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A LARGE SCALE SEISMIC MONITORING PARADIGM AND ACCELEROMETRY TECHNIQUE BASED ON THE GIANT MAGNETORESISTANCE EFFECT

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ABSTRACT An alternative paradigm in seismic monitoring is suggested and demonstrated here, incorporating a stratagem involving large-scale and multi-nodal monitoring using inexpensive sensors. A new seismic accelerometry method and its preliminary testing are reported here, based on the use of the Giant Magnetoresistance (GMR) effect (for the first time). The sensitivity, linearity and noise performance were observed to be satisfactory for the problem at hand, and the chosen magnitude of bias magnetic field was noted to effectively eliminate interference from the geomagnetic field. Analysis of obtained data reveals the technique as a viable method in seismic monitoring. It is proposed that a large array of such low-cost units could be valuable in a large seismically-active zone to monitor foreshock patterns, plate dynamics and developing defects, and could provide valuable insight for seismic monitoring.

INTRODUCTION

Earthquakes take massive toll on large magnitudes of valuable human life and wreak havoc with property, infrastructure and communication networks on mass scales. Escalating occurrences of earthquakes, increasing populations in zones susceptible to large deviations in seismic activity and rising damage from earthquakes have augmented the need for large-scale and low-cost monitoring of earth’s tectonic plate movements, dynamic defect changes and stress interactions, which could possibly aid in saving precious human lives and property. Earth’s seismic activity being a complex phenomenon, function of a number of variables, precludes possibility of exact earthquake forecast till date, however studies have reported that occurrences of anomalous foreshocks may either lead to imminent earthquakes [1, 2, 3] or increase the probability of their occurrence [4]. Monitoring of significant foreshocks as well as displacements corresponding to dynamic defect changes in a number of sensitive zones, especially with large-scale coverage and good spatial resolution of detectors, may assist in providing valuable information to seismologists in establishing a major earthquake in advance.

The central role of seismic monitoring and the need for improved methods in this area, especially with large number of seismic monitoring stations and employment of more efficient and modernized instrumentation, has been highlighted by a number of studies, especially by the U. S. National Research Council in its exhaustive treatise [5]. Suggestions include improving on the deficiencies in the current seismic monitoring methods and expanding the existing endeavor of the United States Geographical Survey (USGS) in the form of its U.S. National Seismic Network (USNSN) of seismic monitoring stations. It has enumerated benefits from improved earthquake, volcanic and tsunami hazard assessment and forecasting techniques. Techniques in seismic monitoring, such as *"Seismic zonation"* (see, for instance [5], the concept involves creations of zones, whereby locations are established in urban regions with higher vulnerability to damaging earthquake ground motions) are viable approaches, which greatly rely on efficient and sensitive seismic monitoring techniques. This establishes the crucial role of seismic monitoring in earthquake forecast and suggests the need for enhanced approaches in large-scale, accurate and inexpensive seismic monitoring.

BACKGROUND

An Alternative Seismic Monitoring Paradigm

An alternative approach in seismic monitoring is suggested here, which involves two important elements. It is suggested that, at first, a large-scale, "*multi-nodal*" strategy may be adopted, which could comprise a large array of sensitive, improved and low-cost seismic monitoring field units ("*nodes*") in a sensitive zone. These could substantially replace or reduce the number of expensive "*intelligent*" base stations, whereby numerous low-cost passive nodes could be controlled and monitored by a single base station. Secondly, online analysis of data collected from nodes could be carried out at a central hub, where incorporation of computing (such as artificially intelligent algorithms) could be made for signal processing and possible deciphering of patterns in seismic activity. Suitable algorithms in centralized data processing could reinforce the strategy, where thresholds on online seismic data can be placed and necessary alarms installed (in software) against some preset parameters, to notify on anomalous foreshock activity or large deviations in crustal stress gradients.

A fundamental and central requirement for this paradigm is the development of a viable seismic accelerometry method which can help chart seismic displacements, vibrations and waves with a large dynamic range and in a sensitive and high-resolution manner.

The role of accelerometers is central to such schemes, which detect and measure displacements, vibrations and accelerations corresponding to ground motion or seismic wave propagation. These are generally based on mechanical devices, such as piezoelectric transducers [6], Micro Electromechanical Sensors (MEMS) [7, 8], Inductive Displacement Sensors, IDT's [9], or Linear Variable Differential Transformer (LVDT) pressure transducers [9]. Depending on particular application, these devices help monitor minuscule to large displacements and accelerations in earth's crust. However, a number of factors in these (which vary from sensor to sensor), such as non-linearity in response, low directional sensitivity, limited dynamic range, significant temperature dependence, constant need of an applied drive current or voltage, are often serious limitations. Another major difficulty is substantial costs, which becomes a major concern when hundreds or thousands of these units are required in order to cover a wide geographic location with good spatial resolution. This often precludes the incorporation of a large-scale, high-resolution seismic monitoring system in a sensitive zone with limited resources. A number of active seismic zones in the world which have fallen prey to catastrophic earthquake or tsunami events in past two centuries, such as Central America, South Asia and Southeast Asia, lie in developing regions where local governments do not have substantial resources to invest in large-scale seismic monitoring infrastructure and achieve the required earthquake predictability. Besides, a number of these units are based on high power-consumption electronic circuits, which cause substantially reduced battery life in the case of field-installed units. In this situation, a device based on a sensing technique which has required linearity, sensitivity, temperature stability, immunity from the need to provide and maintain a drive field/voltage, lower power consumption, nominal costs, and moreover, which needs least electronics and mechanics, is desirable.

