Preparing to Exploit the Science Potentials
The EnMAP Space Mission

What is EnMAP?

Goals of the Satellite Mission

EnMAP (Environmental Mapping and Analysis Program) is a German Earth observation satellite which will use imaging spectroscopy to obtain a diagnostic characterization of the Earth’s surface and record changes in the environment.

Imaging spectroscopy or hyperspectral imaging is an innovative remote sensing technology used to record image data in many narrow contiguous bands. The spectral range extends far beyond the visible light. Each individual pixel of the resulting hyperspectral image contains a continuous spectrum of the solar radiation, reflected by the surface and the atmosphere. These spectra include absorption features, which can be interpreted as so called “spectral fingerprints” of Earth surface materials. They may be exploited to characterize minerals in rocks and soils, analyze vegetation types and conditions, and identify substances in water (Fig. 1). EnMAP’s hyperspectral measurements will provide valuable information to address key scientific questions in a range of application fields such as agriculture and forestry, ecosystem composition and dynamics, geology and soils, coastal and inland waters, and cryosphere.

Fig. 1: Characteristic reflectance spectra for various types of surface cover.
The satellite system is developed in Germany under the aegis of the Space Administration Division of the German Aerospace Center (DLR). The German Research Centre for Geosciences (GFZ) in Potsdam has the science leadership, supported by a Science Advisory Group (EnSAG). OHB System AG in Bremen and Oberpfaffenhofen is responsible for the design and construction of the EnMAP instrument and its satellite platform. The ground segment, responsible for satellite control and data capture, will be operated by DLR in Oberpfaffenhofen (Fig. 2). The project is financed by the Federal Ministry of Economic Affairs and Energy with contributions from OHB System AG, GFZ and DLR.

**Characteristics of the EnMAP mission**

The core of the EnMAP satellite is the hyperspectral instrument that records the reflected sunlight from the Earth at wavelengths between 420 nm and 2450 nm in more than 240 adjacent spectral bands with a spatial resolution of 30 m. EnMAP’s revisit time for any site on earth is 27 days in nadir-view, or every four days with its across-track pointing capability (Fig. 3).
Preparatory science for the EnMAP mission

The EnMAP mission includes an extensive scientific program to exploit the mission’s scientific capabilities from its first day in space on. Its purpose is to assure that a comprehensive network of national and international researchers will be ready to analyze the data in a wide range of scientific topics already when EnMAP is launched. These researchers may build on specifically developed methodologies which utilize the information content of EnMAP data to its full extent. The analysis methods devised during the preparatory phase are freely accessible in the EnMAP Box. This is a software package which is specifically developed for the analysis of EnMAP data (see page 26). The preparation phase also includes intensive training of young researchers in addition to the development of new methodologies. This is being accomplished with activities such as regular EnMAP schools and workshops (Fig. 4). Spectral data, collected in extensive preparatory airborne campaigns, are being used as input to test the developed methodologies. The software which is required to simulate EnMAP data was developed at the GFZ in Potsdam (see page 25).

Fig. 4: Impressions from past EnMAP schools with networking activities (top right), field measurements exercises (top left) and group picture taken during a demonstration of the airborne imaging spectrometer AVIS-3, which was employed in EnMAP preparatory flight campaigns (bottom).
Why do we need EnMAP?

Changes in our environment pose global challenges

Mankind is being confronted with fundamental challenges in the 21st century. The most important ones include a sustainable and global management of land use, the adaption to a manifold of consequences caused by climate change, combating progressive environmental destruction, and the responsible use of natural resources. These complex and interrelated aspects have to be monitored and documented, quantified and understood in order to cope with the growing pressures on society and environment.

Imaging spectroscopy plays a vital role in obtaining a better understanding of the risks and consequences of environmental change. This technology has proven to be a valuable source of information for quantifying and modeling surface processes and analyzing vegetation cover during the last decades. The growing availability of high-quality hyperspectral images in the future will significantly contribute to improve the knowledge of the complex processes and feedback mechanism of the Earth System. EnMAP’s ability to record various regions of the Earth’s surface at short temporal intervals and at high spatial and spectral resolution opens up new possibilities to study the condition of ecosystems. These include the characteristics and composition of vegetation, soil and water and additionally attempt to predict future developments. Therefore, EnMAP is destined to make a significant contribution towards highlighting environmental problems which may lead to improved concepts for the long-term management of land and other natural resources.

EnMAP a milestone in imaging spectroscopy

The development and intensified use of imaging spectrometers for remote sensing has been continuously fostered for nearly three decades. State of the art instruments in satellite operations either do not include the necessary wavelength ranges, exhibit a low spatial resolution, or are not sensitive enough to capture the relevant ground signals. Therefore, advanced imaging spectrometers have been used primarily on airborne platforms for scientific, experimental and commercial purposes. However, airborne instruments do have important disadvantages compared to instruments on satellites. They can only record a limited area on the ground and cannot provide the long-needed global scale and recurrence of measurements of surface processes. In addition, airborne data require a more elaborate correction, and repeated recordings of the same area are very expensive (Fig. 5 and 7).

