3 The Earth Surface

by Stefan Dech

Looking down at Planet Earth from the vantage point of space has always exerted a great fascination, whether on astronauts orbiting the earth or on earthbound beholders of spectacular satellite images. We have become aware of the fragility and vulnerability of the earth, learned to comprehend it as a unit irrespective of political borders, seen that gossamer veil of an atmosphere which protects living organisms from aggressive cosmic rays and, not least, been struck by the beauty of our planet. Space activities at the inception of the 21st century are giving us new views of our "spaceship earth," leading us to new insights.

3.1 Sensing the Earth Surface

Remote sensing of the earth from space was stimulated by the space race of the 1960s between the USA and the USSR. The view from above offered numerous possibilities for observing inaccessible territory and monitoring activities there, particularly from military considerations. But rather soon the great potential for scientific investigation of the earth and its complex ecosystem became evident. The Earth Resources Technology Satellite (ERTS), launched in 1972 and originally designed for military applications, marked the beginning of civil remote sensing from space, at least as far as the land surface was concerned. Soon after launch ERTS was rechristened Landsat 1, and satellites of the Landsat series have been setting milestones in earth observation ever since in the development of successor systems, a multitude of analytical techniques, geoscientific insights and commercial utilization. This chapter provides an overview of current and future possibilities in earth observation and the associated systems with respect to the earth's land surface, oceans and cryosphere. Following chapters will elucidate other application areas, such as atmospheric research (in 4 and 5) and geophysics (in 6).

Geoinformation from Space

Remote sensing is first of all a measuring technique for obtaining data about the earth's surface and the atmosphere without coming into physical contact with the objects to be measured. The procedure can be used to study any celestial body (as has ESA's Mars Express since January 2004). We speak of earth observation if the remote sensing is carried out from space with the earth as target. The goal is to obtain terrestrial measurements of high temporal and spatial resolution for large areas by utilizing the spectral characteristics of surfaces and objects on earth. The data obtained in this way are converted into various geophysical or biophysical information layers with the help of physical-mathematical algorithms. These can serve as the basis for subsequent analyses or be integrated into mathematical models describing many earth processes. The derivation and mapping of environmentally relevant variables and object identification also play an important role in many applications. All told, objective and independent geoinformation can be obtained with the help of modern earth observation technologies for use in the geosciences, marine and life sciences and atmospheric research, as well as in many practical applications concerned with local, regional and environmental planning, and with disaster management and humanitarian aid activities that fall under the category of civil security.

Only earth observation from space allows spatially integrated and continuous recording of measurements covering large areas and at various scales ranging from the global views needed for climate research to the local perspectives required for mapping urban areas. In the 1980s, earth observation started to make serious progress. Geoscientists from the most varied disciplines were quick to appreciate its enormous research potential for environmental studies and monitoring. Thanks to the previously unimaginable availability of high quality, repeatable measurements for vast areas, almost all of the important ecosystems on earth negatively affected by human activity—from tropical rain forests (land clearance) to semiarid and arid regions (desertification) to temperate zone forests (forest dieback) to oceans and coastlines (material transport, algal blooms, El Niño)—could be regularly monitored and analyzed in context.

Promising perspectives for the commercialization of this technology were also soon on the horizon. For example, the vast realms of agriculture, forestry, public planning and environmental concerns turned out to offer a variety of interesting points of departure for usefully integrating the methodology and products of earth observation. Its imaging measurement principle was particularly advantageous for the rapid growth in applications for earth observation data. Thanks to the continuous recording capability of remote sensing instruments, the sum of all the individual measurements (pixels) and the information products derived from them can be represented in the form of digital satellite maps. Seen together, all the individual measurements form a three-dimensional data set in raster format, which results in a continuous, spatial pattern allowing mapping of the area under observation. Such results can easily be integrated in models or put into geographical information systems where they can be combined with other types of data, which can be either in the form of data points or area representations, before further analysis. Another weighty advantage is the option of regularly repeating measurement of the same area without undue logistic effort, making it possible for the first time to extensively monitor landscape changes caused by natural processes or human activity. Finally, rapid access to data from earth observation satellites is encouraging new areas of application. The first step was meteorological remote sensing from a geostationary orbit, which now makes near-real-time weather reports routine. With today's land and ocean observing satellites, images of an affected area can be ideally supplied within hours of a catastrophe (forest fires, floods, earthquakes) to crisis situation centers. Earth observation data are increasingly becoming an important resource for investigating and minimizing damage, supporting emergency humanitarian efforts, and planning measures which improve civilian defense. Thus the information technology known as earth observation is increasingly finding a widely recognized role in a broad range of scientific and public applications.

3.2 Remote Sensing Basics

Data from earth observation instruments have been received for some 35 years. They are usually operated from unmanned satellites which, depending on the application, may be placed in any of a number of orbits. In order to obtain data of high temporal resolution (such as required for meteorology), equatorial, geostationary orbits at 36,000 km altitude are preferred. At that location, one orbital circuit is identical to the length of one day (24 hours) so the earth is viewed by the sensor always from the same viewing angle and as if it were standing still. The disadvantage is that only about 25% of the earth's surface is visible; the polar regions cannot be observed at all from this vantage point. For surface monitoring satellite orbits which cross the polar regions and are inclined some 98 degrees with respect to the equator are preferred. Satellite altitudes may vary between about 300 and 850 km. These almost-polar orbits take about 100 minutes for one circuit and offer sun synchronicity. In other words any point on earth is always observed at the same local solar time of day, a considerable advantage when comparing images. Another advantage of this orbit is that almost any point on the earth's surface can be viewed, the only exceptions being regions very near the poles in the case of sensors with limited side viewing capabilities. Optical earth observation sensors usually detect the irradiance reflected from the earth's surface along the flight path of the satellite and a certain distance to the right and left depending on the defined viewing angle of the sensor in question (so-called nadir viewing). Radar instruments always view to one side of the satellite track.

Earth observation from satellites uses electromagnetic radiation from the optical to the microwave part of the spectrum (figure 3-1). Optical sensors operate in the wavelength region from 0.3 to 14 µm, while microwave sensors cover the mm to dm wavelength range. A distinction is made between passive instruments like digital cameras, radiometers and spectrometers that measure reflected solar or earth-emitted radiance, and active instruments like laser or radar systems that send out signals from their own source of power and measure the returned ("back-scattered") signal, which is a small fraction of the originally transmitted power. There are a number of physical mechanisms involved in the propagation of electromagnetic waves through the earth-atmosphere system. Absorption and scattering take place both in the atmosphere and at the earth's surface. In addition, there is reflection at the surface and self-emission of radiation according to Planck's law. The first 20 years of satellite earth observation were dominated by passive optical sensors which detected primarily irradiance in the visible and near, short-wave or thermal infrared part of the electromagnetic spectrum, depending on the application. Using such multispectral data (ca. 1-10 spectral channels) the most important methodologies for today's applications were developed. The optical systems are usually optoelectronic or electromechanical scanners which split the incoming irradiance spectrally with the help of a grid or prism and then pass it on via elaborate mirror constructions to individual detectors or CCD (charged-coupled device) arrays, whereby each detector in the array senses one pixel in the image field. Optical earth observation data which includes different looks of one and the same object from slightly different viewing angles were successfully processed to yield so-called digital elevation models of the earth's surface. The optical region contains many diagnostic features in the shape of the reflectance and emissivity spectra. In addition, the surface temperature which can be derived from the data is an important biophysical and climatological parameter. However, there are drawbacks. Optical imagery frequently suffers from haze and cloud contamination, and here radar has the advantage. Since microwaves penetrate clouds and atmospheric trace gases to a large extent, the quality of microwave images is almost independent of cloud

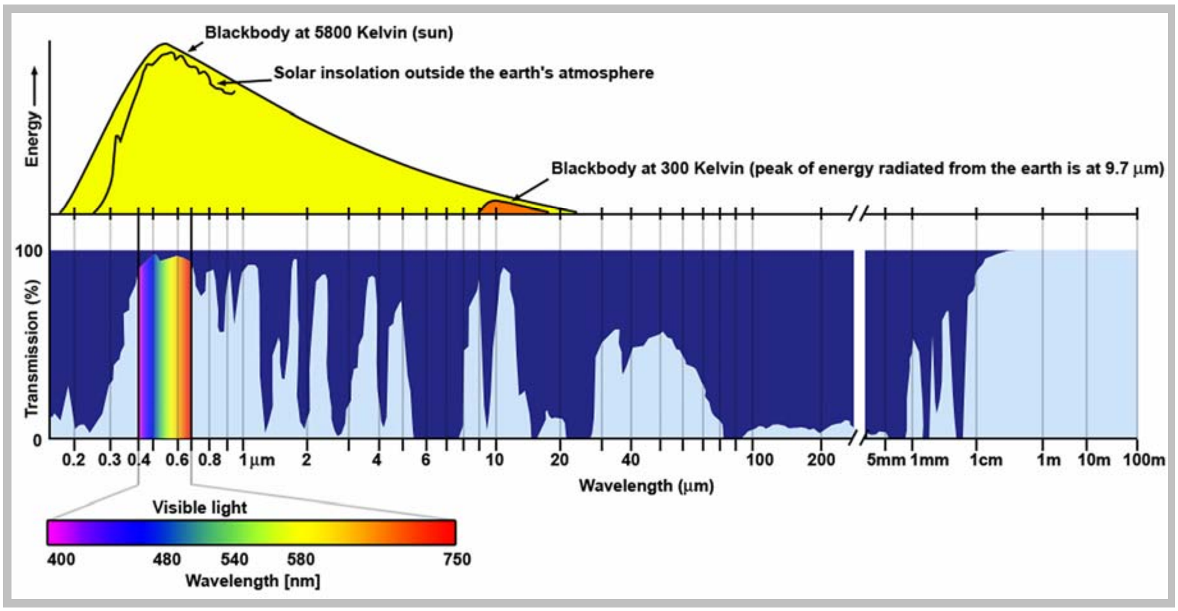

Figure 3-1: The electromagnetic spectrum. Below: the dark blue areas are those portions in which the radiation is entirely absorbed by the atmosphere and thus unavailable. The "windows" (light blue) which let through radiation in the visible (c. 400-700 nm wavelength), infrared (0.7-300 µm) and microwave (1 mm-1 m) portions are used in earth observation. Above: Planck radiation curves for blackbodies at 5800 K (sun) and 300 K (earth). The radiation maximum is in the visible range

coverage, so data can be collected regardless of local weather conditions at the time of recording. Since radar instruments send out their own signals, they are not dependent on solar illumination as are the optical systems, so they can be operated independently of the time of day. Since the early 1990s elevation models can also be derived using data from radar systems. By collecting radar echoes coming from one and the same object from slightly different positions in space, phase differences can be analyzed not only to derive these models but also to detect small, centimeter-range horizontal movements, subsidence and uplifting of the earth's surface. Moreover, multifrequency and multipolarization active microwave systems can be used to derive information on soil roughness and moisture, and they enable good differentiation of diverse vegetation types and urban surfaces. This technique permits a multitude of additional applications, some of which are described below. Each type of sensor and spectral region has its own specific advantages and drawbacks, depending on the target to be viewed. Optical and radar are on principle complementary recording systems, and in the ideal case multisensor optical and microwave imagery are always combined for a detailed retrieval of earth surface information.

Whether passive optical or active radar systems, the signals detected by the sensor are converted into electronic information and transmitted to ground stations via telemetry. The telemetry signal includes the actual payload data, information about the state of the sensor (housekeeping data), and the orbit data, all of which together make it possible to create a calibrated and referenced image. Satellite lifetimes in the inimical environment of space can vary from one year up to ten years under favorable conditions. As many as ten different instruments have been placed on one satellite platform, and they may be operated separately or in various combinations, as is the case with Envisat, launched in 2002. Most of today's earth observation satellites are developed and operated by national or international organizations (NASA, ESA, CNES, ISRO and others) with public funding and in the context of science programs (NASA's Mission to Planet Earth, ESA's Living Planet Program, etc.). Currently, long-term and overall continuity of earth observation is not assured, in contrast with the situation for meteorological satellites. Since the end of the 1990s an intensification of commercial activity could be observed, particularly regarding high spatial resolution systems (like Ikonos, QuickBird). Lastly, there are a number of small earth observation systems (on so-called micro- or mini-satellites) being designed, built and operated by research institutions and/or universities worldwide to meet specific teaching and research goals (BIRD, SUNSat, etc.).

It cannot be attempted here to give even a superficial survey of former, current and planned earth observations missions. There are simply too many, and the field is very dynamic. Table 1 (at the end of this chapter) lists only the most important current and planned missions for sensing the earth's surface and supplies some technical information about them. For the most thorough summary available see Kramer (2002).

3.2.1 Optical Remote Sensing

In the optical spectral region, for wavelengths λ = 0.3-14 µm, a radiative transfer code is used to remove the atmospheric influence on the measured sensor signal and to obtain information from the earth's surface. In the solar-dominated region (λ < 2.5 µm) the surface reflectance signature can be retrieved, while the thermal region (λ > 8 µm) enables the calculation of surface temperature and emissivity spectra. For minerals, rocks, and soils, electronic and vibrational transitions are induced by the electromagnetic interaction, and these cause diagnostic absorption features in reflectance and emissivity spectra. The electronic transitions require higher energy, and thus take place at shorter wavelengths than do vibrational transitions. For vegetation canopies, important factors determining the reflectance behavior are the leaf pigments, particularly chlorophyll-a and chlorophyll-b, leaf water, and canopy geometry.

Depending on the number of available spectral bands (multispectral instruments: typically 5-15 bands; hyperspectral: 50-300 bands), the reflectance signature allows a detailed quantitative extraction of geophysical, chemical and biophysical parameters. For example, different vegetation canopies have different amounts of chlorophyll-a and -b pigments and plant water. The pigments are primarily responsible for the reflectance behavior in the visible (0.4-0.7 µm) region. Plants appear green because of the higher pigment absorption in the blue and red parts of the spectrum. The reflectance in the near infrared plateau (0.7-1.2 µm) is due to the cell structure, and also influenced by the water content ($\lambda > 0.96$ µm). In the 1.2-2.5 µm region the plant's liquid water is the major factor determining the reflectance curve. In the framework of multitemporal monitoring of agricultural areas with satellite sensors, pigment concentration and leaf water content can be derived. This information can be used to assess crop health status and to predict crop yield, in combination with other parameters. Further examples from different application fields are discussed in subsequent sections of this chapter.

3.2.2 Radar Remote Sensing

Synthetic aperture radar (SAR) sensors use microwave pulses of 3 to 25 cm wavelength to image the earth surface. As said above, these waves penetrate clouds and since the radar carries its own illumination, SARs work independently of weather and sunlight. Figure 3-2 depicts the SAR imaging geometry. A radar sensor transmits short microwave pulses (typically 1,000-5,000 per second) to the earth in a side-looking fashion and receives the waves reflected back from the ground. The two coordinates of the image are formed by two different mechanisms:

In the range direction (perpendicular to the flight path) the swath is scanned by the wave pulse sweeping over it at the speed of light. Different objects on the ground are distinguished by their distance to the SAR and, hence, by the arrival times of their wave echoes. The resolution in range is given by the length of the transmitted pulse. The width of a pulse and its bandwidth are inversely proportional. Given a bandwidth of W [in Hz] and a local incidence angle θ_i the ground range resolution in meters is

$$\rho_{g/r} = \frac{c}{2\,W\,\sin\theta_i}\,.$$

The European Remote Sensing Satellites' (ERS-1, ERS-2) family of SAR instruments uses a bandwidth

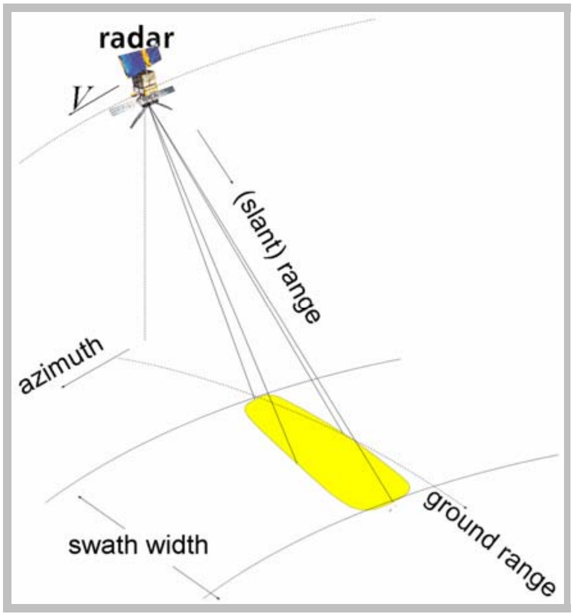

Figure 3-2: Imaging geometry of a synthetic aperture radar

of 15 MHz and an incidence angle of about 23 degrees, resulting in a ground range resolution of 25 m. The German TerraSAR-X satellite will boast a 300 MHz bandwidth.

