# METHODS OF MULTIVARIABLE EARTHQUAKE PRECURSOR ANALYSIS AND A PROPOSED PROTOTYPE EARTHQUAKE EARLY WARNING SYSTEM


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## ABSTRACT


Significant advances are being made in earthquake prediction theory; however, a reliable method for forecasting the occurrence of earthquakes from space and/or ground based technologies remains limited to no more than a few minutes before the event happens. Several claims of earthquake precursors have been put forward, such as ionospheric changes, electromagnetic effects, and ground heating, though the science behind these is far from complete and the successful application of these precursors is highly regionally


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variable. Existing and planned dedicated space missions for monitoring earthquake precursors are insufficient for resolving the precursor issue. Their performance does not satisfy the requirements of an earthquake early warning system in terms of spatial and temporal coverage. To achieve statistically significant validation of precursors for early warning delivery, precursor data must be obtained from simultaneous repeated monitoring of several precursors in focus regions over a long period of time and then integrated and processed. Data sources include historical data, data from ground-based units, airborne systems, and space-based systems.

This paper describes methods of systematic evaluation of regionally specific, multivariable precursor data needed for the identification of the expected time, magnitude and the position of the epicentre. This data set forms the basis for a proposed operational early warning system developed at the International Space University and which is built in partnership with local and national governments as well as international organizations.

## FULL TEXT

### 1. INTRODUCTION: THE TREMOR PROJECT

*Yet we are the movers and shakers of the world for ever, it seems"*

Arthur O'Shaughnessy

During the course of the International Space University's Summer Session Program in Beijing, China, 36 students from 13 countries came together to the study the potential role of space technologies might play in earthquake disaster management. The students came from a range of professional and academic backgrounds. Together they formed Team TREMOR. The mission statement of Team TREMOR is as follows:

*"To develop an integrated terrestrial and space-based global system for mitigating the effects of earthquakes, and improving response"*

The team published their findings in a report entitled "Technology Resources for Earthquake Monitoring and Response (TREMOR)" This paper presents the major findings, proposals and conclusions contained in the TREMOR report.

### 2. MOTIVATION

#### 2.1. Earthquakes

Every year throughout the world, natural disasters cause thousands of deaths and millions of dollars in property loss, not to mention serious, long term social disruption. Earthquakes and the tsunamis that may result from them are of particular concern because they generally occur with very little to no advance warning, stressing the ability of emergency services to mount adequate response. Developing countries, especially, are most affected because response services may not be widely available even in less stressful times.

Fig. 1 shows the geographical location of all major earthquakes from 1963 to 1998. Earthquakes typically occur along tectonic plate boundaries, but some occur along fault lines in the middle of the plates as well. Countries around the Pacific Rim are heavily affected, as are many countries in the Mediterranean region and western and southern Asia.

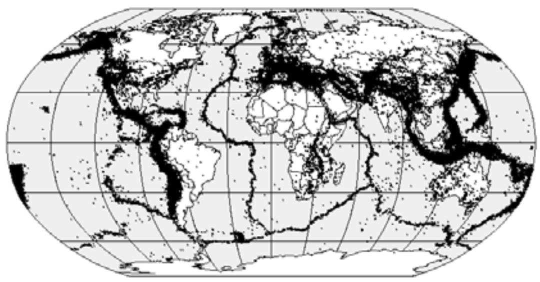

**Fig. 1:** *Occurrence of Earthquakes Globally (DTAM, 2002)*

Fig. 2 below shows the number of fatalities and the economic damage resulting from earthquakes occurring between 1990 and 2006 in all countries. Note that this figure does not account for deaths from tsunamis and other earthquake after-effects. The large peak in 1995 damage results primarily from the Kobe, Japan earthquake. The peaks in fatalities in 1999, 2001, 2003, and 2005 represent major earthquakes in Turkey, India, Iran, and Pakistan respectively.