Application of GMR in Seismic Accelerometry

The idea of an alternative seismic accelerometry technique is suggested here using a different kind of sensor which has not been exploited in seismic accelerometry so far. The idea is using a Giant Magnetoresistive (GMR) sensor to measure relative displacements in a bias magnetic field (from an inexpensive permanent magnet) corresponding to seismic accelerations, if the magnet can be utilized with a magnetic field at least ten orders more than the background from the geomagnetic field. Commercial availability of such magnets and GMR sensors at trivial costs makes this idea feasible.

The GMR sensors [10, 11] work on the principle of Giant Magnetoresistance effect [12, 13], a quantum mechanical effect whereby there is a decrease in electrical resistance of alternating layers of ferromagnetic and non-ferromagnetic materials whenever the device is introduced to an applied or ambient magnetic field. Their satisfactory linearity in the presence of large bias fields, accuracy, repeatability, temperature tolerance and good sensitivity (and in addition trivial unit costs as compared to other sensors) have made them one of the most suitable candidates in magnetometry, susceptometry and gradiometry where the magnitude of fields to be measured is not very small (>10^{-6}T). They have recently been introduced in accelerometry, mainly in applications ranging from aerospace to automotive controls. They are solid-state electronic devices, similar to integrated circuits, involving no moving parts, and thus neither there is gradual wear and tear, nor they entail provision of high-current power supplies, yielding very small power consumption, owing to negligible leakage currents. If a permanent magnet is employed as the source of bias magnetic field, there is no need for a bias drive current or field as well. Although the smallest fields which these devices can measure is limited to a few micro-Testla's (unlike SQUID's, Superconducting QUantum Interference Devices, which can venture down to nano- and pico-Tesla), their dynamic range is sufficient for seismic accelerometry. In addition, they offer remarkable sensitivity, accuracy and linearity [14, 15, 16] within this range and have superior temperature tolerance [14, 15, 17]. In addition, unlike SQUIDs, these sensors do not need cryogenic conditions for operation, factors which are of great significance in the field operation of seismic monitoring units in harsh conditions. These sensors are especially reported to offer higher directional sensitivity as compared to other sensors [18], broad sensitivity to amplitudes [19], and excellent linearity in the presence of externally-applied bias fields [19]. Collectively, these important features present GMR sensors as better alternatives to conventional sensors in seismic monitoring, such as MEMS and piezoelectric transducers.

So far, within the domain of geology and geophysics, GMR technology has not been employed in seismic monitoring or accelerometry, its application has only been restricted to magnetometry in sensing earth's geomagnetic field [20, 21] where the potential of these sensors is currently being evaluated. The main aim of this study was to explore the possibility if GMR sensing can be used in a viable seismic monitoring paradigm, where accelerometry for seismic events could be carried out. The basic tenet of this method lies in measuring bias field of a miniature permanent magnet, perturbed by displacements in a coupled GMR sensor as a result of seismic displacements or acceleration. In addition, the technique has provision for measuring geomagnetic field and its variations with a good resolution, when used without a bias field.

The commercial GMR sensors, such as the ones used in this study [14] have a wide dynamic range of sensitivity, ranging from about 30μT to 2mT [14], sufficient for the problem at hand. If the applied bias field from a miniature permanent magnet is chosen in the range of 500μT to 1mT (depending upon the choice of magnets and their geometries), the background effect from the ambient fields, most importantly the earth's geomagnetic field, prevalent on the order of 30μT to 60μT [22] in the present epoch, does not interfere with the measurement and acts merely as a known, manifolds low-amplitude background, which can be easily subtracted in the signal processing or analysis stage. The sensitivity of technique, as employed in the experiments reported here, to measure minute displacements on the order of sub-millimetre scale to large vibrations on the order of a few centimetres, demonstrated a conspicuous capability to register simulated foreshocks and aftershocks with excellent spatial and temporal resolutions. Accelerations can be measured with a large dynamic range, starting from a few hundredth parts of *g's* to several *g's* (in the units of *g*, the acceleration due to gravity). With a few design improvements, method might also detect minuscule shocks, which we may call *"microshocks"*, involving minuscule accelerations. Another benefit of using GMR sensing is the extremely low-noise susceptibility of these devices [14]. With a strong bias field and while being used on batteries (as done in all the tests carried out in this study), which is a viable option in view of very low power consumption with GMR systems, the noise reduces to Johnson noise, which is many orders lower than the measurements made in recording seismic events.

THE TECHNIQUE

Working Principle

The theoretical idea of the technique as presented in last section was evaluated with the help of some simple experiments based on an active bias magnet-GMR inertial setup, whereby movements in a bias magnet caused magnetic field gradients, which in turn induced proportional changes in the resistance of a stationary GMR sensor in its proximity, as shown in **Figure 1 (a)**. The sensor has an in-built bridge configuration [14] comprising two GMR elements and two ordinary resistors, which collectively generate a total change in resistance, ΔR, corresponding to the presence of an ambient magnetic field **B**.

In this system, one has linear relationship, where change in one parameter (voltage) is a function of the gradient of another (resistance);

$$\Delta V(\Delta R) = I\Delta R(\Delta \mathbf{B}) \qquad (1)$$

where V is the measured voltage at the output of GMR bridge sensor (in milli-volts) as a function of its change in resistance, I is the applied current on the sensor element (in milli-amperes), ΔR is the change in overall resistance of the GMR resistance bridge owing to Giant Magnetoresistance (in ohms) as a function of Δ**B**, which is the gradient in the intensity of the bias magnetic field (in Teslas), corresponding to a change in position.

