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SOCIO-ECONOMIC BENEFITS OF USING SPACE TECHNOLOGIES TO MONITOR AND RESPOND TO EARTHQUAKES

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Abstract — Earthquakes represent a major hazard for populations around the world, causing frequent loss of life, human suffering and enormous damage to homes, other buildings and infrastructure. The Technology Resources for Earthquake Monitoring and Response (TREMOR) Team of 36 space professionals analysed this problem over the course of the International Space University Summer Session Program and published their recommendations in the form of a report. The TREMOR Team proposes a series of space- and ground-based systems to provide improved capability to manage earthquakes. The first proposed system is a prototype earthquake early-warning system that improves the existing knowledge of earthquake precursors and addresses the potential of these phenomena. Thus, the system will at first enable the definitive assessment of whether reliable earthquake early warning is possible through precursor monitoring. Should the answer be affirmative, the system itself would then form the basis of an operational early-warning system. To achieve these goals, the authors propose a multi-variable approach in which the system will combine, integrate and process precursor data from space- and ground-based seismic monitoring systems (already existing and new proposed systems) and data from a variety of related sources (e.g. historical databases, space weather data, fault maps). The second proposed system, the prototype earthquake simulation and response system, coordinates the main components of the response phase to reduce the time delays of response operations, increase the level of precision in the data collected, facilitate communication amongst teams, enhance rescue and aid capabilities and so forth. It is based in part on an earthquake simulator that will provide pre-event (if early warning is proven feasible) and post-event damage assessment and detailed data of the affected areas to corresponding disaster management actors by means of a geographic information system (GIS) interface. This is coupled with proposed mobile satellite communication hubs to provide links between response teams. Business- and policy-based implementation strategies for these proposals, such as the establishment of a non-governmental organisation to develop and operate the systems, are included. © 2008 Lister Science.

Keywords — Disaster management system, Earthquake forecasting, Earthquake mitigation, Earthquake monitoring, Earthquake precursors, Earthquake response, Earthquake simulation, Earthquake early warning, TREMOR

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 study the potential role space technologies might play in earthquake disaster management. The students came from a range of professional and academic backgrounds. Together they formed TREMOR Team. The mission statement of TREMOR Team is as follows:

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

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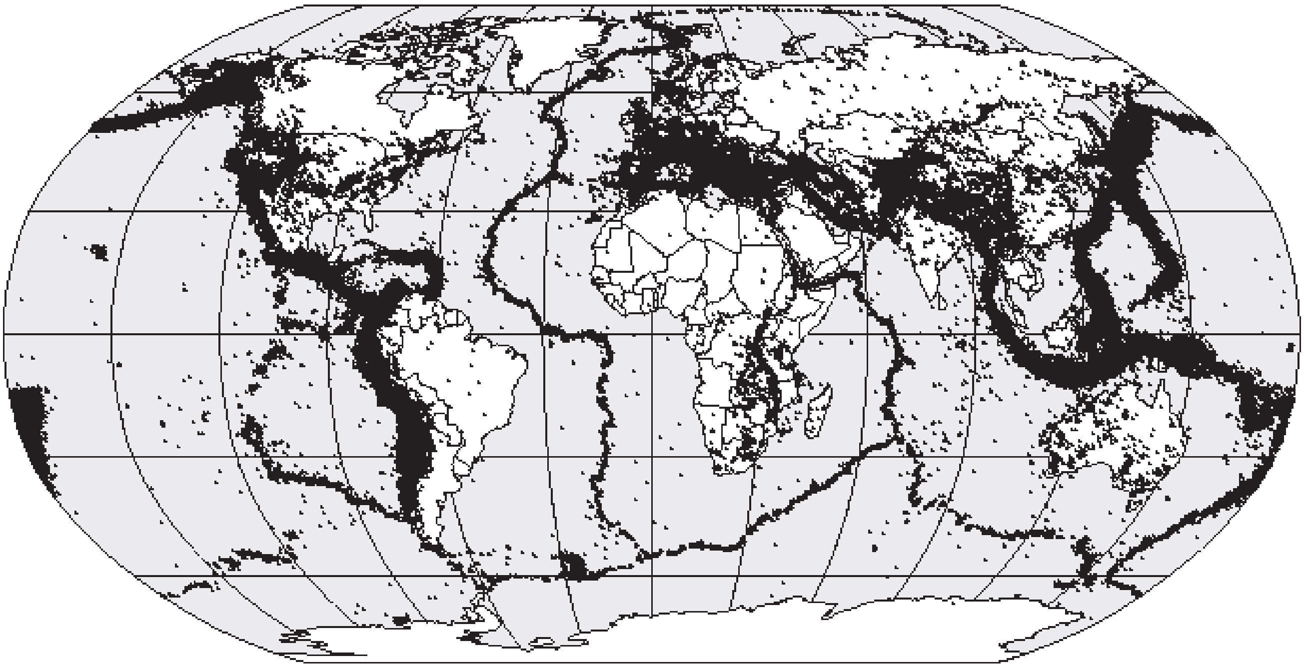

Fig. 1. Occurrence of earthquakes globally [2].

The team published their findings in a report entitled Technology Resources for Earthquake Monitoring and Response (TREMOR) [1]. This report presents the major findings, proposals and conclusions contained in the TREMOR report. A previous version of this report was presented at the 58th Annual International Astronautical Congress, held in Hyderabad, India, September 24–28, 2007.

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 organise adequate response. Developing countries, especially, are most affected because response services may not be widely available even in less stressful times. Figure 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.

Figure 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.

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.

Remote sensing satellites are presently used for many earthquake-related activities, including risk