The present generation of optical satellite sensors comprises of multispectral instruments that measure in individual, relatively broad wavelength ranges. Thus, they usually supply only qualitative information on the composition of the Earth’s surface. Imaging spectrometers provide data with a high spectral resolution which allow a quantitative diagnostic analysis of surface materials for a wide variety of applications. Therefore, the EnMAP mission represents a milestone in optical remote sensing technology and imaging spectroscopy, one which paves the way to an improved understanding of the processes taking place in our environment.

Fig. 5: Simulated EnMAP image (color composite) of the city and surroundings of Potsdam, Germany, showing various urban, agricultural, managed forest and aquatic ecosystems. The simulation is based on airborne hyperspectral image data (HyMap). EnMAP will allow a more frequent coverage of larger areas than feasible in airborne campaigns.
What applications are possible with EnMAP?

**New Horizons in Ecosystem Research and in Resource and Disaster Management**

*EnMAP’s repeated observations with an advanced spectral coverage and resolution will provide new insights into the Earth System (Fig. 6). The selection below focuses on some of the most challenging ones.*

**Climate Change Impacts and Measures**
- How does climate change affect state, composition and seasonal cycles of terrestrial and aquatic ecosystems?
- What measures can effectively combat climate change and how can their implementation be monitored?

**Land Cover Changes and Surface Processes**
- Where and to what extent do land degradation processes and land use / land cover changes occur?
- Which processes drive land degradation and how efficient are countermeasures?
- What are the consequences of land degradation and land use / land cover changes in view of food security and environmental sustainability?

**Biodiversity and Ecosystem Processes**
- What is the spatial pattern of ecosystem and diversity distributions?
- How do ecosystems change over time in their composition and health?
- How are ecosystem processes affected by human activities or natural causes and how can harmful consequences on their biodiversity be reduced or prevented?
**Water availability and quality**
- Which areas are affected by water scarcity and water quality problems?
- How do climate change and human activities, such as intensive agriculture, water demanding industries and high population density, reinforce water scarcity and water quality problems?

**Natural resources**
- How can natural resources, such as mineral deposits, energy sources and ground water sources, be explored and managed in a sustainable way?
- What impact do human activities, such as industry, mining and agriculture, have on natural resources?
- How can environmentally harmful impacts, such as water and air pollution, land contamination and mine waste, be tracked, monitored and managed in order to conserve and sustain natural resources?

**Hazard and risk assessment**
- Which areas are to what extent vulnerable to natural and man-made hazards?
- In case of a natural or man-made disaster, which areas are to what extent affected?

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**Fig. 7: Section of a simulated EnMAP image (false color composite) showing a section of the Pottadder Tantalite Valley Shear Zone, South Namibia, where the Hom River crosses the shear zone (at image center) and where lithium and rare earth elements can be found. The simulation is based on an airborne hyperspectral image mosaic from the HyMap sensor.**
Agricultural production, as a source of food and biomass, is of great importance, considering the continuous growth of the world population. Recent projections by the United Nations claim that by the year 2100 more than 11 billion people will depend on the supply of agricultural goods. This growth in demand was met by a simple increase in agricultural area in the past centuries. This simple adoption strategy has come to an end, as only about 1.5 billion ha of continental land meet the climatic, topographical and soil-forming criteria that enable arable farming in the first place. A possible approach to increase agricultural production is to optimize farming practices, as the yields of currently utilized agricultural land show strong regional differences. An increase in efficiency may be achieved through improved management. Thus, an improvement of cultivation, fertilization, crop-protection and irrigation strategy allows for an increase in production whilst reducing resources requirements at the same time. This increase in efficiency in the form of so-called precision agriculture is increasingly being applied in the agricultural practice. In precision agriculture the land is managed heterogeneously on a small scale (technical term: site-specific). The development of site-specific management strategies relies on spatial information on the current growth state of the plants. Remote Sensing is the only measurement principle capable of providing spatial information about crop status in a comprehensive and non-destructive way.

Agricultural information systems can be designed, by combining remote sensing information with computational modeling. They support farmers in management decisions through continuous, spatially differentiated information. Management strategies may be adapted in a timely and area-specific manner, with the help of these decision support systems, thus preventing or reducing crop failures, e.g. through early detection of nutrient deficiency, water stress or pest infestation. A major challenge is the retrieval of the desired information from the remote sensing data. The previously available multispectral Earth Observation sensors may already be used to perform structural measurements, e.g. to measure the photosynthetically active leaf area from space. The results that have been obtained by these conventional sensors are limited due to their comparatively coarse spectral sampling. Narrow absorption
features and adjacent complex features may not be adequately resolved, which results in a limited number of variables that may be determined. The derivation of the respective land surface variables are associated with larger uncertainties due to this fact. The use of so-called hyperspectral imagery is in many ways a superior alternative, which avoids these problems. The suitability of physically based methods to obtain agriculturally relevant information from hyperspectral satellite data is being investigated at LMU Munich as part of the scientific preparation of the EnMAP mission. Hyperspectral data are first recorded with the help of airborne sensors. They are then converted by computer models into images, whose properties correspond to the data of the future EnMAP sensor. Reflectance models are used to simulate the spectral interaction of sunlight with agricultural crops as a function of vegetation characteristics. If the satellite data used are of good quality with respect to spectral resolution and noise, the reflectance models may be inverted (i.e. reversed) by comparing the modeled reflection with the measured spectrum so that the input parameters may be derived (e.g. see Fig 8).

