Satellite Image Analysis for Disaster and Crisis-Management Support

Stefan Voigt, Thomas Kemper, Torsten Riedlinger, Ralph Kiefl, Klaas Scholte, and Harald Mehl

***Abstract*—This paper describes how multisource satellite data and efficient image analysis may successfully be used to conduct rapid-mapping tasks in the domain of disaster and crisis-management support. The German Aerospace Center (DLR) has set up a dedicated crosscutting service, which is the so-called "Center for satellite-based Crisis Information" (ZKI), to facilitate the use of its Earth-observation capacities in the service of national and international response to major disaster situations, humanitarian relief efforts, and civil security issues. This paper describes successful rapid satellite mapping campaigns supporting disaster relief and demonstrates how this technology can be used for civilian crisis-management purposes. During the last years, various international coordination bodies were established, improving the disaster-response-related cooperation within the Earth-observation community worldwide. DLR/ZKI operates in this context, closely networking with public authorities (civil security), nongovernmental organizations (humanitarian relief organizations), satellite operators, and other space agencies. This paper reflects on several of these international activities, such as the International Charter Space and Major Disasters, describes mapping procedures, and reports on rapid-mapping experiences gained during various disaster-response applications. The example cases presented cover rapid impact assessment after the Indian Ocean Tsunami, forest fires mapping for Portugal, earthquake-damage assessment for Pakistan, and landslide extent mapping for the Philippines.**

***Index Terms*—Crisis information, disaster monitoring, rapid mapping, risk management, satellite remote sensing.**

I. Introduction

IN RECENT years, satellite systems and image-analysis techniques have developed to an extent where civil and commercial Earth-observation instruments can contribute significantly to support the management of major technical and natural disasters, as well as humanitarian crisis situations. Comparing today's availability of satellite imagery to the situation about ten years ago, the amount, timeliness, and availability of satellite imagery covering a certain crisis situation or disaster event has improved substantially. There are several factors which have lead to this fact. First of all, ground pixel spacing of civil Earth-observation systems has developed to the meter domain for optical and radar systems and to the decameter domain for thermal imaging satellites. Second, during the 1990s, communication, networking, and interoperability among the different satellite systems have improved substantially to facilitate international satellite-based disaster-response capacities. Third, through a number of international scientific and technical coordination bodies, international cooperation mechanisms were established, such as the Disaster Management Support Group (DMSG) of the International Committee on Earth Observing Satellites or the International Charter Space and Major Disasters. The main task of the DMSG is to perceive the specifications, basic observations, and monitoring requirements of current and future observing systems fully or partially dedicated to disaster management tasks. Based on conclusions of the DMSG [1] and the UNISPACE III conference, the International Charter Space and Major Disasters [2], from here onwards referred to as International Charter, was founded in 1999. Since this time, the International Charter has been providing a crucial mechanism for globally coordinated disaster response by civilian governmental satellite operators and space agencies for natural and man-made disasters.

Currently, the International Charter is operated by a number of space agencies (Table I) and has been activated over 100 times (July 2006, [2]), providing meaningful mapping and analysis products to the civil-protection and relief organizations at appropriate scale in time and space. Taking into account the increasing rate of natural and technological disaster situations affecting human activities on this planet, the International Charter still bares potential for extension and improvement. First of all, the commitment to provide only plain satellite imagery, rather than analysis results, should be extended to also formally committing the provision of ready to use information products (maps) applicable in the domain of humanitarian and natural crisis situations. Second, the speed of data and information delivery may still be improved in the context of the Charter, as natural, humanitarian or technical disaster often cannot be predicted in space and time and thus requires maximum responsiveness to maximize mitigation efforts. Third, the actors in the domain of satellite-based response to civilian crisis and disaster situations may improve their mutual coordination and cooperation to allow best use of existing systems and mechanisms and to exploit their synergistic potential to the maximum level possible. Such coordination shall address technical and organizational matters, as well as information sharing or capacity building.

Manuscript received February 26, 2006; revised December 27, 2006. This work was supported in part by the research and development grants of the German Aerospace Agency (DLR), by the project funds of the Global Monitoring for Environment and Security (GMES) program of the European Space Agency, namely the RESPOND and RISK-EOS projects, and by research funding granted within the 6th Research Framework Program of the European Commission for the Network of Excellence "Global Monitoring for Stability and Security" (GMOSS).

The authors are with the German Remote Sensing Data Center (DFD), German Aerospace Center (DLR) at Oberpfaffenhofen, 82234 Wessling, Germany (e-mail: stefan.voigt@dlr.de).

Color versions of one or more figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TGRS.2007.895830

TABLE I
OVERVIEW OF SPACE AGENCIES AND SPACE RESOURCES OF THE INTERNATIONAL CHARTER

Member	Space Resources
European Space Agency (ESA)	ERS, ENVISAT
Centre national d'études spatiales (CNES)	SPOT
Canadian Space Agency (CSA)	RADARSAT
Indian Space Research Organisation (ISRO)	IRS
National Oceanic and Atmospheric Administration (NOAA)	POES, GOES
Argentina's Comisión Nacional de Actividades Espaciales (CONAE)	SAC-C
Japan Aerospace Exploration Agency (JAXA)	ALOS
United States Geological Survey (USGS)	Landsat
DMC International Imaging (DMC)	
1. Centre National des Techniques Spatiales (Algeria)	1. ALSAT-1
2. National Space Research and Development (Nigeria)	2. NigeriaSat
3. Tübitak-BILTEN (Turkey)	3. BILSAT-1
4. BNSC and Surrey Satellite Technology Limited (UK)	4. UK-DMC

After several years of research and development in the domain using satellite systems for civilian crisis and disaster response, the German Aerospace Center (DLR) has set up a dedicated crosscutting service, the Center for satellite-based Crisis Information (ZKI), to combine and facilitate the use of its Earth-observation capacities in the service of national and international response to major disaster situations, humanitarian relief efforts, or civil security issues. The aim of this paper is to describe and discuss the assessment of multiple satellite data sources, the crisis support service cycle, the multisource image analysis, and adding of the geospatial context to satellite information in order to rapidly supply self-explaining geospatial information products for disaster and crisis-management support.

II. Accessing Multiple Satellite Data Sources

Maps, geospatial information, and thematic analysis derived from satellite imagery can support decision making and situation awareness during all phases of the disaster and crisis cycle. This is defined through preparedness, alertness, rapid analysis, response, recovery, and reconstruction [3]. In particular, during the analysis, response, and recovery phase, only very fast delivery of up-to-date, accurate, and comprehensive image-analysis products can significantly help in the assessment of large disaster situations, in particular in remote areas, where other means of assessment or mapping either fail or are of insufficient quality. Before the formation of the International Charter, it was mainly by chance or in very special cases where programming, access, delivery, and analysis of civil satellite imagery was fast enough so that a response time of hours or a few days was reached and allowed a proper use for relief-work purposes. Only with the installation of the International Charter, a globally functioning mechanism was established to coordinate the tasking of multiple satellites and archiving systems in very short time, without hindering formalities. Hence, a meaningful satellite observation information capacity was established for a variety of nonexpert users such as civil protection, humanitarian relief workers, and donor/funding organizations.

