Hyperspectral sensing – a geological point of view

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Hyperspectral sensing is a scale-independent, non-invasive and non-destructive method that is based on measuring the interaction between matter and emitted or reflected electromagnetic radiation. The resulting spectra typically have a large number of contiguous bands that can be used for material identification. The data can be acquired in different scales, ranging from millimeter-scale laboratory data to tens-of-meters -scale satellite data. The technology has evolved over 50 years together with advances in computer science and the evolution of spectrometers, resulting in smaller and more compact devices that can easily be transported in the field or mounted on drones. The technology is fast because rocks do not need to be processed prior to spectral measurements, but a lack of easy-to-use data processing tools has held the technology back.

A short history

The development of hyperspectral sensing is tightly coupled with advances in computer science and space technology. In the 1960's, in one of the groundbreaking moments in the history of hyperspectral sensing, NASA launched the Mariner 6 and 7 spacecrafts to investigate the chemical properties of Mars. The spacecrafts carried an infrared spectrometer, built at the College of Chemistry and the Space Sciences Lab of the University of California, Berkeley (American Geological Society 2017). The infrared data was transmitted back to earth to be analyzed and one of the astonishing findings was the detection of water hydrates, interpreted to be goethite, on Mars (American Geological Society 2017). This finding was sensational because it implied that there was once liquid water on Mars (American Geological Society 2017). Also associated with space technology, as noted by Goetz (2009), the impetus for the development of the hyperspectral sensing technology came from the need to support the analysis of Landsat 1 -data. Landsat, first launched in 1972, is the longest-running remote sensing programme, led by NASA and the United States Geological Survey.

One of the fundamental developments of the hyperspectral sensing technology in the 1970s, was a series of publications by Graham R. Hunt, John W. Salisbury, and Charles J. Lenhoff from US Air Force Cambridge Research Laboratories (see e.g. Hunt et al. 1971). In these papers, the researchers established the spectral features of different mineral groups, providing a tool for the interpretation of mineral spectral data. In another milestone paper (Goetz & Rowan 1981), the idea of developing a satellite system for geologic remote sensing was brought up. This pipe dream became reality in 2000 with the launch of the NASA EO-1 Hyperion satellite. Landmark publication by Kruse et al. (2002) demonstrated the usability of satellite data to detect the mineralogy of rocks.

The development of lightweight field spectrometers has been crucial for the development of the technology, as well as

Figure 1. Spectral data acquisition using a field spectrometer. Photo: Martin Schodlok.

Kuva 1. Spektrimittauksia kenttäspektrometrillä. Kuva: Martin Schodlok.

the ability to acquire airborne hyperspectral sensing data (Fig. 1). The latter became reality in the 1980s with the advent of the NASA-developed AVIRIS spectrometer (Goetz 2009). As a result of these developments, by 1982 there was already a critical mass of researchers required to organize a meeting on the topic, which eventually took place in the Environmental Institute of Michigan, USA (Environmental Research Institute of Michigan 1982). In the ensuing decades, spectrometers have become even more compact and lightweight, in addition to having increasingly high spectral resolutions to enable a more accurate identification of minerals.

Benefits and limitations

One of the indisputable benefits of hyperspectral sensing is the speed and ease of data acquisition. Passive hyperspectral sensing does not involve dangerous laser beams, and it is possible to acquire around one kilometer of imaging drill core data in a single day with a suitable setup (Fox et al. 2017). This is made possible by the scientific basis of the technology: the rock surface only needs to be relatively clean and dry, no grinding or other mechanical processing is required.

In terms of mineral exploration, the inability to directly detect sulphide group minerals, gold and other precious metals is one drawback of the technology. Because of this, hyperspectral sensing -based mineral exploration is typically based on indirect indicators, such as the alteration minerals associated with a mineralization. Here, using chemical changes in chlorite group minerals and white micas is probably the most common application.

In general, one of the limitations of the technology is that only the rock surface, until a depth of a few tens of micrometers can be detected. In this sense, the technology differs from certain geophysical methods. This limits the remote sensing -use of the technology to geographic areas with little or no vegetation or soil and is also a reason for why so much of the hyperspectral sensing -based research focuses on arid areas like Australia. However, even in areas with little rock exposure the technology is beneficial for laboratory-based mineral detection.

Data processing

Generally, hyperspectral data analysis is similar irrespective of the scale but the preprocessing methods may vary depending on whether the application is laboratory sensing or remote sensing. When analyzing remotely sensed data, the data can only be effectively used after atmospheric and geometric corrections, whereas laboratory-based data are usually ready to be analyzed after simple calibration steps.

Usually, to obtain optimal results, data should be acquired exclusively from rock surfaces cleaned of any other elements. For instance, lichens on a rock surface can effectively mask the underlying rock, and failure to take their presence into account can make data analysis challenging or impossible. One may also have to consider the effects of different illumination and viewing geometries as well as the textural and structural properties of rocks. Here, both the properties of the spectrometer, distance to the target, and the grain size of the rock will influence the results. In imaging spectrometry, the larger the pixel size and the finer grained the sample, the more spectral mixing there is between different minerals. This, in turn, can make the detection of individual minerals more challenging.

