HYPERSPECTRAL IMAGERY:
Warfighting Through a Different Set of Eyes

by
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Lieutenant Colonel Paul J. Pabich graduated from the Air War College, Maxwell Air Force Base, Alabama, in June 2002. In 1980, he was a Distinguished Graduate of Air Force Reserve Officer Training Corps from the University of Wisconsin-Madison. A career space officer, he began his space systems experience with Orbital Analyst Training at Peterson Air Force Base, Colorado. Following training, Colonel Pabich was assigned to the Alternate Space Computation Center, 20th Missile Warning Squadron, Eglin Air Force Base, Florida, and in 1983, he was part of the initial cadre forming the 1st Space Wing at Peterson Air Force Base as part of the then new Air Force Space Command. In 1985, Colonel Pabich was selected to attend the Air Force Institute of Technology, Wright-Patterson Air Force Base, Ohio, where he earned a Master of Science degree in Space Operations in 1986. He was next assigned to the Air Force Operational Test and Evaluation Center, where he began test planning for the upgrades to the Defense Support Program, the United States' space-borne intercontinental ballistic missile warning system. Colonel Pabich returned to operations in 1990 as the Chief of Tactical Operations at the 19th Space Surveillance Squadron, Pirinclik Air Station, Turkey. In 1991, he was once again assigned to the test community as a branch chief at Air Force Space Command, overseeing the testing of the command's passive space surveillance sensors. He then moved to Vandenberg Air Force Base, California, first as the executive officer to the Commander, 14th Air Force, and in 1996 he assumed command of Detachment 1, 22d Space Operations Squadron, a satellite command and control facility. His final tour prior to Air War College was once again in the test community at the Air Force Operational Test and Evaluation Center where he served as Deputy Director of the Air & Space Mission Directorate, overseeing the Center's initial test efforts for all its test programs.

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I. Introduction

Hyperspectral Imagery, or HSI, is a sophisticated, versatile intelligence gathering technology that could potentially enable the US military to make significant strides towards improving the preparation for and execution of its missions. Many of the difficulties in bringing the promise of HSI to fruition have very little to do with the technology itself. As will be discussed shortly, HSI technology has been successfully demonstrated in a variety of diverse applications. In point of fact, it is the versatility of HSI that may be hindering its implementation into the mainstream of the U.S. military's intelligence gathering capability. The objective of this paper is threefold. The first goal is to introduce the reader to both the technology itself and the myriad potential applications of Hyperspectral Imagery. The second goal is to realistically examine the challenges that HSI must overcome, specifically in the areas of how HSI fits into the world of joint vision, intelligence doctrine, and the intelligence cycle. Finally, the paper will provide a series of recommendations—some focused on organizational issues and others on acquisition issues—that will address the majority of the challenges faced by the intelligence community as they endeavor to incorporate an HSI capability into the U.S. intelligence community.

Hyperspectral Imaging Technology Concepts

While the basic concept behind HSI is relatively straightforward, the implementation is far more difficult. In most applications, HSI sensors collect sunlight reflected from a target area into a number of narrow wavelength bins, usually across the visible or infrared (or both) portions of the electromagnetic spectrum. These bins of photons are both spectrally and spatially resolved and thus can be used to generate a variety of "images" of the target area. The real key to HSI lies in the concept of spectral signatures. In simple terms, all materials will transmit, reflect, or absorb electromagnetic radiation based on the inherent physical structure and chemical composition of the material and the wavelength of the radiation. Said in another way, for any given material, the amount of electromagnetic radiation that is absorbed, reflected or transmitted varies with the wavelength or frequency of the radiation. If the percentage of reflectance for a given material is plotted across a range of wavelengths, the resulting curve is referred to as the spectral signature for that material.[1] Because the spectral signature is different and indeed unique for each material, it should be possible to discriminate between one material and another based on differences in spectral signatures of the materials. For example, HSI can differentiate between desert and farmland. Not only are broad differences such as those just noted detectable, it is also possible to identify particular materials based on a comparison against a database of known signatures. For example, as shown in Figure 1, within a hyperspectral view of farmland it should be possible to differentiate a barley crop from potatoes.[2] This concept forms the basis for HSI.

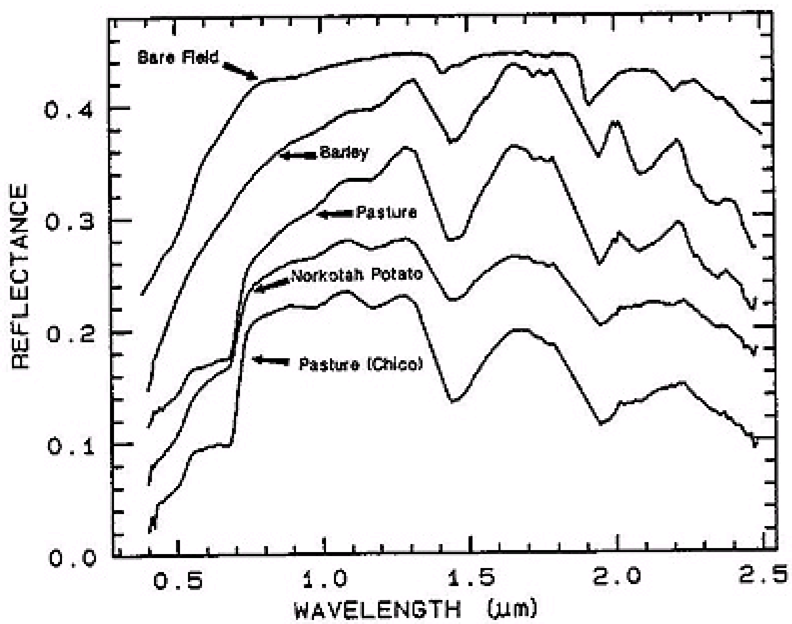
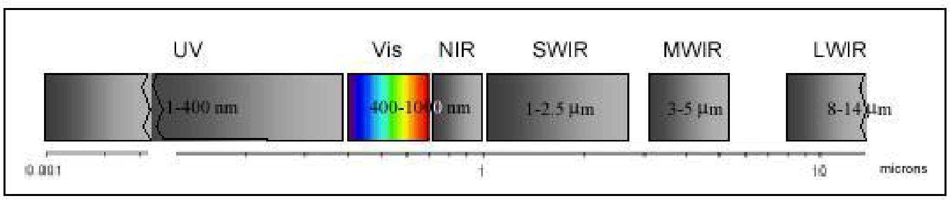


Figure 1: Spectral Signatures Constructed From AVIRIS Sensor

The available literature contains several disparate definitions for the types of sensor platforms that qualify as "hyperspectral" systems. These definitions often include the number of bands, the width of each spectral band, and the idea that the bands are continuous across a region rather than having numerous gaps between the bands. Additionally, the spatial resolution (i.e., the size of the smallest distinguishable item in the scene) can vary tremendously between sensors. One definition for an HSI system indicates it must have "at least sixteen contiguous bands of high spectral resolution over a region of the electromagnetic spectrum;"[3] another source describes HSI systems by the spectral width of the wavelength bands, e.g., .01 micrometer (µm).[4] As one might suspect, there are limited a limited number of photons available for collection during a scan period of a hyperspectral system. Therefore, there is a tradeoff between the number of bands one wishes to collect in and the number of photons one might reasonably expect to collect during a scan period. Nevertheless, because the true strength of Hyperspectral Imagery lies in its ability to use many narrow wavelength bands to distinguish between objects, this paper will consider HSI systems as sensors that collect at least 100 spectral bands of .01µm width. Because HSI sensors will only be effective in spectral regions where the atmosphere is transparent, the nature of the sensor cannot be truly "contiguous" and must be broken into useful bandwidth groupings. As shown in the Figure 2 below, HSI practitioners obtain slices of bandwidth from five wavelength groupings: visible, near infrared (NIR); short wavelength infrared (SWIR)[5]; medium wavelength infrared (MWIR); and long wavelength infrared (LWIR).[6]



Frequency Name	Wavelength (µm)
Visible (Blue, Green, and Red)	0.4–0.68
NIR (Near Infrared)	0.68–1
SWIR (Short Wavelength Infrared)	1–2.5
MWIR (Medium Wavelength Infrared)	3–5
LWIR (Long Wavelength Infrared)	8–14

Figure 2 Wavelength Groupings for HSI Sensors

The HSI sensors reviewed for this paper were either spaceborne or airborne, and the areas of interest may extend from several meters above the earth's surface (e.g., treetop height) to a few meters below the surface (e.g., coral reef depth). These systems most often perform in the visible to

NIR and SWIR ranges, and most HSI sensors do not have the MWIR or LWIR capability. One key difference in the choice of sensor wavelength bands is that photons received by the sensor in the visible to SWIR wavelengths are actually *reflected* from the targeted area. This obviously limits the utility of these sensors to daylight hours. By contrast, HSI sensors that have MWIR and LWIR capability will capture photons that are *emitted* from the targeted area, thus opening the possibility for nighttime and see-through-the-clouds operations.[7] If the processing algorithms for a given sensor can separate cloud signals from the ground signals, the cloud portion can be subtracted from the overall signal and the sensor can essentially "see" through clouds. This is not necessarily as easy as it may appear as the physics of the clouds play a tremendously challenging role. However, if the imaging system has data regarding cloud temperature as well as moisture profile, then algorithms can estimate the radiance of the cloud. The system can then subtract the cloud's estimated radiance from the total radiance to obtain an estimate of the ground radiance, thus "seeing through" the cloud.[8] Therefore, while clouds and nighttime will frustrate HSI collection in the visible and SWIR spectrums, bringing LWIR sensors into the picture can help mitigate that limitation, though they do bring along other challenges such as proper cooling of the long wavelength sensor.[9]

To appropriately differentiate between HSI and other types of imagery, this paper defines panchromatic imagery as black & white imagery that is equally sensitive to all wavelengths in the visible spectrum.[10] Thus a green tree and a green car will certainly have different shapes in the image but their shade of gray will be the same. In addition, multispectral imagery is defined as having fewer than 20 non-contiguous spectral bands covering wavelengths in the visible to SWIR spectrum.

Another important term in HSI is "hypercube," or the data set that is provided by HSI sensors. Whereas visual images typically have spatial reference points (e.g., latitude, longitude or more simply X and Y), hypercubes also provide a third, or Z, axis, which essentially contains an X-Y plane for each of the spectral bands observed by that sensor.[11] Thus, hypercubes provide a spectral "depth" that is exploited to identify the materials within the sensor's field of view. One challenge facing the implementers of HSI is that each hypercube contains a huge amount of data that must be moved quickly within the available communications systems. Thus implementers must remain cognizant of a limited communication system or develop other ways to minimize the size of hypercubes. A visual example of concepts of hypercube depth and size concepts just discussed is shown in Figure 3.

Figure 3 Example of a Hypercube[12]

A not so obvious point that needs to be addressed is that images of a given area from hyperspectral sensors will look far different to the naked eye than they do when appropriate false color has been added. As shown in Figure 4, without prior knowledge, it would be difficult to judge that these multiple views from an HSI imager are the same area. In this instance the leftmost picture is near to natural color, and the two images to its right demonstrate the existence of various minerals in the scene with the reds, yellows, purples, greens, etc. Given this scientific foundation, the next portion of the paper will briefly review some of the potential military applications of HSI.

