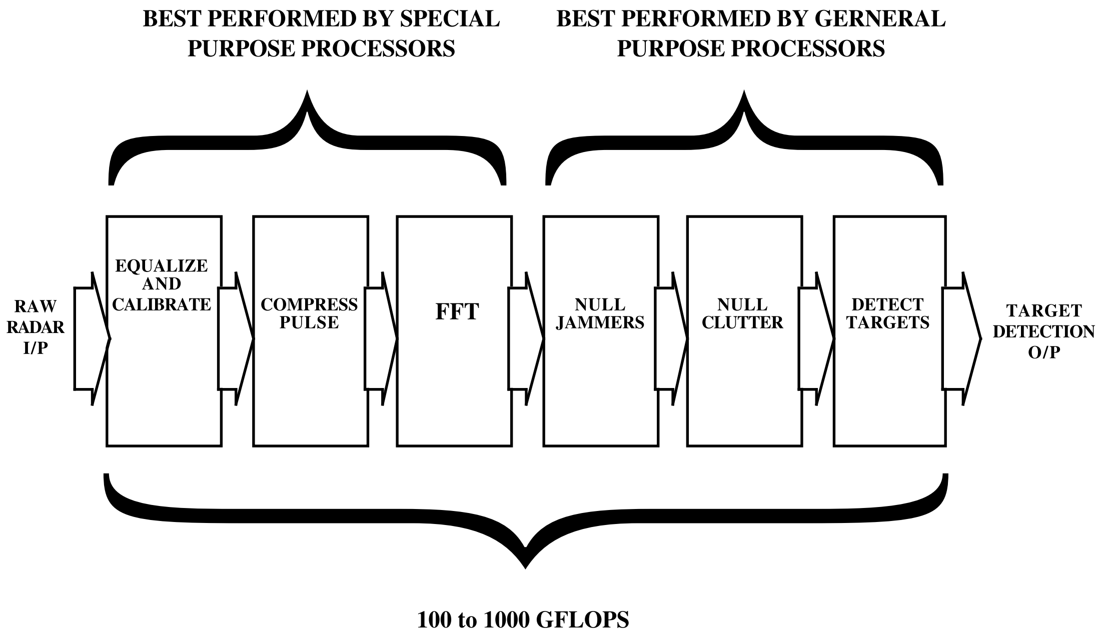


Figure 6-12. Generic Space Time Adaptive Processing Algorithm

State of the Art Sensing

Today we have digital sensors with adaptive and aided detection and context-based displays. Getting the tactical operator involved in the system by allowing real time control over the sensor reflects, at least approximately, the current state of the art in tactical sensing. Indeed, over a number of years avionics systems have been evolving toward more integrated and "open" architectures. Today's typical weapon system has integrated multifunction displays and controls and in some cases, such as the F-22 aircraft, a common processor for all sensor functions.

Future Vision

In addition to the improved cost-performance possible from increased signal processing, discussed above, future vision for sensing systems includes improvements that may be as revolutionary as that obtained from the innovation of digital signal processing. These additional technology innovations include wide area digital communications, improved processing algorithms, and methods for fusing and displaying sensed data.

Wide area digital communications makes it possible to connect multiple sensors together over large geographic regions. High performance computing can then fuse the individual sensing products into one, better, product. Data from *supplementary* sensors (i.e., sensors that are the same as, or similar to, the primary sensor) improves sensing accuracy by averaging noise and improving geometry. Data from *complementary* sensors (i.e., sensors that are basically different from the primary sensor) improves sensing utility by adding information that is otherwise unobtainable.

The requirements are growing for more sophisticated physical/mathematical algorithms to more effectively interpret and fuse existing measurements. This indicates the need for *vigorous* development of application specific processing algorithms.

Fusion algorithms, like detection algorithms, are arithmetically intense. They include Kalman filters, multiple hypothesis trackers, optimization solutions and optimal association/correlation, plus many other algorithmic technologies heretofore unexplored because of lack of processing power. Fusion throughput estimates for an advanced radar system such as Joint STARS approach the 100 GFLOPS level, and next generation systems can easily be expected to require an order of magnitude throughput.

A key part of this concept is development of algorithms of "smart" resource managers that can adaptively allocate the apertures and "back-end" resources that will meet critical mission timelines. Control of the elements of Figure 6-13 from millisecond to minute time increments will be required for adequate control of most timeline requirements. Of particular importance are the limits of communication bandwidths that effectively define the amount of onboard processing and data compression that a given sensor system must provide to realistically be a *supplementary* or *complementary* element of such a "fused" system. For example, data compression based on not retransmitting images of huge areas where conditions are unchanged is certainly called for, and is being pursued quite vigorously in the commercial field for video phones, entertainment and the like.

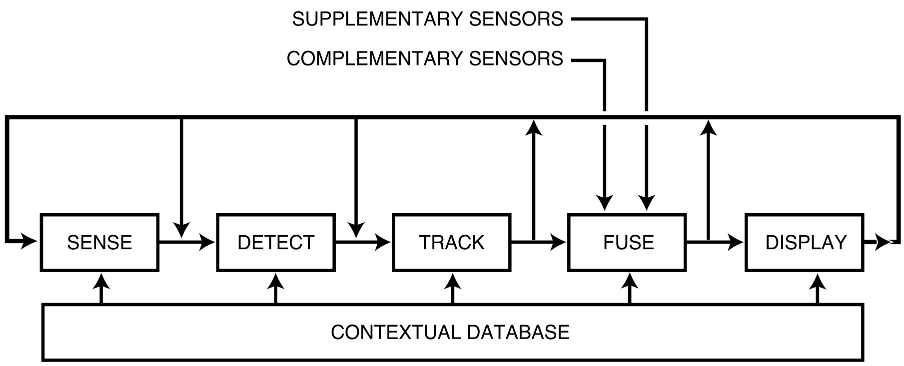


Figure 6-13. Future Sensing With External Sensors and Complex Interconnection

Another future sensing capability involves connecting the innate processing power of the human brain directly into the system. Virtual reality is only just beginning, but the possibilities for revolutionary improvement are apparent (Figure 6-14). The primary technology driver in this case is in algorithms for image generation—how sensor products can be rendered onto a display immersing the operator with complete situational awareness. Current technology supports two-dimensional imaging, while full three-dimensional virtual reality displays may be needed for realistic, next generation tactical applications.

As already discussed, a primary theme of this volume is that a complex system of systems is envisioned to operate over a military theater. As indicated in Figure 6-15, these systems include multiple sensors and multiple airborne and ground-based platforms. They will observe

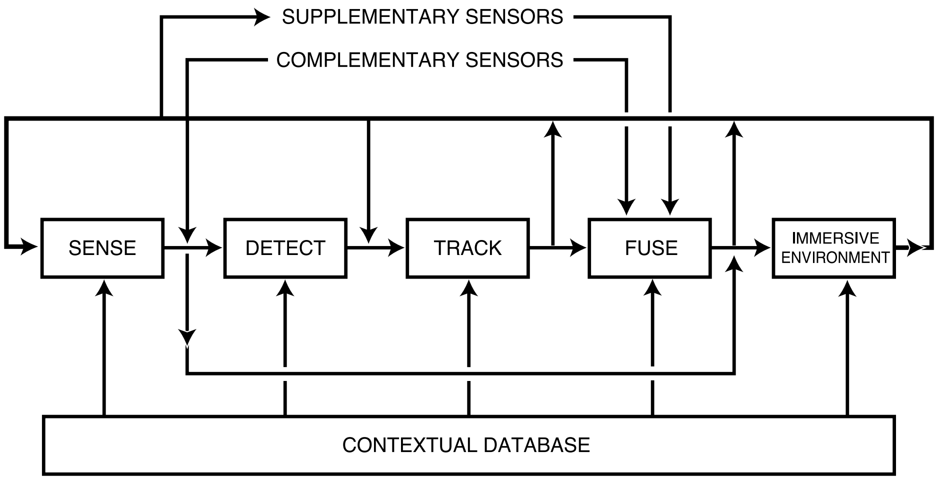
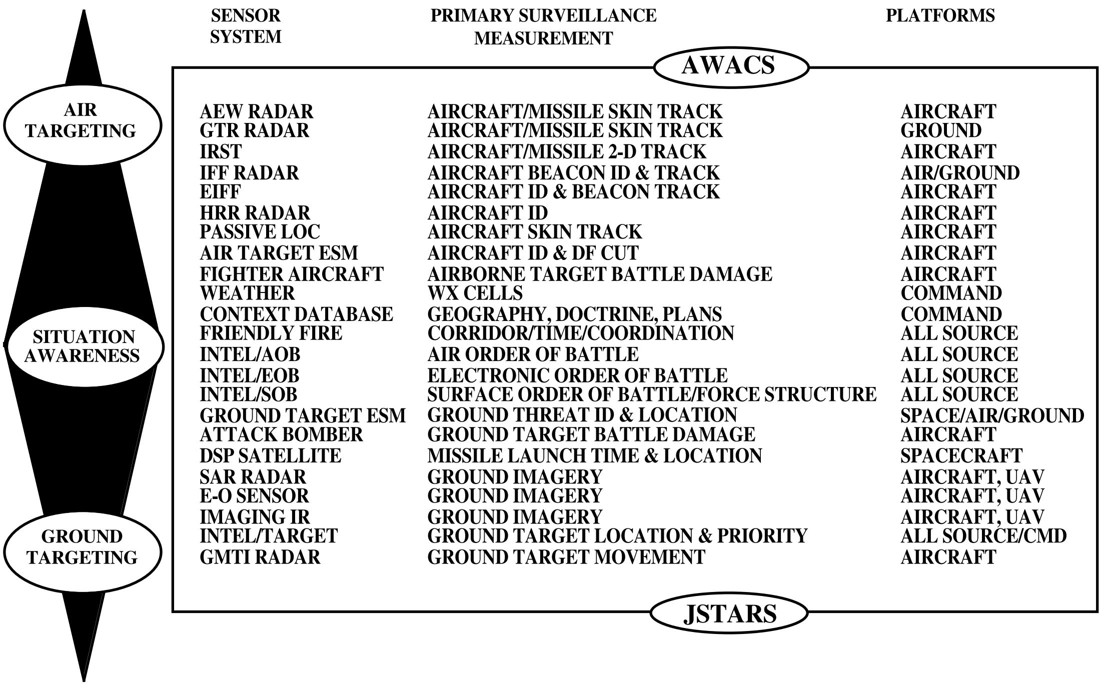


Figure 6-14. Sensing With Immersive Virtual Reality

and measure vast volumes of airspace and large areas on the earth's surface. Representative sensors and data sources shown in Figure 6-15 span the theater surveillance spectrum from air and ground targets to overall situation awareness.



SENSOR SYSTEM	PRIMARY SURVEILLANCE MEASUREMENT	PLATFORMS
AEW RADAR	AIRCRAFT/MISSILE SKIN TRACK	AIRCRAFT
GTR RADAR	AIRCRAFT/MISSILE SKIN TRACK	GROUND
IRST	AIRCRAFT/MISSILE 2-D TRACK	AIRCRAFT
IFF RADAR	AIRCRAFT BEACON ID & TRACK	AIR/GROUND
EIFF	AIRCRAFT ID & BEACON TRACK	AIRCRAFT
HRR RADAR	AIRCRAFT ID	AIRCRAFT
PASSIVE LOC	AIRCRAFT SKIN TRACK	AIRCRAFT
AIR TARGET ESM	AIRCRAFT ID & DF CUT	AIRCRAFT
FIGHTER AIRCRAFT	AIRBORNE TARGET BATTLE DAMAGE	AIRCRAFT
WEATHER	WX CELLS	COMMAND
CONTEXT DATABASE	GEOGRAPHY, DOCTRINE, PLANS	COMMAND
FRIENDLY FIRE	CORRIDOR/TIME/COORDINATION	ALL SOURCE
INTEL/AOB	AIR ORDER OF BATTLE	ALL SOURCE
INTEL/EOB	ELECTRONIC ORDER OF BATTLE	ALL SOURCE
INTEL/SOB	SURFACE ORDER OF BATTLE/FORCE STRUCTURE	ALL SOURCE
GROUND TARGET ESM	GROUND THREAT ID & LOCATION	SPACE/AIR/GROUND
ATTACK BOMBER	GROUND TARGET BATTLE DAMAGE	AIRCRAFT
DSP SATELLITE	MISSILE LAUNCH TIME & LOCATION	SPACECRAFT
SAR RADAR	GROUND IMAGERY	AIRCRAFT, UAV
E-O SENSOR	GROUND IMAGERY	AIRCRAFT, UAV
IMAGING IR	GROUND IMAGERY	AIRCRAFT, UAV
INTEL/TARGET	GROUND TARGET LOCATION & PRIORITY	ALL SOURCE/CMD
GMTI RADAR	GROUND TARGET MOVEMENT	AIRCRAFT

Figure 6-15. Theater Surveillance Spectrum

In the next sections are a few specific examples that illustrate the use of advanced processing to make high performance sensors more affordable.

6.2.4.1 Relaxed-Optical-Tolerance Imaging

Future Air Force Requirement

In the next several decades, the Air Force will have an increased need for fine-resolution optical imaging of targets and scenes of interest. Acquiring such imagery on demand for any place on the globe will be challenging but essential, given the increasing mobility of enemy threats and terrorists and the rapid pace with which events can unfold. The need for these capabilities suggests that a very large number of space-based optical platforms (providing global coverage), each having large aperture (providing fine-resolution imaging), will need to be designed and deployed.

Using current technology, a space-based optical platform with a large aperture would be very heavy to insure structural integrity and rigidity. It would also be cumbersome to deploy. Finally, fabrication of the large optical elements to optical tolerances would be a time-consuming effort. These factors make the design, building, and deployment of multiple platforms prohibitively expensive.

Technology Solution

A candidate solution to the current technology shortfall is to relax optical tolerances (thereby reducing weight) on the primary mirror(s) and recover the loss with post-detection processing. The driving principle is to "trade mass for megaflops." This is a favorable trade-off, given the cost/performance trends in computing technology. By allowing optical tolerances in the primary collector to be relaxed, we seek (1) a significant reduction in structural weight, (2) simplified deployment, and (3) reduced fabrication expense. There are many designs for the primary collector that could be considered. For example, the primary collector might be non-rigid (floppy), monolithic or segmented, filled or sparse. It could be a very thin mylar surface stretched over a skeleton structure that could be deployed like an umbrella. It may be important to design for a small compensating element conjugate to the primary collector to compensate for gross figure errors (larger than a wavelength) in the primary. Such compensation could be passive (fixed) or possibly active with a large dynamic range. Residual aberrations would then be overcome with post-detection processing. Algorithms such as *phase diverse spectral imaging* or multiframe blind deconvolution that uses multiple short-exposure (relative to changes in aberrations) images could be used to get optimal image reconstructions.

Current Status

Several advanced algorithms that perform post-detection correction of turbulence-induced blur have recently been developed. One such algorithm, called *phase diverse speckle imaging* has been used with great success to restore near diffraction-limited images of solar features in the presence of turbulence-induced aberrations. This algorithm requires that an in-focus (but blurred) and an out-of-focus image pair be collected for each of several aberration realizations. The algorithm converts the time series of image pairs into a near diffraction-limited image. The algorithm works extremely well in high-signal regimes, such as is encountered in ground-based solar astronomy or space-based imaging of the earth. Special cameras are needed that can collect short exposure images and provide rapid readout with low noise. Such camera technology is rapidly developing for use as a component in wave-front sensors which in turn are used in adaptive optics. The phase-diverse speckle computations are dominated by two-dimensional fast Fourier transforms (FFTs). A refined reconstruction currently takes (conservatively) on the order of 1000 J FFTs, where J is the number of aberration realizations, and each two-dimensional FFT requires $\log_2 N^2 / \log_2 N$ floating-point operations, where N is the number of pixels on the side of an image. For N = 128 and J = 10, we require approximately $2.3(10)^9$ operations. A current single-processor Sun Sparc 20 workstation operates at about 40 MFLOPS so that a single reconstruction would take about a minute. The computations are highly parallelizable and special-purpose FFT chips could be employed to dramatically increase the computational speed.

Phase-diverse speckle is an example of an algorithm that could logically be developed and adapted for use in relaxed-optical-tolerance imaging, where fewer parameters might be needed to model the structurally induced aberrations.

Commercial Applications

Deploying a constellation of low-cost space-based optical platforms with the capability to perform fine-resolution imaging over the entire globe would have significant commercial and scientific value for use in natural-resource management, environmental studies, and ocean studies.

Impact on Affordability

The proposed technology is motivated by large savings in the cost of fabricating and deploying large primary mirrors in space.

Recommended Development Plan

The development of *relaxed-optical-tolerance imaging* technology requires a coordinated investigation of the kinds of time-varying aberrations that would be introduced with relaxed structural tolerances (by differential solar heating, mechanical vibrations, etc.) and the kinds of aberrations that can be accommodated while maintaining fine-resolution using post-detection processing. Once such aberrations are well defined, various system designs can be investigated, leading to a final design to be built and tested. Post-detection algorithms need to be further developed and adapted to the system concept. The speed of these algorithms can be increased to provide near real-time reconstructions. The development of small compensation elements with large dynamic range that actively correct gross aberrations needs to be investigated. There are also optical-design issues regarding compensation of gross aberrations that need to be resolved.

6.2.4.2 Thinned-Aperture Optical Receivers for Light-Weight Satellites

Technical Concept

One example of a sparse aperture for advanced, large-aperture, optical-reconnaissance satellites is illustrated in Figure 6-16. First, the receiving telescope aperture comprises three segments, thinned to approximately 10 percent of a fully filled aperture. Second, the telescope segments fold to a compact package for launch. Third, when deployed in space, the telescope optics are under active control to maintain alignment and image quality. Fourth, sophisticated image-restoration techniques are employed, so that the performance of the thinned receiver approaches that of a fully filled receiver.

