ON THE RADAR

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Hyperspectral Imaging

A Technology Primer

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TYPE Sensor	**CHARACTERISTICS** Range, Vantage, Precision	**RISK FACTORS** Action-enabling, preemptive, dual use
DOMAIN Space, Air, Sea	**COUNTRY** United States, China	

- Hyperspectral imaging (HSI) is a type of remote sensing that is particularly useful for determining the composition of an object.
- In conjunction with other remote sensing and data collecting techniques, it can be used to identify a country's fixed strategic sites, for example, WMD production facilities or camouflaged military assets.
- Hyperspectral imaging sensors can be deployed on a variety of platforms, including manned and unmanned aerial vehicles and satellites.
- The level of risk introduced when using HSI is platform and deployment-dependent. In most cases, HSI can improve situational awareness without negatively impacting stability.

Introduction

Hyperspectral imaging (HSI) is a type of remote sensing that takes a series of hundreds or thousands of contiguous images in narrow wavebands across the visible and infrared regions of the electromagnetic spectrum. This allows hyperspectral imaging to capture more data about its target than conventional color photography, which only takes images in the red, green and blue segments of the visible light spectrum. The series of images captured by hyperspectral sensors forms a "hyperspectral cube" that contains detailed spectral information about each pixel in the image. HSI can take advantage of differences in the way that materials reflect light (forming unique spectral signatures) to identify the materials present in an image, aiding in the detection of decoys and other camouflaged targets.[1]

Successfully using HSI to find and identify items of interest requires the ability to process an extremely large amount of gathered spectral information to locate the small number of pixels possessing characteristics of

[1] Peter WT Yuen and Mark Richardson, "An introduction to hyperspectral imaging and its application for security, surveillance, and target acquisition," *The Imaging Science Journal* 58, no. 5 (2010): 241-242.

interest and subject them to further scrutiny.[2] Effectively carrying out this analysis relies on the possession of a large library of the spectral signatures of materials ranging from leaves in various stages of health to vehicles, camo-patterns, and countermeasures.[3]

HSI data can be processed in two ways: anomaly detection and signature-based detection. Anomaly detection identifies spectral deviations from the background and subjects them to further analysis, whereas signature-based detection searches large areas for objects possessing a certain known spectral signature.[4] In either case, this already complicated and computing-power intensive task is made more difficult by the need to correct for atmospheric absorption and scattering, the effects of which vary depending on the distance from the target and the weather at the time of information collection. Additionally, due to an inherent level of spectral ambiguity in the field, collected spectral signatures can vary from the information recorded for that material in the spectral library.[5]

Finally, significant complication arises from the interplay between the spatial resolution of the sensor (the amount of space represented in one pixel) and the spatial variability of the ground area being imaged.[6] The sensor integrates the spectral information from all materials in the ground area defined by the spatial resolution into a single image pixel. If the spatial resolution is low and the target ground area is highly variable in composition, the resulting images will contain a high number of mixed pixels, which can present an additional challenge to analysis because their spectral signature will not correspond to any single well-defined material.

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As HSI sensors become more powerful, their increasing spatial and spectral resolution will help to overcome these problems, enabling more effective material discrimination and thus target identification at an increasing range. However, increases in the precision of the sensor are accompanied by increases in the volume of the data generated, resulting in increased bandwidth and computing power requirements to transfer and effectively analyze it. As a rule of thumb, commercial HSI generated about 1TB of data per hour of footage.[7] Recent advances in the theoretical and algorithmic approaches to target identification, spectral unmixing, and anomaly detection, coupled with developments in machine learning, have increased the speed and efficiency of sorting and interpreting the massive quantities of data, increasingly allowing HSI to provide time-sensitive intelligence analysis.[8]

Hyperspectral sensors can be deployed on a variety of platforms, including satellites, unmanned aerial vehicles (UAVs), and unmanned underwater vehicles (UUVs). Hyperspectral sensors deployed on satellites and UAVs are typically passive sensors that rely on reflected sunlight to take images. Sensors deployed on UUVs that

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[2] "Hyperspectral analysis set to expand in coming decade," *Jane's Intelligence Review*, June 23, 2017, http://www.janes.com/images/assets/127/72127/Hyperspectral_analysis_set_to_expand_in_coming_decade.pdf, 4.

[3] Ibid., 249.

[4] Xavier Briottet et al., "Military applications of Hyperspectral Imagery," Wendell R. Watkind and Dieter Clement, eds., *Targets and Backgrounds XII: Characterization and Representation* 6239, International Society for Optics and Photonics (2006): 62390B, publications.tno.nl/publication/34617027/4SzPMU/briottet-2006-military.pdf.

[5] Yeun and Richardson, 249.

[6] Briottet et al.

[7] "Hyperspectral analysis set to expand in coming decade," 4.