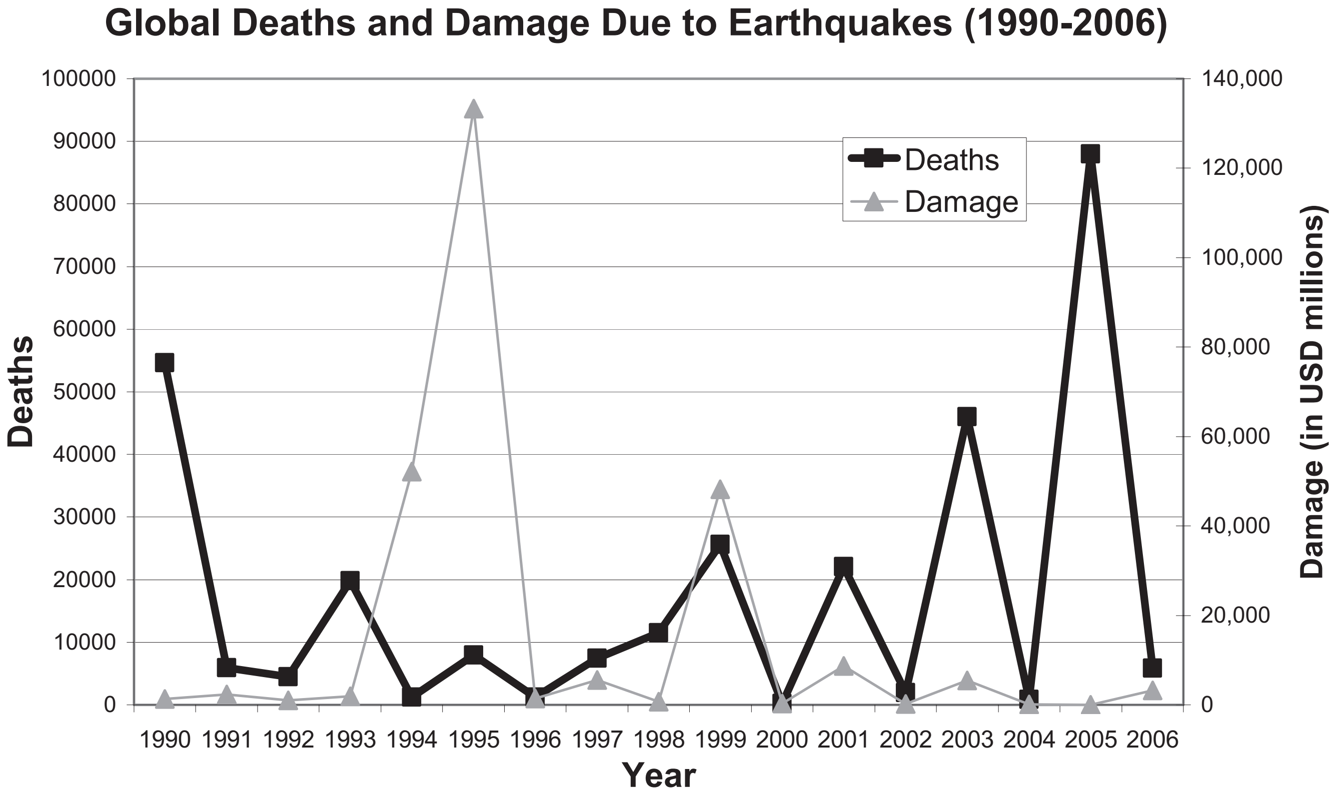

Fig. 2. Global deaths and damage due to earthquakes (1990–2006) [3].

evaluation based on building locations, ground-motion observation, damage assessment in the immediate aftermath of an earthquake and others. 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. In addition, there is observational and theoretical evidence that large-scale fault ruptures may be predictable [4], and recent research suggests that some space technologies, together with advanced land-based systems, may make it possible to provide advanced warning of earthquakes [5,6]. These space and land-based technologies may be used for the investigation and observation of potential earthquake precursor phenomena, such as ionospheric and thermal anomalies and electromagnetic emissions (see Fig. 3).

Finally, 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, position determination, vehicle tracking or bridging the telecommunications collapse or breakdown.

Eventually, the monitoring of earthquake precursor phenomena and processing of related data may form the basis for the forecasting of earthquakes [7,8], as considered in this article. However, the science behind understanding these precursors is far from complete (in fact, it is considered controversial in many quarters) [9,10], and no method can yet reliably predict on time scales of a decade or less the location, time and magnitude of potentially destructive fault ruptures [4].

3. CURRENT NEEDS

Despite the great potential and promise of such technological assets as those described above, there are yet several significant challenges encountered in applying them to improve earthquake disaster management.

3.1. Gap Analysis

With regards to precursor phenomena validation, the most significant gaps in our current ability to meet that potential include the following:

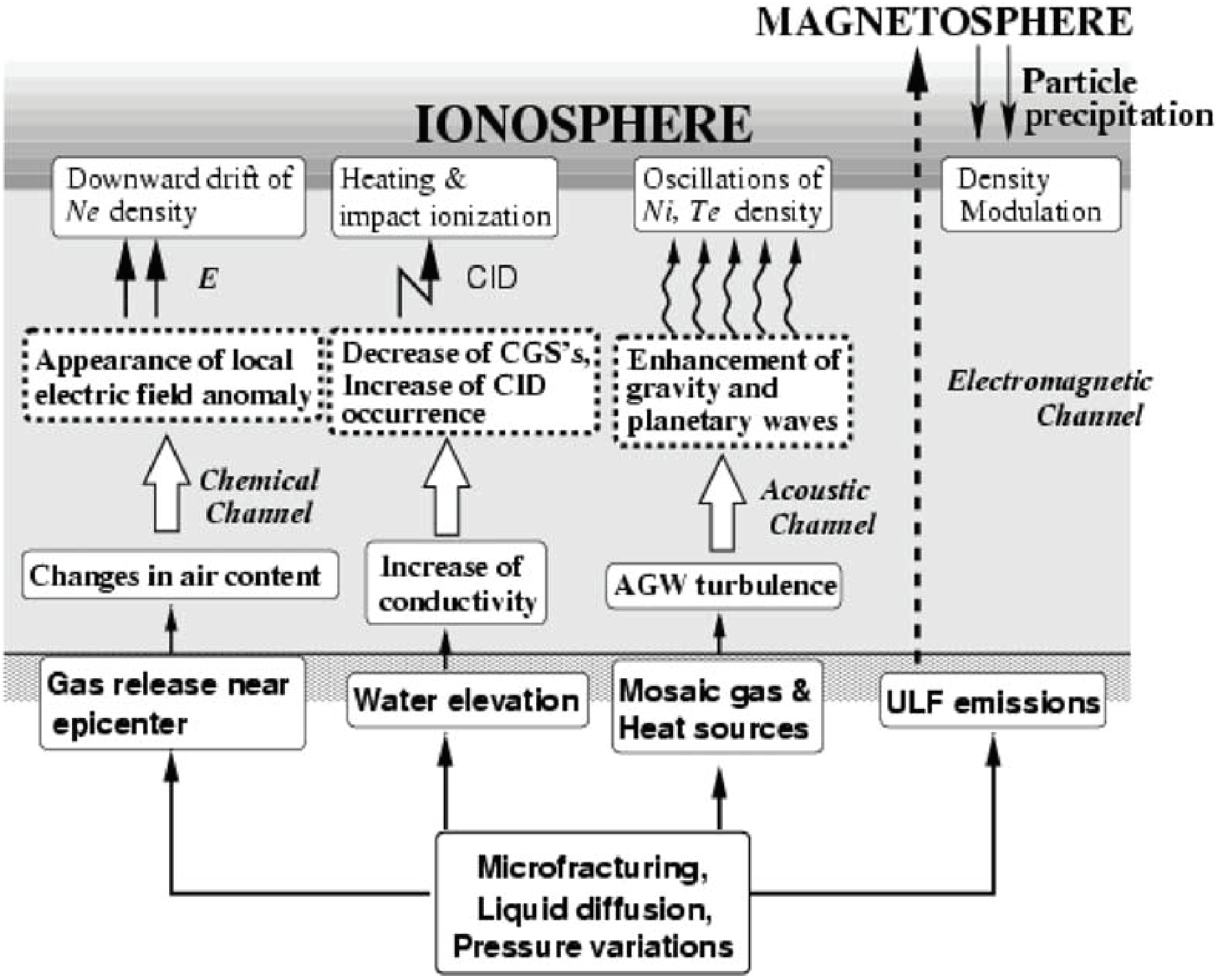

Fig. 3. Possible channels of the lithosphere–atmosphere–ionosphere coupling [5].

