Hyperspectral analysis set to expand in coming decade

Advances in the development of hyperspectral imaging sensors raise the prospect of wider future use of the technology in space. Brian Lim and Melissa Hanham assess what an increase in commercially available hyperspectral imagery would mean for open-source intelligence practitioners.

With rapidly falling costs, reductions in risk, and new launch technologies, there has been a surge of new satellites and capabilities entering the commercial market. According to the US-based Union of Concerned Scientists, as of 31 December 2016 there were 1,459 operational satellites in space. This figure is set to expand during the next decade. SpaceX, business magnate Elon Musk’s aerospace company, is planning to launch 4,425 satellites by 2024, with the aim of using these to provide global satellite-based internet access.

SpaceX prepares to launch the geostationary communications satellite BulgariaSat-1 at the Kennedy Space Center in Titusville, Florida, on 23 June 2017. The company plans to launch 4,425 satellites by 2024. (PA)

The rapid change taking place in the space sector is most apparent in the work of SpaceX. In December 2015, the company successfully managed to land a reusable rocket on Earth. In 1981, it cost nearly USD20,000 per kilogramme to send an object into orbit on the Space Shuttle. For
SpaceX, the comparable figure is currently less than USD2,000 per kilogramme, according to the company.

OneWeb, a satellite telecoms company, is planning to launch more than 2,000 satellites, according to an interview with its founder published on the SpaceNews website in February 2017. Another company, Planet, launched 88 small 'Dove' satellites on a single rocket, taking its total constellation to 149 satellites in February 2017. Based on these trends, Jane's assesses that there could be more than 25,000 operational satellites in space before 2027.

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**Material world**

HSI combines digital imaging with spectroscopy. Unlike collecting red, green, and blue bands of light as is done with traditional electro-optical sensors, hyperspectral sensors collect hundreds of contiguous bands of reflected and emitted energy. Certain wavelengths will display spikes in reflectance, creating unique signatures - or fingerprints - for different types of materials. Hyperspectral data are better able to discriminate signatures of objects on the Earth from multispectral data, which offer fewer data points. The ability to definitively identify an object's nature and composition is significantly enhanced.

HSI systems normally operate from within the visible spectrum of light - between 390-700 nanometres (nm) - up to a point in the long-wavelength (infrared) at 15,000 nm. Although commercial sensors are available for the entire range, they tend to be comparatively bulky and include moving parts unsuitable for use in the microgravity of space.

![Launch cost for vehicles with capacity of more than 5,000 kg](image)

The new generation of sensors, such as those produced by manufacturers including IMEC, are small, lightweight solid-state sensors weighing less than a few hundred grams, which makes them more practical for use in space. These new designs facilitate simplified production, which enables mass production. The trade-off is that these newer sensors have a smaller spectral range and are often less sensitive, which at present would limit their usefulness when based on satellites.
However, it is likely that the performance gap will close over the next five years. The current spectral range of these newer sensors is 400-1,700 nm depending on the model.

The cost of building hyperspectral imagers has also fallen. For example, in 2016, researchers from Microsoft published a paper demonstrating a low-cost hyperspectral camera that cost less than USD100 to assemble, although a camera of this sophistication would have few space-based applications.

There are only a limited number of non-military or government HSI sensors in orbit today. These include: the European Space Agency's Sentinel-3 and Flex; the Indian Space Research Organisation's IMS-1; the Belgian PROBA-1; and PRISMA for the Italian Space Agency. These satellites are generally being used to support scientific research, including for example into waterborne pollution levels.

Hyperspectral sensors have been mounted on aircraft for decades, with the earliest commercial unit being the Geophysical Environmental Research Imaging Spectrometer II, developed by the US and launched in 1987. The introduction of a hyperspectral camera system at the Paris Air Show in 2011 for the US Predator programme marked one of the earliest commercial mentions of HSI for unmanned aerial vehicles, and strongly suggested that HSI was in use by the US military and intelligence community.

**Military and intelligence applications**

The ability to determine the composition of materials from imagery has a range of implications for military and intelligence users. Analysts can compare collected sensor data with libraries of known material signatures, enabling classification. These zones can then be highlighted with a false-colour for analysis of the distribution of the material and its change over time. Software featuring these techniques and capabilities is already available in the commercial sector from companies such as Harris Geospatial, Hexagon Geospatial, and BAE Systems.

Correctly interpreted, HSI can enable an imagery analyst to determine the composition of material visible in imagery. For example, HSI can be used to determine the presence of disturbed earth or particular chemicals. The presence of certain mineral compositions in plant life can be used to infer the presence of minerals underground. The ability to detect chemicals based on their spectral signature could be used to distinguish a camouflaged vehicle from surrounding undergrowth, although the two might appear extremely similar in visual imagery.

HSI is probably already used in the identification of buried roadside bombs or improvised explosive devices (IEDs) and the detection of certain chemical attacks. In 2016, Henrik Petersson and David Gustafsson from the Swedish Defence Research Agency published a paper setting out a series of methods that can be used to detect the presence of IEDs by inspecting disturbed earth using land-based hyperspectral imagery. Similarly, Canadian company Telops sells land- and air-based hyperspectral infrared cameras that can detect the presence of methane in the atmosphere. A similar approach could potentially be used to detect the presence of airborne chemical agents.

TacSat-3 was the first US military satellite with an HSI capability, according to information in open sources. The satellite, which deorbited in April 2012, carried a system called Advanced Responsive Tactically Effective Military Imaging Spectrometer (ARTEMIS) and its associated sensor processor. A 2010 article in *Jane's International Defence Review* gave a sense of the
capability of this system, citing a member of the US Air Force Space Command as noting that by comparing data "against a catalogue of known signatures, we can unambiguously determine what things are - like knowing that brown dirt is actually a certain type of clay".

