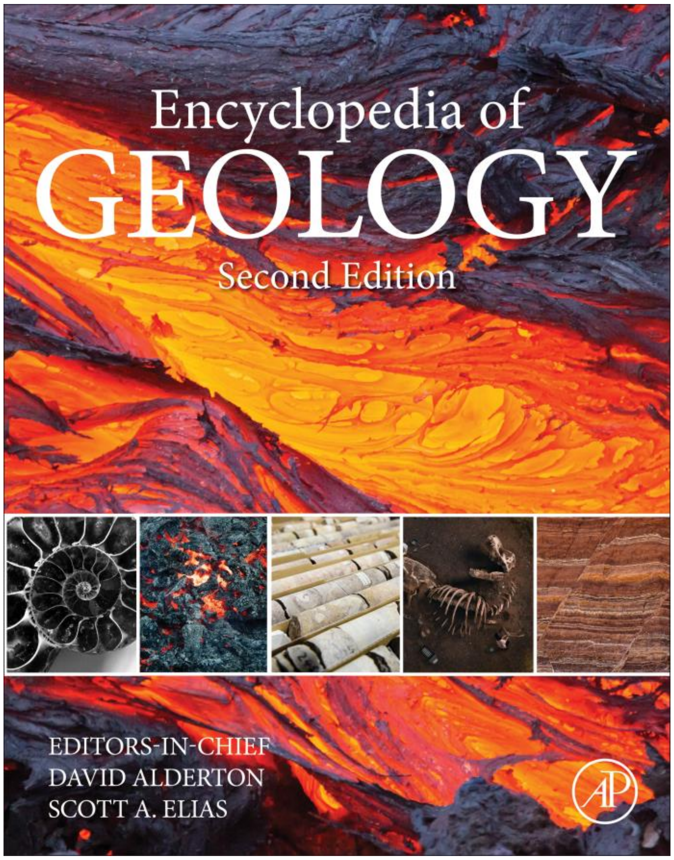

Booysen René, Gloaguen Richard, Lorenz Sandra, Zimmermann Robert and Nex Paul A.M. (2021) Geological Remote Sensing. In: Alderton, David; Elias, Scott A. (eds.) *Encyclopedia of Geology*, 2nd edition. vol. 6, pp. 301-314. United Kingdom: Academic Press.

dx.doi.org/10.1016/B978-0-12-409548-9.12127-X

Geological Remote Sensing

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Glossary

Hypsometry Measurement of land elevation.
Hyperspectral imaging Rasters acquired at hundreds of different narrow, contiguous wavelength bands.
Isobase A topographic contour line on a map, drawn through points of equal elevation in a topographic surface or line.
Multispectral imaging Rasters acquired at up to tens of different broad, contiguous wavelength bands.
Orthorectification The process of removing the effects of image perspective and relief effects for the purpose of creating a planimetrically correct image.
Radiance Radiant energy reflected, emitted, received of transmitted by the surface, calculated per unit solid angle per unit projected area given as W sr^{-1} m^{-2}.
Reflectance The measurement of the proportion of radiation or light reflecting off of a surface.
Topography The study of features and shapes of the Earth's surfaces.
Topographic corrections A correction applied to remotely sensed images to remove the effects of relief.

 https://doi.org/10.1016/B978-0-12-409548-9.12127-X

Nomenclature

CMOS	Complementary metal-oxide-semiconductor
DEM	Digital elevation model
DSM	Digital surface model
DTM	Digital terrain model
EM	Electromagnetic
GIS	Geographic information system
GNSS	Global navigation satellite system
GPS	Global positioning system
GSD	Ground sampling distance
HSI	Hyperspectral imaging
IFOV	Instantaneous field of view
InSAR	Interferometric synthetic aperture radar
IS	Imaging spectroscopy
LiDAR	Light detection and ranging
LWIR	Long-wave infrared
ML	Machine learning
NIR	Near infrared
PolInSAR	Polarimetric interferometric synthetic aperture radar
PolSAR	Polarimetric synthetic aperture radar
RPAS	Remotely piloted aircraft system
SAR	Synthetic aperture radar
SfM	Structure from motion
SNR	Signal-to-noise ratio
SRTM	Shuttle radar topography mission
SWIR	Short-wave infrared
UAS	Unmanned aerial system
UAV	Unmanned aerial vehicle
VIS	Visible
VNIR	Visible and near infrared

Introduction

Remote sensing is commonly defined either as the data acquisition about an object or a process at a distance or the scanning of the Earth by satellite or high-flying aircraft. In the present article, we will consider all the relevant sensors and techniques that allow the imaging, measurement and monitoring of the Earth's surface from a distance greater than 10 m. Sensors are usually divided into two categories: (1) passive sensors that solely record incoming radiation, mostly originating from the sun and, (2) active sensors that emit a radiation and record the returning signal. As illustrated in Fig. 1, the quasi totality of the sensors employed for geology use electromagnetic (EM) radiation either in the visible to near-infrared (400–1000 nm; VNIR), the short-wave infrared (1–2.5 µm; SWIR), the long-wave infrared (7–14 µm; LWIR) or microwaves (0.01–1 m) for synthetic aperture radars (SAR). EM radiation has predictable behavior according to its inherent fundamental properties. One of the main limitations of EM signals originates from interactions with gases and particles in the atmosphere, such as scattering and absorption. Attenuation of EM radiation depends on the wavelength and portions of the EM spectrum with high atmospheric transmissivity known as "atmospheric windows." Remote sensing sensors will usually focus on these atmospheric windows to ensure a maximum signal collection. Once it reaches the target, the radiation is either absorbed, transmitted, reflected or a combination of these phenomena. A target will also emit EM radiation as a function of temperature and wavelength. Usually, the emitted radiation of a given natural target is provided as emissivity, the divergence from the radiation of a blackbody, i.e., an ideal body that will not reflect radiation, at the same temperature. The emissivity of natural objects is usually very low in the VNIR and SWIR and steadily increasing towards the LWIR at ambient temperatures. In most natural settings, reflection dominates in the VIS, NIR and SWIR whereas emission is preponderant in the LWIR. Remote sensing techniques mainly measure a reflected signal, but LWIR processing needs to account for both reflected and emitted radiation. Generally the geometric properties of the target will control the reflection type, from specular (i.e., mirror like) to diffuse. Recorded data are digital and can be used either as a database of geolocated physical properties or as rasters. This leads to two different kinds of applications that were traditionally mutually exclusive; data scientists will use remote sensing data as quantities, whereas application scientists usually utilize them as images.

