2.0 The Sensing Process

2.1 Introduction

In order to escape the constraints of conventional thinking about the preferred approaches to implementing various sensing functions, we take a very broad and generalized point of view. The operation of a sensor necessarily entails: (1) the exploitation of one or more physical phenomena that convey information about the external environment (sensing domain), (2) use of hardware and software designed to interact with the sensing domain and with the people or machines to which the sensor provides information, and (3) schemes for producing, storing, and manipulating the information that the sensor yields. However, in almost every sensing situation there will be multiple choices in each of these categories, and the approaches suggested by conventional wisdom may not be optimal. This is especially true as affordability comes to equal or exceed performance as the driving priority in many systems. The very different taskings that the Air Force confronts in the post-Cold War era are likely to require different sensing capabilities, and this raises questions about the adequacy and appropriateness of the current system inventory. Moreover, advances in technology increasingly create opportunities to share a given set of sensor assets among multiple functions and to coordinate the operations of individual sensors in ways that produce significant operational benefits. All of these considerations motivate a fundamental and comprehensive examination of sensor requirements, the best ways to approach them, and opportunities to improve system capabilities while controlling costs of acquisition and ownership.

2.2 The Sensing Process

Figure 2-1 graphically represents the steps that are present in any sensing process. The underlying phenomena can be as diverse as intercepting reflected or naturally occurring electromagnetic (EM) radiation, detecting seismic or acoustic energy, trapping chemical or biological agents, or measuring the motion of the sensor's platform. We define an active sensor as one that stimulates its external environment and measures a reflection or other response and a passive sensor as one that does not.

2.2.1 Transduction

The sensor proper starts with some means of converting the stimulus of the sensed phenomenon into a signal or data stream that information processing hardware and software can manipulate. Familiar transducers include antennas connected to RF front ends, electro-optical (EO) detectors with associated optics, microphones and seismographs, and the accelerometers and gyroscopes used in inertial navigation (NAV). As suggested in Figure 2-1, multiple apertures of the same or different types may be used to achieve the required field of regard or because multiple phenomenologies are used. In every case with which this volume is concerned, the output of the transducer will ultimately be in the form of an analog electronic signal or a digital data stream. However, at intermediate stages of the process, the sensor's content may take the form of charge packets (e.g., charge-coupled device [CCD] readout from a focal plane array), optical energy (e.g., optical filtering or Fourier transform), acoustic energy (e.g., frequency determination using a Bragg cell), mechanical vibration (e.g., resonant gyroscope), or, presumably, some other form of energy. The transducer will normally operate on the raw collected content to achieve amplification, rejection of spurious or uninteresting content (filtering), or other "signal conditioning." In addition, the transducer will generally be controlled in sensitivity, bandwidth, or other parameters to maximize its ability to sense things of interest while rejecting other stimuli. It is now general practice to perform analog-to-digital conversion (ADC) early in the sensing process to minimize corruption by noise and interference. Ultimately, this stage of the process produces as output one or more signals or digital data streams.

