Environmental Mapping and Analysis Program

Preparing to Exploit the Science Potentials

The EnMAP Space Mission

What is EnMAP?

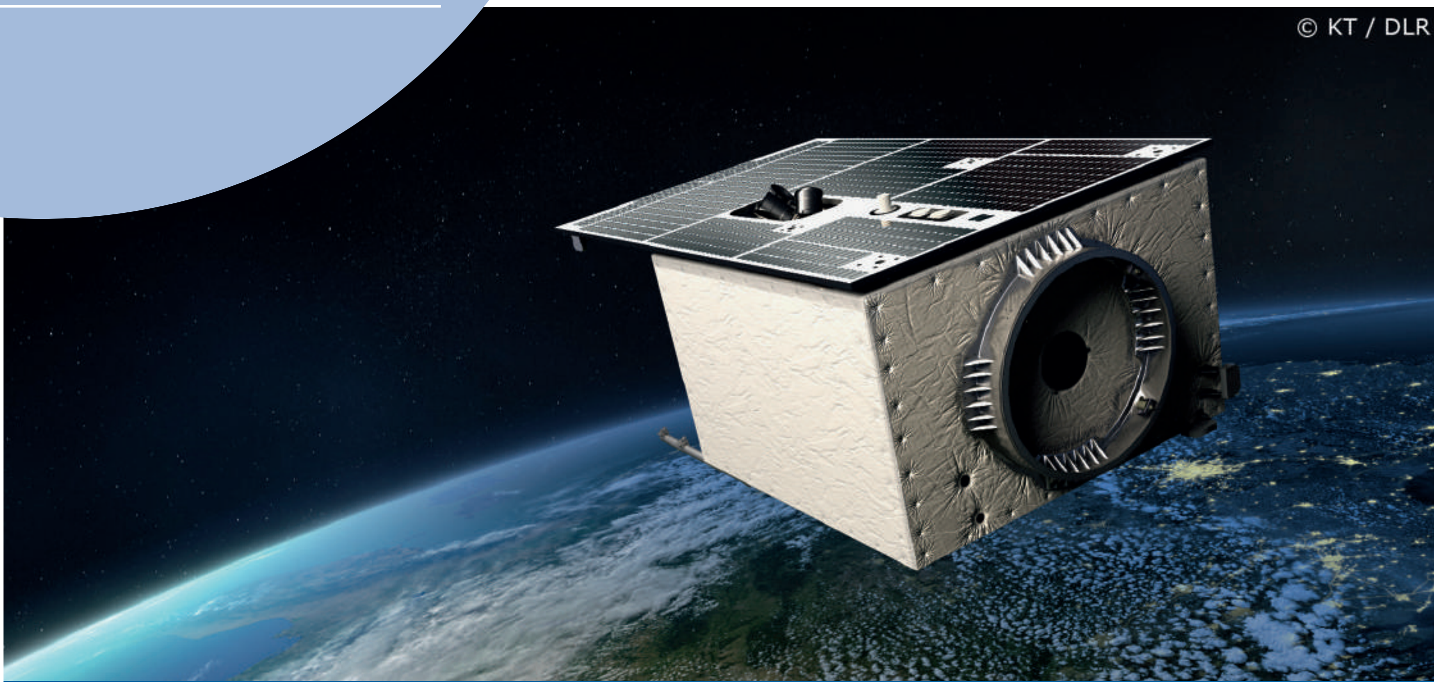


Fig. 1: The EnMAP environmental satellite.

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.

EnMAP's spectral measurements will be used to derive quantitative surface parameters on the status of terrestrial and aquatic ecosystems and the changes they undergo. EnMAP data will supply a basis for quantifying and modeling crucial ecosystem processes, thereby making a major contribution toward understanding the complexities of the Earth System. More specifically, the primary goals of the mission are to investigate globally interconnected environmental processes and changes, to study the diverse effects of human intervention in ecosystems and to support the management of natural resources.

The satellite system is being developed entirely 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). The Kayser-Threde company in Munich is designing and constructing the EnMAP sensor and OHB in Bremen is building the associated satellite platform. The ground segment, responsible for satellite control and data capture, will be operated by DLR in Oberpfaffenhofen (Fig. 2). The project, which will cost more than 200 million euro, is financed by the Federal Ministry of Economics and Technology with contributions from Kayser-Threde, GFZ and DLR.

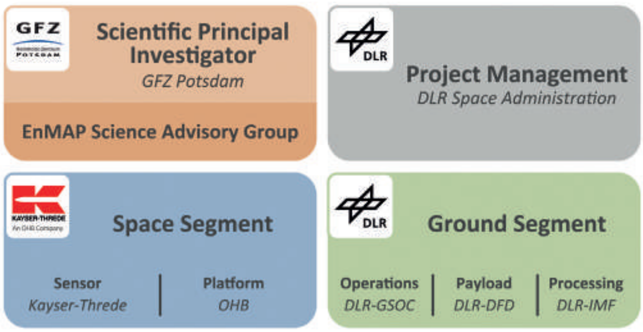
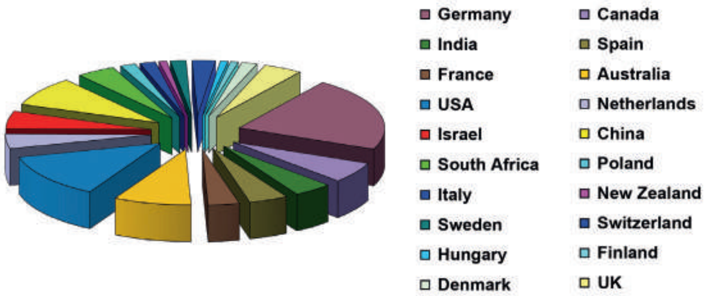


Fig. 2: Schematic overview of the project organization.

Preparatory science for the EnMAP mission

The EnMAP mission includes an extensive program of preparations for exploiting the mission's scientific capabilities. The purpose is to assure that when EnMAP is launched a comprehensive network of national and international researchers will be ready to analyze the data for a wide range of science issues, building on specifically developed methodologies conforming to the information content of EnMAP data (Fig. 3). The algorithms devised during the preparatory phase will be made freely accessible in the EnMAP Box, a newly developed software package. In addition to conceiving state-of-the art methodologies, planning for science applications also includes intensively nurturing the upcoming generation of researchers (Fig. 4). This is being accomplished with activities like regularly held summer schools and workshops. To test the developed methodologies, spectral data collected in extensive preparatory airborne campaigns are being used as input. The software required to simulate EnMAP data was developed at GFZ in Potsdam.



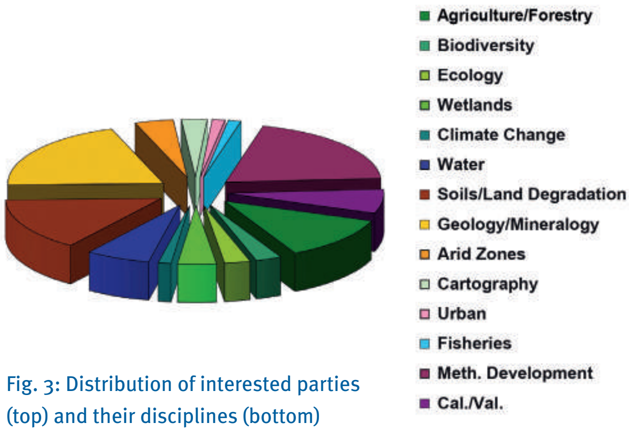


Fig. 3: Distribution of interested parties (top) and their disciplines (bottom) according to a survey conducted after the first announcement of EnMAP.

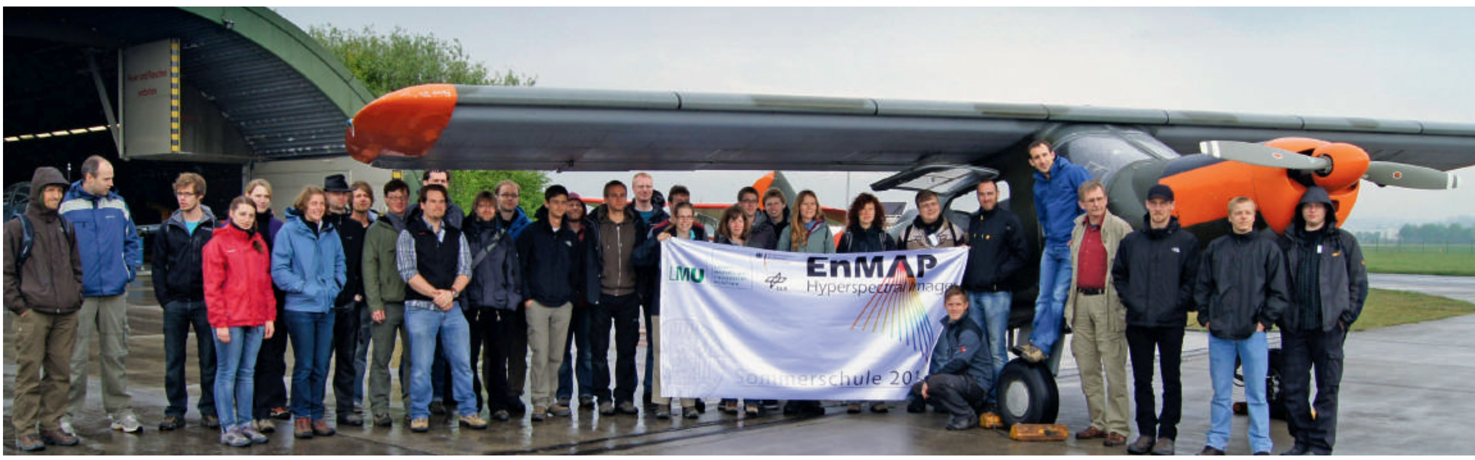


Fig. 4: Participants at the second EnMAP summer school in April 2011 in Munich at a demonstration of the airborne imaging spectrometer AVIS-3 (Airborne Visible and near infrared Imaging Spectrometer), which is being employed in flight campaigns as part of the preparations for using EnMAP mission data for scientific purposes.

Principles of imaging spectroscopy

Imaging spectroscopy / hyperspectral imaging is an innovative remote sensing technology used to record image data over a large wavelength range extending far beyond the visible light and comprising many narrow, contiguous bands. These multi-band images contain for each individual pixel continuous spectra, which permit direct identification and quantification of the recorded material. Such features make it possible to characterize minerals in rocks and soil, record vegetation type and condition, and identify substances in water (Fig. 5). At the heart of the EnMAP satellite are two hyperspectral sensors that record the sunlight reflected from the Earth at wavelengths between 420 nm and 2450 nm in more than 240 adjacent spectral bands. The sensors have a spatial resolution of 30 m x 30 m and can revisit every place on Earth every four days at least.

