WIDEBAND HYPERSPECTRAL IMAGING FOR SPACE SITUATIONAL AWARENESS

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ABSTRACT

Wideband hyperspectral imaging (WHSI) systems simultaneously collect spectral and spatial imagery across a broad spectrum that includes the visible/near infrared (VNIR), short-wave infrared (SWIR), mid-wave infrared (MWIR), and long-wave infrared (LWIR) regimes. These passive optical systems capture reflected sunlight and thermal emissions from targets enabling the characterization of surface material, thermal properties, propellants, and gaseous emissions when targets are sunlit or in shadow. WHSI systems can provide imagery with fine spatial detail but do not require this fine spatial resolution to characterize targets.

It has been shown previously that multi-color photometry using distinct channels in the VNIR part of the spectrum can be used to distinguish objects that are similar to one another and perform some non-resolved object characterization (NROC). Wideband HSI systems collect a much richer signature from each object with the potential to fingerprint and identify specific space objects smaller than one pixel.

WHSI provides unique information on the properties of space objects. Its ability to characterize objects smaller than a pixel is extremely valuable in developing situational awareness of targets at GEO, MEO, and HEO. WHSI can be deployed with cost-efficient, small aperture telescopes or be used as adjuncts to existing and planned assets. This paper will describe the utility and capabilities of ground-based and space-based WHSI systems including rapid identification and characterization of space objects, mitigation of interference from the atmosphere, separation of glints from diffuse signatures, determination of status of space objects, and gauging aging effects.

1.0 INTRODUCTION

Hyperspectral imaging (HSI) has been successfully utilized by Raytheon and others for more than 20 years in a broad range of military and civil applications. HSI systems are passive optical systems that collect spectral and spatial signatures of targets. These signatures are unique to the material and chemical properties of targets. HSI sensors provide unique information to characterize target properties and status without requiring fine spatial resolution; and can even provide significant information when the target is smaller than one spatial pixel. As such, they can address Space Control missions when fielded in conjunction with existing and planned ground-based and low earth orbiting (LEO) telescopes to provide new dimensions of data to characterize both LEO and geosynchronous (GEO) targets. The rich, high dimensionality signatures obtained by hyperspectral sensors can also be used to monitor status and changes in targets as well as to support model-based retrieval of space system configuration and properties.

A number of airborne and space-based down-looking HSI systems have been fielded that detect target signatures resulting from the reflection of sunlight. These sensors operate in the visible (VIS, the region that human eyes detect), near-infrared (NIR), and/or short-wave infrared (SWIR) portions of the optical spectrum. A limited number of HSI sensors have been built that collect the emitted mid-wave infrared (MWIR) and long wave infrared (LWIR) spectral signatures from targets. These sensors operate day or night, provide thermal properties of targets, and are often used for identification of gaseous targets. Emitted signatures are a function of the target's temperature(s) and material properties.

At the 2005 AMOS conference [1] and [2] each reported results using a (non-imaging) spectrometer coupled to the Advanced Electro-Optical System (AEOS). The sensor discussed in [1] spanned the VNIR/SWIR part of the spectrum and the sensor described by [2] collected signals in the MWIR and LWIR. Recently deployed remote sensing systems such as NASA's MODIS and ASTER programs collect imagery in multiple spectral bands spanning the reflective and emissive domains, combining these data to better characterize objects and natural features including removal of the effects of the atmosphere.

This paper describes the detailed information content of wideband HSI (WHSI) data in Section 2.0. Section 3.0 presents the utility of wideband HSI systems for space control missions when high-resolution spatial detail can be collected as well as when only spectral data can be collected. Section 4.0 contains a summary and conclusions.

2.0 WIDE BAND HYPERSPECTRAL IMAGING

Wideband hyperspectral imaging systems simultaneously collect spectral and spatial imagery across a broad spectrum that includes the visible/near infrared (VNIR), short-wave infrared (SWIR), mid-wave infrared (MWIR), and long-wave infrared (LWIR) regimes. These passive optical systems capture reflected sunlight and thermal emissions from targets enabling the characterization of surface material, thermal properties, propellants, and gaseous emissions when targets are sunlit or in shadow. WHSI systems can provide imagery with fine spatial detail but do not require this fine spatial resolution to characterize targets.