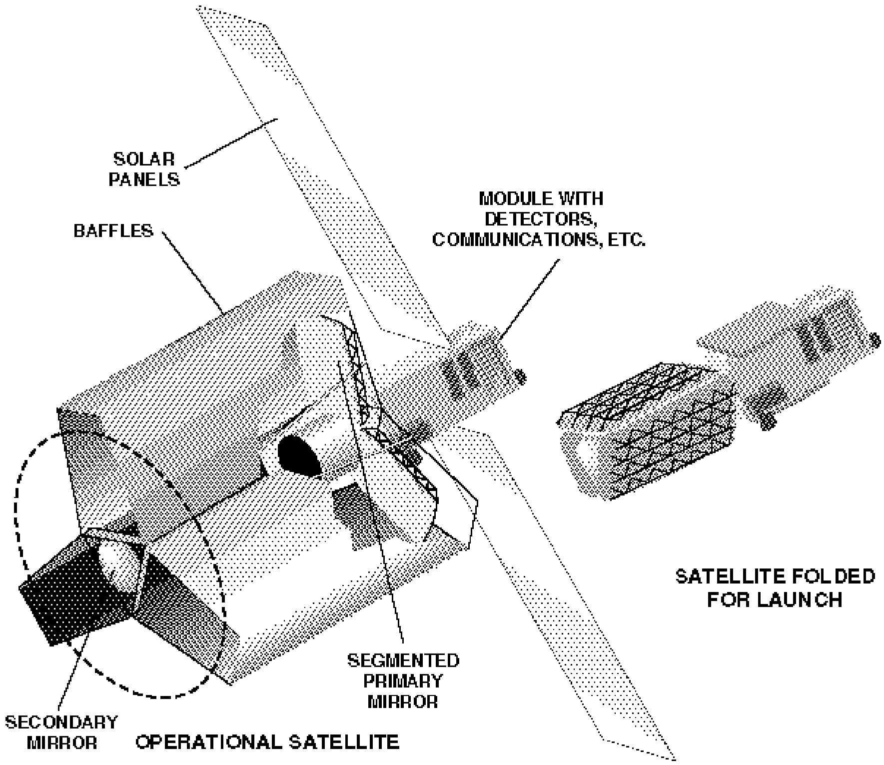


Figure 6-16. Thinned-Aperture Concept

Performance Analysis

Image-restoration algorithms have been developed to process data from a thinned aperture, and the performance has been analyzed using real satellite imagery. To provide a visual demonstration of the potential utility of a thinned-aperture system, a stressing case involving a collector having a fill ratio of only 10 percent was selected for analysis. The specific design is shown in Figure 6-17. Because such a large fraction of the collection area is removed, the high spatial frequencies collected by this system are heavily attenuated and must be restored in the image processing.

To test the image restoration, visible imagery collected by the LANDSAT satellite was used. Figure 6-18a shows the scene as viewed by the full circular aperture. The raw data from the thinned aperture defined by Figure 6-17 is given in 6-18b, which shows considerable smearing and evidence of a point spread function having six-fold symmetry. Partial restoration is achieved for an average signal-to-noise ratio of 10, as indicated in Figure 6-18c. Nearly perfect restoration is achievable at a signal-to-noise ratio of 100, which is graphically illustrated by Figure 6-18d.

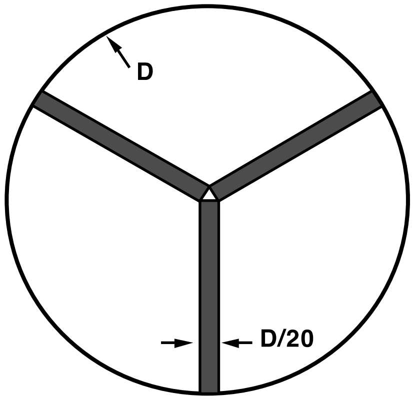


Figure 6-17. Illustration of a Three-Segment Thinned Aperture Having an Outer Diameter of D and Segments of Width D/20. The collection area of the design shown in this figure is approximately 10 percent of the full-aperture.

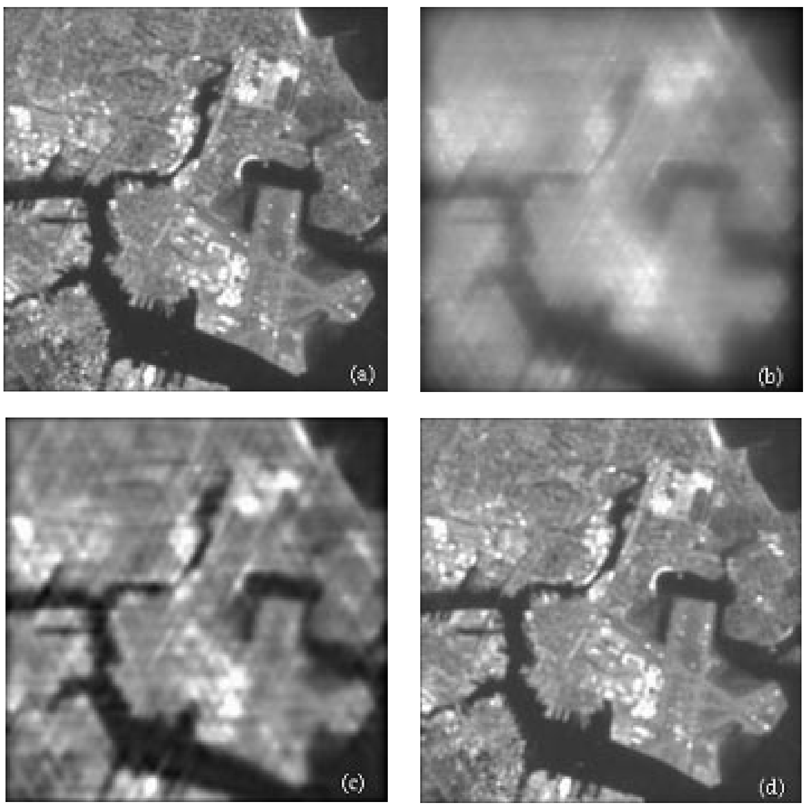


Figure 6-18. Comparison of Images Obtained From (a) a Diffraction-Limited Circular Aperture, (b) a Tri-Petal Receiver Having a 10 Percent Fill Factor, (c) Wiener Deconvolution for S/N=10, and (d) Wiener Deconvolution for S/N=100.

Mission Applicability

This system concept is applicable to virtually all space-based optical reconnaissance, surveillance, and remote-sensing missions. It can be used for both infrared and visible wavelength sensors. It can also be used for active laser radar and LIDAR systems.

Because the concept permits high-altitude, high-resolution systems, it would be ideal for surveillance applications requiring continuous coverage. For instance, it could be used to provide a continuous situation-awareness picture of a battlefield or continuous surveillance of the manufacture, storage, and transfer of weapons of mass destruction.

The thinned-aperture concept is useful for systems to acquire, locate, and track air and ground targets. It can also be used for systems to perform space surveillance from space.

System Benefits

The thinned-aperture concept offers two significant advantages compared to conventional filled-aperture telescopes:

- It would have much lower weight (by perhaps a factor of 5) and a much lower launch volume.
- It can be scaled to very large apertures (i.e., tens of meters).

For any given aperture diameter (and thus resolution), the thinned-aperture concept will be able to use a smaller launch vehicle. Thus, there will be major cost benefits. Thinned apertures may also be made in sizes where it is inconceivable to fabricate or launch conventional telescopes. These very large apertures permit the construction of very high-altitude, high-resolution systems. Such systems can give continuous ground surveillance from relatively safe orbits.

The thinned aperture concept also offers benefits compared to a coherent array of telescopes, which is another method for achieving very large effective apertures in space. Thinned apertures do not have fundamental limitations on angular FOV, as do coherent arrays, and thus are superior for wide-area surveillance. In addition, the active alignment and phasing system is simpler for the thinned aperture than it is for coherent arrays.

Recommended Development Plan

The development plan for the thinned-aperture system should include the following elements:

- **Ground Demonstration Tests.** These tests would demonstrate the critical functions of unfolding the primary-mirror segments, deploying the secondary mirror, controlling the figure of the primary-mirror segments, and phasing the mirror segments to form a coherent image. The ground tests would start at modest size (~2 m) and scale up to greater than 10 m.
- **Detailed Conceptual Design**. It would be helpful to do a detailed conceptual design for a far-term application—perhaps for a high-altitude, tactical reconnaissance system. Such a design would help guide the technology development.

- **Near-Term Space Demonstration**. This test would demonstrate the thinned aperture concept at a small scale (perhaps 1 to 2 m). Such a demonstration could be done as a low-altitude, small satellite package.

6.2.4.3 Space-Time Adaptive Processing

Airborne radars must deal with interference in their sidelobes that can obscure the desired targets. Two kinds of interference are prominent. Returns from the ground enter through the sidelobes as clutter; unlike sidelobe clutter in a ground based radar, this clutter has a nonzero Doppler shift as a result of the relative motion of the radar and the ground. Jammers can also get energy into an airborne radar through the sidelobes. There are a number of techniques available to mitigate this interference. The most straightforward approach is to build an antenna with low sidelobes; this approach is used, for example, by the E-3A. However, this can be very difficult, as it requires very careful consideration of the antenna, radome and aircraft interactions. These difficulties make this approach very expensive and limit the practical sidelobe levels. With an array antenna, better performance against jammers can usually be obtained at lower cost using adaptive nulling; that is, by choosing the weights of the elements, in real-time, to put a null in the antenna pattern in the direction of the jamming signal. This has been deployed for GPS receivers and communication systems. A simple version, sidelobe cancellers, is in fairly common use on surface based radars.

Adaptive nulling needs to be modified for sidelobe clutter, which comes from all aspects. The Doppler shift of any piece of clutter depends on the angle between the velocity of the platform and the vector between the platform and patch of ground. Thus, if one can choose element weights independently for each Doppler filter, one could null out the sidelobe clutter that contributes to that filter. This is called space-time adaptive processing (STAP). To implement STAP requires a receiver for each element and extensive processing power. Modern computer technology makes the processing possible. The advent of sufficiently fast A/D converters to allow an all-digital receiver will make it possible to fit a STAP system in smaller and cheaper packages.

STAP has application to any airborne radar. It is of particular value to radars that are looking for low flying, low radar cross section targets such as cruise missiles. If an adaptive nulling or STAP system could be fit into a missile, it would have great benefit in defeating monopulse endgame countermeasures such as towed decoys and ground bounce jammers. In addition to allowing improved performance at lower cost than conventional low sidelobe antenna designs, adaptive techniques can allow the use of antennas that would otherwise have unacceptable patterns but may be desirable for other reason, such as reduced RCS.

There are a number of other signal processing ideas and applications that rely on ideas similar to STAP. For example, a synthetic aperture radar usually forms a beam that is focused for a particular target velocity, usually zero. With post-detection processing, simultaneous SAR beams can be made, each one focused for a different velocity.

To date, STAP has not been deployed in any fielded system, but there have been field test programs, so this technology should be ready for a development program. This technology must be considered seriously for next generation airborne radar systems.

6.2.4.4 Advanced Airborne MTI

Introduction

As another example of enhanced sensing through signal processing, we discuss advanced airborne MTI radar systems in this section.

MTI systems are important to the military since most targets of interest are in motion at one time or another. Many targets are most vulnerable or pose the least threat when in motion. Many targets are often well hidden when not in motion. Moving targets are hard to conceal/camouflage. Motion of a target is a strong indicator that it is still functional and has not been disabled. From a low intensity conflict perspective, tracking specific vehicles in traffic provides information related to drug trafficking, NBC weapons production and capability, and terrorist movements. The ability to detect/classify these targets in this scenario is, therefore, operationally very important.

MTI systems provide ideal applications to demonstrate and exploit the technological developments in high performance computing. Real-time radar signal processing requirements stretch a digital system's input speed and bandwidth, and the various MTI algorithms (both detection and exploitation) create a requirements pull for scaleable software engineering. MTI sensors benefit through product improvement in radar processing and packaging, as well as through a technology push for backend exploitation of sensor products.

MTI radars are sensors optimized to reject signals from fixed or slowly-moving, unwanted ground clutter such as buildings, terrain and precipitation while retaining for detection and display returns from moving targets. Targets move when they want, not necessarily when it is convenient for a sensor to see. Consequently, day/night, all weather capability is required to find and track moving targets. This motivates the use of radar based MTI systems as opposed to EO systems. As a principal sensing element of an air-to-surface search radar or airborne battlefield surveillance/management system, MTI radars will continue to evolve from their current modes, performances, sensitivities and discrimination capabilities as driven by overall system operational concepts and performance requirements of future Air Force missions. (See Figure 6-19.)

The MTI elements described by this section will more likely require mainly *evolutionary* advancement in sensor and platform implementations. However, system architectures described earlier in this document will show significant potential in effecting *revolutionary* advancement in mission capabilities. Performance gains are expected to be brought about by:

- Projected advancements in computational throughput
- Real-time sensor product creation, fusion and exploitation
- Collocation (in a theater sense) of a wide variety of sensor types
- Automated cross-cueing for on-board and external sensors

Data Rates and Volume

As an element of an integrated "system of systems" in support of the operational tasks described in Section 4, MTI sensors will be required to survey ever larger areas of interests (AOIs) at increasingly higher revisit rates and resolutions. Typical examples of these requirements might be to survey an Army Corps area of some 40,000 km^2 AOI every 5 to 10 secs at resolutions of 5 to 10 meters. These numbers drive sensor output data rates and signal processing requirements to an order of magnitude beyond today's current capabilities.

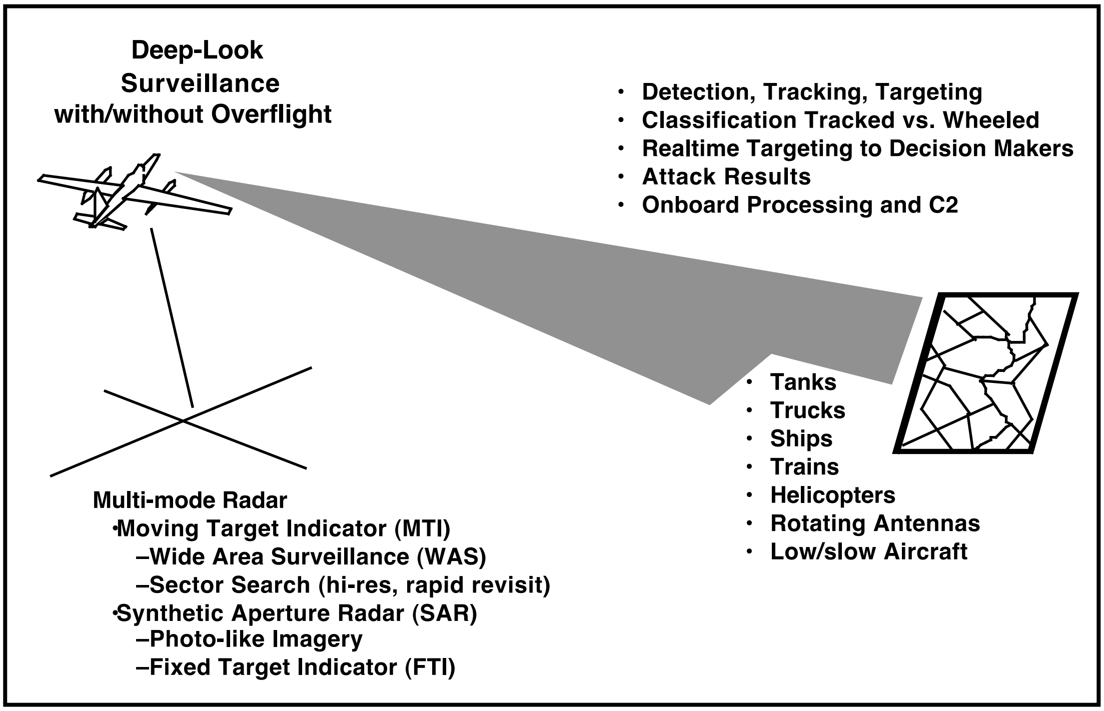


Figure 6-19. Nominal MTI System

Improved Sensor Performance

To meet the demanding operational requirements leading to the above mentioned data rates and volumes, *nominal* performance gains in sensor A/D technology, affordable high power T/R modules and adaptive multichannel antennas will need to be developed. Auto calibration techniques should allow for utilization of lower performance but fully characterized array elements such that sensor level integration of these elements compensates, at a system level, for component level limitations. For example, full system level adaptive processing techniques to include calibration techniques to control antenna sidelobe level, jammer nulling and sidelobe cancellation could significantly reduce the cost for next generation antennas.

Many of the major challenges in moving target imaging can be circumvented by some enabling technologies. Some of the technologies are very straightforward and others somewhat subtle:

- **Faster Platforms**. This provides the ability to synthesize large apertures for fine resolution or multispectral collections quickly. This mitigates the smearing of the signature and reduces the amount of refocusing that must be applied.

- **Single Transmit—Multireceive Platforms**. This is another approach to Faster Platforms mentioned above. With multiple receive platforms, the aperture can be synthesized more quickly and provide finer resolution with less motion smearing.
- **Dynamically Changing PRF**. This provides two benefits. The first is that the PRF would change according to a perceived target motion during collection. This serves to provide a constant sampling rate over the collection aperture which minimizes IPR distortion in the focused target. In addition, this feedback may provide a means to actually change the platform velocity vector to enable the finest possible resolution in the least amount of time.
- **Phase History Based Algorithms**. Applying the focusing algorithm directly to the SAR phase history as opposed to first forming a defocused image has a number of advantages. The first is that sophisticated time series models can be used to predict the target motion, which would help in focusing. The second is that it may be more robust to apply the ATR algorithms directly in the phase history domain and not bother refocusing the signatures.
- **Coded Waveforms**. If there is some prior knowledge regarding the specific target motion (e.g., it will be going through a specific bend in a specific road), the transmission waveform may be coded such that the target of interest is maximally separated from the competing clutter. This would be especially useful in tracking where the target type is already known. The waveform can then be designed for that particular target signature and expected motion.

One advantage of improving MTI radar systems to include SAR based mechanisms for imaging moving targets is the leverage gained with improved and advanced processing for basic SAR image formation. Specifically, in recent years there have been great advances in linear and nonlinear spectral estimation techniques. The techniques have shown promise to provide increased mainbeam resolution, reduced sidelobe levels, and clutter discrimination in a wide variety of radar applications. The algorithms also have the characteristics of being very computer intensive. With the advances of computer technology, the algorithms are soon to be practically implementable for operationally interesting image sizes.

Improved Asset Management

Figure 6-20 is an example of today's MTI system operating over a Corps area. Indicated are a multitude of MTI radar modes to support mission objectives. However, most of today's current MTI modes are driven by resolution and revisit rates where a next generation should eliminate this need by supplying full sensor capability over the entire wide area **simultaneously**. This then enables target track and enhanced target discrimination on all targets.

Elimination of currently redundant MTI radar modes makes possible the scheduling of sensor resources for new and innovative MTI modes such as terrestrial inverse SAR (the imaging of many moving vehicles), enhanced helicopter and slow flying aircraft identification. These new MTI techniques are driven by time-on-target and SNR requirements for development of discrimination signatures, time that is viable only with improved asset management.

