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Earth Observation Imaging Spectroscopy for Terrestrial Systems: An Overview of Its History, Techniques, and Applications of Its Missions

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Abstract

Imaging spectroscopy in the visible-to-shortwave infrared wavelength range (VSWIR), or nowadays more commonly known as 'hyperspectral imaging', for terrestrial Earth Observation remote sensing, dates back to the early 1980s when its development started with mainly airborne demonstrations. From its initial use as a research tool, imaging spectroscopy encompassing the VSWIR spectral range has gradually evolved towards operational and commercial applications. Today, it is one of the fastest growing research areas in remote sensing owing to its diagnostic power by means of discrete spectral bands that are contiguously sampled over the spectral range with which a target is observed. The main principles of imaging spectroscopy rely on the exploitation of light dispersion technologies to split the incoming light through a telescope before being projected onto detector arrays. The light dispersion can be achieved by using prism or diffractive grating optical systems, perpetually aiming for improved performances in terms of efficiency, straylight rejection, and polarization sensitivity. The sensor technique has been first used in airborne imaging spectroscopy since the early 1980s and later in spaceborne hyperspectral missions from the end of the 1990s onwards. Currently, several hyperspectral spaceborne systems are under development and in preparation to be launched within the next few years. Through hyperspectral remote sensing, physical, chemical, and biological components of the observed matter can be separated and resolved thus providing a spectral 'fingerprint'. The analyses of the spectral absorptions often give rise to quantitative retrievals of components of the observed target. The derived information is vital for the generation of a wide variety of new quantitative products and services in the domain of agriculture, food security, raw materials, soils, biodiversity, environmental degradation and hazards, inland and coastal waters, snow hydrology and forestry. Many of these are relevant to various international policies and conventions. Originally developed as a powerful detection and analysis tool for applications predominantly related to planetary exploration and non-renewable resources, imaging spectroscopy now covers many disciplines in atmospheric, terrestrial vegetation, cryosphere, and marine research and application fields. There is an increasing number of visible/near-infrared (VNIR) imaging spectrometers emerging also as small payloads on small satellites and cubesats, built and launched by small-medium enterprises. These are targeted to address commercial applications mainly in agriculture, resources and environmental management, and hazard observations.

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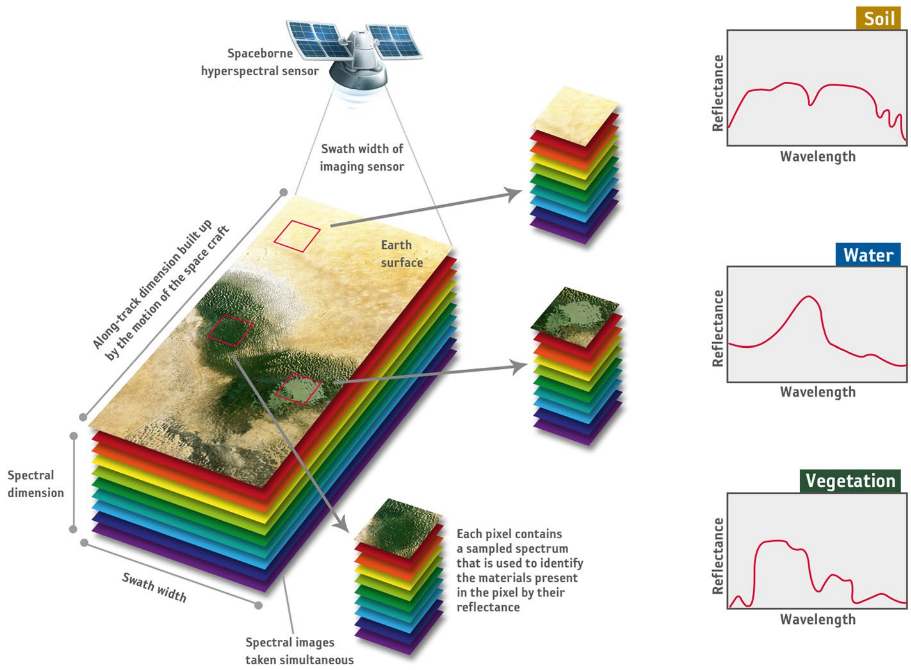

Fig. 1 Imaging spectroscopy—principle of observation (ESA Earth Observation Graphic Bureau)

Keywords Earth observation · Satellite remote sensing · Imaging spectroscopy · Terrestrial ecosystems

1 Introduction

Imaging spectroscopy entails quantitative sensing of the target in the optical range of the electromagnetic spectrum (visible through shortwave infrared) with contiguous, gapless spectral sampling from the visible to the shortwave infrared portion of the electromagnetic spectrum. With this complete spectrally resolved sampling of reflected radiation, imaging spectroscopy is the asymptote concept of passive optical remote sensing, with the only direction forward being improvements in resolutions (spectral, spatial, and radiometric). With a much larger number of spectral sampling intervals or so-called spectral bands than is commonly applied with multispectral remote sensing systems, such as those onboard the US Landsat series or the European Copernicus Sentinel-2 satellites (Drusch et al. 2012), imaging spectroscopy today enables the markedly greater diversity of geophysical, geo-biophysical, and geo-biochemical observation and monitoring of the surface (see Fig. 1). An imaging spectrometer can be defined as an instrument that acquires images in dispersed multiple contiguous spectral bands with high spectral resolution (Goetz et al. 1985; Vane and Goetz 1988; Van der Meer and De Jong 2011).

With increasingly well-established spectroscopic techniques, optical remotely sensed imaging spectroscopy can deliver significant enhancement in quantitative value-added products. This will support the generation of a wide variety of new products and services in the domain of agriculture, food security, water resources, raw material resources, soils, biodiversity, environmental degradation and hazards, inland and coastal waters, urban environments and forestry. Such products are relevant to various EU policies that are currently not being met or can be significantly improved, and also to the downstream private sector.

Hyperspectral imaging has already supported or been used for a large range of applications (to name a few: Asner et al. 2017; Chang 2007; Giardino et al. 2018; Green et al. 2006; Hochberg et al. 2015; King et al. 2014; Ong et al. 2003; Painter et al. 2016; Roberts et al. 2012; Swayze et al. 2000; Ustin et al. 2004). Based on successful airborne deployments over the last three decades and the past satellite missions along with preparatory activities of some national demonstrative satellite missions, hyperspectral imaging from satellite is now ready for operational use.

In general, the application potential of a hyperspectral mission is a direct result of adding an increased number of narrow spectral (contiguous) bands with a relatively high signal-to-noise ratio (SNR) to the conventional passive optical multispectral remote sensing missions, such as Sentinel-2 and Landsat, thereby allowing direct and indirect identification of target compositions and quantities (see Fig. 2).

With hyperspectral remote sensing physical, chemical and biological components of the observed matter can be separated and resolved thus providing a spectral 'fingerprint'. The analyses of the spectral absorptions also often give rise to quantitative retrievals of components of the observed target. Key environmental information can be derived and quantified from the measured spectral signal, e.g., directly through distinct absorption features or indirectly, through inversion, assimilation, spectral un-mixing, and/or (de-) correlation

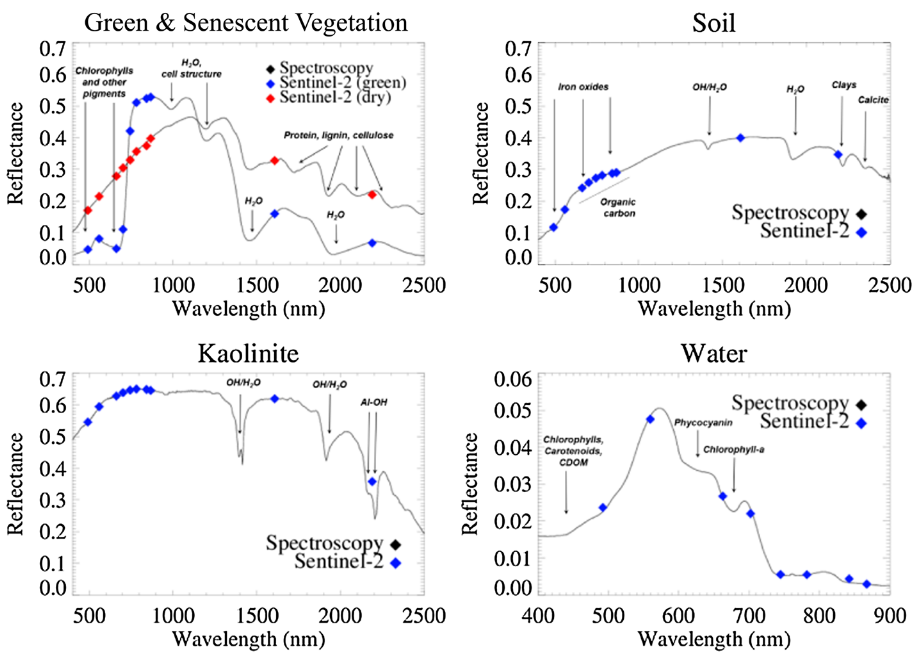

Fig. 2 Reflectance spectra for different Earth surface materials at high spectral resolution and resampled to the spectral response of the multispectral instrument onboard Sentinel-2 (courtesy L. Guanter, GFZ—Helmholtz Centre Potsdam)

techniques. Potential supported policies comprise the UN Sustainable Development Goals (SDGs) and the European Commission Common Agricultural Policy (CAP).