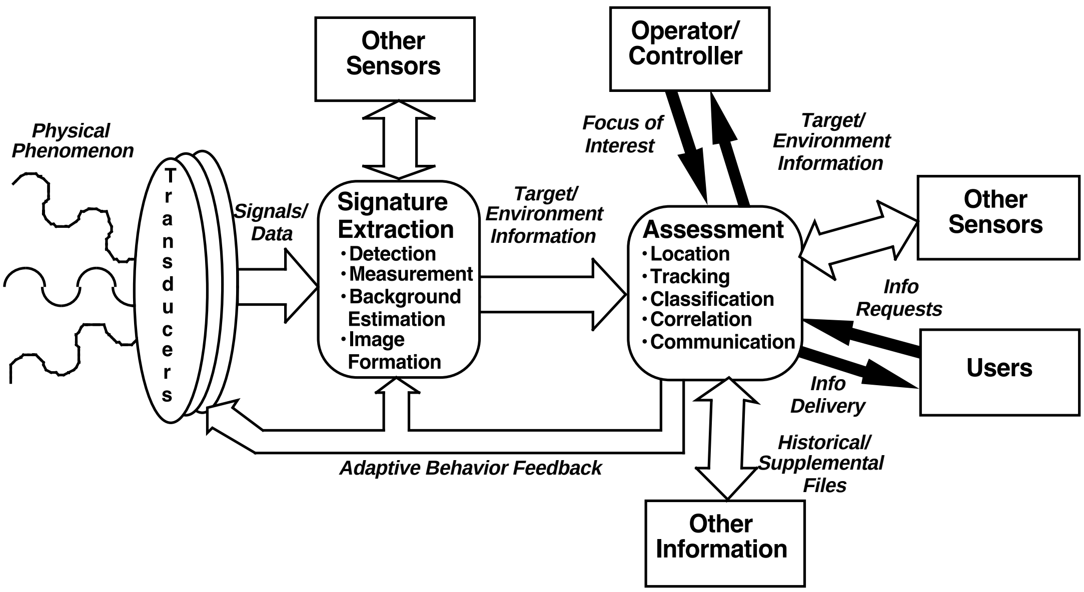

Figure 2-1. Elements of a Generalized Sensing Process

2.2.2 Signature Extraction

The next stage of the sensing process operates on transducer output to determine its content. This may be as simple as declaring that a given signal or data pattern represents a target (e.g., has an amplitude higher than a preset threshold) or may involve a more complex measurement of parameters such as intercepted signal frequency, Doppler shift, time dependent amplitude, and so forth. We denote any object of interest in the sensing domain as a "target" regardless of whether hostile intent is involved. Depending on the nature of the sensor, the bearing and range from sensor to target may be available from pointing angle and round trip time delay, or the signal may be associated with a broad sector of the environment. Sophisticated processing such as MTI and spatial/temporal filtering may be used to extract valid targets from noise or background clutter. Many sensors, for example, synthetic aperture radars, require a significant amount of processing to form (reconstitute) images from the raw collected data. In addition, it may be important to sample and determine aspects of the environment such as the statistics of the noise and clutter background seen by the sensor. As shown in Figure 1, the assessment process may be fed by data from other cooperating sensors in addition to that coming from the system's own transducers. In short, this stage converts transducer and contributing sensor data into information about the sensing domain and objects in it.

2.2.3 Assessment

In a simple sensor system like a first generation radar, all that may remain is to display the detected information to an operator. More generally, the result of signature extraction becomes the input to a more elaborate stage of processing in which information is assessed over time to develop a more complete information base on the sensing domain. Typical examples include:

- Integrating individual target locations over time to reduce the effects of system errors and noise.
- Developing a track for a moving target.
- Evaluating current and historical information to classify a target (e.g., as friendly or hostile or as a specific type or model of vehicle, ship, aircraft, etc.).
- Correlating information from more than one sensor or other information source first to determine that a common target is involved and second to combine the information to improve the system's knowledge of that target.
- Determining that a given body of data is of interest to other systems or users and communicating accordingly, for example, to cue a different sensor to seek a given target.

2.2.4 Interactions

A single function, unattended sensor may be entirely self contained and have no external interactions other than perhaps a data channel to pass along its findings. Most sensors, however, have some or all of the interactions shown in Figure 1.

- **Users**. The ultimate purpose of a sensor system is to deliver information to an operational user—from individual warfighters to national command authorities. Users place requests for required information, and the system initiates and reports the corresponding information collection and analysis activities.
- **Operators and Controllers**. In general, a system will function under the immediate control of an operator or programmed controller. The control authority inputs the search parameters, target types, or other data defining the focus of attention that the sensor is to address and monitors sensor output.
- **Other Sensors**. In addition to the previously described possibility that cooperating sensors may feed data to the signature extraction process, information on targets and environments derived from assessment processing may be shared. This is discussed in more detail under the sensor data fusion topic in Section 3.
- **Stored Information**. Finally, the assessment function may use historical data or other information that is not registered in time and space with the immediate targets of interest. Attribute files may be used to associate new target locations with earlier detections of the same targets, or intelligence data may contribute to target identification. For example, a track history from takeoff may be the best source of non-cooperative target recognition (NCTR) for an unknown aircraft.