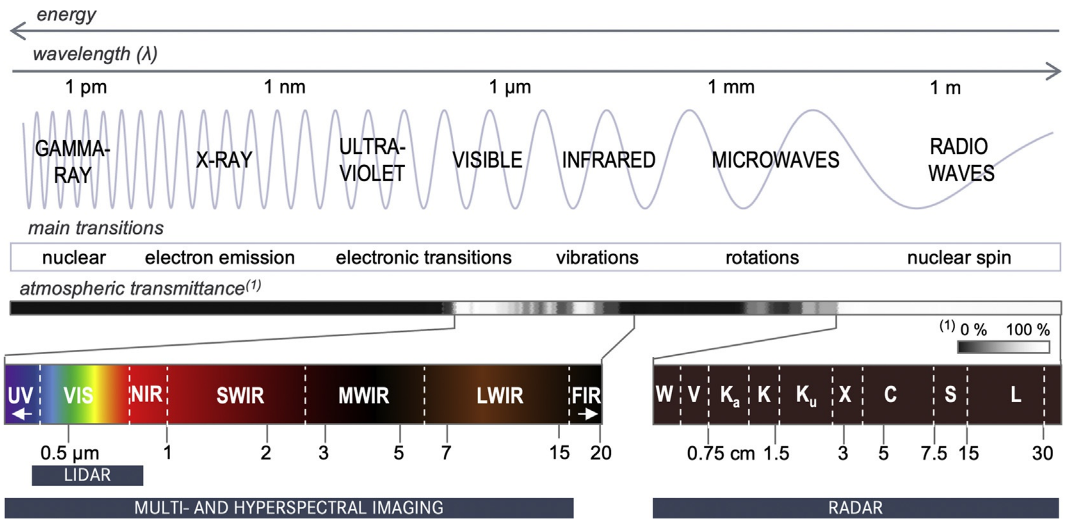

Fig. 1 Characteristics of the electromagnetic spectrum used for spectral and radar imaging.

The large majority of remote sensing acquisitions are affected by geometric distortions. This problem is a direct consequence of imaging a non-planar surface, i.e., the spherical Earth, with a technical device having specific technical limitations. Summarily, these distortions originate from the geometrical and technical characteristics of the sensor itself, the motions of the platform, the relief and the curvature of the Earth. In most instances, it may be possible to eliminate, or at least to reduce, these errors but they always must be assessed and taken into account before the analysis of any remote sensing data for geological applications. The atmosphere itself also affects data captured with satellite and aerial sensors. Before the sunlight is reflected by the Earth's surface, it is absorbed, scattered, and refracted by aerosols, water droplets, and gas molecules in the atmosphere. It is therefore essential to perform atmospheric corrections on remote sensing datasets.

Geologists have increasingly used remote sensing data since the development of the technology for regional mapping, structural interpretation, hazard monitoring, and exploration for ore deposits. The various platforms used for remote sensing are summarized and described in this review. Satellite-, aircraft-, and remotely piloted aircraft systems (RPAS) are some of the platforms described here, and their advantages and disadvantages are discussed. Remotely sensed data acquired from these platforms are used for different geological applications. These applications are discussed and previously performed studies are reviewed.

Sensors

Optical Sensors

Optical remote sensing is a passive technique for earth observation which relies on solar illumination. The earliest application was aerial photography for surveying and military use. Multiple spectral Earth observation systems were introduced in the mid-1960s that captured spectra in the form of images, also known as imaging spectroscopy (IS). Each pixel of the raster consists of multiple values at a specific wavelength interval of the electromagnetic spectrum with a specific intensity. More accurately, the spatially co-registered rasters are acquired quasi-simultaneously in many spectrally adjacent bands known as a data cube. A one-dimensional spectrum can be sampled from a raster at a specific spatial location. The spectrum is usually plotted as reflectance or radiance against wavelength. Rock forming minerals can have specific spectral characteristics, such as absorption features, that are generated by either electronic or molecular processes i.e., resonance between incident electromagnetic radiation at a given wavelength and particular chemical bonds, that are characteristics for a few elements or minerals (Clark, 1999) (Table 1).

Three types of mechanical-optical systems are widespread for IS: (1) whiskbroom sensors (2) push-broom sensors and (3) frame-based (or snapshot) sensors, with the first two typically having relatively high Signal-to-Noise ratios (SNR). Whiskbroom sensors scan the surface spatially in a raster with single point spectral measurements. A single spectrometer is required and the raster is produced by the forward motion of the sensor and a rotating mirror. This makes them impractical for use in non-spaceborne platforms. Whiskbroom sensors are commonly used in space-borne platforms such as Landsat or the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER). Push-broom sensors record a line of pixels across flight direction (swath) at once and thus have higher requirements in terms of optics and sensor sensitivity. The focal plane of a whiskbroom system is a linear array of sensors. As sensitivity decreases towards the edges of the sensor array, specific calibration procedures have to be applied (e.g., across sensor illumination correction, application of sensor specific calibration files). A high-precision Inertial Measurement Unit (IMU) is a prerequisite to correct for roll-pitch-yaw deviation of the platform, and to spatially align the single lines when used on an unstable platform. This type of sensor is predominately used in aircraft and ground-based systems.

Table 1 Mineral detection capabilities for the VNIR, SWIR and LWIR regions of the electromagnetic spectrum.

	Silicates												Non-silicates								
	Pyroxene	Olivine	Garnet	Feldspar	Quartz	White-mica	Phlogopite & Biotite	Epidote	Tourmaline	Amphibole	Chlorite	Clays	Apatite	Carbonate	Gypsum	Gibbsite	Alunite	Jarosite	Hematite	Goethite	REEs
VNIR	Diagnostic	Diagnostic	Non distinguishable	Non-diagnostic	Non-diagnostic	Non-diagnostic	Non distinguishable	Non distinguishable	Non distinguishable	Non distinguishable	Non distinguishable	Non-diagnostic	Non distinguishable	Non-diagnostic	Non-diagnostic	Non-diagnostic	Non distinguishable	Diagnostic	Diagnostic	Diagnostic	Diagnostic
SWIR	Non distinguishable	Non-diagnostic	Non-diagnostic	Non-diagnostic	Non-diagnostic	Diagnostic	Diagnostic	Diagnostic	Diagnostic	Diagnostic	Diagnostic	Diagnostic	Non-diagnostic	Diagnostic	Diagnostic	Diagnostic	Diagnostic	Diagnostic	Non-diagnostic	Non-diagnostic	Non distinguishable
LWIR	Diagnostic	Diagnostic	Diagnostic	Diagnostic	Diagnostic	Non distinguishable	Non distinguishable	Non distinguishable	Non distinguishable	Non distinguishable	Non distinguishable	Non distinguishable	Diagnostic	Diagnostic	Diagnostic	Non distinguishable	Non distinguishable	Non-diagnostic	Non-diagnostic	Non-diagnostic	Non-diagnostic

● =Non-diagnostic ● =Non distinguishable from some other mineral facies ● =Diagnostic response

Frame-based systems or snapshot cameras have the advantage of capturing a two-dimensional raster at a specific wavelength one after the other. Thus, the spectral separation system must be rather fast. Spectral separation can be performed on the following principles: (1) prisms, (2) gratings, (3) filter wheels, (4) interferometers and, (5) tunable liquid crystals. Spatial alignment or stacking of the single frames relies on simple co-registration functions. This type of sensor is predominately used on RPAS due to its robust and lightweight construction and relatively easy signal pre-processing. RGB cameras also belong to the group of frame-based cameras and are generally used to capture nadir looking or oblique aerial digital photographs.