In the azimuth direction (along the flight track) the swath is scanned by the flight motion of the radar. The resolution in azimuth is given by the extent of the illuminated patch on the ground. Focusing it to a few meters, as required for remote sensing, would call for an antenna of several kilometers length, which is not feasible. Instead, the trick of aperture synthesis is employed: the radar returns are recorded coherently, i.e., their amplitudes and phases are measured. The resulting raw data set resembles a hologram. In a second step this is focused to a high resolution image by dedicated digital signal processing software packages, so-called SAR processors (Curlander 1991). The finally achievable azimuth resolution of a SAR with an antenna of physical length L in the flight direction is

$$\rho_{az} = \frac{L}{2}\,,$$

which is independent of range and satellite velocity.

SAR images look quite different from optical ones (figure 3-7, left) (Ulaby et al. 1986). The quantity imaged by a SAR is the (dimensionless) normalized radar cross section or radar backscatter coefficient σ^0. It is equivalent to the surface reflectance known from optical imaging and is a measure of the ability of the ground to reflect the microwaves back to the radar. σ^0 depends on the roughness of the surface, its dielectric constant, the wavelength, and the incidence angle. Surfaces smoother than a wavelength (asphalt, calm water, slick rock) act as mirrors reflecting the waves away from the SAR and, hence, appear dark in the image. Rough surfaces (agricultural fields, forests) scatter the microwaves in all directions and a part of the wave energy can be received by the SAR, leading to brighter areas in the image. Besides the roughness the dielectric properties of the surface play an important role: the higher the dielectric constant the higher σ^0. The dielectric constant is in turn a function of the water content of soil or plants. SAR images are not only maps of the surface. Unlike in the optical regime, microwaves can penetrate vegetation, soil, ice and snow. While X-band (λ = 3 cm) gets reflected in the layers close to the surface, L-band (λ = 25 cm) partially passes through canopy and gets double-bounce reflected by the soil and trunks. C-band (λ = 6 cm) provides measurements from the middle of plant bodies. Finally, SAR allows the polarization of transmitted and received waves to be controlled. Fully polarimetric SARs can transmit and receive horizontally (H) and vertically (V) polarized waves quasi simultaneously. Each pixel of such an image consists of a set of numbers representing the different polarization states, e.g., HV for H on transmit and V on receive, or HH, VV. Each scattering mechanism, like surface, volume or double-bounce, has its own polarimetric signature that can be used to infer the type of surface or land cover.

Interferometric SAR (InSAR)

Since the phases of the received echoes are recorded and preserved throughout all processing steps, each pixel of a so-called single-look complex SAR image is a vector of two numbers, the in-phase (or real) part and the quadrature (or imaginary) part. The length of the vector represents the pixel brightness and its angle the phase. The phase is an extremely sensitive measure for range. A change in range as small as a fraction of the wavelength (λ), i.e., centimeters or millimeters and, hence, much smaller than the range resolution, will lead to a detectable phase variation. The phase information from a single image does not carry useful information, since the scattering at the earth surface may introduce a random phase. However, in the phase difference of two images taken of the same area on the ground, this random phase cancels out to a large degree. InSAR exploits phase differences of at least two SAR images to derive more information about the imaged objects compared to using a single image (Bamler and Hartl 1998). The images are first co-registered accurately and then the phase differences are computed on a pixel-by-pixel basis. The resulting "image" of phase differences is the interferometric phase map or—in short—the interferogram. If the range of an object differs by ΔR between the two images, the interferogram pixel representing the position of the object will exhibit an interferometric phase of

$$\phi = \frac{4\pi}{\lambda}\Delta R\,.$$

In case the images are taken from the (ideally) same orbit but at different times, we talk about differential InSAR. Only objects and areas that have moved between the two acquisitions will give rise to an interferometric phase. Two-dimensional maps of ground motion can be generated by this method. Landslides, glaciers, volcanoes, land subsidence and earthquakes are typical targets of investigation using differential InSAR.

If the images are taken from different positions but at the (ideally) same time, this is referred to as across-track InSAR (figure 3-3). It allows us to recover the three-dimensional coordinates of every pixel and to generate a digital elevation model of the imaged area. As shown in figure 3-2 a SAR system maps the three-dimensional world into the two cylindrical coordinates range and azimuth. The third dimension, the angle θ, is accessible by across-track InSAR. It is directly related to the range parallax ΔR (figure 3-3) and, hence, to the interferometric phase. The center of figure 3-7 (see 3.3.1-Topography) shows the across-track interferogram formed from the image of figure 3-7 (left) and an interferometric

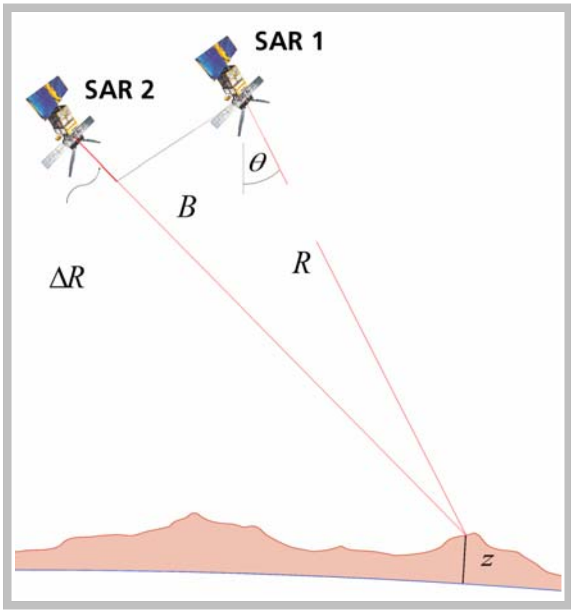

Figure 3-3: Imaging geometry of an interferometic synthetic aperture radar

companion. The iso-phase lines, the so-called fringes, resemble height contours. The finally derived digital elevation model is shown in figure 3-7 (right) in a perspective view.

3.2.3 Processing Data to Information

With the growing complexity of available recording technologies for multispectral optical, polarimetric and interferometric radar systems there is ever more demand for standardized, operational (regular and routine in near-real-time) processing of the raw data into information products. This is accomplished with the help of suitable software which uses algorithms to derive the sensor-specific, viewing, physical irradiance and geometric characteristics of a satellite image and then to generate from them products of varying levels of sophistication (value adding levels). The specific requirements depend on whether attention is being directed at the atmosphere, the solid earth, the oceans or the land surface. For many scientific studies, basic georeferenced and calibrated products are required, for example, surface reflectance or radiance values for each recorded channel (or range within the electromagnetic spectrum), along with the associated geographic coordinates, upon which subsequent calculations and analyses can be based. However, critical to the dissemination of earth observation data for a wide range of applications to people who are not remote sensing experts is being able to generate products which provide information in the form of well-known and scientifically accepted geophysical or biophysical variables like surface temperature, land use, biomass content or evaporation, in familiar cartographic projections. Such earth observation information products can be directly integrated in planning, environmental or climatological analyses. They can be immediately understood by people knowledgeable in the interpretation of the variables presented, but without specific remote sensing expertise. Of course, generally accepted algorithms and margins of error must be identified. As in many sciences, the development of new procedures and the derivation of appropriate algorithms under defined, well known boundary conditions form the basis for methodological innovation. On the other hand, applicability under other conditions (in the case of remote sensing this might involve the use of different spectral channels, resolutions, recording intervals, atmospheric conditions or test sites) is particularly difficult to achieve, since the algorithms often have to be modified for each new case. Standardization and agreement on generally valid and applicable algorithms and procedures is a challenge which must be faced by anyone using earth observation as a technology to gain geoinformation, if broad acceptance and robust applications are to be assured.

3.2.4 Managing Data and Products

Collecting and archiving earth observation data on the atmosphere, solid earth, oceans and land surface and then processing them into information products of various levels of sophistication is the task of so-called payload data ground segments. They also distribute data and products to users who may include the science community, government authorities, commercial companies, the media, or private individuals. For optimal exploitation of sensors on board the satellite, payload ground segments also enable the user to initiate acquisitions of desired locations at desired times. Comprehensive functionality has to be provided in order to establish a bridge between satellite sensors and data users, including:

- Online access via the Internet to existing data, as well as to initiate new acquisitions,
- Order management and delivery of the requested earth observation products to the user,
- Reception of new acquisitions downlinked from the satellites,
- Archiving and cataloging the acquired raw data and derived information,
- Processing the raw data to higher information levels.

Information and communication technology plays a key role in establishing these functions. Depending on the amount of data and number of missions and sensors to be supported, clusters of high performance servers are needed to process the data. Cataloging and order management require database management systems, whereas online access and delivery rely on Web and ftp servers. Local area networks (LANs) which connect the systems on a 1 gigabit/sec basis and high-speed wide area networks (155 megabit/sec) are needed for remotely distributed facilities. In the case of near-real-time services such as providing satellite data for weather forecasts, the possible failure of hardware must be anticipated so that remedial procedures are automatically implemented.

A central part of a payload ground segment is the archiving and cataloging system. All received raw data and derived higher level products have to be stored in a digital data library for comfortable access and long-term preservation. Catalog information describing each product is managed in appropriate databases to enable the search for a desired product among millions of archived items. The image data themselves are kept in automated archives on foreground disks and background tapes which provide online access to recently used data and near-line access to older products. Initiated by a user request, a robot is activated to fetch the tape where the older product is located and put it into a tape drive; finally the data is accessible online on disk without operator interaction.

Online access to earth observation data is provided by user information services. Via a Web-based interface the user can get various information on products from a product guide and directory; a catalog can be searched once the desired items are identified; detailed parameters and browse images can be retrieved. If interested in the full resolution image, the user can order these data and have them delivered either online or shipped on media. In the background, an order management system organizes the ordering and delivery process, handles the user profiles and considers data policy and license issues.

Specific features are provided for customers who request acquisitions by the satellite sensor. First, the possible locations seen by the sensor are visualized, and then the user's specifications for the future acquisition have to be forwarded for incorporation in the mission planning process. Mission planning, including the commanding of the sensor and the uplink to the satellite, are performed by the mission operations segment supported by the instrument operations segment. Once the sensor has taken the measurement and the satellite is in the visibility range of a receiving station, the acquisition data is downlinked and archived and the raw data can be processed to higher information levels.

Although missions are planned and operated by space agencies, the use of data is not limited by political boundaries. The data management systems implementing payload ground segments are linked with the help of networks and international data representation and communication standards (see for example www.ceos.org). This enables the combining of data from various sources to even higher level earth observation information, for example multidimensional georeferenced coverage for use in geographic information systems.

Building and operating payload ground segments is a complex task necessary for systematic and successful exploitation of the acquired data. Considerable savings can be achieved by employing multimission ground segment infrastructures capable of integrating the new data formats and processing facilities of future missions into existing operational structures.

3.3 State-of-the-Art Applications

What follows is a look at a representative selection of current earth observation applications, chosen from a sizeable list. The organization is by field of investigation rather than by the particular technology applied, in keeping with the motivation behind earth observation activities, to obtain information which describes and facilitates understanding of processes taking place on earth.

3.3.1 The Land Surface

Earth's land surface is mankind's primary living space and economic area. Pressures caused by an increasing world population and the accompanying demand for energy and food have led to human activities which have decisively disrupted nature's balance, sometimes irreversibly, on large portions of the land surface. These include agriculture, forestry, pasturage, mining, expansion of urban areas, ground sealing, and a multitude of planning measures too numerous to mention. The consequences of all these influences taken together are formally documented as contributing to climate change (IPCC 2001). Looking beyond the land surface, they are also attributed to changes that can be readily sensed in the atmosphere (key words being the ozone hole, high levels of air pollution, increases in the occurrence of extreme events like major storms), as well as in the oceans and polar regions (pollution, overfishing, melting of inland ice and reduction in the thickness of sea ice). The following section is an introduction to the contributions earth observation can make toward acquiring parameters of the land surface relevant for environmental and planning activities, with the ultimate goal of contributing to sustainable ecological and economic management.

Land Use and Land Cover Mapping

Up-to-date information on land cover (classifying the surface in principal categories) and land use (discrimination within these categories, e.g., corn, rice or wheat crops within the category "agriculture") is a fundamental requirement for a variety of applications in sustainable land management and ecological mapping and can be regarded as one of the most important multipurpose products based on remote sensing technology. As examples, an analysis of current land use and its changes over time can provide a basis for spatial planning, land, water and coastal zone management, sectoral analyses in agriculture and forestry, monitoring soil sealing and urban sprawl, nature conservation, and to a lesser extent for decisions regarding transport, telcommunications and navigation. It can also be used to assess the impact of agricultural policies or of the environmental effects of trans-European transport networks, to support the implementation of biodiversity conventions and similar programs, and to assess air emissions and air quality.

Land cover and land use mapping based on remote sensing is being performed on various scales. On the global scale a land cover map with a coarse resolution of 1 km was generated in the framework of the International Geosphere-Biosphere Programme (IGBP-DIS) (Belward et al. 1999). Recent data sets at 1 km spatial resolution were produced, for example, in the Global Land Cover 2000 (GLC2000) project (Bartholome et al. 2002) and on the European level in the Pan-European Land Cover Monitoring (PELCOM) project (Mucher et al. 2000). At a medium resolution mapping scale of 1:100,000 the most important activity in Europe is currently the CORINE Land Cover program.

The objective of this European-wide program is the generation and regular updating of consistent and comparable information on land cover in Europe for environmental assessment and planning purposes. The mapping is done at a scale 1:100,000 according to a European-wide harmonized nomenclature of land cover and land use classes. The CORINE land cover database, first generated in the 1990s and updated in the CORINE Land Cover 2000 (CLC2000) project, provides up-to-date information for the reference year 2000 and for land cover changes in Europe during the previous decade. The mapping is based on computer-assisted analysis of Landsat 7 ETM+ satellite images with a spatial resolution of 15 m (panchromatic) and 30 m (multispectral). The CLC2000 project is led by the European Environment Agency in cooperation with the member states of the European Union. The database covers an area of about 4.5 million square kilometers.

Approximately 300 ETM+ satellite scenes are necessary for complete coverage of the European Union countries. The data are taken from the vegetation period of the year 2000. In case of cloud cover, scenes from 1999 or 2001 are used instead. Based on these satellite data the mapping is performed in each of the participating countries. The nomenclature of CLC2000 distinguishes 44 land cover and land use categories in three hierarchical levels. The main categories are urban and artificial surfaces, agricultural areas, forests and semi-natural areas, wetlands, and water bodies. In figure 3-4 the land cover map for Germany is shown as an example, where 36 of these 44 European land cover classes are relevant. The CORINE land cover database is being used as a multipurpose product for a wide range of applications at European and national levels.

Agriculture and Forestry

Regularly updated space-based land-use information is one of the key resources for the management of rural and forested areas, including agriculture. Whereas in third world countries agriculture is essential for the daily basic local food supply, in industrialized countries agro-business is gaining relevance. Remote sensing technology is assisting both objectives. On the one hand, the identification of drought and the potential shortages likely to occur in developing countries as a result are fundamental to government and international response programs and relief efforts. At the other extreme, crop assessment as a basis for granting subsidies in industrial agriculture in order to control production has necessitated the development of sophisticated new technologies. Earth observation techniques for crop and yield forecasting have therefore different meanings in a global context. While farmers strive for profitable, efficient and sustainable production from renewable resources, it is political decision makers who have to address and respond to issues of over- and/or under-production, imports, exports, quotas, conservation, protection, food security, subsidy allocation and administration.