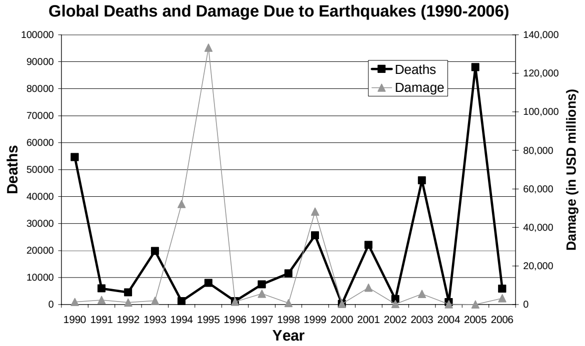


**Fig. 2:** *Global Deaths and Damage Due to Earthquakes (1990-2006) (NCDC, 2007)*

Clearly, earthquakes affect a large number of people globally and result in significant personal and economic impact.

### 2.2. The Role of Space

Fortunately, a wide variety of space technologies, including remote sensing, telecommunications and position, navigation and timing, can contribute to more effective management of these natural disasters. Successful use of these technologies saves lives, reduces property damage, and contributes to long term recovery from the effects of earthquakes. Recent research suggests that some space technologies, together with advanced land-based systems, may make it possible to provide advanced warning of earthquakes (Hayakawa, Molchanov *et al.* 2000).

Remote sensing satellites are presently used for many earthquake-related activities, including ground-motion observation, risk evaluation based on building locations, and damage assessment in the immediate aftermath of an earthquake. Post disaster event imagery of a disaster scene is routinely provided to relevant authorities under the auspices of the International Charter: Space and Major Disasters.

Space-based instruments may also be used for the investigation and observation of potential earthquake precursor phenomena. These precursors, such as ionospheric anomalies, electromagnetic emissions, and thermal anomalies (see Fig. 3), may eventually form the basis for the forecasting of earthquakes (Hattori, Hayakawa 2007, Pulinets, Boyarchuk 2004), as considered in this paper. However, the science behind understanding these precursors is far from complete, and in fact is considered controversial in many quarters (Geller 1997).

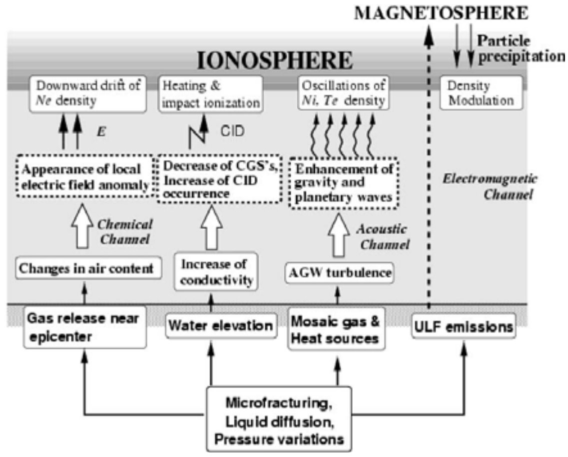


**Fig. 3:** *Possible channels of the lithosphere-atmosphere-ionosphere (LAI) coupling* (Hayakawa, Molchanov *et al.* 2004).

Navigation satellites ( e.g. GPS) are used for some ground motion and ionospheric precursor studies, apart from their key role in the response phase of disaster management, for position determination, vehicle tracking or for bridging the telecommunications collapse or breakdown.

## 3. CURRENT NEEDS

Despite the great potential which space technologies offer to improve earthquake disaster management; there are several significant gaps in our current ability to meet that potential.

### 3.1. Gap Analysis

Despite the promise of such technological assets as those described above there are challenges encountered in applying space technologies to improve earthquake disaster management. The most significant of these gaps include:

- *Today, potential earthquake precursors are measured separately from each other and are not measured with sufficient temporal and spatial resolution in the areas most susceptible to earthquakes.*

  As a result, the available data on possible precursors are presently scarce and far from conclusive. Ongoing satellite missions such as DEMETER are providing additional data on earthquake-related phenomena, but with coverage and revisit times not yet adequate for proper validation of forecasting models. As an understanding of these precursor phenomena is critical for effective early warning, this is a significant gap in knowledge.

- *Processing resources are presently insufficient to store and process already available and future precursor data and much of these data will remain unprocessed.*

  As a result, the earthquake precursor phenomena and the possibility of earthquake forecasting are still a controversial issue. A system that stores and integrates the data coming from several sources and that performs sophisticated data analysis, if implemented, could solve the precursor issue, so this is also a significant gap.

### 3.2. Our Rationale

The Prototype Earthquake Early Warning System described in this paper is proposed by Team TREMOR as the first one of three interrelated prototypes to provide improved capability for earthquake disaster management (see Fig. 4).