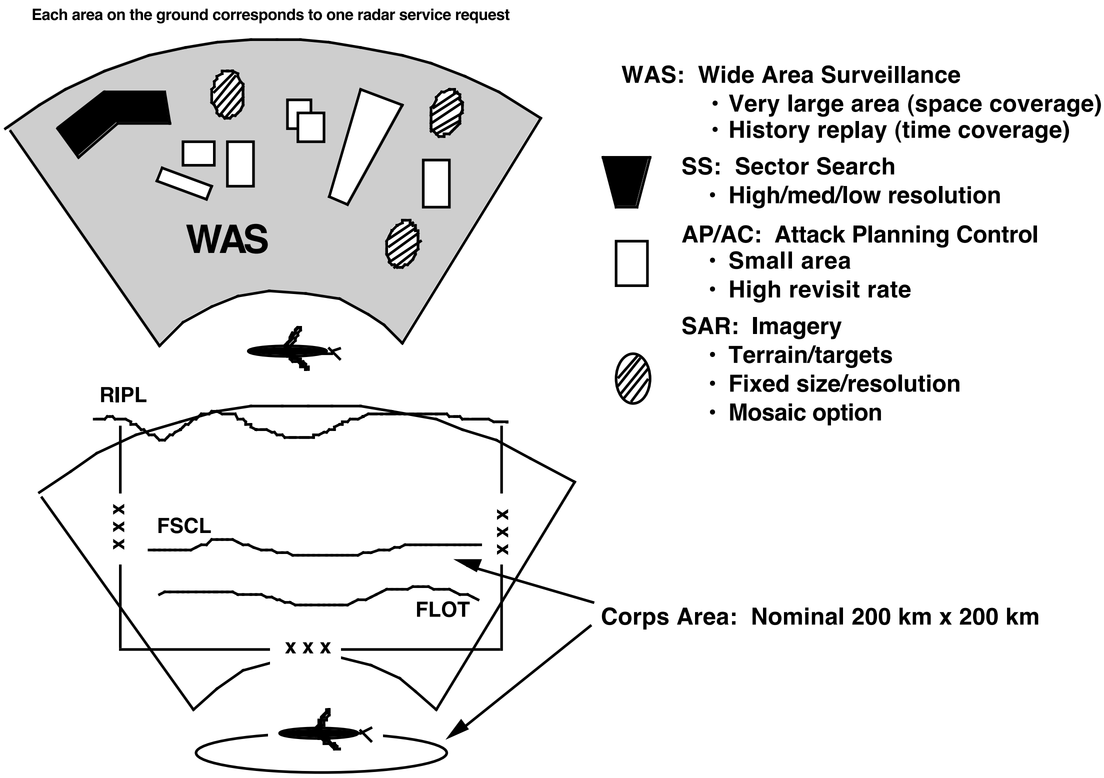


Figure 6-20. Notional MTI System Operation Over Corps Area

The major challenges in detecting/classifying moving targets stem from the size of the targets of interest and the many competing moving objects that may be in the same scene. Previous successes in the refocusing of moving objects have been with large targets. Currently, there is a large amount of research in exploiting fine resolution SAR data to detect and refocus the moving target such that ATR algorithms can be applied for classification. The challenges are:

- Smaller targets motivate finer resolution systems. In SAR, this translates into longer dwell times. Even though the target motion itself can translate into finer resolution through enhanced rotation, there is no control over target motion so there is no guarantee of enhanced resolution.
- Competing moving objects may defocus onto the energy of the target of interest. This added clutter will contaminate the target signature and degrade performance of the focusing and ATR algorithms.
- Focusing algorithms require prominent points to track motion and focus. Performance is degraded by low target-to-clutter ratio either via target signature reduction or high competing clutter.

- The timing of the moving object being in the collection beam of the SAR is tenuous. SAR beamwidths are not so large as to guarantee that a cued moving target will be in the beam.
- The ATR algorithm suite needs to be redesigned since the targets will not be refocused perfectly and the target motion actually changes the sidelobe structure of the SAR IPR. Classic template matching or model based vision algorithms may need to be completely redesigned.

Additional enhancements are summarized for MTI sensors in Table 6-4.

Table 6-4. Sensor Technologies Specifically Applicable to MTI Radars

Technology	Operational Benefit	Area of Improvement Required
Higher degree of dimensionality	Improved Target Discrimination	• Wider operating and instantaneous bandwidth supporting combat ID • Range resolution improvements by a factor of 5-10 • Improved ECCM capability • Higher PRFs for signature development of: helicopter classification tracked/wheeled • Additional MTI radar modes: terrestrial inverse SAR maritime inverse SAR • 2-D active electronically scanned antenna (ESA)
	Enhanced Countermeasure Resistance	• Higher SNR allows smaller target features to be observed • Improved target location accuracy
Adaptive behavior	Enhanced Clutter Rejection & Countermeasure Resistance	• Massively parallel signal and data processing: full STAP 5-10x wide area surveillance update rate • Simultaneous MTI and SAR data collection • Non-conventional signal processing management • Improved ECCM/EMI • Expanded bandwidth • Adaptive beam processing • Automatic sensor resource management • Auto track of any MTI
	Enhanced Operator-System Interaction	• Automatic system health and reconfiguration • Operator interfaces and control
Data fusion	Enhanced Target Detection/ Classification/Identification Redundancy in Critical Functions	• Additional radar modes high resolution large swath SAR interferometric SAR ATR Elements object identification change detection • Area Delimination • Smart scheduling

Development Status of Advanced Airborne MTI

Despite a continuing need to observe *real-time movement* of ground forces on the battlefield at extended ranges, this capability did not exist for wide area coverages until very recently, with development of the U.S. Air Force/U.S. Army system, Joint STARS and for smaller area coverage with helicopter-borne systems like the French HORIZON and Italian CRESO.

While the physics of moving target radar surveillance has been well understood and employed on less sophisticated systems for many years, the technology needed to provide the signal and data processing capacity for wide area surveillance and the detection of slow moving ground and low flying airborne targets has become available only within the last decade. In the early 1980s, the Air Force's PAVE MOVER and Army SOSTAS programs demonstrated conclusively the combined power of emerging digital processing technology and sophisticated radar processing algorithms to detect slow moving targets. As an outgrowth of this program, in 1985 U.S. development was beginning on the Joint STARS featuring a powerful multimode ground surveillance radar system and sophisticated command, control and battle management capabilities installed in a militarized Boeing 707 aircraft. In less than 5 years, the Air Force, the Army and OSD (recognizing the immense potential value of this MTI system) extracted the Joint STARS system from development and deployed it to the Persian Gulf for Operation Desert Shield/Storm

The technologies needed to field an order of magnitude improvement in MTI radar sensors in the next 20 years are near or on the horizon. Specifically, processing technologies will continue to derive benefits from commercial developments and, therefore, enhanced radar algorithms for deriving maximum performance from collected RF should continue at a rapid pace.

Elements of the sensor proper associated with the antenna will continue to be driven by the need for low cost, high performance T/R modules and subarrays as well as the RF electronics. Support of continuing efforts in the technological development of these components will be necessary to insure low cost sensors for the future.

Research into additional ground clutter phenomenology needed for development of enhanced algorithms for even higher levels of space-time-adaptive processing must also continue. As digital processors provide near limitless capacities, newer and more sophisticated detection and identification algorithms need to be developed.

6.2.5 Automatic Target Recognition (ATR)

Introduction

The capability to reliably and automatically recognize sensed visual, IR, and radar images or electronic signatures will provide significant operational benefits to the Air Force in mission areas requiring rapid target identification, intelligence data analysis, and battle damage assessment. The state of the art of (spatial) pattern recognition does not yet provide sufficient accuracy or reliability to perform independent and unambiguous ATR for lethal attack in all mission applications, but it does provide the ability for rapid screening and cueing to support the warfighter.

Current commercial technologies in spatial modeling, geospatial information systems and automated reasoning are being leveraged to support model-based vision developments to expand the performance envelope of commercial pattern recognition systems. We recommend that the Air Force: (1) Expand the model-based technology developments for imagery to include full hybrid ATR including all-source context, (2) Expand and coordinate technology developments to extend model-based reasoning to multiple-sensor applications, and (3) Leverage commercial neural network, image understanding and spatial database technologies to augment model-based ATR with additional contextual data

6.2.5.1 Pattern Recognition Technology Description

Pattern recognition technology provides the capability to automatically discriminate objects or events in visual (2-D or 3-D) imagery, IR and radar imagery or non-image (e.g., SIGINT or acoustic) sensed data. Pattern recognition has applications in military intelligence, security, targeting, real-time target identification, industrial robotics and medical diagnosis. In Air Force mission applications, pattern recognition technology is most often applied to ATR problems.

Technology Description

We can illustrate the general ATR process by describing the application for detecting, locating and targeting objects from surveillance imagery. The ATR process includes a portion or all of the following cascaded stages, each of which performs a pattern recognition function:

- Detection/Bulk Filtering rapidly eliminates uninteresting areas in the surveillance data from further consideration, leaving regions of interest (ROIs) which exhibit target- like properties with respect to the features used for detection/bulk filtering.
- False Alarm Discrimination further removes from consideration those ROIs that are “non target like,” with respect to a more detailed and context-dependent set of features.
- Classification/Indexing associates a given ROI with one or more likely target classes (eliminates highly unlikely target classes from consideration).
- Recognition identifies specific type of object within a given class.

In general, the level of processing complexity increases with the progression from detection/ bulk filtering through recognition. Detection/bulk filtering must process wide geographic areas and is typically implemented using wide area sensors (search resolution SAR), very high speed relatively simple processing algorithms (CFAR, spatial morphology, area delimitation based upon terrain classification, etc.), and features that are independent of specific target attributes (amplitude, polarimetric features, size, etc.). The latter three stages process localized areas and may exploit higher resolution limited FOV sensors (IR, laser radar, ultra high resolution SAR), more demanding algorithms (neural nets, and model-based reasoning), and more target-specific features (texture, fractal dimension, and localized image signature attributes).

Development Status

The preponderance of current research effort in ATR has focused on detection/bulk filtering and false alarm discrimination. Applications of these processes have been successfully demonstrated against medium resolution (1 meter) SAR imagery using two-parameter CFAR, morphology-enhanced CFAR algorithms, and features such as shape descriptor, size, polarimetric purity, and texture measures such as fractal dimension.

While the most stringent criteria for residual false alarm rate (0.01 false alarms/km^2) in autonomous mode have not yet been achieved over all types of terrain, this technology is well in hand for large targets in the open, in low clutter regions. Heavy clutter and targets in "hide" conditions (deployed with CC&D, beneath heavy foliage, adjacent to urban structures, under bridges, etc.) still pose serious challenges to both ATR and sensor technologies. The performance goals and throughput requirements for autonomous detection/bulk filtering operations (medium and large targets in low to moderate clutter with limited CC&D) will be achieved by the end of the decade as techniques for area delimitation are improved and are more tightly coupled with the data processing algorithms and as special-purpose processors mature. Significant utility has already been demonstrated to support analyst cueing for wide area search target detection in a number of programs.

Target classification and recognition are somewhat less mature for two reasons. First, the dimensionality of the problem is significantly greater than for detection/bulk filtering, requiring much more sophisticated algorithms. Second, it is being realized that the use of multiple sensor dimensions offers a key advantage to, and may even be required for, robust target recognition across many scenarios. (Increased sensor dimensionality is discussed in Section 6.2.8.) Specific rigorous research on the selection and use of multiple sensors for target recognition has been slow to happen. The performance of classification and recognition processes is both target and clutter dependent. In addition, efforts to perform reliable automated recognition are confounded by increasingly sophisticated forms of CC&D.

Classification/recognition algorithms all operate by matching attributes of the measured (unknown) signature with *a priori* information about the potential targets that could be present in the scene. Algorithm technologies differ in terms of the type of information used to match, the way in which the *a priori* information is encoded, and the approach used for matching. The matching algorithm technologies which have been the focus of classification/recognition research fall into four broad categories:

- **Statistical Pattern Recognition**. Partitions the space of possible target identities according to how target signature attributes can be partitioned.
- **Neural Nets**. Models the information flow across components in the human brain to perform the reasoning process that matches pre-stored target features against the unknown to identify it.
- **Template Matching**. Codifies the topological structure of the target signatures for all possible unknowns from *a priori* data and matches this against the unknown signature to select its most likely identity.
- **Vision**. Applies reasoning based on incremental signature correspondence between the unknown and the signature properties of all feasible targets to determine the most likely identity of the unknown.

The bulk of the ATR algorithm research to date has focused on statistical pattern recognition (SPR), largely because it draws, in a relatively straightforward way, on well established research in estimation theory. The remaining three matching functions (neural networks, template matching and vision) have recently received increased attention to overcome some of the limitations of SPR that arise from the fact that target signature features seldom conform to the statistical distribution assumptions that must be made to support decision metrics.

The technology roadmap of ATR technology, applicable to ground target surveillance, is summarized in Figure 6-21 showing several legacy developmental systems and the key technologies that formed the basis of those capabilities. The Air Force successfully transitioned statistical pattern recognition to radar non-cooperative recognition applications (e.g., Dual Mode Recognizer) in the 1980s, but these techniques, alone, have not proved sufficient to solve image-based problems.

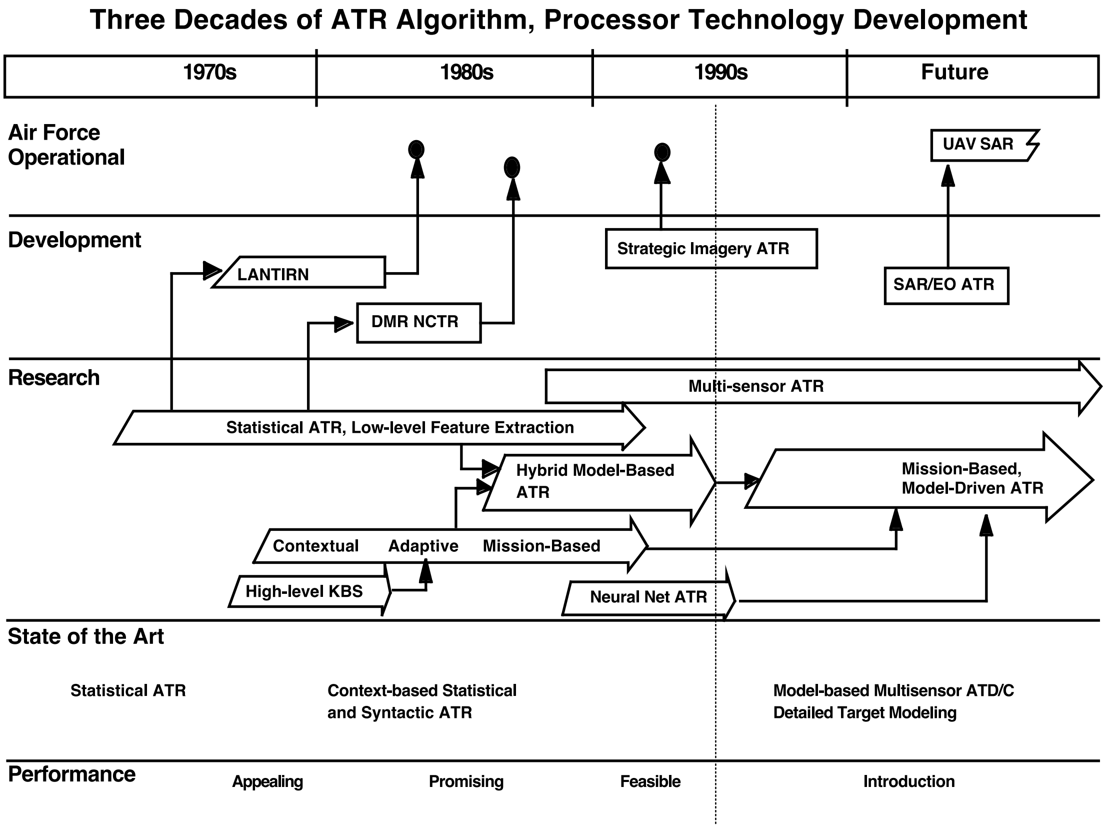


Figure 6-21. ATR Technology Roadmap (for Image-Based SAR and IR/EO Applications—llustrates the Move From Statistical Pattern Recognition Approaches to More Complex Vision Systems That Apply Mission Context Data

In this decade, the transition to *model-based techniques*, supported *by mission-based information* (e.g., precision map and terrain data, real-time fused intelligence data supplying accurate context) will provide ATR system performance improvements at the same time sensor resolutions are increasing, and multiple sensor data sources will provide greater observable dimensionality to discriminate targets. The matching technologies can be supported by *a priori* target characterizations that are data driven, model-based, or employ a combination of both.

Data-driven techniques characterize the signature attributes of the target based upon extensive processing of representative real signature samples (training). While these techniques capture all of the inherent properties of real data signatures, matching strategies that employ them fail or are severely degraded if the unknown signature does not conform to the target configuration or acquisition conditions embodied in the training data.

Model-based techniques codify the *a priori* information about unknown targets using an explicit model of the target geometry, coupled with a sensor model that transforms the target geometry into signature attributes. Model-based target characterization has the advantage that signature attribute predictions can be directly tailored on line to the specific conditions under which the unknown target signature was collected (observed), and thus can adapt real data that may not have been collected previously. The performance of model-based techniques, however, is critically dependent on the fidelity of the target geometry and sensor models in terms of predicting the expected signature attributes for matching. With the advent of improved techniques for target modeling and with higher fidelity and faster sensor models, the focus of recent research is shifting to the use of model-based techniques for target characterization.

The current state of the art in classification/recognition employs model-based techniques for target characterization, coupled with either vision-based reasoning or neural net based algorithms to support the matching function. While significant progress has recently been made in classification/recognition algorithms, the technology is not sufficiently mature in terms of performance, throughput, or miniaturization to support autonomous operation against a broad class of targets. However, the feasibility of the technologies has been demonstrated against sample real data target sets over a range of acquisition conditions. One near term application in which the technology should be pursued is its use in man-in-the-loop applications to support image analyst throughput improvement.

The current state of the art can be summarized in terms of the minimum research thrusts being performed:

- Detecting/identifying target groups (ships at sea, missile launch battalions)
  - Currently in development
- Detecting/identifying large targets in the open (port monitoring, airfield monitoring)
  - Cueing tools robust
  - Recognition possible with modest resolution
- Detecting/identifying small targets in the open (tanks, scuds)
  - Cueing tools robust
  - Recognition requires time resolution or polarimetry
- Detecting/identifying target in hide (tanks in trees)
  - Modest success with cueing; needs more testing
  - New advances in sensor technology
  - Advancements needed in recognition algorithm technology

- Detecting/identifying moving targets in low clutter
  - Cueing techniques in advanced development
  - Identification based on radar signal modulation or one-dimensional/ two-dimensional images shows some promise
- Detecting/identifying moving targets in strong clutter
  - Initial results encouraging; needs more testing
  - Needs development of recognition technology

In summary, ATR technology has had modest success across a spectrum of applications. The most successful application has been to aid the human analyst. The simple and direct problems in the hierarchy above are certain to receive significant gains from this technology. With the advent of improved observables, the use of ATR technology will quickly come to maturity.

6.2.5.2 Relationship to Key Air Force Missions

Pattern recognition technology is applied to automatic target recognition in numerous application areas that require rapid searching of large volumes of data, sorting of events and objects, and accurate identification of those events and objects.

Specific Applications

A wide range of Air Force mission areas, identified in Table 6-5 currently apply or are candidates to apply ATR in the future. The table summarizes the applications and potential enhancements that may be provided by ATR.