- Existing and planned dedicated ground measurement systems and space missions for monitoring earthquake precursors are insufficient for resolving the precursor issue. For example, prediction ability of proposed precursors has been studied independently and not through a multi-variable approach, and ongoing satellite missions do no have good enough performances in terms of temporal and spatial resolution (coverage and revisit times) to allow the latter. Consequently, the data on precursors that these systems have been able to provide those far is scarce and not yet adequate for achieving significant statistical validation of precursor-based forecasting models.
- Computational resources are presently insufficient to store and process already available precursor data, and much of these data remain unprocessed. Furthermore, should the precursor data acquisition and processing rate be increased, as is necessary for solving the precursor issue, the problem of underperformance of the computational resources will be aggravated.
- A poor experimental infrastructure and a lack of testing standards impede the rigorous conduction and evaluation of scientific prediction experiments, which is necessary to fully understand earthquake predictability [4,11].

3.2. Our Rationale

The three interrelated prototype systems described in this article (the prototype earthquake early-warning

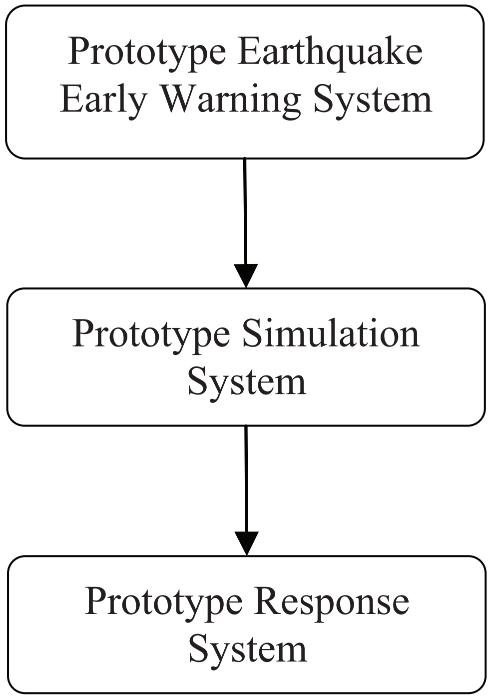

Fig. 4. The TREMOR systems.

system, the prototype simulation system and the prototype response system) are proposed by TREMOR Team as means to provide improved capability for earthquake disaster management (see Fig. 4).

The prototype earthquake early-warning system is to be based upon a robust capacity to observe and analyse 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 tsunamis. Some of the precursors addressed in this article, such as radon gas emissions or ionospheric anomalies, may be also used for forecasting tsunamis. Yet on ground, extensive and local sensor nets are also needed to verify the occurrence of an earthquake, and those could not be deployed (or at least, not as easily) in the sea, resulting in less reliable warnings. In addition, a tsunami early-warning system is already operational in the Pacific Ocean basin and under development in the Indian Ocean. Elements of the TREMOR Prototype Earthquake Response System (to be discussed in a subsequent section of this article) would improve tsunami disaster response.

4. PROTOTYPE EARTHQUAKE EARLY-WARNING SYSTEM

As pointed out before, existing and planned monitoring and computational resources and infrastructure are insufficient for solving the precursor controversy [8]. The TREMOR Team proposes a system that can address this deficiency by filling the gaps previously presented. This space- and ground-based system would at first enable the definitive assessment of whether reliable earthquake early warning is possible through precursor monitoring. If the answer is affirmative, the system would then form the basis of an operational early-warning system capable of performing earthquake forecasting. The ultimate mission of this early-warning system would be to deliver useful alarms based on the identified probability of occurrence of an earthquake in a certain geographical position. A useful alarm should inform of the expected time and magnitude of the earthquake and the position of the epicentre [6].

The flow chart in Fig. 5 describes the proposed early-warning system, which consists of a space segment and a ground segment. The former includes a proposed small satellite constellation in combination with already existing space missions dedicated to earthquake precursor monitoring. The latter segment consists of the ground-based data sources (e.g. earthquake precursor measurement systems, historical databases, space weather data sources) and the data analysis module, a system that performs rapid integration, processing and storage of available data.

Research suggests that the combination and integration of precursor data from space- and ground-based seismic monitoring systems is necessary for precursor validation [5,10]. Should earthquake predictability be proved to be feasible, the ground segment would also be in charge of the delivery of the earthquake early warning. A motivating, complementary reference can be found in the literature [10]. The authors of this article suggest a deterministic earthquake prediction approach that is based on combined ground and space monitoring of earthquake precursor phenomena, aiming also at terminating the precursor controversy.

As shown in Fig. 5, the prototype is to gather earthquake precursor data from the proposed satellite constellation, existing space missions (e.g. DEMETER), airborne systems (e.g. UAVs, balloons), ground-based measurement units, historical databases and also data regarding related topics, such as space weather, fault maps and others.

The performances of the proposed new satellite constellation complement those of the other mentioned resources and are intended to bridge the gap regarding quality and quantity of earthquake precursor data, together with adequate ground-based units. To achieve that, the performances must be such that precursor data are obtained from simultaneous repeated monitoring of several precursors in focus regions over a long period.

Currently, most precursors have been shown to have little reliability [10]. Although a precursor phenomenon might not be reliable when considered independently, the authors propose this multi-variable, multi-disciplinary approach, since it may prove to be adequate for achieving reliable earthquake early warning purposes.

Finally, the proposed data analysis module will remedy the problems referred to the lack of computational resources and the lack of an adequate experimental infrastructure. It will first serve as a suited test bed for earthquake prediction algorithms testing, thus it would eventually allow the statistical validation of precursor-based earthquake forecasting models. Ultimately, through extensive, advanced data integration and processing, it would allow the delivery of reliable earthquake early warning.