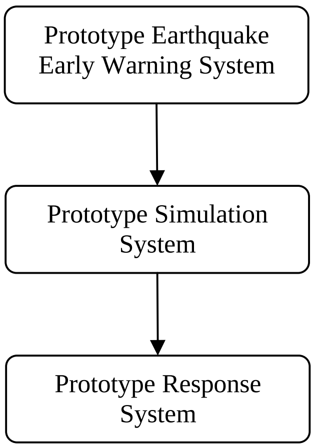


**Fig. 4:** *The TREMOR Systems*

The Prototype Earthquake Early Warning System is to be based upon a robust capacity to observe and analyze potential earthquake precursor phenomena. The Prototype Simulation System will aid countries in pre-planning for earthquakes. The Prototype Response system will improve on the scene coordination of disaster response.

The Prototype Earthquake Early Warning System described below does not consider the tsunamis. Some of the precursors addressed in this paper, such as radon gas emissions or ionospheric anomalies may be also used for forecasting tsunamis. Still on ground local sensor nets are also needed to verify the occurrence of an earthquake and those could not be deployed in the sea resulting in less reliable warnings.

## 4. PROTOTYPE EARTHQUAKE EARLY WARNING SYSTEM

Existing and planned space missions for monitoring earthquake precursors are insufficient for the development of a reliable earthquake early warning system. In particular the mission specifications do not satisfy the spatial and temporal resolution requirements an earthquake early warning system would need (Pulinets, Boyarchuk 2004). The TREMOR Team proposes a space based system that can address this deficiency. At first this system would provide an assessment of whether reliable earthquake early warning is possible through precursor monitoring. If successful, the system will then form the basis of an operational early warning system. The mission of the early warning system will be to identify the expected time and magnitude of the earthquake and the position of the epicentre using precursor data (Dobrovolsky *et al.* 1979, Pulinets 2004).

The proposed early warning system consists of a space segment (a proposed small satellite constellation in combination with already existing precursor monitoring dedicated missions) and a ground segment that performs rapid integration, processing and storage of data. In the future this ground segment will also deliver the earthquake early warning. The space segment's mission is to monitor earthquake precursors. The flow chart in Fig. 5 describes the prototype. Data are gathered from as many sources as possible, namely from the proposed satellite constellation, already existing space missions such as DEMETER, airborne systems (UAVs, balloons, etc), ground-based measurement units, and historical databases. A data analysis module will integrate and process the data to deliver a watch and, if necessary, a warning after the watch has been verified. False positives, false negatives and confirmed warnings will be integrated into the databases so that the early warning system can be continuously improved. Data integration, processing and storage will be addressed in the later sections.