Orbit characteristics		
Orbit / Inclination	sun-synchronous / 97.96°	
Target revisit time	27 days (VZA ≤ 5°) / 4 days (VZA ≤ 30°)	
Equator crossing time	11:00 h ± 18 min (local time)	
Instrument characteristics	*VNIR*	*SWIR*
Spectral range	420 - 1000 nm	900 - 2450 nm
Number of bands	89	155
Spectral sampling interval	6.5 nm	10 nm
Spectral bandwidth (FWHM)	8.1 ± 1.0 nm	12.5 ± 1.5 nm
Signal-to-noise ratio (SNR)	› 400:1	› 150:1
Spectral calibration accuracy	0.5 nm	1 nm
Ground sampling distance	30 m (at nadir; sea level)	
Swath width	30 km (field-of-view = 2.63° across track)	
Swath length	1000 km/orbit - 5000 km/day	

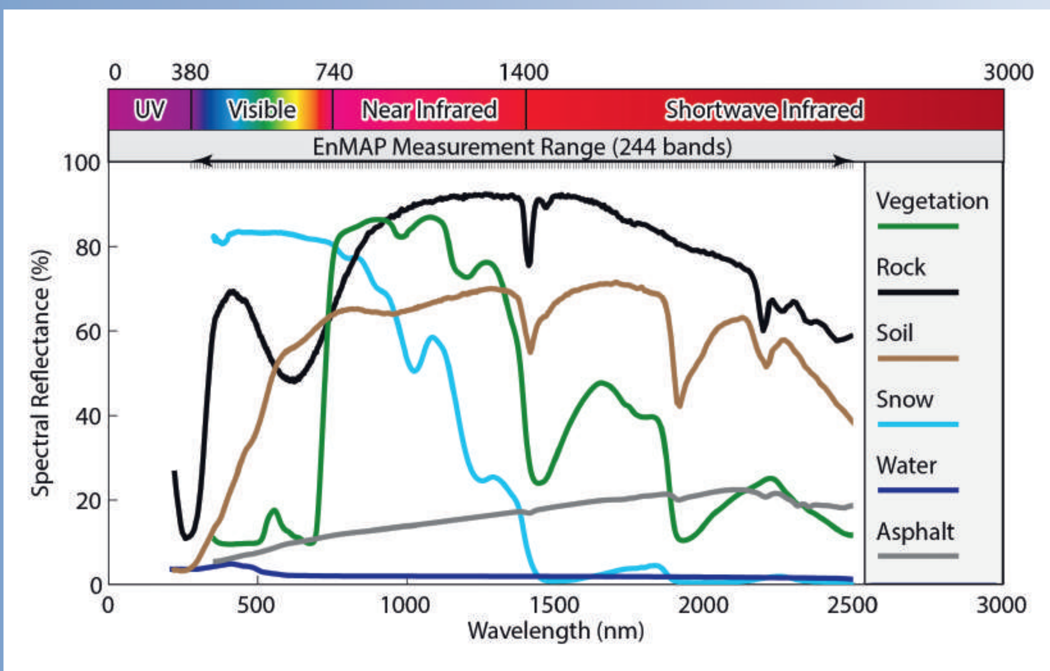


Fig. 5: Characteristic reflectance spectra for various types of surface cover.

Why do we need EnMAP?

Changes in our environment pose global challenges

Mankind is being confronted with fundamental challenges at the beginning of the 21st century. The most important ones include how to achieve sustainable management of land use globally, adapt to the manifold consequences of climate change, combat progressive environmental destruction, and use natural resources responsibly. In order to cope with the growing pressures on society and environment, these closely interrelated and complex aspects have to be spatially and temporally monitored and documented, quantified and understood.

As a diagnostic monitoring technology, imaging spectroscopy plays a decisive role in obtaining a better understanding of the risks and consequences of these environmental changes. During the last few decades this technology has become a cornerstone science for recording, quantifying and modeling surface processes and analysing vegetation cover. The increasing availability of high-quality hyperspectral images in the future will significantly contribute to improving knowledge of the complex processes and feedback mechanism, interconnecting the Earth's various spheres, like the atmosphere, biosphere, pedosphere and hydrosphere. EnMAP's ability to record at short temporal intervals various regions of the Earth's surface at high spatial and spectral resolution opens up new possibilities to study the condition of ecosystems, including the characteristics and composition of vegetation, soil and water, and predict future developments. Therefore, EnMAP is destined to make a significant contribution toward pursuing environmental problems, which can 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. But the instruments used so far in satellite operations either do not include the necessary wavelength ranges, have a low spatial resolution, or are not sensitive enough to capture the relevant ground signals. For such reasons spectrometers have so far been used primarily on airborne platforms for scientific, experimental and commercial purposes. But airborne instruments have important disadvantages compared with instruments on satellites; they can only record a limited area on the ground and cannot provide the urgently required global scale and long-term routine measurements of surface processes. In addition, airborne data require a more elaborate geometric correction, and repeat recordings of the same area are very expensive (Fig.s 6 and 8).
The present generation of optical satellite sensors is for the most part comprised of multispectral instruments that measure in individual, relatively broad wavelength ranges and, thus, usually supply only qualitative information on the composition of the Earth's surface. Imaging spectrometers, by contrast, provide data which can be used for the qualitative and quantitative diagnostic analysis of surface materials for a wide variety of applications. Accordingly, the EnMAP mission represents a milestone in optical remote sensing technology, specifically in imaging spectroscopy, one which paves the way to improved understanding of the processes taking place in our human environment.

Fig. 6: 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?

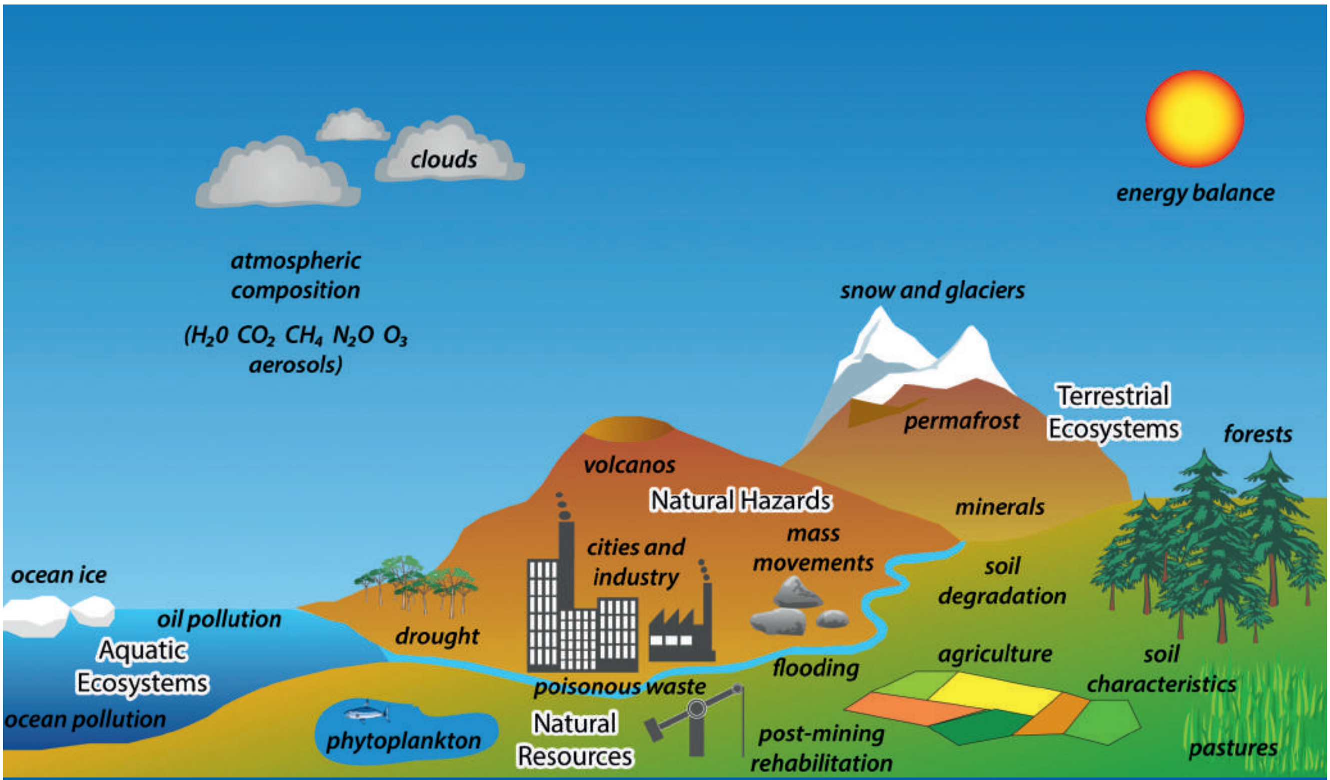


Fig. 7: Principal application fields for EnMAP.

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 multiple interrelated environmental topics (Fig. 7). 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 from local to global scale?
- 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 from local to global scale?
- 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 from local to global and from seasonal to decadal scales?

- 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 impact, such as water and air pollution, land contamination and mine waste, be tracked, monitored and managed in order to conserve and sustain natural resources?

Geohazard and risk assessment

- Which areas are prone or susceptible to geohazards?

- Which land use characteristics affect the vulnerability to geohazards and how can they be mapped and monitored?

- In case of a natural disaster, which areas are to what extent affected and how can this information be provided for short-term coordinated emergency response?

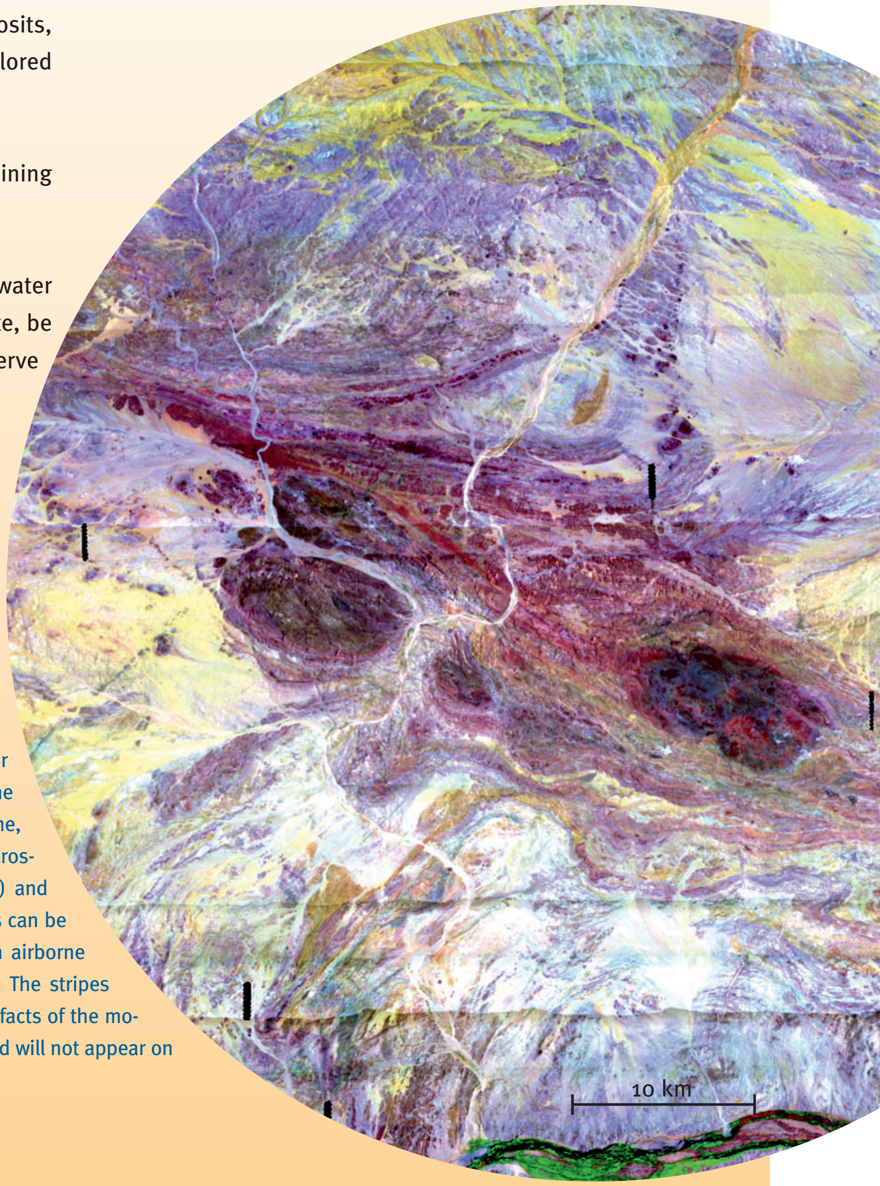


Fig. 8: Simulated EnMAP image (color composite) showing a section of the Poffadder Tantalite Valley Shear Zone, South Namibia, where the Hom River crosses the shear zone (at image center) and where lithium and rare earth elements can be found. The simulation is based on an airborne hyperspectral image mosaic (HyMap). The stripes running in west-east direction are artefacts of the mosaicking of several airborne images and will not appear on future EnMAP images.

