NATURAL HAZARD ASSESSMENT AND MITIGATION FROM SPACE: THE POTENTIAL OF REMOTE SENSING TO MEET OPERATIONAL REQUIREMENTS

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Abstract

The utility and application of remote sensing to natural hazard assessment and mitigation are growing rapidly, pushed by the surge of awareness and activity resulting from the International Decade for Natural Disaster Reduction as well as the growing number of pertinent satellite systems and their capabilities. Remote sensing techniques can be used in all three aspects of disaster management - vulnerability assessment, warning, and damage assessment. They are used in all types of natural disasters including severe storms, floods, landslides, volcanic eruption and earthquakes. All types of remotely sensed data are employed including both medium- and high-resolution visible as well as infrared imagery, and active and passive microwave data. Future systems suggest further improvements in capability (for example, ultra-high spatial resolution, topographic mapping and strain measurements). Many remote sensing applications (e.g. severe storm warning, drought assessment) have already become operational. Others require additional research and/or development or the dedication of effective operational satellites. Growing enthusiasm and commitment among the national and international space agencies indicates that they are ready to meet this challenge.

1. Introduction

The rapid growth of the world's population and its increased concentration, often in hazardous environments, has served to escalate both the frequency and severity of natural disasters. On the other hand, better tools are being devised to meet this challenge. The rapid growth in the number and effectiveness of earth observation satellites presents a wide range of new capabilities which can be used to mitigate the effects of disasters or even to avoid them altogether.

These two considerations - the increase in disasters and in the technical capabilities needed to combat them - gave rise, several years ago, to the proposal for an International Decade for Natural Disaster Reduction. The fundamental principle of the IDNDR, which is currently being carried out by the United Nations and its member states, is to provide a mechanism for the configuration and adoption of available technologies for the improvement of disaster reduction.

The purpose of this paper is to outline the use of satellite remote sensing in the assessment and mitigation of natural hazards and to consider how these applications can be further developed In order to explore these issues, however, it is necessary to understand the underlying causes of natural disasters, how responsible organisations deal with (some may say, "manage") disasters, the relevant technical capabilities of the satellite systems (both now and in the future) and approaches to making these capabilities operationally useful and used.

2. Major natural diasters and underlying causes

A natural disaster is the result of the occurrence of a natural phenomenon (a hazard) with which a population cannot deal thus resulting in mortality, injury, displacement and/or economic loss. Several considerations underlie this simple definition. Most important is the ability to deal with disaster.

Developing countries generally find it more difficult to avoid disasters. For example, it may not be economically feasible to construct adequate flood control systems or earthquake-resistant structures. Or their population may be forced to live in hazardous areas such as low-lying coastal regions prone to storm surge flooding. On the other hand, social conventions may play a part. Some years ago, a moderate earthquake in South Yemen resulted in anomalously high mortality because the three-room dwellings there are customarily built vertically with uncemented stones which crashed down on people as they slept Rapid population growth and its concentration, particularly in the urban environment, have also increased the frequency of disasters. More and more people are living in coastal areas which are vulnerable to severe storms and storm surges. On the steep slopes outside cities such as Bogota, we can see great numbers of shanties thrown together on the hillsides, apparently waiting for a landslide Urbanisation in earthquake-prone regions of California just as in Mexico City are a prescription for disaster. So we see that the basic factors underlying natural disasters are societal including population growth and concentration, unwise land use, ignorance and poverty. It is important to bear this in mind as we try to apply sophisticated remote sensing space technology to the problem of disaster reduction.

Broadly speaking, natural disasters can be divided into two major categories: slow- and rapid-onset. The distinction is important in trying to match the observational frequency of a remote sensing system to operational requirements. Slow-onset disasters, of which drought is the prime example (but also including some vector-borne disease and desert locust infestations) develop over a period of weeks to months. It is quite possible that climate change, occurring on a timescale of decades or longer, might be sufficiently rapid so that societies would find it difficult to adapt resulting, ultimately, in disasters. A potential example of this is the increased vulnerability of low-lying areas to flooding because of sea-level rise. Most natural disasters, however, have onsets ranging from days down to, perhaps, hours or seconds. Severe storms have life cycles, and may be tracked, for days Volcanic eruptions may develop over a period of days (but the eruptive phase vary from weeks down to minutes). Landslides and earthquakes seem to develop rapidly (i.e. within hours to minutes) before cataclysm although both may be the result of slow, long-term (and possibly observable) earth movements.

