Abstract — This paper will discuss Space-based Hyperspectral imaging and its application to military and commercial systems. It will give a brief technical background on the basics of Hyperspectral imaging works, as well as information on current space-based projects including Warfighter 1, Naval Earth Map Observer (NEMO), and Australian Resource Information and Environmental Satellite (ARIES). The main purpose of the paper will be to look at the commercial applications of Hyperspectral Imaging including but not limited to the mining, petroleum, agricultural, and environmental monitoring sectors. By looking at these applications, we will be able to determine whether space based hyperspectral imaging is a commercially viable option and by inference whether a robust commercial HSI capability will exist to support military needs.

1.0 INTRODUCTION

In the past couple of years there has been a lot of interest from the military regarding hyperspectral imagery. The military sees this technology as a very useful tool that could help support the warfighter (e.g. mine detection, search and rescue, and gas detection). Hyperspectral imagery was first developed based on an airborne platform, and now the government as well as commercial industry, are developing this technology on space-based platforms. In the case of Warfighter 1, instead of funding an entire satellite, the military decided to place the hyperspectral Warfighter 1 payload on a commercial based satellite platform. The military will require an initial testing period where it has complete use of the spacecraft. When this is done, the commercial companies will regain control of the satellite, and then the military will have to buy data from the company like any other customer. This allows the military to accomplish what it wants HSI for, a technology demonstrator, and allows the commercial world to expand into this new technology. This paper examines those areas where hyperspectral imaging can be of value in the commercial world.

2.0 TECHNICAL BACKGROUND

Before looking at what applications hyperspectral imaging (HSI) can be used for, it is important to first understand how it works. There are five main spectrums that HSI uses and therefore different sensors are categorized by what spectrums they collect from. This section will discuss those spectrums and the three basic types of imagery; panchromatic, multispectral and hyperspectral. There are also two different methods that the spectral data is supplied to the sensor; reflective and emissive. Once all the data is collected it must be processed, whether through on-board processing or ground-based processing. The data is delivered to the customer/user in the form of a Data Cube. This section will give the basic knowledge needed to understand a HSI sensor.

2.1 FIVE MAIN SPECTRUMS

Hyperspectral imaging can be used in any wavelength of the

| Typical Hyperspectral Frequency Bands (μm) |
|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|
| VIS (.4-.7)       | VNIR (.7-1.0)     | SWIR (1.0-2.5)    | MWR (3.0-5.0)     | LWIR (7.0-13.5)   |

Figure 1: Breakdown of Spectrum
Figure 2: Comparison of Panchromatic, Multispectral and Hyperspectral imaging. Notice object is not clearly visible in panchromatic or multispectral, only in the hyperspectral image can the camouflage be detected.

2.2 BASIC PRINCIPLE

There are several types of imagers in use today; Panchromatic, Multispectral and Hyperspectral. The main difference between the three of them is the number of bands that they use. Within these bands there are two types of spectral energy that the sensor collects; reflective and emissive. Once the data is collected there are several ways to analyze the data, on-board and ground station processing. Once the data is produced the customer/user receives the information in the form of a data cube. This section describes how this is done.

2.2.1 PANCHROMATIC v. MULTISPECTRAL v. HYPERSONSPECTRAL

There is one similarity across these three systems, they all use spectral readings to produce imagery. The difference however is the number of bands of the spectrum and which wavelengths are read. With panchromatic imagery only one or two bands are used and they are located in the visible light spectrum. The use of only one or two bands results in a black and white images, and requires the presence of the sun. Multispectral imaging uses anywhere from 3 to 25 bands. This produces a multi-color image and contains more data than a panchromatic image. A satellite with a multispectral imager can be designed to gather data from all the regions; VIS, VNIR, SWIR, MWIR, and LWIR.

Hyperspectral imaging is very much like a multispectral imager except for it contains 30 to 200 spectral bands. A Hyperspectral imager can be thought of as several multispectral imagers combined into one. This allows the user to use one image from the imager for a variety of tasks, i.e. determine
plant health, determine materials on surface, and detect gases. Figure 2 shows an example of detecting a camouflaged vehicle using the three forms of imagery.