The EnMAP mission will, provide time series of hyperspectral satellite data of a quality that meets the demanding criteria for physically-based, transferable, variable retrievals in terms of spectral resolution and sensor noise. This is unique to EnMAP if compared to previous hyperspectral satellite missions. EnMAP may thus be used to create improved spatio-temporal information products as a basis for decision making in the context of site-specific management measures (see e.g. Fig. 9). EnMAP will pave the way for global coverage with hyperspectral Earth observation data, which will be a valuable contribution to a more efficient agriculture and thus to more ecologically and economically sustainable use of the bioproductive land surface.

EnMAP and agriculture

EnMAP enables the derivation of special information products, which are used for decision-making in the context of site-specific crop production.

Implementing precision technology in farming strategies can lead to more ecologically and economically sustainable utilization of the bioproductive land surface.

Compared to conventional multispectral Earth observation systems, hyperspectral imaging systems such as EnMAP guarantee (1) a greater variety of observable variables, (2) higher accuracy of the information products by avoiding misinterpretations, and (3) global transferability of variable estimation techniques, which are independent from in situ calibration data.

Fig. 9: Simulated EnMAP time series of the growing season 2012 for an agricultural cultivation area in the vicinity of Neusling, Southern Germany. The temporal evolution of the Red Edge Inflection Point (REIP) is shown, which can be an indicator of nutrient under- or oversupply.
EnMAP as an expert forest observer

Monitoring forest ecosystems at a time of climate change

Forest ecosystems cover significant parts of the land surface and offer many key ecosystem services. They are the most prominent terrestrial sinks for carbon dioxide, storing the highest volume of biomass globally. They have essential productive and protective functions in addition to their function as producers of wood. Their role in preserving biodiversity and climate protection cannot be overstated. However, forests and forest ecosystems are increasingly threatened by global warming, a rapidly growing population and by ever expanding economic activities. Destruction of forests, conversion of forests to agriculture acreage, legal and illegal wood harvesting and recurring forest fires are only a few of the processes which add to the burden on forest landscapes and ecosystems.

Ongoing scientific analysis of these processes must consider both the protection and preservation of forest ecosystems and the economic interests behind commercial forest management. The demands on data that form the basis of decision making in an ever more complex world are constantly increasing. Therefore, the information required for balancing economic and ecological interests in sustainable forest management can no longer be retrieved without remote sensing technology.

The hyperspectral satellite mission EnMAP can make a significant contribution towards this goal. It is capable of a regular monitoring of a representative, global network of selected forest locations. The mission has a key role in developing and optimizing methodologies for mapping tree species and their levels of maturity. It is able to assess forest structures and forest resources in discrete land segments. The specific properties of hyperspectral sensors (Fig. 10) are very effective for recording the physiological state variables of forest ecosystems. For example, by characterizing water and pigment content they enable early identification of stress phenomena (Fig. 11). This is the basis for a regular monitoring over several growth cycles, which opens new perspectives for the integration vitality indicators derived from hyperspectral systems. These are found via model calculations of plant production and forest growth. Simulations based on remote sensing data can make a decisive contribution towards assessing forest management concepts in anticipation of future climate conditions at regional levels.
The University of Trier is focusing on those aspects relevant for optimally exploiting EnMAP’s potential for forest research. One example is to study and develop model-based and advanced empirical methodologies for recording eco-physiological state variables. The development of powerful algorithms is being expedited in parallel, for example the integration of atmospheric radiative transfer models with geometric-optical reflectance models for stands of trees.

The next step is to concentrate on collecting hyperspectral image data in order to generate simulated EnMAP data sets, to guarantee the readiness of the developed methodologies for the real EnMAP data, when it will become available. Image sequences, which ideally extend over an annual course of seasons, have to be produced for dynamic forest ecosystems which react sensitively to phenological cycles, stress factors and differences in locations.

**EnMAP and forest ecosystems**

Forest ecosystems are among the most important providers of fundamental ecosystem services to be investigated with EnMAP.

EnMAP will provide information on forest structures and resources critical for an economic and ecological sustainable management of forest ecosystems.

The early identification of climate-related stress phenomena with EnMAP is important for developing appropriate forest management concepts.

**Fig. 11:** Recording drought stress at Donnersberg, a forested area in Rhineland-Palatinate, Germany. At the top, the hyperspectral Photochemical Reflectance Index (PRI), calculated from simulated EnMAP data, shows early signs of drought stress, while the Moisture Stress Index Double Ratio (DRMSI) does not highlight drought-stressed areas yet.
Terrestrial ecosystems are facing unprecedented changes as a result of global change. Deforestation, extensive agriculture or urban growth, as a result of direct human intervention, have significant impacts on the condition, functioning and biodiversity of ecosystems. A better understanding of the interactions between human activities and the surrounding land systems and their ecosystem services is urgently needed. This may only be achieved through monitoring of entire regions over long time periods.

Earth observation is a fundamental method for the characterization of entire ecosystems and ongoing process changes. The concepts of Essential Biodiversity (EBVs) and Climate Variables (ECVs) provide an appropriate implementation framework to meet global standards for ecosystem monitoring. EnMAP data can make an important contribution to the derivation of several EBVs and ECVs such as vegetation leaf area, biomass and community composition.