The objective of this paper is to provide an overview of (terrestrial) imaging spectroscopy for geo-scientific applications, more specifically, about its principles (Sect. 2), instrument concepts (Sect. 3), past, current, and planned airborne and spaceborne imaging spectrometers (Sect. 4), the main applications fields (Sect. 5), and future observational requirements (Sect. 6).

2 Principles of Imaging Spectroscopy

Spectroscopy is defined as the study of light as a function of wavelength that has been emitted, reflected, or scattered from a solid, liquid, or gas. In remote sensing, the quantity most used is (surface) reflectance (expressed as a percentage). Spectroradiometry is the associated technology for measuring the power of optical radiation in narrow, contiguous wavelength intervals. The quantities measured are usually expressed as spectral irradiance (commonly measured in W m^{-2} nm^{-1}) and spectral radiance (commonly measured in W sr^{-1} m^{-2} nm^{-1}) (Schaepman 2009).

Remote, direct identification of surface materials on a picture element (pixel) basis can be accomplished by proper sampling of absorption features in the reflectance spectrum following atmospheric correction of the obtained at-sensor radiance values. The airborne and spaceborne sensors are capable of acquiring images simultaneously in 10 s to 100 s of contiguous bands (for instance the US Airborne Visible/InfraRed Imaging Spectrometer—AVIRIS—acquires 224 bands, 210 remaining after removing the overlaps between spectrometers). The ability to acquire laboratory-like spectra remotely has become a major advance in remote sensing capability (Goetz et al. 1985).

The objective of imaging spectroscopy is to measure quantitatively the components of the Earth system from calibrated spectra acquired as images for scientific research and applications. The radiance of reflected solar electromagnetic energy from the Earth's surface is dispersed in a spectrometer and used to form contiguous, inherently registered spectral images of the scene over the VSWIR spectral range. Each picture element in the scene has associated with it sufficient information for the reconstruction of a complete reflectance spectrum. The value of this technique is that it allows the diagnostic narrow-band spectral features that are present in most terrestrial materials to be used to uniquely identify those materials (Vane and Goetz 1988). These spectral features are typically 20–40 nm in width at the half-band depth (Hunt 1980).

Spectral imaging systems that acquire data in contiguous 10-nm-wide spectral bands can, therefore, produce data with sufficient resolution for the direct identification of those materials with diagnostic features. Conversely, multispectral sensors, with broader spectral bands can not resolve these features because their spectral bandwidths are often as broad as 100–200 nm. Moreover, in multispectral systems the spectral bands are non-contiguously dispersed over the sensor's spectral range (Vane and Goetz 1988).

Starting in the early 1970s, the power of spectroscopic mineral analyses, where charge transfer bands in the ultraviolet and electronic transitions at longer wavelengths of minerals were analysed and diagnostic spectral features appeared as results of either electronic or vibrational processes, was mainly applied in the laboratory (Rast 1991). In the early 1980s, the capacity of spectroscopy analysis was transferred onto airborne imaging systems for the observation of terrestrial and aquatic ecosystems (Vane et al. 1984).

3 Instrument Concepts and Calibration

Imaging spectrometers usually consist of four major elements: A front optic that collects the signal emerging from the observed target/scene; a dispersive element that splits the incoming signal into narrow spectral intervals; an optical component focusing the dispersed signal; and a detector assembly, which is located in the focal plane.

3.1 Instrument Concepts

Three general types of imaging spectrometer systems are used for observations from aircraft and satellite (personal correspondence with U. Del Bello, ESA-ESTEC, Del Bello et al. 2003; Kunkel et al. 2000; Schaepman 2009; Eismann 2012; Rast et al. 2004):

3.1.1 Prism or Grating Spectrometers

In a dispersive imaging spectrometer, two types of dispersive elements are used for the spectral separation of the incoming signal: prism or grating. In prism-based imaging spectrometers, the incoming signal/light is projected onto a prism, resulting in angular dispersion of the incident light into different wavelength components. The thickness of the glass prism and its wedge shape contribute to aberrations in such instruments. To minimize aberrations over the field, imaging spectrometers sometimes employ a combination of prisms with curved surfaces.

In grating-based imaging spectrometers, the spectral dispersion can be varied by modifying the grating design. Blazed grating are used to increase the diffraction efficiency over a limited spectral interval.

Drawbacks of gratings are the emergence of multi-order diffraction, which is mitigated by filters. There are different types of gratings, i.e. convex gratings, volume phase holographic gratings, and spherical transmission gratings.

3.1.2 Fourier Transform Interferometers

Fourier transform interferometers split the incoming radiation into two beams, introducing a controlled phase shift, and recombining them generating interference and introducing sinusoidal variations in spectral transmission, depending on the wavelength and the optical path-length difference in the interferometer. The light intensity is modulated by the path difference of the two beams, and the amplitude of the signal is sampled at an appropriate sampling rate during the acquisition. Subsequently, a Fourier transform converts the amplitude-modulated signal into a frequency spectrum. Not limited by a dispersing component, Fourier transform interferometers have a high spectral resolution and a high optical throughput and spectral accuracy. However, the sampling scheme of Fourier transform interferometers over an extended time period for each sample of a scene along-track in the absence of an entrance slit is of disadvantage and necessitates intensive raw image data processing.

3.1.3 Narrow-Band Adaptive Filters

There are various types of filter imaging spectrometers, which are strictly speaking not falling under the definition of a spectrometer, since the incoming light is not dispersed or 'broken up' into its wavelength components, but through filtering into the discrete wavelengths desired:

- A linear variable filter or wedged filter is a band-pass filter in which the thickness of the filter coating varies linearly along its length so that the spectral content transmitted through it varies in that direction resulting in principle in an unlimited number of different filters. The number of separate spectral channels depends solely on the number of elements in the detector array. The transmission characteristic of a linear variable filter varies with the incidence angle of the incoming light and usually has a moderate spectral resolution of a few tens of nanometres.
- An acousto-optic tunable filter is a pass-band transmission filter, which exploits the acousto-optic interaction inside an anisotropic medium. It consists of a birefringent crystal, onto which a piezoelectric transducer is bonded. The acoustic waves that are generated by means of the transducer create a periodic modulation of the index of refraction in the crystal, and therefore a moving phase grating (or diffraction grating). For a given acoustic frequency, only a limited optical wavelength band can satisfy the phase matching condition and can, as a consequence, be diffracted. The frequency of the excitation source is varied to change the period of the grating formed and thus select the required transmission wavelength. The advantage of acousto-optic tunable filters is the short response time (typically microseconds) and the consequent fast spectral band selection. For a large number of spectral bands, however, the measurement time significantly increases and the optical throughput is generally low.
- A Fabry–Perot interferometer is the basis of tuned etalon spectral imagers. The etalon, composed of two plane parallel partially reflecting surfaces with a precise spacing between them, is the core element of the Fabry–Perot interferometer. It produces very narrow bands and filter characteristics, and central wavelength and bandwidth can be tuned by varying the separation between the parallel surfaces or by electrically controlling the refractive index of the etalon material. It has a limited field of view owing to the light transmission being dependent on the angle of incidence and its sensitivity to temperature variation. Moreover, the operating wavelength range is rather limited.

3.2 Calibration

In order to be able to carry out a quantitative assessment of imaging spectroscopy data and to validate geo-biophysical observations, the measurement values obtained must be accurate in both a relative and absolute sense. Two major factors influence the representativeness of these data, namely the atmospheric influence and the properties of the sensors system including its carrier (Thome 2001).

Absolute and relative radiometric calibration of a hyperspectral imaging system can in principle be provided by repeated observations of well-documented and calibrated ground targets. The spectrometers flown in space so far indicate, however, that onboard calibration is highly desirable, since it is independent from the correction of atmospheric and on-ground morphology effects. Moreover, onboard calibration provides accurate monitoring of the system degradation, which is specifically important for spaceborne systems susceptible to degrading influences such as hard radiation (Guanter et al. 2006).