2.2.2 REFLECTIVE

When a material is exposed to solar radiation, the material absorbs certain wavelengths, the rest are reflected back into the atmosphere. Imaging in the visible and short wave infrared is accomplished through reflected sunlight. The sensor depends on the surface reflectivity and the angle between the surface, the sun, the sensor and the atmospheric transmittance. With these bands of spectral data one can view vegetation, surface materials and non-silicate minerals. [2] The technologies and methodologies to support HSI in the reflective spectral region are in large part an extension of current remote sensing applications.

2.2.3 EMISSIVE

Some materials radiate certain wavelengths into the atmosphere. Imaging in the medium and long wave infrared is accomplished by emissive energy from the radiated wavelengths. The sensor depends on the surface temperature, emissivity, atmospheric radiance and transmittance. The technologies and methodologies for this spectral region are still in the early stages of development.

2.3 ANALYSIS METHODS

The end product of a HSI image is know as a data cube. This is a three dimensional image that contains a XY coordinate plane that covers the area of the collect. On the Z-axis are the different layers collected by the imager, each layer corresponding to a spectral band. The layers can be looked at individually, but are most often combined with other layers and given false colors to display the location of the desired material. (Figure 3) A data cube can only be viewed using a computer program, however once the layers have been chosen the image can be printed out.

With a space-based HSI system there are several methods of producing the data cube. One of the methods is to do the data processing on-board the satellite. The amount of raw data produced for a 50km by 50km area with 200 spectral bands and a GSD of 2m is approximately 32 Tbits. This is an extremely large file that would have to be downloaded to a ground station. If the processing could be done on-board so that the satellite downloads the data cube, approximately 6 Mbytes, the downlink time would be greatly reduced. However, by having an on-board processor several concerns come up. Every pound you add to a satellite costs money, and satellites require a redundant system so in the case one processor fails there is a back up. Similarly the processors will not be upgradable, being a new technology, the algorithms used in processing are always improving. Having the hardware on-board limits expandability of the system by placing constraints on the algorithms.

To solve the problems with on-board processing one can store the raw data and when passing over a ground station, download the raw data. This reduces the cost of the satellite by limiting the amount of processing done on-board. However, since the file has not been processed it will take considerably longer to download to a ground station. The good thing about having the data processed on the ground is the new algorithms can be applied to the raw data with ease.

Another method that is in development now is having the satellite "filter" out the spectral data that are not needed (i.e. mineral signatures in images taken over water). This reduces the size of the file and allows it to be processed on the ground by new algorithms.

3.0 CURRENT PROJECTS

Hyperspectral imaging has many different commercial uses. Currently a majority of the imaging is done off of an airborne platform. There are plans for commercial space-based sensors, however the satellite's launch dates have been pushed back because of a lack of funding.

3.1 SPACE-BASED

There are currently three satellites in development that will have a HSI imager on board that can be used for commercial applications. Two of them are partially funded by the United States military as technology demonstrations. These satellites are Warfighter 1 and NEMO. The military is planning to use these satellites as a technology demonstrator and after tests are complete, turn them over to the commercial companies. The third satellite is the ARIES satellite being developed by AUSPACE for use by the Australian government and commercial sponsors of the project.

3.1.1 WARFIGHTER 1/ORBVIEW 4

Northrop Grumman Space Systems is developing the Warfighter 1 payload for Orbimage's Orbview 4. Orbview 4 is an exact copy of Orbview 3 except for the addition of Warfighter 1. It is a joint program led by Air Force Research...
Figure 4: NEMO satellite broadcasting a hyperspectral image cube from a 30 km wide swath of Florida's coastline. [3a]

Laboratory (AFRL) to demonstrate emerging HSI technologies to address Air Force Space Command (AFSPC), Air Combat Command (ACC), and Army mission requirements.

An array of imaging sensors will be carried aboard the Orbview-4 remote sensing spacecraft into a sun-synchronous circular orbit at an altitude of 470 km. The expected launch date is Summer 2001.