The contributions of pattern recognition, across all applications, can be grouped into one of four areas:

- **Capability to Support Expanding Imagery Workloads**. ATR will provide the critical capability to screen (detect) and ultimately classify/identify targets in the ever expanding volume of image data that is becoming available to Air Force warfighters. Unmanned Air Vehicles (e.g., Tier 2+, 3-), commercial satellite sensors and GIS data sources will provide a deluge of data that must be automatically screened and processed.
- **Improved Detection/Identification Accuracy**. ATR provides the potential to use all available elements of information to achieve higher detection performance (higher P_d, at a given P_{fa}) than achievable by human operators only.
- **Improved Detection/Identification Speed**. ATR also provides speed enhancements over aided (semi-automatic) or manual analytic recognition approaches.
- **Reduced Warfighter Workload**. ATR reduces the workload for pilots, intelligence analysts, planners, and commanders, allowing them to focus on higher-level tactics rather than information screening.

Table 6-5. Air Force Representative Operational Tasks and Related ATR Applications

Operational Tasks	ATR Application(s)	Enhancements Provided by ATR
1. Real-Time Situation Awareness	Target identification Threat assessment Intent recognition	Reduction in manual recognition activities necessary to assess high-level situational patterns
2. Global NBC Capability Surveillance	Facility, equipment, and materials detection	Wide area screening for potential NBC activities Accurate detection of NBC materials, equipment and facilities
3. Hardened/Underground Facility Surveillance	Facility detection and related activity monitoring (change detection, process activity)	Wide area screening for facilities development Focused area monitoring for facility operations
4. Recon and Deliver Weapons to Air-Ground Targets	Non-cooperative air and ground target identification Autonomous seeker target detection and ID	Reliable, lethal detection and identification of lethal targets
5. Detect, Track, Intercept Theater Ballistic Missiles	Missile typing via ground, air, space sensors	Improved speed to recognition and accuracy of type ID
6. Acquire, Maintain, Disseminate Info for MOOTW	Identification of non-military or clandestine vehicles, equipment and materiel	Reliable screening, detection and classification
7. Force Sustainment and Product Assurance	Non-destructive analysis Facial, retinal recognition for security	Rapid, accurate identification of material characteristics, personnel

6.2.5.3 Commercial Developments/Applications

There exist a number of commercial activities that are developing and applying pattern recognition-related technologies that may have leverage potential to support Air Force activities in this area. In two areas, the Air Force should consider evaluation and application of available COTS technology.

Short-Range Industrial Pattern Recognition

Several commercial areas that are providing complementary ATR technology for lower-volume, pattern recognition applications are identified below. Developments in these areas are providing commercial-off-the-shelf (COTS) visual ATR capabilities that are appropriate for the force sustainment and product assurance tasks.

- **Robotics**. Close-range pattern recognition technologies are being developed for assembly line inspection and component handling.
- **Medical Analysis**. Medical image analysis tools are being developed for MRI, CAT, mammography and microscopy applications similar to Air Force non-destructive analysis tasks.
- **Video and Multimedia Processing**. Digital video image processing and multimedia hardware and software are applicable to some screening and bulk filtering applications.

- **Query-By-Information-Content (QBIC) Database Management**. QBIC query and retrieval technology capable of handling image data as well as text can provide supporting technology for context-based reasoning ATR in security and material control applications.

Pattern Recognition Technologies for Geospatial Information

The rapid and expanding development of commercial GIS technology provides the Air Force an opportunity to leverage spatial data technologies to enhance the context-based ATR systems in support of broad area situational awareness tasks. These technologies include:

- **Spatial Data Structure**. Efficient, linked data structures are being developed to handle the wide variety of vector, raster, and non-spatial data sources needed. Commercial standards and the National Spatial Data Infrastructure (NSDI) initiatives should be leveraged.
- **Spatial Reasoning**. The ability to measure, apply spatial logic and infer spatial and contextual knowledge in the context of dynamically changing spatial data is being developed to assess the "meaning" of geospatial data.

6.2.5.4 Impact on Affordability

Once developed, mature pattern recognition technology will improve the affordability and cost-effectiveness of systems and processes (in the previously stated Air Force mission areas) in three ways:

- **Reduced System Cost**. The introduction of ATR into selected systems—as a replacement for manual recognition—will reduce multiple operator displays, mensuration tools, and the training programs necessary to train and support human analysts and operators. As the ATR systems meet or surpass human operator performance levels, confidence in the systems will increase, reducing the need for backup displays and tools to permit operators to review "raw" data. The operational costs for human analysts (e.g., image analysts) and operators will be reduced as the ATR systems accept an increasing level of the data analysis tasks. This savings can be expected to be analogous to the savings accrued by BIT for complex avionics systems. Quantitative measures of reduced cost in any specific weapon system may be measured as: (1) reduced cost of displays—controls and operations and maintenance (O&M), and (2) reduced human training to perform manual analysis.
- **Enhanced Operational Efficiency**. ATR will reduce the low-level workload on warfighters, eliminating the review and detailed analysis of "raw" data, freeing the warfighter to concentrate on higher-level tasks. Reliable ATR detection and identification, coupled with automated situation assessment capabilities, will permit humans and weapon systems to more effectively monitor, measure and target hostile targets. Fratricide, mission planning errors, and overall situation uncertainty will be reduced. Quantitative measures of enhanced efficiency in any specific weapon system may be measured as: (1) improved reaction time to

decision, (2) increased decision accuracy, (3) reduced decision uncertainty, and (4) expanded coverage rate.

- **Improved Operational Reliability**. As the confidence (measured as a posterior probability of correct recognition) of ATR systems increases, the operational reliability of the surveillance and targeting processes will also increase. Quantitative measures of operational reliability in any specific weapon system must compare process reliability considerations (human versus machine decision reliability) rather than a simple hardware reliability.

6.2.5.5 Recommended Development Plan

We recommend that the Air Force: (1) initiate a focused effort to develop a fundamental theory to aid in development and evaluation ATR systems; (2) expand the model-based technology developments for imagery to include full hybrid ATR including all-source context; (3) expand and coordinate technology developments to extend model-based reasoning to multiple-sensor applications; and (4) leverage commercial neural network, image understanding and spatial database technologies to augment model-based ATR with additional contextual data.

We recommend:

- **Expand the model-based technology development for imagery to include hybrid ATR including all-source context**

The Air Force should expand its development of model-based ATR capabilities for imagery, focusing on the detection and identification of critical targets.

Specific recommendations and milestones:

- Expand research to refine understanding of key phenomena to enable accurate all-aspect, all-condition target modeling. Expand worldwide clutter modeling to allow background models to be incorporated in the feature prediction process.
- Develop, by the year 2000, efficient and compact methods to represent and store complex target models (up to 200 types in 60 aspects and 25 configurations).
- Explore and quantify the benefits of complementing target models with surrounding context models (e.g., scenario and behavioral models) that will permit other data sources to be incorporated into target decisions.

- **Expand and coordinate technology developments to extend model-based reasoning to multiple sensor applications**

Increase model-based R&D to include model-based multiple sensor/phenomenology fusion to ensure that single-sensor ATR solutions can be extended to multiple sensor applications. In some cases, a multiple-sensor solution may be the only approach that achieves the stringent performance demands stated earlier in this Volume. Research in multiple sensor model-based reasoning processes should be initiated as the logical extension of current R&D activities focused on SAR data.

Specific recommendations:

- Identify the key sensor combinations in each representative task area and the necessary features and measurement accuracies that permit reliable discrimination.
- Define and develop the multiple sensor phenomenology base necessary to support multispectral modeling. This activity must be coordinated across services.
- Develop multispectral indexing methods (both sequential search and concurrent indexing of multiple models in different spectra) to efficiently reduce the model search space, search time and feature prediction. Demonstrate this by the year 2000.

- **Leverage commercial neural network image understanding and spatial database technologies to augment model-based ATR with additional contextual data.**

Beyond model-based matching, ATR research must evaluate the methods of applying reasoning processes (employing uncertainty management) to apply complex contextual data to the recognition process, such as:

- Precision spatial (geospatial, aerospatial) data
- Temporal behavior of entities and events
- Relationships to other entities and events (spatial, spectral and temporal relationships)

The large commercial investment in neural networks, image processing and GIS provides an excellent base of technology with potential selective application to the higher-level reasoning necessary to apply contextual data. The Air Force should conduct a technology audit of these commercial capabilities and conduct selective laboratory-level technology demonstrations of these capabilities applied to context data integration and reasoning.

Specific recommendations:

- Conduct a technology audit of key, pacing and emerging-embryonic commercial technologies and relate the potential of each to the generic ATR problem and the specific mission-area applications cited in this Volume.
- Identify the most promising commercial technologies and develop strategic R&D coordination activities over the period 1996 through 2003 with receptive commercial developers. (This may include focused small business innovation research [SBIR], or STTR solicitations, or cooperative research and development agreement [CRDA] arrangements as appropriate.)
- Select and acquire the most promising and available technologies that may be integrated with on-going Air Force ATR lab demo systems.

- Plan, integrate, and conduct an evolving demonstration of ATR focused on a specific mission application that incorporates precision, real-time contextual information.

6.2.6 Unattended Ground Sensors (UGS)

6.2.6.1 UGS Overview

The Air Force is in a unique position to capitalize on the combination of unattended ground sensors with its reconnaissance and surveillance aircraft for an improved picture of the battle area. Airborne collection or relay is necessary to overcome the extremely short radio horizon of the ground sensor.

Unattended ground sensors fall into two categories and could serve a variety of purposes. Tags are used to mark targets of interest to allow tracking, and larger sensors are used to provide surveillance in an area of interest.

Mobile Targets

Smart sensor fields will provide timely and accurate data on the status, movement, and location of critical targets. UGS satisfy the needs of continuous surveillance of selected geographic areas, detection and reporting in real time, and reduced risk to personnel. They will provide identification of vehicular types and critical payloads, and provide activity indicators at ground sites of interest. They will also provide bomb damage assessments (BDA) of remote targets. Some studies indicate that modest numbers of UGS sites have potential to reduce TBM launch rates by 70-80%.

As depicted in Figure 6-22, UGS missions would provide detection, classification and tracking of critical targets (TBM, C2, etc.) and their reload sites. A long range array would be seeded over potential hide, reload and fire sites. Missions would support monitoring, reporting and interrogation of the sensors. Low power data fusion could allow sensor packages to communicate between each other to derive vehicle height, weight, number of axles, wheel base, engine type, number of cylinders, transmission type, and spurious emissions. Threat buildup would be derived from information reported by the site sensors. Types and quantities of vehicles entering and exiting the target area would be apparent. Choke points could be monitored to provide unit specific activity. Associate multiple vehicles would provide recognition of unit movements. Particular units could be identified by their unique features. This would provide cues to their identity so that each unit's activities could be tracked. There would be confirmation of hostile activities such as the identification of specific vehicles and events, and the reporting of movements before and after launch events. Sensors would be highly valuable in bomb damage assessment. They would provide intelligence about time and location, and would monitor sites for secondaries and on-site post attack activities.

6.2.6.2 UGS Deployment Concepts

The primary concern with the use of UGS is the ability to insert the devices into areas of interest. The following concepts are suggested:

- Overrun area—leave sensors in place

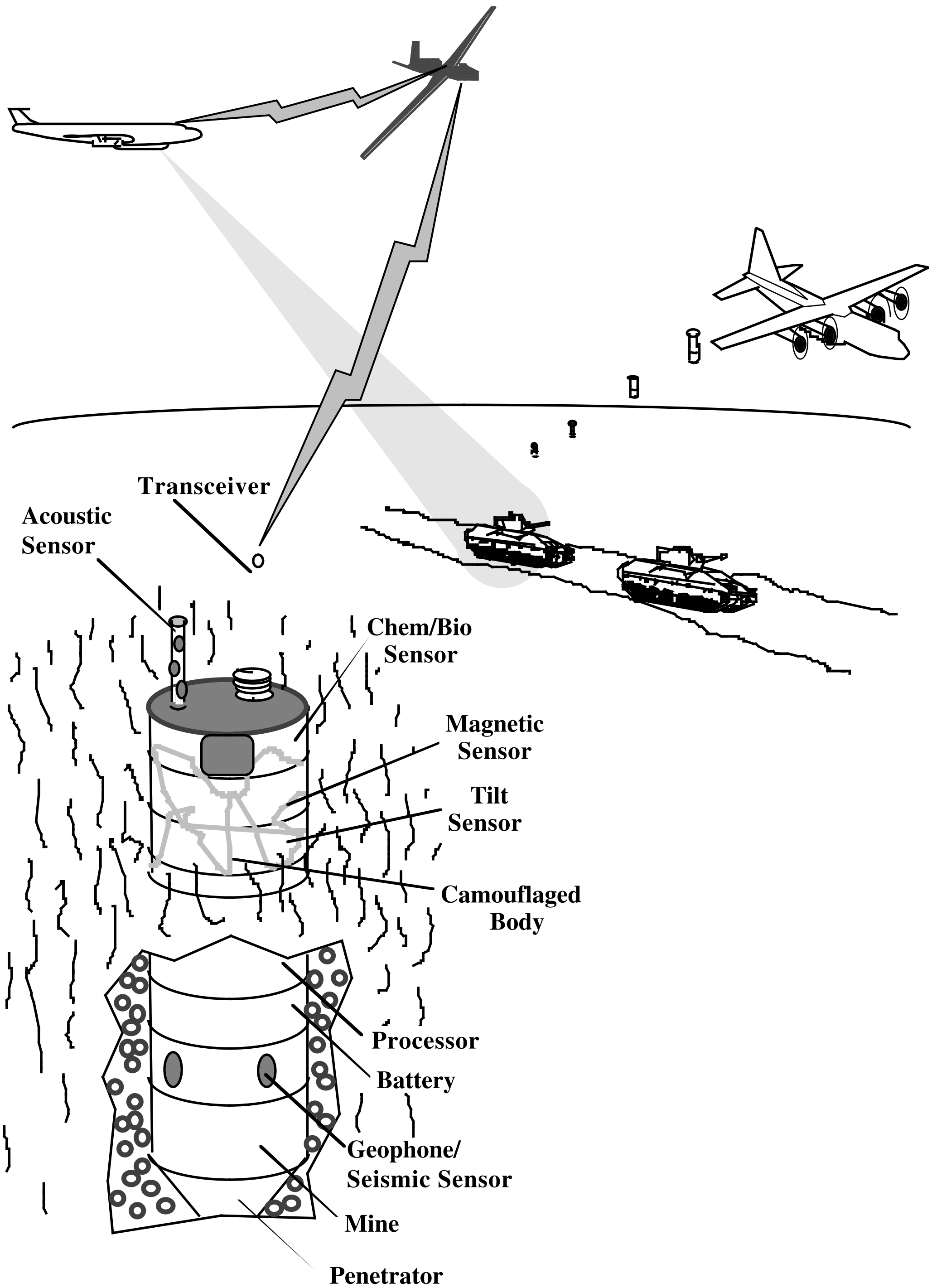


Figure 6-22. UGS Employment Concept

- Fly over—canister dispensed
- Fired from gunship 105 mm
- Injected with ground fired 105 mm
- Balloon borne canisters at night
- Glider launched from high level offset aircraft
- SOF hand emplacement
- Agent hand emplacement
- Trained animals
- Mobile micro machines

Access Through Nanomachine Technology

Even restricted areas need air, which suggests that an approach of close-in access would be through the exhaust air vent. The blower is usually in the intake line and the exhaust is easier to detect from its thermal signature. The ideal explorer would be a micro machine bee, but a practical version is off in the future. A suggested machine would be able to fly and crawl into optimum positions for successful monitoring. Today, small tracked vehicles are readily available in the commercial world, and in the future could be equipped with the intelligence and mechanics needed to navigate a duct that has been designed to make passage difficult.

The military use of these remote controlled vehicles would provide useful transport of close-in sensors, like magnetometers. If these crawlers were equipped with cutting tools (Figure 6-23), and they had access into ventilation systems, they could move freely throughout bunker complexes, detecting speech and various emissions of interest. A turtle-like rock with treads on the bottom as shown in Figure 6-24 could be moved in quite close. The machine could also be removed after the insertion or sample is completed. A simple approach would be to separate the collection package (rock) at the target and recover the tractor.

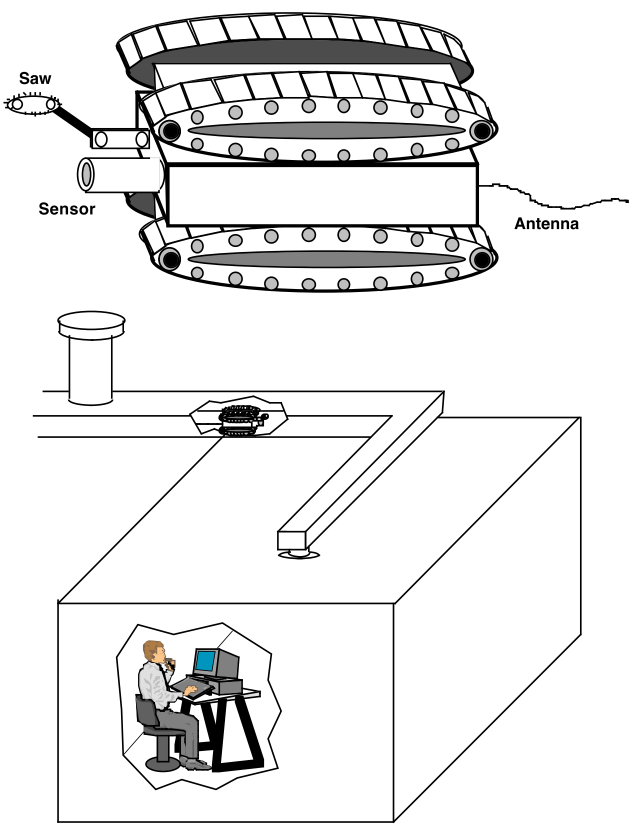


Figure 6-23. Two Track Machine

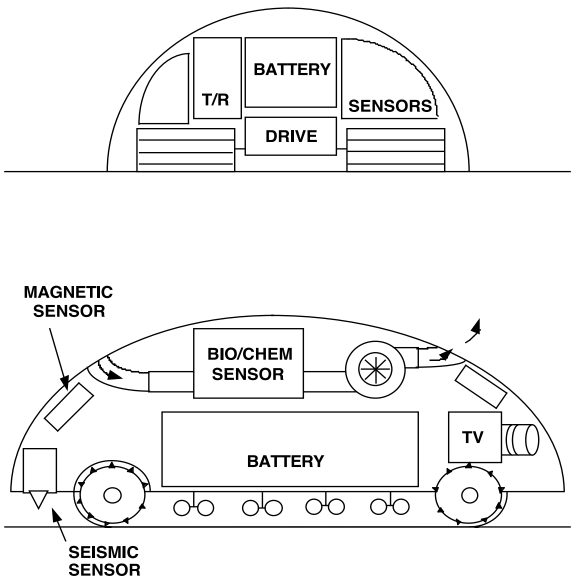


Figure 6-24. Mobile "Rock" Sensor

6.2.6.3 UGS Technologies

Magnetic Sensors

Passive detection, localization, and tracking of targets are possible using magnetometers. Classification of targets could be done with information from magnetic dipole strength, height, size and distribution. Coherent array processing can significantly extend the effective range of the magnetic sensor by increasing sensor directivity and array gain.