Fig. 1 shows the wavelengths spanned by theses different optical spectral regimes. Each regime offers a different view of target properties. Sensors operating in the SWIR and LWIR have the greatest ability to distinguish unique chemical and material spectral properties. Diffraction effects reduce the available spatial resolution in those spectral regimes compared with shorter wavelength regions. Fig. 2 summarizes useful features of data collected in the different spectral regimes. These data can be used standalone or fused with one or more of the other regimes to provide useful information for characterizing targets.

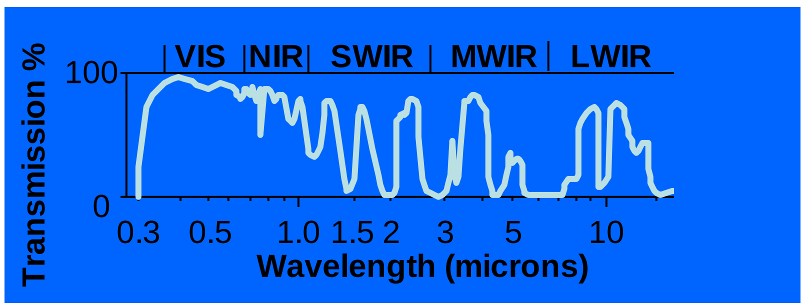

Fig. 1: Transmission of Target Spectra

	VNIR	SWIR	MWIR	LWIR
Material Identification				
Aging Effects	Fused Product		?	?
Engine Plumes				
High Spatial Resolution				
Night Operation				
Thermal/Power			Fused Product	
Atmospheric Correction	Fused Product			
Target Fingerprint	Fused Product			
Model Based Retrieval	Fused Product			

	Significant Capability
	Good Capability
	Some Capability
	No Capability
?	Unknown

Fig. 2: Transmission of Target Spectra

A WHSI system is a spectrometer that collects the combined spectral data of the systems described in [1] and [2] and an imaging system. An entire wideband spectrum of information is collected at each spatial element. It can be configured so that spectra are collected over a very wide field of view (FOV) simultaneously seeing many targets. In such a configuration there is little or no spatial data collected on targets. However, the broad spectral coverage is well suited to perform non-resolved object characterization (NROC).

Alternatively, WHSI can be set up for high-resolution imaging so that spectra are collected on many parts of a target. In this mode a detailed study of a target or small cluster of targets can be made. This mode would be best for assessing the capabilities of a new foreign launch. In both modes it is possible to simultaneously collect data on targets, the atmospheric path, and celestial objects that can aid calibration (e.g. stars).

3.0 UTILITY OF WHSI FOR SPACE SITUATIONAL AWARENESS

There is an increasing urgency that the United States have the capability to find, fix, track, and identify space objects in a timely manner. To support global operations, as well as a counterspace capability, it is necessary to characterize the capabilities, status, degradations, and vulnerabilities of foreign satellites. General Chilton, the CINC AFSPACE, was recently quoted in [3] that we "should be focused more on what is that thing up in orbit and what is its intent?"

Under Chilton's vision for developing space assets, the new chief of STRATCOM's Joint Functional Component Command-Space would be able to report to the STRATCOM chief on the capability and intentions of any new objects launched into space during their first orbit around the Earth -- a task that can now take a week, a month or sometimes up to a year. He summarized the need succinctly "I want to know what it is. I want to know what its capabilities are".

There are several methods of characterizing space systems. The most widely used method is to collect imagery of satellites. Fine spatial resolution imagery can be obtained with telescopes, on the ground or in space, that have very large apertures or are very close to the targets. Such systems are expensive and may not provide resolved imagery for satellites in very high orbits (such as GEO). If they must operate very close to the target it may not be possible to collect data on other targets in a timely manner. Employing WHSI or other hyperspectral sensors enables the use of telescopes of modest size to collect critical data at long range.

