7.0 Conclusions and Recommendations

As is evident from the contents of this Volume, the term "sensors" represents an exceedingly broad spectrum of technologies, concepts, and systems, all dedicated to provide the information and knowledge needed to successfully accomplish Air Force tasks. It has been a humbling undertaking to project this broad spectrum into the future and to speculate about its revolutions. Its results are, by definition, imprecise and incomplete. Hopefully, they will nevertheless prove useful to the Air Force in its planning for the future.

To manage this undertaking, the Sensors Panel of *New World Vistas* has used both a top-down and bottom-up look at the subject. The top-down view is captured by seven "Representative Operational Tasks" discussed in Section 4. These describe key Air Force tasks over the study's time horizon, and they identify information needs and notional sensing concepts to support those tasks. The bottom-up view is captured by the "Sensor Technology" descriptions in Section 6. These examine key sensing technologies as they exist today, project them into the future, and speculate about revolutionary advances that appear on the horizon. Some of the most promising of these possibilities are collected into several illustrative sensor concepts in Section 5. These demonstrate in more concrete fashion what the Air Force's sensing systems might look like in the future, and how they might be used to accomplish its tasks.

Beyond the many specific analyses, projections and recommendations contained in these individual sections, there are several overarching trends and opportunities that emerge from the study; these are summarized below. They lead to some general recommendations about how the Air Force can best participate in the trends, and what it should do to advance the opportunities.

7.1 Sensor Trends and Opportunities

7.1.1 Continuing Performance Improvement

The first, most evident trend in sensor technology is a continuing process of evolutionary performance improvement of traditional sensor systems and components. As described in Section 6, for example, Air Force radar systems are steadily advancing in resolution, bandwidth, ability to penetrate foliage and earth, MTI capability, levels of electronic integration, and in their various 'ilities. Likewise, electro-optical systems boast ever-denser focal planes with broader spectral response, on-chip tunability, and uncooled operation. Inertial systems, similarly, show steady improvement in drift performance, reductions in size and cost, increases in reliability, and ever-tighter integration with external aids. Supporting electronic components, such as A/D converters, I/O modules and embedded signal processors are also improving, becoming ever faster, smaller, less costly and more reliable. These trends can be expected to continue well into the time frame of this study.

7.1.2 Increasing Use of Multidimensional Phenomenology

A second trend in sensor technology is the growing use of multiple physical phenomena in the sensing process. Examples from Section 6 include multi, hyper, and ultraspectral imaging concepts that use information from several, many, or even continuously variable spectral bands. Other concepts combine information from optical and radio frequency bands, from vibration and polarimetry, from reflected spectra, from seismic and RF responses, and so on. Obviously, the combinations are numerous. Their common characteristic is that they provide additional, often critically discriminating, information about objects of interest, allowing these objects to be detected and characterized with much improved error rates.

7.1.3 Increasing Interconnectivity

A third sensor technology trend is interconnectivity. This trend is already well under way and offers the means toward *New World Vistas* vision of "knowledge on demand," providing "global situation awareness" for Air Force planners and "complete knowledge of the battle field" for war fighters. In basic terms, interconnectivity exploits ever-improving communications and processing to move information gathered by many sensor systems to many users in near-real-time. This enables coordination and fusion and provides much greater knowledge extraction from spatial and temporal correlations of observations and events. It also enables global coverage, and permits needed resources to be focused onto specific regions of interest to gather fine-grained information as necessary.

Of course, interconnectivity by itself is not a panacea. There are difficult architectural questions concerning what sensors should be interconnected, what information should be communicated, in what form, when, to whom, under whose control, and under what levels of protection. These questions are discussed in Sections 2 and 3 and in other volumes of the *New World Vistas* report. They are large, largely unanswered, and will need major attention from Air Force system planners in the future.