EnMAP as a valued agricultural engineer

On the path to sustainable agriculture

Fig. 9: Cropland in the Neusling region of Bavaria.

Against the background of a steadily growing global population, agricultural production is highly significant as a source of biomass. According to recent United Nations projections, over 10 billion people will require supplies of food, fibre and energy by the year 2150. In past centuries the increasing food requirements of a growing global population were met by straightforward augmentation of the amount of land devoted to agricultural production. But, the supply of bioproductive land surface is strictly limited, since only about 1.5 billion hectares of the continental land surface fulfil the climatic, topographic and pedogenic criteria that make agriculture at all possible. Because of the unrestrained expansion of areas under cultivation in past centuries, almost 100% of this area is now being used for agricultural production. Further expansion is not possible, or only possible at the cost of extreme ecological consequences, for example, those accompanying the clearance of tropical rain forests, which prevents this option for increasing agricultural production from being seriously considered.

One possible way to increase agricultural production is by optimizing cultivation methods, because there are large regional differences in the yields obtained from areas currently devoted to agriculture. In technologically highly developed countries such as in Europe, average yields of about 9 t/ha are obtained, whereas the global average is only about 1 t/ha. According to model calculations the theoretical maximum yield is as much as some 20 t/ha. The difference between actual yields and what is theoretically possible under given conditions, considering such factors as climate and soil, can be reduced by increasing the efficiency of agricultural production. This increase in efficiency per hectare can first of all be achieved by improved management. For example, by optimizing cultivation, fertilizer use, pest control and irrigation strategies, production can be increased while at the same time reducing investments for working materials and other resources.

Inspired by numerous scientific studies, improving efficiency through so-called precision agriculture, which involves managing a field by dividing it into discrete, selectively managed sections, is increasingly becoming accepted agricultural practice. Devising management strategies tailored to such small units depend on having access to spatial information about the current state of a crop's growth. Remote sensing is the only measurement approach capable of providing spatial information for large areas about crop status. By combining remote sensing information with computer models that describe land-surface variable processes, such as plant growth in physical units, agricultural information systems can be created. These support farmers in their management decisions by continuously supplying them with spatially differentiated information. With the help of such area-specific decision support systems, it becomes possible to modify management strategies at the right time for each sector, avoiding or reducing crop damage by early detection of problems like nutrient deficiency, water stress or pest infestation.

The challenge for such small-scale management is to derive the desired information from remote sensing data. The Earth observation sensors available so far can be used to establish an empirical relationship between the signal recorded by the satellite and the desired ground information, for example, the photosynthetically active leaf area or the water content of plants. But the results obtained in this way are inadequate, primarily for two reasons: 1. The spectral sampling achieved by the availa-

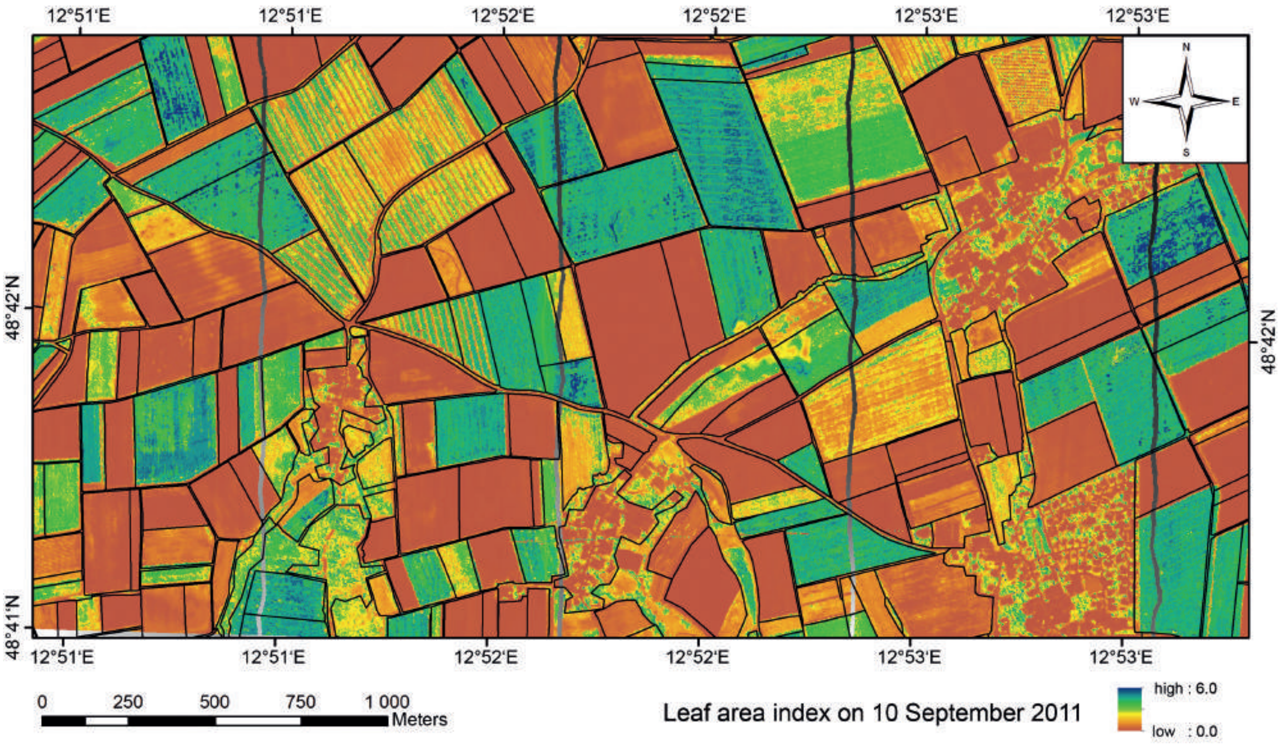


Fig. 10: Spatial distribution of photosynthetically active leaf area near the village of Neusling (southern Germany) on September 10, 2011, derived with the help of the EnMAP-specific software "EnMAP Box" from image data collected by the airborne sensor APEX (Airborne Prism Experiment).

ble systems is often rather coarse, so the signal measured at the satellite can be simultaneously influenced by several different ground surface characteristics. This means that it is not possible to precisely derive one specific land-surface variable 2. Establishing the empirical relationship involves gathering corresponding ground measurements for the desired land-surface variable, which is usually a very laborious undertaking and often impossible in remote or hard to access areas. In addition, the relevance of an empirically derived, modeled relationship obtained by comparing ground measurements and satellite signal is seriously limited, because sensor characteristics, illumination conditions, time of recording and similar factors greatly influence the calculation of the relationship.

An alternative, superior in many respects to this traditional empirical method of gaining information, is to apply physically based reflectance models. As part of the preparation for meeting the science requirements of the EnMAP mission, the suitability of this method for agricultural applications is therefore being specifically investigated at Munich's Ludwig Maximilian University (LMU) using airborne hyperspectral sensors (Fig.s 9 and 10). Reflectance models simulate the spectral reflectance of sunlight reflected by field crops as a function of the specific crop's characteristics. If the modeled reflectance value is compared with actually measured spectral characteristics, for example from an EnMAP satellite image, then the reflectance models can be inverted, permitting conclusions about the input parameters. The advantage of this method is that it does not depend on having ground measurement data. In addition, various sensor attributes and illumination conditions can be taken into account in the analysis in order to assure the global applicability of the method. The difficulty in using this approach is identifying spectral similarities in the modeled and measured reflectances. Just as with empirical models, uncertainties can arise when using so-called multispectral sensors

EnMAP and agriculture

With EnMAP, it will be possible to derive customized crop information products, which will provide improved decision support for precision agriculture.

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

Compared with conventional multispectral Earth observation systems, hyperspectral systems like EnMAP guarantee (i) more precise information products since they are less subject to misinterpretation, and (ii) a globally applicable parameter retrieval methodology, because it is less dependent on calibration information empirically collected from the land surface.

with their coarse spectral resolution, because different combinations of input parameters can produce similar spectral profiles. The result is that the input parameters are not unambiguously determined by the inversion. Only with quasi-continuous, high resolution recording of the spectrum can these uncertainties be minimized, assuring an unambiguous derivation of land-surface variables.

The hyperspectral science mission EnMAP will for the first time in history provide satellite data which meet these ambitious criteria. EnMAP also achieves for the first time regional and more frequent coverage with high quality hyperspectral Earth observation data, so the potential applicability of hyperspectral analytical methodologies using EnMAP can be tested on a regional and seasonal scale exceeding the range of airborne campaigns (Fig. 11). Thus, with the help of EnMAP improved information products can be generated to aid decision making about the measures to be taken to cultivate a specifically characterized limited area of a field. Therefore, the EnMAP science mission paves the way to global coverage with hyperspectral Earth observation data as a step toward more efficient agriculture in the future and, thus, ecologically and economically more sustainable use of the bioproductive land surface.