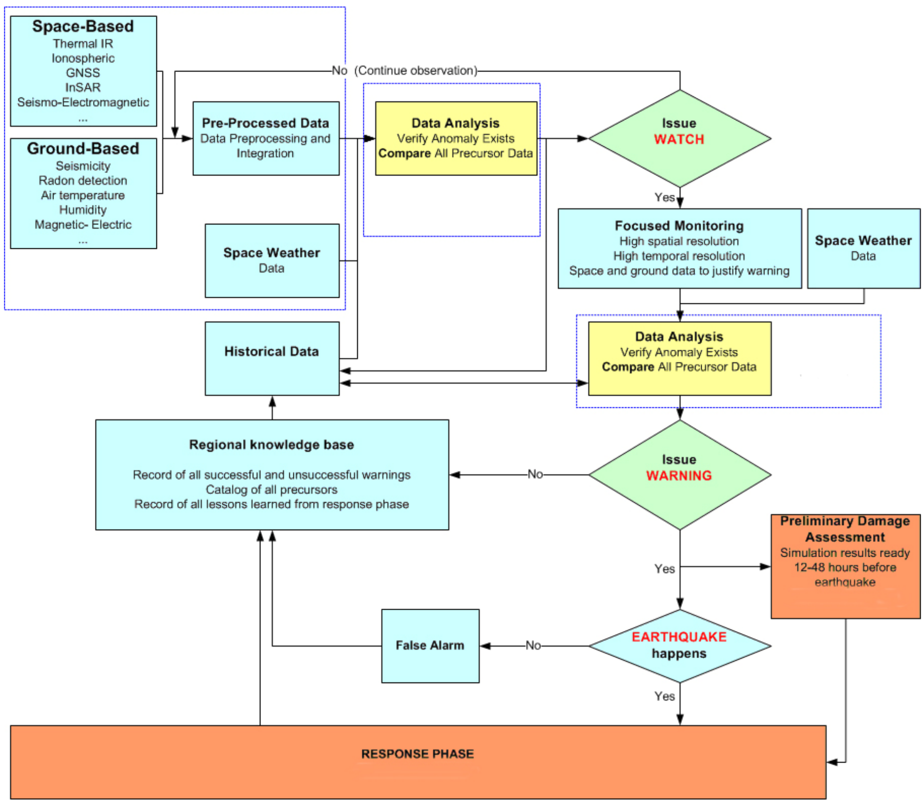


**Fig. 5:** *Earthquake Early Warning Prototype System*

### 4.1. Space Segment

As mentioned before, the space segment of the system consists of a proposed small satellite constellation of two small satellites (around 150kg each one), in combination with already existing precursor monitoring dedicated missions. The constellation is required to provide adequate spatial and temporal coverage of the required precursors (Pulinets 2006). Ideally, the satellite payloads should be capable of sensing multiple precursors. A full sensor payload for precursor research would include SAR, thermal IR, optical sensors and sensors for ionospheric measurements; however, such a large payload of sensors on a satellite constellation would be cost-prohibitive. Therefore it is necessary to provide a more realistic selection of sensors that are a compromise between performance and cost. With this restriction in mind the proposed payload sensors will measure the two most promising precursors: ionospheric precursors and seismo-electromagnetic emissions (Hattori, Hayakawa 2007, Hayakawa, Molchanov et al. 2000, Kodama *et al.* 2000, Pulinets 2004, Pulinets, Boyarchuk 2004, Pulinets 2006). Thermal IR, ionospheric, GNSS, InSAR, Seismo-EM data, coming from the proposed constellation and other space-based systems, and radon, air temperature and humidity measurements from ground-based systems will also be included in the early warning system. Altough thermal IR data are particularly promising, it is not necessary that the proposed payload for the constellation includes thermal IR sensors. This is because sufficient data related to this precursor effect is readily available from existing satellites. Observation of thermal effects related to earthquakes is possible using existing resources (Pulinets 2006). In the future, other payloads and satellites could be added to improve the performance of the early warning system.

There have been numerous proposals for a dedicated space system with the goal of earthquake early-warning (Jason *et al.* 2003, Pulinets 2006, Pulinets, Boyarchuk 2004). Three different proposals of constellations are described in the Team TREMOR report that meet the performance requirements and could fill the existing gaps in precursor monitoring. The 2ESAT (Earthquake Satellite) constellation is the lowest in cost, so it is chosen to be presented in detail later on. While this proposal calls for a two-satellite constellation, it should be mentioned that a larger number of satellites would bring down revisit time and a larger sensor payload would increase the possibility of detecting short lived earthquake precursors.

### 4.2. Constellation 2ESAT

The preliminary design of the constellation 2ESAT and the satellite payloads is based on the proposals from Pulinets (2006) and Kodama (2000). The two satellites are located in the same orbital plane having an inclination of 83º. The upper level satellite, 2ESAT-U, would be placed at an altitude of 960 to 1000 km (higher than the transition height of the ionosphere, which is typically at 750 km). The lower level satellite, 2ESAT-L, would be placed at an altitude of 500 km (below the transition height of the ionosphere).

The payload of 2ESAT-U consists of a topside sounder, a mass-spectrometer, a local plasma spectrometer, a ULF/ELF/VLF wave complex (fluxgate magnetometers and dipole antennas for achieving three-component measurement of ULF/ELF/VLF magnetic field and electric field), a particle spectrometer, and a drift meter. 2ESAT-U and 2ESAT-L are identical except for the fact that 2ESAT-L has no topside sounder. The system can be upgraded in the future by orbiting additional satellite pairs, which will improve revisit time.

### 4.3. Ground Segment

The proposed prototype will integrate precursor data from space and ground-based systems, since it is necessary the combination of space and ground-based seismic monitoring for precursor validation (Hayakawa, Molchanov *et al.* 2000) and ulterior earthquake early warning. Historical precursor data and other kinds of data from related systems (*e.g.* past earthquakes, fault maps) will be also integrated and processed by the prototype.