According to Berz (1991) who presented a record (admittedly incomplete) of major disasters extending from 1960 to 1989, the most costly disasters in this period were earthquakes (440,000 dead, $67 (US) thousand million damage) followed by hurricanes (350,000 dead, $34 thousand million damage) A few caveats to these figures should be noted. First, earthquake mortality is dominated by the Beijing earthquake of 1976 which alone accounted for 242,000 deaths and hurricane mortality is skewed by the 1970 cyclone in the Bay of Bengal, the storm surge of which resulted in 300,000 deaths on the coast of Bangladesh. It is furthermore quite difficult to obtain complete records for disasters and, thus, Berz's record of drought fatalities (48) appears low. Indeed, his record does not mention drought fatalities in the Sahel. However, we can gain from these statistics somewhat of an appreciation for the relative severity of disasters. Volcanic eruptions have had their toll almost 29,000 deaths (largely due to the eruption of Nevado del Ruiz in 1985) but only one thousand million dollars (US) in damage On the other hand, severe storms (hail, snow, etc.) have had a small toll (2000 deaths) but significant economic impact ($17 thousand million).

It is also likely that the major events reported by Berz do not generally equal the sum of smaller-scale disasters which generally escape public notice. Following is a list of a few such small-scale disasters reported *at random* from weekly newspaper notices:

April 13,1990	Tanzania	Worst flooding in 50 years swept away several villages; 54 dead
May 4, 1990	Sahel	Drought left 800 dead; 550,000 near starvation
July 13, 1990	India	Floods and mudslides killed 150
Dec 13, 1990	Iran	Storms killed 22 people; major damage in Lebanon and Egypt
Aug.7, 1992	Venezuela	Nine dead, 10,000 homeless in floods and mudslides
Nov.20, 1992	Sri Lanka	250 dead in tropical storm
Aug.6, 1993	Mid East	Locust swarm across Red Sea toward Algeria
Dec.17, 1993	Vietnam	Typhoon Lola results in at least 78 dead, loss of fishing fleet
Feb.18, 1994	Indonesia	Earthquake and landslides injure 1000; Pinatubo volcano active.

The frequent and worldwide occurrence of disasters will require wide attention extending beyond spectacular events such as the eruption of Mt. Pinatubo, the Beijing earthquake and the Bangladesh floods or the politically interesting events such as the Armenian earthquake. Effective disaster reduction will be a full-time occupation.

3. Disaster management

In general, we cannot control Nature, we cannot stop the development of natural phenomena We *can*, however, control man's relationship *to* Nature. We can control our exposure to hazards, we can try to avoid disasters, and we can try to alleviate the effects of a disaster should one occur. The following steps outline the elements of disaster management. (These definitions are from the "International Agreed Glossary of Basic Terms Related to Disaster Management" available from the Department of Humanitarian Affairs, United Nations Offices in Geneva.) They are:

Prevention: Activities designed to provide permanent protection from disasters. It includes engineering and other physical protective measures, and also legislative measures controlling land use and urban planning. (*Planning, in turn, is based on three important elements: hazard mapping, vulnerability assessment and land cover mapping*)

Preparedness: Activities designed to minimise loss of life and damage, to organise the temporary removal of people and property from a threatened location and facilitate timely and effective rescue, relief and rehabilitation. (*n.b. an essential element of this is disaster warning*)

Relief: Assistance and/or intervention during or after disaster to meet the life preservation and basic subsistence needs. (*In a real sense, disaster relief can be considered to be the result of failure in prevention and/or preparedness.*)

Often, in considering the possible contribution of remote sensing, we focus on relief and, possibly, preparedness (warning). In the case of most (i.e. rapid-onset) disasters, this places a strong burden on frequency of coverage which is often impossible to achieve. It is important to note, however, that in many cases remote sensing can make a valuable contribution to disaster prevention where frequency of observation is not such a prohibitive limitation

It is instructive to consider the organisations responsible for disaster management in terms of these components. Agencies of government at various levels are responsible for disaster prevention. Hazard, vulnerability and land cover mapping often falls to national-level agencies with specific scientific or technical capabilities (e.g. geological surveys for earthquakes and volcanoes; meteorological agencies for floods). However, land use, based on these assessments, involves decisions generally reserved for local jurisdictions. In the case of internationally-financed development projects, funding institutions (e g. the World Bank) often recognise the importance of protecting their investment through vulnerability assessment and proper planning.