The satellite will have three different payloads, the first being a Panchromatic imager with a 1m Ground Sample Distance (GSD), the second a multispectral imager with a 4m GSD. The final payload will be the hyperspectral imager with an 8m GSD [3].

3.1.2 NEMO

The Space Applications International Corporation (SAIC) is designing the Naval Earth Map Observer satellite (NEMO) (Figure 4) for the Space Technology Development Corporation (STDC) part of the Naval Research Labs (NRL). NEMO will demonstrate the utility of a multi-wavelength Earth-imaging system to support Naval needs for characterization of the littoral regions of the world. (i.e. water and coastline areas within 50km from shore) [3]. The Coastal Ocean Imaging Spectrometer (COIS), the HSI sensor on NEMO, will have 200 spectral bands ranging between 0.4µm and 2.5µm. The collected area will be 30 km wide with a GSD of 60m, this can be reduced to 30 m using a hod’ (a satellite maneuver using the pitch to slow down the track of the field of view). NEMO will be in a 600km sun-synchronous orbit with a 7-day revisit time, covering 1 million square kilometers of total land [4]. NEMO will employ the Optical Real-Time Spectral Identification System (ORASIS) which employs a parallel, adaptive hyperspectral method for real-time scene characterization, data reduction, background suppression and target recognition. The use of ORASIS is essential for management of the large amount of data produced by the collect. The Navy will contribute half of the approximate $125 million in total development costs for NEMO.

3.1.3 ARIES

Australian Resource Information and Environmental Satellite (ARIES-1) is an Australian-initiated, Earth Observation project, to build, launch and operate a small satellite. ARIES-1 will provide continuing global resources information to commercial and government users, using a sophisticated imaging spectrometer. Because ARIES is a commercial venture, it must manage its commercial and technical risk. The satellite platform thus will be procured overseas and the launch will be from the most appropriate country. The all-important imaging spectrometer will be designed and fabricated in Australia. The operating company, satellite management, data archiving and marketing will be Australian.

The resolution of the ARIES hyperspectral imager will be 30 by 30m beneath the spacecraft's track. This will increase when viewing sideways. A panchromatic imager capable of 10m resolution will augment the hyperspectral imager. Using “unmixing” software, ARIES will be able to map areas of materials that have defined spectral signatures smaller than 30m. In simulations, targets as small as 10% of a pixel have been located. ARIES will have 105 spectral bands spread across the VIS, VRIR and SWIR spectrum (0.4 to 2.5µm) [5].

ARIES data will be recorded and archived at a number of ground-stations around the world, including Australia. ARIES products and services will be able to be viewed and ordered from a single catalogue using the Internet.

ARIES was scheduled for launch in the summer of 2000, the current status of the satellite is unknown.

3.2 AIR-BASED

The majority of the current HSI systems are airborne-based platforms. This section describes three systems being developed to support military applications; HYDICE, SEBASS, and Probe 1. Along with utilizing space-based sensors the military plans to place sensors on Unmanned Ariel Vehicles (UAVs) for use in areas where hostilities exist.

3.2.1 HYDICE

Hyperspectral Digital Imagery Collection Experiment (HYDICE) was developed by the Naval Research Laboratory (NRL), it operates in the reflective VIS/SWIR spectral regions. The imager is flown on a Convair 580 aircraft and is used to collect HSI data for targets of military and strategic value needed to specify future space system and processing requirements.

HYDICE covers the spectral range from 0.4 – 2.5 µm, with an average spectral resolution of 10.2nm. At a design altitude of 6 km, spatial resolution is 3 m over a 936m swath.
One of the unique features of HYDICE is its dispersing element: a Schmidt double-pass biprism spectrometer. This spectrometer allows imaging over a continuous spectral range rather than separation of the range into discrete channels. Collimated light from the entrance slit is dispersed using a prism doublet, then focused onto the detector. The single detector is designed to cover the full spectrum range of the instrument, and combined with the dispersing element, allows HYDICE to use a single optical path design. [6]

3.2.2 SEBASS

SEBASS is an LWIR/MWIR imaging hyperspectral sensor for airborne remote sensing. The instrument, the Spatially Enhanced Broadband Array Spectrograph System (SEBASS), is intended to explore the utility of hyperspectral infrared sensors for remotely identifying solids, liquids, gases and chemical vapors in the 2μm to 14μm "chemical fingerprint" spectral region. It uses two spherical-faced prisms to operate simultaneously in the two atmospheric transmission windows, 2.0 to 5.2μm and 7.8 to 13.4μm.