Higher frequency magnetics will provide sensing of vehicle alternators, electric fuel pumps, automatic controls for fuel mixture and, when available, ignition coil magnetic fields. If radio equipment is turned on, magnetic emanations from chopper power supplies can be detected also. Power generators are an excellent magnetic source in the 50 to 60 Hz spectrum. Load changes will reveal the activity of the installation.

A line array of magnetometers distributed along electric power lines will allow current monitoring to detect where significant loads are located. This may well reveal the location off large high value buried facilities. Once they are located, magnetics can also sense the distinctive magnetic fields from elevator motors, determining the number of elevators and the number of floors being used.

Acoustic Sensors

Using acoustic sensors would allow evaluation of both time-domain and frequency-domain algorithms for reducing processing and communications by performing peak detection processing and bearing and sound levels processing. Human speech carries very well along with all the other expected battle area sounds.

Nuclear Radiation Detection Sensors

Arrays of fielded sensors that have the capability of detecting nuclear weapons as they pass would be of extreme importance to give warning of their presence in the field.

Tilt Monitoring Sensors

The use of a tilt monitor sensor will allow the relative weight of vehicles passing on the road to be determined, providing further information for classifying unique military vehicles and their loads.

Infrared Sensors

IR sensors can detect heat radiated from vehicles, machinery and people, allowing the detection and classification of activity around the target area. Multispectral IR sensors can also classify or identify effluents. They would also allow determination of the status of industrial and other facilities. The air exhaust temperature from bunkers could be measured, providing data useful in making bomb damage assessments.

Subaudio Seismic Exploration

The elephant has been found to communicate great distances using his trunk as a very low frequency resonator. Long horns on some prehistoric animals were actually subaudio resonators used to communicate significant distances. These subaudio frequencies propagate much better than our normal audio range. The sounds of weapon detonation have been used to locate artillery and mortar fire in both world wars and Korea. The use of low frequency energy detection will take advantage of the enhanced propagation and reduced background noise to locate targets.

Sensor Detection of People at Rest or Asleep

A subaudio sensor will allow the detection of human respiration, a rate that is typically 0.28 Hz. The fixed ground sensor can carry out a FFT to process the data. A two minute sample will provide a 0.03 Hz effective bandwidth to sort out background noise from the respiration of people. The body oxygen requirement will keep the average respiration rate constant even when speaking. Multiple people would spread the response peak and also give a readiness state by seeing the increased rate respiration for active excited people. The use of diode impulse radar sensors could also detect human respiration.

Underground Bunker Detection Using UGS

To locate or confirm the presence of deep bunkers, factories and tunnels, sensors could be used to sample power line current along lines and cables, detecting current drops at the bunker area. Additional sensors with seismic capability could be spread in the suspect area allowing detection of machinery noises such as elevator motors, blowers, and so forth. Subsurface sounding similar to those used for oil detection can be carried out by using a seismic impulse from a shell or bomb in time of combat or sonic booms and thunder for covert probing. The multiple sensor seismic outputs processed in parallel can be used to develop the subsurface geological structure or tomographic picture with the unusual artifact of the target structure.

The same sensors could be used to determine bomb detonation locations and provide error correction for follow-up strikes. Power line current transits and load drops would provide a measure of bomb damage assessment.

Chemical Sensors

Volatile organic chemical (VOC) sensors are composed of two layers: an attractive material that detects the presence of the substance of interest, and a conductive material to carry electrical current to the electronics. They can detect airborne hydrocarbon fumes to 5 ppm with potential down to 1 ppm. The sensor reverts back to its original electrical state after the VOC has dissipated.

Multigas sensors based on organometallic microsensor arrays using a gradient doping process can be used to fabricate an array of microsensors with different composition and electrical response to enable the array to sense a number of gases. This would allow the detection of hydrocarbons, explosives, and nerve agents, and would be reusable by heating the array.

Close-in Jammer/Sensor

Search radars and SAM radars are high on the list for sensor coverage. The sensors would be able to detect readiness, and if the sensor had a low power noise jammer capability, the sensor could mask incoming aircraft over broad sectors. The mask could be remotely applied in irregular patterns to lead the operators to consider it to be an equipment bug since no airborne source is present.

Weather Sensor Module

Accurate and timely weather data from the target area could be very helpful. The most useful sensors related to weather would be solar flux, precipitation, and dew point. Ground visibility could be derived by measuring the received intensity of a pulsed laser diode's IR radiation at neighboring sensors. A broad field of sensors would give a timely and accurate local weather picture. Environmental sensors would provide data for accurate characterization of acoustic signal propagation for increased accuracy.

New Surveillance System Concept

Another concept is to exploit the LEO communication satellites that are expected to become ubiquitous, coupled with an array of UGSs to track aircraft in flight. This concept would work by detecting the near forward scatter of the communication beam by the aircraft with a receiver on the UGS. Similar concepts using earth based transmitters, such as television stations, have been examined in several different contexts over the past few years.

There are two principal applications. One is for technical intelligence, say, with covert receivers near a flight test center. The other is for air defense against a mix of conventional and stealth aircraft. For technical intelligence, the concept has some promise. If the UGS system has sufficient processing to decide when to report data through a covert link, one could monitor the activity in a small area, say a flight test facility, without advanced warning of an interesting test.

To be useful in an air defense mission, a potential surveillance system must couple to a weapon. To do that with this concept, the system must track an aircraft long enough and accurately enough to vector an interceptor close enough for its onboard sensor to acquire the target; the smaller the signature of the target, the closer the spacing must be. To accomplish this, the receivers must cover a large area and be dense enough and well enough integrated to have accurate tracks despite ghosting, false targets, track association problems and the like. For near and midterm situations, these bistatic techniques are more cumbersome and expensive than conventional radars. This will change only if the signature of the threat is reduced significantly below current estimates, and the difficulty and cost of the internetting must be significantly reduced. The Air Force should consider this concept if it faces a threat that is significantly stealthier than anticipated today.

Information Warfare Support Sensors

As this new area of combat emerges, unattended ground-based sensors will be an important part of accessing and disrupting the opposition's equipment. A wide field of attack from close-in monitoring of activities and usurping control or insertion of disruptive data to their system will need proximity. The generation of EMP to destroy equipment in the local area could also be a potential use of sensors. Significant efforts will be required to insert these devices and then collect and control their operation, but it should certainly be a strong area of involvement in the future. Careful coordination of these efforts will be required for their optimum use.

Countermeasure Ground Sensors

When the enemy's sensors can be located or the locations predicted, a line of friendly devices with countermeasure features could be deployed to produce moving acoustic, seismic, magnetic signatures for our tanks that could be used to lure hostile fire and reveal the enemy's location.

Data Link Considerations

Reducing the data link power would be an important technology area that would reduce sensor size. The use of large aperture antennas on platforms like AWACS and JSTARS would provide a power reduction in the order of 1000 by having increased gains of 30 dB over normal data link antennas. This will reduce the battery the same ratio, a major size and weight benefit. This is of particular importance for tagging applications that must be placed on a target and not be noticeable to the user.

Simple Cross Links Between Fields of Sensors

Since most ground sensors are seismic, it seems reasonable to use this capability to provide covert communication links between fields of sensors. Data could be sent on a subcarrier outside the normal band of interest. Considerable power savings may be possible over the expensive spread and hop technology.

Recommendations

A strong push to develop low-power sensors with multiphenomenon sensing elements should be carried out. Their construction should allow stacking of the individual sensing elements into a logic control module to meet specific battlefield concerns. Table 6-6 lists a number of sensing elements and their applications. There should be the development of fusion techniques to display all source data with sensors. Early fielding of feasiblility models will provide needed insight into their capability and proper mix to derive target identification. All source intelligence fusion must be pursued with ground sensors to provide a new level of battlefield awareness.

6.2.7 Miniature Detectors for Chemical and Biological Agents

There are a number of missions that require detections of chemical and biological agents. These include treaty monitoring, counter proliferation and battlefield warning to aid in the use of protective measures. For many of these missions, small sensors can be widely deployed, either on UGS or miniature UAVs. There are a number of technologies that make that possible. These technologies are reviewed in this section.

Table 6-6. Sensing Applications

Sensing Techniques	Vehicles/Tanks	Troops	Overhead A/C	Stealth A/C	Tel	Bunker	SAM	Large guns	Wx
Magnetics	X				X	X	X	X	
Seismics	X	X	X	X	X	X	X	X	
Tomograph						X			
Acoustic	X	X	X	X	X	X	X	X	
IR	X	X	X		X	X	X		
NBC					X	X			
Tilt	X				X		X		
Solar flux dewpoint									X
Close-in comm/ radar jammer	X	X					X		
EMP gen.	X	X			X		X		
Cable access						X	X		
SIGINT freq. trigger	X	X			X	X	X		
Impulse radar element	X	X			X				
LEO-Bistatic radar			X	X					
I&W emulator	X	X	X	X	X				

6.2.7.1 Near Surface Meteorologic Measurements with Radio-Acoustic Sounding Systems (RASS) Technology

Background

Attacks on WMD facilities could result in the venting of lethal materials into the atmosphere producing significant and undesirable collateral effects. The dispersion of these materials will depend on the local atmospheric conditions (particularly wind vectors) and surface topography. A system has been demonstrated using RASS technology that measures the local vertical profile of winds and temperature. These measurements were obtained from small piezoelectric transducers that emit pulses of acoustic energy vertically, and a microwave radar is used to scan the subsequent motion of the acoustic pulses. Lateral motions of the acoustic pattern determine the horizontal winds as a function of height, Doppler shifts indicate vertical winds, and sound speed variations infer temperature. This meteorologic information, possibly obtained from an array of sensors, can be combined with GPS location and stored terrain information as input to a computer model for the prediction of local weather patterns and the subsequent dispersal of venting aerosol agents.

Approach

The RASS is capable of measuring vertical wind and temperature profiles directly above the deployed system to heights of a few hundred meters. The RASS can be battery operated and deployable by one man, or air dropped into an operational area. A system of this type could be constructed with a mass less than 30 kg, a power consumption of less than 100 watts, and a volume less than 0.4 m^3. The system can be designed for unattended remote operation and with advanced modeling would be capable of delivering aerosol dispersion predictions in minutes.

By scaling current RASS technology to higher acoustic frequencies, a small, highly directional acoustic source can be developed. Operation at acoustic frequencies of about 10 kHz limits the effective range of the system to several hundred meters altitude due to attenuation of the acoustic signal. This, however, is sufficient to provide the information necessary for local wind-prediction modeling. At these acoustic frequencies, the transducers are physically small piezoelectric elements. These transducers can be baffled in such a way as to provide a highly directional acoustic pulse. The size of the baffling needed to suppress side radiating acoustic energy is greatly reduced by the choice of an operating frequency of 10 kHz.

The radar wavelength is chosen to be twice the acoustic wavelength so that a resonant backscattering condition is formed. By selecting a shorter acoustic wavelength, approximately 3 cm in this case, a short RF wavelength is specified. This short RF wavelength allows the use of physically small, highly directional, phased-array antennae for the microwave radar. A man-portable, field-deployable Doppler radar of this type has been built, and previous systems have used small, 0.25 m by 0.5 m, planar antennae. This same technique can be used for a counter-proliferation system. The receive antenna would be a moderately wide-beam angle, zenith staring, planar antenna. The tracking of the acoustic pulse would be accomplished by electrically steering the transmit antenna, a narrow-beam, planar, phased array.

In operation, an acoustic pulse would be emitted every few seconds. The radar would then interrogate the pulse every few microseconds. The radar reflects resonantly from the sound pulse as the pulse is carried by the wind field. At these pulse rates, a wind field of approximately 1 m/s to 10s of meters per second can be measured. By chirping the radar frequency, the center frequency of the resonance condition can be measured and used to infer the vertical temperature profile.

This system would carry a small GPS receiver for self-location. The GPS information would be used to retrieve previously stored terrain information for use in the predictive model. The GPS time information also can be used for time correlating measurements from an array of deployed stations. These local, near-surface measurements could then be combined with a single distant (100-km height) wind field measurement up to the boundary layer or coupled to large-scale, gridded forecasts as input to a modified version of existing meteorological and dispersion codes such as HOTMAC and RAPTAD. The single distant measurement can be accomplished using ground, airborne, or space-based assets. The new local, near-surface measurements will allow great improvement in the prediction of local plume dispersal. A key part of the modeling aspect is to determine the best way to integrate the local measurements into the models.

6.2.7.2 DNA-Based Point Sensor for Identification of Specific Microorganisms

Background

Biological species identification using DNA techniques has been demonstrated widely. It is possible to optimize, engineer, and militarize DNA-diagnostic technology, providing a fully automated "point detector" for the rapid identification of microorganisms. The fundamental processes to be optimized for this sensor are the polymerase chain reaction (PCR) that amplifies biological-agent DNA strands, and capillary electrophoresis (CE) that allows identification of the DNA produced. The near-term, first-generation of this sensor system has a projected weight of 70 lbs, and target biological-agent identification time of about 15 minutes, and will be designed and packaged for fielding on a mobile platform such as the Army Biological Integrated Detection System (BIDS). In the more advanced second-generation system, the PCR and CE functions will be carried out on a "chip" that plugs into a hand-held "reader." The projected weight of this hand-held system is less than 10 lbs, with an agent-identification time of 2 minutes.

Identification of characteristic DNA strands is a dependable way to conclusively identify biological organisms. This technique is so powerful that even a single strand of DNA can be amplified to measurable levels using PCR. After PCR amplification, analysis of the products is required to allow identification of the specific biological species from the characteristic DNA signatures. This analysis is commonly done using slab-gel electrophoresis. Presently, both the standard PCR and slab-gel electrophoresis processes are complex, involve a variety of delicate labware, require continuous man-in-the loop operations, and are highly time intensive with a typical biological-agent analysis requiring several hours. The automation, engineering, and packaging effort proposed here will eliminate all these present operational complexities and provide a fieldable system for the rapid identification of microorganisms.

Approach: Mobile-Platform, DNA-Based Point Sensor (Flow-PCR)

Using demonstrated hardware components and a continuous fluid-flow approach, the mobile-platform "Flow-PCR" device will consist of a rapid thermocycler to execute the PCR process and an integral CE system with fluorescence detection to analyze the PCR products. With the exception of periodic servicing, all facets of this device will be completely automated, including the data analysis and reporting.

Fluid Handling: Segmented flow analysis (SFA) techniques, using standard metering pumps and injection valves, will automate sample and reagent handling. PCR reagents (Taq polymerase, buffer, primers, and fluorescent dye) are injected after the analyte solution is concentrated by ultrafiltration. The SFA process injects an air bubble before and after the sample/reagent mixture to create bolus or plug flow, which keeps the reagents well mixed and accelerates the PCR amplification process. Two marker DNA segments will be added to the sample/reagent bolus. These "internal standards" will confirm PCR amplification and verify the CE analysis.

Thermocycler: In commercially available PCR instrumentation, most of the amplification time goes to warming and cooling the aluminum block that holds the sample vials. In the Flow-PCR system, the sample/reagent bolus will flow through a Teflon capillary wrapped around a mandrel. The capillary will carry the sample/reagent bolus repeatedly through three heat-exchange chambers. Each chamber will be held at the optimal temperature for one step in the PCR amplification process. Thirty-second PCR cycles have already been demonstrated using air heating and cooling in a sample vial. At this rate, 30 PCR cycles are completed in 15 minutes. This is 20 times faster than current instrumentation and demonstrates the potential for Flow-PCR.

Capillary Electrophoresis: Coupled with laser-induced fluorescence (LIF), CE will be used for analysis of the PCR products. Ten-minute analysis times and high resolution have already been reported for CE sizing of DNA strands from 100 to 1500 bp. After each sample analysis, the column is refilled with linear polyacrylamide gel. Reproducibility of better than 1 percent relative standard deviation (RSD) is routinely reported from run-to-run using this technique, and the presence of DNA markers improves reproducibility to better than 0.2 percent RSD. Using multivariate statistical data analysis methods, the same performance can be achieved in less than half the time.

Fluorescence Detection: Fluorescence has been demonstrated for very sensitive DNA detection with CE sizing. Sub-nano-gram quantities have been detected. The exceptional sensitivity of LIF means less amplification time, and fewer PCR cycles are required before CE analysis.

Approach: Hand-Held, DNA-Based Point Sensor (PCR-Lite)

PCR-Lite will combine the understanding developed in fabricating and fielding the Flow-PCR with emerging technologic advances in CE on a chip. Analysis times of 2 minutes for the miniaturized PCR-Lite are anticipated. CE on a chip has been demonstrated as a fast, accurate means for doing electrophoretic separations, with analysis times reported in milliseconds rather than minutes.

Using microlithographic fabrication techniques, PCR and CE can be put on a substrate the size of a microscope slide. The disposable slides will be pre-loaded with reagents and replaced after each analysis. Small sample volumes will allow very rapid and efficient peltier heating and cooling of the PCR chamber. The slide will fit into a hand-held “reader” that contains the power supply, the laser (or LED), the detector, and the peltier device. The entire system will weigh 5 to 10 lbs.

6.2.7.3 Biological Toxin Identification with Matrix-Assisted Laser Desorption/ Ionization Time-of-Flight Mass Spectrometry Point Sensor

Background

It is possible to develop and demonstrate a field-deployable point sensor, based on Matrix-Assisted Laser Desorption/Ionization Time-of-Flight Mass Spectrometry (MALDI-TOFMS), to detect and unambiguously identify biological toxins. The sensor system is intended for deployment on stationary platforms for fixed asset monitoring (docks, bases, staging areas, etc.) or mobile platforms for reconnaissance, early warning, and bomb damage assessment. The sensor system will operate autonomously and continuously with only periodic (daily) servicing, be capable of toxin analysis and identification times of less than 10 minutes, and be easily programmable for new toxins. The near-term, first-generation system will not be man-portable, but rather designed for integration into an Army BIDS-like platform, and possibly a UAV. This system will weigh about 100 lbs, occupy a volume of approximately 3 cubic feet, and require on the order of 500-W power. The sensor system will be capable of integration into Command/Control systems, or function in a stand-alone mode.