2.2.5 Adaptive Behavior

The effectiveness of a sensor can be greatly enhanced through constant adjustment of the transduction and signature extraction stages based on the results of processing target and environment information. Detection thresholds, operating frequency or bandwidth, filtering, and other characteristics may be controlled based on operator or user inputs, clutter and false alarm statistics, and other measures of performance.

2.3 A General Model

The process in Figure 2-1 can, with great generality, be mapped onto a functional sensor structure like that shown in Figure 2-2. The aperture interacts with the environment to convert the phenomenology being used into a suitable form of energy. In an active sensor, the aperture also includes the transmitter, which may be a discrete function like a laser or a distributed implementation like the power sources in the transmit/receive (T/R) modules of an active electronically scanned array (AESA). Virtually any sensor has electronics close to or integral with the aperture to detect, amplify, filter, or otherwise condition the aperture signals. Examples include use of charge coupled devices to collect and time integrate the carriers generated in a focal plane array, a low noise amplifier/mixer chain in an RF front end, and a force rebalancing loop for a gyroscope. In any modern sensor, the aperture output will be analog-to-digital converted and passed to a digital processor for signal and data processing. These functions may be centralized for an entire platform or distributed to individual sensors or both. In any case, the types of processing and interactions described in the preceding section occur here.

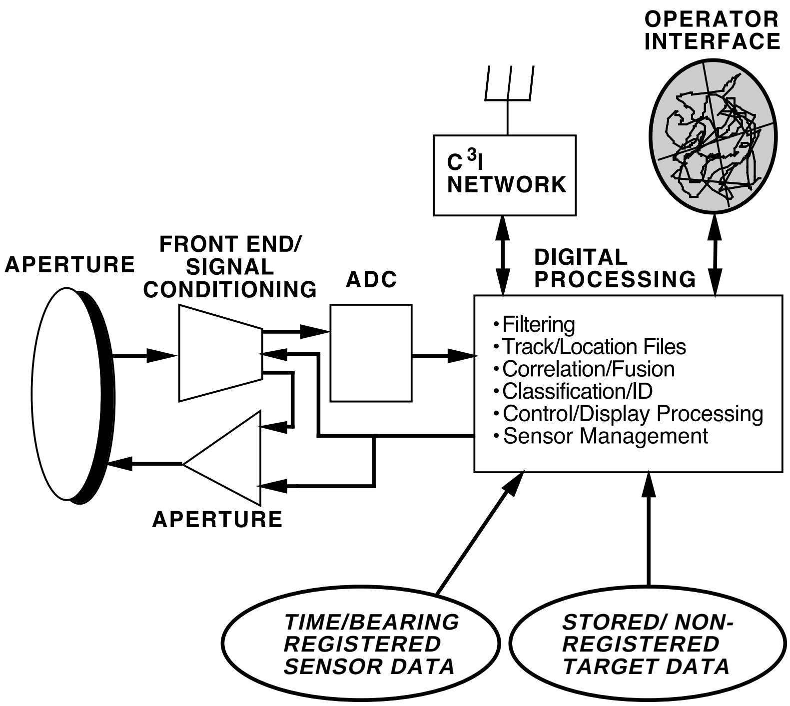

Figure 2-2. Generalized Functional Model of a Sensor

Commonly, the operation of the aperture will be adjusted in real or near-real time based on both the instantaneous attributes of aperture output and commands generated by the processor or entered by a system operator. Such adjustments might include resetting a detection threshold, changing sensor scan volume, changing transmitter power, and so forth. For example, a signal intercept receiver might be commanded to dwell in a specific frequency bin to confirm the presence of a threat signal based on a tentative match by the processor of a received signal to a threat library. Figure 2-2 makes explicit the distinction between two classes of supporting information. Sensor inputs that are to be correlated or fused in near-real time must be registered both spatially and temporally so that the processor can unambiguously associate individual information streams with a common target. Historical files and other *a priori* data may include spatial coordinates, target attribute lists, or other information to allow association with real-time targets.

