POTENTIAL AND LIMITATIONS OF SATELLITE REMOTE SENSING FOR GEO-DISASTER REDUCTION

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ABSTRACT

A disaster is defined as "a sudden calamitous event bringing great damage, loss or destruction". Such events can be earthquakes, landslides, floods, hurricanes, volcanic eruptions etc. To reduce the impacts of natural disasters a complete strategy for disaster management is required, involving the aspects of disaster prevention (hazard, vulnerability and risk analysis applied to planning), disaster preparedness (warning and monitoring of disasters) and disaster relief operations. This paper is concentrating on geology-related natural disasters: earthquakes, volcanic eruptions, and landslides. For each of these types an evaluation is given of the usefulness of satellite remote sensing in the three phases of disaster management.

1. INTRODUCTION

A disaster is defined as "a calamitous event bringing great damage, loss or destruction" [3]. Such events can be earthquakes, landslides, floods, hurricanes, volcanic eruptions etc. Some disasters strike within a short period with devastating outcomes (like earthquakes), whilst others have a slow onset period with equally or even more serious repercussions (such as drought). Disasters can be classified in several ways. One possible subdivision is:

- Natural disasters are events which are caused by natural phenomena (such as earthquakes, volcanic eruptions, droughts, hurricanes)
- Human-made disasters are events which are caused by human activities (such as atmospheric pollution, industrial chemical accidents, major armed conflicts, nuclear accidents, oil spills, desertification).

Another subdivision is into geological disasters (earthquakes, volcanic eruptions, landslides, etc.)and ecological disasters (drought, desertification, deforestation, etc.). Almost all disasters are accompanied by a loss of some kind. This could be in the form of property, infrastructure or human life. The losses experienced vary with the type of disaster, its magnitude and the areas affected. Globally, it appears that the toll of death and damage in natural disasters is increasing, although there is no international databank of sufficient comprehensiveness to verify this supposition. The cost to the global economy now exceeds US $50.000 million per year, a third of which represents the cost of predicting, preventing and mitigating disasters and the other two thirds represent the direct cost of the damage [1]. Death tolls vary from year to year around a global mean of about 250.000, while major disasters kill an average of 140.000 people per year. There seems to be an inverse relationship between the level of development and loss of human lives in the case of a disaster. About 95 percent of the deaths occur in the Third World, where more than 4.200 million people live. Economic losses attributable to natural hazards in developing countries may represent as much as 10% of a gross national product. In industrialised countries, where warning-systems and buildings codes are more sophisticated, it is easier to predict the occurrence of natural phenomena, and to warn people in time. The damages, however, are usually less severe in developing countries, with strictly limited resources [1]. An example of this can be given by comparing the great floods in Bangladesh (1988) which caused the death of 1410 people with the Mississippi flood in the USA in 1993, which only caused about 30 fatalities. However, when one compares the economic losses of the two events, the result are reversed: in Bangladesh a total loss of 1.1 Billion US$ was estimated versus 15.8 Billion US $ in the US. Even more striking is a comparison between the hurricane disasters of 1990 in Bangladesh and the 1992 hurricane Andrew in the US.

These statistics illustrate well the importance of hazard mitigation. The International community has become aware of the necessity to increase the work on disaster management. The decade 1990 - 2000 has been designated the "International Decade for Natural Disaster Reduction" by the general assembly of the United Nations. To reduce the impacts of natural disasters a complete strategy for disaster management is required [4,5], involving the following aspects:

* Disaster prevention
  - Hazard analysis: assessing the probability of occurrence of potentially damaging phenomena.
  - Vulnerability analysis: assessing the degree of loss expected to population, infrastructure, and economic activities, as the consequence of an event of a certain magnitude.
  - Risk assessment: assessing the numbers of lives likely to be lost, the persons injured, damage to property, and disruption of economic activities caused by a particular natural phenomenon.
  - Landuse planning and legislation: implementation of a risk map in the form of building codes and restrictions.
* Disaster preparedness
  - Forecasts/warning/prediction of disasters (for example hurricane warning).
  - Monitoring: evaluating the development through time of disasters (for example floods).
* Disaster relief
  - Damage assessment shortly after the occurrence of a disaster.
  - Defining safe areas to indicate possible escape areas.

- Infrastructural monitoring to ensure an undisturbed supply of aid.

Satellite remote sensing techniques can be used for the reduction of natural disasters if these techniques enable us to collect data about atmospheric conditions and/or the characteristics of the earth's surface which may lead to the occurrence of processes which may bring information about natural disasters or can help us to take actions which reduce the disastrous effects of these processes.