The manifold applications of remote sensing in agriculture make use of radar, standard optical, or new hyperspectral sensors, depending on scale and specific research field. Innovative concepts such as precision farming combine satellite navigation (GPS or the future Galileo) with satellite-derived information (current crop condition) and geographical information systems (soil characteristics, topography, past yield history) to allow the farmer to optimize agricultural production and the distribution of fertilizers, herbicides and pesticides for each individual

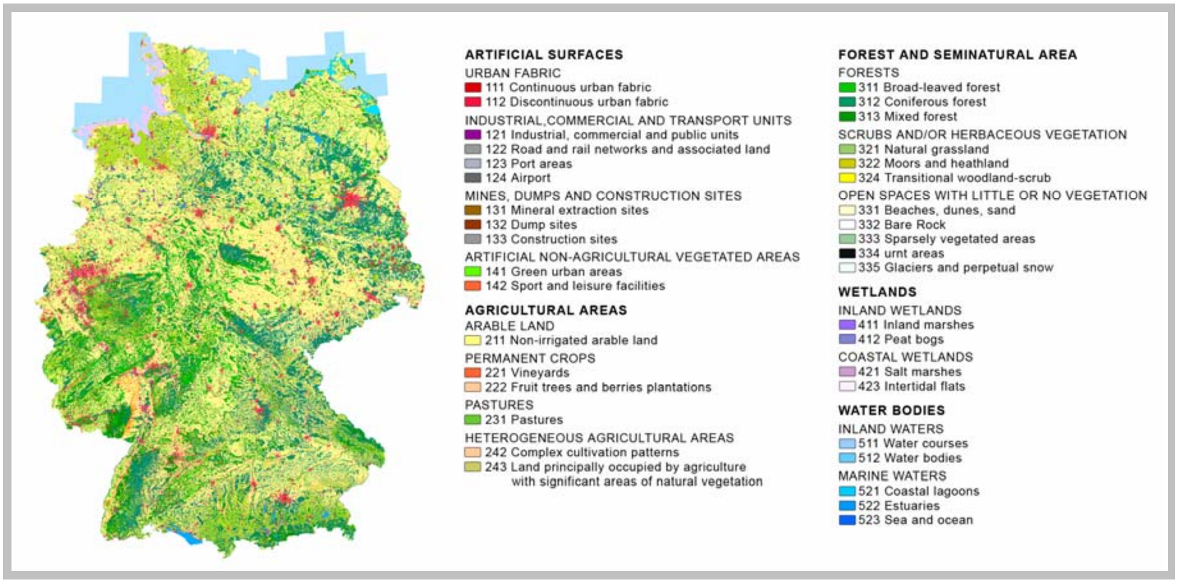

Figure 3-4: The 36 land cover classes for Germany resulting from Corine Land Cover 1990 activities

field, while minimizing environmental impact and encouraging sustainable land management. Numerous factors such as soil variability, field size, and economic and technological possibilities influence the decision for or against precision agriculture, so its adoption is unlikely to be uniform across farm types and sizes. However, traditional management techniques and structures will be—at least partially—replaced as essential data on soil and vegetation can be provided by satellite remote sensing. Vegetation information such as biomass estimation, plant phenology assessment, dryness or wetness of crops, early crop disease detection, yield estimation and land use classification data can be provided by remote sensing, among other sources (Clevers 1999). The synoptic view and the repetitive cover afforded by satellite data allow multitemporal observations of seasonal changes, which is crucial for detecting dynamic vegetative phenomena. Optical multispectral or hyperspectral data can be used to assess crop and soil conditions and to measure quantitatively important crop parameters such as plant canopy water content, nitrogen, chlorophyll, and leaf area index values. In addition, information on soil temperature, soil sealing and land degradation can be provided to the farmer to enhance his production methods (figure 3-5). Crucial information on physical soil properties such as the amount of organic matter has been correlated to specific spectral responses to show the potential for automated classification. Nevertheless, such direct applications of remote sensing for soil mapping are limited because several other variables can impact soil reflectance, such as tillage practices and moisture content.

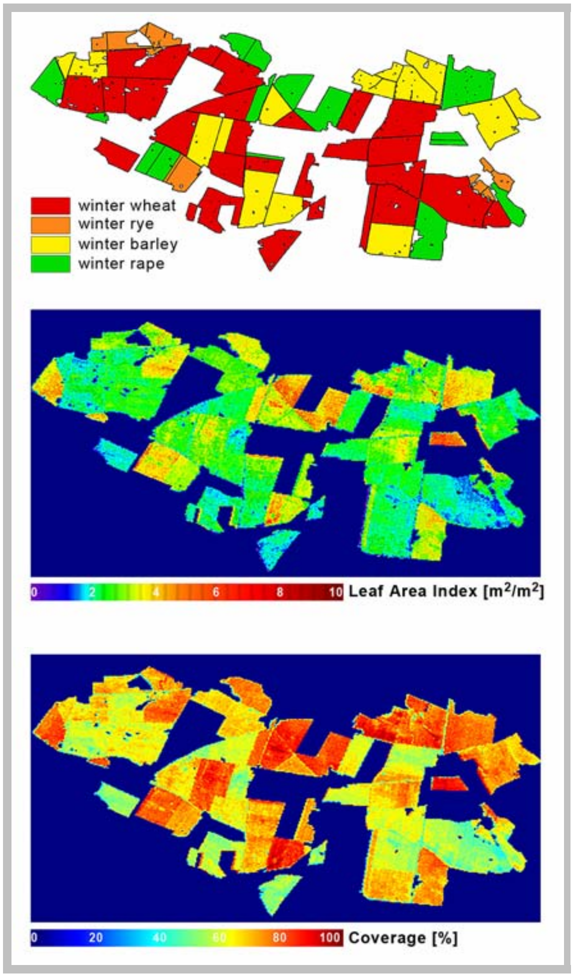

Figure 3-5: This image of farmland in the county of Demmin (Mecklenburg-Western Pomerania, Germany) was recorded by the Landsat 7 ETM+ sensor on May 1, 2000. It shows (above) which crops were planted on these fields, (center) the leaf area per unit ground surface as an indication of vegetation status and (below) how much of the ground was covered with crops. Such information is being used to analyze how much rainwater can be intercepted by vegetation for protection against erosion in endangered areas

Forests cover about one third of Earth's land surface. They produce the majority of land dwelling species; they are the land ecosystems with the highest biomass content and primary production (biomass); their economic use is manifold. They constitute a shelter and living space for many prominent as well as many precious species in economic terms, such as tropical timber (mahogany) or flowering plants (orchids). The world's forests play a vital role as a global climate regulator, as storage for water, energy and carbon, and as a storehouse for genetic resources. As producers of timber they create a livelihood for millions of people who extract wood products for various markets ranging in scale from industrial production to the heating and cooking needs of individual households, with all the positive and negative consequences. There is a broad interest in forests on the part of the scientific community, public authorities, and organizations and companies dealing with their harvested products and their exploitation, preservation and management.

Earth observation offers the means to collect data on global forest resources in a cost-effective, efficient and comparable way, sometimes serving as the only means of data gathering over inaccessible regions like mountainous terrain without infrastructure or population centers. A comprehensive picture of a forest's spectral properties can yield information on forest stand composition, density, health and evolution, biomass content and sub-canopy flooding. This technology also presents a window in time by documenting past changes in Earth's forests as data for the same region are collected and assessed year after year. Early applications focused on the use of optical mid-resolution (30-60 m) to low-resolution (over 1000 m) sensors like Landsat's MSS, TM and NOAA's AVHRR. In recent years medium resolution sensors like MODIS or MERIS with their spatial resolution between 250 and 500 m, ASTER (15-30 m) and even very high-resolution optical sensors like IKONOS or QuickBird (0.6-1 m) are also being used. Synthetic Aperture Radar (SAR) has been used to detect deforestation hot spots.

Standardized forest data and information products can satisfy a range of scientific, public and commercial interests. Remote sensing data has already been successfully used for accurate quantification of forest extension and distinction and quantification of relative proportions of natural forests and plantations, for determining forest health, forest types, age classes, tree density, biomass quantity, and adjacent vegetation types. Commercial and noncommercial forestry uses remote sensing to manage diverse forests worldwide. Due to the versatility and scale of remote sensing, it is invaluable in all stages of forest management (clear-cutting, reforesting, afforestation, harvesting, and damage assessment). Additionally, building on the ideas behind the Kyoto Protocol, the trade of emission certificates will require an up-to-date, timely, global and accurate assessment of the carbon balance in forested areas, for which earth observation can be an essential tool.

Modeling Fluxes

Numerical models are utilized to simulate and predict future developments in the realms of climate and environmental research, as well as for many practical planning tasks. Models are used as a way to link earth's different spheres (the atmosphere, land surface, biosphere, hydrosphere, cryosphere) for the purpose of describing quantitatively the ongoing exchanges of energy, momentum and matter (for example, carbon and water fluxes from the atmosphere to the vegetation on land and ocean and vice versa). Starting from known, measurable conditions, the models extrapolate into the future, simulating the effects of various (human) influences, such as the emission of carbon dioxide or chlorofluorocarbons, the regulation of river beds, deforestation, overgrazing, etc. Reliable models are accordingly an important resource both for scientific research and decision makers. The closer the starting parameters of a model match reality at the beginning of a simulation, the preciser the prognosis. This is where remote sensing is playing an increasingly important role. It provides a number of initial parameters used to drive the model; the process is called parametrization. But remote sensing data can also be used to check the results of models which are already running, by making it possible to compare their prediction of the current situation with actual data. If this succeeds, then it means that the complex interrelationships within the model have been adequately described and it is robust enough to be used for prognoses. Possibilities for modeling material flows which involve vegetation are briefly described below.

Net Primary Productivity (NPP), the uptake of atmospheric carbon dioxide by plants, essentially defines the amount of carbon removed from the atmosphere and fixed as vegetative carbon. Direct observations of NPP are not available globally, but computer models derived from local observations have been developed to represent global NPP (Cramer and Field 1999). On the other hand, monitoring the vegetative carbon sinks is uniquely facilitated through the use of remote sensing, since the imagery can provide timely information on vegetation state over a truly global extent.

The emission of biogenic compounds has implications for both air quality and climate stability either through direct effects, or through changes they cause in atmospheric chemistry. Some important compounds currently being studied are the so-called biogenic volatile organic compounds (BVOC) that include isoprene, monoterpene and methane. Until recently, the role of remote sensing in BVOC estimation was limited to the classification of land-cover types. However, remote sensing data provide much more information and great strides have been made to derive from satellite data related to vegetation information which can be coupled with models of biogenic compound emission in order to make more accurate flux estimations. Through the use of modeling techniques, many scientists are involved in the effort to understand how carbon exchange and BVOC emission can best be estimated. The resulting NPP and BVOC models are of varying complexity and require, as inputs, information about soil, plants, and weather. Since much of the information required for soils is static (texture, soil type, porosity), it is readily available for many areas of the world in well-populated databases. Additionally, meteorological information such as rainfall and temperature is also relatively easy to obtain for much of the world through established data collecting networks. However, obtaining information on other variable inputs, such as soil moisture, photosynthetic active radiation (PAR) and vegetation state, which do not have well established data collection networks, requires the use of remotely sensed data.

When remote sensing products showing current land use or land cover, leaf area index (LAI), land surface temperature (LST) and PAR are coupled with NPP or BVOC models, these data will allow for the characterization of ground pixels in terms of net primary productivity or emissions of BVOCs to improved estimates of these parameters on a continental scale and to increased accuracy of flux predictions by providing timely assessments of the NPP or BVOC sources.

The potential for gaining insight into the way vegetation changes over time and space is based on the knowledge of how reflected solar radiation is altered by vegetation. Sensors that acquire data in the visible and near-infrared portions of the spectrum are usually employed; for estimating biomass radar data are also utilized.

Desertification

Desertification is a process of landscape change in the context of landscape degradation. Mapping of desertification processes involves two steps, measuring parameters for desertification, and detecting changes for assessment of transformation between two or more dates. Remote sensing is exceptionally valuable for monitoring because it provides contiguous and calibrated spatial data at specific temporal intervals and is unbiased and quantifiable for statistical analysis. Satellite earth observation enables analysts to draw conclusions about the speed, stage, and spatial variability of landscape change, and make comparisons to other regions in the world.

Here, desertification describes the process by which landscapes arrive at ecological characteristics truly related to deserts. It involves the biosphere, pedosphere, morphosphere, and hydrosphere and is the final stage of landscape degradation, resulting in a growth of deserts into areas which have not been desert before (Mensching and Seuffert 2001). It requires an inherent natural potential of the region, such as high variability of precipitation, thin soils susceptible to erosion, and negative human impacts like unsustainable land use. Environmental indicators for desertification monitoring can be arranged into four major groups: vegetation, soil, morphology, and hydrology.

Typically, vegetative processes are estimated by time series of indices such as the Normalized Difference Vegetation Index (NDVI) or derivates. The NDVI standardizes the difference between the near infrared and red portions of the electromagnetic spectrum, whereas chlorophyll reflection is maximal in the near infrared and minimal in the visible red. Therefore, vegetation indices provide a measurement of healthy green vegetation density convertible to biomass. Biophysical parameters including Leaf Area Index (LAI) and Fraction of Absorbed Photosynthetic Active Radiation (FAPAR) indicate vegetation coverage and phenological state. Airborne hyperspectral remote sensing reveals non-green vegetation, using specific wavelengths in the short-wave infrared. While sensors with high temporal global coverage facilitate time series analysis, satellites with very high spatial resolution or hyperspectral sensors allow conclusions about ground vegetation distribution, i.e., dispersed or contracted vegetation—an important criterion for deserts.

Pedological indicators encompass soil properties showing changes in soil carrying capacity and top surface layers. Detailed surface characteristics such as grain size, litter, salt, carbon, or iron can be sensed with airborne hyperspectral instruments. High spatial resolution images might depict erosion features such as gullies or arroyos. Remote sensing in the microwave portion of the spectrum penetrates vegetation and the uppermost surface layers, yielding information about soil texture, soil moisture, and salinity.

Morphological processes in semiarid and arid environments are characterized by catastrophic events, usually triggered through intensive rainstorms or long-lasting landfall. Wind is the other agent active in sparsely vegetated areas. Earth's morphology is mainly related to topography, which is best sensed with radar interferometry techniques since they can detect slight changes such as surface creeping, denudation processes, and dune movement.

Remote sensing of hydrological parameters for dryland detection is accomplished by a variety of instruments. Geostationary meteorological satellites record patterns of cloud cover and high water-vapor content in very high temporal resolution, commonly every 30 minutes, and even every 15 minutes with Meteosat Second Generation (MSG) satellites. Precipitation is monitored using weather satellites with sensors which can detect cold temperatures at cloud top, or passive microwave measuring techniques. The measurement of precipitation, hence water availability, allows estimates of variations in regional climate and productivity. Another important issue is surface hydrology in arid areas prone to desertification. Commonly inflow and outflow data are provided by in situ measurements. However, moderate to high spatial resolution earth observation sensors with thermal detectors facilitate calculating surface energy balances in semiarid regions while actual evapotranspiration remains as residual.

A prominent example for a desert building process caused by human activity and documented with satellite remote sensing is the Aral Sea in central Asia (figure 3-6).

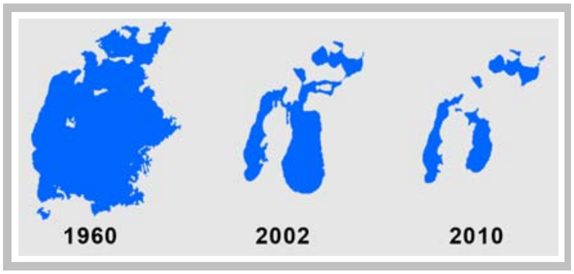

Figure 3-6: Once the world's fourth largest freshwater-fed lake, the Aral Sea has been continuously shrinking since the 1960s primarily due to intensified irrigation using water from its feeder rivers for crop cultivation. GIS bathymetry data combined with multisensor remote sensing data used to monitor the desiccation support the prediction that the present southern lake will split into an eastern and western part by 2010. The lake's salt content is increasing due to this tremendous volumetric shrinking, causing fish extinction and an end to commercial fishery. Toxic salts and dust blown from the now dried lake bottom are being deposited onto the surrounding farmland. These are just two of the many consequences of this water management disaster. The images show so-called "sea masks" which are calculated using historic map information (left), different ratios in the visible and near-infrared portion of Terra-MODIS satellite data (middle), and GIS model output (right)

Topography

Information on the earth's relief is a key parameter for almost any geoscientific analysis and for all precise land-oriented applications and planning purposes. Moreover, precise global topographic data in conjunction with GPS data can play a key role in enhancing civil flight security during bad sight conditions. To better understand what earth observation techniques can provide, we first have to discriminate between three different terms used for the digital representation of the surface topography. The Digital Elevation Model (DEM) is the least specific term and usually refers to a raster or a regular grid of spot heights. The Digital Terrain Model (DTM) describes the true shape of the bare earth terrain, while the Digital Surface Model (DSM) adds to the DTM man-made objects and the height of the vegetation canopy. Today, digital elevation models are one of the most important data applications used in geospatial analysis. Remote sensing from space has evolved into an important supplement to ground observations and aerial photogrammetry. From a global point of view it is the only practicable solution for mapping large areas.

