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TECHNOLOGY SCAN

HYPERSPECTRAL TECHNOLOGY FOR MILITARY APPLICATIONS

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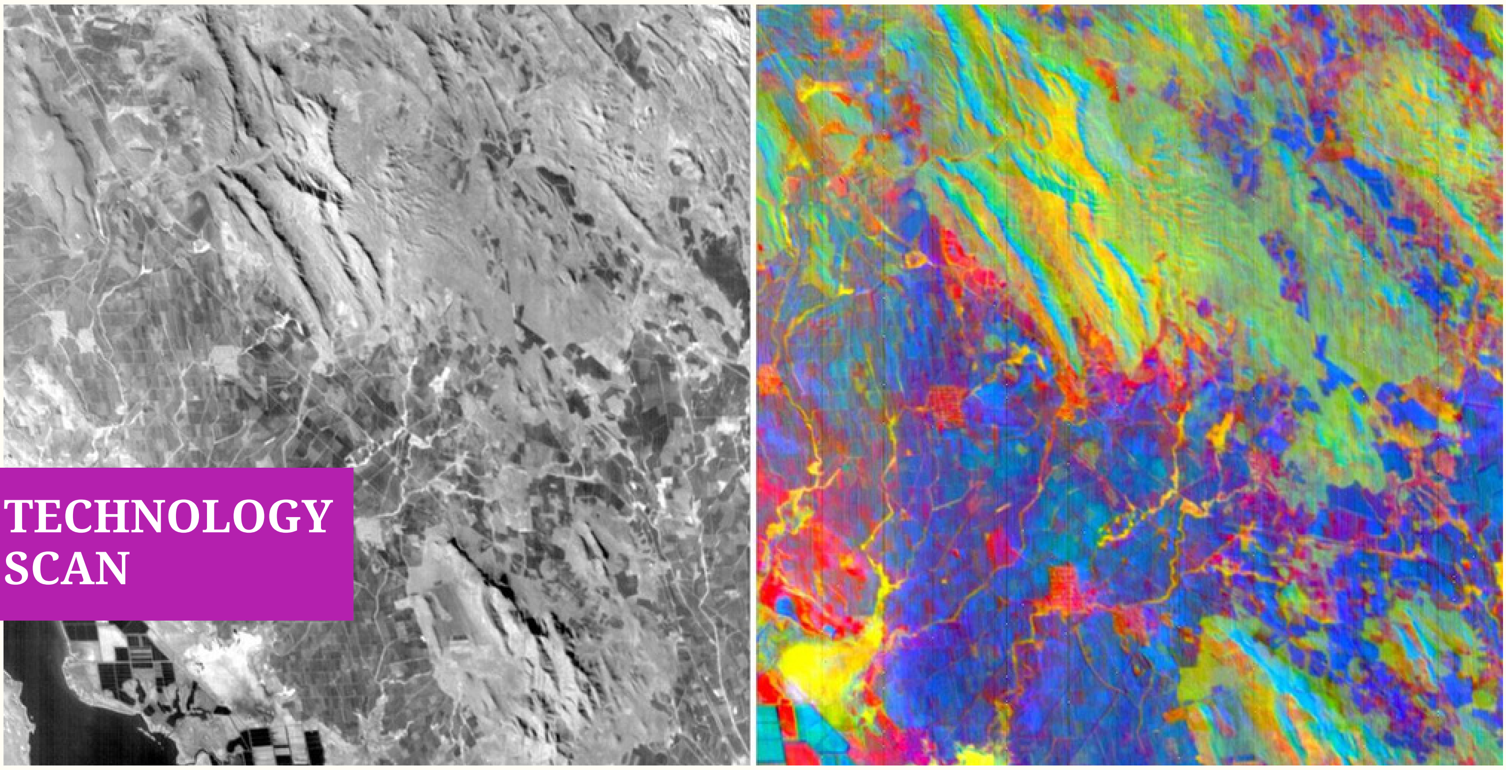