2. CHARACTERISTICS OF SATELLITE REMOTE SENSING AND GIS

Remote sensing data derived from satellites are excellent tools for the mapping of the spatial distribution of disaster-related data within a relatively short period of time. Today many satellite-based systems exist, with different characteristics related to their:

- Spatial resolution: the size of the area on the terrain that is covered by the instantaneous field of view of a detector.
- Temporal resolution: the revisit time of the satellite for the same part of the earth surface.
- Spectral resolution: the number and width of the spectral bands recorded.

The most frequently used systems are given in Table 1.

Table 1 Specifications of some frequently used multispectral remote sensing products.

Parameter	Landsat MSS	Landsat TM	SPOT	
			XS	PAN
Number of spectral bands	4	7	3	1
Spectral resolution	0.5 -1.1 µm	0.45 - 2.35 µm 10.4 - 12.5 µm	0.5 - 0.9 µm	0.5 - 0.7 µm
Spatial resolution	80 m	30 m 120 m in TIR	20 m	10 m
Swath widh	185 km	185 km	2 x 60 km	2 x 60 km
Stereo	no	no	yes	yes
Temporal resolution	18 days	18 days	26 days 5 days off nadir	26 days 5 days off nadir

Besides the use of conventional aerial photographs, which often remain the most useful tools in many types of disaster studies, the application of satellite data has increased enormously over the last decades. After the initial low-spatial resolution images of Landsat MSS (60m x 80m), Landsat is also offering Thematic Mapper images with a spatial resolution of 30 meters (except for the thermal infrared band) and an excellent spectral resolution with 6 bands covering the whole visible and the near and middle infrared part of the spectrum and with one band in the thermal infrared. Landsat has an overpass every eighteen days. Despite this theoretical temporal resolution, weather conditions are a serious limiting factor in this respect, since clouds are hampering the acquisition of data of the ground.

The weakest point of the Landsat System is the lack of an adequate stereovision. Theoretically a stereomate of an TM image can be produced with the help of a good digital terrain model (DTM), but this remains a poor compensation as long as very detailed DTMs are not currently available. The French SPOT satellite, however, is equipped with two sensor systems, covering adjacent paths each one with a 60 kilometres swath width. The sensors have an off-nadir looking capability, offering the possibility for images with good stereoscopic vision. The option for sidewards looking results also in a higher temporal resolution. SPOT is sensing the terrain in a panchromatic band and in three narrower spectral bands (green, red and infrared). The spatial resolution in the panchromatic mode is 10 meters, while the three spectral bands have a spatial resolution of 20 meters. The system lacks spectral bands in the middle and far (thermal) infrared.

Radar satellite images, available from the European ERS-1 and the Japanese JERS, are offering an all-weather capability, since the system is cloud penetrating. Theoretically this type of images can yield detailed information on surface roughness and micromorphology. However, the wavelengths and looking angles applied until now have not been very appropriate for the application in mountainous terrain. The first results of the research with radar interferometry are very promising and indicating that detailed terrain models to an accuracy of around one meter or less can be generated, which creates the possibility to monitor slight movements related to landslides, fault displacements or bulging of volcanic structures.

Remote sensing data should generally be linked or calibrated with other types of data, derived from conventional mapping, measurement networks or sampling points to derive at parameters which are useful in the study of disasters. The linkage is done in two ways, either by visual interpretation of the image or via classification.

A very powerful tool in the combination of the different types of data required for disaster management are geographic information systems. A geographic information system (GIS) is defined as a "powerful set of tools for collecting, storing, retrieving at will, transforming and displaying spatial data from the real world for a particular set of purposes" [2].

The first experimental computerised GISs were developed as early as the nineteen sixties, but the real boom came in the eighties, with the increasing availability of "cheap" (personal) computers. It is estimated that by 1986 more than 4000 different systems had been developed around the world [2]. Many different GIS systems exist today, with different characteristics with regards to the type of data structure (vector versus raster), data compression techniques (quadtrees, run-length coding), two-dimensional versus three-dimensional data storage, mainframe, mini-, and microcomputer hardware, and user interfaces (pop-up menus, mouse-driven, help options, etc.).