SEBASS was deployed in the Joint Expeditionary Force Experiment (JEFX2000) this summer to demonstrate the utility of hyperspectral imaging systems in complex environments of simulated battle conditions involving weapons of mass destruction. SEBASS was applied to the detection of concealed, camouflaged, or deceptive targets; warning of chemical weapons attack; friend-or-foe identification; and detection of land mines.

3.2.3 PROBE-1

Earth Search Sciences Inc. (ESSI) is involved in the HSI spectrometer on the NEMO satellite, to augment its planned space-based services it uses the airborne Probe-1 Sensor (Figure 5). When an HSI imager has a longer collect time the resolution of the data increases, so by placing a collector on a slow, low flying plane ESSI is able to adjust the resolution of the image to what is needed. The resolution of the Probe-1 sensor can vary from 1m to 10m, however this resolution change affects the swath width from <1km to 6km respectively. This sensor can be flown on a variety of platforms including helicopters and Boeing's Heliocourier. The sensor weighs 400 pounds and collects 128 bands in the visible and SWIR spectrums by using four spectrometers and four lineal focal plan arrays covering the 0.4 to 2.5μm wavelength region.

3.2.4 UAV's

There are currently two Unmanned Ariel Vehicles (UAVs) which the military plans to equip with HSI sensors, the Predator and the Global Hawk UAVs. The predator is an existing UAV designed to operate over 24 hours on station with a 500 nautical mile range at up to 26,000 ft of altitude [2]. Currently Predator carries Electro-optical (EO), Infrared (IR), and synthetic aperture radar (SAR) sensors, with the addition of HSI to this platform, the Predator will be able to provide scene commanders with very valuable information. The Global Hawk (Tier II+) UAV is a high altitude, long-endurance UAV that will operate over 24 hours on station with a 300 nautical mile range at altitudes greater than 60,000 ft. The Global Hawk also carries the same type of sensors that the Predator carries.

4.0 GOVERNMENT APPLICATIONS

The most interest in hyperspectral imaging has been from the government, especially the military. The government is interested both in the space-based and airborne platforms, which indicates why most of the development of HSI has been at least partially if not fully funded by the government.

4.1 MILITARY APPLICATIONS

In the near future most of the use of space-based HSI will be the military. The military has several plans to use HSI for Nuclear/Biological/Chemical (NBC) detection, and battlefield reconnaissance. With HSI, the military will be able to detect if a foreign government is producing nuclear, biological, or chemical weapons by the bi-products emitted into the air from factories. This allows the military to determine if someone like Saddam Hussien is violating the UN peace treaty, without placing inspection teams in harms way.

While NBC detection is an important mission for the military, most of the HSI use will be in battlefield reconnaissance. Within battlefield reconnaissance there are several different categories including; target identification, mine detection, and search and rescue. HSI is crucial in the detection of targets under camouflage or hidden under natural objects such as trees. Panchromatic imagery is very easy to fool, by placing similar shaped objects under camouflage, however with HSI the mission planners will be able to tell if the object under the camouflage is an actual tank, or just a wooden decoy. Several times during operation 'Just Cause' (The conflict with Serbia over the occupation of Kosovo) wooden tanks were targeted and destroyed, wasting resources, because the reconnaissance of those images were inconclusive that they contained tanks.

HSI will also be able to detect mines in a field (Figure 6), before friendly forces arrive it does this by detecting not only...
the difference in materials in the ground, but also the disturbance of the ground. Because of the way the ground reflects waves in the VIS, VNIR and SWIR, hyperspectral imagers are able to determine when the soil has been disturbed.