Shortly after the International Charter was introduced, very high resolution (VHR) commercial satellite imaging in the 1-m domain became publicly available. Also, this 1-m domain imagery allowed nonexperts in many situations to read information intuitively from the carefully processed imagery itself or to allow the analysts to generate fast and easy-to-read space maps showing location, situation, scale, or extent of a given disaster or crisis situation. In spite of these crucial developments in the domain of satellite imagery provision, it is important to note that no decision maker or relief worker can work with raw satellite imagery—it always takes a very careful processing, analysis, mapping, and interpretation process to generate the required situation maps, reports, or statistics which can be read and understood by nonsatellite expert users. It has to be mentioned that the International Charter still has quite some shortcomings in this respect as it formally only commits to provide raw satellite imagery to the users. All analysis and value adding work has to be conducted in other frame works and contexts such as described next.

III. Crisis Support Service Cycle

In order to process the full cycle, from an emergency call or request for assistance, through satellite tasking, data acquisition, analysis, map provision, and interpretation, one has to go through a chain of various steps involving coordination of satellite commanding and data reception tasks, as well as data ingestion, preprocessing, correction, and analysis. Just as important as the data processing and delivery is the close contact and interaction with the key actors in the user community (Fig. 1) [4].

Experience over the past years has shown that neither sophisticated image analysis and processing nor mapping capacities or geographic information system (GIS) skills alone allow providing a meaningful disaster-related information service to crisis response staff and within operational scenarios. Only if it is possible to operate the whole crisis support service cycle, linking Earth-observation systems, information extraction, and dissemination with specifically trained decision makers, or field staff of the relief organizations without interrupt, space-based crisis mapping can have a positive impact on disaster-relief operations.

IV. Multisource Image Analysis

Satellite image analysis for disaster and crisis-management support has to rely on whatever geoinformation is available

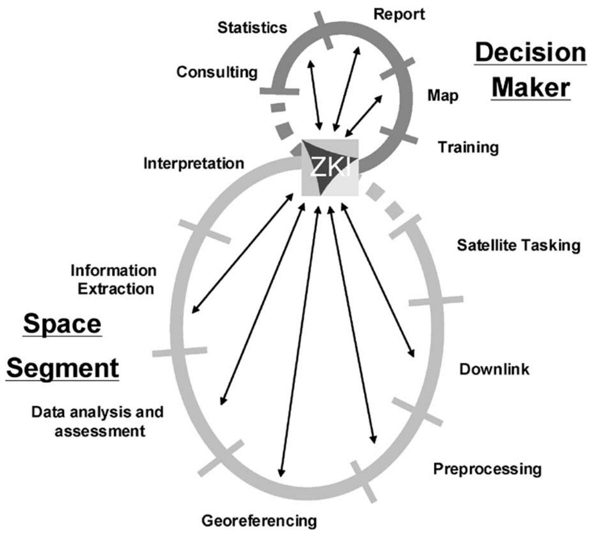

Fig. 1. DLR-ZKI service cycle. ZKI touches both the space segment and decision-maker cycles, and due to this interlinking network, it is possible to provide optimal service delivery to its users.

fast in order to respond as quickly as possible. Moreover, for each disaster type, different data and analysis techniques are required. Consequently, a wide expertise and capacity for various types of data is essential. The most important data sources are VHR optical data, thermal imagery, and synthetic aperture radar (SAR) systems.

Optical data are of great importance for disaster management support such as planning the logistics of relief actions in the field immediately after, for example, an earthquake or tsunami [5]. One major advantage of VHR optical data is that their interpretation is also intuitive for nonexperts. For example, a map at scale 1 : 7500 using predisaster VHR imagery gives the aid workers in the field an overview of the predisaster building structure. Such information is highly valuable to search and rescue operations, as well as for reconstruction planning after earthquakes.

The thermal imagery offers excellent possibilities for mapping of hot spots caused by wild fires. Operational wildfire-detection systems using Advanced Very High Resolution Radiometer (AVHRR) data have been developed for use in Canada [6] and Finland [7], among other countries. Thermal satellite data can give an overview information about the extent and the number of actually burning fires due to the fact that the sensors of the National Oceanic and Atmospheric Administration (NOAA) AVHRR and Moderate Resolution Imaging Spectroradiometer (MODIS) are sensitive to fires that are much smaller than their spatial resolution [8]. In particular, the MODIS sensor is also useful for large-scale flood monitoring [9].

Although most of the commercial or research Earth-observation satellite systems are optical/thermal systems, the SAR systems onboard European Remote Sensing satellites (ERS), Radarsat, ENVISAT, or the Advanced Land Observing Satellite (ALOS) are of great value for the fast response mapping and analysis tasks as they allow imaging at wavelengths almost unaffected by atmospheric disturbances such as rain or cloud. Although radar imagery is somewhat less intuitive to be interpreted by nonexperts, they resemble a very useful source for flood events [6], [10], oil spills [11], landslides, and earthquakes [12], particularly when postevent imagery can be jointly analyzed with archived reference imagery for change detection or interferometric coherence or displacement measurements. The German TerraSAR-X System and the Italian Cosmo-Skymed, which are to be launched in 2007, will extend the civilian SAR availability to the 1-m domain, allowing VHR all weather image acquisitions.

For many disaster-related image analysis and mapping tasks, the availability of appropriate and accurate topographic elevation data on the affected area is of uttermost importance. Thus, interferometrically derived digital elevation models (DEMs), such as which resulted from the Shuttle Radar Topography Mission (SRTM) [13], are of very high value for image processing (e.g., orthorectification) and map generation (e.g., hillshading).

V. Adding the Geospatial Context

It is evident that satellite-derived information alone does not suffice to generate a meaningful analysis of a given disaster situation. Experiences gathered during the work with relief organizations show that it is an absolute key to fuse the satellite-based information with additional data to present it in a proper geospatial context. Thus, in addition to the expertise in image analysis, an equally important task is the generation of comprehensive and easy-to-use map products. For this purpose, reference data sets such as place names, road network, rivers, critical infrastructure, and topographic information are required.

The most crucial problem is the availability and the access to accurate and up-to-date spatial data, particularly in remote regions. The benefits of interoperable spatial data infrastructures (SDI) for data access and dissemination in the framework of disaster response are already demonstrated [14]. This promising approach implies that different organizations provide the data that they are responsible for by web-based systems. However, up to the present, only few countries established and operate an SDI; this is particularly the case for Africa and the Asian-Pacific countries due to technical or legal constraints [15]. Therefore, there is still a gap in the availability, particularly of local-scale geodata.