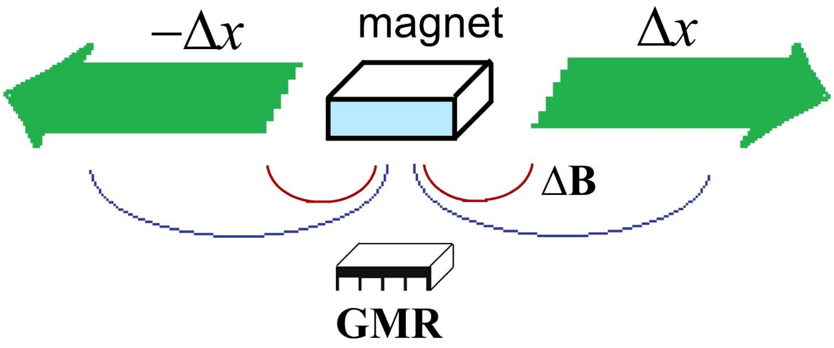

Figure 1 (a). The basic working principle of a GMR-based displacement sensor. Displacements (Δx) or vibrations in a miniature permanent magnet (mounted in close proximity of a GMR sensor) cause varying magnetic field gradients (Δ**B**), as measured by the sensor. By calculating an appropriate transfer function, the measured values of voltage can be transformed into magnetic field gradients as a function of displacement changes. This information is then readily available to calculate displacements, velocities and accelerations experienced by the magnet-sensor system.

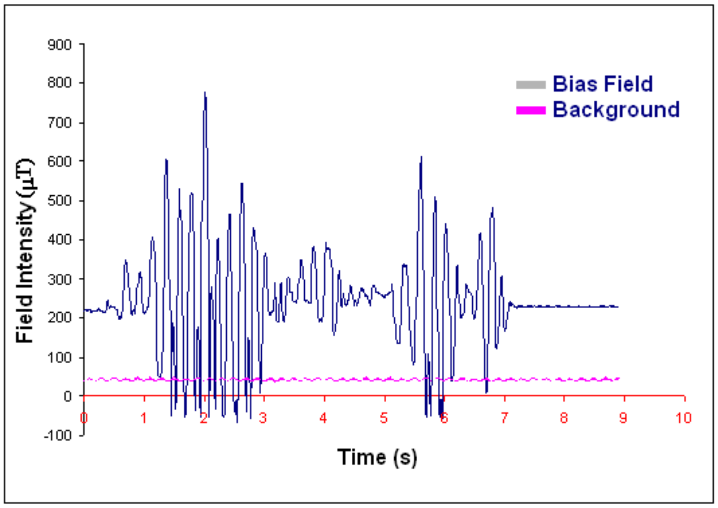

Figure 1(b). A comparison between the magnetic field from an approximately 800μT bias magnet (subject to displacements with one degree of freedom) and the background magnetic field (which is predominantly the geomagnetic field and some *ac* fields generated in the laboratory) is illustrated here, as measured in two separate experiments. As can be seen, the bias field is manifold higher than the background, which has a mean around 62µT, in effect cancelling the interference from the background.

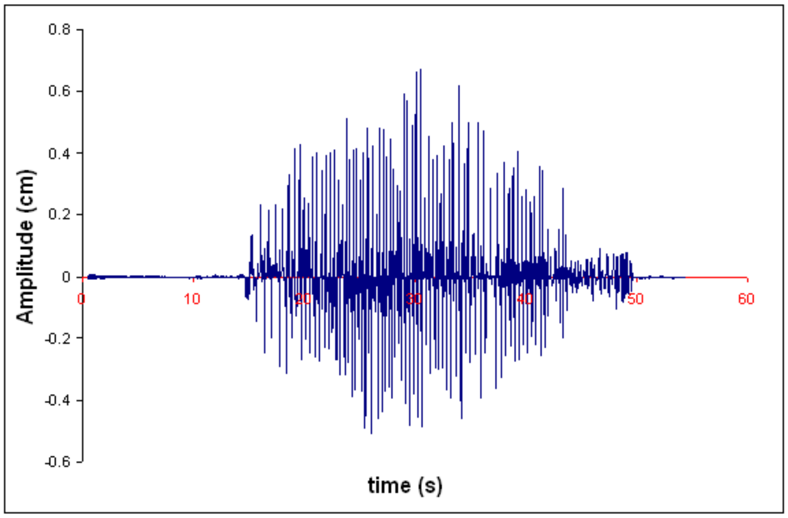

Figure 1(c). Low-frequency displacements of around 1 to 5mm as measured with the help of the GMR technique depicted in Fig. 1a.

Implementation

In the current implementation, the magnitude of bias magnetic field is chosen at a value around 500µT (with a low-cost miniature Neodymium permanent magnet), which is significantly higher than the ambient geomagnetic field (and thus independent of its minute variations [23], which take place on the order of a few nT in few seconds), cancelling the effect of background fields from terrestrial, atmospheric or cultural sources. The comparison of bias magnetic field vs. background field, measured in this study as well as reported earlier for the region [24], is illustrated in the **Figure 1(b)**, shows the lower magnitude of the latter.