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Challenges for adoption

There are three limitations that will have to be overcome before commercial space-based HSI becomes widely available. These are: processing power, communications bandwidth, and power supply.

The amount of information collected by a hyperspectral sensor is significantly greater than with conventional electro-optical imagery. As a general rule, an hour of hyperspectral footage would generate about 1 TB of data. In 2014, one of the first commercially available solid-state hyperspectral sensors tested by Jane’s produced an output of 400 MB per second, enough to fill a 1 TB solid-state drive in a little over 40 minutes. The volume of data storage required presents a challenge for satellite designers working within strict weight limits. Similarly, hyperspectral sensors also require significant processing at the point of collection to make them viable. Given the amount of data produced, communicating this from the satellite to the ground segment using radio frequencies will continue to be a challenge.

Currently, the only solution is to store the data and bring it back to earth for processing, which limits the ability to responsively target the sensor during its mission. As such, at least in the commercial sphere, hyperspectral is not suitable for time-sensitive operations. However, it may be used in agriculture and mining, where longer timeframes are acceptable.
The last limitation is power supply. Infrared imaging systems, including hyperspectral imagers, pose a challenge in this regard, as - beyond a certain wavelength - the heat produced by the electronics will begin to distort the information the sensor collects. In space, where the only way to remove heat is to radiate it, this necessitates the implementation of expensive active-cooling systems and heat tanks. Although advances in solar technology will increase the amount of energy that can be gained from this source, it will remain a limitation, particularly on smaller satellites with smaller solar panels.

Outlook

The decreasing cost of putting technology into space suggests that the amount of commercially available imagery of the Earth is likely to increase dramatically over the next 10 years. The challenges involved in placing hyperspectral sensors on satellites are not insuperable, and indeed there is reason to believe that increases in processing power and communications efficiency will make commercial HSI increasingly widely available over the next 10 years.

In 1965, Dr Gordon Moore theorised that the complexity of integrated circuits would double every two years; Moore’s Law, as it has become known, has been generalised into a view that the processing power of computers will double every 18 months. Similarly, Cooper’s law of spectral efficiency, named after Martin Cooper, one of the inventors of the mobile phone, is the theory that the capacity of a given frequency will double every 30 months. This is a theory that has implications for HSI given the need to transmit large quantities of data from space to ground segments.

Sensors on the market have been riding their own version of Moore's Law, demonstrating exponential growth in data collection performance and cost reduction. It is, however, the rise of lightweight, lower-latency solid-state sensor technologies that is likely to make hyperspectral sensors suitable for potential space applications.

Alternatively, satellite companies may begin adopting workarounds to these limitations. These could include the use of laser-based communication systems for inter-satellite communications to help accommodate the demand for this bandwidth or to distribute tasks requiring greater processing power (cloud computing in space). Advances in spacecraft design enabling satellites to be retrieved intact from orbit would reduce the need to transmit data, as long as timeliness was less of an issue. In-flight refuelling for satellites, or laser-based satellite power grids, could solve or circumvent some of the power limitations.

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POTENTIAL USES OF HYPERSONSPECTRAL IMAGING FOR OPEN-SOURCE ANALYSIS OF NORTH KOREA

Space-based HSI has the potential to play an important role in open-source analysis of North Korea's nuclear weapons programme. Traditional visible-light spectrum products already provide considerable information about North Korea's nuclear programme. By integrating traditional red-green-blue (RGB) electro-optical imagery with other imagery products, such as hyperspectral, analysts can better understand this programme despite North Korean efforts at denial and deception. One very pressing example is North Korea's fissile material production. Although RGB and thermal infrared imagery have increased our understanding of North Korea's plutonium production reactor, uranium enrichment activities are the most difficult to monitor without on-the-ground access to facilities. Enrichment facilities have a visual signature much like other industrial buildings, which makes them difficult to positively identify through visual imagery. These medium-to-large boxy facilities are also easy to bury, hide, and disguise. Although North Korea's enrichment facility at Yongbyon is well known, it is unclear how many more enrichment facilities North Korea may have scattered around the country, if it has any at all. North Korea's mountainous terrain and use of tunnelling further complicate the search for possible secret enrichment facilities. An alternative approach is to monitor North Korea's uranium activities downstream from actual enrichment. Mining and milling processes are distinctive and visible even with RGB imagery. Furthermore, North Korea maintains a small number of mining and milling facilities. Uranium ore and its co-located minerals are visible from the surface, as are the various products used in leaching pure uranium from the ore. In addition, North Korea uses unlined tailing ponds, which could give insight into the amount of waste products released in the process. Hyperspectral data collection is already used with airborne sensors in industrial mining processes. By observing mining activities over time, outside analysts can get a sense of the amounts of materials that are being mined and milled. By cross-referencing this with trade data, analysts focusing on North Korea could attempt to determine how much material remains in the country for its nuclear weapons programme. Although it may not lead to a precise number, it would determine if North Korea's existing enrichment facility is sufficient for the amount of material being produced. There are several barriers to carrying out this research today. Spectral libraries used in hyperspectral imagery analysis contain signatures of ground materials and gases that are known to be associated with the nuclear fuel cycle. However, aerial sensors are not permitted in North Korean airspace, nor can they provide the kind of comprehensive surveillance that would be desired to detect unknown facilities. Similarly, currently operating space-based commercial or publicly available sensors are ill-suited for this task. For example, NASA's Hyperion sensor had 30 m spatial resolution data of some of North Korea's mines from 2004-07. However, it has since been decommissioned and the imagery that it provided was not of a high enough resolution to show smaller amounts of trace minerals or gases that would be used at other types of nuclear facilities. Using a constellation of space-based small-satellite hyperspectral sensors would have several advantages for this task.

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