Fast and easy accessible global data sets such VMap [16] are often not accurate enough for a high-resolution mapping. Hence, high-resolution data sets on infrastructure and settlement boundaries have to be derived by visual interpretation of satellite imagery. Global gazetteers such as the GEOnet Names Server [17] can be used for labeling settlements and physiographical features like rivers and mountains. For a rough estimation of the population affected by a disaster, the LandScan database [18] gives a good representation of rural and urban population densities. A combination of interferometrically derived DEMs from SRTM X- and C-band, ERS, and GLOBE 30-arcsecond data [19] provides a global basis for the derivation of contour lines as an adequate representation of the topography.

Generally, the map-generation process consists of different steps: integration of spatial data, data analysis, layout, quality control, map editing, and dissemination, as well as possible

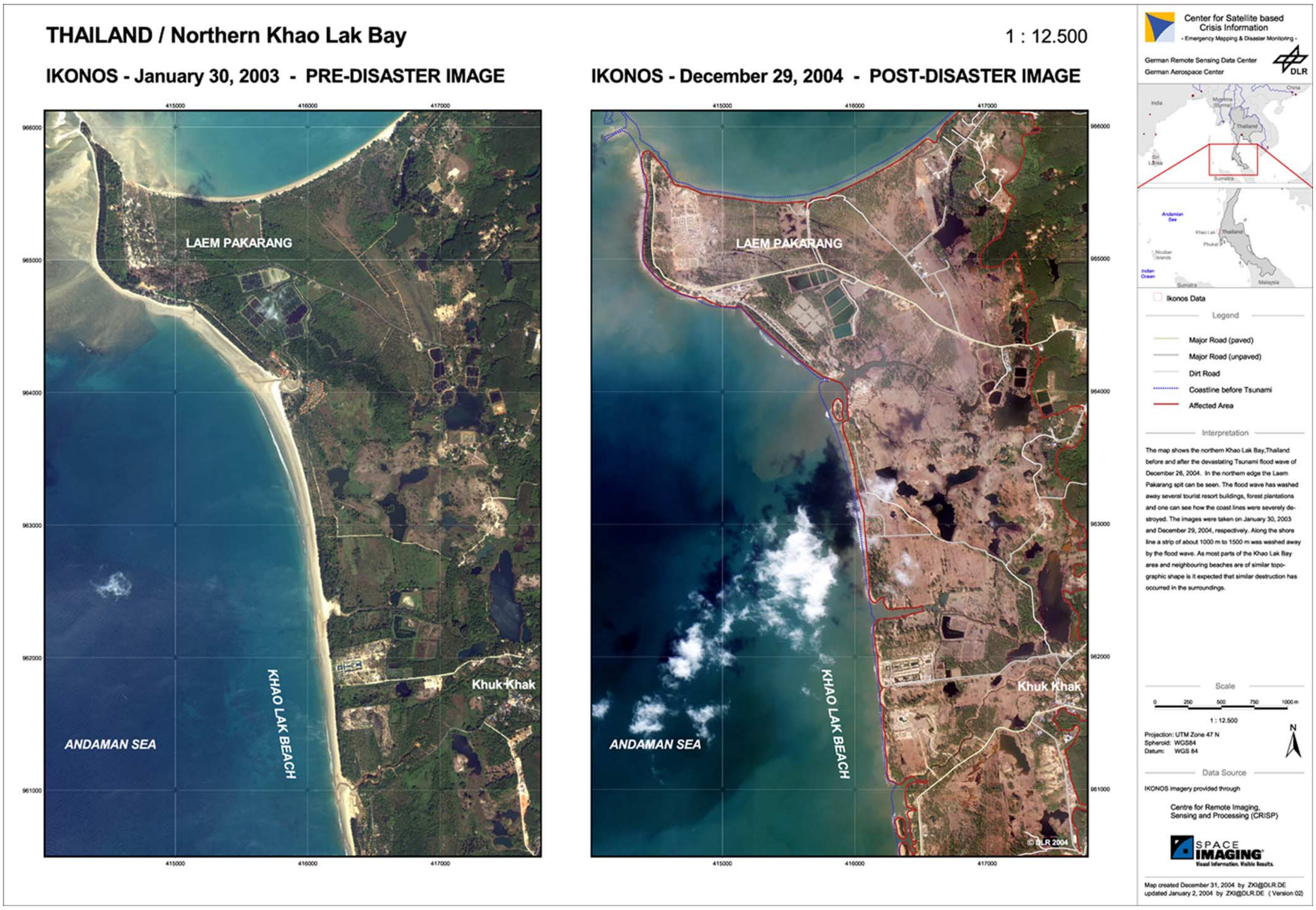

Fig. 2. High-resolution satellite map from new and archived satellite imagery of the northern Khao Lak Region, Thailand (1 : 12.500). The archived predisaster and new acquired postdisaster satellite images allow easy and quantitative damage assessment by visual change detection. Tsunami-affected areas are delinated using a red polygon signature, and in blue, the coastline before the tsunami is indicated.

updating of the map. The following section will show some examples and in more detail how the rapid mapping can successfully be accomplished.

VI. Examples for Applying Satellite-Based Information in Disaster Relief

Going back only for the last two years, several outstanding examples can be given where satellite-based maps could provide information supporting international humanitarian relief teams or domestic disaster-relief operations in very fast and efficient ways. Four of the most prominent internationally relevant application examples, on which DLR/ZKI has worked, are described in the following section and cover disaster situations in the following geographic regions: Southeast Asia (Tsunami), Portugal (fire hot spots), Pakistan (earthquake), and the Philippines (landslide). It is important to note that the following examples of satellite imagery application for disaster relief intend to showcase swift and synergistic use of state-of-the-art processing techniques and rapid data access. These rapid-mapping results could be achieved by building on existing scientific results and long-term engineering experience in the domain of satellite data processing. It is not indented to report major generic methodological research results or method comparison here.

A. Impact Assessment for the Indian Ocean Tsunami

In the early morning of December 26, 2004, a severe earthquake (30 km below sea level, magnitude 9) caused Tsunami flood waves in the Indian Ocean, which struck the coastal regions of Sumatra, Thailand, Sri Lanka, and southern India, and killed more than 200 000 people. Due to the immense extent of the affected coastal areas, the International Charter was triggered three times for India, Sri Lanka, and Indonesia/Thailand. After consultation and coordination with various international partners, DLR/ZKI concentrated its activities on Thailand and Indonesia. Until postdisaster imagery became available, reference maps using archived satellite data were produced giving first basic information about the affected areas. These archived satellite data from the global land-cover facility [20] were combined with geospatial information.