Radiometric calibration is commonly provided using reflectance-calibrated sun diffusers deployed in the optical path of the system. More than one diffuser is often implemented, in order to employ one less frequently deployed diffuser to check for, e.g., effects of Sun exposure on the more frequently used radiance diffuser's reflectance (Delwart et al. 2004).

Dark current calibration is often provided involving the system's shutter. The drift of the dark current between calibrations is often monitored using non-illuminated or covered lines on the spectrometer's detector. Non-illuminated detector areas may also be used to assess stray light in comparison with pre-flight predictions (Rast et al. 1999).

Spectral calibration requirements often include in-flight characterization of wavelengths imaged on detector elements using onboard spectral sources, such as a set of lasers, illuminated diffusers, or doped diffusers. However, sufficiently accurate wavelength calibration can be achieved using atmospheric absorption features (and possibly some deeper solar Fraunhofer lines).

In addition to the various onboard calibration devices, such as solar diffusers, lamps or LEDs, lunar observations can be employed to monitor reflective solar band on-orbit calibration stability and to specifically independently track the performance of solar diffuser calibration. This approach has successfully been used for the calibration of MODIS on the Terra and Aqua satellites, for the Visible Infrared Imaging Radiometer Suite (VIIRS) on the Suomi National Polar-orbiting Partnership (S-NPP) (Xiong et al. 2016) and for Hyperion on EO-1 (Kieffer et al. 2002). The Moon is considered to be a very stable radiometric reference in the VIS/NIR spectral regions (Kieffer 1997), being viewed by the satellite sensors mostly through a dedicated port in the spacecraft regularly and at very similar phase angles, which can be achieved by in-orbit spacecraft manoeuvres (Sun and Xiong 2011).

4 Past, Current and Future Hyperspectral Airborne and Spaceborne Systems

4.1 Airborne Imaging Spectrometers

Most imaging spectroscopy over the last 30 years has been based on airborne spectrometers covering the visible and near-infrared (VNIR) and, in many cases, also the shortwave infrared (SWIR) spectral ranges (~400–1000 nm and 1000–2500 nm, respectively). Since the 1980s, developments in VNIR and SWIR spectrometers were initiated by the US Airborne Imaging Spectrometer AIS-I (Vane and Goetz 1985), built by JPL, which flew from 1982 to 1985 and the Canadian Fluorescence Line Imager (FLI) by Moniteq Ltd., CDN (Gower et al. 1992), which flew from 1983 to 1990. In particular, the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS), designed by NASA JPL in California and operated under NASA contract since 1986, has been a 'trailblazer' for airborne imaging spectroscopy since the late 1980s in a large number of airborne deployments and field campaigns.

The most widely used in the last few years have been the Australian HyMAP (Cocks et al. 1998), the Compact Airborne Spectrographic Imager (CASI) by ITRES Research Ltd., CDN (Gower et al. 1992) and the Airborne Prism Experiment (APEX), by University of Zürich, CH and VITO, BE (Schaepman et al. 2015). Building upon AVIRIS, the Airborne Visible Infrared Imaging Spectrometer—Next Generation (AVIRIS NG) has been developed to eventually replace the AVIRIS instrument with an improved radiometric performance and a higher spectral sampling interval of 5 nm. One of the major assets of AVIRIS, as well as AVIRIS NG, is that the sensors can be flown on lower flying aircraft (e.g., Twin Otter) but also on high-altitude airborne platforms (e.g., ER-2).

In addition, other well-known sensor systems, such as the US built Digital Airborne Imaging Spectrometer (DAIS) by GER Corp. USA (Chang et al. 1993), the German Reflective Optics System Imaging Spectrometer (ROSIS) by German industry and research institutions (Gege et al. 1998), the Finnish Airborne Imaging Spectrometer for Applications (AISA) by SPECIM (Makisara et al. 1993), the US Hyperspectral Digital Imagery Collection Experiment (HYDICE) (Rickard et al. 1993), the Italian Multispectral Infrared Visible Imaging Spectrometer (MIVIS) (Bianchi et al. 1996), as well as the Airborne Hyperspectral Scanner (AHS) (Fernández-Renau et al. 2005), both by Deadalus Inc., US, and the NASA Portable Remote Imaging Spectrometer (PRISM) (Mouroulis et al. 2014), were used in many airborne deployments for research, for commercial applications and as test-beds for spaceborne imaging spectrometer concepts studied worldwide.

In the early 2000s, the coupling of VNIR/VSWIR imaging spectrometers with scanning lidar became more prevalent, as for instance in the Carnegie Airborne Observatory (CAO), which provides an in-flight fusion of a VSWIR imaging spectrometer data with a scanning waveform LiDAR for ecosystem research (Asner et al. 2007), the National Ecological Observatory Network (NEON) on the Airborne Observation Platform (AOP) with again a VSWIR imaging spectrometer, a scanning small-footprint waveform LiDAR for 3-D canopy structure measurements and a high-resolution airborne digital camera (Kampe et al. 2010) and the Airborne Snow Observatory (ASO), a coupled visible/near-infrared imaging spectrometer and scanning LiDAR, combined with distributed snow modelling, developed for the measurement of snow spectral albedo/broadband albedo and snow depth/Snow Water Equivalent (Painter et al. 2016).

From the end of the 1990s, the encouraging results and advances made by means of this observation technique led to the launch of the first generation of spaceborne imaging spectrometers with mainly HYPERION on the US—Earth Observing-1 (EO1) satellite (2000), the European CHRIS (Compact High-Resolution Imaging Spectrometer) on PROBA-1 (2001), or in dedicated application domains MERIS on Envisat (2002), and MOS on IRS-P3 (1996). Today, the US AVIRIS NG and the European APEX count to the best performing and calibrated airborne imaging spectrometers. They have besides fulfilling their scientific application campaign objectives also provided the test-bed for mission requirements analyses for future spaceborne Imaging Spectrometer concepts, such as the US HIRIS and HyspIRI and the European LSPIM and SPECTRA.

In addition to the aforementioned VNIR and SWIR spectrometers, various hyperspectral mid- to thermal Infrared sensors in the 2–14 µm spectral range have been developed. These include the Spatially Enhanced Broadband Array Spectrograph System (SEBASS), intended to explore the utility of hyperspectral infrared sensors for remotely identifying solids, liquids, gases, and chemical vapours in the 2 to 14 µm spectral region (Hackwell et al. 1996), the airborne thermal infrared imaging spectrometer, 'Mako', with 128 bands in the thermal infrared covering 7.8 to 13.4 µm (Hall et al. 2011) and the Hyperspectral Thermal Emission Spectrometer (HyTES), developed as part of the activities associated with the Hyperspectral Infrared Imager (HyspIRI) of the NASA's Tier 2 Decadal Survey Missions for Earth science (Hook et al. 2013).

More recently, the use of Unmanned Airborne Vehicles (UAVs) has been increasing and it is to be expected that these will constitute a significant part of airborne imaging spectroscopy, in particular as the instruments are increasingly more compact and comparably lightweight (Adão et al. 2017).

4.2 Spaceborne Imaging Spectrometers

Over the last two decades, several true dispersive element Imaging spectrometer missions have been flown in space (Staenz et al. 2013), of which the most prominent ones include:

MOS: The Multispectral Optoelectronic Scanner (MOS) was an experimental imaging pushbroom spectrometer for VNIR/SWIR range observations, developed by DLR (German Aerospace Center). The objective was to monitor the Earth's surface (surface–atmosphere interaction, ocean colour, phytoplankton, regional and global distributions of man-made aerosols and their links to gaseous admixtures, spectral and spatial cloudiness characteristics, etc.) in the VNIR/SWIR region of 400–1600 nm. It featured 18 spectral bands, four of which in the NIR had 1.4 nm, 13 bands in the VNIR with 10 nm and one band in the SWIR with 100 nm. The sensor had a 200-km swath and was launched on the Indian satellite IRSP-3 in March 1996. Its operation ended in March 2004 (Zimmermann and Neumann 2000).

Hyperion: Launched onboard EO-1 in November 2000, the pushbroom imaging spectrometer Hyperion was built by Northrup Grumman (formerly TRW), USA, as a technology demonstration mission with an estimated 1-year lifespan and completed over 16 years of successful operations. Hyperion featured a grating imaging spectrometer encompassing the 400–2500 nm spectral range with a spectral resolution of 10 nm in VNIR and SWIR at 7.5 km swath width and a spatial resolution of 30 m. It was operated as the heritage orbital spectrometer for future global platforms, including the proposed NASA Hyperspectral Infrared Imager (HyspIRI) concept and the forthcoming German satellite, EnMAP until the spacecraft was decommissioned in March 2017 (Pearlman et al. 2003; Middleton et al. 2013).