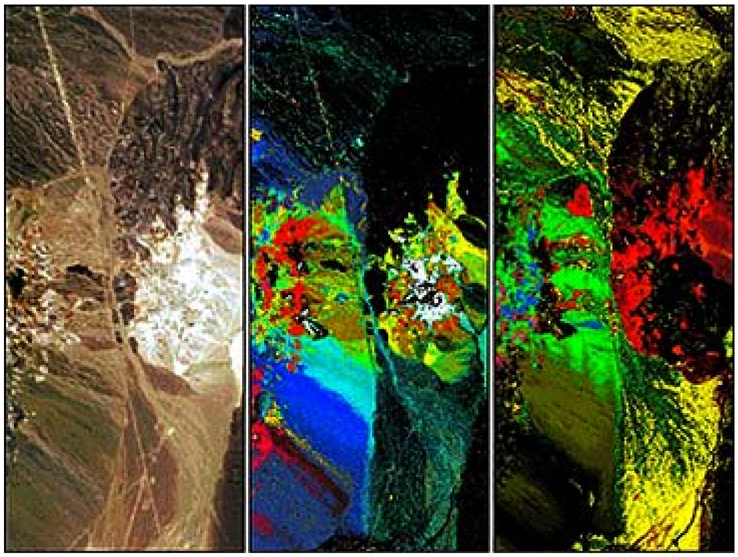


Figure 4: Comparison of Two False-Color HSI Images with Natural Color Photo[13]

Uses of Hyperspectral Imagery

Hyperspectral Imagery holds considerable promise for many military applications. The Navy has already begun developing a spaceborne HSI system to enhance their intelligence preparation of the battlespace. This satellite-based system will collect data for areas of interest in the littoral environment to include: "underwater hazards, currents, oil slicks, bottom type, atmospheric visibility, tides, bioluminescence potential, beach characterization, atmospheric water vapor, and subvisible cirrus along with terrestrial images of vegetation and soil."[14] The utility to the Navy and the Marine Corps comes from the ability to predict the littoral environment with much better confidence and to better prepare for amphibious assault. The satellite will be able to look for hazards down to a depth of twenty meters depending on water clarity. In contrast to other types of sensors, the Navy HSI system is not being built for quick analysis for target determination; instead, it is being developed to provide longer-term characterization of items that are slow to change (e.g., reefs).[15]

The Air Force also has many uses for hyperspectral imagery. In particular, the service is looking for HSI systems that can provide the warfighter with near-real-time information to enable attacks on targets such as tanks hiding under trees. The Air Force is also interested in knowing what *not* to attack, as in the case of decoys. Destroying decoys can be a costly proposition. At $21,000 per copy for the tail kits alone, Joint Direct Attack Munition precision-guided weapons should be zealously guarded from unwittingly attacking decoys.[16] Since decoys will not have the same material composition as real targets, HSI should be able to differentiate between the two. By using HSI to discriminate between real and false targets, the U.S. can save money by avoiding bad targets and at the same time wisely expend precision munitions on true targets. Defeating camouflage is another particularly likely mission candidate for HSI because even though the camouflage may show up as the same color as the surrounding terrain in the visual spectrum, its material makeup will cause it to reflect very differently at other wavelengths.

The Army and Marine Corps (once ashore) would likely find uses for HSI in areas such as large area coverage to characterize a theater of interest. HSI could also be used to focus on specific targets in specific areas. The a priori knowledge of the amount of grass, trees, shrubs, desert, roads and the moisture content of the surface could have tremendous impact on their ability to carry out operations.[17] Another mission for HSI that may be particularly life saving is its potential to detect landmines along roads and other areas where humans gather.[18] Other concepts also come to mind. For instance, in the war in Afghanistan, would it have been possible for an HSI sensor to detect concentrations of carbon dioxide in cave-laden areas where the fighting was occurring? Would these concentrations possibly represent exhaust holes in caves occupied by enemy forces?

This brief look at potential service operational uses for HSI shouldn't cloud the potential strategic uses that could emerge for the Department of Defense (DOD). In years to come, advanced technologies such as HSI could be used to monitor international treaty compliance. For example, the ability of HSI to detect byproducts from the manufacture of chemicals could be used to monitor the Chemical Weapons Convention Treaty.[19] So too could HSI be used to monitor the war on drugs. The fields used to grow illegal drugs as well as the facilities used to process the raw materials into illegal substances could be discovered via HSI. Eradication of these fields and facilities could totally disrupt the distribution cycle, thus preventing drug profits from being used by anti-American organizations.

As can be seen by even in this brief review of its possible uses, HSI has the potential to dramatically change the methods by which the military gathers information about the battlespace across the services, and in turn, makes decisions at the strategic, operational, and tactical levels of war. Having reviewed how HSI works and why it can be so valuable, the remainder of the paper will seek to examine the question, "If airborne and spaceborne Hyperspectral Imagery are to deliver on their promise, how should this technology be integrated into the joint warfighting system?" The paper will attempt to answer this question by addressing important issues in the following three sections.

In the next section, the paper provides the current status of hyperspectral imagery implementation. It will show some of the halting steps that the HSI community worldwide is taking to turn this technology into working systems. The section is broken into three major subsets: military systems, non-military systems, and ground processing systems. The military section will review how the DOD is implementing the technology in both the airborne and spaceborne arenas. The discussion of non-military systems such as NASA's Hyperion satellite will demonstrate that, at least in the spaceborne area, non-military systems are ahead of those in the military. Also included in this review is a description of some example systems that demonstrate how the DOD is also working data processing issues.

The third section of this paper describes some of the doctrinal and organizational challenges that currently face the DOD as it attempts to fully implement hyperspectral imagery. The section addresses the placement of HSI into the existing vision of the DOD and intelligence community doctrine and will show that HSI fits quite easily into the Chairman, Joint Chiefs of Staff vision for the future of the joint force, although there is a challenge with where to place HSI within the intelligence community. The intelligence cycle and the functions of tasking, processing, exploitation, and dissemination will also be reviewed in detail. Finally, current thinking for integrating HSI with other forms of intelligence (e.g., radar) will also be noted.

The final section will address recommendations on how the military can implement hyperspectral imagery. The point of view taken here is that given the current status of technology and doctrine, how can the force of the future best integrate HSI into its warfighting system? The discussion focuses on key issues such as doctrine, organization, and training.

II. Current Hyperspectral Imagery Status

While the theoretical underpinnings of the technology are already well understood, engineers have only recently gained the ability to implement the theory. The following discussion examines the status of HSI implementation but does not focus exclusively on the technology. In fact, it will be seen that, in general, much more thought has been applied to defining the proper organization and use of HSI assets, than has been devoted to development and engineering to field the required technologies.

High Level HSI Documentation

One of the first things noticeable in an investigation of hyperspectral imagery is that at present there is no single organization charged with oversight of HSI for the DOD. A number of entities, however, can claim large stakes in the area. These entities include the Central Measurement and Signature Intelligence (MASINT) Organization and the National Space Security Architect. The Air Force, Navy, and Army also have specific programs they are attempting to implement. Despite the lack of a lead organization, there are some promising signs of purposeful integration of HSI, especially in the processing and dissemination areas. Most notable however are various high level documents that have been published, or are currently in draft, that describe how to best use this promising technology. A review of several of these documents is now provided to show that much thought is being devoted to proper implementation of HSI at both the national and service levels.

The first of these documents is a Congressionally mandated-report published by the National Space Security Architect in December 2000. The National Space Security Architect organizationally sits under the Under Secretary of the Air Force and is responsible for “developing, coordinating, and integrating” future space system architectures for the DOD and intelligence agencies.[20] This classified report listed several items that could potentially improve the usefulness of HSI to the warfighter.[21] The DOD’s own Space Technology Guide repeatedly listed HSI as a supporting technology for a wide variety of missions from target acquisition, to nuclear, biological, and chemical monitoring, to atmospheric monitoring.[22] The Air Force Scientific Advisory Board has also noted that HSI has “great potential,” though the members also cautioned that because of technical limitations (e.g., cloud cover for short wavelength infrared sensors) HSI by itself is insufficient to be a primary source of real-time intelligence.[23]

It should also come as no surprise that national level political leaders are also interested in this topic. Though they did not mention HSI specifically, the US Senate has devoted much time to Measurement and Signal Intelligence (the most likely location within the intelligence community in which HSI will be placed), both praising its potential and simultaneously criticizing its implementation. The Senate language in the Fiscal Year 2001 budget had very positive words to say about how these types of systems can help intelligence agencies accomplish critical missions, specifically pointing out countering proliferation of weapons of mass destruction as an important area of interest. HSI is certainly capable of playing a significant role in such a mission. The Senate language even noted that, historically, they have backed up their praise with significant new funding. Though the Senate had positive words for the community, they were not reluctant to heap blame on the intelligence community for its inability "to come to grips with resources, management, and organizational...deficiencies."[24] In December 2000, yet another Congressionally mandated independent commission report, this one about the National Imagery and Mapping Agency, listed HSI as one of several technologies that could help the Agency to improve its capabilities.[25] The National Imagery and Mapping Agency mission is "to provide timely, relevant, and accurate intelligence and geospatial information in support of national security objectives of the United States."[26]

Organizational Implementation

In addition to the DOD high level thinking on HSI just discussed, various agencies are also working organizational aspects to try to take advantage of HSI technologies, even if most of the anticipated technologies do not yet exist. For example, the Central Measurement and Signal Intelligence (MASINT) Organization (CMO) has already made significant progress by providing HSI training to operators as well as by narrowing the search for the appropriate software tools to enhance the capabilities of the operators. As noted earlier, to the untrained eye HSI does not "look" like standard imagery; thus, standard imagery analyst training is insufficient to prepare operators for this new field. To overcome some of the human and technological issues already identified, the CMO established the Hyperspectral MASINT Support to Military Operations (HYMSMO) Program Office within the Spectral Information

Technology Applications Center. The Center's mission is to provide key infrastructure support to further the DOD's and intelligence community's understanding of HSI and its potential utility.[27] To fulfill the HYMSMO program's mission to increase understanding, the CMO has created the Training Education Coordination Office to obtain the proper training at all levels from the Spectral Information Technology Applications Center. Various training courses exist depending on the levels of detail needed. For example, one course gives senior leaders a broad understanding of what HSI brings to the fight. Other courses are tailored for mid-level leaders and collection managers. Finally, the CMO offers a very detailed course on how to exploit HSI processing. Currently this training is contracted out, but there is already on-going discussion about how to bring the training into standard military intelligence coursework.[28]

The services are also playing a more active role in HSI. For example, the Army took the lead within the former U.S. Space Command, now U.S. Strategic Command, by setting up the Spectral Operations Resource Center. This center's primary mission is to coordinate and manage the command's hyperspectral and multi-spectral production capabilities and to integrate new spectral advances.[29] It achieves this goal by providing the command with access to spectral products and services while advocating new spectral requirements to support the warfighter. The center completes the cycle by staying involved in various activities to bring the latest in spectral technologies and capabilities to operational forces.[30] The basic idea is that as the lead HSI servicer for U.S. Strategic Command, the Spectral Operations Resource Center will act as an HSI clearinghouse along with the Naval Space Command's Remote Earth Sensing Information Center and a yet to be decided capability within Air Force Space Command.[31]

As just noted, the Navy performs much of its spectral operations through its Remote Earth Sensing Information Center. The Navy center has the ability to exploit HSI data and is preparing to use hypercubes provided by a Navy HSI satellite when launched.[32] The center has primarily been involved with multi-spectral imagery and has provided spectral support to Navy and Marine forces in operations spanning the non-combat to combat spectrum for over a decade. This support takes many forms including intelligence preparation of the battlefield, mission planning, order of battle, and change detection among others.[33]

The Air Force is also stepping up its efforts to incorporate HSI into its service roles and missions. The leader of these efforts is Air Combat

Command's Air Force Command and Control & Intelligence, Surveillance, and Reconnaissance Center (AFC2ISRC), which has created an HSI Integrated Product Team (IPT) to bring the maximum HSI utility to the warfighter via "architectures, roadmaps, requirements and standards."[34] The IPT is also designed to maximize Air Force efforts in this technology while minimizing duplication of effort with the other services. It would seem the IPT's greatest contribution is its ability to be the recognized central point for organizations to bring HSI issues to the Air Force.[35] Major projects that the HSI IPT is currently working on include an Air Force level concept of operations and a roadmap for the HSI "Family of Systems."[36] This type of strategic thinking within the service is needed to integrate air and space HSI efforts that are going on in various portions of the Air Force. A recent meeting of the HSI IPT noted the need to ensure Air Force Space Command is brought into the team.[37] This should have a strong positive impact on the service's implementation of HSI to ensure space and air are not at odds with each other, and even more importantly, it can maximize each organization's strengths.