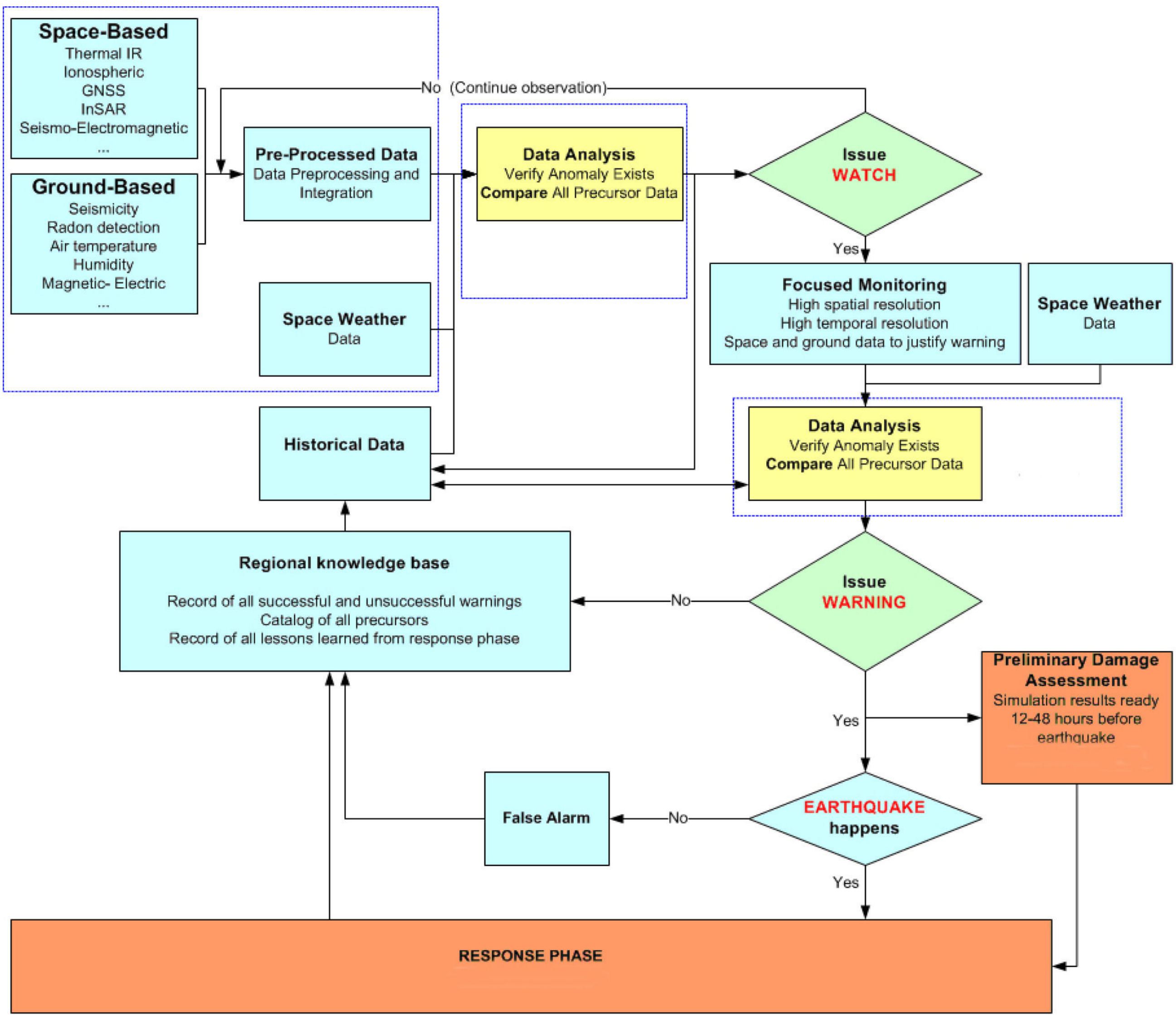

Fig. 5. Earthquake early warning prototype system.

4.1. Space Segment

The space segment of the system consists of a proposed small satellite constellation, in combination with already existing and planned precursor monitoring dedicated space missions. These are not addressed in this article, but extended information on some examples can be found in several references [8,10].

Consequently, in addition to the data acquired by the proposed constellation, the data analysis module will receive thermal IR, ionospheric, GNSS, InSAR and seismo-electromagnetic data coming from other space-based systems. As pointed out before, it will also receive radon, air temperature, humidity and other measurements coming from the ground-based systems.

4.1.1. New proposed constellation

There have been numerous proposals for a dedicated space system with the goal of earthquake early warning [8,12,13]. Three different proposals for new constellations are described in the TREMOR Team report [1]. Essentially based on the previous references, all of the proposals are thought to meet the performance requirements and could fill the existing gaps in precursor monitoring. Amongst all, the 2ESAT (2 Earthquake Satellite) constellation is the lowest in cost, and this is the reason why it is presented in detail in the following section.

The new proposed constellation is requested to provide adequate spatial and temporal coverage of the required precursors [13]. 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 ionospheric precursors and seismo-electromagnetic emissions. These are the most promising precursors, together with thermal anomalies [6–8,10,13–15].

Although thermal anomalies are particularly promising as a precursor, it is not necessary that the payload for the proposed constellation includes thermal IR sensors. This is because adequate observation of thermal effects related to earthquakes is possible since sufficient data referred to this precursor are readily available from existing satellites; all that is needed is a capability to analyse the existing data for correlations with earthquakes [10]. In the future term, larger payloads and more satellites could be considered to improve the performance of the early-warning system.

4.1.2. Constellation 2ESAT

The preliminary design of the constellation 2ESAT and the satellite payloads is specifically based on the proposals from Pulinets [13] and Kodama et al. [15]. The constellation consists of two small-scale satellites (around 150 kg each) that 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 960–1000 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 would consist 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 and electric fields), 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, which is an expensive sensor.

Obviously, the constellation (and thus the system) can be upgraded in many ways. Although this proposal calls for a two-satellite constellation, it should be mentioned that a larger number of satellites (e.g. additional satellite pairs) and a larger sensor payload would improve the overall performance of the constellation (e.g. it would bring down revisit times thus increasing the availability of data and the possibility of detecting short-lived earthquake precursors).

4.2. Ground Segment

The ground segment consists of the ground-based data sources and the data analysis module, which performs rapid integration, processing and storage of available data. The combination and integration of precursor data from space- and ground-based seismic monitoring systems is necessary for precursor validation [14,10] and earthquake early warning. Historical precursor data and other kinds of data from related systems (e.g. past earthquakes, fault maps, space weather data) will be also integrated and processed by the prototype. This is particularly important for the data analysis module to be able to filter the anomalies that are not related to earthquake occurrence but to thunderstorm activity, sun and cosmic rays and others [10].

All these tasks require large-scale computational capabilities that must be met by the data analysis module. To diminish data management and processing complexity and to ease collaboration and organisation, all participating actors (e.g. scientific community, space mission designers, prototype managers) should make a collaborative and organisational effort aiming at the standardisation of procedures, data, tools and others.