Both optical visible and near-infrared as well as SAR data provide DEM generation capability. Several methods for elevation extraction have been developed, one of which is SAR interferometry. As depicted in figure 3-3 two SAR antennas fly on (ideally) parallel tracks viewing the earth's surface from two slightly different positions. Given the sensor locations and the two range distances R and R + ΔR, the three-dimensional position of every point imaged on the surface can be determined by triangulation. The range difference or parallax ΔR is proportional to the terrain height and inversely proportional to the wavelength of the radar. The separation of the flight paths—the so called baseline B—is small (less then 1 km) compared to the ranges R and R + ΔR (up to 800 km). Therefore, ΔR must be determined very precisely. For this purpose interferometry uses the phase information of every pixel. The interferogram provides the phase difference. It is defined by the complex multiplication of both SAR images. The evaluation of the phase difference allows measurement of the parallax to some few millimeters accuracy. The intersection point of the two range circles of the radiuses R and R + ΔR around the antennas then provides the three-dimensional position of the ground target. The Shuttle Radar Topography Mission (SRTM) of 2000 is the most prominent interferometry mission to date. The baseline B was realized by mounting the secondary antenna on top of a mast that was deployed in space to a total length of 60 m from the shuttle's cargo bay, where the primary antenna was located.

Interferometric data can also be acquired by revisit flights where one or two satellites observe the area on the ground from approximately the same orbit on two different dates. This is the ERS-1/ERS-2 situation. However, changes in the atmosphere, and in particular changes on the ground, reduce the coherence of the signals. Loss of coherence means that the signals cannot be evaluated. Additionally, the baseline needs to be known very precisely. During SRTM it could be directly measured, while for repeat pass interferometry it has to be determined from the two independent and less accurately known orbits. New concepts propose simultaneous acquisitions by two very closely positioned spacecraft or the use of passive small satellites operated in parallel to an active SAR.

Figure 3-7 shows the radar image acquired by the onboard antenna, the interferogram of both radar images and the final DEM of the Cotopaxi volcano in Ecuador (left to right). As the viewing angle of the two radar antennas is almost the same, the radar images look very much alike. Therefore, no parallaxes could be measured. However, looking at the color coded interferogram the relief is already visible. The same phase differences and range parallaxes appear along one colored fringe. It can also be seen that the distance between the fringes varies depending on the terrain slope so that they already look like elevation isolines. Within this interfero-

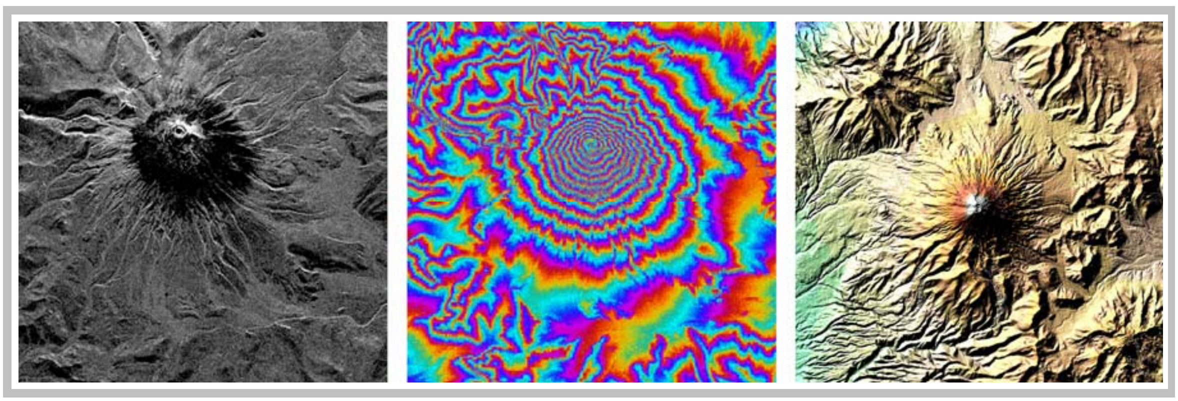

Figure 3-7: Radar image, color-coded interferogram and color shaded DEM of the Cotopaxi volcano in Ecuador (left to right)

gram the phase ambiguity has not been removed. This means that the phase difference, e.g., from yellow to yellow, is 2π or 360°. The phase unwrapping process determines the absolute phase values that will finally be transformed into the individual heights in the triangulation step mentioned above.

DEMs are also generated from optical images in the visible and near-infrared range with stereo-matching techniques. The major disadvantage is the dependency on cloud-free observation conditions, which places limits on this technology for global mapping.

Earthquakes and Volcanic Eruptions

Earthquakes occur all over the world due to plate tectonics. The Global Seismic Hazard Assessment Program has noted that a tenth of the world's population lives in areas classified as having a medium-to-high seismic hazard. Therefore, monitoring these seismic areas on a global basis is important.

For a long time seismology provided the only way to study continental earthquakes. The development of new earth observation techniques has expanded the capability of scientists worldwide to monitor earthquakes using satellites. Besides spaceborne high resolution optical sensors (Ikonos, QuickBird), a variety of sensors measure wavelengths of energy that are beyond the range of human vision, for example ultraviolet, infrared, and microwave. A great contribution is made by Synthetic Aperture Radar interferometry (InSAR), which was first applied to map co-seismic displacements during the 1992 Landers earthquake in California. An interferogram was constructed by combining two SAR images acquired by the ERS-1 satellite before and after the earthquake. The interferogram of this region shows at least 20 fringes (lines of the same phase differences) representing a displacement of up to 560 mm. The range from the ground surface to the satellite agrees well with field measurements and dislocation models. These remote sensing observations initiated a new era of hazard monitoring. Since then, InSAR has been used to map displacements resulting from some 30 earthquakes (figure 3-8). For comparison, conventional surveying techniques had detected the deformation of less than 15 earthquakes before 1992. Conventional observation techniques have some limitations. A network of digital creep meters

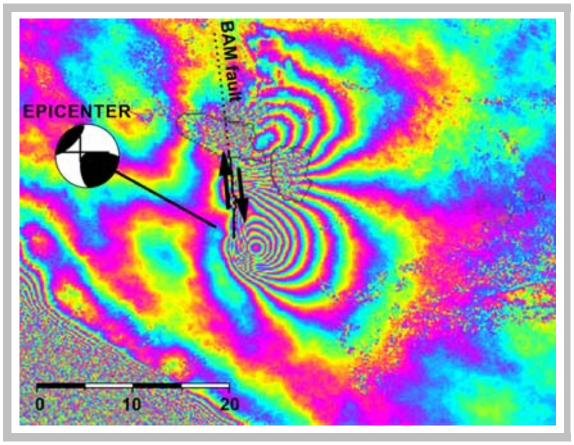

Figure 3-8: Differential radar interferometry can be used to map very small displacements of the earth's surface. This displacement map, derived from Envisat ASAR data provided by ESA, shows co-seismic surface displacements during the December 26, 2003 earthquake in Bam, Iran. Each color cycle (fringe) corresponds to 28 mm relative motion in the line-of-sight direction of the satellite. Such displacement maps help to further understand fault mechanics and the earthquake cycle and may in the future help to better predict the probability of an earthquake

has to be installed for reliable monitoring. Differential interferometry in comparison has high spatial resolution, millimeter measurement precision (Colesanti et al. 2003) and covers a large area (typically 100 km x 100 km for a single image). These advantages of the InSAR methodology have the possibility to overcome the limitations of conventional measurements. Furthermore, many of the last decade's significant earthquakes occurred on faults that had not previously been known to produce large earthquakes (e.g., Northridge, California, 1994; Kobe, Japan, 1995; Athens, Greece, 1999). InSAR helps to improve understanding of earthquake mechanisms and has a better predictive capability with respect to the seismic shock and occurrences of earthquakes. Remote sensing techniques can thereby support better hazard mitigation.

Another advantage is the possibility to observe areas that are dangerous or difficult to access, like volcanoes, without putting field crews at significant risk. There are about 1,000 potentially active volcanoes in the world and it is not feasible to monitor all of them with ground-based methods. For the purpose of studying volcanoes, remote sensing is the detection by a satellite's sensors of electromagnetic energy that is reflected, radiated, or scattered from the surface of a volcano or from its erupted material in an eruption cloud. Different sensors provide different types of useful information. Hyperspectral optical sensors can detect plant dieback on the volcano's surface due to gas effusions, for example, permitting conclusions about volcanic activity. Thermal infrared sensors can detect hot spots in the summit crater or along the flanks of the volcano's edifice, indicating new volcanic activity. SAR interferometry can provide coverage over the entire deforming region around an active volcano. Detailed spatial coverage often gives clues to magma migration and other underground processes, leading to improved understanding of the volcanic processes concerned. The most promising application of radar analysis to volcano hazards might be the detection of pre-eruptive ground deformation due to magma migration.

Mount Etna, the largest volcano in Europe and one of the most active in the world was often the target of remote sensing research. Lundgren et al. (2003) observed the volcano from quiescence in 1993 through the initiation of renewed eruptive activity in late 1995 until 1996 by analyzing interferograms. He evaluated the vertical and horizontal components of the displacement field and detected an onset of sliding coincident with a new cycle of volcanic activity. Field measurements confirmed that the displacements started simultaneously with the volcanic activity.

Soil and Mineral Exploration

Terrestrial life depends to a large extent on the fragile crust of soil that coats the land surface. Just a single inch of soil can take centuries to build up but, if mistreated, it can be blown and washed away in a few seasons. Remote sensing techniques can be used to estimate important factors characterizing soil type and functioning: mineral composition, soil moisture, organic matter content, and soil texture.

The penetration depth of radar waves in the soil crust is related to its moisture content and thus SAR systems can be used to derive this parameter. On the soil reflectance spectra recorded from optical systems, soil moisture differences cause different brightness levels. The mineral composition of soils also affects the reflectance spectrum. Depending on the amount of important soil minerals such as iron oxides, clay minerals, carbonates or gypsum, diagnostic absorption features show up in the reflectance signature of soils that can be measured with spectroscopic methods.

Soil mineral composition, organic components, and moisture content determine to a large extent the possible land use forms and consequently the productivity of arable lands in all climates. Particularly semiarid ecosystems providing important land resources for adapted agricultural production and grazing systems are often at risk due to climatic change and land degradation dynamics. With increasing aridity good irrigation practices become especially important, otherwise free carbonates and salts will ascend with the water table due to capillary action. The consequences are salinization of the soil crust, reduced productivity and ultimately abandonment of previously arable lands. All of the key parameters characterizing (semi-)arid soils such as high concentrations of carbonates, soluble salts and, depending on the parent substrate, SiO_2-rich components in the upper soil horizons can be identified with remote sensing based imaging spectrometry. Thus, based on information derived from remote sensing, land use practices can be adapted leading to sustainable use of the soil crust.

Remote sensing techniques are well-established tools in mineral exploration. The methodology focuses on the specific information necessary to discover mineral or hydrocarbon deposits: knowledge about the geological rock formations and the structure surrounding a deposit, and the abundance of key indicator minerals. Generally, geologic structures and mineral alteration patterns can be quite vivid on satellite imagery. Subtle "color" variations that would go unnoticed on the ground can be made quite bold using the different spectral measurements modern satellite data provide. SAR is especially useful for obtaining topographical information and drainage patterns, particularly in tropical forests or other densely vegetated areas. For humid climates often under heavy cloud cover, spaceborne SAR systems provide excellent additional capabilities for base mapping and for structural and tectonic analysis of many newly attractive exploration regions. Geological mapping based on the use of multispectral optical sensors such as the Landsat (Enhanced) Thematic Mapper, (E)TM, has strongly increased the potential for finding new mineral resources and simultaneously helped reduce the investments necessary for classical mineral exploration based on field geology, core logging and ground based or airborne geophysical methods.

Hyperspectral optical remote sensing makes use of the unique spectral characteristics of many alteration and rock-forming minerals that can be recorded remotely. Information extraction algorithms have been developed that make specific use of diagnostic absorption features of minerals to allow their remote identification and even an estimate of their relative abundance (Kemper and Sommer 2003), see figure 3-9 (top). The interpretation of such mineral abundance maps can make a significant contribution to the field of exploration geology. Especially altera-

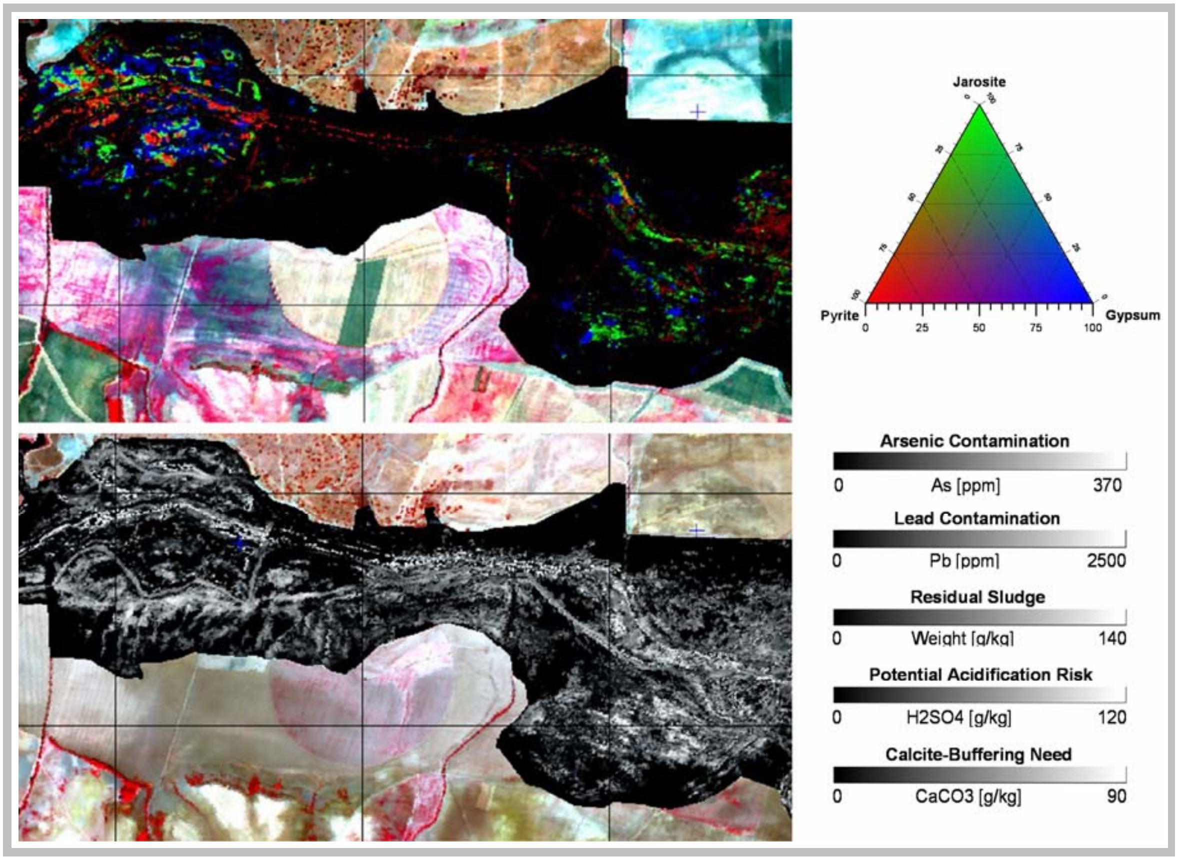

Figure 3-9: (Above): Pyrite, a mine waste material, contaminated the Guadalquivir River after a 1998 mining accident. When exposed to the atmosphere it transforms to jarosite, producing considerable amounts of acidity in the process. Lime was used during the clean-up activities to neutralize the acids, producing gypsum. Pyrite, jarosite, gypsum and other minerals produced during the oxidation process can be identified and quantified using satellite or airborne imaging spectroscopy techniques and presented in a form that can be understood by environmental officers and used directly in the remediation process. (Below): Poisonous contaminants such as arsenic and lead usually leach out of the surroundings under acid conditions. It is possible to determine the levels of these contaminants from the minerals mapped (top) since they are an indicator of acidity. The data were acquired with the HyMap™ sensor in 1999. The affected area is the black part of the image. It was superimposed on a false-color image of the surroundings for better orientation. (Source: Thomas Kemper, used by permission of JRC)

tion minerals such as clays are of interest to the exploration and mining industry because of their potential association with occurrences of precious metals such as gold or silver. In arid or semiarid regions, where the vegetation cover is sparse, airborne hyperspectral sensors have been used for detailed mineral mapping and have led to the discovery of gold or diamond deposits. Currently, efforts are being made to bring the methodology to an operational level for use by the exploration industry. Initiatives towards hyperspectral capabilities in space are being taken in USA, Germany, Canada, Australia and Japan.