As if to highlight the admonition from the AFC2ISRC's HSI IPT, Air Force Space Command and Air Combat Command have already started to build a roadmap to address the notional requirements for a space-based HSI sensor system. The "system" concept is very important because HSI is not merely a sensor; it is only one part of a much larger series of interconnected pieces that starts with a warfighter request for information and concludes when the warfighter receives the requested information. The Air Force Space Command/Air Combat Command draft roadmap for a space-based system recognizes this interconnectedness and highlights some of the areas that must be addressed in whatever final system is chosen. The draft roadmap also highlights the need to leverage the potential of other military and civilian spectral programs.[38] By using this leverage, the two commands can do much to lower acquisition and operational risk.[39] The roadmap also briefly addresses what will turn out to be huge issues such as command and control architectures, sensor development, data processing requirements, and how the information is actually passed to the customer. The preceding paragraphs have identified some of the important doctrinal issues relating to HSI and examined the roles and functions of DOD and service organizations. The discussion will now turn to a review of actual airborne systems, space-borne systems, and ground processing systems with which these organizations intend to, or already have, brought HSI to life.

Military Airborne HSI Systems

The Defense Advanced Research Projects Agency (DARPA) is a key DOD organization that is devoting much effort to HSI, and it controls the first HSI airborne sensor reviewed here. DARPA is the DOD's primary research and development organization, and based on its charter, it actively pursues programs that are high risk yet carry significant potential to produce huge payoffs for military missions.[40] In 1998, the Agency began working on an effort called the Adaptive Spectral Reconnaissance Program (ASRP). The main goal of this effort is to develop hyperspectral technology that can be used to meet some of the potential missions noted earlier, specifically seeing through adversary camouflage, concealment, and deception.[41] ASRP is focused on developing the technology primarily for unmanned airborne systems, and it has four specific "technology thrusts": models and algorithms, data analysis and signature databases, LWIR (long-wavelength infrared) sensor development, and data collections and demonstrations.[42] DARPA would like to see these technology thrusts result in improved tactical intelligence productivity through the use of advanced processing tools for better target detection, eventually leading to higher probability of kill and shortened time-lines to bring the needed information to the warfighter. They hope that through the use of manned and unmanned platforms, ASRP can help successfully resolve nagging issues such as the previously noted camouflaged vehicles and vehicles hiding in shadows or in tree lines. These were particular shortcomings noted from Operation Allied Force in Kosovo in 1999.[43]

Another airborne sensor program called the Hyperspectral Digital Imagery Collection Experiment (HYDICE) was created from a set of Naval Research Laboratory requirements and has been flown aboard a Convair 580 and a C-141 aircraft at altitudes up to 40,000 feet. The advanced design of HYDICE was based on the lessons learned in the multi-spectral imagery arena, and the system has become very useful for assessing the utility of reflective HSI. It collects 206 bands of spectral data in the visible, NIR and SWIR (0.4-2.5 µm, overall). The Hyperspectral MASINT Support to Military Operations program is one effort that has used HYDICE as an HSI sensor to collect data on several targets in a variety of climatic regions.[44]

Military Spaceborne HSI Systems

One success story that recently completed its scheduled mission is MightySat II.1, the Air Force Research Laboratory's first HSI sensor in space. This system had 256 bands covering a wavelength range from 0.35-1.05 μm with a spatial resolution of 1.7 nautical miles.[45] As part of a multi-satellite program, MightySat II.1 was designed to give the Air Force a low-cost platform that is capable of demonstrating high risk technologies for the purpose of accelerating the maturity of these technologies.[46] The main difference between MightySat's sensor and the others in this review is the method used to gain spectral resolution. While other sensors use a grating to spread out the different wavelength photons, MightySat II.1 uses interference patterns on the sensor that are processed to produce the required spectral results. This method has the potential to work very well in the LWIR band where it achieves the combination of a wider wavelength band and smaller spectral resolution (as low as six nanometers) than other types of sensors.[47] Because this spectral resolution is smaller, it has the potential to provide a better spectral signature for items under surveillance. One could say the "fingerprint" of the items is more precise, enhancing our ability to better distinguish between items that are similar to one another.

Following MightySat II.1, military spaceborne HSI success stories are harder to come by. The plan was to follow up the MightySat demonstrator with a much more capable system called Warfighter-1. The Air Force Research Laboratory partnered with ORBIMAGE Corporation to fly this sensor aboard the commercial OrbView-4 satellite. To enhance the sensing capabilities of the satellite, it was designed to be able to simultaneously image a region using panchromatic and multi-spectral imagery techniques in addition to HSI. Its HSI capabilities were to acquire spectral images from .45-2.45 μm in bands about .01 μm in width with a resolution of eight meters and having a swath width of five kilometers.[48] Key objectives of Warfighter-1 were to, first, continue to demonstrate the technology and second, to validate the capabilities of the system needed to produce information useful to a Joint Force Commander.[49] Unfortunately, on 21 September 2001, Warfighter-1's Taurus launch vehicle failed about two minutes into launch and Warfighter-1 was lost.[50] Though this was a very discouraging development, the Air Force Research Laboratory has been quick to promote the idea of another follow on sensor with even greater capabilities than Warfighter-1 called Noble EYE (for Enhanced Hyperspectral

Experiment). This sensor will have the capability to view a twenty-kilometer swath width with a spatial resolution as low as four to five meters. The laboratory is currently working with the National Aeronautics and Space Administration and the Jet Propulsion Laboratory to design and build the satellite bus and sensor for a possible launch in the 2005 timeframe. Expected costs, including launch, are currently in the $200 million range. Naturally, convincing the holders of the necessary funds to release the resources is a large step. The plan is now being proposed to the Under Secretary of the Air Force, the single overseer of space acquisition projects.[51]

Of the other services, the Navy is the closest to putting the next hyperspectral sensor into orbit. The Naval EarthMap Observer (NEMO) is being built to provide unclassified thirty-meter hyperspectral resolution for use primarily by naval forces and the civil sector.[52] It has a designed mission life of five years over which it will map large portions of the Earth's surface, focusing on littoral regions. It will also be able to have repeat coverage over several of these areas to allow for processing algorithm validation and improvement. Its HSI sensor has a range from .4-2.5 µm broken into 210 spectral bands that are .01 µm wide. NEMO also carries a panchromatic camera that can be used simultaneously with the HSI sensor to provide fuller characterization of the scene. Key uses for the Naval EarthMap Observer are expected to include studies of utility for preparing and understanding of the area for amphibious assault, water clarity, underwater hazards, beach characterization, and runoff effects among others.[53]

One area in which the Naval EarthMap Observer is expected to make huge strides is in on-board processing. As discussed earlier, the size of a hypercube will be an issue when it comes to transmitting the hypercube to the user; one source envisions raw data rates one day as high as 50 Gigabits/sec.[54] Even the NEMO's own high band data rate is only 150 Mbps. It would appear that much on-board processing is necessary to extract only the needed data from the hypercube. In fact, the Navy Research Laboratory is attempting to work such an issue with its Optical Real-Time Adaptive Signature Identification System. This patented system is designed to "significantly reduce the amount of data that NEMO must transmit to the ground while preserving 97 to 98 percent of the data fidelity."[55] The system can recognize and eliminate duplicate spectra from a scene, it can recognize important spectra that need to be transmitted to the ground, and it has already been successfully proven aboard airborne vehicles. Another key aspect of the system is that it provides "greater than ten-fold data compression, relieving the bottlenecks of on-board data storage and transmission to the ground."[56]

As of the writing of this paper, the biggest problem facing the Naval EarthMap Observer is money. The satellite's production is currently stalled because of the manner in which the program is funded. The satellite was to be built using a 50-50 split of government and commercial funds. However, the commercial partner has run out of funds and the Naval EarthMap Observer is on hold while further financing is procured.[57] It currently has no launch date, but the delay is expected to be at least two years.[58] This brief review of military systems is now complete, but the military is not the only organization interested in HSI technology and its potential applications.

Non-Military US Government HSI Systems

One government organization that is devoting much effort to HSI is the National Aeronautics and Space Administration (NASA). They have an airborne sensor called the Airborne Visible/Infrared Imaging Spectrometer, or AVIRIS. AVIRIS has 224 bands in the spectral region from .38-2.5 μm, a .01 μm bandwidth, and 20-meter spatial resolution, and it flies aboard a modified U-2 aircraft. On a large scale, the spectrometer is used primarily to sense the makeup of the Earth's surface as well as the atmosphere. Investigations using the spectrometer are typically focused on climate change and the global environment.[59] The spectrometer has been used to study coastal water flows, snow, and forest damage.[60]

NASA has also moved HSI into the spaceborne realm with their Earth Observing-1 satellite, which carries the TRW-developed Hyperion HSI sensor. Hyperion has 220 spectral bands in the .4-2.5 μm bandwidth with thirty-meter resolution. The satellite has been inserted in an orbit where it will sense the same scene as the US Geological Survey's Landsat 7 satellite, which is capable of multi-spectral imagery. In so doing, scientists and engineers hope to validate data from the Hyperion's sensors and add to the research knowledge base.[61]

Hyperion's sensor package is not designed to provide real-time or even near real-time data. This is because its three sensors will need to transmit 20 gigabits of data to the ground. This huge amount of data must then be stored on digital tapes that are mailed to the appropriate organizations for processing.[62] This timetable is sufficient for civil purposes and perhaps to assist the military, especially for long-term strategic purposes. Unfortunately, the system will not be nearly fast enough for military use inside a Joint Force Commander's campaign plan.[63] Interestingly, one report indicates the Hyperion sensor was used over Afghanistan to give researchers "a unique opportunity to compare hyperspectral images of targets before and after they were bombed, adding to the store of signature data that can be used in applying the technology to targeting and post-attack damage assessment."[64]

The next two government sensors to be discussed are not hyperspectral, but are actually multi-spectral imagery sensors that demonstrate the value that multiple spectra viewers can have over and above panchromatic sensors. The first of these is the Landsat satellite run by the Department of the Interior's US Geological Survey. The most recent of the Landsat series is Landsat 7, which is used to acquire multi-spectral images of the Earth's land surface and coastal regions.[65] Landsat 7 flies over the entire globe every 16 days and can sense objects as small as thirty meters, much like capabilities of the Navy's Naval EarthMap Observer satellite.[66] Landsat 7's sensor collects visible and infrared photons in eight different spectral bands. These include four visible and near infrared bands from .4-1.0 μm, two bands in the short wavelength infrared from 1.0-3.0 μm, and one band in the emissive medium wavelength infrared band from 8.0-12.0 μm.[67] The satellite should be able to provide scientists with unprecedented quantity and quality views of changes across the terrestrial environment (e.g., seasonal changes).[68]

The Department of Energy's Office of Nonproliferation and National Security has also orbited its own multi-spectral imagery satellite. The Multispectral Thermal Imager was launched on 12 Mar 2000, and has as the primary objective of demonstrating "advanced multi-spectral and thermal imaging, image processing, and associated technologies that could be used in future systems for detecting and characterizing facilities producing weapons of mass destruction."[69] The system has 15 discrete spectral bands from the visible to the long wavelength infrared. In the visible spectrum it has five-meter resolution; in the infrared the resolution is as low as 20 meters.[70]

US Non-governmental HSI System

US non-governmental organizations are also playing a role in HSI. In addition to the cooperative ORBIMAGE/USAF Warfighter-1 noted earlier, the Aerospace Corporation has created an airborne sensor called the Spectrally Enhanced Broadband Array Spectrograph System

(SEBASS). This HSI sensor is flown in the Central MASINT Organization's Hyperspectral MASINT Support to Military Operations project as well as in non-military projects.[71] A key aspect of the SEBASS system is that like the multi-spectral imagery sensors aboard Landsat 7 and the Multispectral Thermal Imager, and unlike the bulk of other HSI sensors, this system measures in the emissive spectral region. More specifically, it senses in two long wavelength infrared bands, 2.42–5.33 µm and 7.57–13.52 µm.[72] Again, the long wavelength infrared aspect of the SEBASS gives it both a daylight and nighttime capability.