Traditional image analysis relies on humans or machines to interpret the shape and/or texture of gray-scale or color pictures to provide insight into a target. To provide data to characterize targets standard imagery must be collected with a pixel size having an extent much smaller than features of interest on the target. In contrast, a WHSI sensor collects a richer set of data that includes the spatial detail of the target as well as a full spectrum of data for each pixel. Machines routinely process HSI data, either autonomously or as an aid for human interpretation.

Spectral data and high spatial resolution image data are complementary. The utility of both types of data to characterize satellites and their payloads are described by one of us (Robinson) in [4]. Even with infinite levels of spatial resolution it can be difficult or impossible to identify satellite features and characteristics using a panchromatic image.

Fig. 3 (left side) shows a simulation of a satellite in gray scale at extremely high spatial resolution. Several distinct features can be discerned. Using a WHSI sensor to collect data on this target there is a spectrum of information at every pixel. Using the spectra we can determine which surfaces are similar to one another and where there are distinct boundaries (Fig. 3, right panel), we can compare measurements to libraries of spectra to identify the surface material composition and possible the age of the materials. We can assess where power is being dissipated on a satellite and make estimates of volumetric features by observing the satellite crossing the terminator. The MWIR and LWIR spectral bands of a WHSI system enable information to be collected when the target is in shadow or at unfavorable illumination (solar phase) angles. Data collected in the VNIR/SWIR regime on illuminated facets of a target can be correlated with the simultaneous MWIR/LWIR data and then be compared with MWIR/LWIR data of obscured or non-illuminated facets for refined surface characterization.

Imaging mode

Even using large telescopes such as AEOS there are limits to the amount of spatial detail that can be obtained on orbiting targets. Fig. 4. depicts a notional view of a NASA TDRSS (GEO) satellite from AEOS. The blue boxes on the left panel represent the size of a diffraction-limited pixel using a VNIR or panchromatic (PAN) sensor. The right panel shows an oversampled, pixelized image. The latter is barely recognizable as a satellite despite the fact that the two parabolic dishes on TDRSS each span 16 meters. Yet, using the spectral information provided by a WHSI sensor it is possible to identify and distinguish mesh antennas, phased array antennas, bus structure, star sensors, solar panels, etc. and to monitor changes in these components.

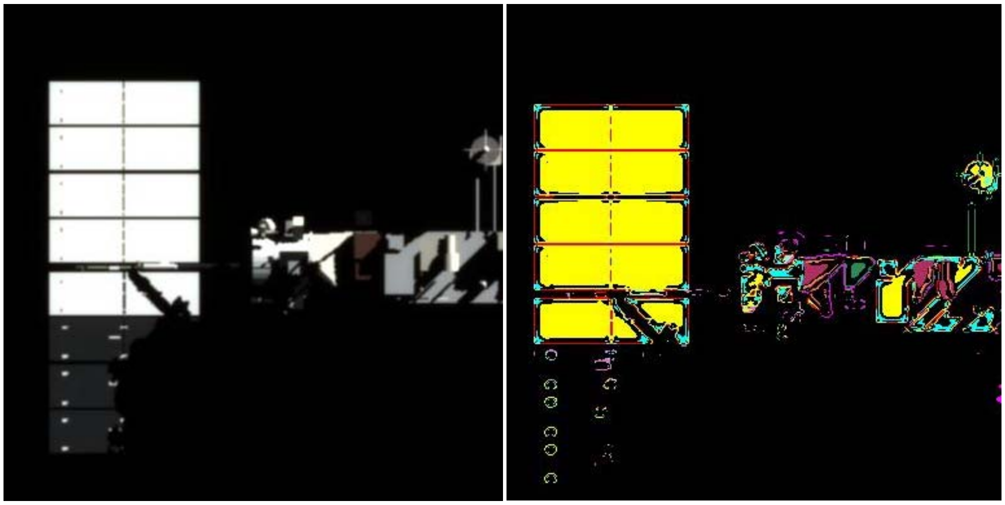

Fig. 3: Simulated Gray Scale Image (left), Surface Classification (Right)