CHRIS: The Compact High-Resolution Imaging Spectrometer (CHRIS) is a hyperspectral instrument developed and built by former Sira Electro-Optics Ltd., later SSTL, UK. With the objective to collect Hemispherical Conical Reflectance Factor data (as sample to estimate Bidirectional Reflectance Distribution Function) for a better understanding of surface spectral reflectance, CHRIS was launched in October 2001 onboard the European Space Agency (ESA) 'On-Board Autonomy' mission PROBA. It is operating until today. The initial technology objective was to explore the capabilities of imaging spectrometers on agile small satellite platforms. CHRIS' full programmability of its spectral bands provides 63 spectral bands with 34 m resolution, or 19 bands with 18 m resolution over a 13-km swath, or 37 bands with 18 m resolution over a 6.5-km swath in the VNIR range (400–1050 nm) (Cutter 2006).

MERIS: MERIS was a pushbroom wide-field imaging spectrometer launched onboard the ESA Envisat satellite in March 2002 to observe the ocean, land surfaces and clouds with high spectral resolution. Developed and built by former Aerospatiale (F), MERIS had individual gain settings to optimize the dynamic range of each of its fifteen spectral bands, which were fully programmable in width and position over its spectral range of 390–1040 nm. The total swath was covered by five identical modules (cameras) each having a 14° FOV, with 0.4° overlap between adjacent cameras resulting in a total swath of 1150 km. MERIS had a dual spatial resolution of 300 and 1200 m. After onboard digital conversion, the data were corrected in real-time with the calibration coefficients to produce raw image data in 15 spectral bands (Rast et al. 1999). MERIS operations ended in April 2012 with a loss of the communication link with the Envisat satellite.

HICO: The Hyperspectral Imager for the Coastal Ocean (HICO) was developed by the Naval Research laboratory, USA, and implemented on the International Space

Station (ISS) in September 2009. It was the first spaceborne imaging spectrometer designed to acquire data over coastal regions at 90 m spatial resolution over the 380 to 960 nm spectral range with a 5.7 nm spectral resolution. As a technical demonstrator, HICO was designed to collect one 50×200 km scene per orbit. The regions to be collected were determined weekly by a scheduling team. During its operation, which ended in September 2014, HICO collected over 10,000 scenes from around the world (Corson et al. 2008).

So far, **Hyperion** onboard NASA's Earth Observing-1 (EO-1) spacecraft, which was operated until 2017, and the Compact High-Resolution Imaging Spectrometer (**CHRIS**) on ESA's Proba-1 microsatellite have been the main spaceborne providers of space-based hyperspectral data for terrestrial ecosystem observations over the last few decades. Both missions have exceeded their planned one-year lifetime by far and have despite of some shortcomings in sampling capacity and some of the performances been very valuable sources of publicly available spaceborne imaging spectrometer data.

In May 2018, China launched the meteorological satellite 'Gao Fen-5'. Among the six payloads on Gaofen-5 is the Advanced Hyperspectral Imager (AHSI), a VSWIR spectrometer, with 400–2500 nm spectral range, a spectral resolution of 5 nm in the VNIR and 10 nm in the SWIR, approximately 300 spectral bands, a spatial resolution of 30 m and 60 km swath width (personal communication with A. Skidmore, Univ. Twente and Andy Zmuda, ESA-ESRIN). At the time of this paper's submission, unfortunately no official publication reference for this mission could be obtained (Fig. 3).

The most recently launched spaceborne spectrometer is the DLR Earth Sensing Imaging Spectrometer (**DESIS**) for coastal zone/aquaculture, land use/cover and forestry monitoring launched in June, and operating since August 2018. DESIS is a VNIR spectrometer built by DLR to be deployed on the International Space Station ISS, with a 30 m resolution over a 30-km swath and 235 spectral bands, each 2.55 nm wide in the spectral range between 400 and 1000 nm (Müller et al. 2016).

Looking towards the future, with a launch planned in early 2019, one of the upcoming terrestrial hyperspectral imaging space-based mission in Europe will be the Italian **PRISMA** (PRecursore IperSpettrale della Missione Applicativa). PRISMA will be a pre-operational system and a technology demonstrator, which will focus with its acquisition on the Euro-Mediterranean Regions. The system will cover a 400–2500 nm

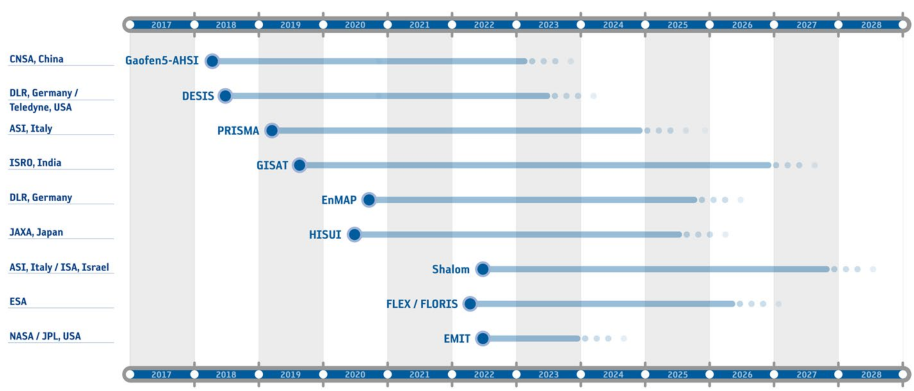

Fig. 3 Recently launched and planned/approved spaceborne Imaging Spectrometers (ESA Earth Observation Graphic Bureau)

spectral range with 237 spectral bands at a variable spectral bandwidth between 6 and 12 nm, and a 30 m spatial resolution over a 30-km swath (Pignatti et al. 2013).

Also planned for launch in 2019 is the Indian geostationary Imaging Spectrometer **GISAT**, which is expected to provide near real-time images over India sector-wise every 5 min and the entire Indian landmass covered every 30 min at 50 m to 1.5 km spatial resolution, depending on the spectral bands used. Application objectives include disaster monitoring, natural hazards and any short-term events (Misra 2017).

As another imaging spectrometer to be mounted on the ISS, the Hyperspectral Imager Suite (**HISUI**), developed by Japanese Ministry of Economy, Trade, and Industry (METI) will be launched in early 2020. HISUI consists of a Hyperspectral and a Multispectral Imager. The Hyperspectral Imager has 185 bands in the 400–2500 nm region with 30 m spatial resolution and 30 km swath. Cross-calibration with DESIS is planned (Matsunaga et al. 2017).

Subsequently, towards the end of 2020, the German Environmental Mapping and Analysis Program (**EnMAP**) is expected to be launched. It will cover a 30-km-wide area in the across-track direction with a ground sampling distance of 30 m over its 400 to 2500 nm spectral range, with 244 spectral bands and a spectral sampling interval varying from 6.5 to 10 nm. Although primarily science-driven, the EnMAP mission will also address applications beyond scientific issues (Guanter et al. 2015).

PRISMA and EnMAP will co-exist with other comparable and complementary missions, such the Italian-Israeli Spaceborne Hyperspectral Applicative Land and Ocean Mission **SHALOM**, which is planned for launch in 2022 with a focus on operational and commercial use. With 10 m spatial resolution over a 30-km swath, the mission covers the spectral range between 400 and 2500 nm with 275 spectral bands, focusing on ecosystems primarily in the coastal zone (Feingersh and Ben-Dor 2015).

In the framework of its Earth Observation Envelope Programme, in 2015 ESA selected the Fluorescence Explorer **FLEX** as its eighth Earth Explorer Mission for launch in 2022. FLEX carries a fluorescence spectrometer (**FLORIS**) to map vegetation fluorescence for quantifying photosynthetic activity, leading to better insight into plant health and stress. FLORIS acquires data in the 500–780 nm spectral range with a high spectral resolution of ~ 0.3 nm around the Oxygen absorption bands. Other spectral areas with less pronounced absorption features will be measured at medium spectral resolution between 0.5 and 3 nm. FLORIS will provide imagery with about 300 m spatial resolution over a swath width of at least 105 km (Kraft et al. 2017).

As one of the two NASA's Earth Venture Instruments, the Earth surface Mineral dust source InvesTigation (**EMIT**) (Green 2018) will use a VSWIR imaging spectrometer mounted to the exterior of the ISS to determine the mineral composition of natural sources that produce dust aerosols around the world. By measuring in detail which minerals make up the dust, EMIT, which is slated for launch to the ISS in 2022, will help to answer the essential question of whether this type of aerosol warms or cools the atmosphere through constraint of regional and global climate modelling.

In early 2018, the US National Academies of Sciences, Engineering, and Medicine released the 2017 Earth Science Decadal Survey, providing a distillation of the broader Earth Science community's recommendations for required measurements in the coming decade (National Academies of Sciences, Engineering, and Medicine 2018). Among these is a measurement concept, entitled Surface Biology and Geology (SBG), that will use a pointable VSWIR imaging spectrometer in polar orbit to address cutting edge science in ecosystems, the cryosphere, the hydrosphere, and solid Earth. This concept replaces the Hyperspectral Infrared Imager (HyspIRI) that has been in intensive study over the last decade (Green et al. 2013).