From a sensor perspective, uncooled complementary metal-oxide-semiconductor (CMOS) sensors, which feature high sensitivity and SNR, can be used in the VIS and NIR. Infrared-sensitive materials commonly used for SWIR and LWIR sensors include InGaAs, HgCdTe or InSb photodiodes. A cooling system is necessary to increase the SNR of the spectral response. This does have an impact on the sensor weight, and thus limits their applications using RPAS.

LiDAR

Active scanning of a surface by using Light Detection And Ranging (LiDAR) is a standard technique in topographic mapping, change detection, and hazard monitoring that can be accomplished from an aircraft or using a ground-based system, where it is known as Terrestrial Laser Scanning (TLS). In particular, TLS is an emerging technique in geological applications for short-term geomorphic change, slope stability monitoring, and fracture mapping. There are numerous sensors on the market and several measurement approaches exist. All use the same principle: laser pulses are emitted, the time of returns is measured and sensor-to-surface distances are calculated. Thus, a knowledge of the precise location of the LiDAR system is essential. Typical spatial resolutions of Airborne Laser Scanning (ALS) are in the range of 0.5–1 m horizontally and 0.1 m vertically. Depending on the target distance, usually from 10 to 1000 m, TLS resolutions typically range from millimeters to centimeters.

SAR

Active microwave imaging, typically using Synthetic Aperture Radar (SAR) sensors, dominate geological applications. Passive microwave applications are restricted to environmental monitoring, for example soil moisture retrieval. Because of their longer wavelengths, microwaves penetrate cloud cover and aerosols and, thus, permit the mapping of areas usually under quasi-permanent cloud cover such as the tropics. SAR sensors include Radio Detecting And Ranging (RADAR) sensors that make use of the platform motion to increase spatial resolution. Radar periodically sends out microwave pulses and records the back-scattered (reflected) signal as a time series of echoes with certain intensities. Because it is an active technique, SARs will allow for both night and day acquisitions and it is possible to control critical signal parameters such as polarization and frequency. With increasing wavelength, radar signals will also penetrate deeper into dry solid matter. Because Radar was originally developed by the military, a now nonsensical nomenclature was attributed to frequency ranges; K, X, C, S, L, P from short to longer wavelengths. Polarization refers to the orientation of the electric field. Most SAR radiations are polarized either vertically [V] or horizontally [H], but in order to characterize the polarization of the back-scattered signal, more complex polarimetric sensors are required. Fully polarimetric sensors will send and record the signal in two planes and thus four combinations (VV, VH, HV, HH). Back-scattered polarization mainly depends on the geometric characteristics of the target and thus can often provide geologically relevant information. Because of the use of the doppler effect, SAR will require side viewing acquisition to avoid simultaneous returns and therefore is very sensitive to (1) relief displacement in slant range (e.g., foreshortening, layover and shadowing) and (2) antenna pattern, a combination of energy distribution in the beam and back-scattering reduction as range distances increase. As SAR are monochromatic, they will be affected by interferences of the multiple back-scattering radiation within one resolution cell, the speckle. Speckle reduction is usually performed during pre-processing (multi-looking) and using adaptive spatial filtering and in both cases result in data smoothing, i.e., information loss.

Resolution

The spatial resolution of optical instruments is mainly controlled by distance to target and the Instantaneous Field of View (IFOV), i.e., the smallest area on the ground that can be imaged. The spatial resolution of a SAR system is far more complex. In a simplistic form, the resolution across-track is mainly controlled by the effective pulse duration, whereas the resolution along-track is generated using a clever engineering trick. Using the forward motion of the sensor, a simulated antenna is calculated as targets that are illuminated several times and will return a signal at different frequencies due to the Doppler effect. It suffices to say that SAR spatial resolutions are non-trivial and a potential user should get additional information prior to use. The radiometric or spectral resolution is the ability of a sensor to detect subtle energy variations at a given wavelength or spectral band. This resolution is also affected by the quantization of data on the storage device. The temporal resolution is usually just the revisit period, but some platforms allow sensors to be oriented, which may increase acquisition rates over a particular area.

Platforms

Various platforms are used in order to capture remote sensing data for geological purposes. Satellite-, airborne-, RPAS- as well as ground-based carriers have specific characteristics that influence the geometric and radiometric properties of the acquired data.

Satellite

Satellite orbits have fundamental characteristics that principally vary with their radius (altitude) and orientation with respect to the Earth's axis of rotation. The geostationary orbit has an altitude of 36,000 km orthogonal to rotational axis, which implies that satellites in this orbit have the same angular speed as the Earth and thus appear stationary to one portion of the Earth's surface. This orbit is seldomly used in geology, but is important for communication and weather satellites for obvious reasons. The large majority of imaging sensors are on sun-synchronous, near-polar orbits. This orbit allows the satellite to fly over the same area at the same time of the day and provides a nearly global coverage of the Earth over a period of typically 1–2 weeks. Sun-synchronicity is particularly important as it allows consistent illumination conditions in a given area and thus facilitates mosaicking and temporal comparisons. The disadvantage is that half the orbits are in the shadowed side of the Earth and, therefore, are not suitable for most passive sensor applications. Orbits used for the global navigation satellite system (GNSS) are of intermediate distance from the Earth, typically 20,000 km, in order to maximize coverage and minimize the number of satellites in the constellation. Finally, due to their altitudes typically between 400 and 1000 km, sensors on orbital platforms will have characteristics that trade-off between swath width and spatial, spectral and temporal resolutions. While scientific missions such as LANDSAT or ENVISAT were historically predominant, hybrid (e.g., RapidEye, Terrasar-X) or purely commercial (e.g., worldview, geo-eye) solutions are becoming increasingly popular. The rising demand for high-resolutions data has led to on-demand acquisitions over small areas, which limits time series analysis and continuous archives.

Aircraft

Sensors deployed on aircraft platforms can provide spectral data at higher spatial resolutions than those on satellite sensors, due to lower flight altitudes. Aircraft systems include fixed-winged airplanes and helicopters. With these systems, the flight altitude is determined on a project-by-project basis. Depending on the required spatial resolution and accuracy, aircraft can be commissioned to fly at an altitude anywhere between about 0.1–6.0 km. These platforms can carry a wide variety of remote sensing sensors that include optical sensors covering the VNIR, SWIR and LWIR, as well as active systems such as LiDAR or InSAR systems. Aircraft have the capability to fly below cloud cover, providing cloud-free spectral imagery. Also, the SNR is better compared to spaceborne systems, as the sensors are closer to the target and the atmospheric effects are much diminished.