To resolve the earthquake predictability issue, the features and performances of the proposed data analysis module will also be in tune with the way paved by the International Virtual Observatory Alliance, the Berkeley Open Infrastructure for Network Computing project and the claims that several authors have already raised, such as the Collaboratory for the Study of Earthquake Predictability [4,11]. It will act as a web-based distributed laboratory to facilitate the international coordination and collaboration amongst the scientific community, providing standards, access to data and software to allow researchers to participate and so forth. It will also provide the scientific community with a controlled frame that supports rigorous conduction and evaluation of scientific prediction experiments, eventually enabling the statistical validation of precursor-based earthquake forecasting models.

4.2.1. Ground-based measurements

Ground-based measurements are used to enhance accuracy and 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 magnetometric 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, such as in GEONET) [8,16].

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 [8,17]. 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 certain types of precursors.

4.2.2. Data processing

The existing space and ground technologies for earthquake precursor monitoring generate large quantities of data. Computational resources are presently insufficient to store and process all of this data, and a major part remains unprocessed [8]. This will be aggravated in the short term if new planned and proposed systems are implemented, which is necessary for solving the precursor issue. This problem 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 [7,10]. This issue is addressed in the following section. The challenges 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 [18]. 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.

4.2.3. Data analysis and integration module

A data analysis and integration module is proposed (see Fig. 6), which will first serve as a suited test bed for earthquake prediction algorithms testing. Provided that precursor-based earthquake forecasting models are validated, the module would ultimately perform extensive, advanced data integration and processing to deliver reliable earthquake early warning.

When a potential earthquake hazard is identified, a watch would be issued as a first form of alarm. Monitoring resources are then intensely focused on the affected region so as to verify the earthquake hazard. If necessary, a warning is issued after the watch has been verified. False-positives, false-negatives and confirmed warnings will be integrated into databases and contribute to a learning process so that the early-warning system can be continuously improved. Watches and warnings would be issued based upon clearly defined earthquake probability criterion levels.

Figure 6 represents the top-level architecture of the data analysis module that acts as the processing core of the TREMOR earthquake early warning prototype. It is organised into two layers: the first performs all real-time computations, whilst 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 [19].

In the first layer, data are received from the external space- and ground-based data sources mentioned before. These data are pre-processed and fed into a reliable forecasting model that identifies trends that can lead to the issue of an alarm. The forecasting model is the key element of the system and is yet to be prototyped, tested and validated through an adequate experimental prediction infrastructure (see Section 4.2). This infrastructure will be provided by the data analysis module itself.

To develop a good forecasting module, extensive processing of past precursor data cross-checked 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, whilst the second set is used to validate the extracted trends. Data mining algorithms [20,21] will be used to establish trends and correlations between various precursors and historical records of seismic events. Two approaches can be used to recognise patterns and perform an analysis of the earthquake database: a human-driven approach using the

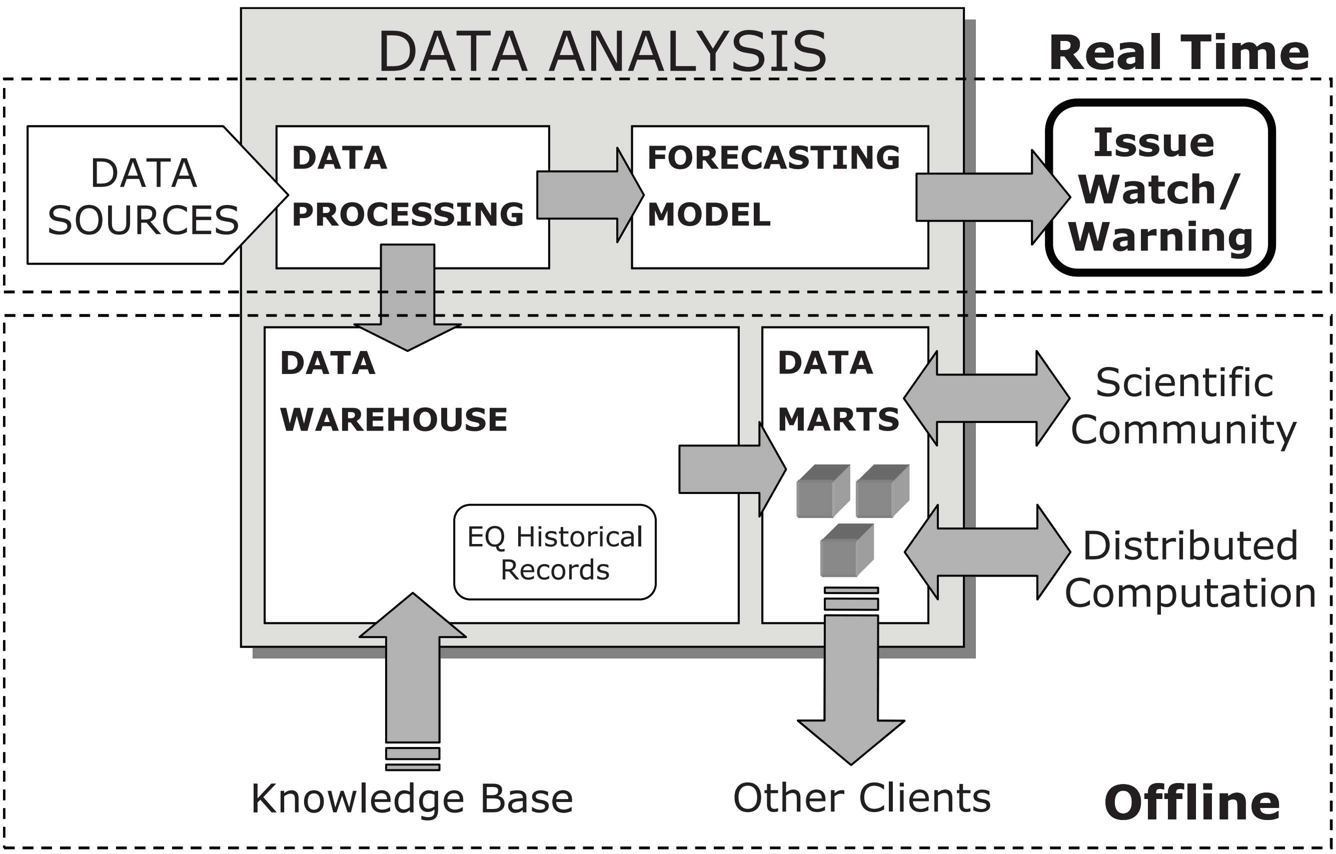

Fig. 6. System architecture of the data analysis and integration module.

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 [22–24]. 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 forms the basis of the web-based distributed laboratory [25] and 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.

4.2.4. 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 (International Virtual Observatory Alliance). 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 [26,27]. 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 data sets [26].