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HYPERSPECTRAL TECHNOLOGY FOR MILITARY APPLICATIONS

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ABSTRACT

Collecting airborne and spaceborne intelligence, surveillance, and reconnaissance information is critical for war-fighting. Modern military and defence environments require proven, reliable, and scalable technologies for evaluating and analysing modern battlefields. Hyperspectral sensors or imaging spectrometers, known as hyperspectral remote sensing, measure earth materials and produce[i] their complete spectral signatures without wavelength omissions. Hyperspectral imaging is the science of acquiring digital images of objects or materials from the Earth in a data cube employing hundreds of small contiguous spectral bands ranging from visible to long-wave infrared wavelengths. The ability to measure reflectance in several contiguous bands across a specific part of the spectrum allows these instruments to create a spectral curve or signature for each pixel that can be compared to reference spectra for object identification and classification purposes [ii]. Hyperspectral remote sensing, though primarily used in civil applications like mineralogy, agriculture and water survey, also has a range of military applications due to its ability to provide highly detailed and specific information about the environment and objects on the Earth's surface. The Hyperspectral sensors can be airborne, space-based and hand-held.

Introduction

Camouflage techniques rank highly among the arts of war. The challenge for forces fighting in the Ukraine-Russia conflict is no longer limited to hiding from human eyes and remains unnoticed. Thanks to the automatic target-detection software, today's battlefields help operators find needles from the collected data in the haystacks of the collected data. For example, today, a thermal sensor, in good weather, can detect a warm vehicle as far off as 10 km. Optical imaging provides solutions to the defence ecosystem, including complex controls, surveillance, intelligence, measurement, monitoring, and execution.

The range at which soldiers using just the naked eye may immediately identify soldiers donning camouflage has decreased thanks to advancements like fractal colouring patterns, which imitate nature by repeating shapes across different scales. Analysing the scene using conventional imaging, whether monochrome or colour, depends on the spatial resolution of the image. Hyper Spectral Imagery provides significant additional information to the spatial dimension by adding the spectrum to each position.

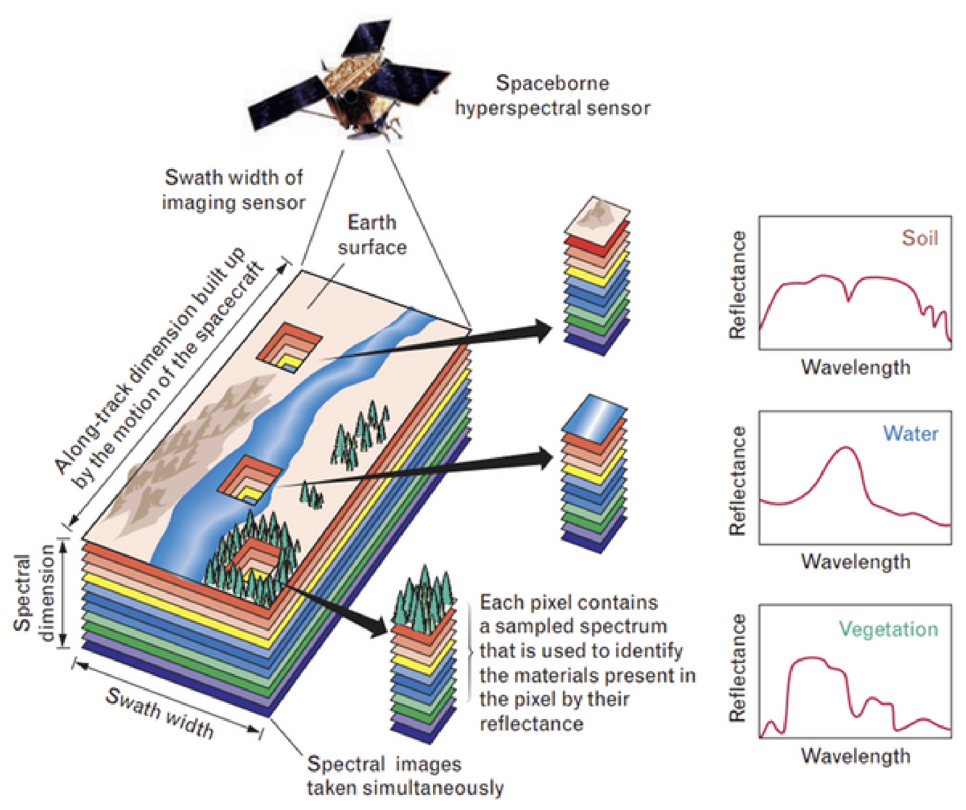
Every material absorbs energy in a particular wavelength of energy in the electromagnetic spectrum due to its molecular structure, which can be detected through hyperspectral technology as this data provides a continuous spectral curve. The absorption dip appears in the spectral curve, which indicates the characteristics/type of material (Fig 1). In remote sensing technology, each pixel of hyperspectral imagery is defined as a ‘spectra’.