Small Aerial Platforms

The advent of new platform technologies such as RPAS and small aircraft, like gyrocopters, has revolutionized the way that remotely sensed geological data is acquired. RPAS, in the context of this review, refers to unmanned aerial systems (UAS) roughly 10 kg in weight that are operated within a visual line of sight (VLOS). These platforms can collect data at a higher spatial resolution than some of their aircraft and satellite counterparts, resulting in greater precision. However, these platforms can usually only carry relatively lightweight sensors due to their reduced payload capacities. Imaging sensors, e.g., those covering the LWIR range, are presently too heavy to be deployed on small, civil aerial platforms while, due to recent technological advancements, miniaturized SWIR sensors have recently been available. An advantage of the RPAS-based technologies is that data collection can occur even under non-ideal weather conditions, such as partial or full cloud cover. However, heavy wind and rain can prevent the flying of some ultra-light weight Unmanned Aerial Systems (UAS). Another drawback, is the limited range that can be covered compared to satellite and aircraft-based surveying. The techniques that are usually performed with these small platforms range from spectral (multi- and hyperspectral) sensing, Structure From Motion (SfM) photogrammetry, and LiDAR to geophysical techniques like magnetic sensing.

Up to this point, geological investigations by means of RPAS-based surveys have mainly utilized two types of UAS; fixed-wing systems and multi-copters. The fixed wing aircraft are generally light and are typically flown automatically at higher altitudes than multi-copters, resulting in larger area coverage. However, they are restricted by their payload capacity, and can usually only carry very light red-green-blue (RGB) cameras. This limits the remote sensing techniques performed with fixed-wing systems mainly to SfM photogrammetry, and aerial photography. Only very recently has there been some lightweight multispectral sensor available for fixed-wing platforms (i.e., the Sequoia Sensor) These sensors typically contain four bands in the VNIR; green, red, red-edge and NIR. To date there are no notable geological studies that have utilized this emerging technology.

By comparison, multi-copters have a limited flight time, which restricts their range. However, payloads for multi-copters are usually greater than for fixed-wing systems and they therefore can carry heavier sensors. In recent years lightweight multi- and hyperspectral sensors have been developed specifically for RPAS surveying that are usually carried by multi-copters. These multi- and hyperspectral lightweight sensors cover the VNIR spectral range with 10s of narrow bands, while also providing images with high radiometric quality. Other sensors like the LiDAR sensor and magnetometers are also mostly carried by multi-copter platforms.

Ground-Based Sensing

Ground-based remote sensing has evolved far beyond the days of using only terrestrial LiDAR systems. Spectral sensors that can cover not just the VNIR but also the SWIR and LWIR range have been developed in the last decade. These sensors are far too large and heavy and demanding of power to be carried by small RPAS. Nevertheless, data can be acquired in the field with these sensors to provide hyperspectral imagery with very high spectral and spatial resolution. The high resolution can be attributed to the proximity at which the sensor is to the target (usually between 10 and 30 m) as well as the increased sensitivity of the instrument. This increased resolution facilitates the in situ mapping of micro-topography and mineralogical and structural features in the mm to cm scale. Terrestrial LiDAR and ground-based SfM photogrammetry are also used to create high-resolution 3-D models of geological targets. Although the high resolution and precision of ground-based measurements add immense value to geological surveys, the equipment itself can be a hinderance in the field. Heavy sensors and their power sources (i.e., generators or bulky batteries) make mobilization for fieldwork challenging. This can restrict field accessibility in extreme environments.

Processing and Data Integration

Pre-Processing and Data Correction

In order to transform raw data to calibrated and thus useable data sets, specific pre-processing steps are necessary. The different types of data require very different transformation methods and are summarized below.

Spectral data sets

To achieve a good spectral and spatial quality, careful pre-processing of any multi- or hyperspectral data is required prior to any data interpretation. Spectral accuracy in an ideal case is achieved when each image pixel reflects the material-specific reflectance of the material composition of the surface observed. Spatial correctness requires the compensation of any geometric distortions in conjunction with the geolocation of the dataset into a reference system. Radiometric and geometric parameters of the targeted surface, but also environmental conditions during the acquisition, sensor movements, viewing angle and distance to the target are important parameters that influence the signal received at the sensor for which compensation is needed. The variety of parameters requires the applied correction workflows to be adapted to the deployed sensor and acquisition platform. In general, internal and external effects need to be considered. Sensor-specific, internal distortions occur due to the technical design and mechanical imperfections of the sensor itself. These can usually be compensated for on a routine basis, as long as the sensor-specific parameters do not change. External parameters are more difficult to handle and comprise a series of geometric and radiometric effects. The main external distortions originate from the viewing angle of the sensor and the illumination source in relation to the morphology of the target. All angles may be stable during the acquisition, or variable due to random and systematic movements of the platform. Orthorectification and topographic corrections are needed to compensate the resulting spatial and spectral deviations. Depending on the acquisition circumstances, numerous further external radiometric effects can influence the measured signal, including changes in the illuminating irradiance during the measurement, influences of atmospheric components on the radiation path or the loss of spectral information due to shadows.

Photogrammetry

Photogrammetry is mainly used to acquire reliable measurements and 2.5-D geometric models through overlapping either aerial or ground-based photographs (also referred as 2-D imagery). The basis is a triangulation between points and subsequent 2.5-D surface reconstruction based on control points of known spatial coordinates in multiple overlapping images. One of the emerging procedures in photogrammetric processing is Structure-from-Motion Multi-Vision-Stereo (SfM-MVS). This procedure combines photogrammetry techniques and computer vision methods. It uses 2-D image measurements to retrieve 3-D object surface information by means of a given mathematical model. SfM simultaneously estimates the camera orientations and sparse 3-D point clouds from a set of image correspondences. This uses the algorithms such as Scale Invariant Feature Transform (SIFT) and the Random Sample Consensus (RANSAC). 3-D reconstruction is fully automated and today is a standard procedure in photogrammetry.

The positions of 2-D features or points in images depend mainly on three variables; (1) their coordinates in the 3-D space, (2) the relative motion between the camera and the scene and (3) the camera's internal geometry. Algorithms such as SIFT deal with the four similarity variances—two translations, rotation, and scale (zoom) of local image features by simulating zoomed-out images and by normalizing translations and rotation. SIFT is able to detect characteristic features that have very large affine distortions. These features are used to identify tie points between the image pairs. Other algorithms such as RANSAC rely on epipolar geometry and enables robust fitting of a given model, even if the data contains many outliers. It removes outliers after SIFT and identifies homologues points in the sparse representation.