5. PROTOTYPE EARTHQUAKE SIMULATION AND RESPONSE SYSTEM

Lessons learned from previous earthquake disasters indicate a need to find a solution to increase the level of performance of emergency response teams, particularly by reducing time delays [28]. A simulation and response prototype (see Fig. 7) is proposed with the goal to increase the level of performance seen in current response systems to decrease the loss of and impact to life following an earthquake. This proposed system coordinates the main components of the response phase to reduce the time delays of response operations, increase the level of precision in the data collected, facilitate communication amongst teams and enhance rescue and aid capabilities. Ideally, it is linked with the early warning prototype, forming an integrated solution to aid in disaster management; however, even in the absence of an operating early-warning system, the simulation and response prototype will be able to improve disaster response significantly.

When an earthquake occurs, there is a limited amount of time for coordination teams to prepare and perform all the tasks associated with response. These tasks include decision-making processes relating to the coordination of search and rescue teams, medical teams, supply teams and volunteers. Because countries differ in the organisation and degree of development of their disaster management systems, a cooperative approach is called for whereby the TREMOR systems will be offered in assistance to local organisations and government agencies for coordination purposes, if requested, without interfering in regional decision-making processes. Automated GPS tracking systems and mobile communications platforms are an embedded feature of the response system and will play an important role in helping search and rescue teams to coordinate their operations and ensuring that emergency, military and supply vehicles are effectively deployed.

5.1. Computerised Simulation Tool

Earthquake damage can be dramatically reduced by using a computerised disaster simulation tool capable of estimating the damage produced in a particular area based on local conditions. A comprehensive disaster simulation system can also be used to develop guidelines for actions to be taken by the public following an earthquake and provide resource allocation recommendations to emergency professionals such as fire brigades, ambulance teams and police forces. Similar simulation systems are being implemented for government preparedness in the event of terrorist attacks, because these types of events are also unpredictable in nature. The framework for the simulation system should be as generic as possible, with the ability to customise the parameters of the simulation for each earthquake-vulnerable region. This will allow the system to take into account regional variations in characteristics including availability of different data [29].

Some simulation models have already been implemented in the field of seismic damage assessment. These models require good inputs for soil and infrastructure information and also consider the use of a learning algorithm that uses multiple earthquake events to improve the representation of the cyclic soil behavior that affects the accuracy of the prediction [30]. The two main sources of uncertainty in assessing damage to structures are the diversity of the structures themselves and the randomness of the ground excitations. Presently, this problem is addressed by estimating the damage caused by a family of seismic waves of different fundamental frequencies to a structure to determine the worst case scenario. Uncertainty can be reduced if earthquake fault models are available for the area under consideration [31].

Models for optimising resource allocation are currently being developed for large-scale catastrophic events including earthquakes. They deal with many different areas that have impact on the response strategy, such as operational performance of hospital

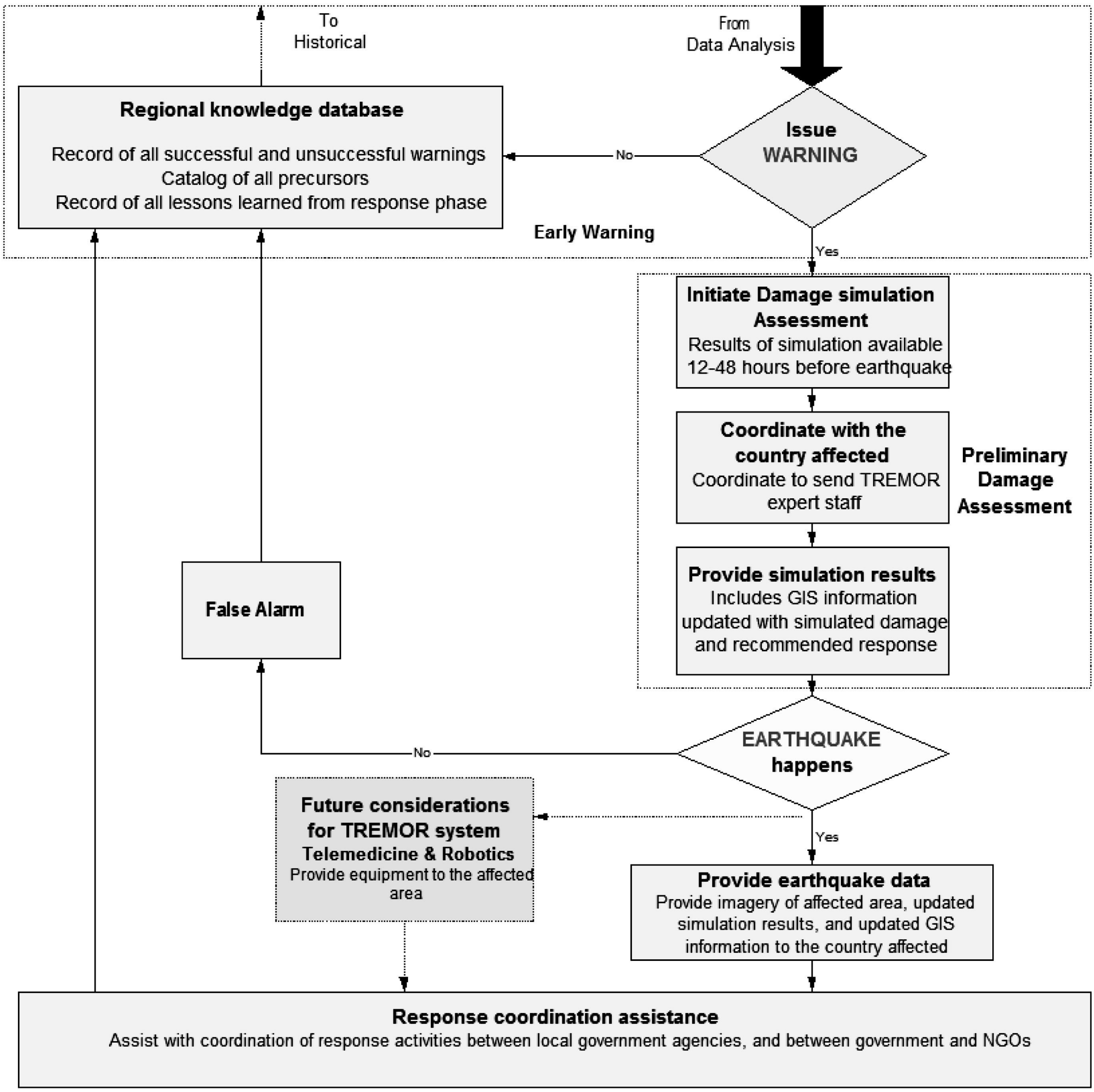

Fig. 7. Simulation and response prototype system.

emergency departments, human behavior during building evacuation, emergency communications infrastructure, travel times after an earthquake and the availability of trained personnel [31–34]. The simulation will give an optimised solution that provides an estimate of the initial response time, including the arrival of trained personnel and other material resources and the impact if the necessary resources are not available [31].

The proposed simulation system will consist of two interrelated parts. The *infrastructure damage assessment model* will be used to predict the operational status of key infrastructure, such as buildings, roads and hospitals, required during the response phase after the earthquake. The *resource allocation optimisation model* will be used to estimate and best allocate available personnel, material and equipment. The simulation will use input from the prototype earthquake early-warning system.