Toxins are poisons resulting from the natural metabolic process of certain microorganisms, plants, and animals. These chemical compounds may be relatively small (e.g., alkaloids), but are often complex, high-molecular-weight species such as proteins. The neurotoxin botulinum type A, with a molecular weight of 150 kDa, has a greater casualty-producing potential than VX, the most lethal nerve agent. With the availability of a large number of readily producible biological toxins, and the ease of development of these agents in tactical, strategic, and terrorist operations, it is critical that sensors capable of detecting and identifying these agents be developed. Fortunately, the unique mass-spectral signatures of the toxins can be used to characterize the threat.

Technology for the rapid identification of large biomolecules, characteristic of biological toxins, has recently taken a significant step forward with the development of MALDI-TOFMS. With this technique, the biomolecule analysis is initiated by mixing the sample (which can be an aerosol, liquid, or solid) with an excess of an appropriate matrix material. A small aliquot of the sample/matrix solution is then applied to a probe that is introduced into the mass spectrometer. Pulsed ultraviolet laser light is absorbed by the matrix, leading to the desorption/ablation of part of the surface. Protonation, cationization, or electron capture reactions then occur, resulting in the production of *intact* high-molecular-weight ions of the analytes. Time-of-flight mass spectrometry is the method of choice for ion detection, due to the pulsed nature of the ion source and the sensitivity and high mass capabilities of TOFMS.

The advantages of MALDI-TOFMS include: (1) the ability to directly measure the mass of biological toxins up to 500 kDa; (2) speed of analysis (< 10 minutes); (3) high sensitivity (only picogram amounts of the target compound are needed); (4) simple, rugged instrumentation; and (5) the potential to identify microorganisms before they begin releasing a toxin. This last point is important because some BW agents do not become pathogenic until they are incorporated into a host (soldier or civilian).

The mass characteristics of bacterial toxins lend themselves well to detection by MALDI-TOFMS. In addition, some toxins require the presence of other compounds in order to express lethality. Many of these "promoters" are also high mass species that can be detected using this sensor technology. Correlation of toxin and promoter presence will provide additional confidence in the analysis.

Approach

The development of a field-deployable, biological-toxin detection and identification system can be based on MALDI-TOFMS technology. Although simple, once-daily servicing of the system during periods of continuous operation are required, a fielded system could be completely automated, including data analysis and reporting. Development of a prototype system will involve efforts in the following areas.

- Optimization of matrix chemistry and composition including use of multiple or mixed matrices and definition of optimum measurement conditions.

- Development of a toxin signature library.
- Vacuum System: Pumping systems require the latest vacuum-system technology to be as small as possible, while still retaining the ability to evacuate the system to high vacuum in a reasonable time (< 5 min). The sample probe needs to be miniaturized, and automatic sample preparation and loading devices are needed though this may be the only physically moving part of the sensor system.
- Laser: Because only very low pulse energies (often < 1 microjoule/pulse) are required for MALDI, compact laser sources can be utilized. Small (cigarette-pack size) ultraviolet lasers are now commercially available and can be integrated into the fielded system.
- Mass Spectrometer: Recent experiments in the literature indicate that acceptable mass resolution can be achieved with flight tubes less than a foot long.
- Electronics and Data Analysis: High-speed digitization is necessary to faithfully record the mass spectral data. The identification algorithms, capable of picking out the desired toxin signatures in potentially complex mixtures, need to be developed and tested. Minimization of false reports (positives and negatives) is of particular concern.

6.2.7.4 Smart Film Microsensor for Detection and Identification of Chemical-Warfare Agents

Background

Sensor technology is needed in the counter-proliferation program for the rapid *point* identification and quantification of the entire suite of chemical-warfare agents as well as the detection of signature chemicals (precursors, degradation products, and solvents) associated with their manufacture and distribution. The specific needs include (a) hand-held or ground-based sensor systems for passive defense (troops, bases, supply depots, etc.), (b) ground-based sensor systems for target characterization, and (c) UAV deployed sensor systems for bomb damage assessment, and (d) a hand-held point sensor for covert activities.

An autonomous portable sensor is feasible for sensitive, rapid, real-time detection and quantification of the entire class of chemical-warfare agents (except HCN) and selected signature chemicals. The notional sensor will be a low-cost, compact, lightweight, rugged instrument weighing a few pounds and consuming less than 10 W of power.

The microsensor is based on technology originally developed for rapid tracking of organic toxins in air. Novel surface modification techniques (molecular “self-assembly”) have been used to *covalently attach* reagents that are *specific for the molecule of interest* directly to an acoustic device surface, resulting in microsensors of great stability and sensitivity. The guest-host interactions between the reagent attached to the transducer surface and the organic toxin are reversible, thereby allowing real-time detection of the molecule of interest. A laboratory sensor prototype has been built based on the marriage of a cone-shaped molecular “bucket”—

called cyclodextrin—and commercially available SAW technology. Through selection of different cyclodextrins (a-, b-, and g-) that have different "bucket" sizes and the chemical modification of these reagents, it has been possible to tune the specificity to different target toxins. Each of these different reagents has a distinct "fingerprint" type response to different toxins and through the use of an array of these smart film SAW sensors, it is possible to identify and quantify multiple toxins in a complex mixture.

Current SAW sensor technology relies on polymer films that are limited in several important ways. First, these films are typically spun onto the SAW transducer surface and the absence of direct bonding leads to failure by delamination. Second, these polymer films are not tailored to specific target toxins and typically respond to a wide variety of different potential interferents resulting in false positive signals and extremely poor capabilities for identification of specific toxins. Third, polymer films are not adapted to specific CW toxins and, therefore, are not very sensitive; efforts to make them sensitive by increasing the polymer thickness leads to poor response times, material stability, and reversibility.

Approach

The general approach utilized here is adaptable to a wide variety of transduction methods. Acoustic transduction (specifically a SAW, transducer) is favored because of its simplicity, commercial availability and small size.

A cyclodextrin-based sensor has the potential to provide ultra-high sensitivity (~50 ppb level) for typical organics such as xylenes. Several different sensors have been fabricated using chemically modified cyclodextrin molecules and the response of each to a suite of organic and halogenated organic molecules was measured. Each sensor (with distinct cyclodextrin molecules) has a unique "fingerprint" response to the suite of organic toxins. It is possible, therefore, to identify and quantitate multiple species in a complex mixture by using an array of such SAW transducers. Existing technology can be used "as is" to develop sensor systems for many "signature" molecules.

This sensor technology can be applied directly for sensing CW agents with further modification of selectivity of the reagent layer; in effect, the selectivity of the sensor will be optimized for CW agents. Chemical selectivity can be enhanced by using a new host-sensing layer. Molecular specificity, sensitivity, and reversibility will be enhanced by attachment of functional groups (R) on the upper rim of calixarenes resulting in a deeper host bucket and wider upper rim, including the ability to tune the polarity of the calixarene "bucket" by adjusting the donor (D)/acceptor (A) characters. Calixarenes are a larger family of synthetic cyclic arene compounds (than the natural occurring cyclodextrins) whose characteristic sleeve-like-cavity shape is defined by the number of phenyl units. The inside of the cavity of calixarene exhibits hydrophobic behavior and depending on the cavity volume and polarity is just such a size and chemical environment to readily incorporate specific chemical agents and/or their degradation products via host-guest interactions. These calix(n) arenes whose size is tunable by varying the number of arene units *(n) only* form inclusion complexes with organic solvents via non-covalent bonding (van der Waals interactions) in much the same way as enzymes and substrates interact; as such, sensor specificity is achieved by the inherent molecular recognition properties of calixarenes thereby allowing for *reversible* binding of the analyte and continuous operation and near real-time sensing.

6.2.7.5 Enzyme-Based Electrochemical Sensor for Detection and Identification of Chemical Warfare Agents

Background

It is possible to development of a small, lightweight (< l lb), self-contained and battery-powered (AA size) electrochemical sensor system for the point detection and identification of the entire range of chemical-warfare agents. The sensor can provide both a warning of the presence of CW agents and a determination of the agent concentration, with response time in the minute range and sensitivity roughly in the ppb range. The sensor package would essentially be single use and thus disposable. The sensor-package configuration will depend on the deployment scenario, with typical shapes being 3 inch by 3 inch by 0.5 inch badge like, or 6 inch-long, l inch-diameter cigar-like. Specific counter-proliferation applications include (1) a hand-held sensor for covert operations, (2) an early-warning system for passive defense (docks, staging areas, bases, etc.), (3) a ground-based system for target characterization, and (4) a UAV-deployed system for bomb damage assessment.

The CW-agent sensor system is based on recent work using enzyme-based electrochemical sensors to monitor glucose. Enzymes are highly specific catalysts for chemical reactions, and the rate of formation of products from these reactions can be monitored electrochemically. A simple, highly-sensitive electrochemical sensor has recently been patented, comprised of a thin enzyme-loaded composite layer adjacent to a layer of electrolyte and sandwiched between two electrodes. The use of this thin-film composite structure is a significant improvement in electrochemical sensor technology because it dramatically increases the sensitivity per unit area and the robustness of the sensor. In operation, one of the electrodes (typically carbon cloth) allows diffusion of the CW agent into the enzyme-loaded layer. This gas-diffusion electrode provides a high-flux gas delivery mechanism, and the combination of the gas-diffusion electrode and the composite layer represents a unique approach to electrochemical sensors for a gaseous reagent. A sensor package including a polymeric electrolyte gel provides all needed reagents for the enzyme chemistry except for the substance to be analyzed (the CW agent), thus eliminating the need for any liquid phase reagents.

The application of this technology for CW detection relies on inhibition of enzyme action by the chemical agent, which results in significant decreases in the rate of generation of products from the catalyzed reactions. The sudden decrease in the electrochemical response of the sensor in the presence of the CW agent will provide an alarm indicating the presence of these chemicals, while the change in response level after exposure to CW agents will allow the determination of concentration. This electrochemical-detector configuration is ideally suited for deployment as a personal clip-on badge-like sensor for the detection and identification of chemical-agent vapors or aerosols. In addition, these sensors can be reconfigured simply for other deployment scenarios, such as a UAV platform.

Approach

To develop a complete electrochemical sensor package for the broad spectrum of CW agents, it will be necessary to tailor the active layers and carbon cloth to allow adequate transport of each class of reagents to the catalytically active site. The approach is to optimize the inhibition of certain enzymes by chemical-agent simulants in the highly sensitive composite layer.

The enzyme inhibition chemistry has been widely reported. Examples of specific enzymes that are inhibited by CW agents include actylcholinesterase, cytochrome oxidase, and pyruvate dehydrogenase, each of which is suitable for a certain class of chemical agents. Enzymes that respond to the full range of chemical agents can be deployed. The effect of the agent is enzyme inhibition. Since the enzyme is a chemical amplifier, the deactivation of small amounts of enzyme leads to a large change in current. 10^{14} molecules of gas-borne agent (1 ppb in 20 l of air) will shut off enzyme equivalent to 160 mA of current.

6.2.7.6 Aerosol-Particle Capture and Fluorescence Detection with a UAV-Based Particle Collector

Background

For counter-proliferation (CP) applications, a UAV-based, aerosol-particle collection/detection system (ACS) could collect and analyze aerosol particles for bomb-damage assessment, target characterization, and battlefield passive defense. The ACS could provide analyses in real-time of the aerosol-particle concentration and size distribution, and detect biological aerosols by their UV excited fluorescence. The aerosol particles collected with this system could also be returned to base for post-mission analysis by battlefield or fixed-laboratory analytical techniques. The notional system is compact (~1 cubic foot in volume), light weight (< 15 lbs), and specifically designed for integration into a UAV.

A series of aerosol collectors have been developed to monitor airborne aerosol sizes and concentrations in cloud plumes that are released during AGEX tests. The collectors use cascade impactor techniques to separate out aerosols by size. The aerosol mass concentration ($\mu g/m^3$) in each of seven size fractions between 0.1 and 10 µm in diameter is determined. Aerosols of each size fraction are deposited onto a quartz-crystal microbalance that provides a real-time measurement of the aerosol mass. The present aerosol-collector system including pump, power supply, collector, and controlling electronics, weighs about five pounds.

The aerosol-collector is presently being incorporated into a small airborne measurement system called the micro-atmospheric measurement system (µ-AMS) that is designed for deployment on a UAV The µ-AMS system includes the aerosol-collector, temperature and humidity sensors, altimeter, airspeed sensor, fluxgate compass, and GPS receiver. The flight package weighs less than 15 pounds including the aeroshell that is 30-inches long and with a seven square-inch cross section. The system collects and measures aerosol concentrations during flight and transmits the data to a ground station in real-time. The remotely piloted vehicle (RPV) position and aerosol concentrations are graphically displayed to the ground-station operator so that the aircraft can be directed to areas of most interest within the aerosol cloud.

A series of handheld UV-excited fluorescence spectrometers have also been recently developed. These detectors were originally designed to monitor low levels of uranium by exciting contaminates that are present in very-small quantities within nuclear facilities. All of the instruments employ a UV-light source to illuminate a surface, and a spectrometer to collect the fluorescence spectrum. The most recent generation detector, including power supply, light source, fluorescent detector, and user data display, weighs only three pounds and is contained within a package volume of about 1/4 cubic foot.

Approach

As part of the development of the CP aerosol-particle collection/detection system, the fluorescent spectrometer and aerosol-collector technologies will be integrated. In addition to the real-time aerosol analyzer, a second collection channel will be added that collects a time-series of aerosol samples. This time-series sampler provides a set of discrete samples on which the fluorescence is measured as the sample is collected. Using this technique, the aerosol-particle is classified by size and fluorescence properties. Real-time analysis of the sample fluorescence spectra will be used to detect biological aerosols in a cloud.

The aerosol-particle airstream drawn into the ACS detector will be split between the real-time aerosol analyzer and the time-series sampler. Each will separate particles by size. The real-time analyzer will separate the particles in eight size ranges between 10 and 0.1 μm. The time-series analyzer will collect particles in two size ranges, 2.5 to 10 μm, and < 2.5 μm. Each collection stage of the time-series channel will be coupled to the fluorescence spectrometer using fiber-optic bundles that deliver the UV-light to each stage and collect the fluorescent light from the sample. Analysis of the fluorescence intensity and spectrum will be carried out within the detector package to determine, in real-time, if the collected aerosols are composed of biological material.

6.2.8 Expanded Sensing Dimensionality

Potential adversaries will continually seek means to reduce the effectiveness of our current weapon systems. From the perspective of mature imaging systems (including EO/IR and radar), which are dependent on the shape signature and reflectivity of the target relative to the background, this will result in the development of tactics and techniques to reduce the contrast (observability) of the target relative to its background. The key to holding the desired target at risk is to sense new and unanticipated target features. Thus the enemy could be using effective countermeasures that deny certain “conventional” image features while providing signature features in another image dimension. At this time, we have barely begun to make use of target dimensionality beyond the conventional three spatial dimensions. Wavelength/frequency, time, and polarization are other available but underexploited dimensions. Another form of multidimensionality is the use of sensors using alternate modalities, such as an acoustic sensor and an electromagnetic sensor or a SIGINT sensor and a radar. Sensor fusion is directly related to increased sensing dimensionality.

To increase the probability of target detection, recognition, or identification while maintaining a CFAR, we can use a limited number of target “dimensions” with very high resolution, or we can increase the number of orthogonal dimensions while making use of limited resolution in each dimension. Orthogonal dimensions in this context mean parameters which have non correlated false alarms. By expanding the dimensionality of target parameters, more difficult targets can be detected, recognized, and identified. Also, if data transmission or storage is an issue, limited resolution with expanded dimensionality will achieve higher performance with much less data bandwidth than high resolution using limited dimensionality.

Technology Description

There is great promise in increasing the dimensionality of the space in which target characteristics are assessed. A partial list of new sensing dimensionality with conjectured payoff/

application is presented in Table 6-7. This list is not all inclusive but rather gives a broad indication of observability trends in both optical and radar imaging applications.

Several of the measurement techniques have been discussed previously in this Volume. Three additional concepts are described below. The first adds a new dimension to the sensing space (MS/HS/US). The second combines two sensors (acoustic and electromagnetic) in a fusion process. The third uses a portion of the RF spectrum that has not been used for high bandwidth imaging (wide bandwidth, low frequency, SAR for FOPEN or ground pen), and also makes use of polarization. Other expanded sensing systems are certainly possible. Vibration sensing can be expanded beyond what has been tested. Coherent laser radar has been used for vibration detection at 10 μm and recently at 2 μm. Polarimetry can be applied for expanded target detection/classification, using passive IR, laser radar, or microwave. For example, polarization is used in the FOPEN/GPEN discussion in Section 6.2.8.3. Similarly, the time dimension can be more fully exploited in passive or active sensors.

Table 6-7. Expanded Sensing Dimensionality Opportunities

Target Feature	Sensing Method	Applications
Target Motion	Temporal response(Doppler) in active coherent systems Motion sensing by MEMS	Machinery activity provides vibration Aircraft engines provide modulation Target motion
Target and Clutter Geometry	Polarimetry in radar, passive IR, or laser radar	Enhanced target discrimination in clutter
Target and Clutter Material Gas Composition	Spectral response in reflection and/or emission, Laser Spectroscopy	Terrain Categorization Target material detection/classification NBC detection
Penetrating Obscuring Media	Combined RF/acoustic earth penetration Use of wide bandwidth, low frequency SAR (uses polarization & an unexploited portion of a dimension)	FOPEN/GPEN detection of hiding targets Detect/characterize underground objects

6.2.8.1 Multispectral/Hyperspectral/Ultraspectral Sensor (Exploiting the Wavelength Dimension)

Description of Sensor Concept

Spectral sensors of this type produce images of ground scenes simultaneously in two or more bands in the thermal infrared (between a wavelength of 3 and 12 microns) with high signal to noise ratios, excellent band to band spatial registration, and very high band to band uniformity of response. That is to say, differences in the measured signal at one subband and another subband must be due almost entirely to differences in the sensed phenomena, not to a different response of the sensor from one subband to the other. Thermal infrared is chosen to obtain night target detection/recognition/ID capability; a 0.4 to 2.5 μm wavelength based sensing may also be used for daytime operation. Air Force and ARPA funded work (including tower based target and background spectral signature measurements) has shown that target signal to clutter ratios for detection of low contrast (CC&D) targets may be improved by over 20 dB with consequent reduction in false alarm rates for a given probability of detection.

Table 6-8 shows the distinction between MS, HS, and US.

Table 6-8. Multispectral/Hyperspectral/Ultraspectral Definitions

	Definitions (either or both apply)	
Class of Sensor	**No. of Bands**	**Spectral Bandwidth**
Multispectral (MS)	10s	0.1 micrometer
Hyperspectral (HS)	100s	0.01 micrometer
Ultraspectral (US)	1000s	0.001 micrometer

MS sensing is probably sufficient for target detection. HS or US may be required for target recognition or identification. As bandwidths become very narrow, an active illuminator may be required due to available signal to noise. This could lead to a tunable laser sensor for wavelength based target identification.