Spatial data, used in GIS, is data with a geographic component, such as maps, aerial photography, satellite imagery, and rainfall data, borehole data etc. Many of these data will have a different projection and coordinate system, and need to be brought to a common map basis, in order to superimpose them. GIS allows for the combination of these different kinds of spatial data, with non-spatial attribute data, and use them as input data in complex models. One of the main advantages of the use of the powerful combination techniques of a GIS, is the evaluation of several scenarios, and the analysis of the sensitivity of the models by varying some of the input data.

3. CHARACTERISTICS OF GEOLOGICAL NATURAL DISASTER TYPES AND THE ROLE OF REMOTE SENSING

Widely known are the potentials of applications of data from satellites to predict weather-related disastrous phenomena such as extreme storms and rainfall. This paper is concentrating on geology-related natural disasters. As these disaster types are concerned with natural phenomena with wide variations in characteristics, size, speed of development, etc., the following paragraphs will concentrate separately on the role of satellite remote sensing in the reduction of the following three types of geological hazards: earthquakes, volcanic eruptions, and landslides.

3.1 Earthquakes

The area affected by earthquakes are generally large (in the order of 102 - 104 km^2), but they are restricted to well-known regions (e.g. plate contacts). Typical recurrence periods vary from decades to centuries. Observable associated features include fault rupture, damage due to ground shaking, liquifaction, landslides, fires and floods. The following aspects play an important role: distance from active faults, geological structure, soil types, depth of the water table, topography, and construction types of buildings.

In the phase of disaster prevention satellite remote sensing can play an important role in the mapping of active faults, using neotectonic studies using Landsat TM/SPOT or radar, and in the measurement of fault displacements, using satellite Laser Ranging (SLR), Global Positioning System (GPS), or radar interferometry. So far the most important data for seismic hazard zonation is derived from seismic networks. In seismic microzonation, the use of satellite remote sensing is very limited, since the data is derived from accelerometers, geotechnical mapping, groundwater modelling, and topographic modelling at large scales. Earthquakes cannot be predicted with the current state of knowledge, and therefore also satellite remote sensing cannot play a role in the phase of earthquake disaster preparedness. In the phase of disaster relief, they can only play a role in the identification of large associated features (such as landslides). Structural damage to buildings cannot be observed with the poor resolution of the current spaceborne scanning or radar systems.

3.2 Volcanic Eruptions

The areas affected by volcanic eruptions are generally small (< 100 km^2), and restricted to well-known regions. The distribution of volcanos is also well known, however, due to missing or very limited historical records, the distribution of active volcanos is not (especially in developing countries). Many volcanic areas are densely populated. Volcanic eruptions can lead to a large diversity of processes, such as explosion (Krakatau, Mount St. Helens), pyroclastic flow (Mt. Pelee, Pinatubo), lahars (Nevado del Ruiz, Pinatubo), lava flows (Hawai, Etna), and ashfall (Pinatubo, El Chincon). V Volcanic ash clouds can be distributed over large areas, and may have considerable implications for air-traffic and weather conditions.

Satellite remote sensing can be used in the phase of disaster preparedness for the distribution and type mapping of the of volcanic deposits using Landsat TM, SPOT, or Radar. For the determination of the eruptive history other types of data are required, such as morphological analysis, tephra chronology, and lithological composition. Volcanic eruptions occur within minutes to hours, but are mostly preceded by clear precursors, such as fumarolic activity, seismic tremors, and surface deformation (bulging). The thermal band of Landsat TM can be used to monitor the thermal characteristics of a volcano, and radar interferometry in the measurement of surface deformation. NOAA-AVHRR data can be used to monitor lava flows or ash plumes. Meteosat, GOES or TOMS (Nimbus-7) can be used to monitor the extent of volcanic ash clouds and the SO_2 content.

Using SIR-C/X-SAR multi-frequency two-pass interferometric radar imagery Lanari et al. (1996) [7] performed a (non classical) textural analysis by estimating fractal fBm parameters over Mount Etna. Furthermore, fractal analysis proved that the pivoting median filter strongly reduces the high frequency artifacts that affect interferometric SAR DEMs, and, on the other hand, makes geological features definitively more apparent. This analysis also showed that the multi-frequency fusion of SAR data preserves all the geological content. In their trailblazing paper the authors state that future developments of the proposed technique for the generation of multi-frequency, two-pass interferometric SAR DEMs combined with thematic information promise an extremly high potential for volcanic disaster issues.

3.3 Landslides and Other Mass Movements

Individual landslides are generally small (0.001 - 1 km^2), but they are very frequent in certain mountain regions. Landslides occur in a large variety, depending on the type of movement (slide, flow, fall), the speed of movement (mm/year - m/sec), the material involved (rock, soil), and the triggering mechanism (earthquake, rainfall, human interaction).