The first postdisaster images of Sumatra were delivered on December 29, 2006, three days after the disaster. Due to the scale of the damage, both medium [Landsat-7 Enhanced Thematic Mapper (ETM), SPOT, disaster monitoring constellation (DMC)] and very high-resolution imageries (IKONOS, Quickbird) were used for quantitative damage assessment mainly by means of visual change detection (Fig. 2). This up-to-date mapping, covering large parts of the affected area, enabled disaster managers to achieve an overview of the situation, to

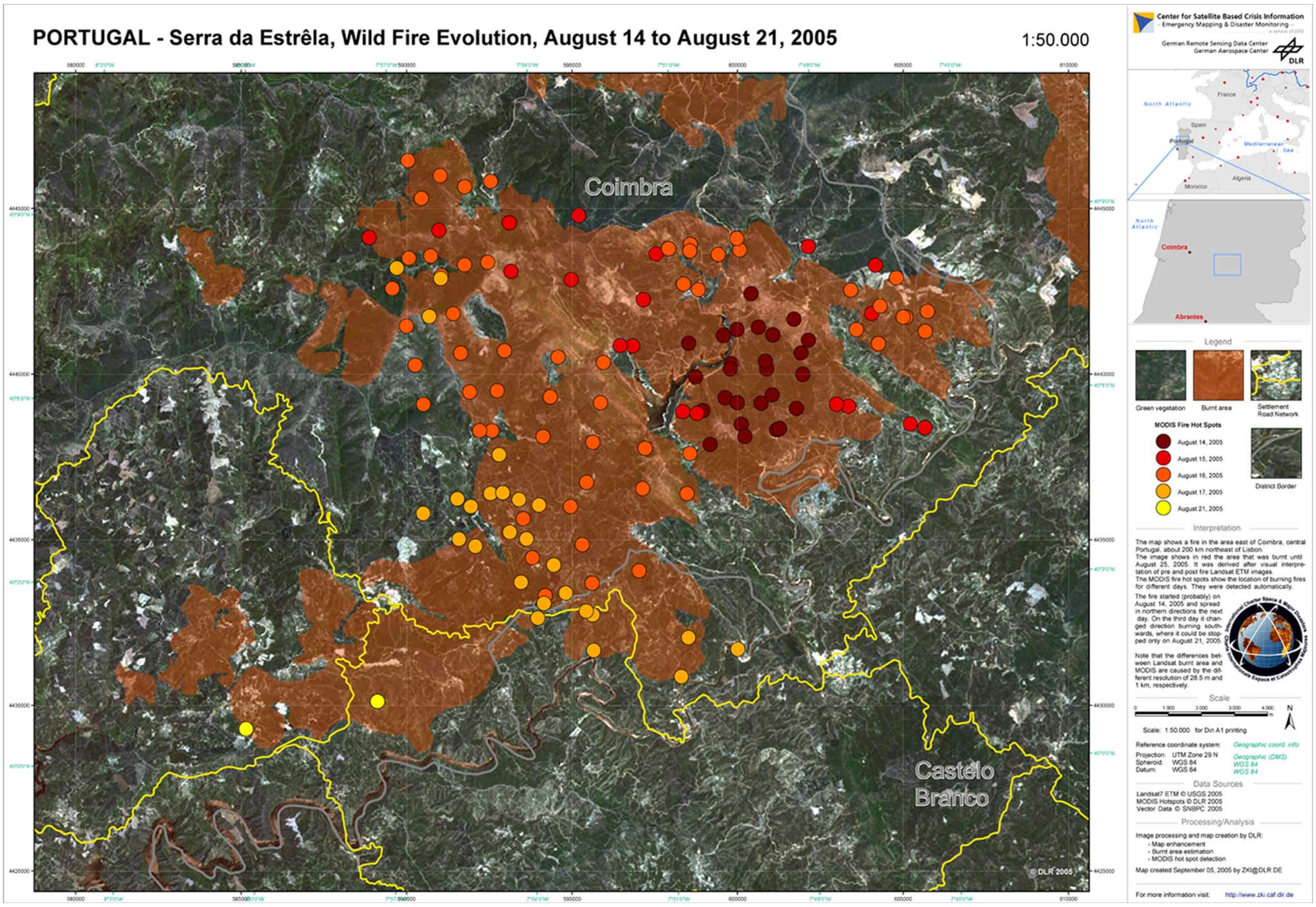

Fig. 3. Satellite map of the Serra do Estrela, Portugal (1 : 50.000). The image shows in red the area that burned until August 25, 2005, where the different colored circles denote the MODIS-derived hot spots between August 14 (dark red), August 16 (red), August 17 (orange), and August 21 (yellow), allowing a detail tracing of the fire propagation.

assess the damage, and to supply local logistic teams with reliable information on a short notice. ZKI provided this service in cooperation with its partners in the Global Monitoring for Environment and Security/RESPOND consortium and followed requests of the crisis reaction team of Germany's Federal Foreign Office (Auswärtiges Amt), the joint federal situation and information center, the German technical relief agency, the German Red Cross, and Medicines Sans Frontiers. The products were also provided to a wide international user community, as well as the press and the public via the Internet.

B. Providing an Overview on Forest Fires in Portugal

In the Mediterranean, each summer, natural- and human-induced wildfires are a threat not only to the environment but also to the local population. In the year 2005, after one of the most severe droughts over the Iberian Peninsula, the wildfires were raging out of control across central and northern Portugal, killing 15 people and destroying more than 150 000 ha of agricultural land and urban area.

The worst-hit areas included the central region of Portugal, where fires were threatening the outskirts of Coimbra, which is the third largest city of the country. Wildfires were also continuing to burn in the northern districts of Viseu and Viana do Castelo. After a request of the Portuguese fire-fighting service, the International Charter was triggered, and the burned area was mapped using SPOT, Landsat-7 ETM, DMC, and IKONOS. The burned area was mapped from visual image comparison of pre- and postdisaster data, as it proofed to be faster and more accurate than automated classification tools. Due to the large areas that were affected, medium resolution satellites such as SPOT-5, Landsat-7 ETM, and DMC proofed to be more advantageous over the very high-resolution IKONOS data, which were used only for the affected urban areas.

In parallel, the situation was monitored using the sensors NOAA-AVHRR 17 and MODIS Aqua and Terra for the detection of fire hot spots. Near-real time hot-spot detection for the Mediterranean is achieved at DLR through an inhouse reception of NOAA AVHRR and MODIS data and direct processing. This processing chain is based on the adapted APOLLO tool for NOAA AVHRR [21] and the enhanced MODIS fire detection developed by [22]. The value-added product was delivered daily, 2 to 5 h after the satellite overpass via the Internet and for direct integration into GISs of the civil-protection units. This continuous monitoring allowed a detailed tracing of the fire propagation and a better planning of fire-fighting capacities by the Portuguese civil protection (Fig. 3).