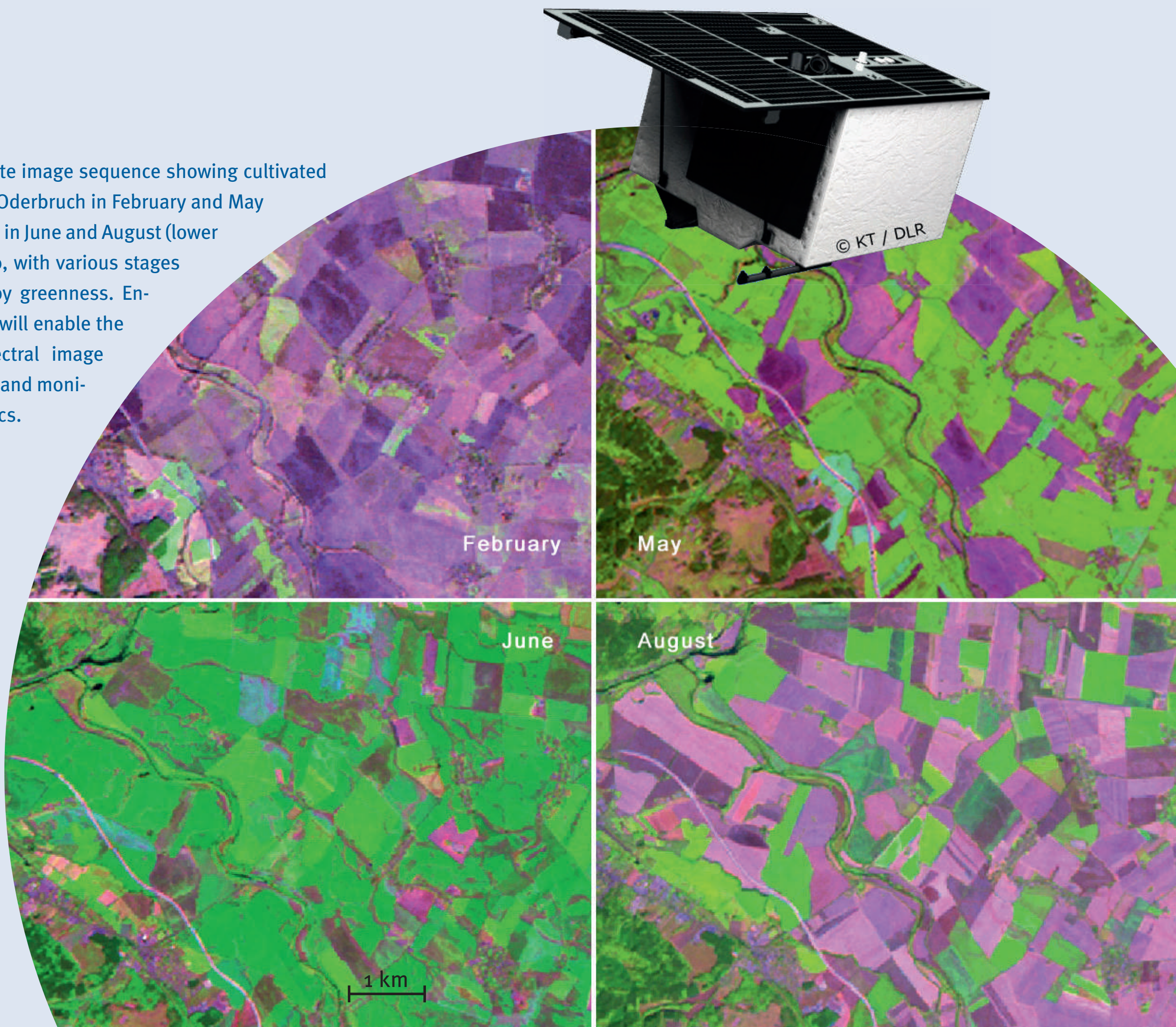


Fig. 11: Landsat satellite image sequence showing cultivated areas in the northern Oderbruch in February and May (top left and right) and in June and August (lower left and right) of 2000, with various stages of growth indicated by greenness. EnMAP for the first time will enable the analysis of hyperspectral image sequences to observe and monitor ecosystem dynamics.

EnMAP as an expert forest observer

Monitoring forest ecosystems at a time of climate change

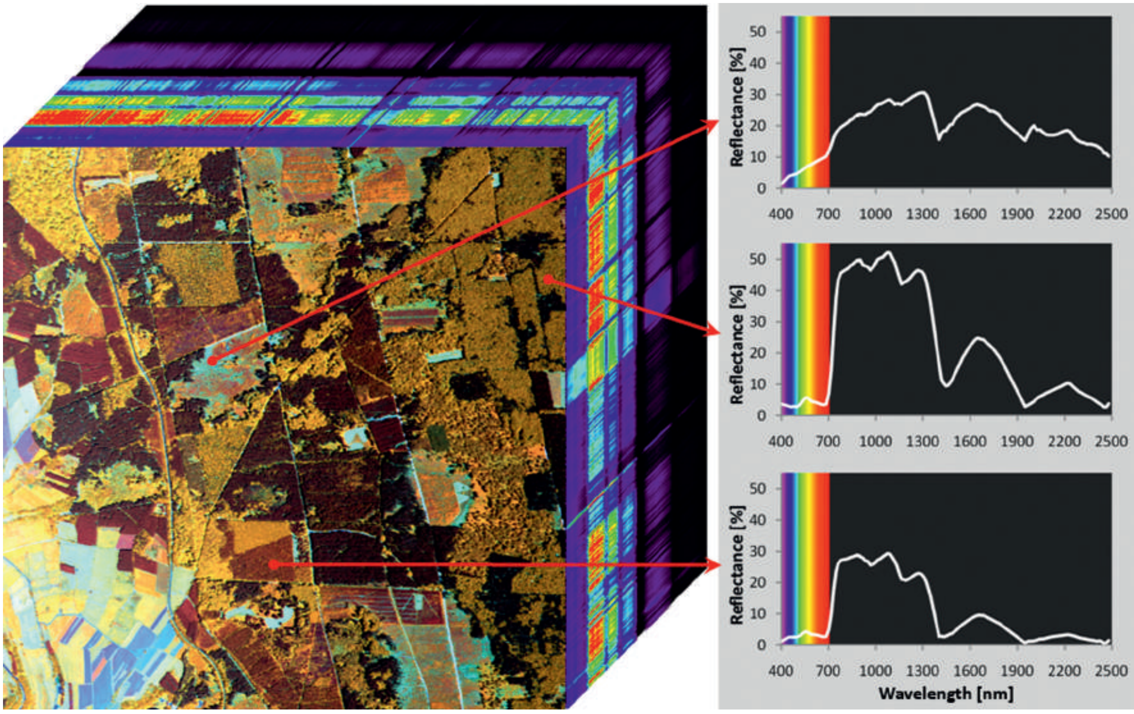


Fig. 12: Hyperspectral cube for a forest segment; each pixel contains a detailed reflectance spectrum.

Seen from a global perspective, forest ecosystems still cover large parts of the land surface and are among the most important guarantors of key ecosystem services. Storing the highest volume of biomass globally, they are the most important terrestrial sinks for carbon dioxide. In addition to their function as producers of wood, they also perform essential productive and protective functions, especially in the areas of biodiversity and climate protection. On the other hand, forests and forest ecosystems are increasingly threatened by global warming, by a rapidly growing global population and by expanding economic activities. Destruction of forests, conversion of forests to agriculture acreage, legal and illegal wood harvesting and recurring forest fires are only some of the processes which to various extents add to the burden on forest landscapes and ecosystems.

Ongoing scientific analysis of these processes must equally consider both the protection and preservation of forest ecosystems and the economic interests behind commercial forest management. Meeting the resulting social challenges is a complex undertaking, which places increasing demands on the data serving as a basis for decision making. In particular, the information required for balancing economic and ecological interests on the way to sustainable forest management can no longer be met without remote sensing technology.

The hyperspectral satellite mission EnMAP can make a significant contribution toward meeting this goal. Because it is designed for long-term, regular monitoring of selected areas, it is not primarily suited to record global forest distribution, but rather to monitor a representative, global network of specified forest locations. The mission has a key role in developing and optimizing methodologies for mapping tree species and levels of maturity, and in assessing forest structures and forest resources for discrete land segments. The specific capabilities of optical systems with hyperspectral resolution (Fig. 12) are especially 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. 13). On this basis, regular monitoring over several growth cycles opens new perspectives for integrating vitality indicators derived from hyperspectral systems with model calculations of plant production and forest growth. As a supplement to experimental investigations, simulations incorporating remote sensing data can make a decisive contribution toward assessing forest management concepts in anticipation of future climate conditions at regional levels.

In preparation of the mission, the EnMAP Science Team is especially focusing on those aspects relevant for optimally exploiting EnMAP's potential. One example is to study and further develop model-based and advanced empirical methodologies for recording eco-physiological state variables. In addition to investigations in heavily instrumented forest locations like Merzalben in Rhineland-Palatinate, detailed studies are also taking place outdoors under controlled, laboratory-like conditions with the help of imaging hyperspectral sensors (Fig. 14). In parallel, the development of powerful algorithms is being expedited, for example, the integration of atmospheric radiative transfer models with geometric-optical reflectance models for stands of trees.

This type of basis research will however only contribute toward optimally preparing for the EnMAP mission if the insights gained for designing new algorithms can also be related to an analysis of hyperspectral image data for natural forest areas. But assessing the suitability of the algorithms for later use with EnMAP assumes the availability of appropriate comparative information on structural and biophysical characteristics. Gathering such information in forests is especially complicated and requires the use of innovative methods like terrestrial laser scanning to generate a precise three-dimensional model of a forest area. By developing suitable data processing concepts, an important foundation can at the same time be laid for integrating passive optical hyperspectral sensors with measurements obtained with airborne laser scanners, which will be crucial for the subsequent analysis of EnMAP data.

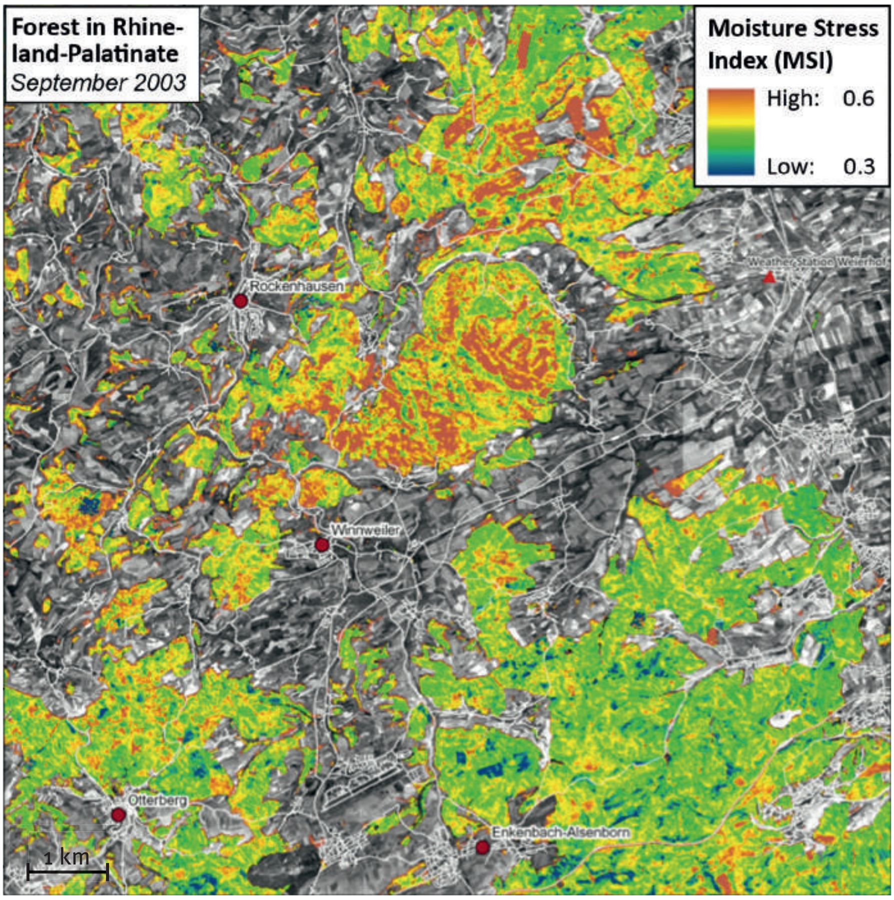


Fig. 13: Recording drought stress in forested areas of Rhineland-Palatinate using the very sensitive Moisture-Stress-Index (MSI) derived from Landsat-TM data. The data were recorded in September 2003, an extremely hot, dry year judged to be representative of the future Central European climate situation. With the hyperspectral sensor EnMAP, it will be possible to map drought response and other stress phenomena more comprehensively and in more detail.