2.4 Sensor Taxonomies

Sensors can be classified in many ways to facilitate an orderly discussion of this exceptionally diverse subject. The two most relevant for the present discussion differentiate sensors on the basis of the exploited physical phenomena and the operational tasks supported.

2.4.1 Sensors Classified by Phenomenology

In Table 2-1, sensor types in each area of phenomenology are further broken out by active and passive types and, in some cases, by advanced types that extend basic sensing modalities. Typical sensor types are listed, but the table is not exhaustive; only types of primary Air Force interest are included.

2.4.2 Sensors Classified by Operational Use

Next, we consider typical operational tasks which require sensing and typical sensors used for each. These applications are indicated in Table 2-2. Most applications can, in principle, be addressed with more than one type of sensor, and considerations of affordability, reliability, flexibility (support for multiple missions and tasks) and ability to contribute to an overall picture derived from multiple individual sensors become important in defining an optimum sensor system inventory.

A further classification of significance is the platform on which a sensor will be carried, since considerations such as weight, endurance, available power, and engagement dynamics may greatly affect the achievable level of sensing performance and the optimum choice of sensor type(s). This is most dramatic in the case of space-based sensors, where severe weight and power limitations combined with relatively short viewing windows (for low earth orbit) or very long ranges (for geosynchronous orbit) dictate very different sensor designs from airborne or ground based systems. Thus, in the past, EO sensors have been the primary choice for space-based wide area surveillance, despite their inability to see through clouds, because they are small and light compared to an active RF sensor. This is changing rapidly as imaging radar technology is developed.

Table 2-1. Phenomenology Classification

Physical Phenomenon	Active Sensor Types	Passive Sensor Types	Extended Sensor Concepts
Electromagnetic			
• DC/Low Frequency		Bistatic radar, conductivity meter	Advanced unintentional RF illumination sensor
• RF Wavelengths (RF, microwave, mm wave)	Radar, IFF I/T	CNI, radiometer, RWR, ESM	Passive imaging radiometry
• EO Wavelengths (IR, visible, UV)	LADAR, LIDAR [1]	Spot tracker (IRST, MLW), imager (FLIR, NVG, FPA)	Multi or hyperspectral imagers
Mechanical			
• Acoustic	Ultrasonic NDI	Microphone	UGS
• Seismic	"Thumper"	Seismograph	UGS
• Inertial		Gyroscope, accelerometer	
Chemical/Biological	Trained organisms	Permeable membrane, spectrometer, chemical reaction	UGS

2.5 Challenges and Opportunities

As noted in the Introduction, the radically different military environment confronting the Air Force creates new and different requirements for sensor capabilities. Two examples of the operational challenges that will stress Air Force sensor systems are the "expeditionary force" posture that requires CONUS-based forces to be deployable almost anywhere on earth, ready to fight on arrival, and the prominence of low-level conflict and operations-other-than-war. Both of these place stress on the ability to rapidly collect large amounts of information about an area of operations with limited on-the-ground access. Constraints on the numbers and costs of sensing systems mean that platforms and sensors must have great mission flexibility and high levels of autonomy. Both evolutionary and revolutionary improvements in sensors are likely to be essential in meeting these challenges.

1. In keeping with common practice, we label an active EO sensor used to detect and track "hard" body targets as a LADAR and one used to sense the presence of clouds, gases, or other diffuse targets as a LIDAR.