Ground-based measurements are used to enhance accuracy and to validate measurements from satellites. The main disadvantage of ground-based stations is that they are stationary and therefore restricted to a limited area of coverage within their local environment. Ground-based instruments have been used in earthquake precursor research to measure the following: radon concentration and other gas concentrations (by LIDAR or spectroscopic measurements), change in water well levels, gravitational and magneto metric disturbances, atmospheric parameters, the vertical electric field, atmospheric emissions (by a ground-based ionosonde), movement of the ionospheric layers (by Doppler measurements), metallic ions in the E-layer of the ionosphere (by LIDAR), and crustal deformation (by GPS ground receivers, like in GEONET) (Pulinets, Boyarchuk 2004, Sagiya, 2004).

A large network of ground stations is required. In particular, at least a network of GPS ground receivers and ground-based ionosondes would be necessary to meet the minimum requirements (Liu *et al*. 2004, Pulinets, Boyarchuk 2004). The earthquake prone nations should deploy adequate ground-based measurement units in their territories to improve the prototype performance. The prototype will be able to integrate and use the data coming from any kind of useful ground-based source to forecast earthquakes. We recommend nations provide, at a minimum, GNSS data. The deployment of ground sensors networks is an interesting and less expensive approach for those precursors where their science is still at an unproven state.

### 4.4. Data Processing

The existing space and ground technologies for earthquake precursor monitoring generate large quantities of data. Processing resources are presently insufficient to store and process available precursor data and much of these data remain unprocessed (Pulinets, Boyarchuk 2004). This hinders the final validation of the precursor-based advance warning methodology. To validate precursor phenomena, a proper monitoring system should be implemented, together with a system that performs sophisticated data analysis (Hattori, Hayakawa 2007). This issue is addressed in the following. The problems are several. The amount of data is increasing as new technologies provide better sensor resolution and higher data acquisition rates. Processing requirements are also taxed by the development of new, complex algorithms for extracting meaningful precursor information from the raw data.

The nature of information coming from different sensors is complementary and the utility in merging them has been widely demonstrated (Hall & Llinas 1997). Thus it is important to merge earthquake precursor data from space and ground segments, but this also aggravates the problem of having limited processing capabilities. The data acquisition rate becomes even larger and the data integration becomes more complex and challenging. There is a need for powerful processing resources in coordination with storage and data management resources.

## 4.5. Data Analysis and Integration Module

A data analysis and integration module is proposed to process the data and generate the watch or warning (see

Fig. 6), below, represents the top-level architecture of the data analysis module that acts as a processing core of the TREMOR Earthquake Early Warning Prototype. It is organized into two layers: the first one performs all real-time computations, while the second layer is executed offline and takes care of the data archiving, further post-processing, and distribution. A similar system has already been applied in the context of space weather (Moura *et al.* 2004).

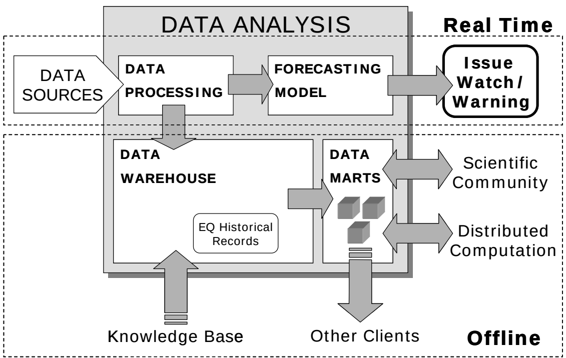


**Fig. 6:** *System Architecture of the Data Analysis and Integration Module*

In the first layer, data are received from external space and ground-based data sources. These data are pre-processed and fed into a forecasting model that identifies trends that can lead to the issue of an alarm. The forecasting model is the key element of the system. In order to develop a good forecasting module, extensive processing of past precursor data crosschecked with historical records of earthquakes is performed. Historical records must be divided into a learning set and a training set. The first set is used to develop the model, the second set is used to validate the extracted trends. Data mining algorithms will be used to establish trends and correlations between various precursors and historical records of seismic events. Two approaches can be used in order to recognize patterns and perform an analysis of the earthquake database: a human-driven approach using the experience and understanding of the mechanism of the phenomena, and a data-driven approach using machine learning algorithms to find patterns where mechanisms may be unknown.