For the hyperspectral sensing data to be most effective, it needs to be accompanied by reference data. This is important because many minerals have similar spectral features, making their accurate detection challenging without an independent source of information. Such a source of information is usually X-Ray Diffraction (XRD) or Electron Probe Microanalysis (EPMA) data. Also, in remote sensing studies ground truthing data acquired using handheld spectrometers are usually needed to guide the data analysis and to validate the remotely sensed results.

Hyperspectral sensing in mineral exploration

In geology, hyperspectral sensing data can be used to map the mineralogy and mineral chemistry of rocks. The method is based on the detection of the properties of the spectral features of minerals, induced by electronic and vibrational processes within them. For a review on the topic, see Bedini (2017).

Sometimes, hyperspectral sensing in mineral exploration is understood mainly as detection of alteration minerals using the short-wave infrared wavelength region (1,300–2,500 nm). A less used wavelength region in mineral exploration is the long-wave infrared region (7,000–13,000 nm) where silicate, phosphate and carbonate minerals have distinct spectral features. Also, the visible-near infrared range (400–1,300 nm) allows for a direct detection of the rare earth elements and the iron oxide/hydroxide minerals. Hence, in mineral exploration the detection of raw materials can be either direct or indirect, the latter being more common than the former since precious metals and sulphide minerals do not have reliable spectral features that could be used for their direct detection.

Recent technological developments

Due to technical challenges related to the miniaturization of hyperspectral cameras, only recently has it become possible to acquire drone-based remote sensing data for mineral exploration. Even if drone-based remote sensing -applications have been around for much longer, the cameras have been operating in the visible-near infrared range and thus have had limited use in mineral exploration. Although it is easier to deploy a drone than a manned aircraft, these platforms are still used quite differently. The flight times of most drones are still measured in tens of minutes at most, limiting the size of the areas that can be explored using the technology. Another obstacle for the large-scale use of drones in mineral exploration is the prohibitive cost of drone-mountable short-wave infrared cameras.

Another significant development to have taken place in recent years is the emergence of lightweight handheld point spectrometers that operate in the long-wave infrared range. This has enabled field-based detection of anhydrous silicates and phosphate group minerals that are not directly detectable in shorter wavelengths. This technical development is accompanied by the onset of small, handheld imaging spectrometers, although to the knowledge of the author, none are currently available to operate in the short-wave infrared range or long-wave wavelength infrared range, limiting their usability in mineral exploration.

A third development in recent years has been the emergence of hyperspectral satellites. Between 2018 and 2025, the Chinese, Italian, Japanese, German, and US space agencies launched satellites that acquire data in wavelengths useful for mineral mapping (Cogliati et al. 2021; Storch et al. 2023; Thompson et al. 2024). There are currently also several commercial satellites acquiring hyperspectral data. This wide array of new satellites allows for a wide surface area of the Earth to be captured using different technical configurations and instrument parameters, providing new data sources for industry and academia.

Summary and future outlook

Hyperspectral sensing is a mature technology for geologic applications. Since its advent over 50 years ago, numerous technological and scientific advances have taken place, leading us to the present day status of hyperspectral satellites and miniaturized hyperspectral cameras with high spectral resolution.

One bottleneck for large-scale use of hyperspectral sensors continues to be the prohibitive cost of the spectrometers. Also, despite recent advances in artificial intelligence and machine learning, hyperspectral data analysis still requires in depth -expertise which slows down the deployment of the technology. In this respect, help may be at hand with the release of new, free-of-charge data analysis tools such as HypPy by the University of Twente (Bakker et al. 2024) and PyHAT by NASA (Laura et al. 2022).

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Tiivistelmä

Hyperspektrikuvannus – geologinen näkökulma

Hyperspektrikuvannus on menetelmä, joka perustuu aineen ja emittoituneen tai heijastuneen sähkömagneettisen säteilyn välisen vuorovaikutuksen mittaamiseen. Menetelmä on näytteeseen tunkeutumaton, ei tuhoa näytettä ja on riippumaton mittakaavasta. Hyperspektrimittausten tuloksena syntyvissä spektreissä on tyypillisesti suuri määrä yhtenäisiä kanavia, joita voidaan käyttää materiaalien tunnistamiseen. Dataa voidaan kerätä eri skaaloissa, millimetriskaalaisista laboratoriomittauksista satelliittidataan, jonka spatiaaliresoluutio on tyypillisesti kymmeniä metrejä. Hyperspektriteknologia on kehittynyt viimeisten 50 vuoden aikana samanaikaisesti tietojenkäsittelytieteen ja instrumentaation myötä. Modernit spektrometrit ovat niin pieniä, että niitä voi helposti käyttää kentällä tai asentaa lennokkiin. Hyperspektrikuvannus on menetelmänä nopea, koska näytteitä ei tarvitse käsitellä ennen mittauksia, mutta helposti saatavilla olevien datankäsittelytyökalujen puute on hidastanut menetelmän käyttöönottoa.

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