Non-US HSI Systems

Non-US organizations are also playing a larger role in HIS. In the space arena, by 2005, an HIS sensor on the Australian Resource Information and Environment Satellite will image across 105 channels in the range .4-2.5 µm split between one visible and two short wave infrared sensor arrays. The spatial resolution of the sensor will only be 30 meters, but as with other sensors reviewed earlier, a ten-meter resolution panchromatic sensor will be used simultaneously to produce composite images. These uses for these images will include geological mapping, mineral exploration, environmental monitoring, forestry, and crop yield assessment.[73] Canada has also fielded an HSI platform, theirs being an airborne system called the Compact Airborne Spectrographic Imager (CASI)-2. Like many other HSI systems, it is used to conduct research in agriculture, environmental studies, water quality, and forestry. Though it doesn't possess the wide wavelength band of many of the HSI sensors reviewed above, it is still capable of recording spectral data from .4-1.0 µm. This range is can be divided into a maximum of 288 bands, and depending on the altitude of the aircraft; the resolution can be between 0.6-10 meters.[74]

Having reviewed several of the major HIS and multi-spectral sensor systems from military, U.S. and non-U.S. governmental, and commercial areas, our attention now focuses on an issue that is just as critical as the sensor—ground processing. Just as the onboard processing system Optical Real-Time Adaptive Signature Identification System is critically important to the success of the Navy's Naval EarthMap Observer satellite, so too will the ground processing be vital to any HSI system that is used to support a military campaign.

HSI Ground Processing

Although there is no single lead for the hyperspectral sensors themselves, the ground processing portion of the overall system is being worked at a much more integrated level, with results that it should prove far more interoperable than other military systems. The overarching ground processing system that will incorporate and process the data from HSI platforms is called the DOD Distributed Common Ground System, or DCGS. The DCGS is really a family of systems employed by each service to exploit the huge amounts of intelligence, surveillance, and reconnaissance (ISR) data produced by a wide array of sensors. Current planning appropriately places HSI processing within the DCGS along with other types of intelligence data processing.

Key concepts regarding the Distributed Common Ground System are being captured in a much needed capstone requirements document. This document plainly lays out the needs and the requirements for all the services' systems within the overall DCGS to interoperate with each other to ensure that field commanders do in fact achieve decision superiority.[75] In addition to merely stating that the systems need to be interoperable, the document dictates that this family of systems must work together with surface, airborne and spaceborne assets. This integration will allow the DCGS to assist a Joint Force Commander across the entire spectrum of conflict, in particular during combat, but in all aspects of campaign planning, execution and assessment as well.[76]

As an example from just one service, within the DOD DCGS structure, the Air Force has a program (the Distribution Common Ground *Station*) that attempts to address shortfalls in the ISR arena. The service is currently circulating a draft plan to list many of the needed attributes of the Air Force portion of the DOD structure. According to this document the Air Force intends to use their system to allocate what is known as "multi-INT" responsibilities across the service's intelligence organizations to take full advantage of information collected by the entire intelligence community. The key thought here is that the Air Force system will eliminate many current systems that are often proprietary or can operate with only one type of intelligence.[77] The Air Force ground station components are designed to be either fixed or deployable, and they will be capable of connecting to a secure Wide Area Network that will allow the multi-INT concept to work. The stations will possess tremendous processing capability, but it is expected that it could still take up to four hours to process a full hypercube. The standard hypercube is defined as less than or equal to 1024 pixels by 1024 pixels by 318 bands, or at least 333 million total pixels. However, hypercubes may get as large as 2048 pixels by 4096 pixels by 512 bands, or more than four billion pixels before FY05.[78] Recognizing that the warfighter may not be willing to wait up to four hours for information, the AF also proposes that their station be able to process a subset of the hypercube, called a "chip," within 20 minutes.[79] Given the size of hypercubes, their analysis is typically very processing intensive, which is one reason why HSI has taken so long to come of age. It is interesting to note that joint doctrine from as recently as 1996 notes that neither Joint Force Commander's own intelligence center, nor the command's subordinate centers, has the capability for MASINT processing.[80] Much progress has occurred in the past six years and this is no longer true. As a result of this progress, the intelligence community is at the cusp of being able to use HSI for direct warfighter support.

As noted earlier, within any ground station program one must consider the software used to actually process the data. The MASINT community seems to have settled on two systems for development. The National Air Intelligence Center (NAIC) is developing processing software called Common Spectral MASINT Exploitation Capability that is used to help the intelligence analyst interpret HSI data. The NAIC software was designed from the start to ensure its algorithms were not limited to one layer of data, but instead could process multiple layers of data such as hypercubes. The software is noted for aiding in defeating camouflage, concealment, and deception and is known for its ease of use.[81] The software currently is used in several HSI applications to include intelligence preparation of the battlefield, camouflage ID, targeting support, change detection, and search and rescue. The software developers hope to soon add other features to support facility characterization, treaty monitoring, and the search for weapons of mass destruction.[82] The second primary software tool under consideration is called Environment for Visualizing Imaging, or ENVI. A leading commercial product developed by Kodak's Research Systems, Inc., ENVI has capabilities to support both airborne and spaceborne sensors by enabling terrain analysis, radar analysis, and more. Just as several of the platforms discussed earlier combined standard imaging sensors with HSI systems, so too does ENVI combine image processing and spectral tools.[83]

The preceding discussion of the current status of hyperspectral imagery systems highlights the fact that while commercial applications abound for HSI, it has still not arrived as a major player within the military intelligence community. On the other hand, based on the wording in the U.S. Senate language, there is still a great deal of interest in what HSI can eventually bring to the warfighter. The next section of the paper will examine some of the roadblocks that are hampering the effort to fully incorporate a robust HSI capability for the U.S. military.

III. Challenges: Vision, Doctrine, and the Intelligence Cycle

This section of the paper will review where HSI fits into the Chairman of the Joint Chiefs of Staff vision for where the military ought to be in 20 years. This discussion will be followed by a lengthier introduction of the intelligence community and some first guesses as to where HSI should fit.[84]

"Fit" into Joint Vision 2020

The armed forces of the United States must be capable of helping the nation achieve its goals across the entire spectrum of military operations. Forces must be organized, trained, and equipped to create the necessary conditions for successful missions across the continuum from non-combat operations (e.g., humanitarian operations) all the way up to large-scale combat operations.[85] The Chairman, Joint Chiefs of Staff published "Joint Vision 2020" (JV 2020) as a roadmap to help guide the transformation of the military into such a force. Though HSI is not touted as a complete solution to the idea of transformation for information dominance, it can certainly play a role in the Chairman's vision. The idea of "full spectrum dominance" is preeminent in the vision. As stated in JV 2020, this dominance is "the ability of US forces, operating unilaterally or in combination with multinational and interagency partners, to defeat any adversary and control any situation across the full range of military operations. Achieving full spectrum dominance means the joint force will fulfill its primary purpose—victory in war—as well as achieving success across the full range of operations."[86]

The Chairman went on to discuss that the key enabler for the future force to achieve full spectrum dominance lies in the area of information superiority[87] or, "the degree of dominance in the information domain which permits the conduct of operations without effective opposition."[88] JV 2020 goes further to say that information superiority is not sufficient, but in fact, superior information must be converted into truly superior knowledge to achieve superiority in decision-making. The Chairman was quick to point out that decision superiority is not an automatic outcome of information superiority, but in fact it requires a foundation composed of sound organization and doctrine, thorough training combined with experience, and the right tools.[89] This paper proposes that HSI is one of the "right tools" necessary to achieve information superiority to offer hope for decision superiority.

The Chairman did offer an admonition, however, in the area of improving technology, and it is one that should be taken seriously and applied to HSI. He noted that it is important to not merely focus on new technology, but to look beyond the technology to understand the importance of organizing properly and to grasp the need for conceptual innovation. Technology can be very useful, but it needs to be integrated with changes in doctrine, organization, training, materiel, leadership and education, personnel, and facilities.[90]

Another concept relating HSI to JV 2020 is precision engagement. Precision engagement is one of the four pillars supporting full spectrum dominance, and it is the one most closely aligned to HSI.[91] Precision engagement is defined as, "the ability of joint forces to locate, surveil, discern, and track objectives or targets; select, organize, and use the correct systems; generate desired effects; assess results; and reengage with decisive speed and overwhelming operational tempo as required, throughout the full range of military operations."[92] The potential of HSI lies within its ability to affect target selection and assess results. Yet HSI cannot fulfill the vision of precision engagement alone. The most important trait of precision engagement is the "family" of sensors, weapon systems, and desired effects. It is in this context that HSI is not a stand-alone technology; it is part of a larger system that leads to the final thoughts from JV 2020.[93]

An idea that is consistent with the preceding discussion and has also permeated military thought since Desert Storm is that of interoperability. Essentially, interoperability is the ability for systems to share information.[94] JV 2020 is quick to point out that there is much more to interoperability than merely sharing data in the technical realm (e.g., bits and bytes). In fact, the document exhorts the services to focus on interoperability of procedures and organizations as well as on gaining knowledge of one another's capabilities and limitations.[95] Though the results of Desert Storm (e.g., difficulty getting the daily Air Tasking Order to all units) have led the military to be much more adept at meeting the technical requirements of interoperability, the DOD must also be on guard to ensure the implementation of this new technology keeps these other types of interoperability in mind as well.

"Fit" Into Intelligence World

Current joint doctrine separates intelligence sources into seven types of disciplines, or "INTs:" Technical Intelligence; Signals Intelligence (SIGINT); Human Intelligence (HUMINT); Open-source Intelligence (OSINT); Imagery Intelligence (IMINT); Measurements and Signals Intelligence (MASINT); and Counter-Intelligence.[96] Of particular interest for this paper is whether HSI can best be described as IMINT or MASINT. The distinction here may be subtle, but it is important nevertheless. It is likely that the owner of the "INT" will get not only the funding but also the personnel to implement the new technology (or, alternatively, the owner will be tasked to take them out of hide). It is reasonable to assume the organization that receives the funding to implement HSI carries with it a certain culture and mindset. For instance, where will HSI be placed in the priority scheme of the IMINT or MASINT communities? Is it really a priority or merely an additional source of funding for other higher priority systems within that organization? Equally important to decide is the key question, "Who is in charge?" Definitions of each of these two intelligence techniques are a helpful guide to highlight where controversy in the intelligence community may arise. IMINT is defined as, "Intelligence derived from the exploitation of collection by visual photography, infrared sensors, lasers, electro-optics, and radar sensors, such as synthetic aperture radar, wherein images of objects are reproduced optically or electronically on film, electronic display devices, or other media."[97] Because the definition of IMINT includes data from both "visual" and "infrared" systems, a plausible case can be made that HSI is an IMINT technology. While HSI products are often not direct representations of the area of interest that are easily recognizable to the human eye (as was clearly seen in earlier figures), certainly the wavelength bands used for HSI fall within the definition if IMINT. Still, others believe that HSI falls within the purview of the MASINT community. Joint Publication 2.0 defines MASINT in the following way:

> Intelligence obtained by quantitative and qualitative analysis of data (metric, angle, spatial, wavelength, time dependence, modulation...) derived from specific technical sensors for the purpose of identifying any distinctive features associated with the emitter or sender, and to facilitate subsequent identification and/or measurement of

> the same. The detected feature may be either reflected or emitted.[98]

Again, the reader can see the ambiguity between the definitions of the two types of intelligence with respect to HSI technology.