In the second layer, the “offline” layer, data are stored in an archive based on data warehousing technologies (Cabibbo *et al.* 2001, Chaudhuri 1997). This information is processed in “data marts” (more compact sets of specific data) to make it more accessible to end-users and potential clients. The offline layer serves the data to several end-users or clients such as the scientific community, private companies, government and the general public. The system can be expanded to include new types of precursor data as necessary. Other types of data can be stored in the warehouse such as geological information, soil, and building types of different regions.

## 4.6. Data Access

The proposed expandable data archive solves the problem of increasing data volume and the difficulties of accessibility and integration. Similar archives have already been created in other scientific fields such as astronomy. The archive should not be seen merely as data storage. The offline layer of the system offers multiple access possibilities to the scientific community. It will integrate analysis tools and computational services to improve the sharing of expertise, data exchange, and interoperability

(Hanish & Quinn 2003). Such an archive will provide an excellent tool for scientific research. The accessed data may also serve purposes other than those of earthquake precursor science or disaster management research as has been observed with other large datasets (Quinn *et al.* 2004).

## 6. IMPLEMENTATION STRATEGY

In order to properly implement the proposed system a number of policy and business considerations must be addressed. These are presented in the following sections.

### 6.1. Business Strategies

To implement the proposed Systems we recommend the formation of a new non-governmental organization (NGO). The long term goal of this NGO would be to become a sustainable entity that will provide technology and support to all countries that are affected by earthquakes. The primary organizational goal will be the reduction of the loss of life and damage to property and environment caused by earthquakes. By providing special support to those developing countries that are most vulnerable to earthquakes, this NGO would hope to enhance the economic and social well-being of these less affluent regions.

This NGO will be responsible for the development of the technology described here, either in-house or by contracting. All data processing required by the Early Warning and Simulation System will be conducted at the NGO's headquarters. The NGO will also provide training to the client entities on the use of the TREMOR systems. In addition this NGO will endeavor to develop any potential commercial spin-offs of the TREMOR systems that might exist.

Establishing an NGO to implement the TREMOR Systems offers several advantages over other options to do the same, such as establishing an intergovernmental agency. An NGO is not dependent on a single funding source, but can instead select from a wider range of options. It can be set up without the lengthy and difficult treaty-based process required for an intergovernmental organization. It can more easily obtain commercial licenses for satellite data and, depending on its country of operation, would also benefit from favorable tax laws. Finally an NGO can conduct its own international arrangements. For example, the NGO envisioned here, could seek to have observer status at COPUOS, consultative status at ITU and WMO, and participation in the Committee on Earth Observing Satellites (CEOS) and the Group on Earth Observations (GEO).

### 6.2. Implementation and Data Policies

Should the TREMOR System result in the validation of the usefulness of precursor observation; the Prototype Earthquake Early Warning System provides the basis for the issuance of earthquake watches and warnings. It is recommended that the watches and warnings will be distributed to a single national authoritative agency responsible for earthquake disaster management in each of the client countries. The concept of a single national authoritative agency is used with success by the Pacific Tsunami Warning System (UNESCO, 2006). This ensures a single point of contact for early warning information and reduces confusion.

Liability will be an important concern in the implementation of the proposed Systems. While it envisioned that these Systems will be developed by an NGO it is also anticipated that that NGO will accept no liability for actions taken as a result of watches and warnings issued by its systems; nor will it accept liability in cases where earthquakes occur that were not forecast by the TREMOR Systems. Actions taken as a result of the watches and warnings issued by TREMOR Systems are the responsibility of the national governments which are clients. Specific provisions concerning liability will be included in the agreements that the NGO responsible for developing the TREMOR Systems makes with the users of its systems.

In order to research patterns in earthquake precursor data it is necessary to obtain as much historical seismic and real-time precursor data as possible. Nations currently undertaking earthquake precursor missions such as France or Russia would be encouraged to provide their data, both historical and real-time, to the TREMOR System. This data will allow research to begin on the integration of ground and space based measurements during the preparation of a dedicated space asset to measure earthquake precursors. Specific agreements governing the provision of this data will have to be negotiated.