In the phase of disaster prevention satellite imagery with sufficient spatial resolution and stereo capability (SPOT) can be used to make an inventory of the past landslides, and to collect data on the relevant parameters involved (soils, geology, slope, geomorphology, landuse, hydrology, rainfall, faults etc.) In the phase of disaster preparedness use could be made of the same systems applied for the prediction of floods (see Section 3.1). Monitoring of displacements of large landslides can be performed with radar interferometry. The assessment of damage using satellites is only possible if the spatial distribution is very high, or if the individual landslides are large.

An important interpretation element for both lithological and structural analysis of SAR with respect to mass movements is the drainage pattern. In general, the geomorphological detail and the synoptic view of a density of a drainage pattern are closely related to the lithology, i.g. resistence to erosion, permeability of the ground, slope angle, and tectonic control.

One reason why imaging radar is useful for mass movements applications is ist sensitivity to surface roughness and slope. The intensity of radar backscatter strongly depends on the local slope and is also affected by smaller-scale surface roughness (Pettengil et al., 1986). The roughness of a surface serves as an important attribute in terrain analysis and is often closely related to the (underlying) geological substrate. Roughness may also be caused by weathering processes, soil composition, or vegetation associations. In areas where the surface is unvegetated and dry, in arid or semiarid regions, deep penetration is possible. On the other hand the penetration capabilities in densily vegetation-covered regions are hampered by surface and volume scattering. It depends on what one is looking for, either to perform topographic analysis or to investigate vegetational effects the obtained results will be completely different. The depth of penetration of electromagnetic waves normally incident from air or space onto the earth increases with longer wavelengths and also with a decrease in the attenuation losses and volume scattering within the shallow subsurface The attenuation in the soil is governed by soil moisture (one per cent effectively rules out any deeper penetration) and soil texture. (Drury, 1993; Carver et al., 1987).

SAR is especially sensitive to the presence of water, either in the form of soil moisture, liquid water in a snowpack, or vegetation moisture. The extraction of hydro information from SAR imagery of terrain surfaces is a difficult task, because the image intensity is a complex function of many radar and target parameters. These may include wavelength, incidence angle polarisation, soil moisture, vegetation cover, surface roughness, slope aspect, and temporal cover, e.g. a snow coverage. Multi-polarised data can, in principle, be used to separate surface roughness effects from soil moisture effects. The dielectric properties of soil are essential in determining microwave backscattering and absorbtion by soil.

An addional approach for using soil moisture data derived with microwave approaches is through change detection. The change detection method minimises the impact of target variables such as soil texture, roughness, and vegetation, because these tend to change slowly, if it all. Also fortunatly for many hydrologic applications, the changes in soil moisture may be more important than the actual monitoring (Engman 1991; Lichtenegger 1992).

Spaceborne SARs are well-suited for soil moisture investigations over large areas. For instance, a SAR flown 800 km altitude with incidence angles of 17° to 23° would cover a swath of approximatly 100 km.

4. CONCLUDING REMARKS

In Table 2 a summary of the usefulness of satellite remote sensing in the different phases of disaster management for flooding, earthquakes, volcanic eruptions, and landslides is given. From this table it can be concluded that most promising results can be expected in the fields of volcanic eruptions and flooding, as both types of disasters result in features that are clearly recognisable with the use of satellite imagery. Earthquakes and landslides generally result in damages to objects that are too small to recognise on the current imagery.

Table 3 lists the current satellite remote sensing data that could be used in disaster management.

Table 2 Usefulness of Satellite Remote Sensing for Disaster Management:

Disaster type	Disaster prevention	Disaster preparedness	Disaster relief
Volcanism	++	++	++
Earthquakes	+	-	0
Landsliding	0	+	+
Flooding	++	++	++

++ = very useful, + = useful, = of limited use, - = not useful

Table 3 The current satellite remote sensing data that could be used in disaster management.

Disaster type	Disaster prediction	Disaster preparedness	Disaster relief
Volcanism	TM/ SPOT (radar)/ ERS/ JERS	TM/ NOAA	TM/ SPOT/ GOES/ TOMS/ ERS/ JERS
Earthquakes	TM/ SPOT/ ERS/ JERS	-	TM/ SPOT/ ERS/ JERS
Landsliding	SPOT/ ERS	NOAA/ ERS/ JERS	TM/ SPOT/ ERS/ JERS
Flooding	TM/ SPOT/ ERS/ JERS	NOAA/ Meteosat	TM/ SPOT/ ERS/ JERS

Finally, the following conclusions can be stated:

* The existing tools can generally be considered adequate. Currently SPOT and Landsat TM are the most used systems.