The hyperspectral analysis algorithms typically cross-check the obtained spectra with known, uniquely referenced spectral ‘fingerprints’ to detect, characterise, and recognize materials or identify anomalies in the spectral signatures to detect targets of interest. Hyperspectral Imaging (HSI) and other sophisticated electro-optical equipment are essential for boosting Intelligence, Surveillance and Reconnaissance (ISR) information content.

The hyperspectral sensor acquires hundreds of contiguous, narrow wavelength band co-registered images of the reflected region. The image analyst cross-checks the obtained spectra with known, uniquely referenced spectral fingerprints to detect, characterize, and identify materials, liquids, or chemical compositions with a precise location.

Signals beyond the optical spectrum give away both people and equipment, and the technology to detect these wavelengths is getting more sophisticated, portable, and affordable. Developing algorithms and processing power within the application is helping the user to glean the requisite information. Fusing a hyperspectral data set with other data obtained at different wavelengths or times has improved detection and classification performance.

Figure 1: Detection of material characteristics from Hyperspectral data



(Source: Lincoln Laboratory Journal, 4)[1]

Hyperspectral Remote Sensing

Hyperspectral remote sensing is a specialised technique used in remote sensing and Earth observation to collect and analyse detailed information about the Earth's surface and features. Hyperspectral Imagery technology involves a sophisticated approach to capturing digital images in multiple spectral bands. Each pixel in these images contains rich information across a spectrum, allowing for generating a complete spectral signature of the observed materials. This signature is critical to identifying and classifying different materials and objects, a capability that has transformative applications in military operations.

Hyperspectral remote sensing acquires digital images in many narrow contiguous spectral bands starting from visible, near infra-red (NIR 780 nm to 1400 nm) and short wave infra-red (SWIR from 1400 nm to 3000 nm) wavelength of the electromagnetic spectrum in which they operate and form a data cube. This optical sensor technology provides high spectral resolution spanning the visible spectrum up to long-wave infrared (LWIR ranging from 8µm to 14µm, i.e. 8,000 to 14,000nm) wavelengths.

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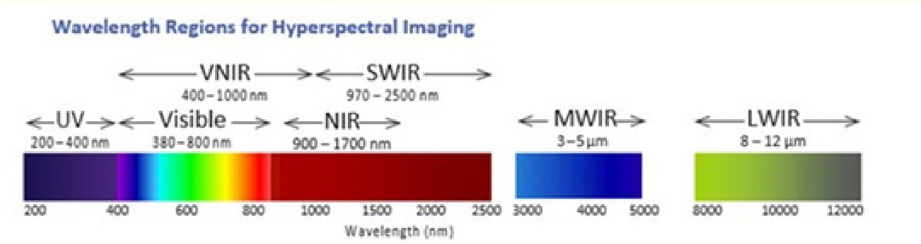
[1] Spectral Imaging - Scientific Figure on ResearchGate. Available from: https://www.researchgate.net/figure/Geological-application-of-hyperspectral-Imaging-3_fig4_334645235 [accessed 7 Nov, 2023]

Figure 2



(Source: Middleton Spectral) [2]

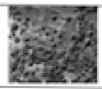
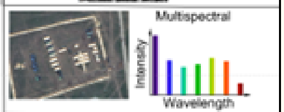
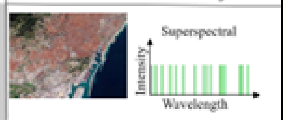
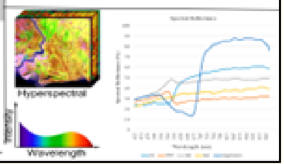
Hyperspectral Imaging Spectrometers

Spectral bandwidth is the width of an individual spectral channel in the spectrometer. The narrower the spectral bandwidth, the narrower the absorption feature the spectrometer will accurately measure.[iii]

Hyperspectral sensors or imaging spectrometers measure earth materials and produce complete spectral signatures without wavelength omissions. Such instruments are flown aboard space and air-based platforms. Hand-held versions are also used for accuracy assessment missions and small-scale investigations. The fundamental difference among panchromatic, multispectral, super spectral and hyperspectral technology is explained below in Figure 3.