Since 2017, an evolution of the Copernicus Space Component is foreseen for the mid-2020s by the European Commission (EC), in order to meet priority user needs not addressed by the existing Earth observation infrastructure from space. The EC together with ESA is studying six Copernicus high-priority mission candidates. One of them is the Copernicus Hyperspectral Imaging Mission for the Environment (CHIME) with the goal to provide routine hyperspectral observations through the Copernicus Programme in support of EU- and related policies for the management of natural resources, assets, and benefits. This unique VIS-SWIR spectroscopy-based observational capability will in particular support new and enhanced services for food security, agriculture, and raw materials. This includes sustainable agricultural and biodiversity management, soil properties characterization, sustainable mining practices, and environment preservation (CHIME MAG 2018).

Furthermore, the French HYPXIM (Carrere et al. 2013), the China Commercial Remote-sensing Satellite System (CCRSS) and the planned Imaging Spectrometer on the Indian Cartosat-3 are among others additional Imaging Spectrometer concepts under development.

An overview of the most recently launched, planned and approved terrestrial spaceborne imaging spectrometer missions is shown in Fig. 3.

5 Hyperspectral Applications

Through the large spectral range that imaging spectrometers cover, there is a wide field of geo-scientific applications encompassing the atmosphere, biosphere, geosphere, hydrosphere, and cryosphere. Some of the main application fields, to which imaging spectroscopy can make major contributions are briefly addressed in the following sections. There are several papers in this Special Issue on ‘Space-borne Imaging Spectroscopy for exploring the Earth’s Ecosystems’ by the International Space Science Institute (ISSI) addressing these applications in detail.

5.1 Vegetation

The properties of plant canopy structure are highly important for ecosystem and vegetation functioning studies. They affect most processes that couple plants to their environment, such as radiation interception and hence photosynthesis and evapotranspiration (Asner et al. 2009) and also provide useful information for the detection of water and nitrogen contents and related stress in plants (Field et al. 1992). One of the key variables in this context is the Leaf Area Index (LAI), controlling many biological processes in plant canopies and characterizing the structure and the functioning of vegetation, with implications in the prediction of plant growth and productivity estimations. Benefits and improvements in the estimation of LAI by hyperspectral data, as compared to multispectral data, are expected in the reduction of soil influence and atmospheric effects, the distinction from competing influences of pigments (e.g., chlorophyll) on canopy reflectance and the reduction of the saturation of vegetation indices for high LAI values (Lee et al. 2004).

Owing to the importance of pigments for photosynthetic function, variations in pigments content can provide information on the physiological state of leaves or plants. Generally, when plants are under stress or during leaf senescence, the content of, and proportions between, individual pigments (chlorophylls and carotenoids) changes correspondingly (Chapin 1991). Leaf chlorophyll density, i.e. the amount of chlorophyll a and b per unit leaf area, is sensitive to soil nitrogen availability, making it probably the most effective biophysical indicator of nitrogen deficiency (Schepers et al. 1996). The fact that the spectral absorbance properties of chlorophyll are apparent in the reflectance spectra of leaves offers the opportunity of using hyperspectral measurements for quantifying chlorophyll concentration in plants (Zarco-Tejada et al. 2001; Colombo et al. 2008). In addition to chlorophyll, hyperspectral data allow the estimations of other pigments, such as carotenoids and anthocyanin (Ustin et al. 2004), which reveal information on photosynthetic and plant stress.

Studies have demonstrated that a high spectral resolution, i.e. the use of narrow bands, is essential to discriminate leaf biochemical components. Nitrogen has long been recognized as the limiting nutrient for plant growth (Heimann and Reichstein. 2008), and thus its monitoring has been a long-term objective for imaging spectroscopy. NASA's Accelerated Canopy Chemistry Program (ACCP 1994) was established in 1991–1992 to estimate nitrogen and lignin concentrations in vegetation from for example AVIRIS (Martin and Aber 1997; Kokaly et al. 2009). Several papers have since reported the detection of nitrogen from imaging spectroscopy (Feng et al. 2008; Kokaly et al. 2009; Schlerf et al. 2010). The detection of other biochemical constituents, which benefit from hyperspectral imaging include the distinction of Carotenoid content from Chlorophyll (content) (Asner et al. 2012; Asner and Martin 2016), and plant functional types (Schweiger et al. 2016), since broadband indices are unable to exploit the subtle spectral features of these pigments. A comprehensive review of the applications of imaging spectroscopy for vegetation can be found in Ustin et al. 2004.

Information on light use efficiency and the concept of fraction of photosynthetically active radiation (PAR) absorbed for vegetation photosynthesis can also be addressed with improved accuracy through the use of hyperspectral data, for example by using the Photochemical Reflectance Index (PRI) (Gamon et al. 1992). The PRI has been proposed to detect the relative downregulation of photosynthesis and has also shown good potential in early water stress detection (Gamon et al. 1997; Suárez et al. 2009). Moreover, hyperspectral data will determine improvement of plant classification, exploring automated techniques incorporating expert knowledge on biophysical variables dynamics (e-GEOS 2018). In addition to plant functioning and structure, imaging spectroscopy has also been used for mapping invasive species (Somers and Asner; Ustin et al. 2004), forest degradation and drought impacts with Hyperion (Asner et al. 2009), and vegetation and land cover mapping such as the vegetation map over California using AVIRIS data (Roberts et al. 1998).

5.2 Agriculture and Food Security

In the context of the main elements of food security (i.e. availability, access, utilization, and stability), spectroscopic techniques can be used to accurately identifies crops (Thenkabail et al. 2000; Miglani et al. 2008), grasslands species (Schmidt and Skidmore 2010; Thenkabail et al. 2004), and to exploit spectral absorption features from leaf pigments (e.g., Chapin 1991; Schepers et al. 1996; Ustin et al. 2004), water content (Gao and Goetz 1995; Serrano et al. 2000; Ustin et al. 1998) and biochemical compounds (Feng et al. 2008; Asner et al. 2012; Asner and Martin 2016; Schweiger et al. 2016) in order to characterize plant functioning and type. Disease detection benefits greatly from extra information hyperspectral imaging may provide, since the spectral signal of plants changes if affected by fungi or bacterial damage (West et al. 2003).

For example, Shafri and Hamdan (2009) used AISA to map disease infection in oil palm plantations based on information from vegetation indices and the red edge spectral region, and Apan et al. (2003) used EO-1 Hyperion imagery to detect orange rust disease in sugarcanes. Sankaran et al. (2010) provide a comprehensive review of hyperspectral imaging for plant disease detection. In addition, hyperspectral imaging may support a better soil management to increase crop production and yield (Fig. 4). This leads to two wide areas of application for hyperspectral techniques regarding agriculture and food security:

i. Vegetation—productivity and functioning, are central to food security applications. Hyperspectral observations are needed for the monitoring of plant productivity and are based on the exploitation of spectral indicators of green biomass, pigment pools, and photosynthetic functioning (Kokaly et al. 2009). Of notable importance is the assessment of stress in crops and ecosystems using hyperspectral remote sensing, for example the detection of drought stressed plants which are characterized by early and accelerated leaf senescence (Munné-Bosch and Alegre 2004). These applications would benefit from a high temporal and spectral resolution to monitor vegetation growth and early-stress detection. Spatial resolution should ideally be in accordance with Sentinel-2 (10–20 m), which would allow the mapping of small agricultural units, but an upper limit up to 30 m is acceptable for many agricultural regions and applications.