The essential element of preparedness, disaster warning, should be the domain of national-level technical organisations. However, this can only be truthfully said in the case of severe storm warnings for which national weather services take responsibility under a formal worldwide agreement with the World Meteorological Organisation. Similarly, flood warnings, where they are made, are generally the responsibility of the national weather services. Operational drought monitoring is being carried out by the Food and Agricultural Organisation and International Oceanographic Commission operates a Tsunami Warning System. Warnings of volcanic eruptions may be the responsibility of national agencies - as in Japan - or may relay on the advice of *ad hoc* groups of scientists (as is often the case in developing countries).

The first line of disaster relief consists of local and national-level agencies in the stricken region: the police/fire services, the local Red Cross and military organisations. Larger disasters, especially those in developing countries, draw support from a large range of voluntary organisations (e.g. Oxfam, Medecins san Frontieres) or official relief groups from other countries. Several international organisations provide disaster relief, often for specialised purposes (e.g. World Health Organisation, Food and Agricultural Organisation) but also for general purposes (League of Red Cross and Red Crescent Societies, UN Department of Humanitarian Affairs)

Most organisations agree that, ideally, the most effective disaster management would focus first on prevention, next on preparedness and lastly on relief In practice, however, certain realities obviate the ideal. A cynical point of view is that economics and/or self-interest militate against effective disaster prevention. In less affluent countries, there are often few options: lives do not have sufficient value to warrant preventive measures. In developed countries, the pressure to develop land, no matter how vulnerable, may be so great as to make people ignore the hazards. In applying remote sensing, it is important to bear these caveats in mind and search out those communities, organisations and mechanisms which are really dedicated to effective disaster prevention. Fortunately, these do exist.

4. Application of remote sensing to disaster management

Examples of the uses of remote sensing in the three aspects of disaster management are presented in Table 1. In this table, a distinction is made among applications which are currently operational, those requiring research and development, those requiring improved observing systems and those requiring, specifically, ultra-high spatial (e g. 1-metre) or temporal (e.g. daily observations) resolutions. The assessments in the table are those of the author and are meant to be broadly interpreted.

Perhaps the most immediate contribution which remote sensing can make is to disaster prevention, primarily because it imposes less stringent requirements on frequency of coverage. Land cover and land use maps, at ever-improving cartographic resolutions, are routinely available using satellite data. In addition, physiographic features (e.g. slopes, bathymetry) may be inferred or even measured and natural features (e.g. lineaments, volcanic features)

Table 1. Examples of the uses of space remote sensing in disaster management

	PREVENTION	PREPAREDNESS (WARNING)	RELIEF
EARTHQUAKES	Mapping geological lineaments and landuse	Geodynamic measurements of strain accumulation	*Locate stricken areas, map damage*
VOLCANIC ERUPTIONS	**Topographic** and landuse maps	**Detection/measurement of gaseous emissions**	Mapping lava flows, ashfalls and lahars, *map damage*
LANDSLIDES	**Topographic** and landuse maps	**Soil porosity; rainfall, slope stability**	*Mapping slide area*
FLASH FLOODS	Landuse maps	**Local rainfall measurements**	*Map flood damage*
MAJOR FLOODS	Flood plain maps, landuse maps	Regional rainfall, evapotranspiration	Map extent of floods
STORM SURGE	Landuse and land cover maps	Sea state, ocean surface wind velocities	*Map extent of damage*
HURRICANES		**Synoptic weather forecasts**	*Map extent of damage*
TORNADOES		Nowcasts, local weather observations	*Map amount, extent of damage*
DROUGHT		**Long-ranged climate models**	Monitoring vegetative biomass; station communications

Normal - Operational or needs very little research
Underlined - Research and development required
Bold - Requires improved observation capability
Italics - Requires improved spatial or temporal resolution

can be mapped to produce, or improve, vulnerability maps. A major new benefit could be provided by global digital topographic maps, for example in assessing vulnerability to landslides or volcanic ash flows Such maps also are integral to the production of flood plain maps for assessing vulnerability to floods.