Fig. 2 and Fig. 3 illustrate some of the results from these studies, carried out on a miniature shake table. After extensive data runs and calibration, the sensitivity of the technique was observed to be ranging from approximately 0.01g to 2.5g, with frequency range spanning from around 0.001Hz to 150Hz (the range as tested). The amplitude range detectable with the present form of apparatus is ±5cm (total 10cm), which can be curtailed or extended to some extent (roughly ±50%) with modifications in the mechanical assembly.

A straightforward experiment was conceived to demonstrate the technique as well as calibrate the positions of sensors and magnets. Some preliminary results were obtained with the help of this experiment to assess the accuracy of the technique as well as gauge its utility in seismic monitoring and earthquake forecast. A ground-bolted static platform, housed a GMR magnetometer (or gradiometer) and associated electronics (mainly comprising an operational amplifier and some passive components), over which a freely movable, specialized polyacrylic frame housed a miniature permanent magnet. The base platform had one or more GMR sensors mounted on it (one for each axis), corresponding to which there was a bias magnet on the movable frame. **Figure 1c** illustrates a set of sample displacements as measured with the proposed technique.

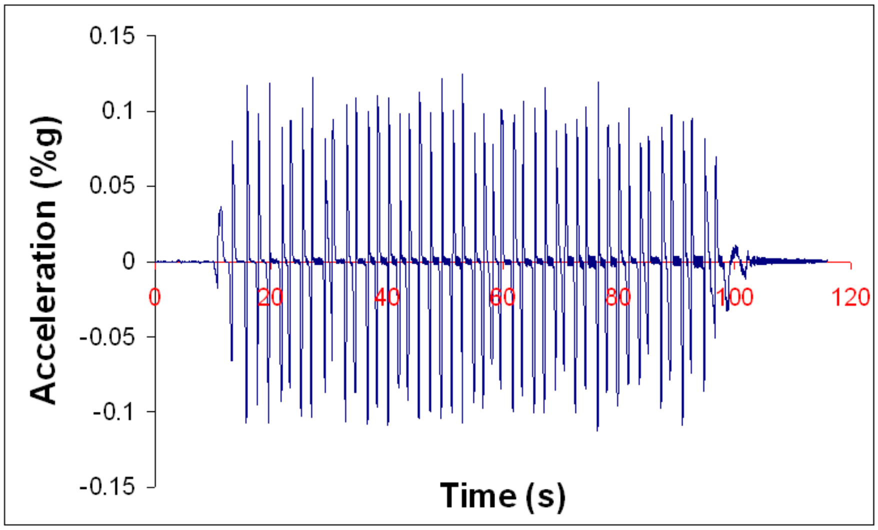

Figure 2(a): (a). A sample snapshot of a system of small low-frequency accelerations as measured with the experiment prototype. Acceleration is expressed in the units of *%g*, corresponding to a percentage of the acceleration due to earth's gravity *(981cm/s^2)*, as is a convention in seismology. Measurements were made on a custom-made shake table which could make displacements from 1mm to 3cms and accelerations from 0.1g to 2g.

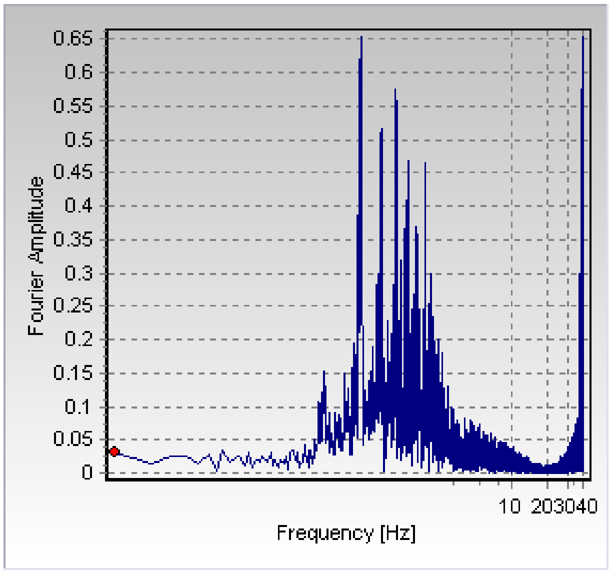

Figure 2(b). A log-linear Fourier spectrum of the data plotted in Fig. 2a, showing the frequency-domain representation of the signal. This plot was constructed by using a Fourier Transform on the time-domain data presented in Fig. 2 (a).

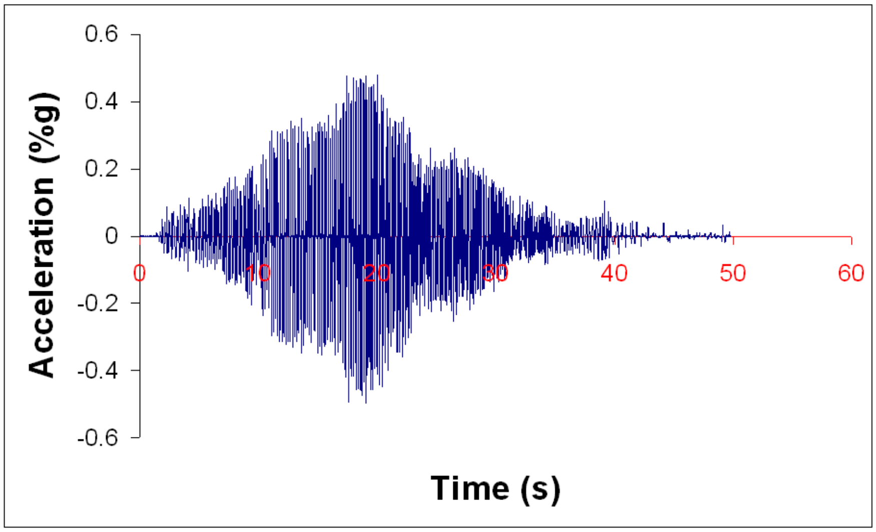

Figure 3(a). Measurements of a system of relatively higher frequency accelerations, corresponding to large and faster vibrations on a shake table. The system was subject to small displacement motions of around 1mm accelerating all the way to a peak amplitude of approximately 5mm, followed by a decelerating motion to the minimum amplitude possible.