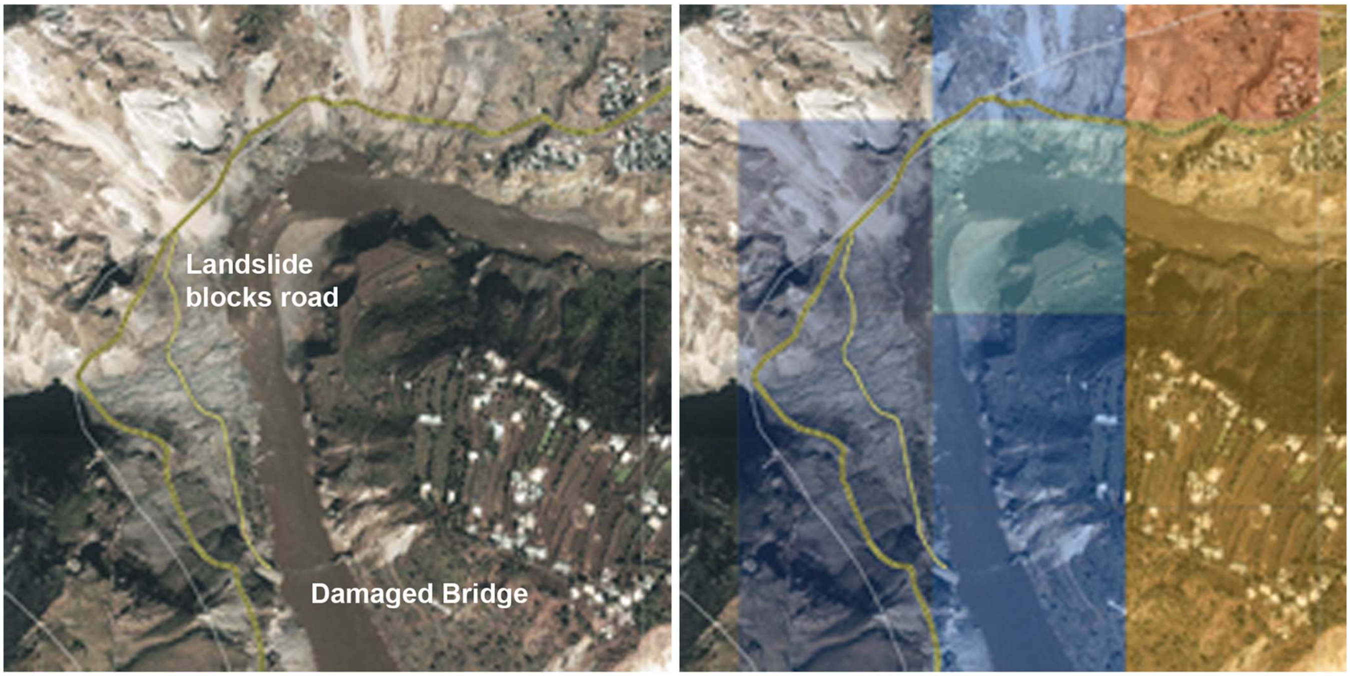

Fig. 4. Damage assessment for the northern Muzaffarabad city area, Muzaffarabad District, Pakistan (1 : 7500). Visual interpretation on pre- and postdisaster images with 250 × 250 m grid cells is applied to interpret damage to infrastructure and build-up areas by means of UN housing damage classification: no damage, moderately damage (< 33%), severely damage (33%–66%), and completely destroyed (> 66%). Semitransparent color map overlay is used to visualize damages, and blue-colored grid cells show those areas with moderate (light blue) to high (dark blue) damage to infrastructure, whereas the orange- and red-colored grid cells show damage to build-up areas.

C. Earthquake Relief Support for Pakistan

A series of severe earthquakes (maximum magnitude of 7.6) struck the Kashmir region on Saturday October 8, 2005. The epicenter was located on the India–Pakistan border, which is about 100-km northeast of Islamabad, and Pakistani authorities reported some 49 700 casualties and over 74 000 injured. On October 11, which is two days after activation of the International Charter, DLR produced several detailed maps (1 : 7500) of a number of cities in the earthquake-affected region, which are derived from very high-resolution IKONOS imagery. Typical image preprocessing for such rapid-mapping services includes atmospheric corrections [23], orthorectification [24], pansharpening [25], filtering, contrast enhancements, and visualization.

The positional accuracy of uncorrected VHR imagery is poor in mountainous areas such as the Kashmir region, and therefore, VHR imagery requires orthorectification before application in high-resolution earthquake-damage (change) mapping. The initial positional accuracy of about 300 to 1000 m, which was acquired with 15°–30° off-nadir viewing angles [26], was improved to about 3–5 m to meet the CE90 accuracy requirement [27].

However, since rapid mapping often places very difficult time constraints on production, time-consuming processes such as a full sophisticated atmospheric correction [23] are only applied when crucial for the image analysis and interpretation process. This is because the emphasis in rapid mapping is primarily on visual interpretation rather than on automated extraction of quantified environmental variables.

Damage assessment is an important task within the framework of rapid mapping, and there are almost unlimited applications of change analysis [5]. However, standard change analyses are not always suitable for VHR, e.g., object-based classification is very time demanding (up to 30 h or more) and not as straightforward as the more conventional Bayesian methods. Change analysis using polygons of varying size and type is a very time-consuming approach, as the identification of homogeneous image sections is a very difficult and time-consuming task. SAR imagery may be used for assessing damages to houses and buildings [28]; however, depending on the type of damage and the type of structures affected, results may also be limited. Another common approach is to visualize change analysis through color coding by means of the predisaster image, e.g., in green, and the postdisaster image, e.g., in red. Hence, an image combination by superimposing the different colors (color additive mixing process) will then reveal unchanged properties in yellow. This method requires very accurate image coregistration and does not allow intuitive reading by the user.

Therefore, a new damage-assessment method was tested for the city of Muzaffarabad (Fig. 4) using visual interpretation on pre- and postdisaster images with 250 × 250 m grid cells. This method, which was proposed by the European Joint Research Center team working on the satellite-based disaster-response efforts, interprets damage to infrastructure and build-up areas for each grid cell by means of the UN housing damage classification [29]: no damage, moderately damage (< 33%), severely damage (33%–66%), and completely destroyed (> 66%). The method uses semitransparent color map overlay to visualize damages (Fig. 4) where blue-colored grid cells show those areas with moderate (light blue) to high (dark blue) damage to infrastructure whereas the orange- and red-colored grid cells