7.1.4 Dramatic Algorithm Improvements

A fourth trend concerns computational algorithms for processing raw sensor data, distilling it down automatically into information and knowledge. This is an opportunity for the Air Force, rather than a trend, because it will not happen on its own. It must be caused to happen. Even in today's sensor systems, the data distillation step is a major weakness. There is not enough time to analyze the raw data manually and/or there is simply too much of it to move around in interconnected systems for display and use. Dramatic improvements are needed in algorithmic capability for basic sensor signal processing and for "intelligent" functions such as automatic target recognition, target classification, tracking, general pattern recognition, speech recognition, translation, and others. As described in Section 6, such improvements appear to be possible with appropriate R&D efforts exploiting the continuing growth of computational capacity and advances in computational architectures seen in the last decade. In the future, these algorithms will be critical to rapid exploitation and use of already vast and ever-increasing volumes of data gathered by our sensors.

7.1.5 New Enabling Technologies

Section 6 also identifies other technology opportunities that promise fundamental changes in the way sensors are designed and used. One of these is MEMS. This technology uses material processing methods from the microelectronics industry to make useful structures including pressure sensors, uncooled IR detectors, bio/chem detectors, accelerometers, gyroscopes, valves, and switches. The distinction is that these devices can be very small (down to lithography scales) and can be mass-manufactured with electronics already integrated, making unit costs potentially very low. Combined with communications and processing, these features enable sensing concepts comprised of many small distributed elements. Such concepts represent a major change of philosophy away from today's larger centralized systems. They also create entirely new sensing possibilities, some of which are described in Section 5.

A related emerging technology area is opto-electronics, which also uses microelectronics processing methods to build optical components integrated with electronics. These devices enable very small optical systems, pure delay elements, optically controlled microwave phased arrays and optical phased arrays, again supporting the sensor concepts in Section 5.

7.1.6 Commercial Trends for Affordability

Equally significant trends for Air Force sensors come from the commercial world, where certain technologies are applied in much greater volumes, driving affordability. Key ones of these are the continuing explosion of computational capacity (ever increasing MIPS per pound, watt and dollar), the growth of commercial interconnectivity (the information super highway), the exploding commercial use of GPS, the impending widespread applications of MEMS technology in consumer products, and the increasing availability of commercial systems for space launch, satcom, and satellite imagery.

7.1.7 New Concepts for Key Air Force Problems

Other opportunities identified in Sections 5 and 6 consist of several illustrative sensing concepts, including:

- A UAV "target reporter" for continuous long-duration surveillance of large battle areas
- An integrated array of distributed micro-sensors, including UGS packages, tags and other small flying or crawling mechanisms able to penetrate hostile facilities
- A surveillance concept for underground facilities (NBC, command and control, weapons storage, etc.)
- A concept for detecting concealed targets under all battlefield conditions
- A global weather surveillance and prediction concept
- A modular, integrated multifunction EO phased array
- A low cost space-based surveillance system using SAR radars and EO sensors on small satellites, launched on demand

These concepts combine various technology trends from above to solve key projected Air Force problems.

7.2 Recommendations

The trends and opportunities identified above call for concrete Air Force actions over the next few years and diligence extending well into the future. Trends should be exploited, and opportunities should be pushed forward toward real benefits.

Essentially, each item leads to a corresponding recommendation. First, for *evolutionary performance improvement* of traditional sensors, the Air Force must recognize and continue its current role in bringing these improvements about through its R&D efforts and technology demonstrations. Key sensors such as radars, EO systems, inertial systems, and their supporting components will remain essential for the foreseeable future, and their continuous improvement remains a valid strategy.

Some specific improvements identified in Section 6 include affordable, broadband apertures for multifunction radar systems, integrated multifunction EO modules, and tactical navigation systems using micro-machined inertial devices.

The *multidimensional phenomenology* trend is less well established and needs to be nurtured energetically. Air Force programs should deliberately seek additional unexploited phenomena to clearly discriminate objects of interest in various difficult sensing situations.

As noted above, the third trend, *interconnectivity*, is already well under way. However, it poses difficult architectural issues and operational problems concerning information requirements and control. These call for major system design studies, trade-offs, and even organizational changes. Indeed, the Sensors Panel believes that the Air Force should designate a single central authority to define and control the information architecture and its sensor segments. The objective must be to halt the proliferation of stovepipe, non-interoperable systems and to begin migrating to the "system of systems" architecture described in Section 2.