The EnMAP mission will allow for global sampling of hyperspectral data on a regular basis. The high spectral resolution of EnMAP will allow for a better interpretation of spectral signatures and their relations to physical processes. It will be possible to derive more detailed parameters regarding the type (e.g., species composition), structure (e.g., biomass) or condition (e.g., leaf nitrogen or water content) of vegetation with EnMAP data.

In addition, EnMAP’s ability to regularly monitor contiguous areas over long periods of time will complement dense time-series from multispectral sensors such as Landsat-8 OLI and Sentinel-2 MSI. This will further allow for assessments of gradual, continuous changes, such as assessing the effectiveness of a protected area in terms of biomass or biodiversity, or the impact of disturbance events such as droughts on vegetation condition and recovery.

The focus of the EnMAP-related research at Humboldt-Universität zu Berlin is on the gradual spatial and temporal changes within individual ecosystems as well as on the transitions between different types of ecosystems. The following aspects receive special attention: (1) quantification of vegetation types and their fractional coverage or biomass in different ecosystems, (2) assessment of the gradual evolution of agricultural areas following abandonment, and (3) characterization of land use gradients in urban areas and their direct surroundings.

Traditional processing approaches for multispectral images often fail to effectively exploit the additional spectral information when applied directly to hyperspectral images. Machine learning approaches are adapted and further enhanced for spectral analyses to better utilize the potential of data from modern, spaceborne imaging spectrometers such as EnMAP, particularly with regard to quantitative mapping assessments. A specific focus is put on finding linkages between empirical and physical approaches and on the generalization of empirical models to optimally exploit the improved spatial and temporal data availability that EnMAP will provide.

The gradual spatial and temporal ecosystem change of Castro Verde, southern Portugal, has been comprehensively monitored over the last 15 years. The region is characterized by the abandonment of degraded agricultural land and subsequent succession of natural vegetation. Regular habitat mapping surveys complement remote sensing campaigns and associated field campaigns (Fig. 12).

The Castro Verde region is currently characterized by fallow land, which was formerly used for agriculture. This has increasingly led to shrub encroachment (Fig. 13). Part of the study area is also within the Natura 2000 Special Protection Areas for Birds with steppe bird communities of national and inter-
national significance. Analyzing an ecosystem with obviously conflicting ecosystem services, such as increasing carbon storage of encroaching shrubs and enhancing bird biodiversity of the steppe grasslands that initially replaced agricultural lands, illustrates the complexity of such natural environments.

The core of the hyperspectral image analysis of this case study is the mapping of the gradual shrub encroachment process across space and time. The quantification of different shrub types and steppe grasslands, as input for subsequent modeling of biotic processes for example, is particularly challenging considering the various phenological stages of dryland vegetation. The performance and robustness of new machine learning techniques to describe subtle spectral differences between vegetation types have been tested. The developed approaches allow the production of quantitative maps illustrating fractional shrub cover, i.e., information content which reaches far beyond conventional maps derived from discrete land cover classifications (Fig. 14). In particular the detection of areas with lower shrub fractions is of high relevance for different ecological applications and decision making and early detection of ecosystem changes. The developed methods are made freely available in the EnMAP-Box. Results obtained from simulated EnMAP-data have demonstrated that EnMAP will provide an essential contribution to quantitative, ecological investigations of vegetation in sub-humid to arid zones.

**EnMAP and ecosystem changes**

Adequate research is lacking on the transitions between ecosystems and on the gradual changes within them. So far it has been difficult to comprehensively describe these changes in space and time.

EnMAP will offer basic and innovative analyses to improve the understanding of global change as well as the interactions between humans and their environment.

Characterizing and recording ecosystem services using a combination of qualitative and quantitative approaches is an important goal of the research within EnMAP.

Analyses of simulated EnMAP data reveal subtle processes that cause an ecosystem change.

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Fig. 13: Abandoned landscape with progressive shrub encroachment.

Fig. 14: Fraction map showing shrub cover in the Castro Verde region, Portugal, derived from a Support Vector Machine Analysis and simulated EnMAP data. False-color Landsat-5 composite shown in background.
Soil is not a renewable resource, viewed on the time scale of a human being. It is worth to protect it because of its numerous important functions. These are for example food production, water regulation, filtering pollution, and carbon storage. The ecosystem services provided by soil are threatened worldwide by climate change, natural hazards and human activity. The consequences are an increased soil removal due to wind and water erosion, or land-slides, as well as a reduced soil quality due to the loss of organic matter, contamination, salination and soil compaction. In 2006 the European Commission issued a guideline on protection and preservation of Europe’s soils. Its goals are sustainable soil use, preservation of soil quality and functions, as well as soil restoration.

A main reason for global soil degradation is widespread inappropriate land use. These are for example deforestation and over-grazing (Fig. 15). The loss of vegetation cover, unsuitable land use like monoculture farming or farming with inadequate irrigation systems lead to erosion and exhaustion of the soil (Fig. 16). The silting-up of rivers and dams is another severe effect. Soil degradation is especially problematic if it progresses at a slow pace and is only recognized at a late stage. Nearly 70% of the Earth’s drylands are already showing signs of degradation. The precondition for the control of erosion is the precise knowledge on how much area is potentially endangered and on the development of erosion over time. The need to monitor, analyze and assess soil degradation processes worldwide is particularly emphasized in the United Nation’s Convention to Combat Desertification (UNCCD), which has been signed by 180 states.