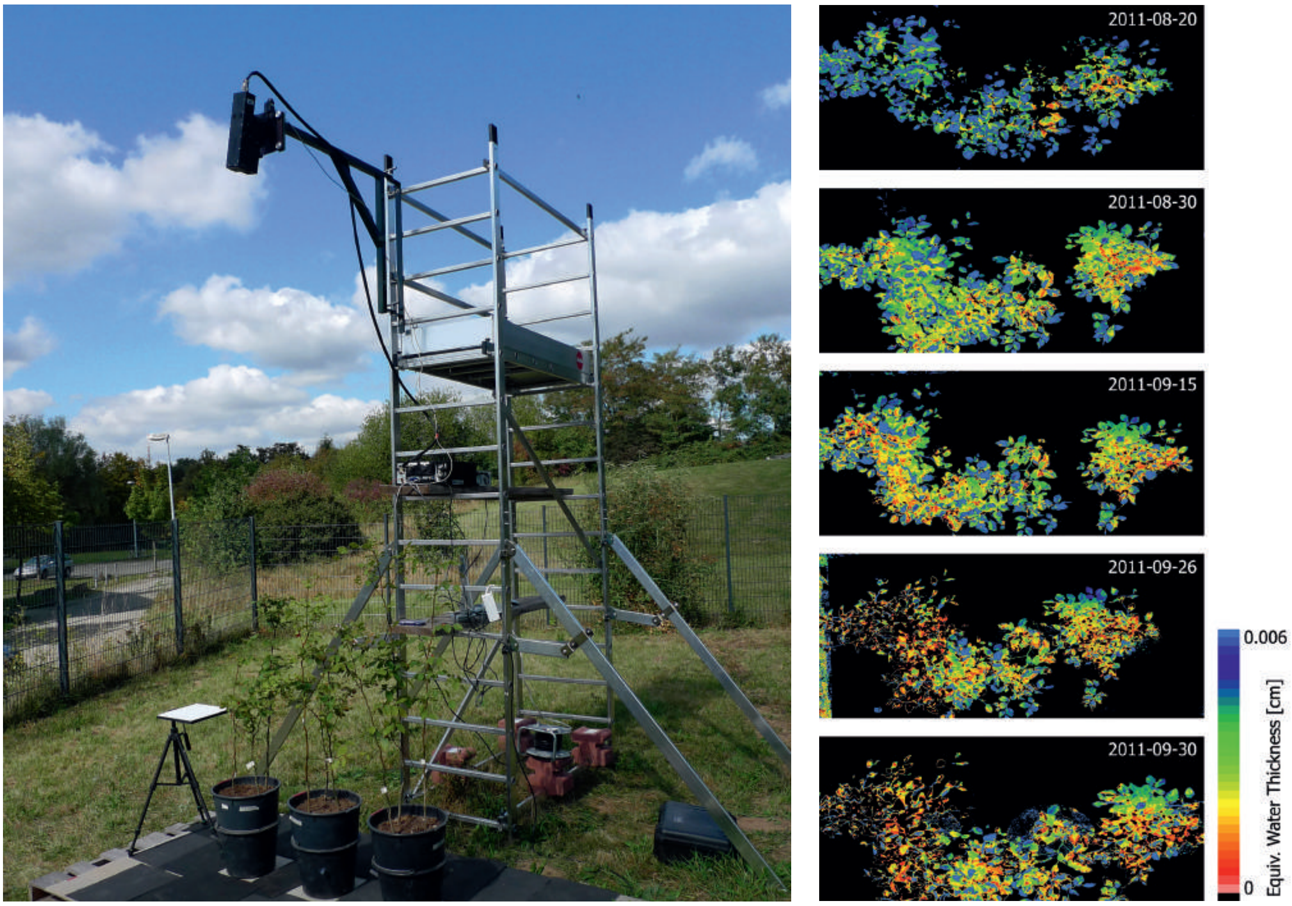


Fig. 14: Monitoring beech tree seedlings with Trier University's imaging hyperspectral system HySpex. By comparing hyperspectral indicators with time series gained in parallel with eco-physiological studies, stress phenomena can be analysed in detail.

EnMAP and forest ecosystems

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

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

The early identification of climate-related stress phenomena possible with EnMAP is important for developing appropriate forest management concepts and providing model calculations of ecosystem services.

To optimally incorporate the knowledge gained so far into the process of developing methodologies for analysing the EnMAP data that will become available, the next steps must concentrate on collecting hyperspectral image data in order to generate simulated data sets. For dynamic forest ecosystems reacting sensitively at different locations to phenological cycles and stress factors, image sequences have to be produced which ideally extend over an annual course of seasons.

EnMAP as an objective ecosystem analyst

Investigating gradual spatial and temporal changes in ecosystems

Fig. 15: Spectral field measurements validate the results of remote sensing image analysis.

Maintaining and expanding ecosystem services like carbon sequestration, biomass production and flood regulation is essential for an intact global human-environment system. The availability of such ecosystem services is being negatively influenced by such factors as global climate change and land use. Improved understanding of the diverse processes determining the availability of ecosystem services is urgently needed and can only be gained through long-term, wide-coverage monitoring of large regions. Earth observation with remote sensing instruments is usually the only practical approach for characterizing entire ecosystems and recording constant ecosystem change over wide areas.

For many years, satellite Earth observation has been limited to multispectral sensors or sensors with low spatial resolution, which provide only meagre spatially-detailed information. Accordingly, there continue to be knowledge gaps in understanding ecosystem processes. For example, although multispectral sensors permit reliable qualitative description of land cover, making it possible to map objects like forests, agriculture, or water, they do not allow accurate quantification, such as estimating forest biomass or soil nutrient content. On the other hand, sensors with better spectral resolution are not capable of revealing ecosystem changes because of their low spatial resolution, since there are often several different processes going on simultaneously in the area represented by one pixel.

EnMAP data, by contrast, will provide a large amount of spectral information along with considerable spatial detail. So in the future it will be possible to make quantitative predictions relating to ecosystems at the spatial scale on which the underlying processes actually take place. With the opportunity to routinely monitor contiguous areas for long periods of time, gradual, continuous changes can be recorded and described. For example, this will make it possible to evaluate the effectiveness of establishing nature reserves by identifying changes in biomass or species diversity, or to quantify increases in carbon sequestration after the ecosystem restoration of former agricultural areas.

In order to optimally exploit the potential of data from modern imaging spectrometers like EnMAP, existing analytic methodologies must be further developed. Traditional methods of analyzing satellite images have to be refined in order to make use of the additional spectral information for quantitative analyses. Existing procedures, not so far applied to large areas, have to be adapted to enable repeated detailed mapping of the EnMAP entire landscapes.

The focus of the EnMAP 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 are receiving special attention: (1) the development of nature conservation and conversion zones; (2) the gradual evolution of former agricultural areas; (3) changes in forest ecosystems; (4) the decreasing geobiophysical capacities of ecosystems; and (5) land use gradients in urban areas and their immediate surroundings.

Case study: Castro Verde, Portugal

Investigations in the Castro Verde region of southern Portugal are one of the priorities at Humboldt Universität zu Berlin. For about ten years comprehensive monitoring has been undertaken of gradual temporal and spatial ecosystem changes associated with the abandonment of degraded agricultural areas and the subsequent succession of natural vegetation (Fig.s 15, 16 and 17). The relationship between these gradual processes and basic ecological issues is being studied with the help of habitat analysis and other approaches.

The Castro Verde region is currently characterized by totally abandoned agricultural land lying fallow. This is leading to increased shrub intrusion on what was formerly farmland. Part of the study area is also within the Natura 2000 Special Protection Areas for Birds with steppe bird communities of national and international significance. Analysing an ecosystem with obviously conflicting ecosystem services, such as carbon storage and stimulating biodiversity, illustrates the complexity of such natural environments.

Hyperspectral remote sensing analysis concentrates on mapping progressive shrub encroachment as a gradual spatio-temporal process. A differentiating description of various types of bush vegetation and steppe grasslands, for example as a preliminary step toward modeling biotic processes, is particularly challenging considering the various phenological stages of dryland vegetation. Therefore, new methods from the field of machine learning are being studied to precisely and consistently describe subtle spectral differences. The most promising approaches will then be implemented and made generally available in an easy-to-use form. With hyperspectral data, reliable representation of various vegetation types can be expected, but factors like the scale and time frame used for the analyses greatly influence the precision of the results. The expected insights will make a relevant contribution to determining the potential of EnMAP data for ecological investigations in sub-humid to arid zones and at the same time create a foundation for developing concepts for the temporal investigation of these processes.

Fig. 16: Abandoned landscape with progressive shrub encroachment.

EnMAP and ecosystem changes

Adequate research is lacking on the transitions between ecosystems and on the gradual changes within ecosystems, and it has so far been difficult to comprehensively describe these changes in spatial and temporal terms. Here EnMAP offers basic and innovative analyses and contributes to improved understanding of global change and the interactions between human beings and their environment.

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

Analysis of simulated EnMAP data reveals which processes underlying ecosystem change it will be possible to adequately describe in the future.

Fig. 17: Simulated EnMAP data for the Castro Verde region, Portugal. False-color representation superimposed on a Landsat-5 TM satellite image.

EnMAP as a modern soil scientist

Worldwide analysis of soil and degradation processes

Fig. 18: Consequences of overgrazing (to the right of the fence at image center) in the Albany Thicket Biome (South Africa).

Viewed on the time scale of a human life, soil is not a renewable resource, and it is worth protecting because of its numerous important functions. They include its roles in food production, regulating the water inventory, filtering pollution, and carbon storage. These ecosystem services performed by soil are being threatened worldwide by climate change, natural hazards and human activity. The consequences are, on the one hand, increased soil removal due to wind and water erosion or land slides, and on the other hand, reduced soil quality due to the loss of organic matter, contamination, salination and soil compaction. Because of the outstanding significance of soil, the European Commission put together in 2006 a guideline on protecting and preserving Europe's soils. Its goals are sustainable soil use, maintaining soil quality and functions, and soil restoration.

A main reason for global soil degradation is widespread inappropriate land use. This leads to deforestation or overgrazing (Fig. 18), the loss of vegetation cover, unsuitable land use like monoculture farming or farming with inadequate irrigation systems, eroding and exhaustion of the soil (Fig. 19), and the silting-up of rivers and dams. This is particularly true of Earth's drylands, where 70% of the land surface is already showing signs of degradation. Soil degradation is especially problematic if it progresses at a slow pace and is only recognized at a late stage. The precondition for its control is knowing precisely how much area is potentially endangered, and how the situation is developing over time in order to be able to initiate suitable countermeasures. The need to monitor, analyse and assess soil degradation processes worldwide is particularly emphasized in the United Convention to Combat Desertification (UNCCD), which was signed by some 180 states.

Going beyond recording degradation processes, there is a large global need for systematic, wide-area soil mapping which reflects the relevant topsoil characteristics with high spatial resolution and precision. So far, soil maps are often based on data collected only for individual field locations. Large-coverage maps are needed for many applications, including agriculture, developing soil preservation strategies, or as a basis for climate models.

Compared with traditional satellite systems, EnMAP offers new opportunities for the quantitative spatially-distributed collection of key parameters useful worldwide for characterizing soil conditions and deriving degradation indicators. Besides improved

Fig. 19: Formation of an erosion rill over the course of one winter in unstable soil in southeast Brandenburg (Germany).

EnMAP and soil

EnMAP makes possible repeated, quantitative, diagnostic derivation of key soil parameters.