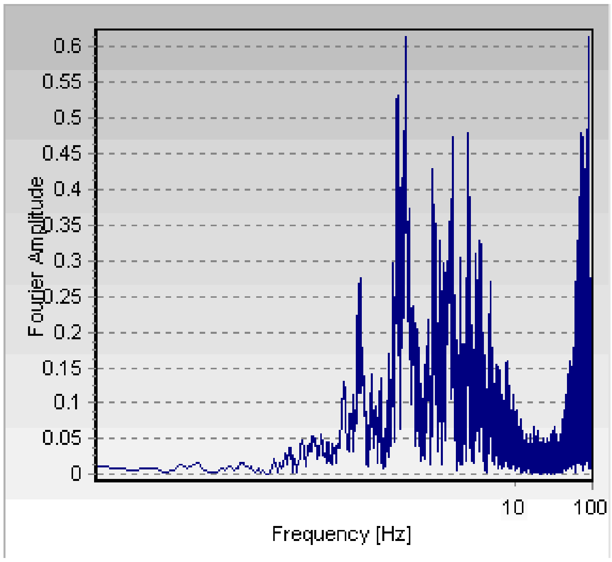

Figure 3(b). The figure depicts a log-linear Fourier spectrum of the signal shown in Fig. 3(a).

Mechanical Construction and Data Acquisition

Fig. 4 (a) illustrates schematic of the experimental apparatus designed for testing and calibration of the technique, whereas a photograph of the prototype apparatus is shown in **Fig. 4(b)**. A specialized plastic platform (dimensions LBH: 20cm x 15cm x 6cm, and bolted on ground), with a movable polyacrylic frame (dimensions LBH: 10cm x 9cm x 6cm) on its top, was designed and developed to house the experiment. Its main purpose was to mount a set of a miniature Neodymium magnet (acting as bias magnetic field source) magnetically coupled to a Giant Magnetoresistive (GMR) sensor (in either a magnetic field magnetometer or gradiometer configuration [14]), placed in close proximity (2 cm) of each other on the frame and station, respectively.

There is a set of retraction spring mechanism on either side of the frame, installed to reset the frame to center position after every displacement. The carefully-devised geometry of experiment and the high strength of source magnet (>500μT) preclude the interference in measurement from the magnetic fields in the surroundings of the rig, such as the geomagnetic field or *ac* fields from nearby equipment.

After assembling, the whole setup was enclosed in a tight metal casing, isolating the effects of wind and dust deposition, as well as minimizing electromagnetic interference. Although the GMR sensors have great tolerance to thermal effects, additional thermal isolation is provided in the form of a canopy and a specially-made Styrofoam enclosure, to enable operation of device in harsh and scorching summer weather. The frame position and the length of thread are carefully calibrated with reference to the static GMR sensor, so as to remain at a position where no field or a minimum (in the case of magnetometer configuration) is registered by the sensor. Calibration is done both manually, by visually taking readings with the help of a metric ruler mounted on the platform, as well as with the help of an attached Data Acquisition System logging the data.

In the case of two- or three-dimension measurements, the rectangular geometry of the apparatus can be replaced with a circular geometry. This idea is illustrated in Fig. 5, where the design of a two-dimensional GMR accelerometer [19] is depicted for making seismic vibrational measurements in the x and y axes[§]. The design has a spherical geometry, based on