This paper asserts that HSI is part of MASINT, but the reasoning for this assertion is qualitative rather than quantitative. While HSI certainly uses the tools of IMINT, such as the visual and infrared spectrum, strictly categorizing HSI as IMINT severely limits the perceived usefulness of this technology. If an analogy can be drawn between types of intelligence and the senses of the human body, IMINT can be associated with seeing with the eyes and SIGINT with hearing with the ears. MASINT, on the other hand, with HSI as one of its components, can be considered a discipline that uses all the senses.[99] Because HSI uses many wavelengths, does in fact have spatial resolution aspects, and certainly facilitates identification of items within the field of view, an even stronger case can be made that HSI is actually a MASINT technology. MASINT proponents as well as the preponderance of available literature suggest HSI should be overseen by an organization responsible for exploiting these types of data, yet with significant input from the IMINT community.

Current Joint Doctrine Perspective

Having established that HSI clearly has a role in the intelligence arena, this portion of the paper will use current joint doctrine to show how the Joint Force Commander could best use available processes to exploit HSI. This part of the paper also demonstrates that current intelligence doctrine is not in bad shape, but some accommodation for HSI is necessary. For instance, existing doctrine discusses how intelligence agencies are arranged to support a Joint Force Commander, yet this discussion shows there are some holes regarding where HSI fits into intelligence, who is in charge of HSI, the resulting lack of "ownership" when it comes to funding, and technical issues that need to be resolved (such as interoperability and standardized databases) to take full advantage of what HSI has to offer.

According to joint doctrine, a broad network of intelligence organizations supports the Joint Force Commander. The support may come from the commander's own organic intelligence organization or from national level capabilities. The most important roles of these organizations are to help the commander and his supporting staff to understand the battlespace they are facing, to appraise the capabilities and will of the opponent, to identify the enemy's key areas of strength and power, and to try to determine the enemy's intent. Therefore, a key role for the commander is to ensure the intelligence networks are brought fully into the campaign plan.[100]

According to doctrine, organic support takes form in the commander's own intelligence staff as well as the command's Joint Intelligence Center, or in the case of a Joint Task Force, the support of a Joint Intelligence Support Element. The commander's intelligence staff provides the strategic lynchpin for many aspects of intelligence support to the campaign. Some of the functions of the staff include ensuring intelligence and operations are synchronized, developing detailed intelligence plans, establishing the command's intelligence architecture, and integrating national and theater intelligence support. The intelligence staff coordinates both up the chain (e.g., with the National Military Joint Intelligence Center) as well as with subordinate agencies (the commander's Joint Intelligence Center and component agencies) to ensure the commander is provided with well integrated, all source information. In times of crisis a Joint Force Commander may also stand up a Joint Intelligence Support Element to augment the commander's intelligence staff. The intelligence staff directs the Joint Intelligence Support Element efforts that would usually consist of collection, production, and dissemination of intelligence for the joint force.[101]

If the intelligence staff provides the strategic intelligence effort, then the command's Joint Intelligence Center, or JIC, is the combatant commander's primary source of intelligence at the operational and tactical levels of war. The JIC brings together the supporting services' capabilities into a central location to enhance intelligence support. The JIC is not expected to fulfill every request for support, but it is designed to maximize the ability to fill requests by coordinating support from all echelons of organization: higher, lower, and peer. To complete its duties, the JIC carries out many functions that not only have clear implications to HSI but also apply generically to all types of intelligence collection as well. These functions include coordinating intelligence efforts of subordinate commands, coordinating the use of sensors assigned to the theater as well as supporting sensors, and validating Battle Damage Assessments from whichever source (e.g., national, organic) that provides it.[102]

At the national level, the Joint Force Commander has access to key organizations that are designed to support the campaign. While there are many intelligence players at the national level, this paper will focus only on those most closely related to HSI. These are Defense Intelligence Agency, the Joint Staff Directorate for Intelligence, the National Military Joint Intelligence Center, the National Imagery and Mapping Agency, the National Reconnaissance Office, and the Central MASINT Organization. These will likely be the key organizations in the debate and resolution on how HSI is eventually implemented. A brief description of each of these organizations is included below.

The Defense Intelligence Agency (DIA) has the responsibility to plan, direct, collect, process, exploit, analyze, produce disseminate, integrate, and evaluate all-source intelligence for the DOD.[103] In this role, the Agency is the peacetime focal point for the Joint Force Commander's JIC to request and receive intelligence information gathered by not only this agency but the other intelligence organizations as well.[104] Thus, to the best of its ability, the JIC is responsible for reviewing, validating, and acting upon intelligence requests from the command. Then, if organic resources are not available, the JIC would make the intelligence request to DIA.[105]

The Joint Staff Intelligence Directorate provides all-source intelligence to many customers including the Chairman of the Joint Chiefs of Staff, the Joint Staff, the Office of the Secretary of Defense, and the combatant commands.[106] One item of note regarding this staff is that it is also a directorate of DIA that draws heavily on its parent organization to accomplish its myriad roles.[107]

As noted earlier, DIA is the peacetime direct link between the JIC and other intelligent agencies. In crisis situations, this link is provided by the National Military Joint Intelligence Center (NMJIC), which is operated by the Joint Staff Intelligence Directorate. The NMJIC not only has members representing the Directorate's own specialists in regional affairs, targeting, and operations, but it also has members representing outside organizations such as the National Imagery and Mapping Agency and the National Security Agency.[108] It is conceivable, and perhaps even likely that based on current intelligence gathering architectures, the Joint Force Commander will not control all the HSI assets that can sense the commander's theater of operations. Naturally, the Joint Force Commander can task the sensors that are under the command's control, but in crisis situations or for sensors outside the Joint Force Commander's control, the NMJIC is the point of contact for requests for intelligence information. Additionally, three of the intelligence agencies are outside the Joint Force Commander control, yet they will likely have a large role in HSI. These agencies—the National Imagery and Mapping Agency, the National Reconnaissance Office, and the Central MASINT Organization—are described in the next two paragraphs.

As discussed earlier, the National Imagery and Mapping Agency (NIMA) provides intelligence and geospatial information in support of national security objectives. To help fulfill this role, NIMA has an Operations Center at the Pentagon that provides full-time imagery analysis support to the Joint Staff Directorate for Intelligence, the Joint Force Commander, components and other joint staff members. Another organization very closely related to NIMA that will most likely have a large role in HSI is the National Reconnaissance Office (NRO). This organization's mission is to provide the United States with space-based reconnaissance. Though current doctrine indicates that the acquisition programs and intelligence operations conducted by the NRO are in Imagery and Signals Intelligence, this doctrine could be modified to assign duties for HSI procurement to NRO. In fact, once HSI space sensors are in orbit, an extension of current doctrine would lead to the national level MASINT request process discussed in the following paragraph. Unfortunately, one issue that remains is that joint doctrine assigns no organization with the responsibility of overseeing the procurement of *airborne* systems, thus leaving each service to independently procure its own airborne HSI platforms.

Tying these organizations together for peacetime intelligence requests would work as follows: a Joint Force Commander's request would first go through the JIC and then to DIA. Next, the request would flow to NIMA, which would then task NRO to obtain the desired data. In crisis situations a similar flow would occur except that coordination by the NMJIC would be inserted between the JIC and DIA.[109]

The third national level organization that must be reviewed is the Central MASINT Organization. As its name implies, the Central MASINT Organization is the MASINT manager for the DOD and other members of the intelligence community.[110] As a part of DIA's Directorate for Intelligence Operations, the Central MASINT Organization is currently seen as the frontrunner for leading HSI efforts. Even the Senate recognizes the organization's expertise in that the Central MASINT Organization has been tasked by the Senate Committee on Intelligence to produce a Spectral MASINT Study in 2002 that will focus on issues such as who should be the lead proponent for HSI.[111] Though the documentation would indicate that NIMA is particularly interested in panchromatic types of imagery products, because of the spectral nature of HSI, it is understandable that they would like to play a large role. But later on in this paper, it will be shown that it could be difficult for NIMA to add HSI to its oversight because of difficulties already present in disseminating the intelligence they currently produce.

To best conceptualize how HSI should be employed to bring out the potential results described earlier, one needs to look no further than existing joint doctrine. Since there is no argument that HSI definitely fits within the intelligence arena, then it should be viewed in terms of the intelligence cycle used by the intelligence community to support the Joint Force Commander.

The Intelligence Cycle

The intelligence cycle that is shown in Figure 1 is merely a model of how intelligence functions are conducted and is composed of six phases: "planning and direction; collection; processing and exploitation; analysis and production; dissemination and integration; and evaluation and feedback." [112] Each of these phases is described below, but one overarching concept that deserves mention here is that the cycle may not strictly follow the continuum as drawn out in the model. It is not unusual for the cycle to sometimes be cut short because interrelationships exist between each of the phases. For example, in some cases, the processing and exploitation phase could be bypassed if data were passed directly from the sensor to the user without having been processed or exploited.[113] Joint Publication 2-01, "Joint Intelligence Support to Military Operations," describes the intelligence cycle in detail and is summarized in the following paragraphs.

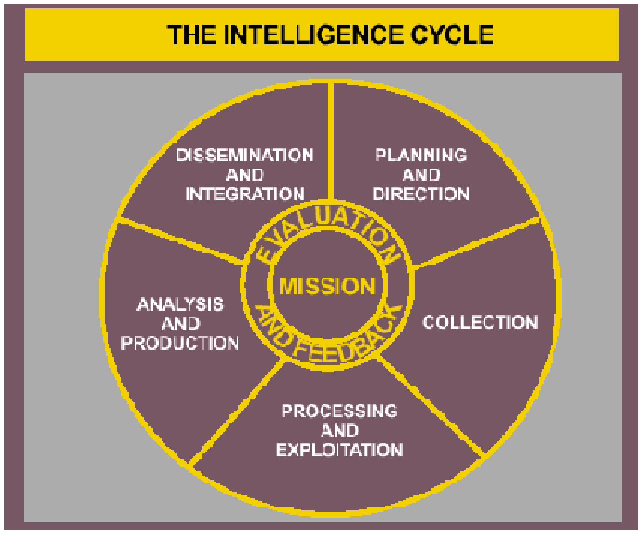


Figure 5 The Intelligence Cycle

The intelligence cycle begins with a user need in the form of an intelligence requirement. The requirement sets the direction for the first phase of the cycle, Planning and Direction. It is likely this requirement is just one of many requirements before the Joint Force Commander's intelligence staff, which are all prioritized by that staff. In principle, the staff's prioritization will focus all of the various efforts in line with the Joint Force Commander's intent.[114]

The second phase, Collection, is where the tasking of appropriate collection assets occurs. To acquire the required data, the intelligence staff will first task the Joint Force Commander's own intelligence assets. If organic assets are not available, then intelligence support may get more complicated. Working through the JIC, the Joint Force Commander's staff will request support via DIA (or NMJIC during a crisis) for external support. In some instances that require use of high value, low-density systems such as the Joint Surveillance Target Attack Radar System aircraft and associated ground stations, the approval authority may go as high as the Secretary of Defense.[115]

Once data is obtained that might meet the requirement, the cycle enters the Processing and Exploitation phase. During this phase, the raw data (e.g., a hypercube) is transformed into a product that intelligence operators can use in the analysis and production of useable intelligence (e.g., a picture of a tank partially hidden under trees). Just as the requirements for collection are prioritized, so too must be the processing and exploitation of the data be prioritized to ensure that the most critical information is delivered to the decision maker.[116]

The Production phase entails analyzing and evaluating the information gathered above to prepare the finished product. Other available sources of data can also be brought in to combine with the gathered data. For example, the Distributed Common Ground Station, discussed earlier, is being designed to be interoperable with a number of "INTs." Therefore, if either radar or standard imagery is available for the same scene as an HSI hypercube, then the two could be integrated in the Production phase to provide the Joint Force Commander with a more thorough view of the battlespace. To encourage such synergistic processing, a central database of standardized HSI signatures should be created and called out explicitly in doctrine. This would encourage interoperability between services and also meet the required interoperability between "INTs." Joint doctrine already acknowledges that modern constraints on the battlefield are beginning to make the Processing and Exploitation phase look "indistinguishable" from the Production phase.[117] This is not a bad thing. As noted earlier in the discussion of JV 2020, one main vision for the force of the future is decision superiority through overwhelming operational tempo across the full range of operations. If HSI systems can help to get finished products to the Joint Force Commander faster, then the warfighter is one step closer to realizing the vision.