Vegetation—crop types as well as vegetation structure are recognized as Essential Biodiversity Variables (EBVs) (Pereira et al. 2013). Hyperspectral applications in biodiversity and forestry take advantage of the high potential of hyperspectral information to separate

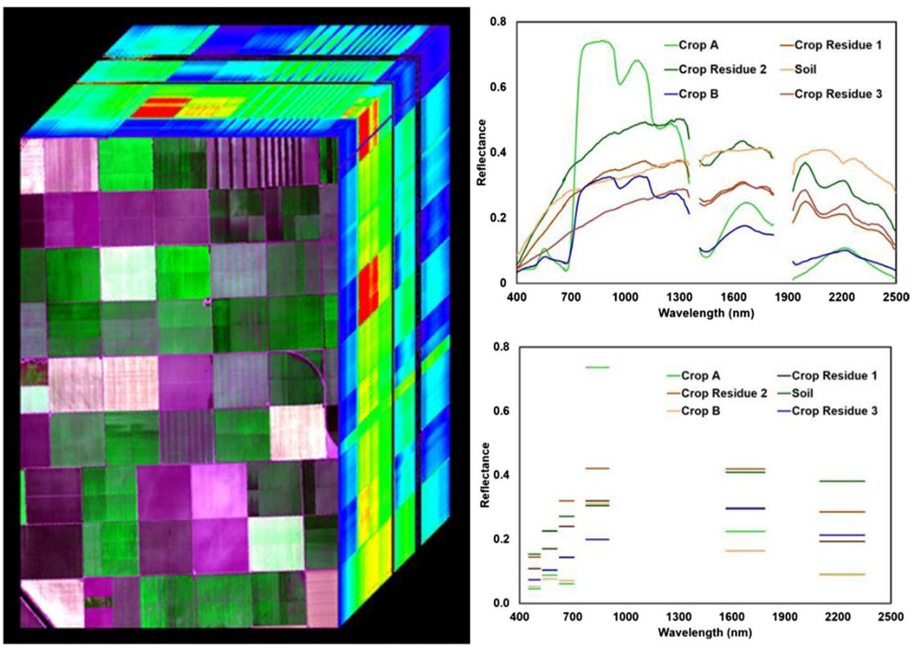

Fig. 4 Imaging spectrometer data set from the San Joaquin Valley, California, highlighting the addition spectral content available for a larger set of agriculture and food security products. (Courtesy R.O. Green, JPL)

vegetation classes and to retrieve critical plant functional traits (Schweiger et al. 2016). The highest spatial resolution possible would be required for the monitoring of ecosystem composition in the most heterogeneous areas (e.g., for forests, for monitoring of protected habitats and for the monitoring of species occurrence). Also, the detection of invasive species for land management activities would highly benefit from the highest spatial resolution possible (ideally in the range of 20 m). On the other hand, a relatively high temporal resolution would still be necessary to track seasonal changes in plant structure and traits, which is also relevant to biodiversity applications.

ii. Soils—the potential of hyperspectral data for mapping and monitoring soil properties relies mostly on direct chromophores that are soil mineralogy (clay, carbonates and iron oxides) (Ben-Dor et al. 2009; Swayze et al. 2000, 2014) and organic carbon and on soil properties that are highly correlated with those parameters (e.g., Cation Exchange Capacity is highly correlated with clay content and type) (Gomez et al. 2008; Lagacherie et al. 2008). Current multispectral sensors cannot extract mineralogical composition, and so hyperspectral imagery is crucial for the derivation of fundamental soil properties linked to food security such as organic carbon content, clay and water topsoil content, soil degradation stages, and soil quality status. In the case of soil mineralogical composition, high spatial resolution is preferable to high temporal resolution; in the case of soil organic carbon, high spatial resolution would be required for the derivation of soil organic content baseline inventories, but high temporal resolution would also be important for a monitoring system optimized to quantify changes especially during the vegetation-free period.

In the case of indirect soil properties, high spectral resolution and knowledge of the relationship between all soil properties are important. This can be extracted from Global Soil Spectral Libraries that are now very popular and widely available for potential users (Rossel et al. 2016).

While the multitemporal domain is the necessary requirement for food availability and production, specific information extracted at regular intervals by a spaceborne hyperspectral imager will provide a unique opportunity to extend the analysis also for food nutrition. In this context, soil quality indices can be derived from combining several important properties, as demonstrated by (Paz-Kagan et al. 2015).

5.3 Raw Materials

The potential to map mineral resources and other raw materials is one of the most compelling cases for imaging spectroscopy compared to multispectral systems (King et al. 2014; Swayze et al. 2014). Currently, no multispectral system is able to resolve mineralogical compositional information. In general, geological applications benefit the most from high spatial resolution, where many minerals and raw materials present absorption features. Mineral mapping and geological applications typically occur over relatively stable areas, so temporal resolution is not considered as a limiting factor.

Mining applications such as resource management will benefit from moderate temporal resolution and high spatial resolution. Mine environmental monitoring including mine waste rehabilitation, dust contamination, and other surface pollution is an application requiring a high spectral resolution and a moderate temporal resolution of several months, but a higher spatial resolution would be preferred over high temporal resolution. The specific case where high temporal resolution is required is for emergency responses in the case of an accidental release such as a tailings dam breach. Here, a high revisit time and real-time product delivery are required.

With a long history of development, hyperspectral imaging for mineral resources applications has matured and has become one of the most advanced applications. It is now at a stage where regional scale maps are being produced for baseline geological mapping and mineral exploration. Such data help to better define prospective ore bodies and focus exploration, thereby also reducing the environmental impact. Additionally, acquired with appropriate calibration data, the same data are also useful for baseline environmental monitoring in raw material exploration areas.

With the increasing use of hyperspectral sensing for mineral mapping, semi-operational software packages have become available and are readily used for the identification of surface minerals materials, e.g., from the USGS (Clark et al. 2003) and from the GFZ (Mielke et al. 2016), which have proven their suitability for the use with spaceborne imaging spectroscopy data, e.g., from Hyperion and the planned EnMAP mission (see Fig. 5).

5.4 Hydrology/Cryosphere

Water is arguably the most critical resource on planet Earth. Within the water cycle, the cryosphere contains vast volumes of freshwater, whereby changes in snow cover, mountain glaciers, and ice sheets have first order feedbacks on regional to global climatic change, water resources, and sea level rise (IPCC 2013; Gardner et al. 2013). Monitoring of the snow cover is of importance for hydrology in high latitude or alpine areas, while in low

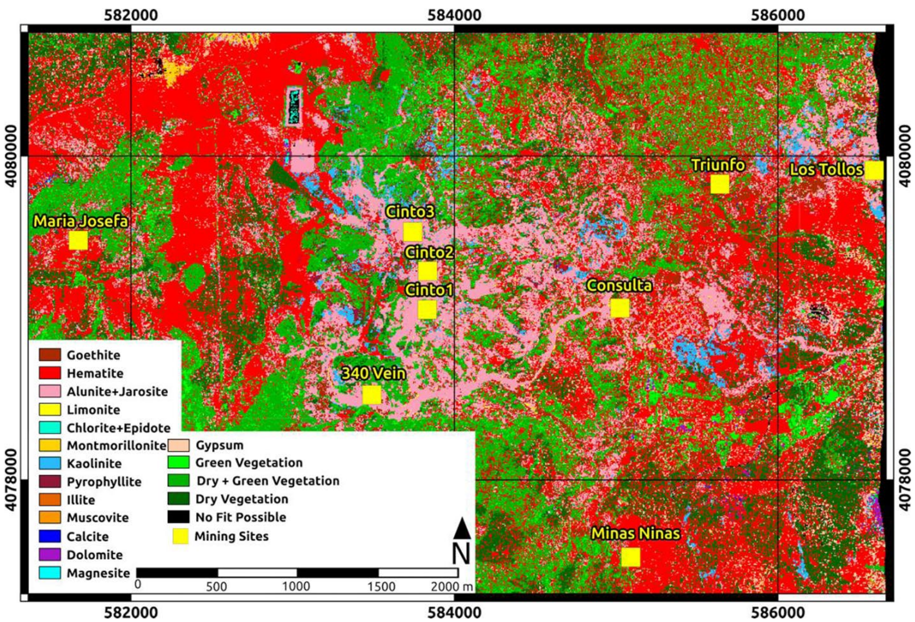

Fig. 5 Automated mineral classification (EnGeoMAP) of a high sulphidation, epithermal gold deposit, in Rodalquilar, Spain, calculated from airborne HyMAP data, used as simulation input to produce the EnMAP data (Mielke et al. 2016)

mountain ranges significant snow dynamics occur as well. Due to temperature alteration, the snow pack accumulates and melts off several times during a winter season.

New hyperspectral products lead to deeper knowledge of snow physical properties that can be used to constrain regional to global scale climate and water cycle modelling. In addition to the fractional snow cover (Painter et al. 2003), also snow grain size, radiative forcing by light-absorbing impurities in snow (Painter et al. 2013), snow biological constituents (Painter et al. 2001), and snow surface liquid water content (Green et al. 2006) can simultaneously be retrieved. An example showing the combined impacts of grain size and dust on snow albedo is shown in Fig. 6. From the composite of these, snow albedo can accurately be mapped and the controls on its deviation from clean and dry properties well understood (Painter et al. 2013). Likewise, these properties can be retrieved from imaging spectrometer data for glacier ice properties for further constraint on mountain glaciers (Naegeli et al. 2015). A comprehensive review of the use of hyperspectral imaging for snow and ice can be found in Dozier et al. (2009).