Table 2-2. Applications Classification

Sensor Applications	Typical Sensor Types
Wide Area Surveillance	Radar (AWACS, Joint STARS, OTH, etc.), Passive EO Imaging, SIGINT
Threat Warning	Passive EO (missile launch detection/approach warning), RWR, CNI/ESM, SIGINT, Radar
Reconnaissance/Battle Damage Assessment	Imaging EO, Imaging Radar, ESM, Fire Control Sensors
Air-to-Air Detection, Tracking, & Fire Control	Radar, IRST, ESM (e.g., ARM seeker)
Air-to-Ground Targeting & Fire Control	Radar (SAR), FLIR, LADAR, ESM
Missile Guidance	Inertial, Stellar, GPS, Radar, LADAR, Passive EO, ESM, Beam Rider, Proximity Fuze
Navigation	Inertial, GPS, Imaging Radar, Stellar, CNI
NBC Detection	Specialized Detectors, DIAL, Hyperspectroscopy, LIDAR
Ground Traffic	Acoustic, Seismic, including UGS
Weather	Radiosondes, Doppler Radar, Imaging EO, LIDAR
Science and Technology	Imaging EO and Radar, ESM/SIGINT
General Intelligence and Indications and Warning	ESM/SIGINT, Imaging EO and Radar, Wire Taps, Acoustic/Seismic, UGS
Medical/Crew Health Monitoring	Multiple Biomedical Instruments
System Health Monitoring	TSMD, Built-In Fault Detection/Isolation, NDI

We begin with several overall “grand challenges” which affect the area of sensors in general. Later discussions will focus on specific challenges associated with representative operational tasks. Among the grand challenges confronting sensor system designers and users are:

2.5.1 Data Rates and Volumes

A pervasive theme is the fact that technological advances in sensing apertures and phenomenology have created a situation in which our ability to collect raw data significantly exceeds our ability to extract useful information from that data. A high resolution (10^6 pixel) spaceborne imaging sensor in low earth orbit that collects 10 images over an area of interest per pass with 10 bits of gray scale data per pixel would dump 100 Mbits of data into a theater C^3I network every 90 minutes. Multiple sensors of various types easily take the input data flood to many Gbits. The great majority of this can be expected to be routine background of no interest to the warfighter, but the small percentage of valuable content on forces, targets, defenses, and so forth. must be separated out, characterized, and disseminated in near real time. This is one of the key points of tangency between the domains of sensing and information processing. Among the implications of this huge data volume are:

- The need for very high speed representation, storage, and retrieval of enormous data files.
- The need for efficient, fast indexing techniques to allow rapid sorting and processing of selected data contents.
- The need for means of reconciliation among distributed databases to ensure consistency and accuracy, referred to here as “truth maintenance.”

2.5.2 Improved Sensor Performance

Growing needs for sensor-derived information, coupled with limited numbers of systems in the affordable force structure, create ever-growing demands on the performance of sensors of all types. Examples of these challenges include:

- The need for precise registration, both spatial and temporal, of individual target signatures both for accurate location and track determination and to support correlation and fusion of outputs from multiple sensors.
- The need for calibration of the sensor itself and of its output, including continuous adjustment of apertures and processors to maintain accuracy, coordinate conversion and orthorectification of target data, and continuous measurement of clutter, false alarms, and other environmental parameters to assess the quality of target signatures.
- The need for greater sensitivity and discrimination, especially as demands increase for detection of small targets in highly cluttered backgrounds.

2.5.3 Improved Asset Management

Another pervasive theme of this analysis is the importance of using all available sensing assets in a fashion that delivers the greatest support to decision makers and warfighters. Once again, this involves the ill-defined boundaries among the domains of sensing, communications, and information processing. Among the specific challenges are:

- The need for an architectural hierarchy which allows timely sharing and use of information, both to use sensor outputs to meet operational needs and to optimize sensor operation based on customer priorities.
- The need for coordinated control of similar and dissimilar sensors, both to employ available assets in a way that delivers the greatest possible information value to customers and to facilitate reconciliation and correlation of multiple target detections and tracks.