A complicating factor is the current organization of Air Force laboratories along phenomenological lines (e.g., radar, EO/IR, ESM, ATR) instead of mission lines (e.g., surveillance, target attack). Full-time, mission application-oriented laboratory technical staffs created to supplement the Technology Planning Integrated Product Team (TPIPT) process provide a way to alleviate this problem.

Also already noted, the *algorithm improvement* trend is an opportunity that must be exploited. While the commercial world will contribute some of these improvements for problems such as automated inspection and assembly, military environments are typically much more variable and difficult. This calls for sustained Air Force involvement in the full spectrum of R&D, from basic theoretical foundations of algorithms, to advanced architectures and hardware for computation and data storage/retrieval, to early demonstrations and exploitation of extant capabilities in fielded systems.

In *emerging new technologies* and *commercial trends for affordability*, the Air Force must selectively act as prime mover of the technologies in some situations, and as intelligent user in other situations. The MEMS technology, for example, is a case where both stances are appropriate. Commercial uses of MEMS will provide many interesting components (pressure sensors, low-accuracy inertial sensors, valves, etc.) that can be applied in Air Force systems as appropriate. However, other components serving primarily military needs and/or military performance requirements (e.g., bio/chem sensors, tactical inertial sensors) will not likely be produced by commercial trends. The Air Force should therefore selectively invest in the MEMS technology, to influence processing methods and develop design concepts and device structures manufacturable on high-volume commercial lines, yet meeting military needs. In short, the Air Force should encourage true dual-use of MEMS.

Other commercial technologies are similar. The exploding consumer applications of GPS will provide ever smaller, cheaper receivers for potential military use. However, the Air Force must insure that these devices can be adapted to meet military requirements, and particularly, that jam-resistant versions can be affordably built on commercial lines. Likewise, the continuing explosion of computational capacity will offer ever more affordable processing options that fundamentally change the way sensors and sensor systems are designed. In essence, cheap MIPS will be available to offset expensive mass in Air Force sensor designs. Yet, the Air Force must continue to insure that its special requirements on the processing capability (e.g., radiation hardness) continue to be affordable. Similarly, while the growing commercial infrastructure for interconnectivity and communications will provide affordable means of internetting sensors and users, Air Force investments must insure security, availability, and robustness for times of stress.

In summary, we offer the following specific recommendations:

1. Establish a central authority to define and control the information architecture, and its sensor segment, as a system of systems
2. Improve multifunction radio frequency apertures (see Section 6.2.3)
3. Improve multifunction electro-optical/infrared modules (see Section 6.2.2)
4. Develop a family of air-monitored, unattended ground sensors (see Section 5.2.2)
5. Develop a family of micro-sensors for use in airborne, spaceborne, and ground sensor systems (see Section 6.2.6)
6. Develop tags for air-monitoring the movement of materials and equipments (see Section 6.2.10)
7. Stress sensor affordability through emphasis on revolutionary and evolutionary signal processing concepts (see Section 6.2.4)
8. Exploit the advantages of the multidimensionality offered by multiple sensor regimes (see Section 6.2.8)
9. Develop ATR and ASC for sensor systems (see Section 6.2.5)
10. Finally, the Air Force should initiate programs to develop some of the *new concepts* identified in Section 5 or, at minimum, to develop and demonstrate their supporting technologies. Specific development programs should include:
    - A family of military-capable microsensors for acoustic, seismic, inertial, pressure, bio/chemical, and other phenomena.
    - A variety of doping materials and tagging devices to help locate and track weapons systems, munitions, vehicles and personnel.
    - A program in unattended ground sensors, using dopants, tags and internetted sensors from above, together with communications and fusion processing, to obtain detailed battlefield surveillance. The common need to activate and read-out these devices from airborne platforms justifies strong Air Force involvement in this technology.

These programs provide key capabilities for an overall sensing “system of systems” architecture leading to *New World Vistas* general vision of “knowledge on demand.”