One problem facing the military these days is the rescue of downed pilots or lost soldiers. When a pilot goes down he must evade enemy capture while keeping in contact with the rescue forces. When it comes time for the rescue the pilot must signal his position to the rescue party, however sometimes this can signal the attention of the enemy as well. Imagine a pilot taking a powder that blended in well with the surroundings, pouring it out in a pattern so the rescue team would know the exact location without any visible change to the environment. A hyperspectral imager could take an image of that area and look for the materials contained in that powder. Once found the rescue party would know exactly where the pilot was and the enemy would have no clue the signal had been set.

4.2 CIVIL APPLICATIONS

Although the military would be the prime government user of space-based HSI, many civilian agencies could use the technology. Three civilian agencies, EPA, NASA and ATF, are interested in HSI.

The Environmental Protection Agency (EPA) is constantly monitoring industry to ensure that they are not letting known toxins into the environment. Sending a team to each plant or mine for an inspection is the current method, but if the EPA could consistently monitor factories and mines, it would allow better enforcement of the environmental laws. Another use of HSI is monitoring the amount of air pollution over the larger metropolitan cities.

To aid NASA with their planet exploration, HSI sensors have been added to their deep space and Mars explorer satellites. This allows NASA to determine what the surface of planets are composed of, helping them analyze the planet. One problem encountered is the atmospheric interference of earth is different than that of Mars or any other planet.

In the war against drugs in America, the ATF could use HSI to seek out where illegal crops of drugs are being grown in America. An airborne sensor could do this locally, however if they wanted to move operations into South America, airspace would be restricted, so the use of space-based HSI would be imperative. The ATF could use SB-HSI to find the major crops of illegal drugs and then monitor them and watch for shipments, enabling them to intercept the drugs before entering the US.

5.0 COMMERCIAL APPLICATIONS

Since hyperspectral imagery is a relatively new technology, not many commercial companies show a deep interest in it. This is also seen when looking at remote sensing in general, that market is just starting to show promise in commercial applications. The three big industries that will benefit the most from HSI are; mining and mineral exploration, petroleum and agricultural industries.

5.1 MINING INDUSTRIES

Mining companies will probably benefit the most from HSI because of the large areas of land to be searched, the relative ease of detection and the larger than normal budgets for exploration. Noranda Mining, a Canadian based company, is one of the first to use HSI for mineral exploration. It employs the services of Earth Search Sciences Inc. (ESSI) with its Integrated Spectronics HyMap system flying the Probe 1 sensor.

Mineral exploration is possible through HSI by using the long-wave spectrum to locate certain surface crystalline structures. (Figure 7) These structures, which are exposed to HSI sensors by ground erosion, indicate the presence of mineral or ore deposits.

Currently mining companies require approximately two years of land surveying to assess plots. HSI will allow companies to focus these surveys to areas where minerals are suspected. HSI will also help because many of the areas of exploration are in remote locations, and the use of space-based HSI sensors will make it even easier than airborne sensors.

A possible concern with HSI is the current restriction on resolution of data and images that commercial companies can purchase. The government limits Warfighter 1 to allow only raw data of 24m resolution and 8 meter processed images to be purchase by commercial companies. Mining companies will want to purchase the 8m raw data so that their own experts can analyze it using experience gained in previous mineral explorations.
Another concern is the demand of space-based HSI systems by mining companies. The revisit time required by the companies is considerably larger than that of say the agricultural industry (discussed later on). The reason for this is that geological features do not change very rapidly, making it a waste of resources to keep viewing the same areas. The minimal use of a space-based sensor would make it difficult for an imaging company to rely on mining as a prime customer.

Noranda Mining tends to only use HSI to survey an area that has already shown prospect using traditional methods. Traditional methods involve sending a geologist to collect “tiret bags” at selected points. This can be done for about $100 to $500 per square kilometer. Airborne HSI sensors can be leased for around $100k per week. Noranda imaged an area in Mexico of roughly 40,000sq km in four weeks [7]. Using these numbers, HSI imaging is approximately $10 per square km, but this is only for the imaging. Some other costs that aren't included in that number are the cost of processing the data, fuel for the aircraft and other unknown expenses.