[8] "Hyperspectral analysis set to expand in coming decade," 5.

operate in the deep-sea need to actively illuminate their subject in order to take images.[9] Both passive and active sensors have drawbacks. Passive hyperspectral sensors' operations may be hindered by bad weather and darkness. Active hyperspectral sensors can operate in darkness, but their light source may give away their presence to adversaries.

State of Play

Although hyperspectral remote sensing techniques have long existed (for instance, an early aircraft-mounted commercial hyperspectral sensor was launched in 1987), the applications of the technology were initially limited by the size of the requisite sensors.[10] Since the start of the 2000s, advancements in lightweight materials and improvements to sensing technology have made hyperspectral sensors a more practical and widespread technology.[11] A number of countries and commercial entities have launched hyperspectral satellites, including the United States, China, the European Space Agency, and BlackSky Global.[12] However, capable commercial and scientific hyperspectral sensors face enduring challenges with data storage, transmission, and cooling that, without further technological advances, limit their ability to be employed effectively on smaller satellite platforms.[13]

The majority of hyperspectral sensors are used for non-military purposes.[14] HSI was originally developed for mining and geological applications and continues to have many commercial uses, including agriculture, environmental monitoring, and life sciences.[15] Sensors with high spatial and spectral resolution remain expensive, but prices are likely to decrease as sensors become more ubiquitous. Sensors with lower resolution can already be built for very low cost; for instance, in 2016 researchers at Microsoft demonstrated that a hyperspectral camera could be built for less than $100, although its resolution was too low to have any real utility for remote sensing.[16]

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[9] "Underwater Hyperspectral Imaging reveals the secrets of the sea," *Specim,* March 4, 2016, http://www.specim.fi/revealing-the-secrets-of-the-sea/.

[10] "Hyperspectral analysis set to expand in coming decade."

[11] Jay Pearlman et alia, "The EO-1 Hyperion Imaging Spectrometer" (slides from presentation given at SPIE San Diego, August 2000) https://eo1.gsfc.nasa.gov/new/validationReport/Technology/TRW_EO1%20Papers_Presentations/06.pdf, slide 4.

[12] See "Introducing BlackSky Spectra," *BlackSky Global*, April 4, 2017, https://www.blacksky.com/2017/04/04/introducing-blacksky-spectra/.

"China launches new hyperspectral imaging satellite to monitor air pollution," *Financial Express*, May 9, 2018, https://www.financialexpress.com/lifestyle/science/china-launches-new-hyperspectral-imaging-satellite-to-monitor-air-pollution/1160758/; and "Hand-sized Hyperspectral Camera to Fly on ESA's next cubesat," *European Space Agency*, January 8, 2018, http://www.esa.int/Our_Activities/Space_Engineering_Technology/Hand-sized_hyperspectral_camera_to_fly_on_ESA_s_next_CubeSat.

[13] "Hyperspectral analysis set to expand in coming decade," 4.

[14] The military surveillance segment of the hyperspectral market is only projected to reach $13.9 million (out of a $82.3 million market) by 2019. See John Keller, "Hyperspectral imaging market to grow by 76% through 2019; military market to hit $13.9 million," *MilitaryAerospace*, June 22, 2015, https://www.militaryaerospace.com/articles/2015/07/hyperspectral-imaging-market.html for more information.

[15] Yeun and Richardson, 241; and "Hyperspectral Imaging System Market by Product (Camera, Accessories) & Application (Military, Remote Sensing, Environmental Monitoring, Agriculture, Mineral Map, Machine Vision/Optical Sorting, Life Sciences & Medical Diagnosis) - Global Forecast to 2023," *Markets and Markets*, August 2018, https://www.marketsandmarkets.com/Market-Reports/hyperspectral-imaging-market-246979343.html.

[16] "Hyperspectral analysis set to expand in coming decade," 3.

Publicly acknowledged military hyperspectral programs include the experimental ARTEMIS payload on the TacSat-3 and an ongoing program to develop an improved high-resolution ACES-Hy for UAVs. The Tac-Sat-3 deorbited in 2012, but while it was operational, it could provide HSI to combatant commanders at four-meter resolution with approximately 400 spectral bands within 10 minutes of overpass.[17] The original Raytheon ACES-Hy program deployed a hyperspectral sensor on the MQ-1 Predator, mainly for improvised explosive device (IED) detection and other tactical use. The project to improve the resolution of the ACES-Hy has $14.5 million in funding through 2020.[18] In addition, in June 2018, Reuters reported that the Pentagon is investing in secret research efforts to use artificial intelligence (AI) to track and target mobile missiles and to anticipate missile launches by processing large amounts of satellite imagery and other data.[19] It is possible that this research uses hyperspectral data, or that the algorithms developed during this research could be adapted to apply to hyperspectral data in the future

Effects on Situtational Awareness

HSI has the potential to improve strategic situational awareness by providing more data about targets from an existing *rang[20]e* and *vantage* point (overhead and long distance, as HSI sensors will likely be mounted on satellites or UAVs). Specifically, when used in conjunction with other imaging techniques, HSI can increase the *precision* of data collected by adding another layer of information. For example, thermal HSI can provide information about whether or not a previously identified facility is operational. Similarly, HSI could be used to locate camouflaged objects within an area of interest.