Figure 3: Difference Among Panchromatic, Multispectral, Super Spectral and Hyperspectral Data and Analysis

Multispectral, Superspectral and Hyperspectral

Technology	Wavelength Range (µm)	No. of Band	Detection Technique	Graphical Representation
Panchromatic imaging	0.4 to 0.7	Single band	Imagery interpretation	
Multispectral imaging	0.4 to 1.3	Less than 10 bands (Generally 4 bands) Discrete bands	Imagery interpretation Classification	
Superspectral imaging	0.4 to 1.3 1.3 to 2.5	More than 10 bands Discrete bands	Imagery interpretation Classification	
Hyperspectral imaging a. Reflective Spectroscopy b. Emission Spectroscopy	0.4 to 2.5 8 to 14	Contiguous bands 240 to 300 bands 20 to 50 bands Small spectral band width	Spectral analysis Analysis of reflectance spectra Analysis of emissivity spectra Spectral based classification	

(Source: Author’s Own)

Hyper Spectral Imagery provides additional information to the spatial dimension by adding the spectrum to each position. This powerful method creates a “data cube” that contains information about a target's physical and chemical properties at tens to hundreds of narrow-wavelength bands within the system’s field of view. [iv] Because of its high multidimensional data, HSI requires large data storage capacity, high computation cost, innovative processing techniques, and new analytical skills. Once the data is received, it has to be calibrated to eliminate atmospheric influences, normalised using the relationship between radiance and reflectance and analysed using libraries and algorithms. The technological advancements which have led to the proliferation of these sensors are:

▶ **Miniaturisation of Sensors**: There has been significant progress in reducing the size of hyperspectral sensors, enhancing their deployability in various contexts, including Unmanned Aerial Vehicles (UAVs) and portable field instruments. Smaller components typically mean less material and manufacturing costs, making the technology more accessible. Two significant material and component innovations have helped in miniaturisation.

- **Micro-electromechanical Systems (MEMS)**: The adoption of MEMS technology has been crucial in miniaturizing optical components. By integrating microscopic mirrors and optical switches, MEMS technology allows for smaller hyperspectral imaging systems.

- **Advanced Detector Materials:** Developing new, more compact materials for detectors, such as quantum dots and nanostructured materials, provides enhanced sensitivity and reduced size.

▶ **Integration of Artificial Intelligence (AI) and Machine Learning (ML):** The application of AI and machine learning algorithms in analysing hyperspectral data offers improved pattern recognition and anomaly detection, crucial in military operations for identifying subtle, otherwise overlooked details.

▶ **Enhanced Resolution:** Technological improvements have enabled higher resolution in hyperspectral imaging, allowing for the detection of finer material differences and improving target identification accuracy. The factors which have contributed to the optical system redesign are:

- **Diffractive Optical Elements:** These elements allow the design of more compact spectral dispersion elements. Diffractive optics can reduce the size of traditional refractive optics while maintaining high spectral and spatial resolution.

- **Integrated On-chip Spectroscopy:** On-chip integration of spectroscopy components, where the entire optical path is integrated onto a semiconductor chip, dramatically reduces the sensor's footprint.

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[2] “What Is Hyperspectral Imaging? - Hyperspectral Imaging Cameras and Systems: Middleton Spectral Vision.” Hyperspectral Imaging Cameras and Systems | Middleton Spectral Vision, August 13, 2019. https://www.middletonspectral.com/resources/what-is-hyperspectral-imaging/.

▶ **Enhanced Sensitivity:** Enhanced sensitivity allows for the detection of subtle spectral differences. These developments have broadened the operational scope of HSI in various military contexts.

- **Advancements in Sensitivity:** Improved sensitivity in HSI sensors means they can detect and distinguish between spectral signatures more effectively. This capability is instrumental in identifying materials with close spectral profiles or detecting slight changes in the spectral signature due to environmental factors or material alteration. For example, the enhanced sensitivity allows for detecting trace gases or effluents, indicating underground military facilities or chemical weapon factories. The sensors can pick up faint spectral signatures of these gases, which would be undetectable with less sensitive equipment.