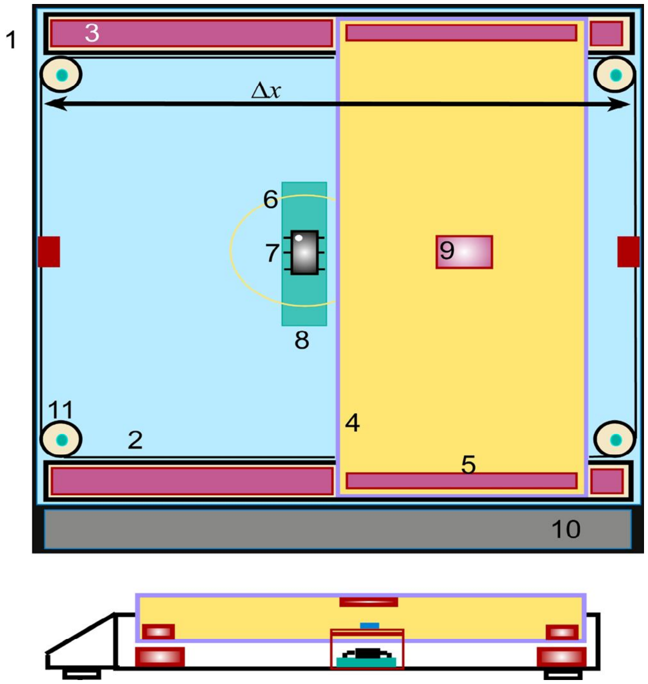

Figure 4(a). Schematics of experiment to measure and calibrate bidirectional displacements and accelerations in one dimension as a result of ground movement. Experiment was mounted on a shake table for calibration before fixing on the ground. The top schematic shows the top view whereas the schematic on the bottom depicts the side view of the apparatus designed. 1: The setup rig comprising a base platform (fixed on ground with bolts) and a mobile top, 2: Railing for free movement of the mobile top, 3: Railing on base platform, 4: a low-mass plastic movable top which undergoes inertial movement (Δx) with one degree of freedom, 5: railing in the movable platform, 6: inverted glass petri dish as cover for the magnetic sensor mounted in the center of the base platform, 7: GMR detector chip, 8: Printed-Circuit Board housing GMR chip and Op-Amplifier chip, 9: Neodymium magnet (~800μT) to create source field for the sensor, 10: metric ruler mounted on the front of rig for manual measurement and calibration of displacements in the mobile frame, 11: spring retraction mechanism.

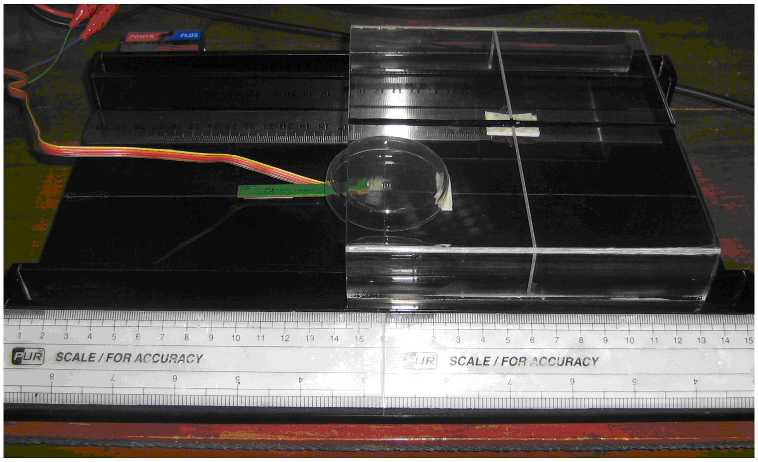

Figure 4(b). A photograph of the first prototype of the uniaxial seismic displacement sensing and accelerometry unit, the schematic for which was depicted in Figure 1.

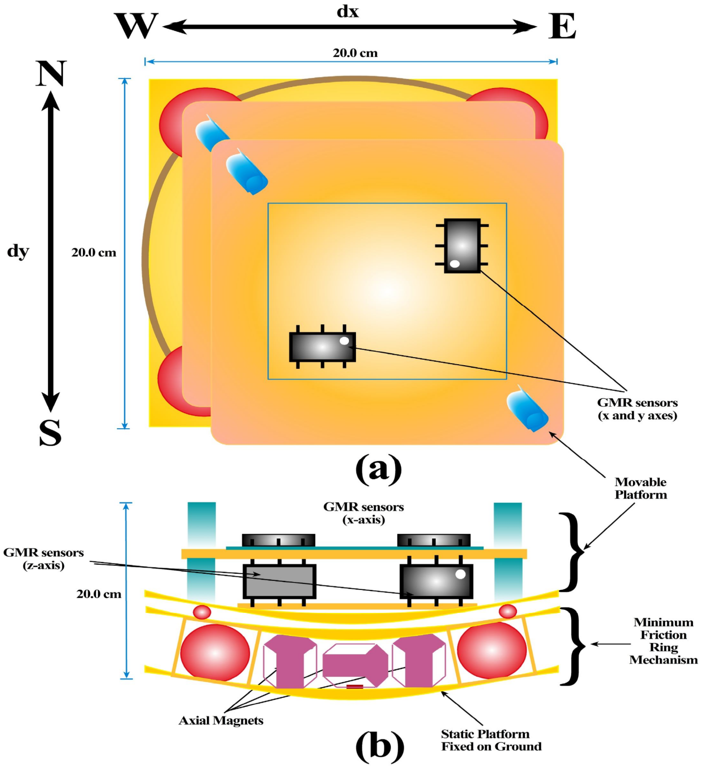

Figure 5 : (a). Top and (b) side views of the bi-axial version of the experiment to measure bidirectional displacements in two dimensions. The setup is formed in the form of a spherical geometry platform with one chip and magnet set corresponding to displacement over each axis. Either an (x, y) or (r, θ) coordinates system choice can be made to make a concurrent two-dimensional measurement.

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§ In recent times, some miniature 2- and 3-axis ready-made GMR magnetic sensors have become commercially available which have potential for use in biaxial and triaxial accelerometry applications like these. Some examples of these devices are given in recent literature [19].

two sets of sensors and magnets, with the whole experiment devised around two concentric spheres. Another idea to achieve this design could be to suspend the magnet (levitated with threads connected to frame) on the surface of a high-viscosity fluid, to further reduce friction. These ideas are so far not implemented, but just provided here for completeness and further exploration.