The NGO responsible for developing the TREMOR Systems will cooperate with leading earthquake precursor researchers and institutions. Part of this cooperation will involve sharing data acquired from national agencies and organizations for research and development purposes. However, should an organization choose not to share its data with a particular third party, accommodation will be made to respect its request.

In the end, for the Early Warning System, the role of NGO responsible for the TREMOR system is only to serve in an advisory capacity. Any decisions made concerning disaster response and management must be made by local authorities.

## 7. APPLICATION IN FOCUS COUNTRIES

A global system of this magnitude also comes with a significant financial investment. A specific way to reduce the initial investment, while at the same time building confidence in the functionality of the system, is the implementation of the TREMOR systems in a set of focus countries. In the development of this investigation, three countries were considered as good choices for initial development and implementation. Japan, China, and Peru were selected and are ideal for studying the impact of the TREMOR systems for several reasons. Earthquakes occur with regularity in each of the three countries, as shown in Fig. 7. The figure shows the earthquakes that have occurred in these regions over the 10 year period between 1990 and 2000. Each dot indicates an earthquake: the larger the dot the bigger the magnitude.

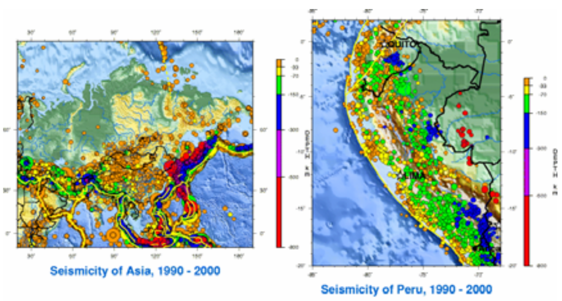


**Fig. 7:** *Occurrence of Earthquakes in Focus Countries (Source: USGS)*

Japan and Peru are both situated along tectonic plate boundaries, while China is characterized by earthquakes that occur along intraplate faults. Japan, as the most developed country of the three, is important as a focus country because it has a very advanced system for detecting earthquakes and for managing their effects. China is presently experiencing rapid economic growth, which opens up new financial possibilities for augmenting existing earthquake measures. The consequent social upheaval - and in particular, the rapid urbanization of the country - has increased the vulnerability of its population to earthquakes. Peru was selected because of its status as a developing country, which presents additional challenges for earthquake response, principally due to lack of economic resources and limited existing infrastructure. Its geographic separation from China and Japan also allows the global applicability of our systems to be demonstrated.

## 8. CONCLUSIONS

In 1868, the entire 600 km-long western fault along the Peruvian Coast slipped in what was the largest earthquake in the last several hundred years in South America. The estimated 8.1 magnitude earthquake left tens of thousands of people dead and hundreds of thousands of people homeless. Geological history has shown that this fault has major slips every 100-150 years. On June 23$^{rd}$, 2001, 200 km of the central part of this fault slipped, hitting the same areas with an earthquake of magnitude 7.9 and affecting more than 220,000 people. On August 15$^{th}$, 2007, during the final preparation of this report, the northern part of this fault once again slipped, producing an earthquake with a magnitude of 7.9. As of the time of writing, hundreds of deaths have been confirmed and thousands of people have been left homeless (La Republica, 2007). Sometime in the next few years, the southern portion will also slip, causing equal or greater damage. The question is what difference would an early warning system have made for the residents of southern Peru on the 15$^{th}$ of August.

In its report, Team TREMOR has reviewed the present and future use of space- and ground-based systems to monitor and respond to earthquakes. We have identified gaps in the scientific, technological, legal, policy, and educational aspects of these systems. Based on the gap analysis, we have proposed an

Earthquake Early Warning Prototype System. Realizing that early warning is important but not sufficient for reducing the impact of earthquakes, we have also developed an Earthquake Simulation and Response Prototype System as a complement to the Early Warning Prototype System. We have deployed both policy and business strategies for the implementation of our proposals.

One of the most important aspects of the proposed Systems and implementation strategy is that they will function in an international, intercultural and interdisciplinary manner. It is our belief that the approach described in this paper and in the TREMOR Final Report offers the best opportunity to use global data, technology, and human resources to help solve this global problem. Ultimately, the intent of any earthquake monitoring or response system is to minimize the loss of life, injury, and damage to property that these disasters cause. It is our firm opinion that the solutions proposed in the TREMOR report will contribute in a significant way towards this goal.

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