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

EnMAP recognizes early stages of progressive soil degradation for large areas and, thus, facilitating the development of timely countermeasures.

soil mapping, regular monitoring also means early identification of degradation stages, which enables timely implementation of suitable countermeasures. Important parameters measurable with EnMAP yield soil and vegetation information, such as the ratio of vegetated to bare soil, the water and pigment content of plants, the soil organic content, clay, carbonates and salt in the soil, and soil moisture (Fig. 20), which so far could not be measured from space to the precision anticipated with EnMAP. Especially in drylands, the vegetation cover consists not only of green plants but also a high proportion of withered biomass. This dry material is very important for preventing erosion. It can be detected and quantified with an imaging spectrometer like EnMAP, but not with conventional sensors.

For the above-mentioned reasons, at the German Research Centre for Geosciences (GFZ) in Potsdam important aspects of preparing for EnMAP include developing methods to detect and characterize soil properties and recording and analysing spatio-temporal changes in vegetation and soil patterns for purposes of erosion and soil degradation modeling. A suitable suite of algorithms for the quantitative derivation of erosion-relevant ground parameters has already been developed (EnSoMAP, the EnMAP soil mapper). The studies are being undertaken in different climate zones around the world at test sites in South Africa, Australia, Spain and Germany selected as typical representations for the observed processes.

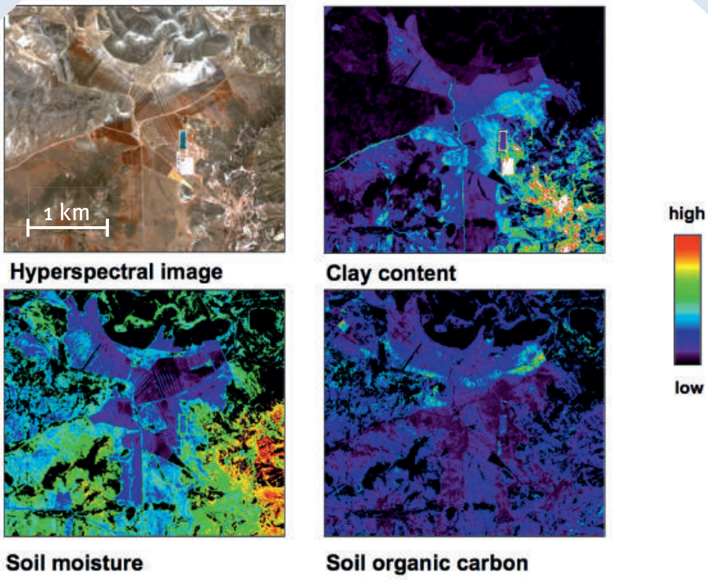


Fig. 20: Deriving soil indicators in Cabo de Gata-Nìjar Natural Park (southern Spain).

EnMAP as a skilled mineral deposit prospector

Mapping geo-resources and using them responsibly

Fig. 21: Tailings from platinum mining near Johannesburg, South Africa.

Because prices for raw materials are increasing in the global marketplace, many deposits can again be economically exploited. This is mainly true for metallic ores; energy raw materials like petroleum, natural gas and coal; salts; and industrial raw materials. At the same time, an increasingly critical awareness of human modification and contamination of landscapes (Fig. 21), along with growing demands for environmentally responsible and sustainable use of geologic resources, is posing new scientific and technological challenges for the geosciences. Innovative remote sensing technologies like imaging spectroscopy are making significant contributions to general-purpose mineral and geologic mapping as well as in the areas of exploration, development and management of deposits in a global context.

A unique advantage for the diagnostic identification of minerals in rocks, and in some cases also in soil, is their characteristically varying, wavelength-specific spectral features, their so-called absorption bands, which cannot be identified with the naked eye or traditional satellite technology (Fig. 22). These bands can only be unambiguously identified with a detailed spectroscopic recording technique and, depending on the target's surface characteristics, also quantified. Building on this fact, a technological innovation was realized with the design of the imaging spectrometer EnMAP, which can record the mentioned spectral features using a multitude of narrow bands. All system parameters have been designed by scientists so that the characteristic absorption and reflection bands for the minerals that occur most frequently on the Earth's surface can be detected. Besides oxides and hydroxides, phyllosilicates, sulfates and carbonates, these also include the economically especially relevant rare earth elements.

The position and shape of the absorption bands in the spectrum reveal the identity of the mineral, whereby the depth of the relevant bands correlates with the areal concentration of the material in question. This physical basis in turn allows new analytic approaches that were so far not feasible using multispectral data (Fig. 23). For example, different minerals and materials can be identified, classified by percentage and quantified down to the subpixel level with the help of semi-automatic algorithms, making spectro-analytical comparisons with databases. Relocating this kind of "spectral laboratory" in space opens up a wide application area, extending far beyond what is possible with the presently employed, traditional qualitative classification of rocks and soil and makes far more detailed diagnostic statements about surface processes feasible as well.

In this context, one GFZ goal is to develop an innovative expert software tool (EnGeoMap, the EnMAP Geological Mapper) for the semi-automatic identification of minerals in rocks and soil. A preliminary step is to simulate EnMAP scenes, which are then analysed to improve the applicability and reliability of the EnGeoMAP program package. Concepts and the associated software are also being generated, which not only optimize the

Fig. 22: Spectroscopic identification of rocks in Naxos, Greece.

EnMAP and geology

EnMAP enables a unique diagnostic assay of minerals in rocks and soil.

EnMAP makes significant contributions to mineral and geological mapping and to the detection and exploitation of ore deposits.

EnMAP allows for synoptic assessment of mining regions as to their temporal evolution, future prospects, and possible restoration and recultivation approaches.

basic geological mapping and mineral identification functions, but also the analysis and assessment of surface materials and restoration processes.

Encroachments affecting landscape appearance and ecosystems due to the extraction of raw materials and their industrial processing have reached a high level worldwide. Especially mining activities and the related slagheaps have far-reaching effects, including changes in the landscape caused by erosion and subsidence, reduced biodiversity, and the contamination of soil, groundwater and surface water.

Accordingly, part of the EnMAP preparatory phase is to study cause-and-effect cycles that can be identified via indicators and driving factors whose repercussions on the ecosystem can be identified. For example, mining regions can be analysed over a wide geographical area as to their temporal evolution, future prospects, possible restoration and recultivation.

In order to achieve the goals set, together with cooperating scientists, specimens are being collected and investigations undertaken locally in selected mining regions in Canada, South Africa and Mongolia. These activities are complemented by laboratory experiments and placed in a context with the help of airborne spectral measurements. This approach makes it possible to develop a methodology for multiscale temporal comparisons over large areas for the purpose of characterizing mining activities and contaminants, which will then be operationally implemented by EnMAP.

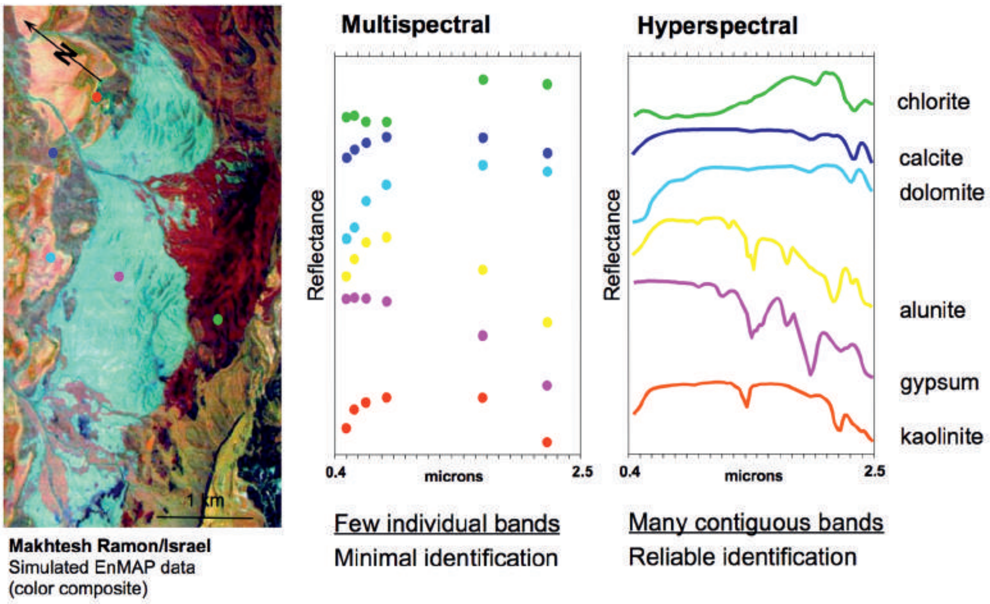


Fig. 23: Quantitative mineral identification at Makhtesh Ramon, Israel.

EnMAP as a versatile hydrologist ...

Detecting changes in the Wadden Sea

Fig. 24: 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.

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 an important tool for monitoring and assessing this sensitive and unique natural environment.

The distinguishing elements of the Wadden Sea are narrow channels, open tidal flats with sandy or muddy sediments, extensive mussel populations and resurgent seagrass beds (Fig. 24). Especially for the usually low-contrast mudflats, whose surfaces lack the sharp borders and land use variations customary on dry land, it is essential to record the radiation reflected by this tideland at the highest possible spectral resolution.

In the context of preparing for EnMAP, terrain measurements were made in order to spectrally characterize different tideland surfaces. In addition, laboratory analyses of sediments were undertaken to calculate parameters like chlorophyll content. An airborne campaign with an on-board hyperspectral scanner (AISA) supplied the corresponding remote sensing data (Fig. 25). The potential of a hyperspectral Earth observation satellite like 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.

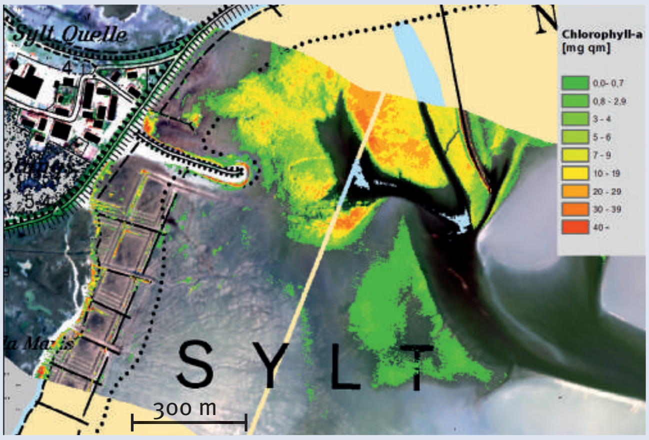


Fig. 25: Chlorophyll map derived from hyperspectral airborne scanner data (AISA).