The fifth phase, Dissemination and Integration, brings the intelligence product from out of the "art" of exploitation and returns it to the "science" of formatting and transmission. Here the product is provided to the requester in the required, standardized format so he can use the product to help make appropriate decisions and planning choices. As an aside, even though new systems are being created to provide users with much greater communication capabilities than in the past, the producer of the finished product needs to take care not to overload the requester's capabilities to accept the product.[118]

The final phase, Evaluation, is of concern to intelligence personnel at all levels. As the cycle begins anew, critical eyes must look for opportunities to improve any and every phase of the cycle. For example, transitions between the various phases are particular points to scrutinize for potential gains. In addition, the JIC is a facilitator that may also help cut down on the intelligence cycle by approving methods by which the requestors of intelligence can go directly to the outside producers for products not typically produced by the JIC. Naturally, it must be the focus of all requests to obtain such direct information.[119] This could have implications to HSI depending on how the overall HSI architecture is created. It is easy to see that many intelligence agencies that not directly under the Joint Force Commander control will have sensing capabilities that can be brought to bear in the campaign.

Tasking, Processing, Exploitation, and Dissemination

In spite of the fact that joint doctrine identifies the conceptual six-phase approach described above as the approved process, the intelligence community often combines, or even eliminates, phases into a more compact model called the Tasking, Processing, Exploitation, and Dissemination cycle. This cycle is by far the most common model found in the intelligence literature. Note that even experts in the intelligence cycle have difficulty with this model versus the joint doctrine cycle. One study noted, "It appears that an acronym for the functions of tasking, processing, exploitation, and dissemination has somehow become the name for an entity without benefit of a common understanding of the content."[120] Yet because of the prevalent use of the abbreviated model by the intelligence community at large, this paper will also recognize it as the model of choice. While joint doctrine phases (or parts of phases) such as Production, Collection, and Evaluation may not be explicitly included in four-step model, the associated activities are in fact still present in the process.

As discussed earlier in this paper, HSI information is particularly valuable when it is combined with information from other intelligence sources. With any new system, the ultimate goal is to improve intelligence products, and the benefits gained by leveraging data from multiple sources must be continually reenergized. One prognosticator is already looking beyond the technology limitations of HSI to a time when the multi-INT transition is seamless:

> [T]he next evolutionary step would be to collect and fuse data from all sensory inputs—optical, olfactory, infrared, multispectral, tactile, acoustical, laser radar, millimeter wave radar, X-ray, DNA patterns, and human intelligence—to identify objects, people or processes. The idea would be to compare a sensory signature against a

> preloaded database to identify matches or changes in the signature for identification or comparison. Once again, it's just a matter of time before satellites can be packaged with stronger sensors and faster computer packages to accomplish this task.[121]

The lack of such purposeful integration was one major critique during a recent study on NIMA. The report concluded the Agency's plans for Tasking, Processing, Exploitation, and Dissemination fail to assure such integration between similar-INT airborne, commercial and space systems (another MASINT such as Synthetic Aperture Radar for example). In addition, NIMA plans also fail to address multi-INT integration.[122] This problem is recognized elsewhere such as in the Capstone Requirements Document for the DOD's Distributed Common Ground System. This document elaborates on these woes by stating flatly that there isn't enough Tasking, Processing, Exploitation, and Dissemination capacity to meet defined requirements, and unfortunately, adding new sensors and technology will only worsen the problem.[123]

The final major challenge on the way ahead is money. The issue of resources is a fight that will continue when it becomes time to find the money to pay for HSI. Where doctrine puts HSI will be a critical matter when planning for this technology's future. The National Imagery and Mapping Agency commission noted this very topic when addressing their findings:

> [T]he Commission suggests that serious, far-reaching review is required of evolving US military doctrine and its dependence on an ever-expanding definition of information superiority, so as to determine the contingent liabilities placed on intelligence. These and these alone must define the needed level of investment in intelligence resources by the military services. Anything less is reckless and irresponsible.[124]

To avoid being "reckless and irresponsible," the intelligence community will need to make difficult budgeting decisions. For instance, one of the main focuses of the NIMA commission report noted earlier was the general belief that the entire intelligence community is too heavily focused on the collection aspect of their work rather than on tasking and dissemination. The problem is that resources are just not available to improve tasking and dissemination systems and modernize legacy systems, while at the same time integrating multiple INTs. The report recognized the important task of merging IMINT and SIGINT is "a bigger, more costly, more demanding job than the sum of the two respective pieces done separately."[125] This makes the report's finding that no one is even planning for multi-INT integration even more disheartening. Current MASINT literature does not seem to indicate that it will replace any current systems but will merely be added to existing systems. In light of all the other taskings requiring resources, it is no wonder the report noted that trying to bring about the needed changes by staffing for multi-INT integration in the government's traditional manner seems to be "a nearly insuperable hurdle." The ability to find and develop the needed personnel is not there.[126]

As has been amply shown above, the DOD continues to devote much energy to key efforts for turning the dream of HSI into reality. Still, much work remains to fulfill the promise of HSI. The next section examines several recommendations that should help promote successful HSI implementation.

IV. Recommendations

Organizational Recommendations

First, the question of who is in charge of HSI needs to be resolved. It may turn out that no one will be given the lead in HSI, and the services will be left to develop their own stove-piped systems. This would be a big mistake. DOD wants to ensure interoperability between the services, at least in the Processing phase, and these efforts should be encouraged. [127] A single organization could bring vital leverage that would be lost if the lead for HSI is split among various services. This paper recommends that the Central MASINT Organization be given the responsibility as the lead organization for all implementing all HSI platforms. The first reason for this is that HSI "fits" better into MASINT than into IMINT. Another reason is that within the MASINT community, the Central MASINT Organization already has the leading role in HSI and has the capability to take a broad view across the DOD. Pulling together the airborne, spaceborne, theater, and national aspects described earlier into an integrated technical architecture will be a huge undertaking, but the effort needs to be made if the military is to ensure HSI reaches its full potential.

The essential requirements for such an integrated architecture can already be identified in joint doctrine. Several key points should be kept in mind when developing the integrated roadmap for HSI. First, as this paper has continually stressed, HSI must adapt to the Joint Force Commander's needs, supporting the full range of missions. For example, the system should support the gamut of operations—from humanitarian efforts to major theater wars. Second, the system should avoid single points of failure. A robust air, space, and ground architecture would likely lead to a very survivable capability. Third, the system must be able to accommodate the Joint Force Commander's decision-making and execution cycle. The decreased processing time requirement noted earlier for USAF's Distributed Common Ground Station is merely one example of trying to speed up the decision-execution cycle. Fourth, the system must allow for operator training during peacetime. Finally, to keep the HSI system relevant to the warfighter, it must allow for new technologies to be incorporated.[128]

The lead organization recommendation espoused here is not to say that the Central MASINT Organization must do all the work, merely that it should lead the way through the myriad efforts that will bring HSI to reality. For organizational purposes, the work should be divided between space and air systems with yet another organization to review ground station architectures. For example, the Central MASINT Organization should give space architecture work to the National Space Security Architect, and the actual acquisition of any national-level HSI satellite program should be given to NRO. According to joint doctrine this agency is "responsible for the unique and innovative technology, large scale systems engineering, development and acquisition, and operations of space reconnaissance systems and related intelligence activities needed to support global information superiority."[129] Though joint doctrine does not currently give a MASINT satellite role to NRO (IMINT and SIGINT only), the doctrine should be formally changed to accommodate the new technology.

The DOD should not limit satellite acquisitions to national-level sensors alone. Assets that could be tasked directly by the Joint Force Commander's intelligence staff should also be investigated to help fill any gaps in coverage or decrease turn-around time. Any satellite of this type should be given to the Air Force to procure, because recent direction from Secretary of Defense Rumsfeld has directed the Air Force to become the DOD's "Executive Agent for Space."[130] The Air Force Space Command/Air Combat Command draft HSI roadmap is a good start down that road. This document should be finalized with appropriate resources and provided to an acquiring agency to turn the requirements into a working system.

Unfortunately there is no acquisition agency similar to the NRO for airborne sensors. The Defense Airborne Reconnaissance Office was designed to be such an agency, but it was disbanded, and each service has been left to create its own airborne systems. The Unmanned Aerial Vehicle concept for airborne reconnaissance is gaining strength throughout the DOD, with each service procuring its own vehicles. To encourage interoperability and reduce redundancy, the Central MASINT Organization, or an organization working under the auspices of the Central MASINT Organization, should work with the services to integrate HSI onto these new platforms.

The Central MASINT Organization would also be assigned the responsibility to oversee development of ground stations that are capable of processing a wide variety of HSI data, including data not collected by the military, as mentioned earlier. The capstone requirements document for the DOD Distributed Common Ground System is pursuing such a vision. This document should be finalized to ensure the services work toward common HSI technical architectures.

Another organizational challenge that has its roots in the technology is the issue of a central spectral database. One report noted that spectral intelligence such as HSI needs a "thorough catalog of objects and surface chemistries to detect the meaning of this or that reflection."[131] In order to recognize any type of target in a given scene, the processing system must have a standard against which to compare the scene as well as a robust methodology to access the growing number of catalogued spectral signatures. The catalog would also need to take into account that not all spectral signatures have the same resolution because these signatures would have been built using a variety of sensors. The HSI community is addressing these issues via several forums. One is the Spectral Products Users' Group that is developing the standard formats in which HSI should be communicated between users. This "common language" is a significant first step toward promoting interoperability between users.[132]

The methodology being developed to access a common database of HSI products is also encouraging. A new organization called the National Air Intelligence Center (NAIC) Spectral Exploitation Cell (NSEC) is being created at Wright-Patterson Air Force Base, Ohio, to provide a location from which users can request and process HSI information. At first NSEC will provide products to its customers in an off-line mode, with products arriving at the customer within twenty-four hours. Later, the capability will be placed on-line. The disseminated information will follow the approved formats from the Spectral Products Users' Group and will include both graphic and text reports. Additionally, assured interoperability will come about because these reports will be mandated across all services and systems, including the DOD Distributed Common Ground System.[133]

In his final report to Congress, former Secretary of Defense Cohen provided a fitting conclusion to the discussion of organizational needs for HSI. He noted some encouraging news for MASINT and HSI by pointing out that in FY 2000, the Central MASINT Organization received the first increment of a planned six-year resource increase.[134] Perhaps to deflect some of the Senate's stinging criticism from May 2000, he went on to say the following:

> The focus of the first year was on improving support to joint military operations through the creation of MASINT operations and production coordination elements. DOD is placing particular emphasis on strategies and techniques to strengthen MASINT [Tasking, Processing, Exploitation, and Dissemination] and increase analytical depth, particularly in the arenas of...multi/hyperspectral information...[135]

Doctrinal Recommendations

Despite this good news on the organizational front, it seems that even if the technology of HSI is nearly ready for implementation, it is clear from other evidence in the earlier discussions that other obstacles still remain. For instance, doctrine needs to be updated to reflect the addition of HSI into the MASINT community under the proposed umbrella organization. The doctrine should be explicitly directive to ensure that resources can be provided to the appropriate agencies rather than risk having these same resources spread across several agencies whose primary role is outside the MASINT arena.