Compositional mapping has long been the dream of geologists since it focuses on fundamental geological attributes, not just pictures of the terrain. Data collected by airborne hyperspectral spectrometers have already been used to demonstrate that it is possible to identify certain types of exposed minerals, to automatically label them, in some cases to determine their chemistry, and to ascertain the fractions of the minerals occurring in small, sub-pixel units. Thus a new type of map, a mineral map, is helping explorers home-in on zones of mineral alteration around mineral deposits, detect previously unrecognized mineral patterns across whole mineralized districts, document mineralogical components of the weathered regolith, and locate waste products such as the sulphate minerals which cause acid mine run-off from mine tailings.

Pollution

Ecosystems and their components have been considerably affected, and in some cases destroyed, as a result of many decades of human economic activity and increased consumption of natural resources, particularly in the industrialized countries. Causes are the introduction of harmful matter into the ambient air or water bodies, where they can be further distributed by such forces as wind or currents, or the direct deposition of harmful substances onto the land surface (garbage, industrial waste, sewage). Common catchwords characterizing the consequences are forest death, acid rain, land contaminated with inherited toxic waste from now-defunct refineries, factories or military installations, heavy metals in rivers or garbage dumps, the eutrophication of lakes or the pollution of agricultural land by overfertilization (primarily nitrates and phosphates). We could add the sometimes very considerable poisoning of the environment caused by accidents in the chemical industry, such as the Sandoz catastrophe of 1986 when water used by firefighters flushed huge amounts of pesticides into Europe's busiest waterway, or in mining (the 1998 contamination of the Doñana wildlife reserve in southern Spain after the collapse of a retention dam for mine tailing slurry loaded with poisonous heavy metals from the Aznalcóllar iron mine upstream, see figure 3-9.

The measuring approaches described at the beginning of this chapter and the unique advantages of remote sensing predestine earth observation as a supporting tool for locating many cases of environmental pollution, analyzing the processes at work, and monitoring the consequences. One cannot usually detect the contamination itself with remote sensing of the surface from space. Exceptions are perhaps open ground with surface contamination by highly concentrated materials that can be identified in hyperspectral optical data on the basis of their unambiguous spectral behavior, like hazardous military waste (Dech and Glaser 1993). In general, indirect evidence is used, for example, observing stress symptoms in vegetation (leaf yellowing or dieback) or algal blooms in inland waters. Besides the spectral analysis of surfaces under environmental pressure, change-detection procedures are especially suitable. They provide for every pixel in an image a measurement of changes occurring between observations. Thus, regular repeated mapping of potentially endangered areas can reveal changes in ecological constraints, or suspicious deviations from normal spectral behavior, which may hint at pollution. Ground samples can then be collected on location and the cause for the spectral changes investigated.

In addition to these quantitative and statistical approaches, earth observation data can be consulted at short notice for information about the affected surfaces, both during an environmental catastrophe for purposes of limiting damage, or later for ecological mapping and monitoring of contaminated areas.

3.3.2 The Oceans and the Cryosphere

Over two thirds of the earth's surface is covered with water, in the polar regions some of it in the frozen form of sea ice. In addition, an entire continent, the Antarctic, as well as Greenland are covered with huge ice shields containing about half of Earth's fresh water inventory. The oceans and the cryosphere profoundly influence the climate, on the global level (both as a sink and a source of carbon) as well as on the regional level (consider the effects of warm ocean currents like the Gulf Stream). They are also important tracers indicating global climate change, admittedly with long reaction times, similar to the situation in the atmosphere. Sea surface temperature, ocean height, sea ice thickness and extent and amount of fresh water entering the oceans as a result of glacier or shelf ice calving are important evidence of global climate change. The oceans are also one of mankind's economic areas; whether for the food supply, as transport medium, or as a renewable energy source. Large-scale, continuous, objective measurement of parameters relevant for the processes occurring in the oceans and cryosphere is one of the pillars of earth observation, making monitoring and scientific analyses possible. The data are also used to optimize the economic exploitation of the oceans (fishery), to monitor ecological changes (algal blooms), to increase the safety of ship traffic (wave heights and direction) and to plan off-shore wind energy converters (wind speeds). In both realms we are talking about a two-sided coin; the basic processes can be used for good or ill, as with all technologies. Being able to locate fish can lead to aggressive overfishing, for example. And indeed, most of the sea surface temperature maps generated primarily for climate research are popular with the fishing industry because of their usefulness in optimizing fishing fleet harvests.

Sea Surface Temperatures

Sea surface temperature (SST) is an important geophysical parameter because it provides the boundary condition used to estimate heat flux at the air-sea interface. As the most widely observed variable in oceanography, SST is used in many different studies of the ocean and its coupling with the atmosphere. Mapping SST makes it possible to find out, for example, where water is cold or warm enough for certain species, where currents are carrying water, where storms gain energy from the ocean or where ocean mixing is happening. On the global scale this is important for climate modeling and study of the earth's heat balance, and gives insight into atmospheric and oceanic circulation patterns and anomalies. On a local scale, SST can be used operationally to assess eddies, fronts and upwelling, and to track biological productivity. Over the long term, SST data can be used to study annual shifts in ocean currents and temperatures. SST data are also crucial to understanding periodic phenomena (like El Niño) and long-term climate shifts attributable to global warming.

Although a key parameter in many scientific fields, SST is difficult to define exactly because of the highly variable and complex vertical structure of the upper ocean (to about 10 m in depth) (Donlon et al. 2002). The depth at which measurements are made and the method of measurement can have a significant effect on the SST that is reported. The SST at the surface, within the top few micrometers, is termed the “skin” SST, and the SST immediately below, down to 1 m depth, the “bulk” SST. The skin SST is usually cooler relative to the bulk SST immediately below it because heat transfer is in general from the ocean to the atmosphere and the ocean loses heat to the atmosphere by molecular conductance. But during daytime, solar insolation and low wind speeds can cause increasing skin SST, while the bulk SST is relatively free of these effects.

There are two main sources of SST measurements: in situ and satellite. Traditional in situ observations are direct temperature measurements made from ships and buoys, whose ranges are limited. Satellite remote sensing by contrast makes possible a synoptic view of the ocean allowing the examination of basin-wide upper ocean dynamics as well as measurements of a given area several times per day. Methods for determining SST from satellite remote sensing include thermal infrared and passive microwave radiometry; both methods have their strengths and weaknesses. Thermal techniques are the most accurate and have the best resolution, but require cloud-free conditions (figure 3-10). Microwave approaches have the great advantage of being able to

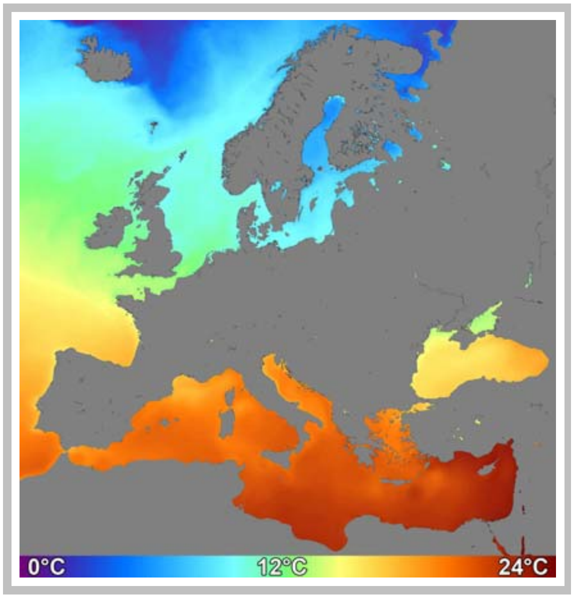

Figure 3-10: Since 1993, multitemporal SST maps (composites) have been compiled at DLR based on thermal infrared AVHRR measurements. Products are generated in a daily, weekly and monthly fashion, which allows enough time to capture cloud-free pixels for the entire region. This unique image averages SST data for the European seas over the ten years from 1993 to 2003 and was derived from monthly AVHRR composites. In total, roughly 18,000 AVHRR images were analyzed to calculate this data set which serves as a climatological reference from which temperature anomalies can be easily detected

measure under all weather conditions excepting rain, because the radiation at these longer wavelengths is largely unaffected by clouds. In either case the radiometer measures radiation over a number of finite channels. For any radiance measured within a specified wavelength window, there is an associated temperature (called the brightness temperature) which can be determined by ascertaining at which temperature a blackbody would emit the same radiation. The emissivity of an object is the ratio of the amount of radiation emitted by the object to that of a blackbody at the same temperature and wavelength. Therefore, knowing the brightness temperature and the emissivity of the ocean surface allows determination of SST. Various algorithms exist for converting radiance to SST (McClain et al. 1985, Wentz et al. 2000). Because satellite sensors can only measure the skin SST, the retrieval algorithms are tuned against in situ bulk temperatures from ships and buoys in an attempt to determine a "pseudo-bulk" SST. The best satellite-derived SST absolute accuracy possible today is on the order of 0.3 to 0.6 K.

Topography and Currents

Before the first oceanographic civil radar satellite (Seasat, operating in L band in the 30 cm wavelength range) was launched in 1978, many scientists, including radar experts, doubted that its images would show ocean waves. A new quality of sea state measurement capabilities was demonstrated when the Seasat images not only showed ocean-wave-like structures in general, but very distinct features of ocean waves, internal waves and bathymetry. Further, it could be shown by their direction and wavelength that these waves could be traced back to the storm centers that had generated them.

When ERS-1 was launched 13 years later, SAR images of ocean waves started to become available on a regular basis. They yield high resolution two-dimensional images of the radar backscatter properties of the sea surface and can thus be used to measure wind fields and sea state from space. Sea surface features, spatial variation of wind speed, rain, current and motion of the sea surface all have imaging effects which can be used to derive directional ocean wave spectra, revealing wave height, wavelength (the distance from wave crest to wave crest) and the direction the wave is propagating. This information is important input for improving wave model predictions. Other information can be gathered from the radar images directly, like individual wave height, crest length and grouping of ocean waves. Thus the distribution of maximum wave height can be investigated globally, or wave refraction and diffraction in coastal areas can be studied in detail (figure 3-11).

These results of basic research efforts are starting to bear fruit in practical applications. There is now 12 years' worth of global ocean wave measurements that can be analyzed for decadal variations. ERS image mode data (100 x 100 m coverage at 30 m resolution) show wave refraction and wave reflection at coastlines and are being drawn on for coastal applications like offshore wind farming or oil well siting, coastline detection, current feature determination, and ship and harbor safety considerations. ERS

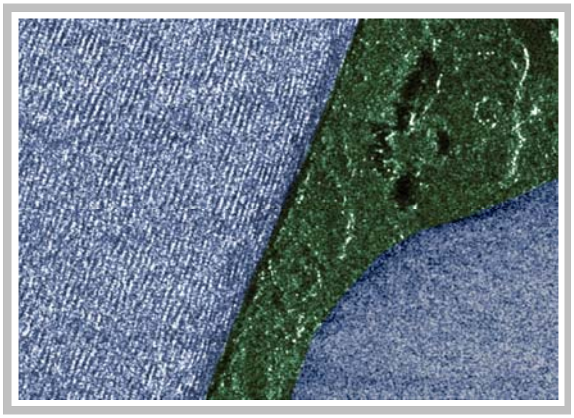

Figure 3-11: The potential of SAR data for providing directional ocean wave information and topography is illustrated in this ERS-2 SAR image of an area about 10 x 7 km in size. It was acquired over the north tip of the island of Sylt in the North Sea on 15 Oct. 1998, 10:06 UTC. Ocean waves of about 100 m wavelength are approaching the coast. As they get closer to the shoreline their wavelength becomes shorter

wave mode data (5 x 10 km coverage at 30 m resolution acquired once every 200 km along the satellite track) are used for detecting sea surface features, sea ice, storm tracks, the propagation direction of ocean waves and wave groups, and for measuring high individual ocean waves, as well as to improve sea state forecasts at weather centers by assimilation of satellite SAR spectra. An improved wave mode became available with the Advanced SAR (ASAR) on Envisat, making it possible to acquire images every 100 km along the satellite track; some 2,000 are in the meantime available per day as a standard data product.

Primary Production

Primary production is the process of building up plant tissue by photosynthesis. For the oceans and other waters phytoplankton species are the dominant primary producers, converting inorganic material (nutrients) into new organic compounds through photosynthesis. The production of phytoplankton starts the marine food chain and is thus one of the most important and basic processes for marine life in general (Lalli and Parsons 1993).

Another aspect is the consumption of carbon dioxide (CO_2) by photosynthesis. Recent estimates equate the total amount of CO_2 fixation by phytoplankton in the global ocean to the amount fixed by the entire rain forest. Although the mechanisms of marine primary production, drivers and limitations differ from those for terrestrial primary production, and although the CO_2 fixation is compensated to some extent by respiration, it is still a significant factor for the balance in the global CO_2 cycle.

Primary production by phytoplankton is a process which cannot be accessed by remote sensing techniques alone. A description and determination is only possible using biophysiological models involving a complexity of different parameters, such as: species, abundance and vertical distribution of phytoplankton in the water column, availability of nutrients (e.g., nitrate, phosphate) as well as physical parameters and processes (temperature, available light, currents, turbidity in the water, vertical mixing) and more. Due to this complexity there is no generic, globally applicable model to derive primary production on a global scale, ranging from various coastal ecosystems to large basins and the global open ocean. Hence, up to now assessment of global marine primary production remains an estimate with a significant level of uncertainty.

Earth observation is the ideal technique to provide a number of essential parameters in time and space for model computations on different scales (Platt and Sathyendranath 1988):

- Surface chlorophyll concentration, representing the biological state with respect to phytoplankton;
- Turbidity of the water column;
- Sea surface temperature (SST);
- Photosynthetically available radiation (PAR);
- Wind, waves and currents as driving forces for physical processes in the water column.

The focus here is on chlorophyll and turbidity since the other parameters have already been discussed above. After passing through the atmosphere, sunlight penetrates the water body, where some portions of the light are absorbed and some are scattered by water molecules or particles in the water. These absorption and scattering processes determine the wavelength composition (spectrum) of the light remitted from the water body or, in other words the “color” of the water. Pure water itself almost totally absorbs at wavelengths below about 400 nm and above 750 nm. For this reason only the wavelength range between these two borders may be used to look into the water body (the visible and near infrared spectral range). Three main water constituent groups additionally influence the spectrum: the phytoplankton, showing scattering due to its cell structure and absorption due to pigments, unpigmented suspended or particulate matter showing scattering, and dissolved organic matter showing typical absorption behavior. Each component may be characterized by its specific spectral optical properties.

For the open oceans phytoplankton and covarying components are the dominating constituents in the water. As its major part contains chlorophyll-a as pigment, the concentration of chlorophyll-a is used to characterize phytoplankton abundance in the water. Since chlorophyll is a direct measure for the ability to perform photosynthesis, it is an essential parameter for the calculation of primary production. Pigments other than chlorophyll (e.g., carotenoid) which also play an important role are accounted for by special correction procedures.

In coastal zones or closed basins the situation is more complicated than in the open ocean: in addition to phytoplankton the water here mostly contains other suspended material (e.g., sediment) and dissolved organic matter (e.g., humid acids). These components may vary independently of the phytoplankton and therefore need to be treated separately.

With respect to water constituents remote sensing uses the measurement of the light spectrum remitted from the water body (ocean color) in the visible and near-infrared spectral range by imaging radiometers or spectrometers.

Knowledge about the specific optical properties of the different water constituents is used to calculate maps of concentrations for chlorophyll, suspended matter and dissolved organics (figure 3-12). Knowing the concentrations, one is able to calculate the extinction of light in the water body, and therewith turbidity, which is a measure for the penetration depth. Both parameters are essential inputs for models estimating the primary production.