- **Superior Spectral Discrimination:** Greater sensitivity also improves the performance of hyperspectral sensors in low-light conditions. This is essential for night-time operations or penetrating areas with limited light due to canopy cover or deliberate concealment. For Example, In night-time reconnaissance, hyperspectral sensors with higher sensitivity can detect enemy troop movements or equipment operations by capturing the spectral signatures emitted by these sources in near-total darkness

▶ **Extended Spectral Range:** The spectral range of hyperspectral imaging has been broadened, especially into the mid-wave and long-wave infrared, improving the detection capabilities under diverse operational scenarios.

▶ **Real-Time Processing:** The shift towards real-time data processing, facilitated by advanced onboard processing systems and edge computing, provides immediate analysis crucial for swift military decision-making. Two significant reasons for better signal processing and data handling are:

- **Embedded Processing:** Integrating advanced, compact processing units within the sensor for onboard data processing helps reduce the size of the overall system by eliminating the need for bulky external processing hardware.

- **Compression Algorithms:** Efficient data compression algorithms are critical in managing the high data volume generated by hyperspectral sensors, facilitating smaller storage requirements and faster data transmission.

▶ **Enhancements in Resolution/Finer Spatial Detailing:** High-resolution HSI sensors capture images with greater pixel density, allowing for identifying smaller objects and finer details in the scene.

This enhanced detail is crucial in identifying hidden or camouflaged enemy installations and equipment. In terrain analysis, high-resolution hyperspectral sensors can differentiate between natural foliage and camouflage nets to conceal enemy assets. These sensors can discern patterns and textures not visible to standard (Red, Green, Blue) RGB cameras or the naked eye.

▶ **Improved Target Recognition:** Enhanced spatial resolution enables identifying specific target features. In a military context, this can be vital in distinguishing between different types of vehicles and weaponry or even detecting subtle alterations in landscapes indicative of enemy activities. A hyperspectral image with high resolution can reveal the specific type of vehicle used in an enemy convoy by analysing the spectral signature of the vehicle paint or the thermal signature emitted by different engine types.

▶ **Power Consumption and Management:** Modern electronic components have resulted in lower power consumption. Two major reasons are

- **Low-power Electronics:** Utilising low-power electronic components and optimising circuit designs significantly reduces overall power consumption, an essential factor for portable and remote sensing applications.

- **Energy Harvesting Technologies:** Innovations in energy harvesting, such as solar cells or piezoelectric materials, are being explored to power these sensors, particularly in unmanned, remote deployment.

Military Applications Of Hyperspectral Imaging Technology

In hyperspectral technology two approaches are used for detection of military objects such as ‘Spectral Anomaly Detection’ and ‘Spectral Signature Matching processes’ which can be explained as follows:

- A spectral anomaly detection algorithm tries to identify those pixels, which have different spectra in comparison to the background. These algorithms do not require any prior information about the target.

- Spectral signature matching algorithm tries to match the spectra of a pixel with the reference spectra of targets of interest. It tries to identify those pixels whose spectra has high correlation with the given reference spectra of targets of interest.
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Hyperspectral images and spectral signature libraries are critical for applying hyperspectral remote sensing to various defence applications. The applications presented in this scan are representative, and these techniques can be applied whenever

In many examples, field collection of spectral signatures is essential for an accurate comparison with hyperspectral images since the supply of materials such as soil and vegetation alters their spectral signature. Though Hyperspectral imagery technology has found large applications in the civil sector in the field of agriculture, like crop cultivation and water management, the dual use of this technology has found its way into the following military applications [v]:

(a) **Broadened Spectral Range in Hyperspectral Imaging:** The extension of the spectral range in hyperspectral imaging (HSI) is crucial in enhancing its applicability, particularly in military and environmental monitoring contexts. A broadened spectral range implies the ability of hyperspectral sensors to capture electromagnetic energy across a wider range of wavelengths, significantly beyond the traditional visible and near-infrared (NIR) spectra. This advancement has operational implications and examples, emphasizing its transformative impact on detection and classification accuracy in various scenarios. Hyperspectral imaging traditionally focussed on the visible (400–700 nm) and near-infrared (700–1000 nm) spectral ranges. However, recent technological advances have expanded this range into the Short-Wave Infrared (SWIR, 1000–2500 nm), Mid-Wave Infrared (MWIR, 3–5 μm), and even the Long-Wave Infrared (LWIR, 8–12 μm) regions.