There is a large global need for systematic, area-wide soil mapping which reflects the relevant topsoil characteristics with high spatial resolution and precision, which goes well beyond recording degradation processes. Soil maps are often based on data that has been collected for individual field locations only. Large-coverage maps are needed for many applications, including agriculture, for the development of soil preservation strategies, or as a basis for climate models.

EnMAP will offer new opportunities for the quantitative spatially-distributed collection of key parameters useful for a worldwide characterization of soil conditions and derivation of degradation indicators. Regular monitoring facilitates an early identification of degradation stages, which enables timely implementation of suitable countermeasures for example in agricultural areas to sustain soil quality and yield production. This supports sustainable agricultural practices. Important parameters measurable with EnMAP apply to soil and vegetation information, such as the ratio of vegetated to bare soil area,
the water and pigment content of plants, the soil organic content, clay, carbonates and salt in the soil, and soil moisture. These parameters could not be measured from space to the precision anticipated with EnMAP (Fig. 17) so far. Especially in drylands, the vegetation cover consists not only of green plants but also of a high proportion of dry biomass. This dry material is very important in the prevention of erosion. It can be detected and quantified with an imaging spectrometer such as EnMAP, whilst conventional multispectral sensors are unable to do so.

Important aspects of the EnMAP preparation phase at GFZ include the development of methods to detect and characterize soil properties. This input data is critical for erosion and soil degradation modeling. A suitable set of algorithms for the quantitative derivation of key soil and erosion parameters has already been developed (EnSoMAP, the EnMAP soil mapper). The studies are performed in different climate zones around the world at test sites in Germany, Europe, Asia, Australia and southern Africa selected as typical representations for the observed processes.

**EnMAP and soil**

EnMAP will allow for a repeated, quantitative, diagnostic derivation of key soil parameters.

EnMAP will make an important contribution to the generation of soil maps worldwide.

Early stages of progressive soil degradation will be recognizable.

EnMAP will, therefore, facilitate the development of timely countermeasures.
The current strong increase in commodity prices at the world market, driven by population growth and consumption, enables mining operations in previously uneconomic regions. Ferrous and non-ferrous metals as well as energy resources (oil, gas and coal) are in the focus of the industry. Modern society demands the environmentally friendly and sustainable extraction and usage of these resources. This challenges geo-scientist to develop new scientific-technological solutions in the mineral resource sector. A key factor is the minimization of land-use in mining operations (Fig. 18) for a cost effective and environmentally friendly extraction. Remote sensing methods, particularly imaging spectroscopy, deliver a significant contribution to mineralogical and geological mapping during the full lifecycle of a mine: from exploration to extraction and later closure and reclamation operations.

A unique feature of imaging spectroscopy is the characterization of minerals in rocks and soils based on characteristic absorption features (termed „spectral fingerprints“), which are neither visible to the human eye nor with previous spaceborne sensors (see Fig. 19 and 20). These absorption features may only be characterized and analyzed in detail by detailed spectroscopic records, which enable a quantitative analysis of surface cover materials. The EnMAP instrument was designed to record the “spectral fingerprint” of surface cover materials via its innovative technology, which enables the sampling of the spectral signal in more than two-hundred narrow spectral channels. Scientists have designed all system parameters to be able to record the characteristic absorption features (Fig. 20) of common geological materials. These are for example oxides and hydroxides, phyllo-silicates, sulfates, carbonates as well as the economically important group of rare earth elements.

A mineral is identified by the position and form of its characteristic absorption feature. The depth of the spectral fingerprint is correlated with its abundance. These physical relationships enable the development of new analysis techniques which previously would have not been possible using multispectral remote sensing only (Fig. 20). Automatic algorithms are now able to characterize and quantify minerals and materials up to the sub-pixel scale making use of spectral analytical comparisons of the unknown signal to known spectral reference libraries. The spaceborne spectral laboratory, represented by EnMAP enables new, more detailed diagnostics of surface processes, which go well beyond the ordinary classification of rocks and soils.

As part of the EnMAP scientific preparations, GFZ in Potsdam is working to develop a new innovative expert system (EnGeoMap) for the automatic identification of minerals and soils. Simulated EnMAP images are used in the development process of EnGeoMap to ensure reproducible and robust analysis results. New concepts and associated software is being developed alongside the general rock mapping and mineral exploration, which include the characterization of mine-waste material and reclamation sites.
Human impact on natural ecosystems worldwide has grown through the increased extraction and usage of mineral resources. Especially land use in mining and post-mining landscapes has a significant influence on nature and its biodiversity, a fact which has to be accounted for in modern mining operations (Fig. 18). An effective land management and low-impact mining is in the best economic interests of every mining company today. The smaller the quantity of material that has to be extracted, the lower the amount of money that is spent on the mine and hence the greater the revenue. A win-win situation between economy and ecology made possible by imaging spectroscopy in mining.

Drivers and indicators should be identified in the EnMAP preparatory phase that enable the development of new tools for environmental impact assessments on the basis of imaging spectroscopy data. This allows for the monitoring of the spatiotemporal evolution of large mining and post-mining landscapes. This leads to a better landscape management as well as later more effective reclamation operations.