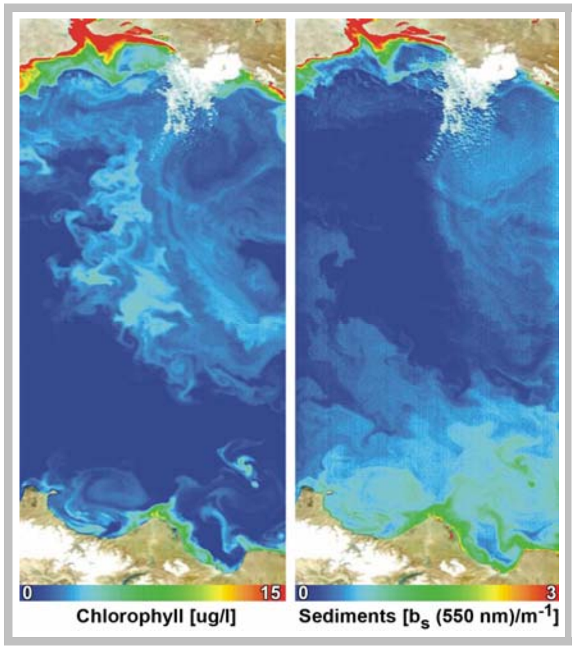

Figure 3-12: Algorithms making use of different channels of the MOS sensor can reveal in a single image two different kinds of phytoplankton blooms in the Black Sea: the presence of chlorophyll (left) or sediment produced by lime-depositing or calcareous algae (right)

Sea Ice and Polar Ice sheets

As polar regions are particularly inaccessible to regular monitoring from the ground, satellite images provide the most important spatial data source for scientific evaluation at different scales. Due to the orbit characteristics of polar orbiting satellites, scenes of neighboring orbits widely overlap, which leads to excellent scene coverage for most polar regions. Important information about the cryosphere is derived from instruments acquiring images in visible, infrared, and passive microwave wavelengths, but also from active radar sensors.

Large portions of the polar and subpolar oceans are covered with ice year-round. For all of Earth's oceans taken together, about 5% is covered with ice in March; in September the figure is some 8%. Temperature and salinity determine when seawater freezes; usually not above -2 °C.

Depending on age and compression, sea ice can become remarkably thick, up to about 12 m. In the

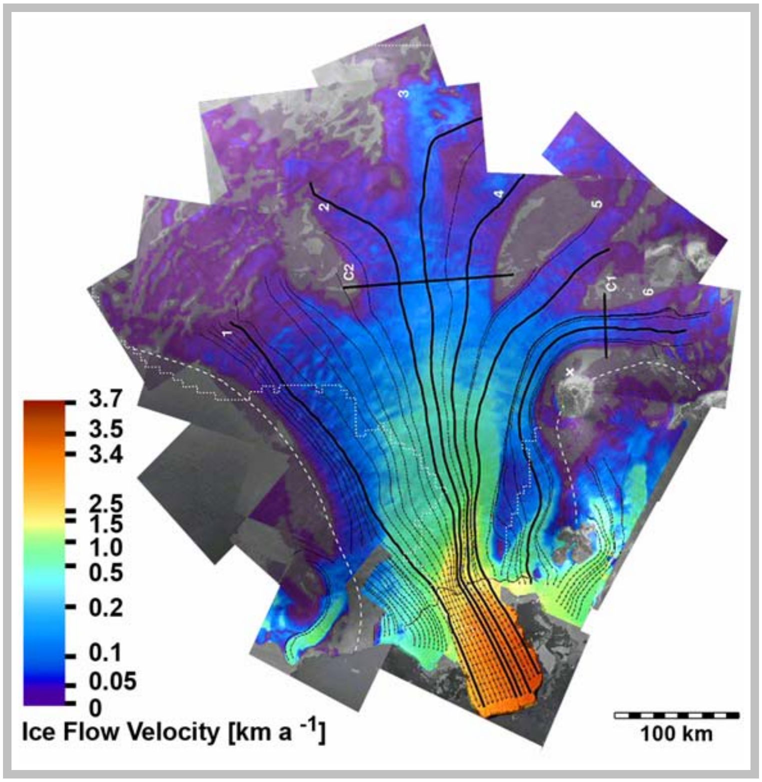

Figure 3-13: Interferometrically derived two-dimensional surface velocity map of the Antarctic Thwaites Glacier. The glacier was mapped with 45 interferograms based on data collected between 1995 and 2000 by the ERS-1 and -2 satellites. Topographic phase contributions were eliminated with a coarse external DEM. The velocity map covers almost 180,000 square km and comprises more than 80 percent of the glacier's catchment. Six individual tributaries were identified; their center-line velocities increase from 0 at the catchment boundary to some 0.3 km per year when they join the main glacier trunk. Velocity increases up to 3.6 km per year on the floating tongue. This value indicates that Thwaites Glacier is one of the fastest moving ice streams in the world

Arctic Ocean the average is 3 m, near Antarctica only about 1 m. Depending on how dirty the surface is, sea ice has a very high albedo (between 0.6 and 0.9). Up to 90% of incoming solar illumination is accordingly reflected back to space from this light surface. As a consequence, sea ice has the effect of an energy sink and therefore plays a significant role in the climate system. Sea ice also acts as a layer of insulation preventing heat exchange between the relatively warm ocean (-1˚C) and the colder atmosphere. (-30˚C). Over sea ice the atmosphere is much colder than it is over the open ocean. Sea ice also influences the oceans by facilitating the production of deep water. Ocean water has an average salinity of 34‰, sea ice only about 5‰. When sea ice freezes it releases to the ocean a considerable amount of salt, which makes the surface water heavier, causing it to sink down to deeper ocean levels. This dense, heavy, deep seawater generated in winter in polar regions drives oceanic thermohaline deep circulation. For such reasons monitoring the formation and extent of sea ice is an important aspect of climate research, and remote sensing technology has been contributing to this effort for the past three decades by recording the dynamic process of sea ice expansion and contraction. Besides being used for sea ice research, satellite data on sub-polar waters is in high demand as reliable information for vessels at sea (ice floes and iceberg warning).

Optical sensors, passive microwave radiometers and radar systems of a variety of designs are utilized, during polar night especially radar or thermal infrared sensors such as AVHRR on NOAA satellites. The reliable data on sea ice extent based on earth observation data available since the 1970s reveal that the ice cover increased in the mid-1970s, followed by a noticeable decrease between 1978 and 1990. Since that date the situation has remained fairly constant. In the Antarctic surface ice dramatically decreased in the 1970's and has been slowly increasing since 1980 (Eicken and Lemke 2001). The significant global warming of air temperatures observed since the 1990s has not yet had an effect on the extent of sea ice in either polar region.

Whether it has had an effect on sea ice thickness is one of the burning issues of climate research. Remote sensing techniques are being developed to estimate the age of sea ice by measuring its thickness with optical and passive microwave instruments.

Satellite images are used to investigate changes in large Arctic and Antarctic ice shelves as well as to track the drifting of icebergs and monitor glaciers (figure 3-13, Lang et al. 2004). In January 1995, 4,200 square kilometers of the northern Larsen Ice Shelf on the Antarctic Peninsula broke away. Satellite images, complemented by field observations, showed that the two northernmost sections of the ice shelf fractured and disintegrated almost completely within a few days. This break-up followed a period of steady retreat that coincided with a regional trend of atmospheric warming. The observations imply that after an ice shelf retreats beyond a critical limit, it may collapse rapidly as a result of perturbed mass balance. Calving of large portions of a polar ice sheet is a regular process. The broken parts sometimes reach the size of small countries and drift for many years in the polar sea. In order to prevent collisions with ships, icebergs are permanently monitored using satellite images supplied by various sensors. Images and information are regularly updated and are accessible via the Internet (Web: National Ice Center).

Off-shore Wind Farming

Because of a shortage of suitable sites on land, wind farms (arrays of turbines rotated by wind-catching blades and thereby converting wind energy to electrical energy) are increasingly moving offshore. So far about 280 MW_e of power has been harvested by offshore installations in the North and Baltic Seas, advantageous locations because their shallow waters and high mean wind speed promise a vast potential for wind farms. In the near future wind farms with over 100 wind turbines and an output of over 5,000 MW covering areas over 200 square km are planned or already under construction (Web: North and Baltic Seas). The largest wind park in operation is Horns Rev situated in the North Sea on the west coast of Denmark, where 80 wind energy converters are producing 160 MW_e. Looking at the global picture, wind energy is about to replace hydropower as the most important commercial source of clean, renewable energy, with Europe as the main market and leading operator.

An innovative application for earth observation technologies for all those interested in tapping this energy source is based on the fact that active microwave radar instruments transmit and receive radar signals with wavelengths in the range of a few centimeters to one meter, making them suitable for measuring the roughness of the sea surface, and thus determining ocean wind and wave fields. It has been demonstrated that SAR systems can provide information about the wind across areas up to 500 x 500 km in size (nearly the entire North Sea, for example) at resolutions down to 100 m (Horstmann et al. 2002). Techniques developed to measure wind fields in coastal regions are relevant for offshore wind farming, since local wind speed is the key parameter for estimating the generating power of a wind farm (power output is in a first approximation proportional to the cube of the wind speed). Wind turbines are usually operated at wind speeds between 4 and 25 m per sec. In the range of interest, even small uncertainties about what is the average wind speed result in big differences in the estimated energy output. For this reason, offshore wind farming requires high resolution regional operational forecasting of meteorological and ocean conditions, with earth observation technologies playing a significant role.

Determining wind fields with SAR is typically a two-step process. In the first step, wind direction is determined, a necessary input for the second step, which is to obtain wind speeds from the intensity values recorded as the wind-roughened ocean surface was imaged by the SAR. Wind direction is determined by identifying wind-induced phenomena aligned in the wind direction, which are usually visible in SAR images.

Wind, hail, strong rain or surface slicks change the roughness of the ocean surface and thus the intensity of the SAR image, and accordingly what speed is calculated. But wind directions can also change, as for instance within an atmospheric front. In addition, areas with ocean current shear can show a pattern in the scale of wind streaks that can be misinterpreted as the wind direction. To avoid the influence of such features not due to the local wind, complementary wind measurements have to be considered. Depending on the specific application (optimal siting of the wind farm or optimization of the wind farm design at a given site) these are either obtained from atmospheric models or in situ measurements.

Since SAR images have been acquired over the oceans on a continuous basis by radar systems on the ERS and Envisat satellites for the past 12 years, it is possible to compare current and historic data. This exercise yields valuable information for site planning. Relevant geophysical parameters are mean wind speed and direction, wind variability (changes over time in wind direction, speed and intensity), and turbulences induced by individual wind turbines and by the entire wind park taken as a whole (which affect output and can damage equipment).

Optimal siting means not only optimizing the power output but also minimizing the impact of wind parks on the environment. SAR data gathered from ERS, Envisat, and Radarsat sensors enable investigation of changes in wind field due to the presence of wind turbines, such as turbulent wakes and blockage effects in front of the wind farm, as well as ocean surface wave fields, all of which are of environmental relevance. Although some studies have been made on the effect on birds and fishery, no joint studies have been undertaken on how this new technology can be assisted by operational wind forecasting. The situation is similar with respect to the offshore oil industry.

Pollution

The generic term pollution refers to a broad variety of substances and the mechanisms that bring them into marine environments, including all influences which change marine ecosystems (open oceans, coastal waters, sea bed) in a manner causing harm or threat to flora and fauna or people, as well as pollution from waste material in general. Most sources of pollution are caused by human activity. However, there are also some natural processes causing marine pollution, such as oil seepage from the ocean floor. Earth observation offers a variety of ways to detect and monitor all the main categories of marine pollution:

- *Air pollution* due to fuel burning and industrial combustion places significant amounts of problematic substances (hydrocarbons, nutrients, sulphur oxides) into the oceans, either through rainwater or by runoff from land.
- *Drainage and runoff from land and rivers* can be polluted by agriculture and farming activities (nitrates, phosphates) and industrial waste. These substances are transported into coastal waters through surface water runoff, groundwater or rivers.
- *Dumping, leakage and accidents* on ships or marine platforms put large amounts of oil and other chemicals as well as bacteria and other invasive species into ocean waters; marine oil disposal and bilge water flushing are common.
- *Aquacultures* may cause overloads of nutrients or organic waste material on local or regional scales.

Pollutants can be detected by remote sensing technologies if they change either the optical properties (color), surface roughness, or temperature of the water. Since chemicals (nitrates, phosphate, toxic acids) are dissolved in the water and most bacteria do not show specific optical properties, these components may only be detected by in situ biochemical analyses. However, the spread of substances discharged by rivers can be traced and monitored by the suspended matter to which they are bound. Suspended matter is a water constituent which can accurately be accessed by optical remote sensing instruments.

Oil slicks (from tanker leaks or dumping) and natural surface slicks (extreme algal blooms) flatten the roughness of the sea surface by changing the surface tension of the water and thereby the properties and occurrence of capillary waves, which can be precisely detected by radar imaging. However, it is only possible to detect the occurrence and areal distribution of such spills, not the abundance of oil in total. This can only be done by specially equipped airplanes.

Biological "pollution" in the form of invasive species or harmful algal blooms is a phenomenon of growing importance. Worldwide shipping introduces through bilge water dumping alien species of bacteria, algae, macroalgae and macrophytes into basins far from their natural occurrence. Changing ecosystem conditions (nutrient enrichment, warming) may support the invasion of these species into new habitats, which may cause damage to native species or fish schools and disrupt entire ecosystems.

Instruments primarily designed for scientific research open up the possibility of operational detection and monitoring of pollution in the oceans from space. Before this can be achieved, however, optical and radar systems have to be merged to obtain the most useful data, and if long-term monitoring capability is the goal, dedicated operational systems will have to be put in place.

3.3.3 Security, Disaster Management and Humanitarian Aid

One can readily come up with a long list of disasters for which the vantage point of a satellite might be desirable, even critical: pollution on land or sea, floods, tsunami, hurricanes, storms, droughts, failed harvests, desertification, erosion, fires, earthquakes, volcanic eruptions, landslides, wars, terrorist attacks, refugee migrations, and technological disasters, not even to mention the sometimes horrendous results of incompetence, ignorance or criminal negligence leading to bad construction, engineering and siting, or errors of judgment. All too often daily news broadcasts confront us with the depressing consequences, whether they be to persons, property, infrastructure, the environment, the economy, or even to the very social order. This is not the place to speculate on the causes, and as a matter of fact earth observation technologies cannot themselves hinder the natural processes, looming crises or military conflicts that undergird such catastrophes. What they can do, in many different ways, is help increase safety and security by contributing to the early recognition of potential problems, in some cases even predict approaching catastrophes, monitor an ongoing crisis, assess damage, and contribute to the organization of relief measures during and after the event.

Earth observation can be used to record and keep track of those environmental conditions which exert a significant negative influence on human living conditions by leading to drought, floods, erosion, and scarcities. These kinds of environmental changes can quickly give rise to destabilizing economic and social problems (water shortages or failed harvests leading to poverty, hunger, health hazards and migration, for example). Interpreters of remote sensing imagery are also able to contribute to effectively monitoring international treaties, with the aim of supporting the prevention or early warning of disasters, be they environmental, political, economic or social. Satellite data can be used to generate better estimates of static (informal settlements) and dynamic (refugee migration) populations on a global scale. They can also contribute to better surveillance of borders and sensitive infrastructure like nuclear power plants, and in some cases to monitoring the proliferation of weapons of mass destruction. A new application since September 11^{th} 2001—at least in the USA—is the use of remote sensing techniques for homeland security.

Floods, Forest Fires

River valleys have always been desirable locations for human settlements. All over the world, as populations increased rivers were modified to facilitate shipping, their beds were confined, their natural catchment areas were drained and their courses were redirected. Such human intervention often exacerbates the consequences of natural flooding by permitting the flood surge to spread faster over wider areas than it would naturally do. Large scale flooding of settlements, towns, transportation routes, industrial areas, forests and crops are the damaging consequence. The 1988 Ganges-Brahmaputra flood in Bangladesh, the 2000 flooding of the Mekong in southeast Asia and of the Zambesi in Mozambique, the German Elbe floods of 2002, and the 2003 flooding of the Rhone River in France are recent examples.