* Temporal resolutions (and spatial resolution) should be improved. There is however, a clear need for certain types of disasters (earthquake, landslides) to have stereoscopic data with a larger spatial resolution.

* In many applications weather condition are the most important drawback. In the near future, however, it is expected that many applications will derive from the use of ERS and JERS data, especially in areas where

the use of satellite data was seriously limited by the nearly continuous cloud coverage.

* New tools should be analysed:
Viewing and target parameters confine the possibilities of SAR imagery. Radar systems with variable system parameters such as multiple frequencies, electable look directions and depression angles, and full polarmetry will considerably increase the utility of radar imagery for geological and hydrological studies (cf. Tab. 5 and 6). However, the user must be aware that the efficiency of imaging radars is best in flat terrain and decreases in hilly and mountainous terrain, respectively.

Table 5 The potential of SAR for the application to major geological and hydrological phenomena concerning disaster management

Disaster Mangement / Geolog. & Hydrogeol. Phenomena	Hazard/ Vulnerability Analysis	Early Warning	Disaster Effects/ Relief	Planning/ Mitigation
Rockfall	+[2]	+[3]	+[2]	+
Landslide	++	++	++	++
Creep/flow[1]	+[5]	+	n.a.	+
Mudflow	++	+	++	++
Soil moisture	+	∅[4]	n.a.	∅
Ground water aquifer	∅	∅	∅	++[3]
Flood	+++	++[4]	+++	+++
Snow smelt	++	+[4]	n.a.	++
Snow avalanche	++	+	+++	++

[1] no sudden events
[2] only detectable if debris shows up sufficiently
[3] fractures/faults can be mapped as idicators
[4] provided, repetition rate is suffcient
[5] time-series required

Key:

n.a.	not applicable
∅	fair
+	good
++	better
+++	exellent

Table 6 Potential of major SAR features for the ascertainment of physical ground properties with regard to their relevance for mass movements. Incidence angle mainly based on NASA 1987.

Geolog. & Hydrogeol. Phenomena	MULTI-FREQUENCY λ				MULTI-POLARISATION HH,HV,VV,VH				POLARIMETRY				INTERFEROMETRY				Inc. ang. θ
Disaster Management	HA	EW	DR	PL	HA	EW	DR	PL	HA	EW	DR	PL	HA	EW	DR	PL	
Creep/flow[1]	+	n.a.	+	+	∅		∅	∅	+		+	+	++	+	++	++	10-25
Mudflow	++	n.a.	++	++	+		+	+	++		++	++	++		+++	+++	10-20
Landslide	++	n.a.	++	++	+		+	+	++		++	++	+++		+++	+++	10-20
Rockfall	+	n.a.	+	+	+		+	+	++		++	++	+++	∅	+++	+++	35-55
Flood	+++	+++	++	++	+++	+++	+++	+++	+++		+++	++	+	+	+	+	30-40
Aquifer	n.a.	n.a.	n.a.	+	∅	∅	n.a.	+		∅	n.a.	+	+	∅	∅	+	20-30
Soil moisture	++	+	++	+	++	∅	++	++	+++	∅	+++	+++	∅	∅	∅	∅	20-30
Snow smelt	++	+	n.a.	++	++	++	n.a.	++			n.a.		∅	∅	∅	∅	10-20
Snow avalanche	++	+	++	++	++	+	+	+	+++	∅	+++	+++	+++	∅	+++	+++	25-40

[1] no sudden events

θ = Recommendable optimum INCIDENCE ANGLE

Key:

HA	hazard analysis
EW	early warning
DR	disaster relief
PL	plannin/mitigation

n.a.	not applicable
∅	fair
+	good
++	better
+++	exellent

* However, the application of the satellite data is seriously limited by a lack of funding. Funding of research in applications is in no relation to funding for space technology research.
* Accessibility of data is a problem. Applications in real time are mostly only possible on paper, as the time needed for ordering and acquiring satellite images is mostly excessively large.
* Satellite remote sensing can only give part of the answer to Geological Disaster Management. It will always be combined with other types of data.
* Policy decisions are required to make operational use of satellite remote sensing in the following fields:
  - Investments in hard- and software
  - Compatibility and continuity of systems
  - More training
  - Improving awareness among decision makers.

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