LiDAR

The most important step in LiDAR processing is the computation of the best smooth trajectory of the data acquisition based on merging inertial measurement unit (IMU) and GNSS data. Next steps consist of tie-line leveling to smooth out minor elevation deviations between single swath lines, followed by the filtering of point outliers and the classification of ground and non-ground returns. The final classified point clouds can then be meshed and texturized to form 2.5-D surface models.

PolInSAR

Interferometric synthetic aperture radar (InSAR) techniques use the potential of coherent (monochromatic and polarized) radiation to directly measure the phase change between two acquisitions of the same ground pixel of the Earth's surface. The acquisitions can be simultaneous (single-pass, and thus necessitate two antennas) or consecutive (repeat-pass). InSAR requires that the two co-located acquisitions are spatially congruent (i.e., spatially correlated and coherent) in order to measure phase differences that can be identified as fringes in the resulting interferogram. Several factors such as atmospheric interactions affect the fringe patterns and must be remediated in order to allow the two main applications of InSAR in geology: DEM generation and surface deformation monitoring. Polarimetric SAR (PolSAR) allows the identification of scatterers via the discrimination of their scattering mechanisms which are directly related to the geometrical structure, the orientation, and the geophysical properties of the Earth's surface. PolInSAR makes use of both PolSAR and InSAR techniques.

Processing

Processing of data sets refers to the methods used to perform the data analysis and interpretation. Spectral, SAR and topographic data use feature-specific algorithms for processing. The results provide geologists with the means to interpret and evaluate the surficial geology and monitor surface processes.

Spectral analysis

A fully corrected spectral dataset contains valuable information about the chemical composition of the analyzed material. Interpretation and mapping of the observed spectral characteristics over a spatial extent can be used to create abundance maps of specific materials or material domains.

The spectral component can be either interpreted directly, (1) by the determination of position, depth and symmetry of specific spectral features or (2) by comparison of the dataset to reference spectra (i.e. end members) that represent the domains of interest as well as indirectly by (3) unsupervised clustering into a predefined amount of spectrally similar classes.

Approach (1) may comprise band ratios or minimum wavelength mapping algorithms. The results are usually mineral abundance or composition maps that provide information on important mineral components or bonds according to the depth, shape, and position shift of characteristic absorption features. Approach (2) comprises most supervised classification and spectral unmixing approaches. Ideally, these return information about the location and abundance of materials that are spectrally similar to a set of pre-defined reference spectra, which can be either selected from the data itself or be external spectra derived from libraries or validation samples. These spectral classes or end-members do not necessarily have to be mineralogically pure, but can represent mineral mixtures or spectral domains of interest. The result may be an image classification or separate end-member abundance maps. Unsupervised classifications and clustering approaches (3) rely on a data-driven separation of spectral information into a usually predefined number of classes. The classification map generated may give an overview on the main spectral variability within a dataset. Mineralogical interpretation of the derived classes needs to be conducted afterwards. Common challenges to spectral image processing comprise:

- *Selection of training and validation datasets*: Labeled data are of paramount importance in all image processing tasks, both for the meaningful selection of training samples as well as for the evaluation of the resulting accuracies. Distribution, number, type and targeted selection of validation data from all domains of interest must be decided upon for each imaging campaign.
- *Dimensionality reduction*: An imbalance between the dimensionality of the spectral data and the amount of available training samples can have a dramatic influence on the performance of supervised classifiers. In geological applications, the accessible number of labeled data is often highly limited by the accessibility of the study area, while the number of spectral bands in HSI is high. Common solutions comprise the reduction of data dimensionality by the extraction of image features that represent the informative value dataset in a lower-dimensional space, or the use of particularly robust classifiers.
- *Spectral mixing*: Mixing can originate from a range of effects, such as mixing of the received signal at the sensor due to limited spatial resolution or mixing of spectral contributions within the material, e.g., due to intimate mixtures of different spectrally active materials within one sampling point. Mixing can be considered linear and non-linear, each requiring adapted approaches. A wide range of algorithms has been developed to address this issue.
- *Resolution enhancement/pan-sharpening*: Many hyperspectral sensors offer a limited spatial resolution, which can complicate the detection of small objects. Algorithms for resolution enhancement have been developed utilizing a fusion of the HS image with high-spatial-resolution RGB or multi-spectral data.
- *Denoising*: There are numerous sources for noise in spectral data and these are usually related to an imbalance of sensor sensitivity and intensity of the received signal. For example, the specifications of the sensor may not be sufficient to distinguish a specific weak signal, or the signal intensity may be partially decreased due to atmospheric effects or shadows. Highly corrupted bands should be discarded from the analysis, the remaining data can be improved by denoising or image restoration algorithms.
- *Change detection*: The acquisition of multi-temporal datasets allows the detection of changes over time, however it requires geometrically and spectrally highly accurate data to allow the assignment of subtle spectral and spatial changes to target-related processes.
- *Big data processing/fast computing*: Recent improvements in sensor technology allow for finer spatial and spectral (and temporal) sampling to enhance the informative value of the data. However, the increased amount of data generated demands improvements in fast computing, a factor that is crucial for an efficient data exploitation and analysis.
- *Data integration*: The acquisition of data from various sensors with different specifications (e.g., acquisition principle, platform, spectral and spatial resolution, and spectral range) is a common occurrence and one that multiplies the information available for data classification and interpretation. Machine learning approaches can be used to efficiently extract and combine the core information from each input dataset.

Topographical analysis

The DEMs derived from photogrammetry, LiDAR, or radar provide valuable data on topographic relief that can be used to extract information about both lithology and geological structure. This information is utilized in disciplines such as geomorphology and tectonics to assess interactions between tectonics, surficial processes, and climate that act to shape the Earth's surface. The analyses of topographic surfaces and drainage networks are standard approaches in geomorphology. Analysis of landforms can differentiate between different erosional and thus evolutionary stages. And analysis of river spatial patterns is used in the detection of active uplift and in estimating the amount of uplift for different river segments. Basins with different erosional stages or lithological units are commonly distinguished with hypsometric curves. Furthermore, linear features like fault scarps and dikes can be mapped with approaches such as image discontinuity extraction. Computation and analyses of geomorphic indices can be performed with open source software (e.g., TecDem, TopoToolbox) which permit the extraction of river networks, drainage basins and geomorphologic parameters from the DEMs. Topographic information can also be used to assess the changes that occurred during geological hazards such as landslides, earthquakes and volcanic edifice collapse.