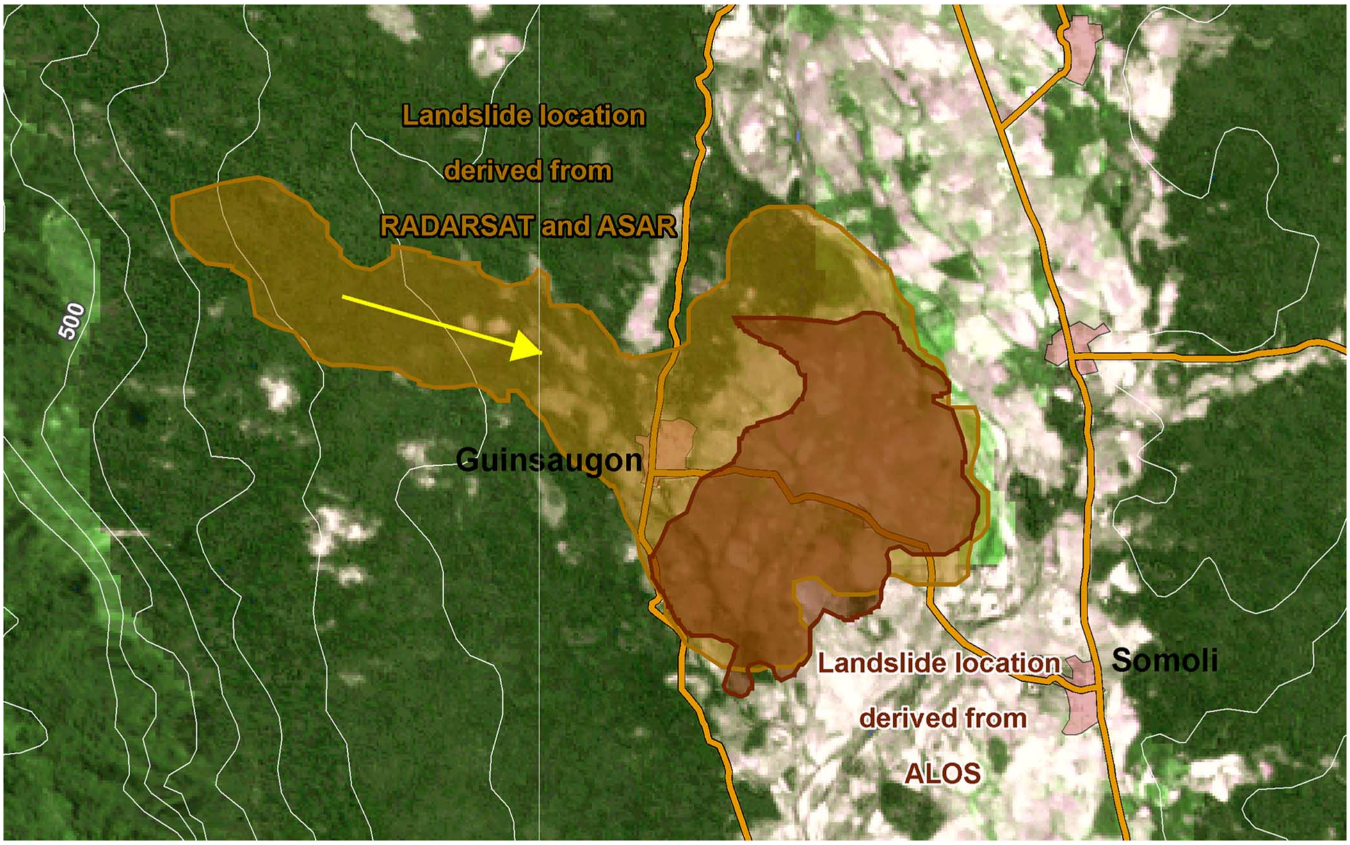

Fig. 5. Crisis map at a scale of 1 : 25 000 of the landslide-affected area around Guinsaugon, Saint Bernard, Southern Leyte Island, Philippines. The backdrop image shows a predisaster SPOT5 image, and the landslide extent was derived from a number of different sensors: Radarsat, ASAR, and ALOS AVNIR-2.

show damage to build-up areas. If enough time is available, map overlay with critical infrastructure information (bridges, airports, tunnels, ports, hospitals, clinics, and schools) should be generated.

According to the users' feedback, the maps and layers (streets, damage, etc.) yield vital information with respect to evacuation planning, general "pathfinding/tracking," to get a better overview and understanding of problems on site. In addition, the maps proved very useful for negotiations about logistics and joint operation among relief organizations in the field.

D. Mapping a Devastating Landslide in the Philippines

On Friday, February 17, 2006, a landslide triggered by heavy rains buried the village of Guinsaugon, Saint Bernard, Southern Leyte Island, Philippines. Most of the approximately 300 houses and the elementary school were fully covered by the mudslide, affecting the 1411 village inhabitants (including 246 elementary school pupils and 7 teachers) at the time of the incident.

The crisis map at a scale of 1 : 25 000 of the landslide-affected area uses a predisaster SPOT5 image, which was acquired on June 1, 2003, as image backdrop. Image processing carried out includes atmospheric correction [23] and the generation of a synthetic blue channel (to provide a true color image to the map users), orthorectification by means of direct georeferencing of SPOT HRS stereo data [30], [31], and image enhancement such as stretching and filtering. VMAP level 0 yielded input as the main gazetteer information source, whereas Google Earth and Microsoft Encarta provided additional information where the VMAP data were missing or inaccurate.

The landslide extent was derived and crosschecked from a number of different satellite sensors: Radarsat, Advanced Synthetic Apperture Radar (ASAR), and ALOS Advanced Visible and Near-Infrared Radiometer (AVNIR)-2. Geocoding of the radar imagery is carried out using a geocoding system developed by DLR [32]–[34], which supports Envisat-ASAR, ERS, J-ERS, Radarsat-1, SIR-C / X-SAR, and TerraSAR-X. The pixel spacing of the in- and output data, as well as the Doppler reference function, are parameterized and are stored in configuration files used by the system. The geocoding product is "enhanced" ellipsoid corrected, which means that the product is projected and resampled to UTM using WGS-84 geodetic reference, and terrain-induced distortions are corrected considering a DEM. The geometric quality of the product is good, due to the height accuracy and resolution of the used SRTM (C-band and X-SAR), ERS-derived elevation models, and the GLOBE elevation information, in combination with the type of terrain and the incidence angle. Even though most SAR processors refer to zero Doppler, the geocoding system is able to consider other reference functions. Multipolarized data are considered as multilayer images. Hence, the landslide extent was derived by means of on-screen digitizing.

The ALOS imagery from the Japanese Aerospace Exploration Agency, which was launched on January 24, 2006, yielded optical data input; however, the sensor only partially imaged the landslide due to partially cloudy weather situation. Hence, accurate geocoding using the SPOT reference scene was established, and again, the landslide extent could be derived by means of on-screen digitizing.

The landslide mapping (Fig. 5) shows the potential of the usage of a number of data sources (SPOT, SRTM, and ALOS) for the benefit of humanitarian relief organizations.