... and reliable Arctic researcher

Studying remote Arctic coastal regions

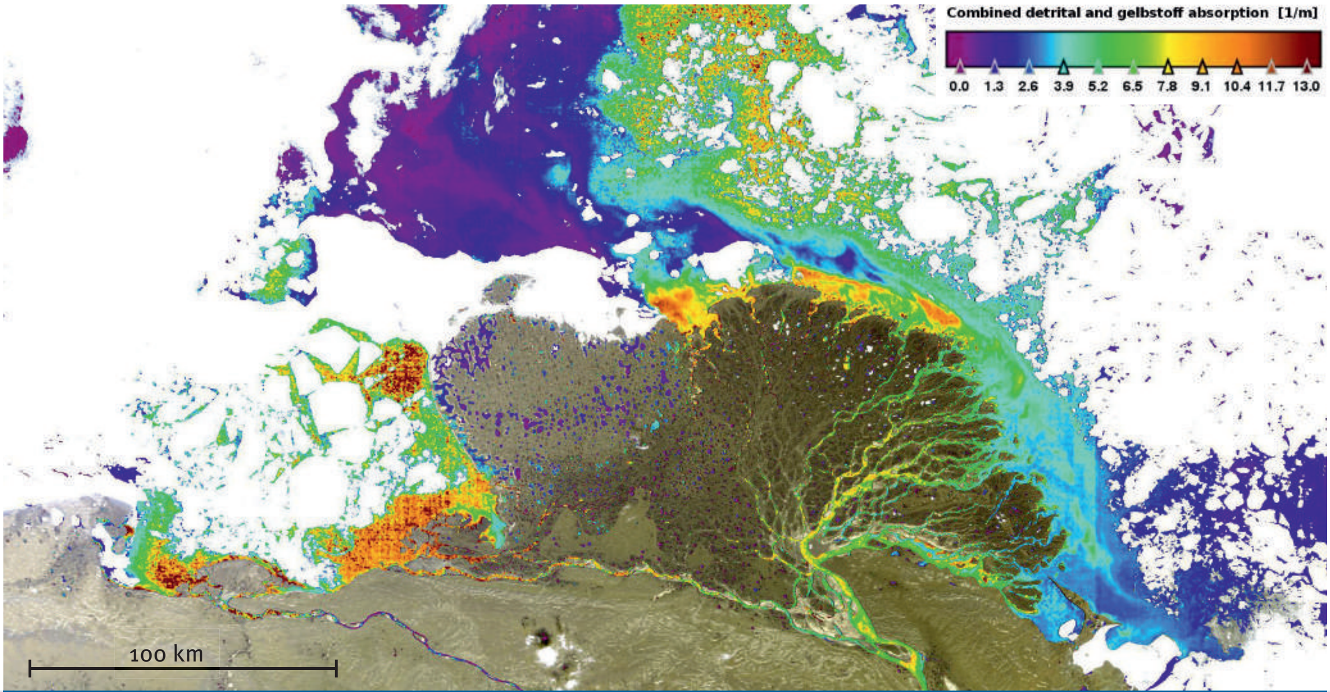


Fig. 26: Satellite image of the Lena delta (eastern Siberia), recorded on 04 July 2011 with the MERIS sensor.

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 escalating 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. 26 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 for these waters means less than 0.5 m visibility depth. The Lena is therefore transporting a very large amount of carbon into the Arctic Ocean, in this image into the shallow Laptev Sea, making it one of the largest carbon sources. Also in coastal waters (in the image partly under the ice), the concentration of humic substances is still 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%. With EnMAP, it will be possible to carry out such investigations at significantly greater spatial and spectral resolution and, thus, to study the development of specific, highly structured and optically complex coasts.

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 make it possible to identify substances in water like suspended particles, dissolved organic matter, phytoplankton and dominant species.

EnMAP data make it possible to better understand the regional and global roles of coastal and inland waters in the carbon cycle.

EnMAP as a farsighted urban planner

Monitoring the condition and development of urban areas

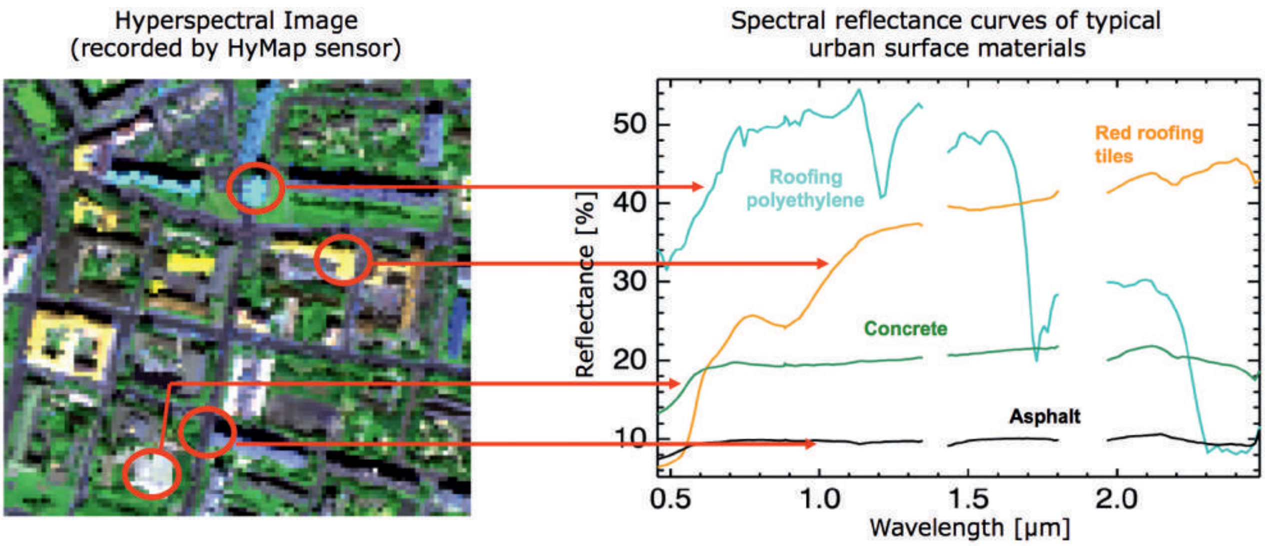


Fig. 27: Urban surface materials can be identified by their material-specific spectral reflectance signature.

Rapid, often drastic conversion processes are taking place worldwide in urban population centers. Already today, over half the global population lives in cities and the global trend toward urbanization progresses with increasing dynamism. 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 urban-climate-relevant pollution. The susceptibility of cities to natural hazards like storms and flooding also poses special planning challenges.

These problems are especially pronounced in megacities. It is therefore necessary, despite population growth and the constant shortage of space, to balance the claims of ecologically sound, economically profitable and socially compatible development, while at the same time preserving 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 Earth observation with the imaging spectrometer EnMAP can make an important contribution. Continuous monitoring of the Earth's surface from space provides a unique and always current overview of the spatial fabric and development of built-up areas and cultural features. Because of EnMAP's

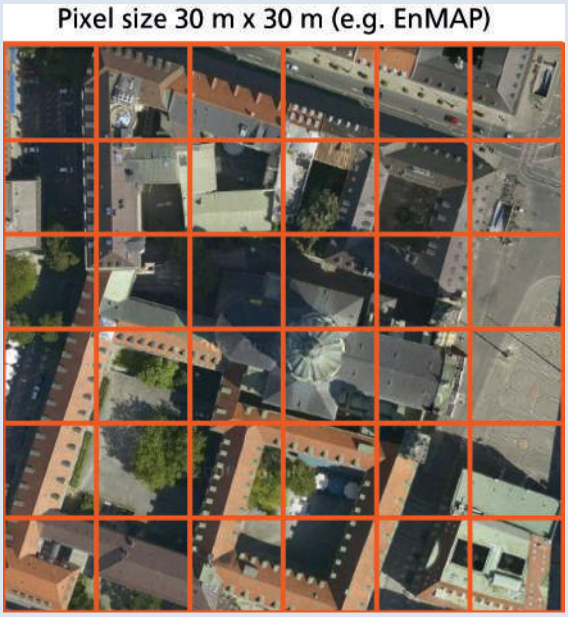


Fig. 28: The ground resolution of the EnMAP sensor is 30 m. This means that one EnMAP pixel contains information on several types of urban surface materials that can be quantified with spectral unmixing methods.

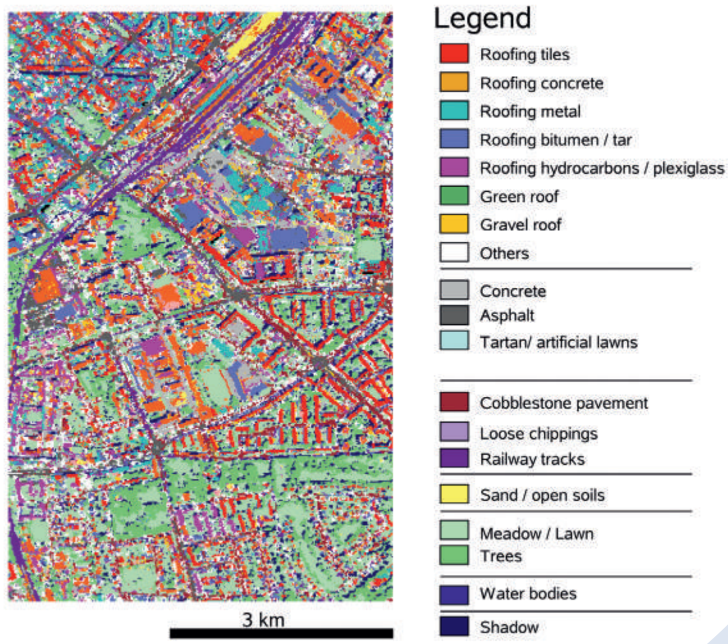


Fig. 29: Identifying urban surface material by spectral unmixing of a hyperspectral airborne image (HyMap) of the city of Munich.

high spectral information content, detailed qualitative and quantitative information on the nature and distribution of urban surfaces can also 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 as to their ground sealing properties. Areas covered with asphalt and concrete, for example, are considered to be fully sealed from a city planning perspective. This is because most of the rainwater or any environmentally problematic liquids they receive enter the sewerage system. Partially sealed surfaces, by contrast, allow some of the rainwater to be absorbed by the ground. Urban areas bearing vegetation have many positive benefits for the local climate and, thus, on the quality of life of a 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 like EnMAP. Studies with airborne hyperspectral sensors have shown that each kind of surface material has its own characteristic spectral reflectance signal, which can be measured in acceptable detail only with imaging spectrometers (Fig. 27). 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 scans the Earth's surface. Figure 28 shows that one EnMAP pixel (red outlined square) contains spectral information for a number of different surfaces. Because of EnMAP's high spectral information content, information about the nature of sealed surfaces and vegetation can be satisfactorily reconstructed from the so-called spectral mixture. The percentage of the individual surfaces can be determined with a procedure known as spectral unmixing (Fig. 29).

The knowledge obtained in this way about the nature and areal extent of urban surface materials at the subpixel level makes it possible to derive with high precision indicators relevant for ur-

Fig. 30: Extent of ground sealing per block of buildings for the eastern part of Munich, derived from hyperspectral data.

ban planning, such as sealing maps (Fig. 30). These indicators can be presented using different types of reference units. Because a pixel map is often difficult to interpret (Fig. 29), a block of buildings is a more convenient basis for comparisons in the case of large cities. This level of abstraction is especially needed for a quantitative analysis of change. The extent of ground sealing is key information when monitoring the development of urban areas, particularly megacities, which have rapidly expanded in recent years. With EnMAP data, such information can be automatically generated for various reference bases.

Whereas for calculating the extent of ground sealing the permeability of surfaces is taken into account, surface materials can be flexibly used to derive other indicators which give a detailed look at inner city structure and how it is changing. Figure 31 shows urban indicators derived from simulated EnMAP data for individual blocks of buildings in the eastern part of Munich. Aggregation of this information by urban planning experts makes it possible, not only to monitor the development of cities, but it also makes available basic geographical data important for actively designing the future of our cities.

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 sealing and the percentage of vegetation in urban conglomerates, factors which have numerous consequences for the urban climate and, thus, for the quality of life of city dwellers.

EnMAP will provide basic spectral data important for the active planning of sustainable cities and enable a better understanding of urban trends.