We seek both opportunities to improve existing sensor technologies and areas where new and different approaches are required. An example of the latter might be to move away from the familiar picture of a sensor as a relatively large, expensive and powerful device toward a concept of “pervasive sensing” in which huge numbers of small, cheap devices saturate a sensing domain.

Table 2-3 lists several generic characteristics which apply to virtually any sensor system. Specific operational sensing tasks and the associated technologies and challenges are discussed in detail later in this Volume. However, before considering individual operational situations, it will be helpful to provide an architectural framework for thinking about sensors in the context of an overall force structure.

Table 2-3. Sensor Characteristics and Related Benefits

Characteristics	Operational Benefits
Higher Degrees of Dimensionality [2]	• Improved Target Discrimination • Enhanced Countermeasure Resistance
Adaptive Behavior	• Enhanced Clutter Rejection & Countermeasure Resistance • Enhanced Operator-System Interaction
Data Fusion	• Enhanced Target Detection/Classification/Identification • Redundancy in Critical Functions

2.6 Architectural Considerations

As the discussion thus far has suggested, individual sensors are increasingly employed as elements of an overall force structure in which many systems participate cooperatively in surveillance and intelligence gathering, target detection and tracking, fire control (FC), battle damage assessment, and so forth. Thus, while specific actions like locking up a target with a fighter's radar to launch a missile are focused narrowly on a single sensor, the engagement as a whole is likely to include inputs to the commander, weapon controller, and shooter from many other sensors which facilitate target location and identification, threat avoidance, and other aspects of a successful mission. Furthermore, the ability to combine information from onboard and offboard sources is widely held to be a significant means of cost containment in future weapon systems. It is therefore increasingly vital that sensors be specified, developed, and used with a clear understanding of the interfaces and shared functions that they will encounter as nodes in the force structure architecture.

Figure 2-3 suggests the major segments of a theater conflict force structure (ground, air and spaceborne) and the fact that any system in any segment may need to communicate with any other. An operation of smaller scope might not involve all these assets, but the general principles are the same. The airborne segment is divided into three subsegments to reflect the practical differences between high value standoff platforms such as Joint STARS, AWACS, and ABCCC, the growing significance of UAVs that overfly hostile territory, and the continuing importance of manned fighter and attack aircraft and their weapons. Although the full elaboration of this notional architecture is beyond the scope of this Volume, several aspects must be effectively dealt with if sensors are to make their full contribution to force effectiveness.

2. We use this term to denote expansion of the sensor variable space, for example, by adding time, spectral regions, or other phenomenologies to the list of things that are measured, tracked, and analyzed in order to improve sensitivity and discrimination.