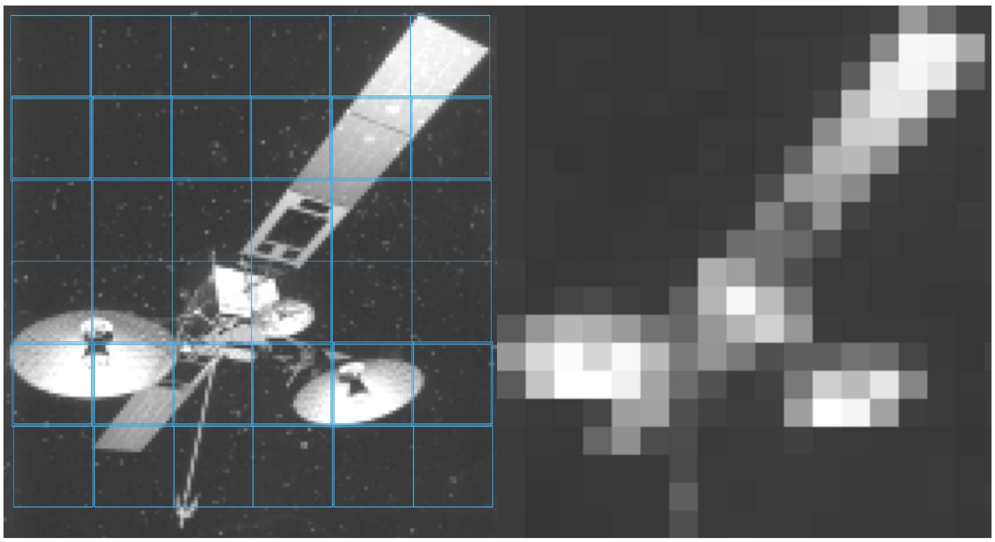

Fig. 4: Notional Pixel Sizes for VNIR Collection of TDRSS

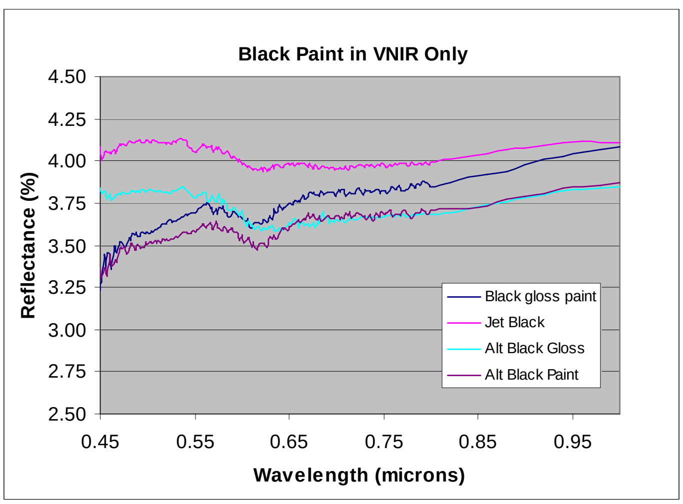

Fig. 5: Paint Reflectance in VNIR (note scale)

Figs. 5 and 6, respectively, illustrate an example of the power of collecting a full spectrum on a target. Fig. 5 shows the spectra of several black paints whose reflectance is constant within 0.6% in the VNIR regime. Fig. 6 shows they are easily separated using the other spectral regimes of a WHSI sensor. The differences are not simply academic. If we want to build a model of the target satellite including estimates of power generation (which could be quite important to assessing capabilities such as communications capacity or jamming potential) then it is necessary to know the reflectance of the surfaces on the target. It is also potentially important for distinguishing distinct surfaces that likely correlate to different boxes and functions on the target.