Fig. 6 illustrates a block schematic of the electronics associated with the test measurements in the experiments reported in this paper. Output of GMR sensor is amplified by on-board amplifier mounted on GMR PCB (Printed Circuit Board) and the signal is conveyed to one of the analog input channels of a Data Acquisition System (DAQ), which was Keithley KUSB3101 (http://keithley.com), connected to a personal computer via the USB (Universal Synchronous Bus) interface. A public-domain software *"Seismosignal"* (http://seismosoft.com) was used in the analysis of data and construction of accelerograms and spectra, as reported in this paper. Data acquisition was carried out at various sampling rates, ranging from 10Hz to 1KHz. Concurrent measurement and calibration were performed with the help of precision instrumentation, constituting Fluke 8840A Digital MicroVolt Meter, Fluke PM3094 4-channel Oscilloscope (http://fluke.com) and Hewlett-Packard 3585 Spectrum Analyzer (http://hp.com). Measurements of magnetic fields were carried out with the help of a Bell 6000 Series precision GaussMeter (http://sypris.com).

Fig. 7 shows the proposed design of a self-contained field unit based on this technique. This design is not achieved so far, but is in the development stage. The DAQ system and PC in current experiments would be replaced by a one-chip Microcontroller or Microcontrol Unit (MCU). These devices have all the necessary functions on-board, including a microprocessor, ADC (Analog-to-Digtal Converter), DAC (Digital-to-Analog Converter), timers and PC interface. These chips are pre-programmed with a BIOS (Basic Input-Output System) software (the *firmware* or *embedded system*). In addition to the MCU, there is a local FLASH RAM memory for on-the-fly data storage and an RF Transceiver to communicate control commands as well as data to a central base station of the network. A GPS (Global Positioning System) is an optional accessory, not required for operation of the field unit. It is only required as a one-time accessory to identify the bearing of the field unit at the time of installation or relocation.

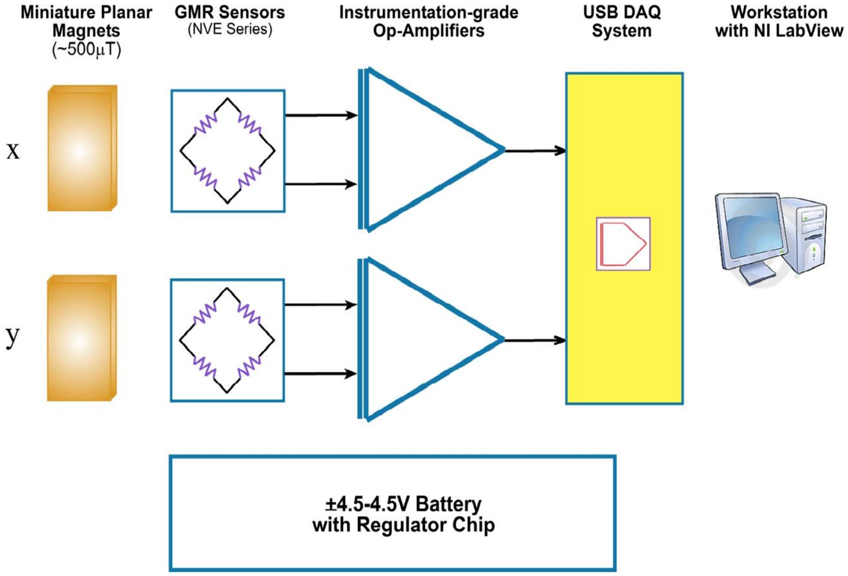

Figure 6. Block schematic of the computer-based test prototype design as used in the experiments reported in this study. It was used for testing as well as calibrating the setup in association with a measurement rig (as given in FIG. 1), based on a suitable PC-based general-purpose Data Acquisition (DAQ) system. The specific model used here was a 12-bit Keithley KUSB-3102 DAQ device.

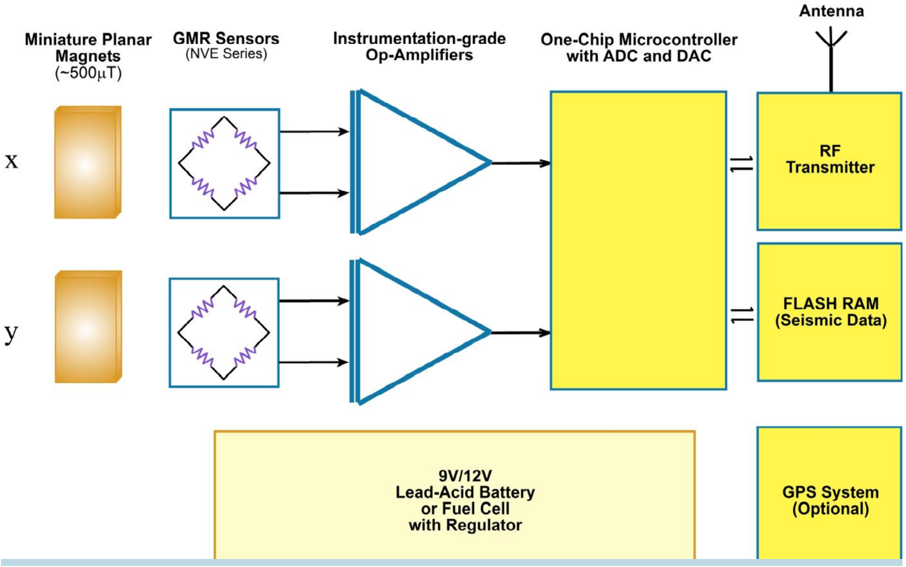

Figure 7. Block schematic of the design of a telemetric field unit (which may be called a *node*), as part of a large array of units to be installed in a seismically-active zone or region (with necessary electromagnetic, thermal, wind and dust isolation). Any general-purpose Microcontroller chip with on-board ADC, DAC, Flash RAM and firmware becomes the heart of the whole device. An RF transmitter constantly transmits the ground movement to a remote central processing unit for online monitoring and analysis.