VII. Conclusion and Outlook

Examples could be shown how multiple satellite image processing and analysis techniques may successfully be applied individually or in a combined manor to serve rapid-mapping tasks in the domain of disaster and crisis-management support. It can be concluded that no single commercial or research-oriented satellite system alone can effectively provide and guarantee fast and reliably image access on archive or new postevent imagery. Thus, effective and well-balanced coordination among the different observing systems is required in order to allow best service to the civil-protection and humanitarian relief community. As military observing capacities are usually even more efficient with respect to temporal coverage and spatial resolution, it may be interesting to improve civilian–military cooperation in this domain in the future. There is still a need for an improvement of the availability of consistent, comparable, and reliable high-resolution geospatial data. Initiatives to establish SDI can facilitate the access to reference data, as well as the dissemination of rapid-mapping products. As discussed in this paper, just as with the civil-protection work itself, effective satellite-based disaster-relief efforts rely on international, interdisciplinary, and interorganizational cooperation mechanisms and team work. The European Initiative in GMES provides an important frame in this context.

Acknowledgment

The authors would like to thank the various colleagues of German Remote Sensing Data Center and DLR working in the frame of ZKI, as well as all other national and international institutions cooperating in the global disaster-relief efforts. The authors would also like to thank all the colleagues and institutions involved in the International Charter—Space and Major Disasters and to the team of European Space Imaging in Munich, Germany, and GeoEye for the rapid imagery provision efforts. They would also like to thank D. Ehrlich, C. Louvrier, and D. Khudhairy of the Joint Research Centre for the excellent collaboration and for providing the grid-cell damage-assessment procedure.

References

[1] CEOS, "The use of earth observation satellites for hazard support: Assessments and scenarios. Final report of the CEOS Disaster Management Support Group," 2002. [Online]. Available: http://www.ceos.org/pages/DMSG/pdf/CEOSDM SG.pdf

[2] The International Charter, "Space and Major Disasters," 2000. [Online]. Available: http://www.disasterscharter.org

[3] UN/International Strategy for Disaster Reduction (ISDR), "Terminology of disaster risk reduction," Geneva, Switzerland, 2004. [Online]. Available: http://www.unisdr.org/eng/library/lib-terminology-eng%20home.htm

[4] S. Voigt, T. Riedlinger, P. Reinartz, C. Künzer, R. Kiefl, T. Kemper, and H. Mehl, *Geo-Information for Disaster Management*. Berlin, Germany: Springer-Verlag, 2005.

[5] M. Pesaresi, A. Gerhardinger, and F. Haag, "Rapid mapping assessment of built-up structures using VHR satellite data in Tsunami affected areas," *Int. J. Remote Sens.*, 2006. to be published.

[6] G. Nico, M. Pappalepore, G. Pasquariello, A. Refice, and S. Samarelli, "Comparison of SAR amplitude vs. coherence flood detection methods—A GIS application," *Int. J. Remote Sens.*, vol. 21, no. 8, pp. 1619–1631, May 2000.

[7] Y. Rauste, E. Herland, H. Frelander, K. Soini, T. Kuoremaki, and A. Ruokari, "Satellite-based forest fire detection for fire control in boreal forests," *Int. J. Remote Sens.*, vol. 18, no. 12, pp. 2641–2656, Aug. 1997.

[8] Y. J. Kaufman, C. Ichoku, L. Giglio, S. Korontzi, D. A. Chu, W. M. Hao, R.-R. Li, and C. O. Justice, "Fire and smoke observed from the Earth Observing System MODIS instrument-products, validation, and operational use," *Int. J. Remote Sens.*, vol. 24, no. 8, pp. 1765–1781, 2003.

[9] G. R. Brakenridge, H. Carlos, and E. Anderson, "Satellite gaging reaches: A strategy for MODIS-based river monitoring," in *Proc. 9th Int. Symp. Remote Sens., Int. Soc. Opt. Eng. (SPIE)*, Crete, Greece, 2003, pp. 479–485.

[10] P. A. Townsend and J. R. Foster, "Assessing flooding and vegetation structure in forested wetlands using Radarsat SAR imagery," in *Proc. IGARSS*, 2002, pp. 1171–1173.

[11] B. Jones, "A comparison of visual observations of surface oil with synthethic aperture radar imagery of the sea empress oil spill," *Int. J. Remote Sens.*, vol. 22, no. 9, pp. 1619–1638, Jun. 2001.

[12] C. Bignami, M. Chini, N. Pierdicca, and S. Stramondo, "Comparing and combining the capability of detecting earthquake damage in urban areas using SAR and optical data," in *Proc. IGARSS*, 2004, pp. 55–58.

[13] B. Rabus, M. Eineder, A. Roth, and R. Bamler, "The shuttle radar topography mission—A new class of digital elevation models acquired by spaceborne radar," *ISPRS J. Photogramm. Remote Sens.*, vol. 57, no. 4, pp. 241–262, Feb. 2003.

[14] A. Mansourian, A. Rajabifard, M. J. Valadan Zoej, and I. Williamson, "Using SDI and web-based system to facilitate disaster management," *Comput. Geosci.*, vol. 32, no. 3, pp. 303–315, Apr. 2006.

[15] J. Crompvoets, A. Bregt, A. Rajabifard, and I. Williamson, "Assessing the worldwide developments of national spatial data clearinghouses," *Int. J. Geogr. Inf. Sci.*, vol. 18, no. 7, pp. 665–689, Oct./Nov. 2004.

[16] National Imagery and Mapping Agency (NIMA), "Vector Map Level 0 (Digital Chart of the World)," Bethesda, MD, 2000. [Online]. Available: http://geoengine.nga.mil/geospatial/SW_TOOLS/NIMAMUSE/webinter/rast_roam.html

[17] National Geospatial-Intelligence Agency (NGA), "GEOnet Names Server (GNS)," Bethesda, MD. [Online]. Available: http://earth-info.nga.mil/gns/html/

[18] J. E. Dobson, E. A. Bright, P. R. Coleman, R. C. Durfee, and B. A. Worley, "LandScan: A global population database for estimating populations at risk," *Photogramm. Eng. Remote Sens.*, vol. 66, no. 7, pp. 849–857, 2000.

[19] A. Roth, W. Knöpfle, G. Strunz, M. Lehner, and P. Reinartz, "Towards a global elevation product: Combination of multi-source digital elevation models," in *Proc. Joint Int. Symp. Geospatial Theory, Process. and Appl.*, Ottawa, ON, Canada, 2002, pp. 675–679.

[20] C. J. Tucker, D. M. Grant, and J. D. Dykstra, "NASA's global orthorectified Landsat data set," *Photogramm. Eng. Remote Sens.*, vol. 70, no. 3, pp. 313–322, 2004.

[21] K. T. Kriebel, G. Gesell, M. Kästner, and H. Mannstein, "The cloud analysis tool APOLLO: Improvements and validations," *Int. J. Remote Sens.*, vol. 24, no. 12, pp. 2389–2408, Jun. 2003.

[22] L. Giglio, J. Descloitresa, C. O. Justicec, and Y. J. Kaufman, "An enhanced contextual fire detection algorithm for MODIS," *Remote Sens. Environ.*, vol. 87, no. 2/3, pp. 273–282, 2003.

[23] R. Richter, "Correction of satellite imagery over mountainous terrain," *Appl. Opt.*, vol. 37, no. 18, pp. 4004–4015, Jun. 1998.