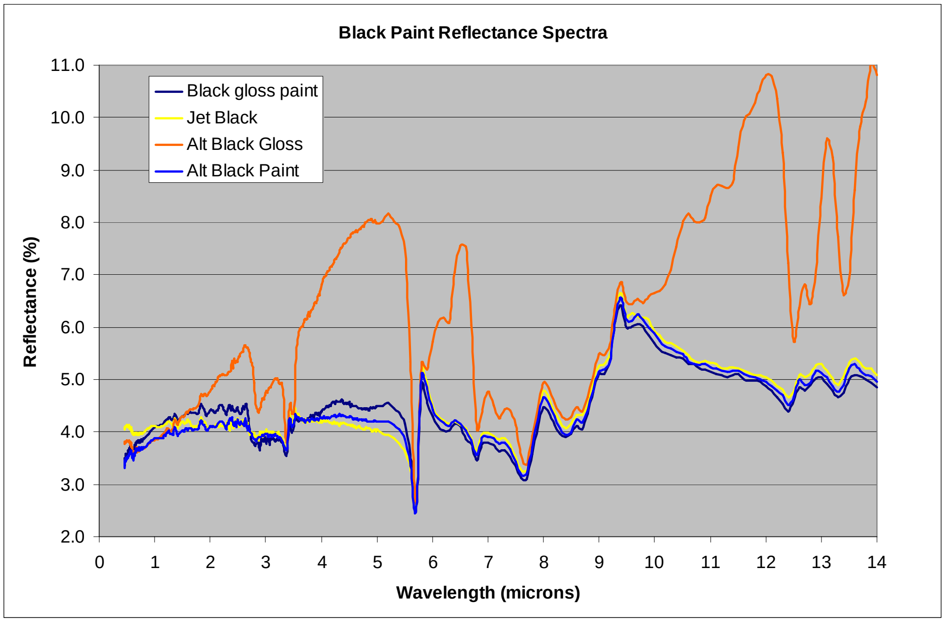

Fig. 6: WHSI Paint Reflectance

Reference [5] describes the use of VNIR spectra for monitoring space material aging. It may be possible to refine this characterization using fusing data in the VNIR with other WHSI data as the reflectances in the other regimes are not expected to diminish and shift as they do in the VNIR. Often there are clusters of similar spacecraft at a single longitude in GEO orbit. The combination of aging signatures and power/thermal curves derived from the WHSI MWIR/LWIR data have the potential to enable rapid identification of older and newer models of the same space system. The WHSI data also has the potential to differentiate specular (glint) reflections from surfaces that diffusely reflect light. The LWIR data and possibly the MWIR spectra will be provide material properties independent of the glint. The entire spectrum provides insight into the size and smoothness of the glinty surface.

NROC mode

A WHSI sensor can operate both as a detailed spatial/spectral sensor and in a mode where the target is one pixel or smaller. Fig. 7 is reproduced from Ref [6], presented at the 2005 AMOS conference, which describes the many space control missions that can be performed using Non-resolved Object Characterization (NROC).

References [7] and [8] describe examples of mission performance and utility using existing NROC sensors. Ref 7 describes separation of rocket bodies from satellites using VNIR spectra and Ref [8] multi-color photometry to distinguish similar satellite systems. These NROC systems collect signatures that reveal some material properties of targets to provide their results but a WHSI sensor can provide far greater amounts of detail on material properties, separate similar facets/materials, assess generation and use of power on the system, and to interpret the significance in changes in signature.

The combination of spectral regimes collected by a WHSI sensor enables separation of changes due to total surface area, total illuminated area, and total amount of the viewable materials facing the sensor. These data will enable analyst to distinguish differences between a target changing orientation and a similar signature change that occurs from deploying or moving an appendage.   Other NROC sensors are unlikely to provide unambiguous data to resolve such on-orbit changes.