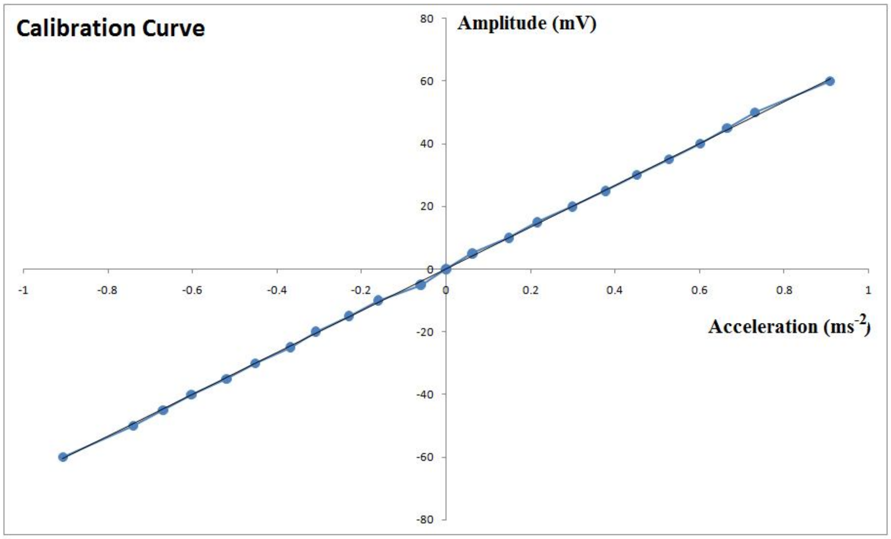

Figure 8. A calibration curve for the proposed technique, as measured in one of the experiments. Horizontal axis is the magnitude of acceleration (in ms^{-2}) and vertical axis is the amplitude of the measured voltage (in mV). Raw data is illustrated by the wavy line, whereas the straight line is a fit, using a linear function $y=66.86x + 0.094$, giving a slope of 66.86mV/ms^{-2} (as the coefficient of conversion).

Testing

The tests were carried out in Karachi, Pakistan (latitude 24°56'51.4", longitude 67°08'15.9"), where general magnetic field magnitudes are reported [24] on the order of Bx~35µT, By~27µT, Bg~44µT, with typical field variations of around 25nT to 1nT over a few seconds [24]. A calibration curve for the instrument is illustrated in **Fig. 8**, which shows the amplitude of the measured voltage

(in milli-volts) against accelerations (in ms^{-2}) experienced on the shake-table. Amplified data (wavy line) was fitted to a straight line using a linear fit ($y=0.015x - 0.002$), yielding a slope of $0.015(ms^{-2})/mV$ (or 66.67mV for an acceleration of approximately 0.1g) , which is the coefficient of conversion. It shows sufficient linearity, as needed for the application, and is comparable to any other accelerometry detector used in seismic application. The inherent non-linearity, as seen in the plot, mainly arises from mechanical implementation of the design on experimental basis. Improvement in the assembly of apparatus can significantly improve the linearity of detector.

The present implementation of the technique appears to be in intermediate to strong motion seismometry, where measurements can be made from approximately 10^{-2}g to 4g, depending upon individual implementation and calibration approach adopted in the design. However, the technique can be modified for use in weak motion seismometry, owing to the large dynamic ranges of GMR sensors commercially available.

The method as reported here is an alternative technique in measuring seismic displacements and accelerations, with the capability to record low to high amplitude seismic events and waves in a simple manner. After a few modifications it finds utility in virtually any application where accelerometry or differential measurements of stress-induced displacements may be required in broad-based seismic monitoring. These applications include charting crustal stress gradients in studying tectonic plate dynamics and in making measurements of minute displacements in known defect boundaries. Other important applications could be in studies on reaching deeper understanding of the theory of stress-triggered earthquakes [25, 26] by mapping stress vectors and their gradients on fault boundaries and adjoining zones, and in Real-time Seismic Amplitude Measurement [5] in situations where individual earthquakes cannot be discriminated in the wake of a high number of earthquakes occurring in a short time scale. In such applications, the high sensitivity and good spatiotemporal resolution of GMR sensing-based accelerometry can be invaluable.

CONCLUSION

In the wake of escalating earthquake occurrences and their catastrophic effects, the need for viable large-scale seismic monitoring paradigms has become crucial. An alternative paradigm in seismic monitoring is suggested here, which incorporates a stratagem involving large-scale, multi-nodal monitoring, using an accelerometry method based on the Giant Magnetoresistance (GMR) effect. The idea of a GMR-based seismic accelerometery technique is proposed, based on measurement of relative displacements between a permanent magnet and a GMR sensor corresponding to seismic motion or waves. The idea is demonstrated with the help of some simple experiments and the design of a realistic technique. The sensitivity, linearity and noise performance were observed to be satisfactory for the problem at hand, and the chosen magnitude of bias magnetic field was seen to effectively eliminate interference from the geomagnetic field. It is proposed that a large array of such low-cost units, in association with a centralized processing and pattern analysis center, could be valuable in a large seismically-active zone to monitor foreshock patterns, plate dynamics and developing defects. It could possibly be used in analyzing anomalous variations in seismic activity and crustal stress changes bearing potential for occurrence of extraordinary seismic events.

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