These characteristics of HSI could allow it to meaningfully improve strategic situational awareness, especially by detecting hidden or camouflaged enemy mobile assets. However, several challenges remain. HSI (and remote sensors in general) generate large amounts of raw data that must be processed either by analysts or by computers. Unless data processing capabilities can be mounted on the same platform as the sensor, secure, fast datalinks with large bandwidth will be required to relay information to the processing center. The *speed* with which HSI data can be used is entirely reliant on datalinks and data processing.

One of the reasons that HSI is becoming more useful for defense applications is advances in algorithms and artificial intelligence to process large amounts of HIS data. However, it should be noted that using artificial intelligence to process overhead imaging comes with its own trade-offs. AI can dramatically improve the speed and quantity of data processed but can make mistakes or be deceived.

Overall, HSI is unlikely to improve a country's strategic situational awareness (SA) independently. HSI is most effective when paired with other remote sensing techniques. For example, as described in a 2002 RAND report, synthetic aperture radar using change-detection software could detect tire tracks leading off the road but might not be able to detect vehicles in the vicinity. At this point, a hyperspectral satellite could be cued to look for

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[17] Michael Kleimann, "TacSat-3 to demonstrate rapid delivery of imagery," *U.S. Air Force 377th Air Base Wing Public Affairs*, April 17, 2009, http://www.af.mil/News/Article-Display/Article/120599/tacsat-3-to-demonstrate-rapid-delivery-of-imagery.

[18] James Drew, "Boeing, Pentagon discussing space-based hyperspectral sensor options," Flight Global, May 19, 2015, https://www.flightglobal.com/news/articles/boeing-pentagon-discussing-space-based-hyperspectra-412549.

[19] Phil Stewart, "Deep in the Pentagon, a secret AI program to find hidden nuclear missiles," *Reuters*, https://www.reuters.com/article/us-usa-pentagon-missiles-ai-insight/deep-in-the-pentagon-a-secret-ai-program-to-find-hidden-nuclear-missiles-idUSKCN1J114J.

[20] To learn how this project defines the italicized terms, please visit the *On the Radar* website glossary, https://ontheradar.csis.org/glossary.

transporter erector launchers (TELs) and could potentially find them even if they were hidden under a radar-reflective camouflage net or were obscured by a forest canopy.[21]

Effects on Strategic Stability

HSI's impact on strategic stability is largely dependent on the way it is used. For example, HSI sensing from space may have no impact on stability because it can provide high-quality information without entering adversary airspace. Although satellites are often detectable to adversaries, satellite sensing is perceived as a legal, fair form of intelligence gathering. On the other hand, HSI sensors deployed on manned or unmanned vehicles would be more *intrusive*, as they would likely have to operate within enemy airspace to collect information.

HSI poses a risk to strategic stability primarily because it is *action-enabling*. HSI could be used to locate a country's fixed strategic sites (i.e., WMD production facilities), or to track mobile assets, potentially leading a country to believe (rightly or wrongly) that it could act against these assets. Similarly, HSI could enable *preemptive* behavior: for example, if a country is tracking an enemy's mobile missiles and determines (again, rightly or wrongly) that they are preparing for an attack, the observing country can attempt to prevent the attack by acting preemptively. HSI is not inherently *predictive*, because it can only detect actions once they have been taken; but the more complete asset-tracking information HSI can provide, it could enhance the capability of predictive algorithms.

Given its widespread commercial use, HSI is not a *clandestine* capability. This makes it more *vulnerable*, because countries may be better able to develop countermeasures to HSI. It should be noted that, because HSI sensors are likely to be mounted on existing platforms (satellites and UAVs), countries don't necessarily need to develop HSI-specific countermeasures to deny the enemy of the capability. Existing anti-satellite weapons, air defenses, and electronic warfare capabilities could be used to disable enemy platforms carrying HSI sensors. However, these countermeasures may in turn be more detectable to the observing nation, and some may lead to unintended escalation. As a result, countries may be motivated to develop countermeasures that simply better hide their military assets.

Finally, HSI is inherently *dual-use*. It cannot track nuclear and conventional assets independently. Furthermore, HSI is used for both military and non-military purposes.

[21] Alan J. Vick, Richard M. Moore, Bruce R. Pirnie, and John Stillion, Aerospace Operations Against Elusive Ground Targets. Santa Monica, CA: RAND Corporation, 2001, https://www.rand.org/pubs/monograph_reports/MR1398.html, 71.

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