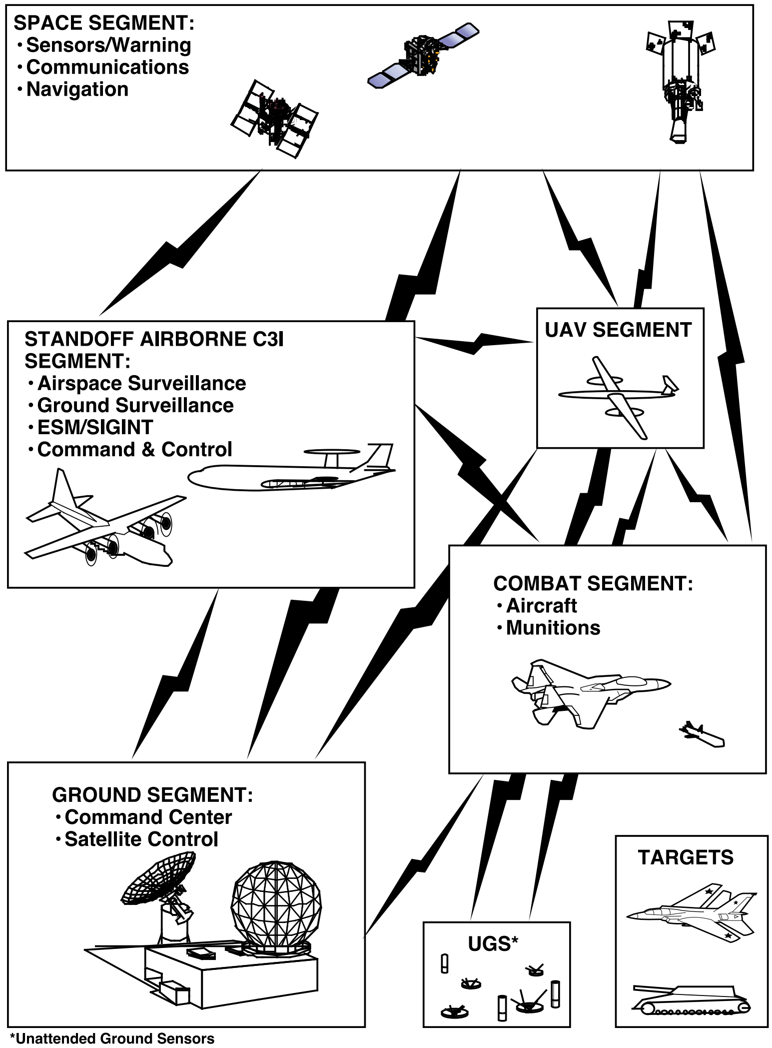

Figure 2-3. Elements of a Force Structure Architecture With Multiple Sensor Systems

2.6.1 Requirements Allocation

A cost-effective force structure demands that individual platforms and sensors be defined in a system-of-systems context that optimizes overall functionality while avoiding over- or under-specification of individual systems. An important consideration here is a combination of complementarity and orthogonality in the set of sensors that addresses a given operational task. *Complementary* sensors exploit the same phenomenology to provide target information from various vantage points in space and time, allowing a more complete and accurate signature. *Orthogonal* sensors exploit differing phenomenologies to derive more information about a target. Orthogonality is one aspect of the use of higher orders of dimensionality, and this and the other concepts in Table 2-3 are important in requirements allocation decisions.

2.6.2 Internetting

In order for an array of sensor assets to function as a single, coordinated entity, communication channels for data, imagery, voice, and other traffic involved in the operations of the architecture must have the capacity, robustness (including jamming and interception resistance), and interoperability (which implies standardization) to allow the necessary near-real time interchanges of data and commands. Command and data links can easily range from a few hundred bits/second to many gigabits/second.

2.6.3 Cooperative Sensor Functions

As discussed in more detail elsewhere in this Volume, sensor fusion and efficient, timely interaction with operational customers are critical to the support sensors deliver to warfighters. A properly designed force structure architecture provides for cooperative functioning among sensors and with commanders, controllers, shooters, and other users. That architecture must provide for distributed processing of sensor information and for cooperative management of sensor assets.

2.6.4 Global Conventions

For effective management of assets, especially correlation and fusion of sensor outputs, all systems must speak a common language of coordinates, timing, status reporting, communications protocols, and other universal attributes. Standardization of ground control stations, constellation management, hardware and software configuration items, and other aspects has great potential for reducing the costs of acquisition and ownership, especially of space-based systems.

2.7 Summary

The overall subject of sensors is exceptionally diverse, both in the range of physical phenomena available and in the array of difficult information gathering requirements that sensors must address. Sensors are challenged to deliver comprehensive, precise information about many kinds of objects and activities over very wide areas in near-real time, and to do so with assets that are affordable and robust in the face of hostile countermeasures. The key to meeting this challenge lies in the use of a carefully orchestrated array of sensors, from geosynchronous orbit to embedded in the earth, which operate cooperatively and whose outputs are combined and analyzed to extract the greatest level of useful information. The elements of this sensor architecture have been sketched in this section. The sections which follow expand on specific technical and operational aspects.