For disaster preparedness flood plain maps (and topographic maps) are fundamental in producing flood warnings. In addition, real-time input on other parameters such as rainfall (and soil moisture) are needed Ground doppler radar data are also very valuable for this purpose. However, it is possible that, in the future, such measurements will be supported or replaced by satellite microwave, and radar systems such as those being flown experimentally on the Tropical Rainfall Mapping Mission.

Precise geodetic positioning based on laser ranging, very-long-baseline interferometry and, more recently, the Global Positioning System, has been used to map strain accumulation which may, eventually, contribute to a capability for predicting earthquakes Very recently, however, the ability of synthetic aperture radar interferometry to observe and map very small earth movements has been demonstrated Such products, obtained by precise comparison of the return radar phase in two images taken days or weeks apart, have been used to investigate the strain release after an earthquake It is possible that, with additional research, we will be able to observe the accumulation of strain which may help warn of earthquakes, or the slow earth movements which may precede volcanic eruptions or landslides (see Rossi, this volume).

Using geosynchronous and polar-orbiting meteorological satellites, we can now track hurricanes and alert coastal areas in danger. The required operational infrastructure based on these systems is in place However, the large differences in rainfall and wind velocity in these storms, particularly with respect to their rotation and forward velocity vectors, makes it highly desirable to predict landfall within about 100 km and this is not as yet always possible even hours in advance Clearly, improved models and observations which will increase the anticipation time and enhance the accuracy of hurricane forecasts should be developed.

Diaster relief applications generally require both high spatial- as well as high temporal-resolution. Perhaps the only exception to this requirement is in mapping droughts and major floods as these occur over large areas and persist for relatively long periods. Other disasters (flash floods, landslides, earthquakes and volcanic eruptions) are more transitory and generally occur in restricted areas dictating the need for high spatial resolution. In the case of landslides, eruptions and flash floods, the land cover is sufficiently altered that high-resolution (e.g. 15 metre) imagery may suffice. In the case of earthquakes, however, it may be necessary to detect damage to individual structures, requiring spatial resolution of one metre. At the same time, in this case, it would be necessary to be able to make such observations within a few (e.g three) days of an event. While difficult to achieve, this would be a very worthwhile capability. For example, in the case of the 1988 earthquake in (then) Soviet Armenia, the extent of damage after the recent Loma Prieta earthquake was not realised for several days. A major difficulty is that an earthquake often destroys normal means of communication and the area of potential damage is so great that aircraft surveys are not feasible and, as a result, valuable time is lost before medical aid and supplies can be provided.

5. Satellite remote sensing systems for disaster management

A summary of remote sensing systems for disaster management (Walter, 1993) has recently been completed covering over 40 spacecraft and instruments with capabilities for making contributions in this area. The survey considered meteorological satellites (low to moderate spatial resolution) and Earth observation satellites (moderate to high resolution) [see table at end of this volume].

A major consideration for development of remote sensing for disaster reduction is the extent to which operational users can rely on a continued supply of data Of the types of satellites considered, meteorological satellites are more often operational that is, there is a commitment to continually provide data with, at worst, minor interruption. Many nations and consortia have risen to this commitment so it is likely that these geosynchronous and polar-orbiting satellites will continue to be available. On the other hand, there are a significant number of research systems being developed which may be prototypical of future operational systems. The following section considers both research and operational systems but attempts to clearly distinguish between them.

Although designed and operated to observe and forecast weather patterns, meteorological satellites have found application in several other important disaster applications due generally to the high frequency of coverage and moderate resolution. For example, short-wave infrared data are used to monitor vegetation and drought conditions and the sudden vegetation growth which can give rise to desert locust swarms. Visible and thermal infrared imagery from geosynchronous satellites are used to estimate rainfall and rainfall rates and passive microwave systems on polar orbiting satellites yield data on soil moisture. Visible, thermal and ultra-violet data are used to detect and track volcanic plumes which pose danger to jet aircraft.

New and future capabilities of meteorological satellites should also be of use in disaster management Scatterometers are being used to map wind fields over the oceans and these fields should be useful in assessing the severity (and perhaps to predict the path) of hurricanes. Radar and microwave systems on the Tropical Rainfall Mapping Mission should demonstrate an improved capability for direct measurement of rainfall over the land as well as the oceans. Such a capability (especially when available outside the tropics and when combined with geosynchronous satellite data) may contribute to greatly improved rainfall estimates.