As discussed earlier, the intelligence cycle for Joint Force Commander "owned" assets is fairly straightforward. Essentially, the Tasking, Processing, Exploitation, and Dissemination cycle is done within the Joint Force Commander's own intelligence staff structure. This cycle becomes somewhat more challenging when the combatant command intelligence director needs to request resources outside the command. In this case, existing joint doctrine can serve well with only minor changes. For example, DIA currently coordinates national level requirements, and tasking is currently given through DIA to obtain IMINT data from the NRO via NIMA tasking. The link to DIA should be applied to space HSI as well.[136]

It should also not be forgotten that what is valuable for an ally is also valuable for the enemy. Doctrine should be reviewed to address the implications of adversaries possessing HSI capabilities. Even if other nations' militaries are not developing HSI systems on their own, commercial systems are being developed that have the potential to be exploited by our adversaries. During preparation of the intelligence battlespace, planners must determine what the adversary hopes to achieve and how HSI can help that adversary. Current joint doctrine already provides some guidance in that efforts to prepare such information should include, at a minimum, the options available to the adversary, the likelihood of these options occurring, and the intelligence needs to determine more about each option.[137] Similarly, planners should look at any pieces of information that HSI could reveal about allied military posture in the theater of operations.

Other Key Recommendations

In addition to the organizational and doctrinal issues, other challenges also remain. On the technical front, acquirers have a continuing task to ensure the station's MASINT capabilities are interoperable with all other national and tactical agencies. Additionally, these capabilities are to be integrated to ensure that the multi-INT capabilities are likewise preserved.[138] Simply said, "it goes both ways." All services should coordinate their MASINT activities with the ISR community as a whole (i.e., not only the MASINT community) to ensure their equipment can transmit their own products while being able to receive and process other services' products. The important thought here is that the services will take care to match up with the standards as they are developed. Likewise, other agencies need to know what is being developed to ensure the full multi-INT capability is preserved on their end.

The long discussion of ground processing systems earlier in the paper serves to illustrate the difficulty in bringing together the extensive MASINT community in such a way that it can best serve the warfighter. Below are five activities whose successful completion is essential to bringing aboard these types of processing systems.[139]

First, and not surprisingly, user-validated requirements and concepts of operations must be developed and adhered to. Items listed earlier, such as standard formats, interoperability, and multi-INT capability, must also be adhered to if the Joint Force Commander is to gain the greatest amount of information with the minimum resources. Second, resource allocation and management is critical to ensure funding and manning are both appropriate to the task. It is reasonable to assume that incorporating HSI will require more funding for system acquisition and sustainment and must be planned and budgeted for as early as possible.

Third, systems integration (i.e., new sensors being added to the network) is going to be very difficult. Without set standards and databases of spectral signatures, it could be very difficult to get the services working together. Though as noted earlier, some efforts are already underway to develop such standards, the acquiring commands for each service must be cautiously vigilant to ensure that the hardware and software of new sensors are compatible with the existing baseline. Likewise, the services must continue to pay very close attention to the needed communications requirements. In fact, the DOD Distributed Common Ground System capstone document reminds the readers that DOD instructions require the services to prepare the communications support plans to ensure that communication requirements are known and accounted for before systems are introduced to the field.[140]

Fourth, operational integration (e.g., changes to the processing station baseline) is going to be a challenge as well. It is imperative that strong change management processes be used to ensure that baseline capabilities are not degraded. Thorough test and evaluation, attentiveness to standards (machine and human factors), plus prior use in experiments will help ensure these types of changes are successful.

Fifth, just as those who are responsible for operational integration need to pay close attention to human factors, implementers must remember the human element of Training and Education. HSI is not standard imagery; so standard imagery training alone will not suffice. Training should not merely be an afterthought, but it must be integrated into development. Training will be of concern at all levels of the joint force and should become standardized. As noted earlier in the ground processing discussion, training for the analysts will be critically important. Also, just as the Central MASINT Organization has contracted for training programs based on the level of detail needed for each individual, so too should the organization overseeing HSI prepare a training plan for personnel from the imagery analyst up to, and including, at least the director of the Joint Force Commander's intelligence staff. If the lead organization does not do the actual training plan, then the services must.[141] The service-based training approach is not the preferred method since it could invite redundancies into the training schemes, especially if each service prepares their own plans without integrating with other intelligence organizations. Though each service may choose to independently procure training for operators, this does not necessarily need to be the case. Because the MASINT community will be growing and many organizations will be involved, these organizations may be able to leverage off of each others' training programs.

No matter what the final training plan looks like, as with other career specialties, the training for the operators must be continuous, advancing methodically from the basic through advanced levels.[142] It is not clear at this point whether or not the Joint Force Commander needs to receive anything other than the briefest HSI overview because of the "finished" nature of the HSI products by the time they reach that level of command. As shown in the series of photos at the top of the paper, raw HSI data reveals little to the human eye; so it seems unlikely that the Joint Force Commander will be presented such information.

In addition to standardized training, HSI capabilities must be continuously integrated into wargames, exercises, and demonstrations to improve the operators' performance as well as improve the methods by which HSI is incorporated into campaigns. Air Force doctrine is a strong proponent for such a proposal, reasoning:

> Exercises provide realistic training that is essential for proficiency and readiness. Realistic exercises determine possible shortfalls and corrective actions to achieve success in future operations. Exercises train individuals, units, and staffs in the necessary skills and tools for ISR operations and ensure that staffs can plan, control, and support such operations.[143]

In fact, HSI has already been incorporated into at least one experiment, JEFX 2000 (5-15 Sep 00). Using both air and spaceborne sensors such as MightySat II.1, the HSI portion of the experiment attempted to meet many objectives. First, experimenters attempted to show that one workstation could process hypercubes from multiple sensors. Second, they evaluated the functionality of four software programs for processing HSI, including the Common Spectral MASINT Exploitation Capability and ENVI discussed earlier. They evaluated Air Force Distributed Common Ground Station hardware and software requirements against the HSI systems used in the experiment. Next, they attempted to get a sense of what is needed in terms of operator training requirements.[144]

The results of the experiment were very positive for HSI. Analysts and evaluators agreed that HSI is now at a sufficient level of maturity to provide useful information to the Joint Force Commander. In fact, operators were able to find targets not detected by the electro-optical or radar systems. In addition, the use of the Spectrally Enhanced Broadband Array Spectrograph System long wavelength infrared sensor showed that by using the emissive properties of materials, it can in fact differentiate targets, a huge boon when operating at night or through cirrus clouds.[145] On the down side, because this evaluation took place in an experiment rather than an exercise, the suite of sensors, processors, and people were far from standardized in terms of doctrine, organization or training. Nevertheless, the exercise clearly showed that such issues could be resolved. As might be expected, using systems mixed in an essentially ad hoc manner rather than an integrated one, led to some conclusions that the "system" is not yet capable of meeting a warfighter's time critical information requirements. Additionally, the issue of the slow processing of full hypercubes also arose.[146] Yet, this experiment shows the value of taking advantage of such opportunities on a continuing basis.

In addition to the JEFX experiment noted above, on 5 March 2002, the Under Secretary of Defense for Acquisition, Technology and Logistics announced that an HSI project has been funded for an Advanced Concept Technology Demonstration, or ACTD.[147] ACTDs "emphasize technology assessment and integration rather than technology development. The goal is to provide a prototype capability to the warfighter and to support him in the evaluation of that capability. The warfighters evaluate the capabilities in real military exercises and at a scale sufficient to fully assess military utility."[148] The HSI ACTD, called the Hyperspectral Collection and Analysis System, will integrate a variety of HSI sensors onto different platforms (e.g., manned and unmanned aircraft and satellites). It will be used to show the utility of an integrated HSI system in such areas as search and rescue, counter camouflage, and the search for weapons of mass destruction.[149]

The 11 September 2001 attacks appear to have caused some dramatic positive shifts in funding priorities in addition to the new ACTD noted above. As reported in a December 2001 issue of Defense News, just two months after the attacks several information technology units of major defense contractors were awarded study contracts worth about $100 million to develop a computer network named Multi-ISR (for Intelligence, Surveillance, and Reconnaissance).[150] Though no government officials would publicly acknowledge the existence of the contracts, the

Intelligence Authorization Act 2002 Conference Report highlights investment in new technologies for collection processing and analysis.[151]

The process for funding HSI is not particularly mysterious. The intelligence resource process is broken into three major categories used to represent the three broad uses of the intelligence—strategic, operational and tactical. Strategic intelligence is for use primarily by the President, Secretary of Defense and other very high level military and political leadership. The category name for procuring strategic level systems is called the National Foreign Intelligence Program. This procurement level is not the focus of this paper, but certainly HSI products could be used at this level to help decisionmakers with national policy and military strategy. As noted earlier, in combination with other intelligence methods, HSI could be used for such national level concerns as treaty verification. Procurement dollars for an NRO HSI system would come from this funding source. Though the focus of an HSI system acquired under the National Foreign Intelligence Program would be strategic in nature, it should not be assumed that this would exclude its usefulness to a Joint Force Commander. Certainly national level systems can be and are used to support the commander's intelligence preparation of the battlespace for campaign planning or indications and warnings.[152]

The resource category for the operational level of intelligence is known as the Joint Military Intelligence Program. This level of intelligence resource allocation is at the heart of the current discussion on how HSI can support a Joint Force Commander overseeing multiple DOD components. This funding source was established to improve DOD intelligence efforts when those efforts require resources from more than one DOD component or the customers of the produced data come from more than one component. In addition to supporting the warfighter, this funding source also supports policymakers and modernization planners by helping bring increased effectiveness to the planning and oversight of this level of intelligence activity.[153] The Joint Military Intelligence Program could justifiably fund programs such as a non-NRO space-based HSI system. Airborne platforms could likewise receive funding from the Joint Military Intelligence Program.

The third level of intelligence resourcing is called Tactical Intelligence and Related Activities. This funding is focused on individual services or agencies and where the customer is at the operational and tactical level. These levels usually include the "corps, wing, naval battle group, and Marine expeditionary force level and below."[154] While this level of intelligence funding from this source may be too low for procuring an HSI sensor, it may be very applicable to each services for acquiring processing stations or their follow-ons (e.g., Distributed Common Ground System). However, this particular application does reinforce the requirement to appoint a lead HSI organization to ensure HSI remains integrated across the services.

The lead organization concept noted earlier in this section would be given the responsibility of negotiating the various methods by which each HSI system would be programmed and budgeted. The lead organization would also need to work closely with the other "INT" agencies to ensure that HSI is properly integrated with the larger intelligence arena.