(b) **Camouflage Detection and Countermeasures:** Advancements in detecting technology, like fractal colouring patterns and thermal sensors, have challenged traditional camouflage techniques. Hyperspectral imaging, with its expanded spectral range and enhanced resolution, provides a more nuanced detection of objects, penetrating even sophisticated camouflage. The advanced camouflage materials can thermally conceal a target in the mid-wave infrared (IR) and long-wave infrared wavelengths parts of the spectrum. Still, they cannot replicate emission features of abundant minerals in the continental crust like quartz, silicates or gypsum. Thus, a hyperspectral detector, which operates in the reflective and thermal wavelengths, can detect these signatures. LWIR imaging can penetrate camouflage by detecting the heat signatures of objects or people, even in densely vegetated areas or under coverings that would typically evade detection in the visible spectrum.

(c) **IED and Landmine Detection:** The sensitivity of hyperspectral sensors to specific spectral signatures enables the detection of buried explosives, Improvised Explosive Devices (IEDs), and landmines using specific sensors and algorithms influenced by environmental and operational conditions. SWIR sensors can help identify disturbed soils and hidden explosives, which exhibit distinct spectral signatures compared to the surrounding undisturbed earth.

(d) **Geospatial Intelligence Integration:** The fusion of hyperspectral data with geospatial intelligence allows for a comprehensive understanding of the battlefield. This integration facilitates detailed terrain analysis and target identification, directly beamed to soldiers for enhanced situational awareness.

(e) **Spectral Anomaly Detection and Signature Matching:** In hyperspectral data analysis, the spectral anomaly detection algorithm identifies targets without prior knowledge, whereas spectral signature matching requires pre-existing spectral data of targets. Both techniques are pivotal in determining hidden or disguised objects.

Civil / Military Applications of Spectral Characteristics

Broadening the spectral range in hyperspectral imaging significantly enhances the technology's versatility and application scope. By capturing a more comprehensive range of electromagnetic signatures, from visible light to long-wave infrared, it allows for a deeper, more nuanced understanding and detection of materials and their states. This broadened spectral capacity, coupled with advanced data analysis techniques, presents transformative opportunities across military, environmental, and industrial sectors, providing detailed insights that were previously unattainable. As we continue to harness and integrate these expanded capabilities, the operational impact and utility of hyperspectral imaging are poised for significant growth, offering unparalleled benefits in numerous real-world applications. This expansion unlocks new potential in identifying, classifying, and understanding objects' and materials' chemical and physical properties based on spectral characteristics.

▶ **SWIR (Short-Wave Infra-Red) Applications**

- **Mineralogy:** In geological applications, SWIR is pivotal in mapping mineral resources.
- **Geology:** Minerals like kaolinite, alunite, and muscovite exhibit unique spectral features in the SWIR range, aiding in mineral exploration and environmental monitoring
- **Agriculture and Vegetation Studies:** Plant species can be differentiated based on their SWIR spectral responses, which is crucial for agricultural monitoring, forest management, and biodiversity conservation.

▶ **MWIR (Mid-Wave Infrared) Applications**

- **Military Surveillance:** MWIR is instrumental in detecting and identifying vehicles and infrastructure based on thermal signatures, especially under low-light or night-time conditions. It effectively identifies heated objects or activities, such as recently .