Some commonly used approaches for geomorphic analyses are:

- *Topographic position index (TPI)*: TPI is measured based of the value of elevation of a cell relative to the average elevation of its neighboring cells.
- *Hypsometric integral*: Shows the distribution of landmass volume remaining beneath or above a basal reference plane. The hypsometric integral (HI) for a given area or catchment corresponds to the area beneath a cumulative curve which is obtained by plotting elevations on the vertical axis and areas above the corresponding elevations on the horizontal axis.
- *Surface roughness*: This is a measure of the texture of the surface. It is determined by the deviations in the direction of the normal vector of the true surface from its ideal shape. The surface is deemed rough when the deviations are large, while the surface would be smooth when the deviations are small.
- *Slope*: The slope is calculated by the steepness of a feature compared to the horizontal plane of the area.
- *Aspect*: This is defined as the slope direction. It identifies the downslope direction of the maximum rate of change in value from every cell compared with its neighbors.
- The spatial distribution of stream height is a useful proxy for investigating geologic or tectonic processes. Streams of similar orders are of similar geological age and are related to similar geological events. Isobase maps can be seen as a smoothed version of the original topographic surface, from which the "noise" was removed from the 1st-order streams erosion. Sharp topographic changes affecting an isobase surface may indicate structures associated to tectonic movements or extreme lithological changes.

- Swath topographic profiles provide a useful way to characterize the relief of orogenic belts. An elongated and rectangular patch of relief is extracted and the calculated topographic values (usually the maximum, minimum and mean elevations) are projected onto a vertical plane parallel to the long axis of the swath rectangle. The curve for maximum elevations provides information on the initial relief while the curve for minimum elevations reflects the base-level of rivers. Thus, swath profiles provide a rapid estimate of the incision by the drainage network (the difference between the maximum and minimum elevations).
- River networks are highly responsive and adapt quickly to the changes of surface slope and, thus, they can register tectonic activity better than hillslopes. Deviations from the typical concave-up shape of stream longitudinal profiles, such as knickpoints or convex segments, indicate adisequilibrium state resulting from tectonics, base-level or lithological perturbations.

Radar interferometry

Typically, DEM generation requires very high correlation between acquisitions and small distances between the sensor locations. DEM missions, therefore, will typically perform better with single-pass approaches like the now-famous space shuttle experiment SRTM or dedicated missions such as Tandem-X. In the case of a ground displacement in the range direction, i.e., the line of sight (LOS) between the radar and the target between two acquisitions, a noticeable phase shift will occur with respect to surrounding areas. InSAR is theoretically capable of measuring ground-surface deformation with centimeter-to-subcentimeter precision at a tens-of-meters spatial resolution over a large region. But, in order to be detected, the ground displacement must be locally uniform (in the order of the wavelength of the SAR signal) and homogeneously distributed spatially; the fringes will be easily identified and transformed to distances (phase unwrapping). To mitigate these restrictions, a different approach makes use of multi-image Permanent (or Persistent) Scatterers (PS), isolated points with strong and stable radar returns. PS will be used as a time series and allows for the monitoring of ground deformation with millimeter-scale accuracies even in areas with strong temporal decorrelation (e.g., vegetation cover). More recently, a new technique, Small Baselines (SB), has been introduced to produce pairwise differential SAR interferograms with small temporal and spatial baselines that are generated with multiple-master images to minimize decorrelation.

Polarimetry

The scattering matrix is used to deterministically describe the polarization state of the backscattered radiation by representing the polarimetric backscattering coefficients of the two co-polarized and the two cross-polarized signals. In nature, random scattering leads to partially polarized waves and the non-deterministic description of the scattering mechanisms using the polarimetric covariance or coherency matrix is generally preferred. The matrix is extracted for each pixel of the image, and an eigen-decomposition used to obtain a set of three eigenvalues and three eigenvectors that can be used to produce polarimetric parameters that describe the scattering characteristics. The three-component scattering mechanisms include surface, double-bounce and volume scattering. The Entropy, Anisotropy decomposition is the most common approach to characterize the scatterers and can be also be used to classify the SAR data.

Geographic information system (GIS)

GIS is a scheme for gathering, managing, and analyzing geodata. A GIS integrates different types of geolocated data and can be used to analyze spatial positions, organize information into layers, and then visualize the data using maps and 3-D scenes. These layers of information provide the user with a more holistic insight into the data, such as patterns, structures and relationships. Remotely sensed data is frequently integrated into open-source software such as SAGA GIS, QGIS and GRASS GIS to visualize and analyze the information.

Applications

The geological applications from remote sensing data can vary based on the platforms used. This leads to the acquisition of various data resolutions, densities, precision and area coverages. The properties of the target, such as its size, structure and exposure will determine which platform's data is required.

Satellite

When it comes to space-borne remote sensing, radar and spectral sensing is widely used by the geological community. Satellite-based optical sensors can cover the VNIR, SWIR and LWIR part of the electromagnetic spectrum. The area coverage for these datasets is relatively large and the spatial resolution can vary between ~20 and 100 m. Satellite-based data are usually used for regional mapping and to understand large-scale structures and geological processes.

Most of the early pioneering work on satellite-based geological remote sensing was initiated by the availability of the Landsat sensors. Some of the early work performed with Landsat sensors was based on band ratios to indicate the possible occurrence of alteration zones (e.g., Goetz and Rowan, 1981). Multispectral sensors, such as Landsat and ASTER, are now routinely used by geoscientists because the data allows for a wide coverage with a medium spatial resolution (~30 m) and is free of charge. Other multispectral sensors such as SPOT, GeoEYE and WordView, just to name a few, have higher spatial resolutions and specific view geometries, however they can be costly. Since the emergence of ASTER multispectral data in 2000, geologists have taken full advantage of the added value of its extra channels in the SWIR and LWIR regions to map alteration facies for the exploration of epithermal gold (e.g., Crosta et al., 2003), porphyry copper deposits (e.g., Di Tommaso and Rubinstein, 2007) or mapping the typical phyllic-and argillic-alterations of volcanic zones (e.g., Mars and Rowan, 2006) by using specific absorption features of sulfates, clays, carbonates, silica and iron oxides. It should be noted that the ASTER SWIR detectors stopped functioning in 2009 and that the SWIR data acquired since April 2008 cannot be used. However, recent studies still make use of archived ASTER SWIR data for geological studies, for example, to perform lithological mapping (e.g., Mars and Rowan, 2011) or to identify specific minerals (e.g., Rockwell and Hofstra, 2008).

A major advancement in space-borne remote sensing has come in the form of hyperspectral imaging. Hyperion, for example, has over 200 channels covering the VNIR and SWIR range with a spatial resolution of 30 m. Techniques such as spectral matching methods, whereby the spectrum of a pixel in the image is compared and matched to library spectra, and spectral unmixing methods have led to a more quantitative mineral mapping and the derivation of enhanced surface compositional information for mineral exploration. Hyperion data can be used to map characteristic alteration minerals such as biotite and iron oxides as vectors for mineral exploration (e.g., Zadeh et al., 2014). Not only can satellite sensors provide information on the regional mineralogy, structural information can be derived as well. Manual or automatic image discontinuity extraction methods help to map geological structures such as large scale folding, faulting, layering and dikes. Fraser et al. (1997) demonstrated how the integration of Landsat TM data and a DEM can be used to generate surface geological structure data for hydrocarbon exploration.