The NASA Airborne Snow Observatory (ASO) described above, along with snow depth and snow water equivalent maps entire snow covered mountain basins every 1–2 weeks

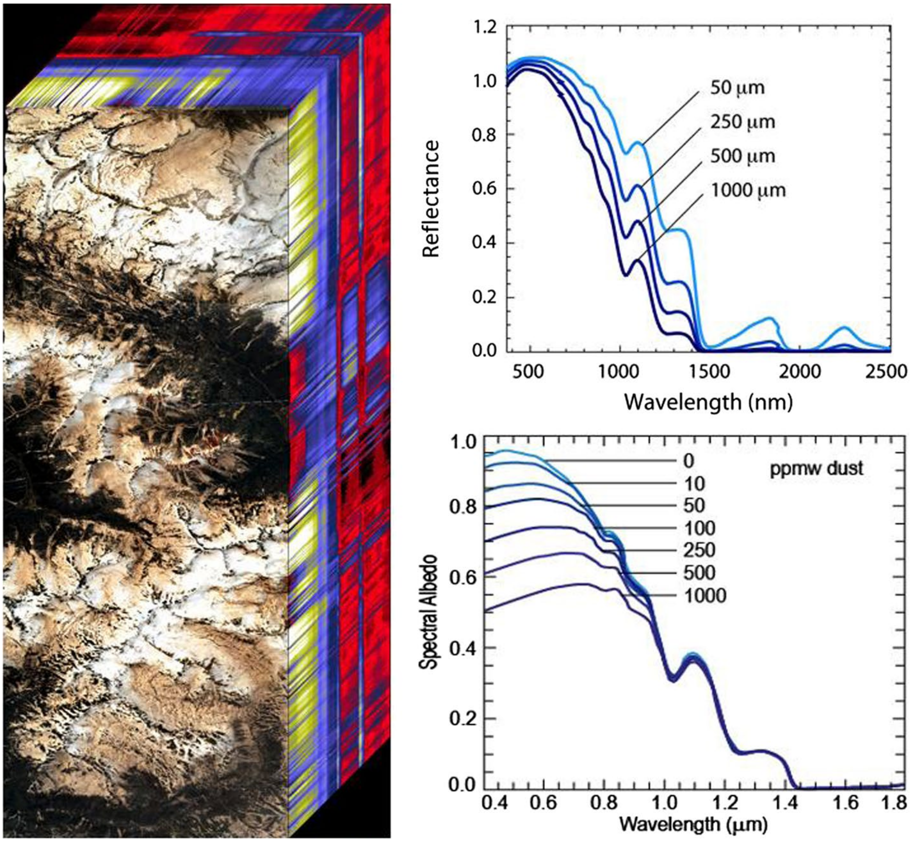

Fig. 6 AVIRIS imaging spectrometer measurements of dust-impacted snow in the Colorado Rocky Mountains (left). VSWIR spectroscopic leverage used to retrieve grain size (right top) and dust albedo impact (right bottom) to constrain radiative forces and model melting rates and water resource runoff (Painter et al. 2013)

with these properties at 3 m spatial resolution and provides the first coupled information at temporal scales required to constrain physically based hydrologic models (Painter et al. 2016; Henn et al. 2018; Hedrick et al. 2018). These models, constrained by the ASO measurements, are now being implemented for operational runoff forecasting and water management in the states of California and Colorado, USA.

In the US 2017 Earth Science Decadal Survey, the Surface Biology and Geology measurement concept as a spaceborne VSWIR imaging spectrometer was indicated as a designated measurement that must be implemented to fill critical science voids. Among the most important measurements that motivated this concept as a Designated measurement was the Hydrology panel's objective to: '*Quantify rates of snow accumulation, snowmelt, ice melt, and sublimation from snow and ice worldwide at scales driven by topographic variability'*, describing the need to understand the controls on snow albedo (that are only available from the imaging spectroscopy retrievals described above) and, snow- and ice melt.

5.5 Coastal and Inland Waters

Inland and coastal water ecosystems are vital for human consumption, irrigation, sanitation, transportation, recreation, and industry. Earth observation has been used for decades to acquire information from local to global scales of aquatic ecosystems. These systems encompass gradients of clear to turbid and oligotrophic to hypertrophic productive waters and with varying contents of macrophytes, macro-algae, benthic micro-algae or corals. To observe such optical complexity, imaging spectroscopy provides more accurate assessments than multispectral sensors starting from turbidity and transparency, chlorophyll, suspended matter and coloured dissolved organic matter concentration up to more sophisticated products, such as particle size distributions, phytoplankton types and pigments, harmful algal blooms, estimating water depth and mapping heterogeneous substrates and cover types, as well as different types of sea grass (see Fig. 7). Submerged aquatic vegetation is one of the biological quality elements used in monitoring the ecological status of surface waters within the process recommended by the European Water Framework Directive, where the abundance of aquatic plants is needed to define the deviation from the ecological conditions of reference (Hestir et al. 2015).

Since 2000, spaceborne hyperspectral sensors (e.g., HYPERION, CHRIS, HICO) have shown increasing capabilities in inland, estuarine, and coastal water applications. Water quality-related applications, like the retrieval of chlorophyll content and secondary pigments as proxies for harmful algae blooms, the identification of phytoplankton types, or the benthic habitat mapping, strongly benefit from hyperspectral information (Hestir et al. 2015; Giardino et al. 2018). Those conclusions are supported by the findings of a recent Committee on Earth Observation Satellites (CEOS) study towards the assessment of potential hyperspectral mission concepts for aquatic ecosystems (Dekker et al. 2018).

5.6 Environmental Degradation and Hazards

Natural and anthropogenic hazards have the potential to impact on all aspects of society including its economy, its habitats health and well-being, and the environment. Diagnostic information to inform decisions is critical for hazard management, whether as an emergency response for routine monitoring or assessments of potential risks. Hyperspectral imaging has unique contributions to make via the ability to provide some key quantitative diagnostic information.

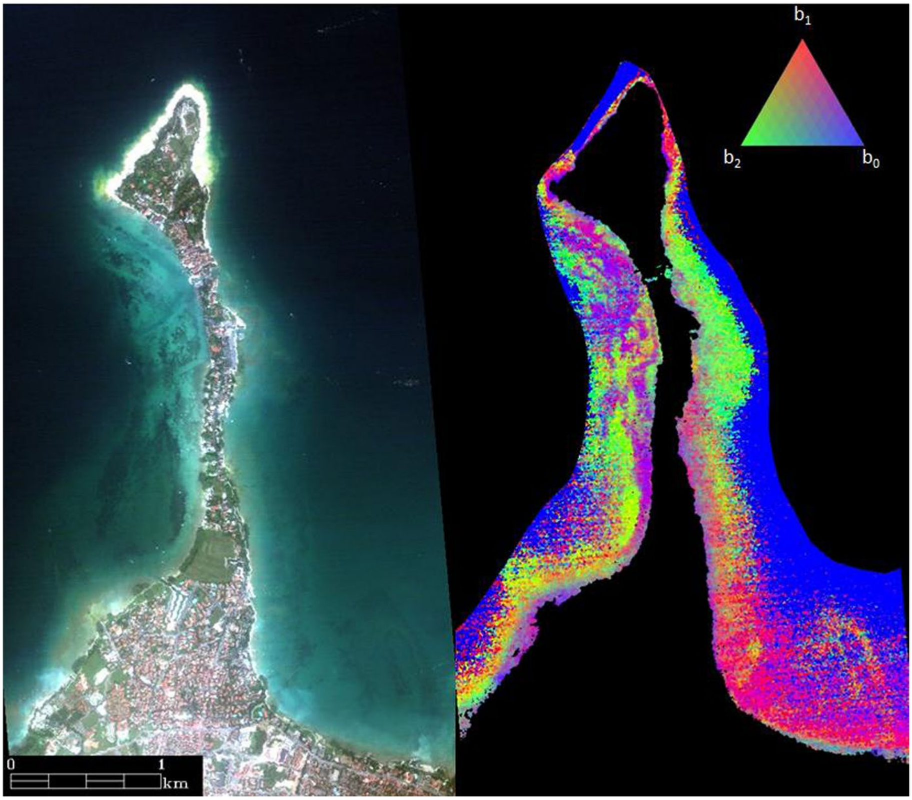

Fig. 7 Airborne Multispectral IR and Visible Imaging Spectrometer (MIVIS) data Lake Garda, Italy, 15.7.2015. Left: Pseudo-true-colour composite. Right: Submerged vegetation to 7 m depth, containing main bottom cover classes of sand (b0, blue), submersed benthic vegetation (b1, red) such as *Chara sp.*, and submersed tall vegetation (b2, green) such as *Vallisneria spiralis*; black areas are masked optically deep-water areas and land (Courtesy C. Giardino, IREA-CNR)

Examples where imaging spectroscopy has been used for mapping environmental degradation and hazards other than those provided for the raw materials are steadily growing.