The greatest potential of currently operational Earth observation satellites (e.g. SPOT, Landsat) is in disaster prevention (e.g. mapping volcanoes, lineament mapping, flood plain mapping, landslide vulnerability assessment) where the spatial and temporal resolution characteristics are not limiting. In disaster warning, there have been some experiments in which thermal state of volcanic craters has been monitored Visible data have also proven interesting in determining the extent of flooding or storm damage.

The new synthetic aperture radar capability of ERS-1 and JERS-1 (and, in the future, Radarsat) will provide high (ca 15-20 metre) spatial resolution while offering increased temporal resolution because of cloud-penetration. This should greatly improve our capability to map the extent of flooding and the effects of volcanic eruptions and landslides.

However, further improvements in Earth observation satellites' capabilities for disaster management will have to await some additional developments Examples of these are:

- global topographic mapping at precision of 10 metres (vertical) or better for input to landslide vulnerability and flood plain maps;
- satellite-based radar interferometry for detection of dilatancy of volcanoes and strain accumulation in earthquake regions or earth movements in landslide areas;
- high-spatial, high-temporal resolution systems for damage detection and assessment To be effective for, say, earthquake damage assessment, spatial resolution of one metre and a (potential) acquisition within three days would be needed. This capability is being proposed by Japan with the HIROS system slated for

launch in the next century and commercial US companies.

6. The future of remote sensing for disaster reduction

As a result of the IIDNDR, there is increased worldwide interest, awareness, and planning for the future Remembering that the IDNDR was created to focus available technology on disaster reduction, it is entirely fitting that we consider how satellite remote sensing can be organised so as to maximise its capability and contribution.

The elements of this organisation already exist, or are being developed. Many of the world's space agencies are developing relevant systems and/or programmes Japan, as noted, is devoting its future HIROS system, at least in part, to disaster reduction. The subject is an important part of NASDA's future plans in space. In the US, NASA is just beginning a programme specifically aimed at geological hazards. China and other countries in the Pacific have initiated programmes in which remote sensing is used for disaster reduction research and operations

At the international level, the United Nations Outer Space Affairs Division continues to sponsor regional conferences on the subject of disasters and in February 1994 the IAF and COSPAR once again organised a Symposium on Space and Natural Disaster Reduction for the Committee on the Peaceful Uses of Outer Space After a year under the Space Agency Forum, the Committee on Space and Natural Disaster Reduction has been constituted under the aegis of the International Astronautical Federation Last summer, an international group of about thirty advanced students at the International Space University published a plan for a, "Global Emergency Observation and Warning System". Next year, in The Netherlands, and under the auspices of ESA, we expect to convene a Workshop and Symposium which will include both representatives from developing countries as well as from most of the world's space agencies to review requirements (and hopefully begin to draft plans for) a coordinated global space-based disaster observing system.

What would such a system look like? How might it be organised? Perhaps we can draw from the experiences of weather forecasting and Global Change. Both subjects deal with the application of satellite technology to global problems. In the case of weather forecasts, activity centres around the World Meteorological Organisation, but the space component is coordinated largely through separate international understandings. Satellites being developed for Global Change investigations are coordinated under the aegis of the Committee on Earth Observing Systems while other organisations (e.g. IGBP) are concerned with carrying out the general programme. It thus appears that it is not necessary to have one single organisation responsible for disaster reduction as well as coordination of an observing system To accomplish the latter, a consortium or committee created by the space agencies could be effective. However, in order for it to work, it must be linked to, and have the support of organisations which have a recognised responsibility in disaster management. The designation of this organisation and its linkage to the space community might well be a major significant result of the IDNDR.

7. References

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Discussion

In his responses to several questions Dr Walter said that TRMM data might be made available to developing countries via Internet, but that NASA might be approached for direct reception The ultimate resolution of satellite data is determined by several factors. and for example the vibration of the satellite sets a limit of around 1 cm Use of several satellites would not overcome this, as other problems would become significant. The requirements to see cracks in bridges would be hard to satisfy! Professor Wadge said that Lockheed were planning to launch an instrument with 1 metre resolution in 1996