Selected mining regions in Namibia, South Africa as well as Greece are analyzed with local academic partner institutions to achieve these goals. Data is analyzed in the field (Fig. 19) and in the laboratory using spectrometers. Airborne surveys and simulated EnMAP data calculated from them help to develop the aforementioned new techniques, which are intended to be ready for use once EnMAP delivers the first data.

EnMAP and geology

EnMAP enables a unique characterization of minerals and rocks via imaging spectroscopy.

EnMAP delivers a significant contribution to the mineralogical and geological mapping of mineral resource sites.

EnMAP enables an area wide spatio-temporal assessment of mining regions and their related mining activity, highlighting key areas for later reclamation operations.
EnMAP as a versatile hydrologist ...

Detecting changes in the Wadden Sea

The spatial extent of the Wadden Sea, its dynamic change triggered by currents and tides, and the associated inaccessibility of the area make remote sensing data an important source for monitoring and assessing this sensitive and unique natural environment.

The distinct elements of the Wadden Sea are narrow channels, open tidal flats with sandy or muddy sediments, extensive mussel populations and resurgent seagrass beds (Fig. 21). It is essential to record the radiation reflected by this tideland at the highest possible spectral resolution, especially for the usually low-contrast mudflats, whose surfaces lack the sharp borders and land use variations as for example on dry land. In the frame of the EnMAP preparation, in-situ measurements were made in order to spectrally characterize different tideland surfaces.

Laboratory analyses of sediments were undertaken to calculate parameters like chlorophyll content. An airborne campaign with a hyperspectral scanner (AISA) supplied the corresponding remote sensing data (Fig. 22). The potential of a hyperspectral Earth observation satellites such as EnMAP is clearly evident in the improved discrimination of various surfaces and the possibility to apply narrow-band indices and algorithms. Calculating parameters like the intensity of microalgae colonization (the phytobenthos index) and chlorophyll content provide important information about the primary production of biomass in tidal flats.

Fig. 21: Satellite image of the Wadden Sea with low spectral resolution (Landsat) in the background and a strip of high-spectral resolution airborne scanner data (AISA). This figure exemplifies the different spatial coverage of extensive landscapes like the Wadden Sea achievable with locally collected airborne data compared with region-wide satellite data such as future EnMAP data.

Fig. 22: Chlorophyll map derived from hyperspectral airborne image data (AISA). The coarser resolution of the future EnMAP data is indicated by the larger coloured semi-transparent pixels.
The thawing of permafrost soil and the progressive melting of sea ice, as a consequence of global warming, have received worldwide attention. The melting process leads to a strongly increased inflow of substance-rich freshwater and to serious erosion of unstable coastal areas, especially in eastern Siberia. Little is known about the state and distribution of permafrost soil and its decomposition in highly structured coastal areas.

The satellite image in Fig. 23 shows an extremely high concentration of humic substances (high molecular weight compounds in organic soil) in the Lena delta of eastern Siberia. Their absorbance values can exceed 8 m⁻¹, which means less than 0.5 m visibility depth for these waters. The Lena is therefore transporting a very large amount of carbon into the Arctic Ocean in this image, making it a very large carbon source. The concentration of humic substances in coastal waters still is very high with values of 3-6 m⁻¹. Comparisons with in-situ measurements made on the same day show good correlation with deviations under 10%. EnMAP will facilitate these investigations at significantly greater spatial and spectral resolution.

**EnMAP and water bodies**

With its high spectral resolution, EnMAP will provide comprehensive information on the water quality of inland and coastal waters, leading to a better perception of local ecosystems.

EnMAP’s high spectral resolution will allow to identify substances in water such as suspended particles, dissolved organic matter, phytoplankton and dominant algae species.

EnMAP data will help to better understand the regional and global roles of coastal and inland waters in the carbon cycle.
Rapid conversion processes are taking place in urban population centers worldwide. Today, more than half of the global population lives in cities. This development has numerous negative consequences, and avoiding or at least reducing them places enormous demands on those attempting to manage urban regions. The most urgent problems include urban sprawl, high traffic density, and climate-induced impacts. The susceptibility of cities to natural hazards such as storms and flooding also poses special planning challenges.

These problems are especially pronounced in megacities. It is therefore necessary, to balance the needs of ecologically sound, economically profitable and socially compatible development, whilst at the same time preserve the unique character of a city and its environs.

The key element for this kind of sustainable urban development is a profound understanding of the evolution of and the interactions between natural, built-up and socio-economic environments. The central component for assembling this knowledge is, in turn, an extensive database of up-to-date geo-information on the spatial and temporal development of built-up areas and the surrounding natural and cultural landscape.

This is where EnMAP can make an important contribution. Continuous monitoring of the Earth’s surface from space provides a unique overview of the spatial fabric and development of built-up areas and cultural features. Because of EnMAP’s high spectral information content, detailed qualitative and quantitative information on the nature and distribution of urban surfaces and their climatic effects can be derived.

Cities contain a wide range of natural and artificial surfaces with characteristics of varying relevance for city planners. Roofing materials are especially diverse, and knowing their nature
and grouping pattern permits conclusions about the urban structure. Open spaces vary in their ground sealing properties. Areas covered with asphalt and concrete are considered to be fully impervious, because most of the rainwater or environmentally problematic liquids enter the sewerage system. Partially impervious surfaces allow some of the rainwater to be absorbed by the ground. Vegetated urban areas provide many benefits for the local climate. They have a positive influence on the quality of life of the city’s inhabitants.