Applications of SAR in geology usually involve interferometry to monitor ground motion for uses such as hazard identification and started with the launch of ERS, Radarsat and Envisat. The ground surface deformation that can be detected by InSAR may be caused by any process that leads to a LOS distance change between image acquisitions: crustal deformation (e.g., Earth tides, earthquakes, volcanoes), surface subsidence (e.g., large groundwater movements or underground mining activities), river water level changes, etc. InSAR is now routinely used by seismologists to monitor the seismic cycles of active faults and to estimate their geometries and the slip distribution. The inflation of a volcanic magma chamber and associated dykes caused by refill may lead to measurable surface deformation that can be detected by InSAR (e.g., Amelung et al., 2007). The temporal and spatial monitoring of volcano deformation contributes to a better understanding of volcanic processes, the forecasting of eruptions and flank instabilities and sector collapses. SRTM data and multispectral satellite-based data are used to identify and study debris avalanche deposits in different settings (e.g., Kervyn et al., 2008). Morphological characterization is performed with the elevation data to assess volumes and thus to identify collapse scars, deposit edges characteristic of debris avalanche deposits and estimate the thickness of the avalanche deposits. Other structures like ridges in the avalanche deposits can be identified, thus contributing to the structural study of volcanoes. Hidden geological structures in arid environments can also be identified by SAR, such as craters, faults and paleorivers (e.g., Paillou et al., 2010).

InSAR also can be used for landslide hazard monitoring and possibly for early warning systems but is more than often impeded by the typically severe relief in landslide-prone areas, commonly large rates of movement, and spatial decorrelation. PS- and SB-InSAR can partially overcome those problems and have been successfully used for mass-movement monitoring. InSAR can be used to measure superficial deformations with high accuracy allowing for the monitoring of landslides threatening built-up areas (e.g., Farina et al., 2006; Tralli et al., 2005; Mantovani et al., 1996). Polarimetric applications are currently limited by data availability, but these have a huge potential in geology, with applications focused on the retrieval of soil moisture and surface roughness. The synergetic potential of optical and SAR satellite data using machine learning is currently being developed and will lead to better geological mapping and monitoring. PolInSAR applications are still rare in geology and focus on landform mapping and the InSAR contribution is usually only the coherence.

Aircraft

Aerial photography has been one of the first remote sensing techniques performed by aircraft. Orthophotos are geometrically corrected or "ortho-rectified" that can be handled in the same way as a map. Stereo-photographs form the basis of photogeology and the interpretation of geological features based on their surface expression. Aerial photographs from consecutive years allow to identify major landforms and their evolution (e.g., Evans et al., 2007). Photogrammetry, on the other hand, allows the generation of high resolution DSMs which have largely contributed to improve and accelerate conventional geological field work. Photogrammetric DEMs from archived aerial photographs permit to recover the history of landslides occurrences in remote areas (e.g., Prokešová et al., 2010).

Since the early days of aerial photography, airplane-based remote sensing has matured into a truly advanced form of geological data acquisition. Hyperspectral and LiDAR sensors have been deployed on aircraft since the advent of these devices. Information ranging from the VNIR to LWIR part of the electromagnetic spectrum has been acquired with high spectral and spatial resolution. A wide range of minerals can be mapped at the sub-meter scale because of high spectral and spatial resolution. Airborne hyperspectral data can aid to map inaccessible or remote lithologies using the characteristic spectral information of rock types (e.g., Bedini, 2009) or typical alteration minerals (e.g., Kruse et al., 2006; van der Meer, 2004).

ALS has been the preferred airplane-based method to produce high quality DEMs since its development. Geologist use the DEMs produced with ALS to map prominent relief features such as fault scarps, elevated dikes, or circular bodies outcropping on the surface such as pipes. DTMs from airborne LiDAR can support lithological discrimination by using morphometric variables (e.g., Grebby et al., 2010).

RPAS

High-resolution spectral and topographic information can be acquired with RPAS (Fig. 2). Photogrammetry and ALS have dominated the field of RPAS surveying for geological purposes. Topographical information captured with RPAS-based sensors are used to map structural orientations (e.g., Thiele et al., 2019), characteristic textures and shapes of the landscape (e.g., Mancini et al., 2013), or prominent structures such as dikes (e.g., Dering et al., 2019). In the field of geomorphology Lucieer et al. (2014) and Turner et al. (2015) demonstrated the advantages SfM photogrammetry from UAV-based data to precisely map landslide displacements. In fields peripheral to geology such as mining, UAV-based SfM techniques benefit mine and tailings monitoring (e.g., Tong et al., 2015; Rauhala et al., 2017).

Very few geological studies have focused on multi- or hyperspectral sensing with RPAS, due to the recent availability of lightweight sensors. However, these techniques have been shown to support the monitoring of opencast mines (e.g., Padró et al., 2019), the classification of intertidal sediments (e.g., Fairley et al., 2018) or environmental monitoring, (e.g., Jackisch et al., 2018).

Ground-Based

One of the major advantages of ground based surveying is the oblique angle at which the imaging or measurement takes place. Some outcrop faces or opencast mine walls are not observable from nadir remote sensing (i.e., satellite or plane-based), therefore applying oblique or side-looking surveying techniques are a better option. The mineralogy of vertical outcrops are often mapped with ground-based data. An increasing amount of researchers have taken advantage of the benefits ground-based surveys such as close-range hyperspectral imaging and LiDAR techniques to map outcrops (e.g., Kurz et al., 2013; Boesche et al., 2015) or the mineralogy and structures of mine faces (e.g., Murphy et al., 2015) with centimetric resolutions. Terrestrial LiDAR can produce high resolution 3-D models of geological targets. 3-D modeling of opencast mines and geological outcrops are routinely produced by terrestrial LiDAR. These high resolution models are especially advantageous to structural geologist who map fractures and faulting on vertical outcrops (e.g., Bellian et al., 2005).

Multi-Source, Multi-Scale Approach

Up to now, geological remote sensing has focused mostly on the resulting data acquired from one type of data source. However, in recent years, researchers have perceived the added value of integrating data sets from various sensor types and platforms (Fig. 3). This approach uses the advantages of each sensor in an integrated way. For example, structural and mineralogical information can be derived simultaneously by combining topographic/geomorphological data with multi- and/or hyperspectral information. Additionally, the incorporation of varying spatial and spectral resolutions can provide information on large-scale geological exposures as well as small geological structures. Multi-scale approach such as ground- and UAS-based photogrammetry (e.g., Bemis et al., 2014) or terrestrial LiDAR and ground-based hyperspectral data (e.g., Buckley et al., 2013) can be used order to map complex geological structures with high accuracy. Topographic information from radar and aerial hyperspectral data can be fused with airplane-based hyperspectral data for mineral exploration (e.g., Zimmermann et al., 2016), The integration of terrestrial and RPAS-based hyperspectral and photogrammetric sensing methods has become an operational approach for geological mapping and mine monitoring (e.g., Kirsch et al., 2018).