5.2 Petroleum Industries

Although currently HSI has not been used by petroleum companies specifically for oil and gas exploration, there is still applications for HSI in petroleum. Oil and Gas deposits do not have the same surface markers that minerals do. Until these markers are better understood the use of HSI will not be used for oil and gas exploration. However Texaco and Chevron use HSI for environmental monitoring, which is a big problem facing petroleum companies. Texaco uses TEEMS (Texaco Energy and Environmental Multispectral Imaging Spectrometer) to survey it's sites, to monitor the plant life and to identify any changes to the surrounding areas. This has proven useful in many cases; one in particular is a legal case from Equador. The Equatorian government was suing Texaco for $500 million claiming that Texaco was causing excessive damage to a rainforest surrounding a road to one of their sites. Through the use of archived TEEMS data, Texaco was able to prove that the damage to the rainforest was not from them, in fact they were not even using that road. The case was dropped shortly thereafter.

ESSI believes that HSI will soon be able to assist petroleum companies in oil detection. Through the use of geographical maps, combined with hyperspectral data on oil microseepage, one can determine where possible oil reservoirs might be. (Figure 8) Earth Search Sciences Inc. recently announced plans to exercise this technique on the Found Soldier area project, Green River-Hanna Basin area, Central Wyoming.

5.3 Agriculture

The agriculture industry is one of areas where hyperspectral imagery could prove to be a very useful application. Such applications include; detection of crop water stress, nitrogen deficiency, stand density, soil moisture, weed and insect infestations. Combine these applications to precision farming and crop yields would increase and production cost would notably decrease (Figure 9).

There are several issues that make the use of HSI a concern for commercial agriculture. The first being the cost, to make HSI an appealing venture, the profits must outweigh the costs. Farmers are not going to want to pay several thousand dollars per image. The next issue is revisit time and processing time. For HSI to be useful the revisit time should be once every three days or so. This is because the farmer must see how his crop is changing through out the season, so that he may adjust how much water to add to a section, or to add more pesticide to an area. A revisit time of three days also requires that the data processing must be done in a 24hr period, because if the data is three or four days old then it might already be to late to combat the changes seen in the crop. The data given to the farmer must be completely processed so that they can determine by themselves what is happening, or an easy to use software program that will assist the farmer in the analysis must be provided by the imagining company.

Figure 8: Left: Probe-1 HSI providing geologic mapping of outcrop lithology and surface structure. Right: HSI used to identify subtle features due to topographic offset, vegetation change and/or soil alteration [3a]
Another concern is the resolution of the image, for example, pest infestation might require 1m resolution but irrigation might only require 10 to 20m resolution. In this example, it would be better to use an airborne system because you can vary the resolution by varying the elevation at which the instrument collects.

6.0 CONCLUSIONS

When looking at all the applications that HSI can be used for, one question comes up: is there a need of space-based HSI? For the government the answer is yes, because a majority of the areas of interest are in sensitive airspace. The military would like to use an HSI sensor for recon of potential targets or current hot spots around the globe. On the civilian side of the government, the EPA would like to collect information on remote areas of the globe, but it might be cost effective to send an airborne sensor.

The problem is that a majority of the commercial applications do not require the use of a space-based system. For example, the agriculture industry might not even have a use for a space-based system because of the revisit time and the resolution that a satellite could produce. It is my conclusion that the commercial industries, with the possible exception of mining, do not have a use for a space-based system for now. Until the resolution of a space-based system increases, most customers to HSI will be the government, both civil and military.

7.0 RECOMMENDATIONS

When the Global Positioning System (GPS) was first introduced as a project, many people thought that there would be very little use for it, especially on the commercial side. Today GPS is everywhere; fishermen using it to find predicted quality fishing areas, farmers using it in precision farming, and everyday people using it in their cars to get from one place to the next.

The same situation applies to remote sensing, it is just now getting a strong showing from commercial industry. I believe that space-based HSI will eventually become a very valuable resource to commercial companies. However, the technology is new and not many people know of its capabilities. It is my recommendation that the government continues to invest in advancing the technology, and eventually the resolution and cost will become appealing to commercial industries.

8.0 REFERENCES


8.1 IMAGES


Figure 9: Three images showing the growth of a field over a three-month period [6a].


9.0 BIBLIOGRAPHY

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