Conclusions

The time has arrived for Hyperspectral Imagery—theory and technology can now intersect. The main question is, does the nation have the will to devote the proper effort to HSI to turn it into reality? This paper has reviewed the benefits of HSI to the warfighter as well as some of the current systems that show why HSI has now moved into the art of the possible. The view is encouraging on many fronts. Several airborne sensors are already in operation and the number of spaceborne sensors continues to increase. Ground stations and software programs within those stations are maturing, and it is also clear that much thought on the military side has been developed to ensure that these ground stations maximize interoperability. This interoperability is being further enhanced by standardized formats and the proposed central database for data products. So too, the funding for HSI appears to be on the rise. The MASINT umbrella under which HSI primarily resides has strong support in our nation's legislature.

Still, other challenges remain. The primary question of "Who's in charge?" remains. This paper recommends that the Central MASINT Organization be assigned that role to ensure the services proceed with their programs, not only to ensure interoperability but also to avoid redundancy and the associated opportunity costs. Just as new organizational structures will be required, updates to joint and service intelligence doctrine will be needed as well. On paper it appears that this could be relatively simple, yet doctrine's impact on funding will likely introduce some conflict. Finally, many of the technology issues are being solved, but others continue to pose problems. Tasking, Processing, Exploitation, and Dissemination will continue to be difficult, especially as HSI is tied into the "multi-INT" arena. To avoid difficulties from stove-piped systems, integration of new systems, and the myriad tasks that go along with that integration (e.g., training), will require close scrutiny. Yet even with the challenges that await the Hyperspectral Imagery community, the future looks bright, in no matter what wavelength you are looking.

Notes

[1] Short, Nicholas M., Sr, “The Remote Sensing Tutorial,” Goddard Space Flight Center, Greenbelt MD, No date, n.p., http://rst.gsfc.nasa.gov/Front/tofc.html.

[2] Short, Nicholas M., Sr, “Other Remote Sensing Systems - Hyperspectral Imaging,” Goddard Space Flight Center, Greenbelt MD, No date, n.p., http://rst.gsfc.nasa.gov/ Intro/Part2_24.html.

[3] Commonwealth Scientific and Industrial Research Organisation, “Earth Observation, An Overview of Hyperspectral Remote Sensing,” no date, n.p., http://www.eoc.csiro.au/ hswww/Overview.htm.

[4] Short, Nicholas M., Sr, “The Remote Sensing Tutorial,” Goddard Space Flight Center, Greenbelt MD, No date, n.p., http://rst.gsfc.nasa.gov/Front/tofc.html.

[5] Ibid.

[6] Lao, N.Y., and F.C Wong, “Hyperspectral Imagery Market Forecast: 2000-2005,” Systems Engineering Division, Aerospace Corporation, Los Angeles Air Force Base, CA, Dec 2000, p.5, 13.

[7] Pirolo, David G., et al., “Hyperspectral Imagery System Roadmap (draft),” Air Force Space Command, Peterson Air Force Base, CO, no date, pp 3-4.

[8] Caudill, Dr Thomas R., Fast Fourier Transform Hyperspectral Imagery Program Manager, Space Vehicles Directorate, Air Force Research Laboratory, email, 31 Jan 02.

[9] Caudill, Dr Thomas R., Fast Fourier Transform Hyperspectral Imagery Program Manager, Space Vehicles Directorate, Air Force Research Laboratory, Interview by author, 17 December 2001.

[10] Lao, N.Y., and F.C Wong, “Hyperspectral Imagery Market Forecast: 2000-2005,” Systems Engineering Division, Aerospace Corporation, Los Angeles Air Force Base, CA, Dec 2000, p.5.

[11] “Air Force Distributed Common Ground System Measurement And Signatures Intelligence Capabilities Integration Plan,” Draft Version 8.0, HQ USAF/XOIR, Washington, D.C., 1 Oct 2001, p. 47.

[12] “Information in Hyperspectral Imagery,” Digital Imagery and Remote Sensing Laboratory, Chester F. Carlson Center for Imaging Science, Rochester Institute of Technology, Rochester, NY, http://www.cis.rit.edu/research/dirs/research/hyper_spectral.html.

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[13] "Prospecting from Space," Earth Observatory, Goddard Space Flight Center, Greenbelt MD, no date, http://earthobservatory.nasa.gov/Newsroom/NewImages/images.php3?img_id =5038. As noted at the web site, "The image on the left is true color, showing how the scene would look to our eyes. The exposed rock is fairly uniform in color, with little to distinguish specific types of minerals. The central image uses spectra from 2.0 to 2.5 µm, which are sensitive to absorption caused by molecular vibration. The image shows Hydroxide (OH), Carbonate (CO_3), and Sulfate ($S0_4$) bearing minerals. The red, orange, and mustard colored pixels in the center of the image represent different types of alunite, a sulfate mineral often associated with gold deposits. On the right is a map of minerals derived from electronic absorption features in the 0.4 to 1.2 µm spectral regions. This technique detects Ferrous (Fe 2+) and Ferric (Fe 3+) minerals—different types of iron-rich rock. Red and orange areas to the right of center in this image indicate the presence of hematite (an iron oxide) with different grain sizes."

[14] "Science," Naval EarthMap Observer, Naval Research Laboratory, Washington D.C., 1998, http://nemo.nrl.navy.mil/science.html.

[15] Davis, Dr Kurt, Naval Research Laboratory, Interview by author, 27 November 2001.

[16] "Joint Direct Attack Munitions GBU 31/32," USAF Fact Sheet, May 2001, http://www.af.mil/news/factsheets/JDAM.html.

[17] Martin, David, Captain (USN), "Hyperspectral Technology Overview," Assistant for Battlespace Environments, Office of the Under Secretary of Defense (Science and Technology), 18 February 2000, p. 9.

[18] "Hyperspectral Mine Detection," Technical Research Associates, Inc., Camarillo, CA, no date, http://www.tracam.com/hmd.htm.

[19] Snyder, Robin A., Lt Col, USAF, "The Chemical Weapons Convention Treaty: Present And Future Issues," Air War College, Air University, Maxwell Air Force Base, AL, April 1998, p. 22.

[20] National Security Space Architect website, Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics, Washington D.C., no date, http://www.acq.osd.mil/ nssa/. This role is being modified somewhat due to October 2001 direction from the Secretary of Defense. The Secretary's directive charged the Under

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Secretary of Defense for Policy to prepare the necessary documentation to make the Air Force the military's executive agent for space. This will formalize the service's role as the DOD's leader for budgeting and acquisition of space systems. With that formalized role in mind, the Rumsfeld directive also ordered an organizational change for the NSSA. Its mission will stay much the same in terms of its responsibility toward space architectures but the Rumsfeld directive also indicated that the NSSA will assist the Under Secretary of the Air Force in the assessment of the "trades between space and non-space solutions to meet user requirements as well as appropriate integration of space with land, sea, and air forces." (*Rumsfeld, Donald, "National Security and Space Management and Organization," Office of the Secretary of Defense, Washington D.C., 18 Oct 2001, pp. 3-4.*) In fact, as this paper was being written, the move to put NSSA organizationally under the Under Secretary of the Air Force was completed.

[21] The existence of this report is noted here but is not used as a source due to its classification. All sources for this paper are unclassified.

[22] "Dept of Defense Space Technology Guide, FY2000-01," Assistant Secretary of Defense (Command, Control, Communications, and Intelligence) and Director, Defense Research and Engineering, Washington, D.C., no date, pp 8-2 and 9-4.

[23] "A Space Roadmap for the 21st Century Aerospace Force Volume 1: Summary," United States Air Force Scientific Advisory Board, Washington, D.C., November 1998, p. 20.

[24] "Authorizing Appropriations For Fiscal Year 2001 For The Intelligence Activities Of The United States Government And The Central Intelligence Agency Retirement And Disability System And For Other Purposes," Senate Report 106-279, United States Senate Select Committee on Intelligence, Washington D.C., 4 May 2000, p. 17. These deficiencies include areas such as lack of funding appropriate to Congressional priorities and failures in tasking, processing, exploitation and dissemination.

[25] "The Information Edge: Imagery Intelligence and Geospatial Information in an Evolving National Security Environment," Report of the Independent Commission on the National Imagery and Mapping Agency, Dec 2000, p. 99.

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[26] "National Intelligence Support to Joint Operations," Joint Publication 2-02, Joint Staff, Washington, D.C., 28 September 1998, p. VIII-1.

[27] Pirolo, David G., et al., "Hyperspectral Imagery System Roadmap (draft)," Air Force Space Command, Peterson Air Force Base, CO, no date, p. 8.

[28] Rodriguez, Marc, Central MASINT Organization, Interview by author, 30 November 2001.

[29] Dunaway, Robert, "Spectral Operations Resource Center," Briefing, U.S. Army Space Command, Remote Sensing Branch, Colorado Springs, CO, no date, p. 3.

[30] Ibid., p. 3.

[31] Ibid., p. 6.

[32] "Space Imagery Resource Center 'Virtual Reality' for the Modern Warfighter," Naval Space Command, Dahlgren, VA, no date, http://www.navspace.navy.mil/factsheets/resic.htm.

[33] Ibid.

[34] Stout, Angel, Maj, USAF, "AC2ISRC Hyperspectral Imaging (HSI) Integrated Product Team (IPT) Charter," Aerospace, Command and Control & Intelligence, Surveillance and Reconnaissance Center, Langley AFB, VA, 10 January 2000, p. 1.

[35] Ibid., p. 1.

[36] Vtipil, Sharon D., Captain, USAF, "AC2ISRC HSI IPT General Membership Report," AC2ISRC, July 2001, p. 1.

[37] Ibid., p. 2.

[38] Pirolo, David G., et al., "Hyperspectral Imagery System Roadmap (draft)," Air Force Space Command, Peterson Air Force Base, CO, no date, pp. 20-22.

[39] Ibid., p. 20.

[40] Defense Advanced Research Projects Agency Website, http://www.darpa.mil

[41] Tousley, Brad, Lt Col, USA, "Adaptive Spectral Reconnaissance Program," Defense Advanced Research Projects Agency, 20 March 2002, http://www.darpa.mil/spo/ Programs/adaptivespectralrecon.htm.

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[42] Tousley, Bradford Lt Col, USA, "Emerging Hyperspectral Technologies -New Eyes for the Warfighter" Defense Advanced Research Projects Agency, February 18, 2000, p. 5.

[43] Ibid., p. 12.

[44] Pirolo, David G., et al., "Hyperspectral Imagery System Roadmap (draft)," Air Force Space Command, Peterson Air Force Base, CO, no date, p. 9.

[45] "Fourier Transform Hyperspectral Imager," Air Force Research Laboratory, Space Vehicles Directorate, Kirtland AFB, NM, no date.

[46] Ibid.

[47] Caudill, Dr Thomas R., Fast Fourier Transform Hyperspectral Imagery Program Manager, Space Vehicles Directorate, Air Force Research Laboratory, Kirtland AFB, NM, interview by author, 17 December 2001.

[48] Tira, Dr Nour, "Orbview 3 & 4 Capabilities, PAN, MS, and Hyperspectral," Orbimage, no date, p.5.

[49] Cooley, Dr Thomas, "Modifying a Commercial Satellite for Military Applications," *Technology Horizons*, Space Vehicles Directorate, Air Force Research Laboratory, Kirtland AFB, NM, 20 March 2002.

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Airborne Reconnaissance Office (DARO), failed and its duties were then split up among various agencies. Apparently, the services' own airborne reconnaissance cultures were too ingrained to allow fruitful oversight from a perceived outsider. Thus it would seem the window of opportunity for an umbrella organization's oversight is not open for long.

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