Because of the temporal and spatial dimension of catastrophic floods and tsunami, it is often possible to record their effects and document their progress with earth observation technology. Both optical and radar sensors capable of recording the spatial distribution of the floodwater are utilized. Depending on the time and location of the area flooded, data from satellite or airborne sensors with their different spatial resolutions can be consulted. There are several methods to generate a water mask indicating pre-

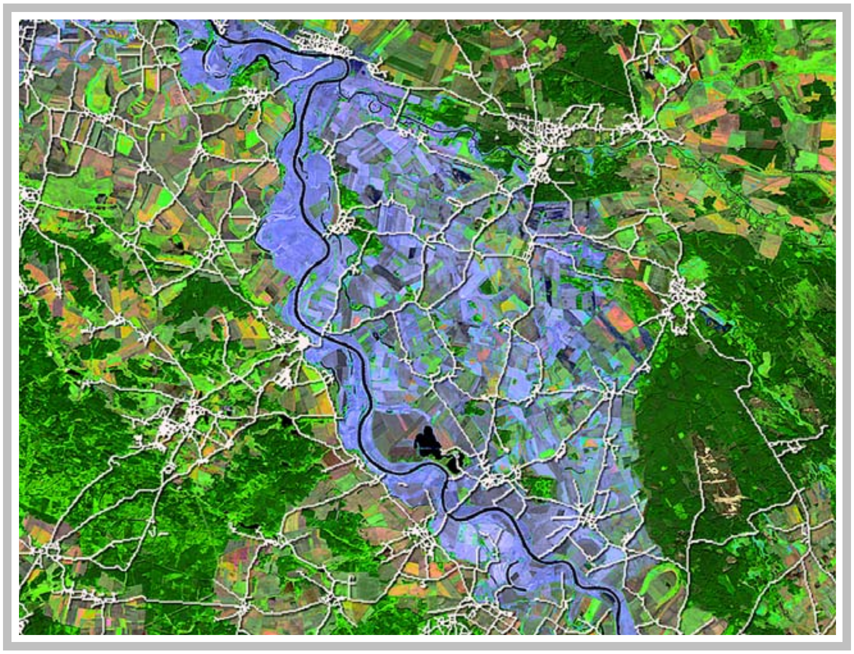

Figure 3-14: Flooding of the Elbe River near Torgau, Germany in August 2002 as seen in a Landsat image overlaid with information about the surrounding roads and settlements. The flooded areas (in lilac) were extracted using a change detection method based on two different ETM data sets, the first representing regular river level conditions, the second the situation during the flooding. As a result, a "water mask" was calculated showing the flooded areas. This mask was superimposed on the reference, permitting a view of the land structures below the water

sumably flooded areas from optical data based on calculations of the relationships and indices of different spectral channels. For example, the surface of clear water appears dark in the spectral range between 0.8 and 2.3 µm, since reflection off clear water is very low in this part of the spectrum. Flooded areas can accordingly be classified on the basis of their spectral and textural characteristics, although precisely what can be discriminated depends on the spatial and spectral capabilities of the sensor. Thermal data can be additionally consulted wherever there is a significant difference in the surface temperatures of land and water.

Computed satellite maps of flooded areas can be underlaid with traditional maps showing topography, land use, or the transportation network to produce a valuable tool for use by decision makers in crisis teams and situation centers when assessing threats or damage (figure 3-14). The ambitious precondition is timely and routine access to reliable and up-to-date data on location, ideally as soon as possible after the image has been recorded. In the context of the "International Charter on Space and Major Disasters" founded in 1999 it is possible for a limited community of users to obtain satellite data free of charge for rapid assessment of natural catastrophes (see http://www.disasterscharter.org).

In addition to spatially detailed damage assessment, early warning methodologies based on satellite data are also being investigated. Changes in ground moisture over a defined period can be analyzed with data from scatterometers for the purpose of identifying trends and developments. Since floods are not only influenced by intensive and complexly structured rainfall but also especially by the condition of the soil in the area of interest (whether the soil is dried out or soaked, for example), predictions about flood disposition can be derived from ground moisture indicators.

An intensifying problem common to semiarid regions, boreal evergreen forests and tropical rain forests alike are catastrophic fires, often resulting from human activity. One underlying cause is clearance by fire of land to be made available for agriculture. Another is the pressure to find housing for growing populations and the associated land speculation. On average, some 22 million hectares of boreal evergreen forests (Cofer et al. 1996) and 600,000 hectares of brushland and forests in the Mediterranean area are consumed annually by fire. Both the number of fires and their extent has multiplied in recent years, whereas the share of fires in-

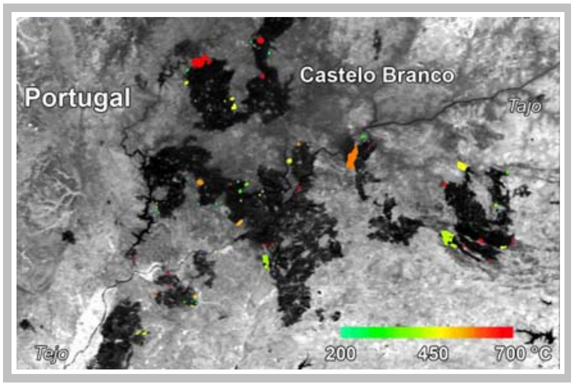

Figure 3-15: During the disastrous forest fires in Portugal of 2003, some 300,000 hectares burned, about 30 percent of the country's forests. This image of actively burning fires was recorded by the experimental DLR satellite BIRD, which detects not only hot spots, but also information about the physical properties of the fires, such as fire temperatures over a wide range above 200 degrees C (this example) and released energy. Mapping useful for setting fire fighting priorities in the field thus becomes possible. For this image the sensor's near infrared channel was used for the background grey values; the fire scars are dark. The mid- and thermal-infrared channels were used for the hot spots and reveal the fire temperatures

duced by natural causes has remained roughly the same at 1-5% of the total.

This increase, along with improvements in earth observation technology over the past few decades, led in the 1980s to fire monitoring by satellite. Near-real-time recording of actively burning fires is accomplished using satellites equipped to record channels in the mid- and thermal-infrared ranges (3-6 µm and 8-14 µm), including experimental satellites such as the DLR micro-satellite BIRD (figure 3-15). Primarily optical satellite data are used for the subsequent spatial damage assessment, whereby burned areas are classified using traditional procedures which make it possible to estimate the extent of affected area. Depending on requirements, either the extent of large fires or small-scale damage, particularly to infrastructure, can be determined.

Improving Safety at Sea

Individual ocean waves of exceptional height and shape, popularly known as rogue waves, are believed to have been the cause of significant damage to offshore constructions and the reason for the loss of many large ships at sea. For this reason, studies are being undertaken to detect, investigate and explain rogue wave phenomena (Sand et al. 1990). Plans are being made to publish in the form of an atlas the statistics which are being gathered on these extreme wave events for different areas of the ocean, together with historical information wherever the relevant data sets are available for analysis. This resource will be available to the science community, the shipping industry, marine designers and engineers, port authorities, certifying institutions, insurers and various international organizations.

For a variety of periods and geographical areas with different sea state conditions, data gathered by spaceborne SAR sensors are being combined with more traditional data from wave-riding buoys, from stationary marine radar installations on oil platforms, and from marine radar used on board container vessels for ship traffic control and navigation at sea. Whereas buoy records provide reliable information about the temporal variability of wave phenomena at a fixed ocean position, ship and platform radar systems provide spatial information on the nearby sea surface at a given time, and additionally a temporal sequence of consecutive radar sea surface images. Satellites complement the picture by observing the ocean surface continuously on a global scale, providing a synoptic picture of waves over large areas, including the less-studied vast southern oceans, and extreme events such as hurricanes. Traditional methods of analyzing radar images are being extended by new analytical approaches which exploit the information contained in satellite images for better description and proper identification of individual waves and wave groups.

Depending on the receiving mode, SAR images of the sea surface can be obtained for areas extending anywhere from 10 x 5 km ("imagettes") up to 500 x 500 km. Beyond providing a synoptic overview, they have been successfully used to derive mean sea state parameters in the open ocean. From a collection of radar imagettes for areas in the North and South Atlantic Ocean for which complementary buoy and marine radar data were also available, algorithms have been developed to detect and identify individual waves, as well as wave groups.

The sea surface images which radar systems provide are a function of many electromagnetic scattering mechanisms at the sea surface, influenced by currents, wave tilting, velocity of water particles, local wind, etc. Taken together, all these phenomena, known as radar imaging effects, yield a single radar measurement of intensity. Hence radar images contain information about how the sea surface backscatters the radar fields, rather than the wave elevation itself. Therefore, to detect individual waves, it is necessary to reverse the relationship or invert the radar imaging effects in order to obtain an estimation of the original sea surface scanned by the radar sensor, typically in the form of elevation maps. Once the wave elevation map is obtained, detection of single waves is possible, for example, by determining wave height in the spatial domain. It is also possible to trace a maximum in the elevation map through all the available radar images for a comparison of its spatial and temporal evolution.

Wave groups also play an important role in the design and assessment of offshore platforms, breakwaters or ships, because successive large single wave crests or deep troughs can cause severe damage due to their impact, or they can excite the resonant frequencies of the structures. For ships, an encounter with wave groups can sometimes cause capsize or severe damage. An extreme wave can develop from a large wave group due to interference of its harmonic components. Therefore the detection of wave groups in space and time is of high interest for ocean engineers and scientists.

Swell tracking is another type of study which can be carried out on a global scale with satellite data. All such earth observation techniques help to find empirical relationships between mean sea state characteristics and probabilities of extreme wave events. Furthermore, they help to identify hot spots and thus to improve risk maps (figure 3-16). At the time of writing, only 4,000 images for 27 days, corresponding to three weeks of data, have been processed. This data set is too small for firm conclusions, but ten years of SAR raw data are ready and waiting for processing, subsequent analysis, and comparison with complementary data of all types, thanks to the archiving around the world of an untapped treasury of satellite images.

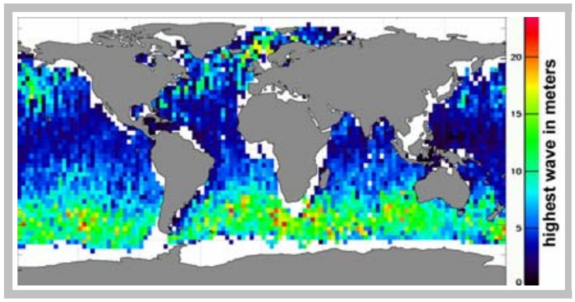

Figure 3-16: Map showing maximum single wave heights derived from three weeks of ERS-2 SAR data acquired in August-September 1996. The rough areas in the southern hemisphere and the path of Hurricane Fran in the northern Atlantic are visible

Political Conflicts, Effects of War

Politically and strategically, empires and nations have always needed means to keep watch over their territories, allies, and enemies. In the past, ground based reconnaissance and surveillance were used to penetrate enemy defenses, risking human lives and armed conflicts. From the 1960s on, space technology was also employed for these tasks and insured that more information of better quality could be collected without the risks, embarrassment and consequences associated with conventional international espionage. Remote sensing, imagery intelligence, reconnaissance, and surveillance all became terms used in billion-dollar space programs designed at first by the United States and Russia to spy on each other's abilities, tactics, hardware, and military activities. Since these beginnings, nonintrusive reconnaissance using satellites to obtain information about other nations has gained international acceptance as a legitimate procedure.

Conclusions about whether activities might be security relevant must be based on long-term observation of areas suspected to be breeding grounds for international threats. In the West, primarily the USA has access to powerful satellite surveillance networks; France also operates spy satellites and other European nations like Germany will soon follow with their own systems. The technical capabilities of these military systems are not made public in full detail and the imagery obtained is only made available to the satellite operators themselves. However,

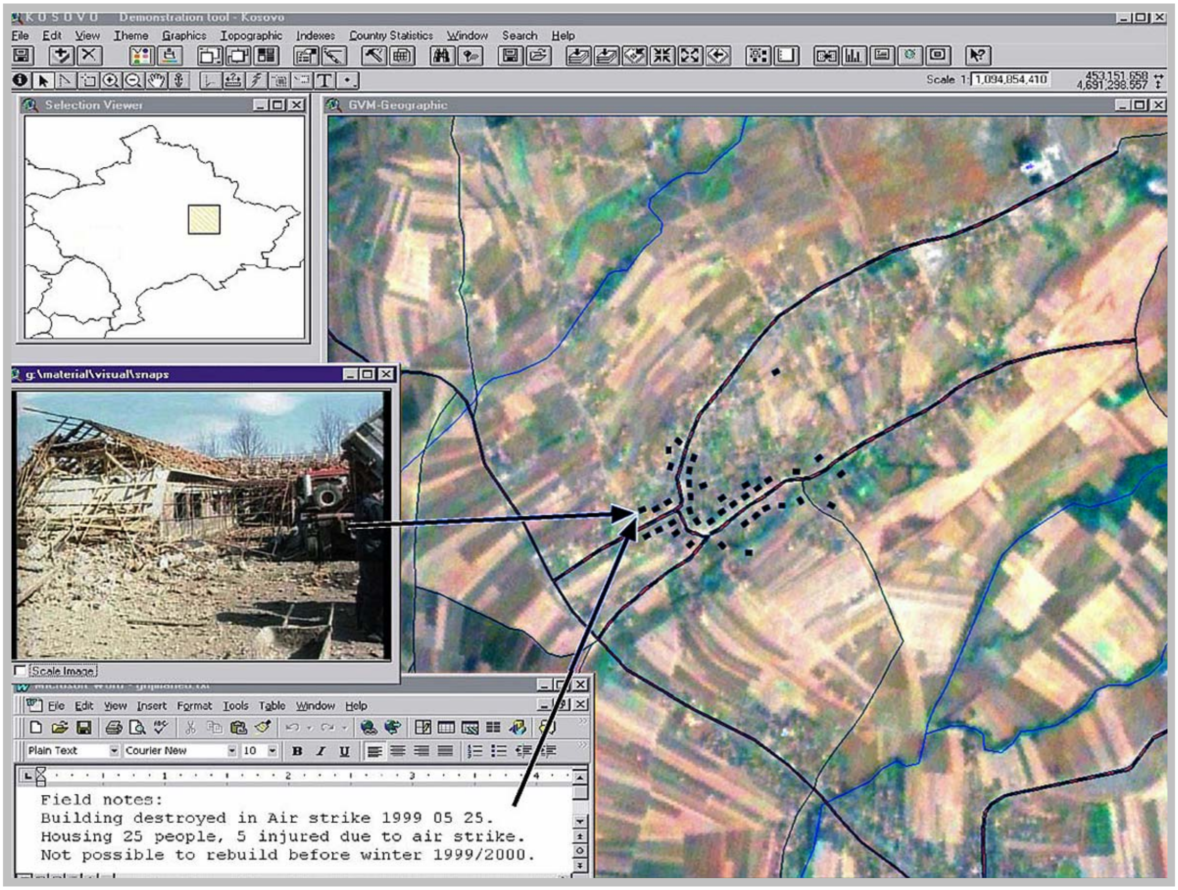

Figure 3-17: Prototype of an information system foreseen for field workers, developed to facilitate the reconstruction of Kosovo after the 1999 Balkan war. The information layers include a land use classification, the network of streets, rivers and railways, settlements, a map and a satellite image, all in the same map projection (UTM zone 34, WGS 84) and draped over a digital elevation model. This screenshot also shows photographs and field notes. A notebook contains part of the database, which is the reference for further data acquisition. A GPS for positioning, a digital camera for snapshots of infrastructure and a mobile phone for data transmission to and from the central database are connected as external elements

the recording instruments on board military reconnaissance satellites closely resemble those used in civilian remote sensing systems. The former have higher resolution capabilities, but the borders between civilian and military systems are disappearing and this trend will continue. Already today, imagery from civilian satellites is also being used for surveillance purposes. The highest optical imagery resolution from civilian satellites is currently about 60 cm (QuickBird) and will improve in the future (Ikonos Block II: 50 cm and better). Optical systems, however, always depend on good weather and visibility conditions. They need to be complemented by radar sensor systems for utilization in any kind of weather, day and night. Civilian radar satellites so far offer up to 10 m resolution (Canada's Radarsat); systems providing 1-3 m resolution (Germany's TerraSAR-X) are under development.

Due to the large number of images, the evaluation of any kind of data set for purposes of detecting suspicious changes or identifying security-relevant relationships can only be accomplished with the help of highly automated image processing procedures.

Techniques like data fusion, knowledge-based image interpretation and data mining are required. It is also necessary to make use of geographic information systems (GIS) so that remote sensing data can be combined with other data sources providing, for example, information on population statistics, border locations and transportation infrastructure in crisis situations. What is being undertaken in postwar Kosovo (Ehrlich et al. 2000) can serve as an example:

The 1999 Balkan war has had dramatic economic and humanitarian consequences for this province of the former Yugoslavia. It has been estimated that one third of the dwellings have been damaged or destroyed, a half million people displaced, half of the farm land damaged, and telecommunication infrastructure severely disabled (European Commission and World Bank 1999). The economic and social restoration process requires up-to-date, precise and readily available spatial information, and a decision was made to set up a GIS suitably customized for Kosovo which can be consulted in the offices of government authorities or relief agencies, or on location in the field (figure 3-17). It benefits from the ongoing addition from many sources of maps, data from earth observation sensors and field campaigns, and ancillary information like cadastral boundaries and demographic statistics. Embedding information derived from earth observation in a GIS is an ideal way to facilitate its interpretation, exploit its strengths and temper its weaknesses. The following is typical of the kind of information the Kosovo GIS is providing:

- Perspective landscape views (generated by combining digital elevation models with satellite data);
- A variety of maps, including land use maps based on satellite data (from which availability of timber for reconstruction can be calculated, or crop yields predicted);
- Visualization of data at different scales (building clusters, settlements, regions), depending on the area of interest;
- Location of any of Kosovo's almost 2,000 villages;
- Highlighting of villages where hospitals, schools or utilities are available;
- Display of roads with visualization of the distance and elevation profiles, also based on satellite imagery and digital elevation models (for planning activities involving transport and calculating distances);
- Visualization of statistics by village, municipality or province (damage assessment, population).