The requirements for the simulation system include the following:

- *Integrated solution*: The secondary effects caused by earthquakes, such as floods and fires, must be taken into consideration, along with combinations of effects. Evacuation of a population might be another hazard considered by the tool. A solution based on the immediate effects of an earthquake is not enough, since decisions have to be made based on the combination of all the effects.
- *Effective data presentation*: The amount of information processed by an integrated system will be enormous. An efficient data-processing system will present only data relevant to the decision making process.
- *Human behavior simulation*: To understand better the secondary effects produced by earthquakes, models of human behavior will be considered to identify problems such as bottlenecks in evacuation plans.
- *Continuous connection to local government services*: Simulation tools will assist in planning over the longer term recovery phase by providing recommendations related to logistics, relief delivery, shelter management, waste disposal, urgent repair and post-earthquake reconstruction.

5.2. Communications, Resource Tracking and Data Handling and Distribution

Communications, resource tracking and data handling and distribution are the key components to the response system and the integrated system shown in Fig. 8.

An emergency communications network is intended to provide reliable communications to emergency response personnel and citizens. The ability to set up and maintain communications is a critical task to optimise disaster relief efforts. Emergency communications systems will need to be easy to transport, assemble and use; require minimum power; have scalable architecture to manage the increased demand during the relief process; have the ability to bypass the existing network; and must support voice, data and video applications. Additional considerations for the system are to include a full secondary backup system placed at a location distant from the damaged primary infrastructure, user terminals that integrate a wide variety of communication technologies such as mobile satellite phones, VoIP handheld units, laptops, PDAs, webcams, VSAT and Ham radios and to have sufficient bandwidth to accommodate the various disaster relief applications. The architecture of the proposed system will provide global coverage to meet regional and international communications requirements. This will include tactical communications amongst relief workers on the disaster site with province and state administrators and strategic communications between the affected area and the outside world. When possible, terrestrial infrastructure will be integrated in the proposed system, including cellular terrestrial systems and VHF/UHF/HF terrestrial radio systems.

One of the most important tasks in the coordination process is the GNSS-based vehicle tracking subsystem. The existence of multiple uncoordinated tracking systems for each of the response organisations (e.g. Red Cross and Red Crescent, non-governmental organisations [NGOs], military, police) can sometimes lead to inefficient management of resources and delays in the reaction time. The TREMOR proposal provides an integrated system based on GPS tracking to monitor all existing vehicles from the response teams that enter an affected area. The use of such a system from the deployable unit centre can provide a more efficient and coordinated response. The system will provide vehicle tracking, safe routing information, coordination amongst teams, intercommunication and interoperability. This will result in reduced delays in the treatment of medical emergencies and faster search and rescue operations. The information gathered from all vehicles by the control centre has the additional benefit of real-time mapping of drivable roads and areas accessible by vehicle and could be processed to generate useful maps of the area or improve existing

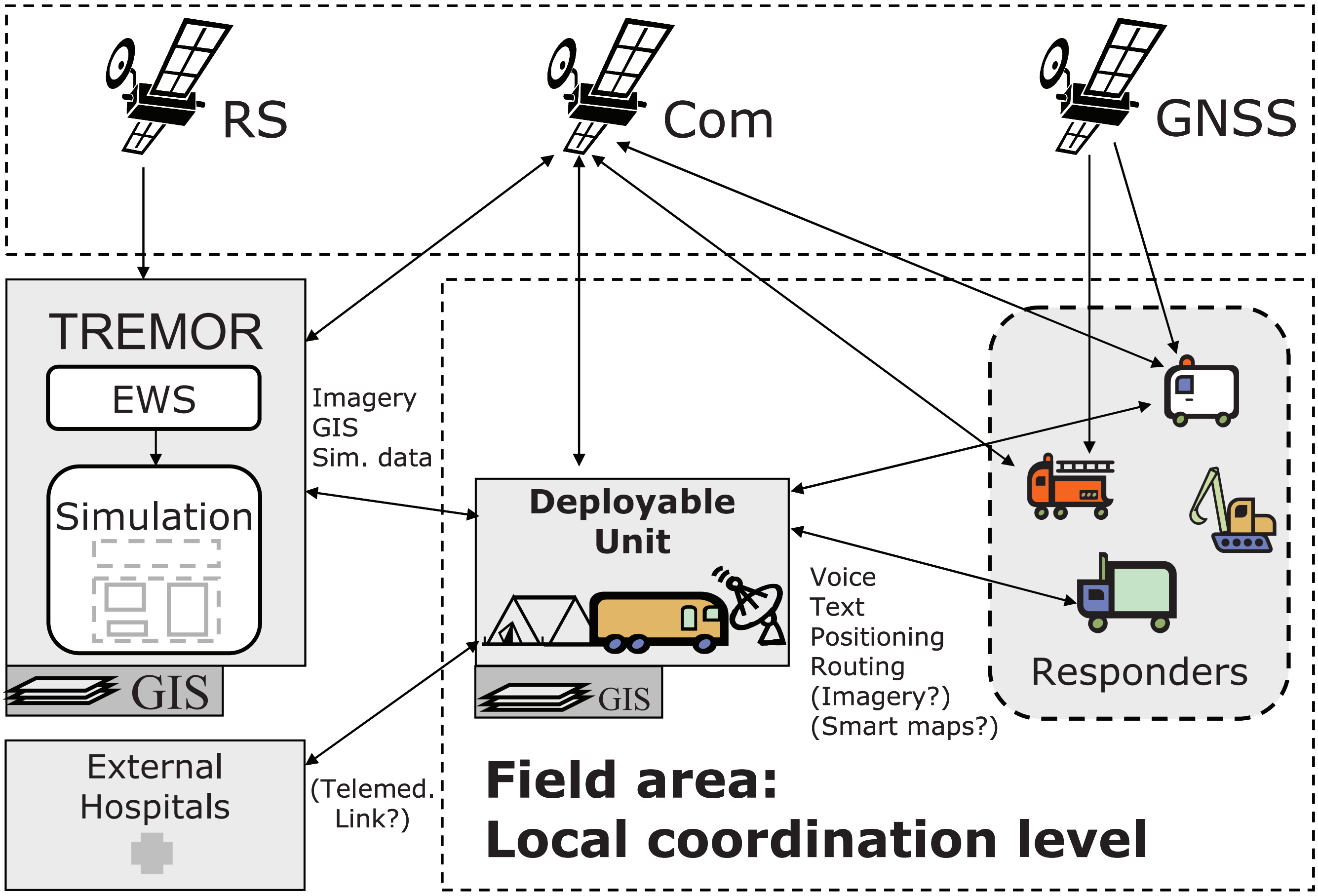

Fig. 8. Schematic diagram of the deployable on-site unit.

ones. The vehicle terminals normally consist of a GNSS receiver, a microprocessor and a transceiver or transmitter to send the information to the command centre. A simple user interface is required to present processed information, messages and maps of the area. GNSS receivers and transmitters compatible with existing GNSS systems should be used. This may require establishing guidelines and recommendations in the design of GNSS receivers and data exchange protocols to allow for the possibility of a universal transmitter. Several examples of systems using vehicle tracking for disaster management exist. For example, ESA's Real-time Emergency Management via Satellite (REMSAT I and II) has been used in cooperation with several Canadian universities and agencies to target forest fire hazards in British Columbia, Canada [35].