In the spatial domain, the trends include finer spatial resolution and greater area coverage. Beginning with 80-m resolution for LANDSAT MSS, LANDSAT TM reduced this to 30 m, SPOT to 20 m multispectral (and 10 m panchromatic), and future commercial systems are projected to have MS resolutions down to 15, 10, or 4 meters. Wide area coverage is an operational need, as is orthorectification, geo-referencing, and, potentially, generation of three-dimensional information.

Polarization effects in both reflected and emitted radiation have been known for some time, but their exploitation has not proceeded as rapidly as for ordinary spectral phenomena. Experimental sensors are now available. This is another expanded area of dimensionality.

Airborne and ground-based ultraspectral systems have been developed and tested for detection of gases, such as chemical vapors, CBW agents, and pollutants. Typically, these operate at LWIR wavelengths, where gases have distinctive absorption lines, and exploit differential absorption at adjacent wavelengths. Passive systems rely on having a temperature difference between the cloud of gas and its background and may have relatively coarse resolution. Active systems utilize laser radiation at two or more different wavelengths. An active system might continue to interrogate additional wavelengths until it achieves predetermined probabilities. Another type of US sensing could take advantage of Fraunhofer absorption lines in the solar irradiance spectrum (e.g., at visible wavelengths). Radiation in those narrow lines then is due to emission of hot sources (such as rocket exhausts) or to a wavelength conversion process, such as fluorescence, in which radiation at those wavelengths is stimulated by absorption of radiation at different wavelengths (this also occurs in ocean phytoplankton).

Relationship to Air Force Missions

The Air Force has a need to search wide areas with a high probability of detection, and a low probability of false alarm. Use of the spectral dimension allows us to use much larger pixels, and still discriminate against clutter. This in turn allows us to search large areas with acceptable false alarm rates. Without the use of this additional dimensionality, the required spatial resolution for acceptable probabilities would be prohibitive. In addition, the Air Force has a strong need to be able to detect partially obscured targets, either through foliage or camouflage nets. The use of the wavelength dimension can make this possible. Signal to clutter will be lower than for unobscured targets since the whole pixel is no longer filled with target, but so long as a reasonable portion of the pixel is filled with target it will still be possible to detect the target. Detection through foliage or camouflage would be very difficult with conventional means. Another area that has been identified is intelligence preparation of the battlefield. Multispectral remote sensing can provide useful inputs through generation of spectral categorizations of the terrain classes present in potential battle areas. Even the current 30-meter data from LANDSAT can yield useful products. HS/US systems have the potential to detect, identify, and map the dispersion of chemical agents dispensed in battlefield areas due to their selective absorption of infrared radiation. HS/US systems similarly have potential for detecting and identifying effluents from NBC production facilities which may be indicative of the existence and type of activity that is in progress. This capability might also be employed in a BDA role, to assess whether or not a target area was an NBC facility based on effluents released as a result of an attack and confirm a successful mission. One element of countermeasures against hardened/ underground facilities is early detection of their construction and/or modification. Often, such facilities are placed in remote areas and search for their presence or routine monitoring can be a problem. Multispectral change detection with a broad-area sensor could serve a broad-area search function. Detection of construction activity has been shown to be possible with LANDSAT data and future systems should have added capability. Detection and identification of effluent gases with HS/US sensors could also aid facility detection and characterization. There is the possibility of improving IFFN capabilities by introducing hyperspectral markers into the paints and/or fuels of friendly equipment. These would introduce characteristic spectral absorption lines into reflected or emitted spectra. Multispectral systems have long been used to support environmental assessments, resource assessments, natural disaster assessment infrastructure mapping, and so forth. This type of information will become increasingly important to Unified and Specified (U&S) commands for non-war planning and operations assistance.

Relationship to Commercial Developments

The Air Force can leverage commercial development of thermal infrared focal plane arrays, mostly in the 3 to 5 micron region, to reduce sensor cost. Most current commercial development of spectral sensors is in the 0.4 to 2.5 micron region. Commercial thermal infrared spectral sensors will be developed later. There are some important commercial applications such as mineral exploration, and pollution detection that will benefit from these sensors. Satellite and airborne EO sensors of today are primarily the result of governmental funding. Direct government sponsorship has been common, because of the required amounts of technological development and the specialized needs of military users and other government users. In those cases where governmental organizations do not have complete ownership of space assets, heavy subsidization has been the rule, as in the French SPOT system and Japanese MOS and JERS systems. In the

U.S., LANDSAT was commercialized for a period of several years, but was not able to stand alone without substantial subsidy. After the failed launch of LANDSAT 6, the U.S. government resumed its lead role for future LANDSAT. The SeaWiFS program represents a more recent venture into commercialization of multispectral imaging systems. Commercial satellite imaging appears to be taking two thrusts, both of which are seeking markets that would yield large-volume data sales. One thrust is toward high-resolution panchromatic data (e.g., 1 to 3 meters) for engineering and land-use applications, as well as imagery for the news media. The other thrust, more pertinent to the topic of this paper, is toward multispectral data for agricultural and other earth resource applications. Of particular interest are market segments, such as high-technology prescription farming and high-value cropping, which could substantially benefit from advanced remote-sensing technology. Projecting 10 to 20 years in the future, panchromatic and multispectral data of fine spatial resolution may be directly downlinked to major users, perhaps through a relay satellite. Hyperspectral data also may be available, but on a more restricted basis. Rather than transmission of all spectral channels, users will likely be able to select only those most important for the particular need being addressed. A key to exploitation of MS and HS image data will be the ability to spatially register them to geographic coordinate systems and allow referencing to other types of information in geo-referenced databases. It can be anticipated that commercial remote sensing data will satisfy nontime-critical AF MS information needs such as terrain analysis, infrastructure changes bathymetry, and so forth, which could be served from a data archive refreshed every few months or yearly.

The Air Force could leverage off commercial activities in any of several ways, including buying commercial data. This approach frees the government of system maintenance responsibilities and long-term investments in infrastructure. Possible disadvantages include less control over system characteristics and restricted ability for prioritization and control of information to adversaries during times of conflict. Amelioration possibilities include purchase guarantees, augmentation of sensor development costs for more timely development of new capabilities or addition of specific capabilities, and agreements about government intervention during times of conflict. Data purchased from commercial MS and/or HS imaging systems could likely fill some Air Force mission needs. For instance, spectral imaging should be adequate for generating terrain categorizations for intelligence preparation of the battlefield and similar functions. The Air Force might increase timeliness of data from a commercial system by subsidizing the cost for additional satellites, so as to increase revisit opportunities. The Air Force could investigate placement of its own sensors aboard commercial platforms and using the commercial data links for data retrieval. The Air Force could provide funding for performance enhancements of commercial sensors that go beyond existing commercial needs. Environmental monitoring is an important concern of the civilian and commercial communities. Technologies developed to monitor facilities and detect releases and improper disposal of pollutants and wastes could also serve or be adapted to related military missions.

Impact on Affordability

Although thermal infrared spectral sensors in themselves may be more expensive than current Air Force thermal imagers, they could substantially reduce mission costs by reducing the amount of operating time required to perform the mission. The dramatic drop in required flight time to accomplish a mission will also result in many fewer lost aircraft, a savings in money as well as Air Force lives. We also will have fewer false targets, so we will waste fewer weapons. Intelligent preparation of the battlefield and chemical detection could also have major impacts on the effectiveness of our forces and therefore on the cost to achieve mission objectives.

Recommended Development Plan

Continue the joint multispectral program to conduct multispectral imaging tower tests, followed by multispectral imaging flight tests. Continue development of a first principals understanding of the required band pairs for maximum clutter rejection, verifying theoretical hypotheses using the collected imaging multispectral data. Once enough understanding of the phenomena is achieved, begin sensor design. IR sensors in the 3 to 12 micron band with 0.1 micron bandwidth and tunable over a yet unknown subset of the available wavelengths will be required.

Initiate an active sensor/ultraspectral sensing task, with the goal of identifying partially obscured targets. In particular, strive for target recognition with high values of target obscuration, such as 95 percent.

Consider change detection systems deployment to take advantage of the large scale changes over time due to construction of facilities and so forth.

6.2.8.2 HF/VHF Radar and Seismic Tomography for Observation of Underground Structures and Environment

Technological Approach

There is an increasing need for underground observations of both the geological environment and manmade structures covering volumes of the order of 100 to 1000 meters in size with resolution from a meter to a few tens of meters. Such a capability would find both important military and civilian applications. For example, military operations often require knowledge of underground structures, such as tunnels, bunkers and underground manufacturing facilities. In the civil sphere, the emphasis is on three-dimensional maps of the geological setting, including soil and rock types, fissures and voids as well as manmade structures. Some specific applications are in civil engineering construction and clean up of leaking underground storage containers.

The concept is to use both electromagnetic and seismic waves transmitted from underground sources to underground sensors. One issue is the transmission of the electromagnetic wave. However, this concept uses two distinct types of sensors and therefore fits in the category of expanded dimensionality. Observations between a number of source and sensor sites surrounding a region to be surveyed would be used in a tomographic scheme to construct a three-dimensional map of the electromagnetic and seismic properties of the volume observed. These data would then be interpreted in terms of geological characteristics and manmade structures.

Some characteristics that are likely to be useful are signal amplitude and phase, time delay of both the first arrival and subsequent arrivals reflected or refracted by the underground structure (natural and manmade), change in signal strength with frequency and coherence of the received signal. For example, signal time delay along a path allows calculation of average propagation speed. Compressional seismic propagation speed varies from a few kilometers per second (varying with rock) to only 331 m/s in air. Thus, voids would show up as decreases in propagation velocity along a path. For small changes in propagation speed, signal phase would be the appropriate observable. Electromagnetic waves, on the other hand, travel more slowly in rock than in air and thus voids would show up as increases in the average group propagation speed. The important point here is that seismic waves respond to mechanical (elastic) properties of materials while electromagnetic waves respond to the electrical properties of materials. Thus, by using both types of waves one can gather a much better data set from which to map out estimates of the underground structure of a site.

To implement this electromagnetic/seismic tomographic scheme, one needs to use wavelengths that are short enough to provide good spatial resolution, yet long enough to limit propagation loss to a level such that signal to noise ratios are in the 10 to 20 dB class. Sensor capabilities need to be considered. A first order estimate for ranges of 100 to 1000 meters indicates that electromagnetic waves in the meter to perhaps a few tens of rneters and seismic waves from perhaps large fractions of a meter to ten meters are appropriate. Sources and sensors for both electromagnetic and seismic waves exist, and most have been used in underground sensing applications. Improvements in sources and sensors are likely, but are probably not necessary for testing the idea in a realistic situation. Emplacement by penetrating devices is possible, but not to the depths of deep bore holes.

Relationship to Air Force Missions

Air Force missions are increasingly likely to require knowledge of underground structures for targeting of command bunkers and vehicles emerging from underground structures as well as the structures themselves. As the Persian Gulf War demonstrated, precise placement of munitions is a great advantage in destroying enemy forces and material. The scheme above allows such precise location, that is, it allows one to move from a vague idea of the location of a possible underground structure (km) to precise location (meters) in both horizontal coordinates and depth. In general, one would be denied access to a site and would need to emplace sources and sensors by covert means, for example, penetrators deployed by aircraft. However, in some cases surveys of known sites can be made for future use, for example, in peacekeeping and treaty enforcement missions.

Relationship to Commercial Applications

Surveys of underground sites on the size scales described here have commercial applications in both civil and environmental engineering. In civil engineering, the construction of highways, buildings or other large structures requires a survey to insure the competence of the rock below the site. Otherwise, subsidence may occur from unknown voids. Environmental clean up is another important commercial application. The conventional method is to use test bore holes to characterize the site geologically. This method is both costly and invasive. For example, a bore hole may allow pollutants trapped above an impermeable layer to escape to layers below by passing through a test bore hole and its surrounding fractures of the layer. Once an accurate survey of the contaminated region is done, a plan can be devised to remove or mediate the pollutants in a cost effective manner. In particular, an underground survey allows modeling of pollutant flow, and thus one can make a targeted search rather than having to excavate a larger volume. Mineral exploration may be able to use similar techniques. Also, archeologists certainly would be interested in finding underground cavities.

6.2.8.3 HF/VHF/UHF SAR for Foliage and Ground Penetration

Description of Technology

HF/VHF/UHF SAR has the potential to detect and classify military targets concealed by foliage and objects/targets buried at shallow depths. It is also expected that metallic objects inside manmade structures such as buildings will be detected by this kind of radar. In summary, the HF/VHF/UHF SAR has the potential to penetrate line of sight obscuring materials while imaging the desired object of interest.

Current radar system concepts indicate a VHF/UHF SAR will use a very wideband waveform, and can be classified as an ultra-wideband (UWB) radar. The pulse bandwidth could easily be in the 400 to 600 MHz range with a center frequency of 300 to 500 MHz. Typical spatial resolution needed is 0.5 meter in both range and azimuth to provide adequate clutter suppression. [Three-dimensional aperture concepts to help resolve clutter in a volume cell (voxel) are also a possibility.] The radar will transmit and receive a complete set of polarizations, that is, it will be a polarimetric radar. This too is needed for clutter suppression. The radar will also need to provide for multiple images (looks) over a 90 degree interval. This angle diversity is needed to enhance the target signature. The radar system concept needs the fine resolution, multiple polarizations, and multiple looks to reliably detect the targets under foliage with a false alarm rate of less than one per 10 square kilometers.

The main technology issues for this radar are ultrawideband antenna and transmitter components, affordable high throughput signal processors providing 100’s of gigaflops/sec, and robust target detection algorithms. The capability of this technology to provide reliable target classification is yet to be proven.

Development Status

This technology is under development (6.2 and 6.3a) and is showing good potential. An airborne test radar developed under primarily ARPA funding, with some support by the Air Force and Navy, has recently started flying and collecting data to determine the performance in detecting military targets. This testbed is the P-3 UWB SAR flying on a NAWC P-3 aircraft. The ARPA FOPEN (foliage penetration) program conducted many experiments with existing radars prior to developing the P-3 UWB SAR. This radar provides for 500 MHz of pulse bandwidth placed within the overall band of 200 to 900 MHz. It is also a polarimetric radar. It produces broadside looking strip map imagery. It does not provide multiple looks over a 90 degree interval as needed. Data collections can be done with multiple flight paths to acquire the equivalent of multiple look data. Also the P-3 UWB radar use an antenna and transmitter that were off the shelf, and they are not suitable for any operational aircraft except for a cargo size aircraft. The airborne radar from the A/Ds are recorded. The data are processed later to produce imagery.

The Air Force Wright Laboratories have also developed FOPEN technology in a program called Concealed Target Detection Technology Development (CTD program). Both LORAL and ERIM under this program investigated and modeled the phenomenology of foliage effects on radar signals propagating through the canopy, scattering from the canopy and from tree trunks. Signatures of targets were measured and modeled. This information was collected in a simulation that was capable of producing radar imagery for targets under foliage. These data were then used to develop a target detection algorithm and to get a first assessment of expected performance. A simulation was used to produce imagery since there were no airborne radars with the appropriate capabilities. This was prior to the P-3 UWB SAR being built.

The Air Force Wright Laboratories has a follow-on CTD program under way called Radar Detection of Concealed Time Critical Targets (RADCON). This program is developing a real time image formation processor for the P-3 UWB SAR, and it is continuing to develop and refine target detection algorithms.

The implementation issues of the antenna and transmitter are not being addressed under any program. In addition, there are no plans for an operationally significant demonstration.

Current and Projected Performance

The VHF/UHF SAR will be capable of detecting targets concealed by foliage and targets buried at shallow depths. The FOPEN radar performance is characterized by parameters shown in Table 6-9.

The FOPEN performance shown in Table 6-9 will provide significant operational capability to detect military targets the size of trucks and larger under forest conditions typical of temperate zone conditions. The ability to classify targets with this technology is unclear and will be determined experimentally. Also it is not clear what detection performance can be achieved for targets under more difficult circumstances such as triple canopy jungle forests, as found in the equatorial regions. The level of attenuation produced by equatorial forests has not been measured. This prevents the prediction of target detection performance in equatorial regions.

The detection performance for buried targets is unclear at this time. Various experiments have been conducted. For example, the detection of recently buried 55 gallon oil drums has been demonstrated under typical midwestern soil at depths of 1 meter. Experiments in arid regions in the western United States have been less successful. This is due to the soils being more conductive than in the midwest or eastern areas of the United States. The detection of partially buried structures such as bunkers are projected but no experiments have been conducted.

Table 6-9. FOPEN Radar Performance

Performance Parameter	Current Performance	Projected Performance
Forest Type	Temperate zone (e.g., Europe)	Best performance in temperate zones but some capability in equatorial forests at higher grazing angles and for larger targets.
Detectable Targets	M-35 trucks and larger	artillery, and vehicles jeep size and larger
Probability of Detection	0.8 to 0.9	0.8 to 0.9
Probability of False Alarm	1.0 per square kilometer	1 per 10 to 100 square kilometers
Swath Width	0.8 km	5 to 10 km
Area Rate	4000 square nmi/day	20,000 to 40,000 square nmi/day
Grazing Angle Region	30 to 60 degrees	15 to 60 degrees for temperate zone forests, >45 degrees for equatorial forests

Relationship to Air Force Missions

The Air Force has the mission of detecting and classifying targets from airborne platforms to support the missions of interdiction and deep strike. Today, the Air Force cannot reliably detect and classify targets concealed by foliage. The use of concealment by foliage can be done by parking targets on roads or clearings in the forest, and by parking targets next to tree lines where the radar does not have clear line of sight. While this was not important in the Middle East, this capability is critical in most parts of the world including Korea, Europe, South America, and Southeast Asia.

Finding artillery and armor concealed by foliage today would be very difficult using existing Air Force assets such as the Air Force ASARS-2 radar flown on the U2-R aircraft. While this SAR was very useful in Desert Storm, it would not be nearly as useful in finding military targets where tree lines or forests could be used to prevent line of sight viewing of the target. The benefit of this technology being applied to Air Force missions of deep strike and interdiction is to enable prosecution of targets now successfully concealed by foliage, structures and earth emplacements. The Air Force will be much more effective in prosecuting armor concealed in forests or aircraft hidden in hardened structures.

Relationship to Commercial Developments

The processing capability required by a VHF/UHF radar is significantly larger than needed by current or near term SARs. Current SARs require approximately 10 Gflops/sec of peak computing capability. A VHF/UHF SAR will require 100's of Gflops/sec for acceptable performance. Affordable signal processing will be accessible by the Air Force by using COTS computing technology. The operational deployment of VHF/UHF SAR's will await affordable signal processing of 100's of Gflops/sec.

There is a potential commercial benefit of FOPEN radar for forest surveys by using the imagery to count trees and to determine trunk size. The scattering from tree trunks for HH polarization produces bright point responses in the imagery. These points can be counted to estimate tree densities. The amplitude of the point response indicates the size and moisture content of the tree trunk. The soil conditions also affect the amplitude of the point response and make it more difficult to determine tree trunk diameter. Surveys of the soil conditions at a very modest number of sites could eliminate this issue.