Hyperspectral images were acquired following the 11th September 2001 World Trade Centre (WTC) attack, and the data were used for mapping thermal hotspots and potentially hazardous dust (Clark et al. 2005); see Fig. 8.

Hyperspectral imaging was used to estimate the distribution and volume of the oil slick on the surface of the ocean and the impact of oil on the terrestrial ecosystem (Kokaly et al. 2013) from the largest oil spill in US history in the Gulf of Mexico. Spaceborne hyperspectral imaging from EO1 Hyperion also mapped a very large accidental gas release (Thompson et al. 2016). Pioneering work from Chabrillat et al. (2002) demonstrated the potential of hyperspectral imaging for detecting and mapping swelling clays with a study along the Front Range Urban corridor near Denver, Colorado, USA. Chudnovsky et al. (2009) documented the use of spaceborne hyperspectral imaging data acquired by NASA EO-1 Hyperion sensor for determining the composition of the dust at the Bodélé Depression of Northern Chad, considered to be one of the world's largest sources of atmospheric mineral dust. Further, imaging spectrometer measurements have in the recent past been used for detailed

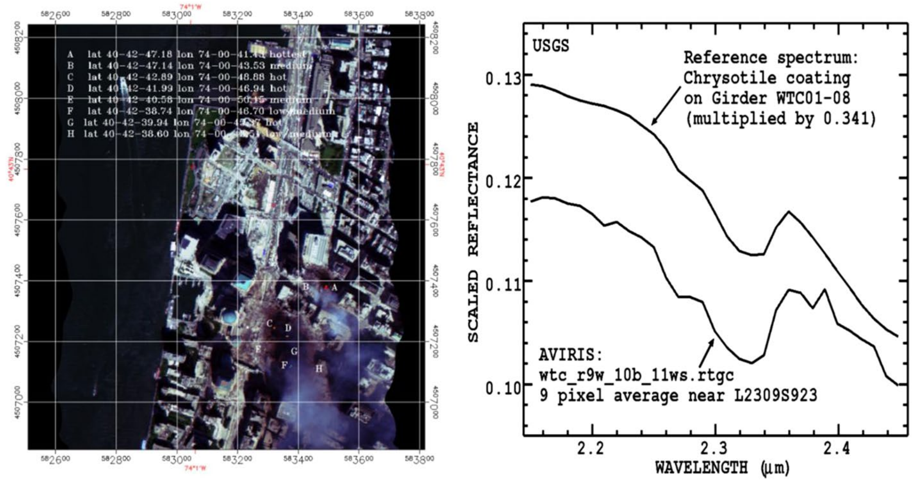

Fig. 8 AVIRIS measurements of the WTC site on the 16th of September 2001. Hot spot fire temperatures were calculated from AVIRIS spectra and delivered to ground teams (left). Surface debris composition includes Chrysotile. Mineral asbestos was mapped from AVIRIS spectroscopy by the USGS (Clark et al. 2005)

mapping of fire fuel (Roberts et al. 2003), temperature (Green 1996; Dennison 2006; Veraverbeke et al. 2018), burn severity (Kokaly et al. 2007), and recovery (Riaño et al. 2002).

6 Observational Requirements

Observational requirements of a spaceborne imaging spectrometer mission are driven by the mission's scientific and/or operational objectives and are based on experience, state-of-the-art technology and results of previous hyperspectral airborne and experimental spaceborne systems. On a rather generic level, overarching observational requirements comprise:

- Spectral resolution: Contiguous spectral coverage between 400 and 2500 nm with a spectral sampling interval at FWHM of less or equal 10 nm is aspired to by land-observing sensors, driven by the need for atmospheric characterization and reflectance retrieval, as well as some geophysical, geo-biophysical, and geochemical retrievals for environmental measurements and agricultural applications. For ocean-observing sensors focusing on 'Ocean Colour' variables often, a spectral sampling around 5 nm is required. For radiative forcing by impurities in snow, 20 nm is the generally accepted requirement. Ultimately, a sensor with a semi-static spectral resolution that can accommodate the science requirements is more cost-effective than varying the spectral resolution across the spectrum.
- Spatial resolution: While airborne imaging spectrometers typically have a spatial sampling of ≤ 1 m (depending on the flight altitude), spaceborne land observation imaging spectrometers have a spatial resolution in the range of tens of metres, i.e. 20–60 m to resolve the scales of spatial variability of the observed constituent. For Ocean Colour imaging spectrometers, the spatial sampling requirements range typically between 100 and 300 m.

- Temporal resolution: The cadence of clear-sky acquisitions varies according to the science or application question. For snow and ice, an average of one clear acquisition per week is required, whereas for ocean observation a cadence of the order of about 3 days is required. For agricultural applications, repeat observations every 5–10 days are needed, for biodiversity and biogeochemical measures seasonal clear acquisitions will suffice but generally require a broader spatial coverage.

The above sensor requirements for future terrestrial imaging spectrometers were subject to and outcome of the discussion at the 'conclusion session' of the Workshop: 'Exploring the Earth's ecosystems on a global scale', in November 2016 at the International Space Science Institute in Bern, Switzerland.

Desired temporal and spatial resolutions stretch the technology and the data rates for a spaceborne imaging spectrometer. In future, the requirements for terrestrial and oceanic science might be achievable under likely budget availability, but for the next decade or two, a feasible strategy is to exploit the combination of imaging spectroscopy with the variety of multispectral sensors already operating or in the international launch queues. Specifically, imaging spectroscopy can play a valuable role in calibrating multispectral sensors and validating interpretations made from them. In this vein, compelling opportunities are seen in synthesizing observations from imaging spectrometers, the Landsat and Sentinel-2 missions, the global daily observations from sensors such as VIIRS and the MetOP satellite series, and the very frequent observations from geostationary missions such as GOES-16 and 17, Himawari-8 and 9, Fengyun-4, and Meteosat-9 through 11 (presentation J. Dozier at ISSI Workshop: 'Exploring the Earth's ecosystems on a global scale', November 2016).

7 Conclusions, Outlook, and Perspectives

Owing to well-established spectroscopic techniques, optical hyperspectral remote sensing has the potential to deliver significant enhancement in quantitative value-added retrievals, as compared to multispectral remote sensing, thus supporting the generation of a wide variety of new products and services in the domain of agriculture, food security, raw materials, soils, biodiversity, environmental degradation and hazards, snow, water resources, inland and coastal waters, and forestry.

Corresponding variables have been derived from the observed spectra, e.g., directly through distinct absorption features or indirectly, through inversion of physically based models, assimilation, spectral un-mixing, and/or (de-) correlation techniques. Based on successful airborne deployments and some satellite missions along with preparatory activities, imaging spectroscopy from satellite is now ready for operational use.

The potential of airborne and spaceborne imaging spectrometers has intensively been researched to monitor land and water surfaces and the atmosphere to provide valuable quantitative information for the better understanding of a large number of environmental and ecosystem processes. These applications include vegetation monitoring and agriculture, geology and soils, the mapping of snow properties and coastal and inland waters.

Over the last three decades, remotely sensed imaging spectroscopy has steadily evolved and by now has become one of the most powerful diagnostic and quantitative retrieval techniques from both air- and spacecraft. Indeed, spectroscopy from space represents the asymptote for optical remote sensing—that is, the pinnacle of optical RS—spectral and spatial resolutions will continue to improve, but the concept of imaging spectroscopy will continue for as long as the Sun is being used as an illumination source. Advances in technology facilitate improvement in the spectral sampling and the radiometric performance of imaging spectroscopy systems, thus yielding higher signal-to-noise ratios. Starting from airborne in the late 1980s and also spaceborne technology demonstrators from the early 2000s, imaging spectrometers are meanwhile viewed also as potential operational sensing systems, such as the Airborne Snow Observatory's spectrometer use in this operational programme for snow water resources. One of the remaining challenges is to deploy systems with high radiometric performance in the shortwave infrared where many diagnostic absorption features of vegetation, soils and minerals are to be found. In parallel, compact imaging spectrometers encompassing the visible–near-infrared range have been deployed into space and are increasing in number rapidly.

The superiority of imaging spectrometers over multispectral imaging systems with a limited number of spectral bands gives rise to the expectation that in the future multispectral systems will be superseded by imaging spectrometers in Earth observation remote sensing of terrestrial as well as aquatic ecosystems.

Evolution in technology also enables building increasingly compact systems and deploying them into space. It can hence be expected that smaller VNIR imaging spectrometers together with some VSWIR systems will form monitoring constellations in future.

With the advent of Big Data, Artificial Intelligence, Machine Learning and Data Analytics, it can be expected that the handling of large data volumes such as those acquired by imaging spectrometers will be less of a challenge in future to the Earth observation science and operational user community, and the retrievals will thus be poised to straightforwardly inform climate modelling, hydrologic modelling, and resource management and operations.

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