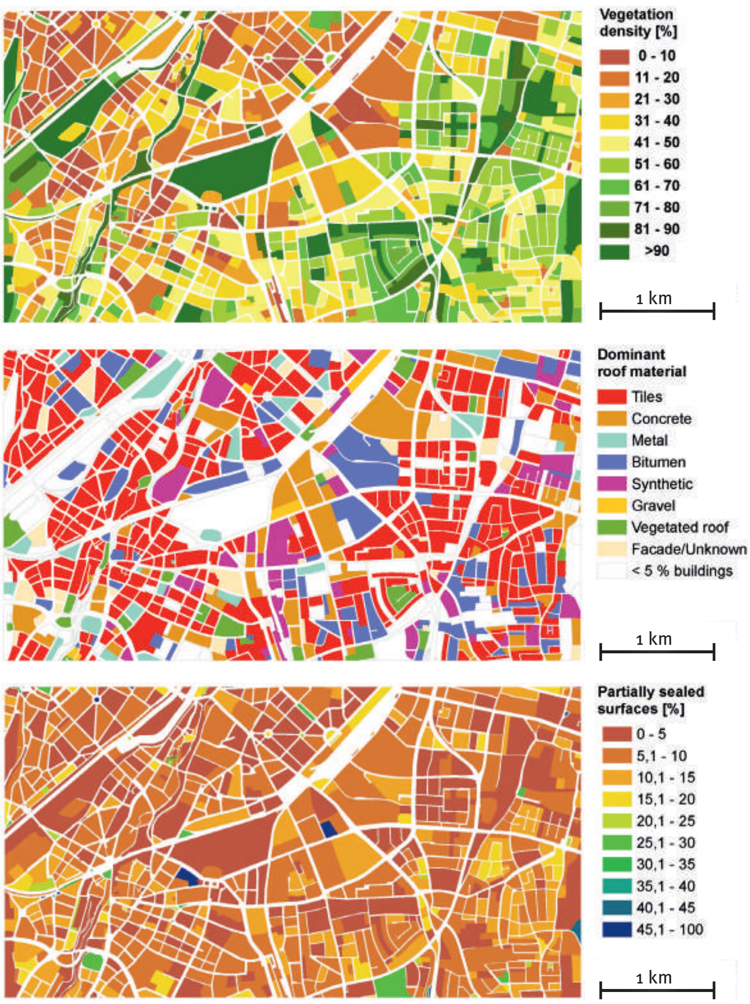


Fig. 31: Urban indicators per block of buildings for the eastern part of Munich, derived from hyperspectral data.

EnMAP sees the Earth from various viewing angles

Standardizing the signal variance of multitemporal off-nadir views

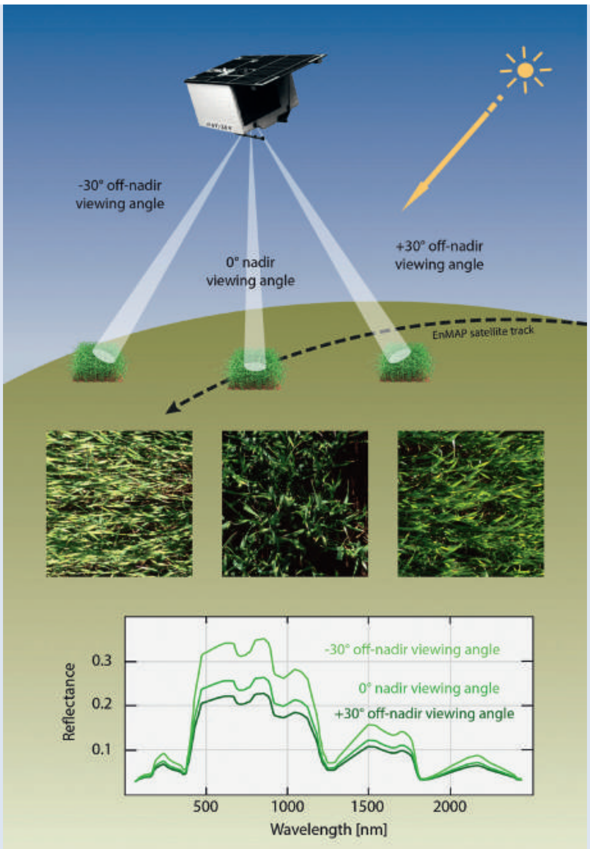


Fig. 32: Schematic representation of EnMAP signal variance as a function of viewing angle.

A satellite system like EnMAP is in principal designed to record processes on the land surface globally. Due to its 30 km swath width the sensor has a revisit rate in nadir viewing (perpendicular to the ground) of only 27 days. But by rotating the satellite sideways up to ±30° any point on Earth can be revisited in less than four days. This much higher repeat rate, useful for particular science studies, has the disadvantage that the spectral signal recorded for a given area is significantly altered if it is viewed from different directions. Vegetated surfaces are especially problematic since in these cases the differences in the relationship between signals from the ground and from plants, and between signals coming from shaded and illuminated surfaces, are exceptionally large (Fig. 32).

To record and correct these effects, a spectral, spatial and temporal simulation syetm was developed at GFZ, which 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 raytracing methodology taking into account all possible viewing angles (Fig. 33).

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 value of vegetation indices was analysed. These indices are often used to quantify biophysical parameters that are in turn used to model various ecosystems. This research led to the development of a standardization method for transforming vegetation indices derived from off-nadir measurements into nadir-view vegetation indices. The developed procedure was successfully applied to simulated EnMAP data and the practical relevance of this correction method was demonstrated using the example of the leaf area index (LAI). The LAI can be determined up to 48% more precisely (on average 25%) thanks to the correction of the vegetation index. These results show that in the case of off-nadir viewing angles the elimination of angle-dependent influences is necessary and leads to considerably improved results. The newly developed methodology is thus capable of making an important contribution toward deriving high-quality thematic products from EnMAP data.

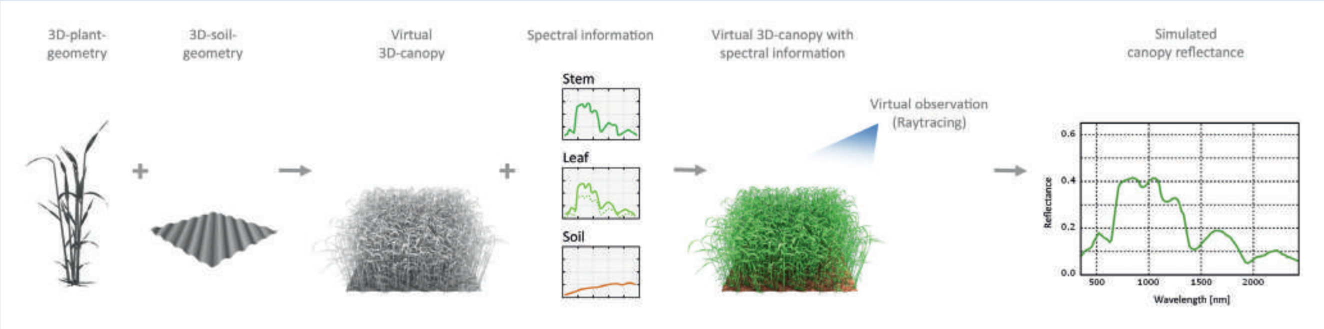


Fig. 33: Visualization of the system for simulating the spectral, spatial and temporal development stages of winter barley.

EnMAP images already before launch

Generating future EnMAP images with simulation software

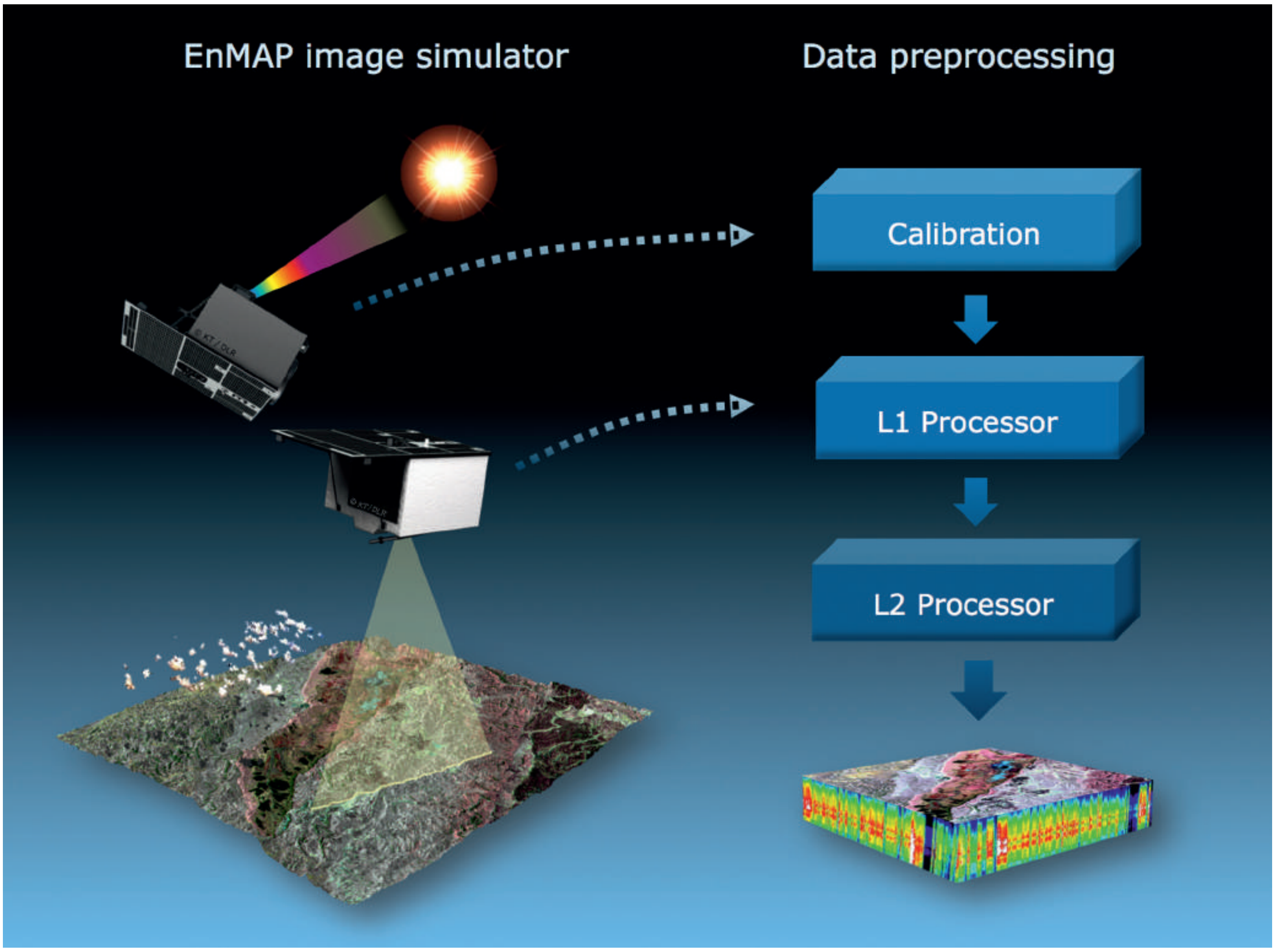


Fig. 34: EeteS (EnMAP end-to-end simulation software) processing scheme.

Expected 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 to obtain this essential information. EeteS consists of two components, an EnMAP image simulator and the associated data preprocessing chain (Fig. 34). 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 made visible in the image data, and in turn optimized. This requires preprocessing 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 nonlinear 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.

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