Knowing the type and distribution of surface materials in cities is therefore essential for planning and developing urban areas. They can be identified and recorded with imaging spectrometers such as EnMAP. Studies with airborne hyperspectral sensors have shown that each kind of surface material has its own characteristic spectral reflectance signal. This can be measured in acceptable detail only with imaging spectrometers (Fig. 24). Environmentally problematic materials like asbestos or specific components like solar panels can be identified. Multispectral systems with their limited number of bands are, by contrast, unsuitable for recording urban surfaces at the material level.

The challenge in using EnMAP data for identifying materials relates to the pixel size with which EnMAP observers the Earth’s surface. Figure 25 shows that one EnMAP pixel contains spectral information for a number of different surfaces. Because of EnMAP’s high spectral information content, information about the nature of impervious surfaces and vegetation can be reconstructed. The percentage of the individual surfaces can be determined with a procedure known as spectral unmixing.

The knowledge about urban surface materials at subpixel level makes it possible to derive planning-relevant indicators with high precision. The quantification of the imperviousness is one of the key elements when monitoring the development of urban areas, particularly megacities, which have rapidly expanded in recent years. With EnMAP data, such information can be automatically quantified (Fig. 26).

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**EnMAP and Urban Areas**

Knowledge gained with EnMAP about the nature, distribution and changes in surface materials, such as streets, roofing and vegetation, is important for planning and developing urban areas.

EnMAP data can be used to quantify the degree of imperviousness and the percentage and quality of vegetation in urban conglomerates.

EnMAP will provide basic spectral data important for the active planning of sustainable cities.
Anthropogenic pollution is induced by human forces and can be of intentional as well as of accidental nature. It can occur from activities such as non-renewable resource exploitation, industrial processing, agriculture, urban development, transportation, and shipping, and can have the potential to impact on all aspects of society including its economy, its habitats’ health and well-being and the environment.

Diagnostic data to inform decision making is critical for anthropogenic hazard management whether as an emergency response, for routine monitoring or assessments of potential risks. Imaging spectroscopy has unique contributions to make via the ability to provide some of these key quantitative diagnostic information, and, there have been numerous case histories demonstrating the value of imaging spectroscopy from characterization and monitoring the impacts of non-renewable resources activities to providing guidance to emergency responses.

The best known use of imaging spectroscopy in this area relates to determining the impacts from the mineral industry. Minerals are valuable resources used throughout modern society and there is little doubt that the demand for these commodities will increase. However, the extraction and processing of minerals are associated with a number of sustainable development challenges, including various economic, environmental and social issues (Fig. 27). Therefore, evidence of responsible exploration and mining is crucial to gaining license to operate for the continuity of current mineral resources operations and expected expansion. Over the last three decades, the use of hyperspectral imaging in support of responsible non-renewable resources has been demonstrated as one of the most compelling cases of the use of imaging spectroscopy. This is because this technology is able to provide (1) crucial mineralogical information unattainable from other exploration and mining tools contributing towards improved resource characterization, thereby reducing environmental footprints as well as contributing towards more efficient and safer mining practices; and, (2) quantitative, direct environmental information required for decision making and substantiating compliance with regulatory requirements. Figure 28 shows the use of imaging spectroscopy for monitoring acid mine drainage conditions.

In addition to mine waste monitoring, imaging spectroscopy has been successfully used for mapping other anthropogenic hazards including hazardous dusts and oil spills. Often large amounts of dust fallout can be generated as a result of accidental spills or human misdemeanors. In some occasions, the dust can be hazardous. Therefore, the deployment of imaging spectroscopy for the task of remotely and rapidly detecting and locating the dust fallout presents an important tool for emergency responders and those involved in the clean-up. Such was the case during the World Trade Centre attack on 11 September 2001. Imaging spectroscopy was deployed diagnosing the composition and mapping the distributions of potentially hazardous dust to guide the clean-up process.

An oil spill is oil, discharged accidentally or intentionally, that floats on the surface of water bodies as a discrete mass and is carried by the wind, currents, and tides. Oils spills have the potential to have detrimental impacts on humans, fauna, natu-
Fig. 28: Maps of secondary minerals (yellows, orange, reds and brown colours) and effluorescent salts (blue and cyan colours) resulting from acid mine drainage mapped from multi-temporal imaging spectroscopy data acquired in the Soteil Migollas Mine, Andalucia, Spain. Changes in the tailings pond (fan shape in middle of image) can be seen from 1999 to 2005 due to the development of efflorescent salts as the pond dries out with the drought in 2004 and 2005. The analysis is based on hyperspectral images acquired with the HyMap sensor at 5 m spatial resolution.

Fig. 29: Map of the oil contamination in the Gulf of Mexico in 2010 after an explosion on the Deepwater Horizon (DWH) offshore drilling rig (left) and spectral laboratory measurements of oil spill samples taken in the Gulf of Mexico (right)

EnMAP and anthropogenic pollution

EnMAP will assist in the characterize, monitoring and rehabilitation of areas affected by different types of anthropogenic pollutions.