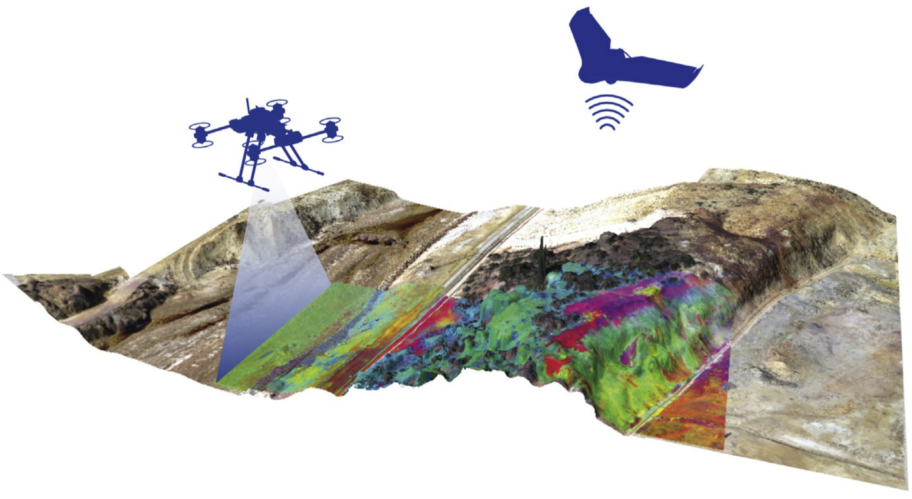

Fig. 2 RPAS-based data collection; Image depicting hyperspectral imaging performed with a multi-copter while the DEM was constructed through aerial photography captured with a fixed-winged UAV.

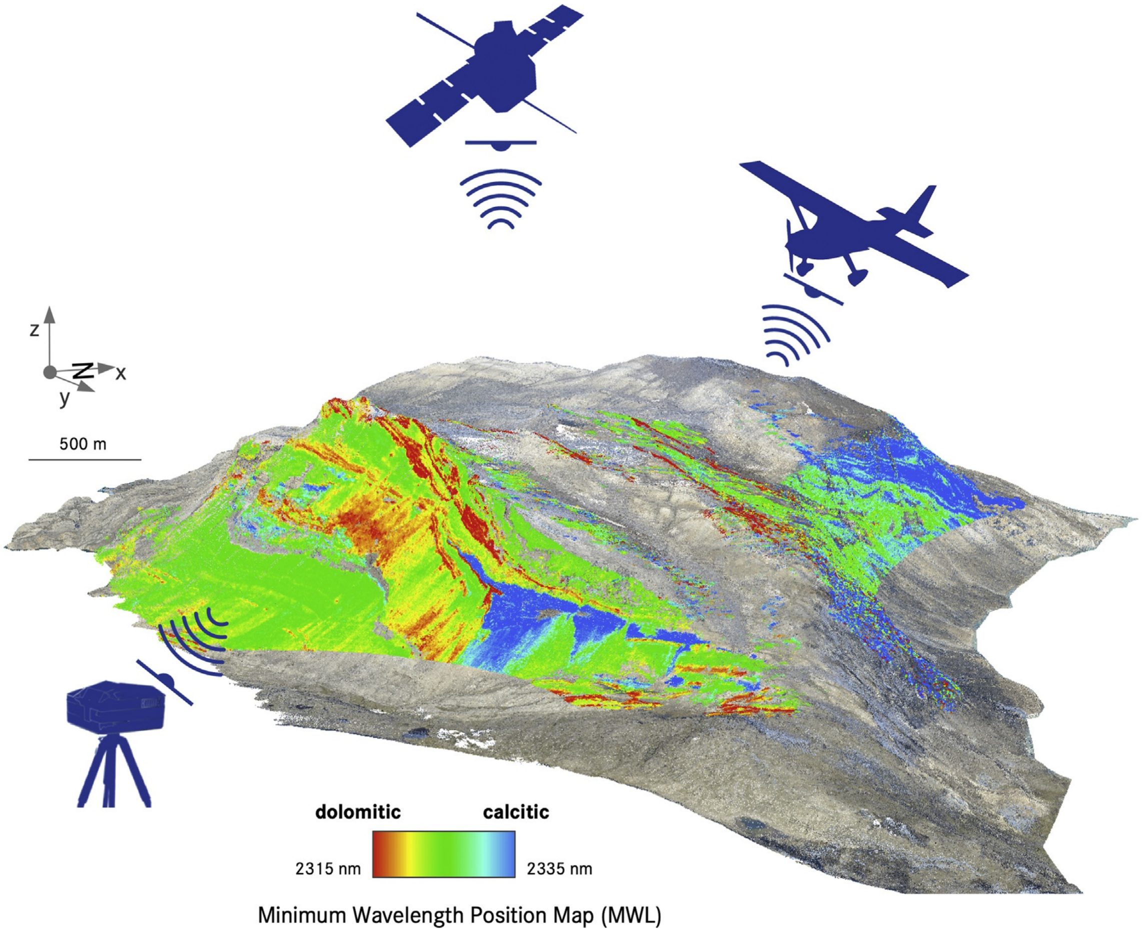

Fig. 3 Image depicting the integration of various data sets acquired with satellite, airborne and ground-base platforms.

Conclusions and Outlook

Over the years, remote sensing has become an important, if not essential, tool in the study of the Earth. Remotely sensed data sets provide indispensable information on the topography, structure, and main mineral compositions of an area. This has enhanced the way conventional geological work is performed. By using remotely sensed data, geologists have been able to map inaccessible areas, improve existing geological maps, and acquire valuable geological data rapidly and safely. There is still the need for efficient ways to combine radar and optical data from the current mission catalogues as well as future hyperspectral missions such as EnMap, which will specifically address the needs of the geological sector. Additionally, further geological solutions must allow for the integration of other sources of information such as geophysical, RPAS (e.g., hyperspectral, LiDAR), and geolocalization (e.g., GNSS) data. There is a need for innovative data processing methodologies (Artificial Intelligence [AI], Machine Learning [ML]) for optimally exploiting the data acquired by different platforms at multiple spatial and temporal scales. The complexity of rapidly evolving technology represent a challenge regarding both the design of short- and long-time series analysis and the amount of data to be processed. These aspects require new methods and approaches for the "Big Data" future, such as scalable image search, retrieval architecture, and deep learning frameworks for efficient information discovery. These approaches will build the foundation of predictive tools.

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