[24] T. Toutin, "Geometric processing of IKONOS Geo images with DEM," in *Proc. ISPRS Joint Workshop High Resolution From Space*, Hannover, Germany, Sep. 19–21, 2001, pp. 1–9.

[25] J. Nichol and M. S. Wong, "Satellite remote sensing for detailed landslides inventories using change detection and image fusion," *Int. J. Remote Sens.*, vol. 26, no. 9, pp. 1913–1926, May 2005.

[26] T. Toutin, "Block bundle adjustment of IKONOS in-track images," *Int. J. Remote Sens.*, vol. 24, no. 4, pp. 851–857, Feb. 2003.

[27] C. H. Davis and X. Wang, "Planimetric accuracy of IKONOS 1 m panchromatic orthoimage products and their utility for local government GIS basemap applications," *Int. J. Remote Sens.*, vol. 24, no. 22, pp. 4267–4288, Nov. 2003.

[28] M. Matsuoka and F. Yamazaki, "Image processing of building damage detection due to disasters using SAR intensity images," in *Proc. 31st Conf. Remote Sens. Soc. Jpn.*, 2001, pp. 269–270.

[29] D. Ehrlich, A. Gerhardinger, C. MacDonald, M. Pesaresi, I. Caravaggi, and C. Louvrier, "Standardized damage assessments and reporting—A methodology that combines field data and satellite data analysis for improved damage reporting," EUR. Rep. 22223 EN, European Communities, 2006.

[30] P. Reinartz, R. Müller, M. Lehner, and M. Schroeder, "Accuracy analysis for DSM and orthoimages derived from SPOT HRS stereo data using direct georeferencing," *ISPRS J. Photogramm. Remote Sens.*, vol. 60, no. 3, pp. 160–169, May 2006.

[31] R. Müller, G. Palubinskas, P. Reinarrtz, and M. Schroeder, "From airborne digital raw data to image maps," *PFG Photogrammetrie, Fernerkundung, Geoinformation*, vol. 4, no. 4, pp. 317–326, 2003.

[32] A. Roth, D. Kosmann, M. Matschke, B. Müschen, and H. John, "Experiences in multi-sensoral SAR geocoding," in *Proc. IGARSS*, Lincoln, NE, 1996, pp. 2338–2340.

[33] A. Roth, M. Huber, and D. Kosmann, "Geocoding of TerraSAR-X Data," in *Proc. 20th Int. Congr. ISPRS*, Istanbul, Turkey, 2004, pp. 840–844.

[34] D. Kosmann, M. Huber, M. Bollner, A. Roth, H. Raggam, and D. Small, "Value added geocoded ENVISAT-ASAR product service," in *Proc. ENVISAT/ERS Symp.*, Salzburg, Austria, Sep. 6–10, 2004, [CD-ROM].

Stefan Voigt received the M.Sc. degree in physical geography, physics, and remote sensing from Ludwig-Maximilians-University, München, Germany, in 1997, and the Ph.D. degree, working on a European Commission research project on the remote sensing and runoff/flood forecasting, from Berne University, Berne, Switzerland, in 2000.

Since then, he has been with the German Remote Sensing Data Center (DFD) of the German Aerospace Center (DLR), Wessling, leading a research team on "Crisis Information and Rapid Mapping." Furthermore, he is in charge of the scientific and operational coordination of the DLR/DFD's Center for satellite-based Crisis Information (ZKI) which is contributing to several national and international activities and projects in the field of disaster mitigation, humanitarian relief, as well as civil security. Since 2001, he has been coordinating an international research initiative on innovative technologies for detection prevention and monitoring uncontrolled of coal seam fires in China.

Thomas Kemper was born in Wickede, Germany, in 1969. He received the degree in physical geography and the Ph.D. degree from the University of Trier, Trier, Germany, for his work on quantification of heavy metals in soils using reflectance spectroscopy, in 1997 and 2003, respectively.

From 1998 to 2004, he was with the Institute for Environment and Sustainability of the Joint Research Centre (JRC) in the context of soil degradation and desertification. He joined the German Remote Sensing Data Center of the German Aerospace Center in October 2004 and is currently working in the Center for satellite-based Crisis Information, Wessling, Germany.

Torsten Riedlinger received the M.Sc. degree in physical geography, climatology, and soil science from the University of Trier, Trier, Germany, in 1999.

From 2000 to 2003, he had a Ph.D. scholarship on analyzing and modeling the landscape evolution of a semiarid watershed in southeast Spain. Since the spring of 2003, he has been working in the Center for satellite-based Crisis Information at the German Remote Sensing Data Center of the German Aerospace Center (DLR), Wessling, Germany, including remote sensing and geographic information system analysis, as well as national and international coordination, related to man-made and natural disasters, humanitarian relief, and civil security. Furthermore, he is responsible for DLR's project management within the International Charter on Space and Major Disasters, and he is Project Manager for the German Contribution to the Indian Ocean Tsunami Early Warning System.

Ralph Kiefl received the Diploma degree in physical geography, with a major in geographic information systems (GIS), from Johannes Gutenberg-University, Mainz, Germany, in 2002.

Since April 2002, he has been working at the German Remote Sensing Data Center of the German Aerospace Center, Wessling, in projects for land-cover classification. Since autumn 2003, his main task has been the application of desktop and web-based GIS in the context of satellite-based crisis information.

Klaas Scholte received the M.Sc. degree in physical geography from Utrecht University, Utrecht, The Netherlands, in 1998, and the Ph.D. degree, focusing on geologic applications by using hyperspectral remote sensing, InSAR, and geophysical methods, from the Delft University of Technology, Delft, The Netherlands, in 2005.

He worked for two years with the International Institute for Geo-Information Science and Earth Observation, The Netherlands, and JRC-Ispra, Italy, on remote sensing methods for desertification and vegetation monitoring. Since the autumn of 2005, he has been working with the German Remote Sensing Data Center of the German Aerospace Center, Wessling, in the context of the European Space Agency Global Monitoring for Environment and Security Service Element RESPOND on satellite-based information for humanitarian relief.

Harald Mehl received the Diploma degree in geography and the Ph.D. (Dr. rer nat) degree in remote sensing from Ludwig-Maximilians-University of Munich, Munich, Germany, in 1988 and 1991, respectively.

He was a Senior Scientist with the Working Group Remote Sensing at the Institute for Applied Geology of the Ludwig-Maximilians-University of Munich: organization and realization of research projects in Latin America and South East Asia, in 1992–1996. In 1996–1998, he was Head of the Executive Office of German Aerospace Center Organization and Management. Since 1999, he has been Head of the Unit Environment and Security of the German Remote Sensing Data Center, Wessling, Germany: Management of the unit and definition of new application areas. His profile includes the following: Specialist in remote sensing, geographic information system, geography, geology, and land use, and Education Generalist in agriculture, forestry, soil science, cartography, and hazards.