An organised GIS database is vital to emergency management. The GIS system will include pre-existing layers of information with soil types, building types, infrastructure and population. Critical infrastructure data that will be collected in advance of an earthquake include those on transportation, political boundaries, telecommunications, electrical power, water, oil and gas utilities, bank and finance, emergency services and government continuity plans.

New layers of data that are updated during the response phase will include remote sensing imagery and vehicle and resources tracking. A component for handling vehicle tracking and routing through GNSS needs to be integrated. Data collection and updated mapping capabilities in the field would be provided by the TREMOR central office. Distribution of local maps to responders in the area is one of the most important applications for the data stored in the GIS system. Pre-disaster mapping data would be gathered and analysed by the TREMOR central office. At the same time, remote-sensing imagery is obtained from Earth observation satellites. The deployable on-site unit collects additional information using the mobile GIS mapping capabilities and information from GNSS and sends the information back to the central office.

5.3. Virtual Constellation of Imaging Satellites

The TREMOR Team also proposes a "virtual constellation" of high-resolution electro-optical satellites. This system would take advantage of current and planned high-spatial-resolution satellites, combining these capabilities with the TREMOR systems' data processing and in the field communications capabilities to provide high resolution imagery to actors and entities involved in the on-the-scene response activities for a given earthquake. This capability would operate as a complement to the International Charter: Space and Major Disasters.

6. IMPLEMENTATION STRATEGY

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 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 organisational 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. A communication link between the NGO and the mobile response unit(s) will be provided. 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 organisation. 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 and the Group on Earth Observations.

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 [36]. 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. Whilst 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 that 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.

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. These 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 these 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 organisations for research and development purposes. However, should an organisation choose not to share its data with a particular third party, accommodation will be made to respect its request.

The simulation activities conducted by the TREMOR system also have associated data policy issues. These activities will require the use of potentially sensitive data (e.g. detailed maps, building plans, infrastructure capacity) from the individual client countries. These data must not be made public or available to anyone apart from the national authoritative agency of the client country. Simulations and associated data will be made available to other entities beyond the national authoritative agency only at the request of that agency. At the request of a client country, simulations will be run for areas where no watch or warning is in place for planning purposes. However, areas with active watches or warnings will receive processing priority for simulation activities. It is the responsibility of the client country to provide feedback regarding the value and accuracy of simulations. This feedback will be used to improve the simulation process.

In the end, for both the early warning and response systems, the role of the NGO responsible for the TREMOR systems 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 and at the same time build 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. 9. 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 larger the magnitude.

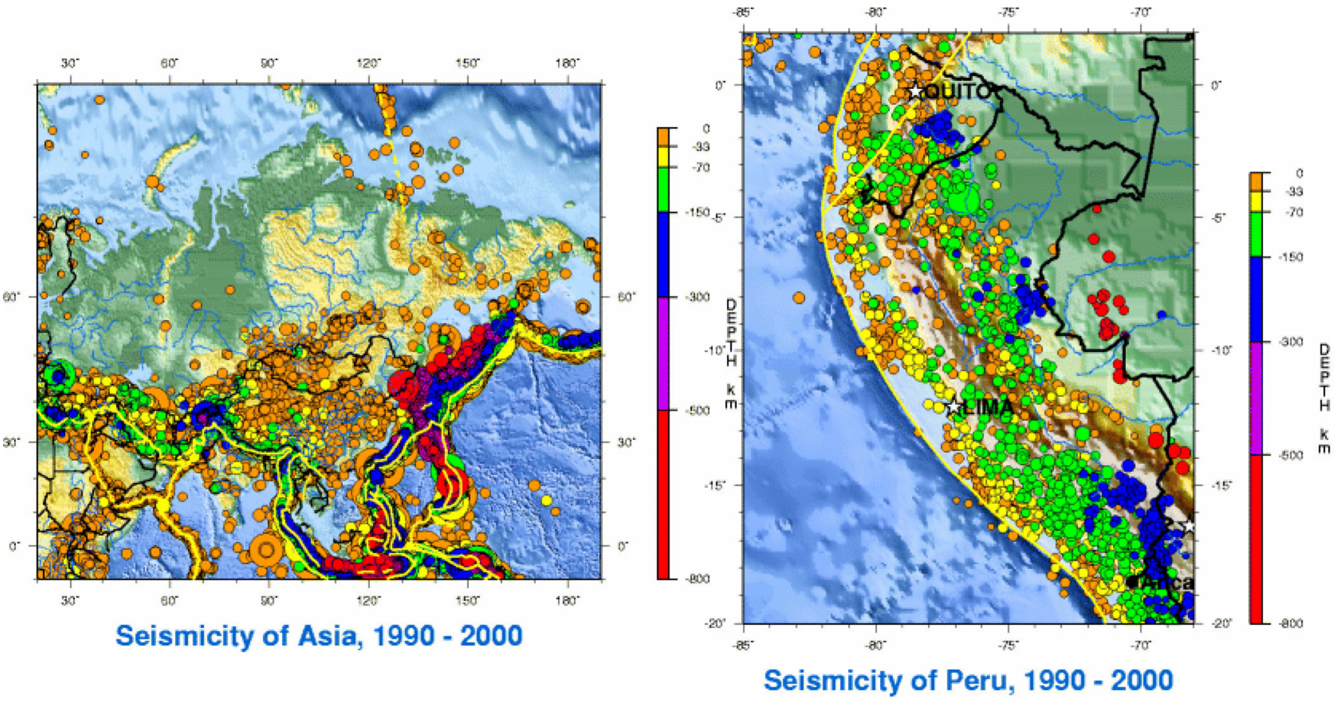

Fig. 9. Occurrence of earthquakes in focus countries [37].

Japan and Peru are both situated along tectonic plate boundaries, whilst China is characterised 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 urbanisation 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 23 June 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 15 August 2007, during the final preparation of the TREMOR report, the northern part of this fault once again slipped, producing an earthquake with a magnitude of 7.9. Hundreds of deaths have been confirmed and thousands of people were left homeless as a result [38]. 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 15th of August and what difference would a more effective response system now be making as the recovery efforts proceed.

In its report [1], TREMOR Team 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. Realising 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 article 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 minimise 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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