			Suitability		
SC#	SC Name	Function (space-looking, not terrestrial except for SC04)	Suitable for Other collection techniques	Suitable for NROC collection techniques	NROC best suited over other techniques
1	Monitor and Analyze Natural Environment	Forecast space weather			
2	Maintain General Space Population	Search for all objects			
		Track all space objects			
		Type objects		■	■
		Correlate & differentiate objects		■	■
3	Maintain Small Space Population	Add very small objects			
4	Maintain Terrestrial Space Asset Data	Locate terrestrial space-related objects			
5	Detect and Process Space Events	Quickly detect and process status changes		■	■
6	Provide Precision Position Data	Generate precision orbit on satellites of interest	■		
7	Analyze Space System Properties	Routinely collect spacecraft physical features	■	■	
		Routinely categorize spacecraft properties & physical configuration	■	■	
8	Analyze Space System Functions	Routinely collect payload features & mission characteristics	■	■	
		Routinely categorize payload functions	■		
9	Analyze Space System Users and Networks	Routinely collect spacecraft/payload activity	■		
		Routinely categorize spacecraft/payload uses	■		
10	Analyze Space Systems for Rapid Response	Quickly detect changes to properties & physical configuration	■	■	■
		Quickly detect changes to functions	■	■	
		Quickly detect changes to uses	■	■	
11	Determine Status of Cooperative Space Forces	Overlay cooperative spacecraft/payload information			
12	Provide Anomaly/ Attack Data	Quickly process anomalies to determine causes	■		
13	Provide SSA Information Services	Produce conjunction assessment, RFI/laser deconfliction, reentry assessment, etc. for users. Produce services (CA, LCH, RA, etc.)			
14	Determine Non-Cooperative Strategies / Tactics	Fuse info for SSA			
15	Integrate and Disseminate SSA Data	Disseminate data & information			

Fig. 7: Space Control Missions That Can be Addressed With NROC Sensors

It is particularly useful to collect WHSI data with very detailed optical or radar imagery. This enables the development and refinement of target models. These models aid in the assessment of the capabilities and intentions of foreign satellites and aid in the interpretation of changes of WHSI signatures.

4.0 SUMMARY AND CONCLUSIONS

WHSI can provide unique spatial/spectral data for target characterization as well as unique NROC data. Ground-based laboratory and field measurements of known materials and space systems can be used to build a database of signatures to interpret stand-alone WHSI data and to correlate WHSI data with other collections, especially literal and radar imagery. NASA has already compiled a significant database in the VNIR/SWIR regimes [5]. Measurements in the MWIR and LWIR regimes of many man-made materials are available from other government organizations.

WHSI spectral imagery that is correlated with a spectral database or library can provide significant information on the composition and layout of potential threats. Correlating the resolved and non-resolved WHSI data with high-resolution images will enable development of models of potential threats and interpretation of the significance of changes in spectral signature.

WHSI data can be used to rapidly determine new or changed space-related object deployments (e.g. appendages), configurations, object types, and to differentiate similar systems in the same orbit. WHSI provides information on the composition and layout of satellites and their power generation and usage.

Space Command has identified NROC sensors as highly desirable tools for SSA. NROC sensors are desirable because they can be fielded with small aperture, passive optical systems to collect useful and unique target data to distinguish and identify targets. Wideband HSI provides a significant advance in the capability to "fingerprint" non-resolved (e.g. GEO) objects, interpret changes in signature, and cue imaging and other assets in a timely fashion.

WHSI systems deployed with ground-based telescopes and/or with planned or future space assets can provide a timely and affordable piece of Space Control mission capability. WHSI can be inserted into future blocks of the space-based surveillance assets (e.g. SBSS) to rapidly distinguish one space object from another and to characterize objects that are smaller than one pixel (using NROC). WHSI would be a useful insertion into a space-based imaging system (e.g. ODSI) or similar architecture to provide unique capability to identify and characterize material and chemical properties of orbital objects. It can also be inserted into dedicated or collateral ground-based sensors of the Space Surveillance Network (SSN) to improve characterization of both resolved and unresolved objects.

Raytheon can provide an existing WHSI sensor to demonstrate and validate capabilities using AEOS or other available ground-based telescopes.

5.0 REFERENCES

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