Market Trends

The global hyperspectral imaging systems market, in terms of revenue, is estimated to be worth $ 16.8 billion and is poised to reach $ 34.3 billion by 2028, growing at a CAGR of 15.4 % from 2023 to 2028 [vi]. ISRO launched rocket PSLV-C43 carrying India's earth observation satellite Hyperspectral Imaging Satellite (HysIS) from Sriharikota on November 29, 2018. [vii] In the private sector, a start-up based at Bangalore Pixxel is now close to deploying the "world's first hyperspectral satellite constellation" comprising 24 satellites by 2024-2025, providing a 24-hour revisit period for rapid satellite imagery.[viii] It is set to manufacture miniaturised multi-payload satellites for the Indian Air Force. The contract results from a multi-crore grant from the Innovations for Defence Excellence (iDEX), a flagship scheme under the Indian Ministry of Defence. In Jul 2023, it also bagged a five-year contract for supplying technical hyperspectral imagery to the United States National Reconnaissance Organization (NRO). Many drones fitted with hyperspectral sensors are available for undertaking agriculture and other related tasks. The list of few satellites launched by different countries is listed under [ix]

- NASA- EO-1 launched in 2000, covering 242 spectral bands with a resolution of 30 m
- PROBA-1 (ESA), launched in 2001, has 63 bands for medium-resolution hyperspectral imaging
- PRISMA (Italy), launched in 2019, is a medium-resolution hyperspectral satellite which generated 250 bands
- EnMap (Germany) is an Environmental Mapping and analysis satellite with 228 bands and a GSD of 30m.
- HISUI (Japan) has 185 bands and a resolution of 30m
- HyspIRI (US) was launched in 204 and had a VSWIR imaging spectrometer with a 60m resolution

Challenges and Future Directions

(a) Despite its remarkable advancements, hyperspectral imaging faces challenges like data overload, the need for robust algorithms to handle complex scenarios, and the necessity for faster processing speeds. Future research might optimise data processing algorithms, improve sensor sensitivity under varied environmental conditions, and explore new spectral ranges for deeper insights into material properties.

(b) While the miniaturisation of electronics presents numerous benefits, it also poses challenges. Maintaining high spectral resolution and image quality with smaller optics is important. Still, the heat dissipation in compact devices, durability under varying environmental conditions, and consistent performance over a broad spectral range require ongoing research and innovation.

(c) Integrating artificial intelligence and machine learning directly onto these compact hyperspectral platforms offers a promising future direction. Such advancements could enable real-time, intelligent analysis at the point of data capture, opening new frontiers for responsive, autonomous hyperspectral sensing.

(d) The miniaturisation of hyperspectral imaging sensors marks a significant technological advancement, making the technology more adaptable, cost-effective, and suitable for a wider range of applications. As research progresses, we can anticipate further innovations that will address the current challenges and expand the capabilities of these compact hyperspectral systems, especially in dynamic and demanding environments like military operations.

(e) HSI provides accurate detection and identification of threats in static scenes. It is impractical for dynamic scenarios and relies on fusion with other techniques to perform tracking. Technological developments will focus on active hyperspectral imagery because real-time reconnaissance requires rapid detection and monitoring.

(f) Development of miniature cryogenic coolers. Accurate spectral detection and discrimination in the thermal IR wavelengths require high thermal resolution, achieved using advanced optronic technologies while maintaining cryogenic temperatures (typically 77 k using liquid nitrogen), which can be used as UAV payloads.

Conclusion

Hyperspectral Imagery technology involves a sophisticated and promising approach to capturing digital images in multiple spectral bands. Each pixel in these images contains rich information across the spectrum, allowing for generating a complete spectral signature of the observed materials. This signature is critical to identifying and classifying different materials and objects, a capability that has transformative applications in military operations.

Hyperspectral sensors or imaging spectrometers meticulously capture earth materials' spectral signatures without omitting any wavelength. The technology measures reflectance across numerous contiguous bands, helping to generate detailed spectral curves. These curves are then compared against established reference libraries to identify and classify the observed objects or materials accurately.

Hyperspectral remote sensing will play a crucial role in enhancing the capabilities of defence and military operations by providing detailed and actionable information about the environment, targets, and potential threats. Its ability to detect subtle spectral differences makes it a valuable tool for various defence applications. Hyperspectral imagery technology, with its extensive spectral range and fine resolution, is revolutionising military reconnaissance and surveillance. By providing detailed spectral information of the target areas and integrating this data with advanced machine learning algorithms and geospatial intelligence, hyperspectral imaging paves the way for a more informed, responsive, and technologically advanced military strategy. As this technology evolves, it is expected to play an increasingly pivotal role in modern warfare, enhancing strategic and tactical decision-making processes in the military domain.

Endnotes

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