EnMAP will allow timely assessments of the spatial distribution of potentially hazardous dust, oil spills, contaminants and mine waste and thus provide valuable information for emergency responses.
EnMAP sees the Earth from various viewing angles

**Signal variance of multitemporal off-nadir views**

Vegetated surfaces are especially problematic in this context, due to the exceptionally large differences in the relationships between signal mixtures at different view angles. A part of the signal emanates from the ground and from plants with shaded and illuminated surfaces in between (Fig. 30).

A spectral, spatial and temporal simulation system was developed at GFZ, to record and correct these effects. It can be used to model the reflectivity of any kind of vegetation. The core of this simulation are 4D (3D geometry + temporal development) plant models whose individual geometries are overlaid with the relevant spectral information, after which they are linked using a ray tracing methodology taking into account all possible viewing angles (Fig. 31).

As a first step the viewing-angle-dependent variations in the reflectivity of grain crops were investigated using simulated reflectance data. Then the extent to which these variations affect the quantitative prediction of bio-physical (e. g. leaf area index) and bio-chemical (e. g. chlorophyll content) vegetation parameters were analyzed. Such vegetation parameters allow to draw conclusions on the condition and, if monitored over time, on the development of the observed canopy. They can also be used for ecosystem modeling. A good prediction quality was achieved with machine learning techniques for vegetation parameters of individual angle observations even with very strong tilting (± 30°). However, the prediction quality deteriorates considerably if the observation geometries differ between training and prediction data sets. Including all observed geometries in the training of the data leads again to a good prediction quality. These results show that the prediction of bio-physical and bio-chemical vegetation parameters is also possible with off-nadir data sets, if all observation geometries which are representative for this data set are included in the analysis.

A satellite system such as EnMAP is in principal designed to record land surface processes globally. The sensor has a revisit rate in nadir view (perpendicular to the ground) of only 27 days, due to its 30 km swat width. However, by rotating the satellite across-track up to ± 30° any point on Earth can be revisited in less than four days. This higher repetition rate will be used for special applications and scientific studies. It has the disadvantage that the spectral signal recorded for a given area is significantly altered when viewed from different directions.
EnMAP images already before launch

Generating future EnMAP images with simulation software

Research topics guide the design of any new Earth observation sensor. But optimizing essential sensor parameters assumes that influences affecting data quality, the expected accuracy of results and the possibilities for correction are known in advance.

The simulation software package EeteS (EnMAP end-to-end simulation software) was developed at GFZ in Potsdam to obtain this essential information. EeteS consists of two components, an EnMAP image simulator and the associated data preprocessing chain (Fig. 32). The image simulator first generates typical EnMAP raw data by calculating the overflight of the sensor above an artificial three-dimensional landscape. It takes into account the spatial, spectral and radiometric characteristics of a numerical EnMAP sensor model as well as different atmospheric conditions. By modifying a large variety of sensor parameters, their influence can be studied in the image data, and in turn be optimized. This requires preprocessing of the EnMAP raw data in a second step using on-board calibration measurements. They include, for example, absolute radiometric calibration based on a solar measurement, and detector non-linearity and dark-current measurements, all of which can also be simulated with EeteS. The data are then transformed into top of atmosphere radiance values using an in-house Level 1 processor, and afterwards into spatially corrected surface reflectances with a Level 2 processor. These values are the starting point for application-oriented research and sensor optimization.
The availability of EnMAP data will mark a major step forward from airborne case studies, i.e. single observations of limited spatial extent, towards a more operational use of imaging spectroscopy data. Current analysis approaches from the field of imaging spectroscopy will have to be adapted to be used on larger areas. Classical workflows for spaceborne multispectral data have to be refined to make best use of the additional spectral information content. The use of image spectral libraries collected from a global EnMAP image archive or the work with radiative transfer models can be expected to enter the world of more applied users. Several algorithmic developments have been accomplished as part of the EnMAP mission preparations and further developments are underway. All of them are distributed in a toolbox the EnMAP-Box.

The EnMAP-Box provides algorithms and applications for the processing and analysis of the future EnMAP data. For each application domain, e.g. geology, forestry or agriculture, state-of-the-art workflows for the analysis of EnMAP data are provided. Various user-friendly machine learning applications for image classification and regression or tools for integrating spectral library information are available as well. The EnMAPBox includes algorithms for a customized data preprocessing. It is developed for and serves the needs of a variety of users, reaching from imaging spectroscopy novices over experienced users to scientific programmers.

Starting with version 3.0, the EnMAP-Box is realized as a plugin for the geographic information system QGIS. The plugin is programmed in Python and builds on selected packages, e.g. GDAL, NumPy, scikit-learn or PyQt, plus an application programming interface (API). The EnMAP-Box has its own graphical user interface to offer a bridge between the worlds of GIS and imaging spectroscopy. Most of the algorithms that are made available through the EnMAP-Box can be used directly in the QGIS Geoalgorithm framework or Model Builder.

The free and open source nature of the EnMAP-Box and its packages for the easy use of Python resources on imaging spectroscopy data opens the floor to external developers. Anyone is invited to share new approaches that proved successful for the work with EnMAP data. Efforts to provide those in a standardized manner are minimized. This way, sharing of algorithms and the enhanced availability of latest developments shall be increased within the growing EnMAP community.

The EnMAP-Box and all related resources, including documentation and application tutorials are available through www.enmap.org and bitbucket.org/hu-geomatics/enmap-box.
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