Management of Urban Areas

The reason natural occurrences become disasters has much to do with human activities. In the course of industrialization, the creation of agroindustrial structures, and modification of formerly natural ecosystems into forms that are more economically efficient (wetland drainage, riverbed regulation, consolidation of arable land), one of the most significant developments of the last century has taken place, namely urbanization. In 2007 for the first time in human history more people will be living in towns and cities than in rural areas. Almost two thirds of the world's population of currently 4.9 billion people will live in cities by 2030. Most of this growth will be concentrated in the developing countries (United Nations 1999). This trend will be accompanied by an increasing emergence of megacities—urban agglomerations with at least 8 to 10 million inhabitants. Accordingly, the current number of 40 megacities is projected to rise to 60 within the next 15 years.

One of the consequences of this migration is that people are settling on land that was previously avoided because of natural processes (periodically flooded coastal areas, slopes prone to mudslides); another is the socioeconomic and ecological problems accompanying the formation of megacities. Their existence increases the likelihood of a large number of victims in any natural disaster. One reason is the concentration of many people in a relatively small area, complicating any systems for their early warning and mass evacuation. Another is buildings whose construction is inadequate to withstand stresses from earthquakes and storms, and whose high density almost assures the propagation of damage.

Rapid urbanization comes along with numerous ecological, social and economic challenges that hold risks of profound ecological or socio-economic

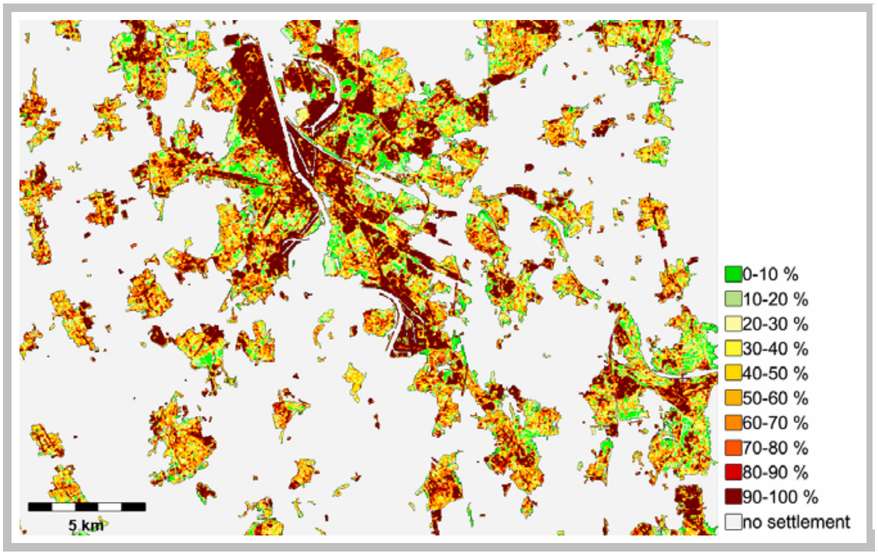

Figure 3-18: The color coding in this Landsat 7 ETM+ image of Germany's Rhein-Neckar region indicates the percentage of land surface sealed within built-up areas on 12 August 2001 (the disregarded countryside is white). The highly sealed area at top center represents the cities of Ludwigshafen and Mannheim, including a large industrial chemical facility

crises. The development of effective policies and plans for sustainable management of urban areas significantly relies on a proper understanding of both the dynamics of the urban system and the interaction between human activity, city structure, and the surrounding environment. Earth observation satellites offer promising and cost-effective opportunities to provide some of the required spatial and socio-economic information on a regular basis.

On a global scale remote sensing is a valuable technology for investigating the interactions between urban agglomerations or megacities and environmental phenomena like air or water pollution or ozone depletion, and their consequences. In this context satellite data play a significant role in monitoring relevant atmospheric parameters and improving atmospheric and hydrological models.

In a regional urban context remote sensing is mainly employed to monitor urban sprawl, population growth patterns and ground sealing (figure 3-18) and is usually based on optical satellite imagery with ground resolutions of ca. 5-30 m. Especially with regard to megacities the detection and mapping of informal settlements is of particular interest. Analysis of time series allows a detailed review of the spatial behavior of urban sprawl, the tracing of emerging environmental or socio-economic risks and a rough estimation of the population development. Urban heat islands have also been investigated successfully in order to verify the climatic effects and impacts of urban agglomerations on both the urban system and the surrounding environment.

On a local scale the spatial characteristics of typical urban structures demand satellite data having a ground resolution of at least 5 m, down to 1 m. Such data can be used to map urban land use and existing infrastructure, analyze housing characteristics (a socio-economic feature), risk assessment in view of man-made or natural hazards (urban vulnerability, disaster management) and the position or distribution of selected public utilities. A highly differentiated analysis of urban surface types as well as the direct measurement of water or ground pollution on a local scale can be achieved using hyperspectral optical data, currently only available on airborne platforms, but expected to be available on satellites in the near future.

As far as standardized information extraction over urban areas is concerned, the lack of a classification approach sophisticated enough for automated data analysis has been keenly felt. Procedures are being developed to locate and group pixels into objects meaningful for urban analyses (buildings, streets, parks), to distinguish between different structures in close proximity by considering their likely function, based on their immediate surroundings (whether a green patch is recognized as a lawn or an agricultural crop, for example), and to display different objects in a single image at the various scales appropriate for the applications (a park might be simply identified as such without further elaboration, whereas a city block might be resolved into individual buildings and passageways). If successful, such procedures will make possible a wide variety of applications, from long-term urban planning to short-term disaster relief.

3.4 Future Developments

It can be predicted with some confidence that earth observation data for research in the geosciences will continue to gain in importance. In combination with other types of geodata from nonsatellite sources, or when integrated into models, remote sensing data will lead to new insights and improved understanding of ecological and climate processes. At the same time, scientific methodology and procedures will continue to be operationalized in order to make their output available to a community of users far more numerous than the original remote sensing science teams. The gap between 30 meter Landsat-like resolution and meteorological satellites is being closed by special and daily-revisit medium resolution imagers. Global daily vegetation status is being provided by the MODIS sensor currently operated on two U.S. satellites. This kind of environmental observation with multiple spectral bands is becoming a standard for global weather and climate observation. Hyperspectral imagers are driving the demand for high spectral resolution and will become operational assets in the coming years.

As of today, the use of earth observation data for environmental monitoring and mapping is primarily driven by government funded research projects and a few operational mapping programs. The vast majority of the medium resolution optical and SAR data is being used for such purposes. Commercial satellite operators also rely heavily on governmental users. In the United States as well as in Europe government agencies form the largest single class of customers. With the increased demand for security and military applications and a 6-14% prospected growth of the satellite image based geoinformation market (according to various forecasts), this dependency on governmental contracts will even increase. The total volume of the earth observation market in 2001 was estimated for the United States at $2.4 billion (ASPRS 2004) and in Europe at $1.2 billion (Frost & Sullivan 2001). These numbers do not include the in-orbit and ground segment systems, but might include the entire aerial survey market, which still forms the bulk of the geoinformation market. In the U.S. aerial platforms are used about twice as often as space platforms to collect remotely sensed data.

Fundamental to the establishment of commercial markets is on the one hand a clear market for the generated products (for use in agriculture or cartography, for example), and on the other hand a reliable guarantee of long-term availability of the basic data. And commercial value adding, that step from raw data to information products, will only be possible when the available instruments and systems are designed to meet market demands, provide good value for money, and are reliably available long term. The failure of a single component on Landsat 7 has vividly demonstrated the vast implications for the many studies worldwide that have been based for decades on data provided by the Landsat series.

Since the late 1990's former military optical reconnaissance technology has emerged on the public and commercial satellite imaging scene. The availability of very high resolution imaging has provided the largest stimulation to the earth observation market during the last few years. However, the new commercial providers—some of whom originated in defense companies—were forced to learn many lessons about the needs of a diversified commercial and governmental market for high quality services at affordable prices. Due to the new threats to security and the associated reorganization of national military capabilities, the highest demand for these kinds of data is coming from military agencies.

On the nongovernmental customer side, the largest revenue in earth observation services comes from mapping services (cartographic, thematic including environmental, and elevation), followed by various kinds of agricultural monitoring. While the majority of applications is still based on medium to high resolution satellites (above 15 m), the demand for very high resolution data is increasing. Interestingly, it is observed (ASPRS 2004) that very high resolution space data and aerial information are not competing but rather augmenting each other. This is also because traditional aerial analog imaging technologies are now becoming digital. Also, laser based imaging (lidar) can only be operated from aircraft.

Currently, the establishment of sturdy and commercial structures making use of remote sensing for deriving market-tested information layers is significantly dependent on public investment. And thus decisions made in the political arena will shape the future of commercial applications.

Political Framework

The monitoring of the earth from space is considered to be the most important tool for assessing the environmental state of the earth's ecosystems and delivering important information to allow forecasts of global ecosystems development and climate change (table 3-1). Triggered by findings about the depletion of the ozone layer, the Kyoto Protocol fostered many activities using a multitude of satellite based earth observation systems to monitor environmental change. Using existing global science entities and the framework of meteorological organizations, space agencies are contributing their data to global observing systems established from 1991 onwards in response to climate, ocean and terrestrial concerns. To focus on specific environmental themes, integrated global observing systems for atmospheric chemistry, global carbon, the global water cycle and the oceans were created between 1999 and 2002. All these programs are meant to be a framework to harmonize international policy, space programs and science topics. Satellite operation and data supply are left to the space agencies and meteorological satellite operators. Meanwhile, the European Space Agency is evaluating first results of studies in order to define the needs for next generation operational environmental monitoring satellites.

In July 2003, the U.S. government invited the international community to an "Earth Observation Summit" held in Washington, DC. Over 30 countries and 20 international organizations agreed at this summit on a "Global Earth Observation" (GEO) initiative, aimed at better integrating the existing earth observation systems and closing identified gaps in the observation of environmental parameters.

Under the umbrella of the European Union and ESA, the European countries are contributing to this process with the "Global Monitoring for Environment and Security" (GMES) initiative. After having agreed on a European satellite based navigation system (Galileo), the ESA and European Commission councils approved in 2001 a "political … initiative to secure Europe with an autonomous and operational information production system in support of environment and security policies" (ESA and European Commission 2003, European Commission 2003). GMES concluded its initial period in 2003 and is aiming for a fully operational system in 2008.

GMES also addresses the security of European citizens from the viewpoint of civil protection. This somehow mirrors the U.S. homeland security program, where satellite based information is used to monitor critical infrastructures. Driven by the new geopolitical situation and manifested in their "Common Foreign and Security Policy" (CFSP), European governments wrote the strategic advantage of satellite imaging into their long term plans. Following the French Helios optical reconnaissance system, Germany and Italy started to build high resolution satellite radar reconnaissance systems (SARLupe and COSMO SkyMed). Meanwhile and in addition, commercial high resolution systems are used as sources to fill the increased need for data for humanitarian aid, peacekeeping missions and military intelligence.

In the early half of the first decade of the new millennium, the general political environment for earth observation is characterized by tighter governmental budgets, efforts to establish viable markets for earth observation data, and the implications of new U.S. space priorities. Opportunities can be seen in the increasing awareness of European and other countries of the importance of earth observation, the establishment of public funding schemes to launch operational missions, and the development of innovative technologies for both space and ground segments, all helping to make space-based observation an affordable tool for earthbound problems.

1	2	3	4	5	6	7	
	Satellite or Mission/Sensor	Agency or company/ country	Resolution min/max in m	Swath min/max in km	# of bands/ SAR band	2004 2005 2006 2007 2008 2009 2010	Remarks
	Landsat class, high resolution/ multispectral						
P	Landsat -5	NASA/US	30/120	185	7		
P	Landsat -7	USGS/US	15/30	185	8		
P	Terra/ASTER	NASA,JAXA/US,JAP	15/90	60	14		Stereo
C	SPOT 1,2, 4	SPOT,CNES/F	10/20	60	5		3 Satellites
C	SPOT 5	SPOT, CNES/F	2.5/5/10	60/120	5		
C	IRS-1C / D	ISRO/IND	5/23	70/142	5		
	DMC	SSTL /UK&others	32	640	3		3 Satellites
	DMC BilSat-1	SSTL/Turkey	12/16	25/55	3		
	DMC+4 CHINA	SSTL/China	4/32	24/600	3		
	SAC-C/MMRS	CONAE/Argentina	175	360	5		
C	ResourceSat-1,2	ISRO, ANTRIX/IND	5.8/23	23.5/140	3/4	2	2 Satellites
	CBERS-1,2	CAST/CHIN, INPE/BRA	20/80	120	8		2 Satellites
	CBERS-3	CAST/CHIN, INPE/BRA	5/10/80	60/120	4/8		
P	ALOS/PRISM	JAXA/JAP	2.5/10	35/70	5		Stereo
C	RapidEye	RapidEye/D	6.5	78	5		5 Satellites
	Lower resolution multi/hyperspectral						
P	Terra,Aqua/Modis	NASA/US	250/1000	2330	36		
C	Envisat/MERIS	ESA/EU	300/1200	575/1150	15		
	EO-1	NASA/US	30	15	233		
C	ResourceSat 1,2	ANTRIX, ISRO/IND	70	720	3	2	2 Satellites
C	OrbView-X (4)	Orbimage/US	0.5/5	12	5/200		
	Very high resolution						
C	IKONOS-2	Space Imaging./US	0.8/3.2	11	1/4		
C	IKONOS-BlockII	Space Imaging/US	0.4/1	15.4	1/4		
C	EROS-A1	ImageSat/ISRAEL	1.8	13.5	pan		
C	EROS-B1-3	ImageSat/ISRAEL	0.7/2.8	10.4	1/3	1 2 3	3 Satellites
C	Quickbird-2	DigitalGlobe/US	0.6/2.5	16.5	1/4		
D	WorldView	DigitalGlobe/US	0.5/1.8	16.5	1/8		NextViewI
C	OrbView-3	Orbimage/US	1/4	8	1/4		
C	OrbView-5	Orbimage/US	0.4/1.6	15.3	1/4		NextViewII
C	ROCSat-2	NSPO/Taiwan	2/8	24	1/4		Stereo
	Theos	GISTDA/Thailand	2/15	22/90	1/4		Stereo
C	CartoSat-1	ISRO, ANTRIX/IND	2.5	30/60	pan		Stereo
C	CartoSat-2	ISRO, ANTRIX/IND	1	12	pan		
	KOMPSAT-2	KARI/Korea	1/4	15	1/4		
	Resurs-DK1	Spaceproject, FSA/RUS	1/ 2.5	28.3	1/3		
D	Pleiades	CNES/F	0.8/2.5	21/40	1/4	1 2	2 Satellites
	Synthetic Aperture Radar (SAR)						
P	Radarsat-1	CSA,RSI/CAN	8/100	45/500	C		
C	ERS-2	ESA/EU	30	100	C		
C	ENVISAT/ASAR	ESA/EU	30/150	100/400	C q		
P	ALOS/PalSAR	NASDA/JAP	7/100	70/350	L Q		
P	TerraSAR-X	DLR & InfoTerra/D	1/16	10/100	X Q		
P	TerraSAR-L	ESA & InfoTerra/EU	5/50	70/200	L Q		
D	COSMOSkyMed	ASI/I	1/100	10/200	X q	1 2 3 4	4 Satellites
C	Radarsat-2	RSI/CAN	3/100	10/500	C Q		
	SAOCOM 1A/B	CONAE/Argentina	10	100	L	1 2	2 Satellites
	RISAT	ISRO/IND	3/50	10/240	C		

Column	Explanation
1	C = commercial mission or commercialized outside country of origin; P = public/private partnership between space agency and commercial partner; D = dual use: military and commercial; no sign indicates limited regional or science availability
6	Capital letters C, L, X denote radar frequency bands; P = fully polarized; p = partially polarized; pan = optical panchromatic
7	Numbers denote launch of satellite in a series; mission end dates are as planned or estimated; "- -" denotes that satellite might operate longer
8	Numbers of satellites in the mission; special capabilities are abbreviated

Table 3-1: Overview of current and anticipated land surface earth observation satellites

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