Another potential commercial application is the use of FOPEN SAR to do terrain elevation mapping under heavy canopies using two closely spaced passes. This has applications for resource exploration and management. Either interferometry or stereo are candidate approaches.

Recommended Development Plan

A comprehensive development plan is needed to (1) determine the conditions where the VHF/UHF SAR will adequately perform, and (2) to develop the subsystem components suitable for installation in Air Force aircraft such as the U2-R, cargo type aircraft or in future UAVs.

Phase 1. Duration 2 to 3 years

- Develop transmitter and antenna components suitable for high altitude operational reconnaissance platforms.

- Demonstrate utility of FOPEN imagery for automatic cueing of military targets using testbed FOPEN SAR.
- Demonstrate utility of FOPEN SAR in imaging land features under foliage.

Phase 2. Duration 3 to 4 years

- Demonstrate prototype system on operational system. Test under many foliage conditions and seasons.

6.2.9 Inertial Sensing, Geolocation and Positioning

Description

This sensing technology provides accurate, reliable, and affordable location information anywhere on the globe and in near-space surroundings. The information is obtained either internally via inertial accelerations integrated to velocity and position, or externally via radio, optical, or other external navigation aids. Most often, it is obtained from a combination of both methods, with inertial data providing accurate short-term information and external aids used to bound long-term error growth.

The technology is well established and has evolved gradually over time, experiencing only a few major revolutions. A condensed history of this evolution is shown in Figure 6-25, starting with the World War II time period when inertial measurement systems were first introduced to replace historical navigation methods based on stellar sightings, clocks and catalogs. The early inertial sensing technology used spinning mass gyroscopes on stabilized gimbaled platforms to provide a reference frame for proof-mass accelerometers. While this was compelling because it provided accurate and continuous position information independent of external references, the arrangement proved costly and unreliable. It was eventually replaced with optical gyroscopes (ring laser and/or fiber optic gyros) on stap-down platforms attached directly to a vehicle. In this new arrangement, embedded digital computers are used to transform the continuously changing reference frame of the platform back into a fixed frame for navigation. It is the combined development of airborne computers and optical gyroscopes that made this revolution possible. Reliability has improved dramatically, from MTBFs in hundreds of hours to many thousands of hours. Size, weight, power consumption, and cost have all declined. Based on current commitments, the strapdown optical technology is expected to dominate Air Force systems and commercial transports systems well into the 2020s.

External radio aids have evolved on a similar gradual time line. These systems began with the installation of radio transmitters at known locations so that ranging and/or direction finding to these sources allow receivers to calculate their location. Examples are the OMEGA system and LORAN. Their accuracy is relatively poor (measured in nautical miles) and their coverage is incomplete. This situation is experiencing a major revolution with the introduction of full constellations of GPS and GLONASS satellites. In effect, these systems place many radio transmitters in orbit, so that some are visible to receivers at all times, for global coverage. They also utilize frequencies and coding schemes that provide accuracy in the tens of meters for basic modes, meters for differential modes, and centimeters for so-called carrier-phase modes.

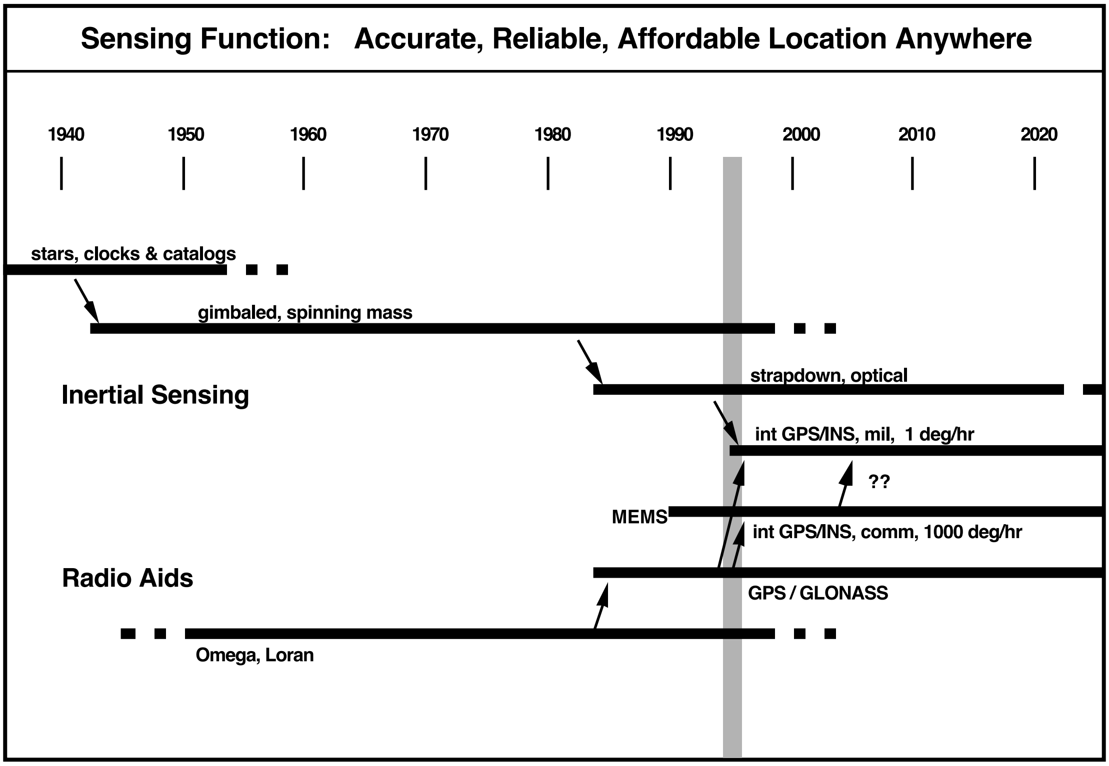


Figure 6-25. History of Geolocation and Positioning

One part of the ongoing GPS/GLONASS revolution is the growing trend to integrate these radio aids with inertial sensors in the same package. Such integration is occurring both in "loosely coupled" ways, where the radio aids are simply used in the navigation computer to bound long-term inertial errors, and in more "tightly coupled" ways, where the radio aids are used to continuously calibrate major inertial error sources (e.g., gyro biases) and the inertial data are used to help receiver tracking loops and antenna steering loops operate in adverse signal-to-noise environments. Loosely coupled integration is already common in new aircraft navigators, both military and commercial, while tight coupling will be widely used in weapons systems, where jamming is an important issue and where the inertial performance relief offered by tight integration promises cost reductions of today's strapdown optical systems.

Another aspect of the GPS/GLONASS revolution is the promise that a new very low cost inertial sensing technology may meet military needs. This is the MEMS technology described in Section 6.2.1. This technology relies on semiconductor processing methods from the microelectronics industry to make large numbers of very small mechanical structures with various useful properties. One useful structure, for example, is a vibrating tuning fork. In this structure, vibrations in one plane are transferred to an orthogonal plane through Coriolis-coupling whenever the structure is rotated. With electronics added to sustain the in-plane vibrations and to read-out the orthogonal response, the structure thus becomes a gyroscope. Some design concepts even use micro-machined proof-mass accelerometers as the read-out scheme, so the structure also doubles as a linear accelerometer. Substantial R&D is currently on-going to design such devices for low cost commercial use in applications such as camcorder image stabilization, automotive suspension, braking and yaw control, and commercial vehicle navigation. These applications typically have gyro accuracy requirements of several thousand deg/hour. The closest military needs for tactical weapons, on the other hand, call for accuracy of a few deg/hour. Thus, a full three orders of magnitude currently separate commercial and military needs.

Relationship to Air Force Missions

Location information is a basic requirement for virtually all Air Force missions. It is required on all airborne platforms, both own-ship location and location relative to others. It is also required on all weapons except “dumb bombs” and on most vehicles or agents on the ground, down to individual airmen.

Relationship to Commercial Developments

As indicated above, the major trends today are the shift toward GPS as the primary radio aid for navigation, its integration with inertial sensors in the same package, and the development of very low cost MEMS devices as gyros and accelerometers. Commercial developments will drive the evolution of the GPS ground segment—the receivers, differential ground stations, and pseudolites for carrier phase concepts. This evolution will be driven by the pace of consumer electronics and communications technology. Similarly, low cost MEMS devices will be driven by commercial developments for consumer products such as automobiles and camcorders.

Development Plan

Basically, the Air Force should “go along for the ride” on the various commercial developments. It should exploit GPS evolution, undertaking its own developments only to cover un-addressed military needs (e.g., integrity, availability, jam resistance). It should also seek to drive MEMS technology into the tactical arena. The latter may prove very difficult, however, if “tactical” continues to mean 1 deg/hr gyro performance. These specifications are based largely on stand-alone requirements for inertial systems when GPS-aiding is disabled. Broader system level decisions that assure greater GPS availability could relax this requirement substantially and thereby encourage the use of MEMS devices in tactical systems.

6.2.10 Tagging Technology

This technology involves a wide variety of devices or materials that can be attached to targets of interest in order to clandestinely monitor their activity. During construction or periodic maintenance, vehicles will be under relatively light security and could be tagged. This would allow a continuous sampling of the target’s activities and locations being visited that could include wartime security bunkers. Replacement of items like fuel caps with sensor caps would allow quick tagging. Agreement signing pens and award/gifts like watches would be another avenue to get tags on the desired target. Friendly troops can also be tagged to prevent accidental targeting. Some of these tags could be placed during inspection visits by attaching decals that would hide efficient flat patch antennas and retrodevices.

During manufacturing, military components of high value targets could be modified to provide a remote access to data and control systems, or to simply provide an ID number when transponded. There are many accessible approaches, such as through replacement tires, batteries, brake lights, light fixtures (provides battery charging), placards, bumpers, and printed circuit boards or chips, to name a few. The enemy's deployment and readiness state would be available by a polling of all sensors and noting the changes in location and other data like movement, engine on, computer up, and so forth.

Retroreflectors can be as simple as resonant optical spheres that look like ground-up ash. Items can be tagged with this powder and interrogated with pulsing laser sources. Optical grating arrays used as retros are able to modulate backscattered light at rates high enough to pass 20 nanosecond pulses. These speeds allow enormous amounts of data to be dumped in a quick strobe of the laser.

RF Retroreflectors

In the past, the Army communicated using the Heliograph, a device for signaling by means of a movable mirror that reflects beams of light, usually the sun. This passive concept could be useful again by operating in the microwave region of the spectrum to modulate radar backscatter energy. Instead of a mirror to reflect the sun, a set of resonant dipoles could be turned on and off with a simple diode switch, producing a modulated retro reflection. This modulation would identify the backscatter energy from the user's azimuth and range to be friendly.

The possible illuminator would be the Joint STARS platform or other coherent radars. The modulated retroreflector would appear as a unique Doppler target, say 100.15 miles per hour. Figure 6-26 depicts the concept. The power drain of the identification oscillator is exceedingly small with the life expectancy limited by the battery's shelf life. The optimum retro would be a cluster of tuned dipoles connected with diodes that all have the same source of identification data.

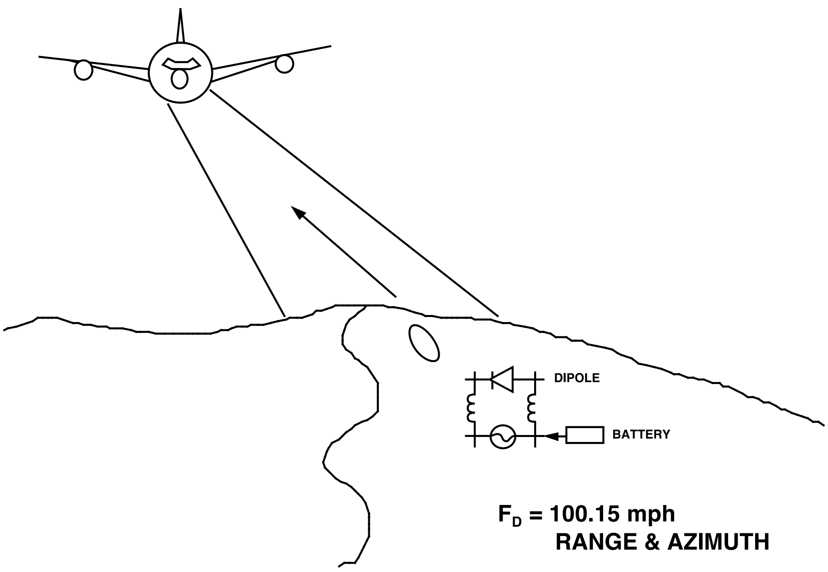


Figure 6-26. Joint STARS Retroreflector Concept

Tire Tag Concept

A possible concept for tagging high value targets or associated vehicles using retroreflecting radar concepts could be accomplished by inserting snow studs into the rubber tread of a tire, constructed to resonate at the Joint STARS frequency to provide a chaff-like response with the Doppler offset generated by the tire's rotation. An ID number could be impressed on the return by switching the antenna diode.

Battery charging is possible using a piezo-electric crystal in the tip of the stud that is compressed on each contact with the road. As the tire rotates the response will be cross-polarized, producing a cyclic modulation that reveals vehicle speed.

Dual Purpose Tags

Most high-value tag targets have associated vehicles with power generators that require fuel tanks. Replacement of fuel tank caps with one of our Trojan horses would provide an easy access and concealment for a UHF transponder and a remote controlled squib that could rupture and ignite the fuel tank This would provide an excellent marker for other ordinances to take out associated targets. This type of device would be well suited for tagging Scud support trailers to tip off activity and destroy or mark weapons.

Parasite Tagging

The concept of parasiting on a target of interest by inserting a microdisc inside the cable connector, allows access to power from its battery bus and tapping data from the rest of the pins. Thin discs have been developed to provide a simple fix for RFI problems. These discs weigh one half gram each and easily slide onto the male pins of the typical cable connector. Current EMI filter wafers work by placing a discrete capacitor (or any other discrete electrical component) between each signal pin and ground in the host connector, significantly reducing radiated susceptibility and radiated emissions for new and retrofit applications.

The tag disc would perform exactly the opposite function by radiating the control data and adding an ID number. The sensor burst would then be transmitted on a selected frequency when interrogated by the collection platform. This microdisc does not appreciably change the size, shape, environmental seal, or electromagnetic compatibility of the host system. The wafers can be installed in under a minute by simply demating the host connector pair, inserting the disc, and remating the connectors.

Fuel Tagging

Laser fluorescing of engine exhaust particularly in aircraft has been demonstrated. To enhance this technique and to mark hostile aircraft, even stealth, very active fluorescing elements could be added to the general fuel supplies that will eventually get to the hostile combat targets. This will provide additional detection capability and help in identification of hostiles.

6.2.11 SIGINT and ESM

The use of signal intelligence (SIGINT), electronic (ELINT), communications (COMINT), and ESM for support to the warfighter, including both intelligence and operations, is an important sensor area. The intelligence support is well-known; and the support to operations must include direct support both as a cue to higher resolution sensors (SAR, for example), and as a direct targeting tool. The technologies are primarily those related to transitioning to all-digital signal processing.

6.2.11.1 Advanced SIGINT and ESM Technologies

Programmable All-Digital Receivers

The advancement of RF devices, along with the advancement of A/D converters and signal processing techniques, offers the opportunity to move the conversion to digital data for subsequent processing for signal detection and demodulation, analysis, and cataloging.

The fundamental desire is to convert an intercepted signal to digital data at the earliest possible stage, and process multiple digital channels with those algorithms that provide filtering, extraction from noise and co-channel signals, analysis, signal identification, and so forth. Thus, an architecture that achieves analog to digital conversion for frequencies from 100 MHz to 40 GHz is highly desirable. Moreover, as many as 100 or 1000 simultaneous channels might be necessary to handle all newly detected signals.

The key need is for high sample speed, high quality (spur-free, low aperture jitter, etc.) A/D converters. The state of the art at this time is 4 giga samples per second at 8 bits resolution for high quality conversion. Ultra high speed integrated circuit technology will bring the higher performance. (See Section 6.2.3.3 for more information on A/D converters.)

Signal processing techniques for some key analysis functions must be developed. While most functions are now accomplished by software at some nominal quality, the use of high speed digital processing offers the opportunity to significantly advance the ability to de-interleave signals, determine precise location, establish signal/system identity, and extract signal internals.

Micro-Signals Receivers

Some forms of equipment unintentionally radiate very low level signals of special importance to military operations. For example, computers radiate at their clock frequencies. While the content of the computing activity might not be radiating, the detection and location of the clock frequency radiation might provide the Special Operations forces with important information as to where in a building the computers are located, and even some information about type and quantity. Similar emanations can be expected from other equipments ranging from large machinery to digital watches.

Receiver technologies have improved significantly and it is likely that in the year 2025 we can expect to be able to develop a radiometric receiver on a chip with associated processing that would extract signals, including low probability of intercept signals, from electrically noisy backgrounds. The extremely small size would allow carrying the sensor extremely close to facilities and forces.

Wire and Cable Taps

From the U.S. Civil War through the Vietnam War, wiretap has been an important source of tactical intelligence. In the aftermath of “Watergate,” the services dropped all tactical wiretap training and destroyed all equipments for fear someone might use it for some illegal purpose!

A robust sensor program should have the capability of providing access to enemy command communications that are currently secured in wire and fiber optics. The future is clearly moving to fiber optics to provide the wideband multiple user requirements of the future.

Net Analysis

A major limitation in tactical SIGINT is the ability to build a "cherry sheet" list of the enemy's net frequencies. This requires significant frequency activity to allow search operators to intercept and direction-find (DF) transmissions from the battle area of interest. The tactical field commander is primarily interested in data that come from the enemy that can cause harm. Radio silence is a standard practice for disciplined troops with only a quick communications check to assure readability by the net members.

A technique to assure high probability of intercept is an approach that uses a COTS radio frequency counter that has the ability to count the strongest signal's frequency in the 10 to 2800 MHz band. The counts are time tagged and store up to 400 events. For the field commander, this equipment could provide a first order analysis of externals and present an emitter map (electronic order of battle [EOB]).

The output data are also available for relay to remote collection (such as Rivet Joint) locations where a collection receiver would be automatically assigned to the detected frequency. This provides the operator a hands-free system. The intercepted traffic would confirm the user and provide intelligence on the target area of interest back to the commander. If a decision is made to jam the activity, the relayed counter readouts could be passed to resources such as Compass Call to allow a jammer to be on frequency in a very short time.

Spacecraft Sensor

The close-in technique discussed previously could be used in space to determine all intentional and unintentional transmissions emanating from an enemy satellite. The sensor spacecraft would be maneuvered in proximity to assure that any radiation will be easily detected over the background signals and noise. The locally detected signals would be characterized and a message sent to earth stations to allow large antennas and prepared receivers to be targeted against the satellite for collection. Especially low signal levels might call for collection in space. Other satellite emanations (magnetic, for example) could also be collected.