Development of a Potassium Super Gradiometer for Earthquake Research Applications

Dr. Ivan Hrvoic[1], H. Ginzburg[2], H. Zafrir[2], G. Steinitz[3], B. Shirman[4], G. Hollyer[1]

[1] GEM Advanced Magnetometers, 52 West Beaver Creek Road, Suite 14
Richmond Hill, Ontario, M4L 2Z6 Canada.

[2] Soreq Nuclear Research Center, 81800 Yavne, Israel

[3] Geological Survey of Israel, 30 Malkhe Israel St., 95501 Jerusalem

[4] Survey of Israel, 1 Lincoln St., 65220 Tel Aviv

SUMMARY

This paper describes a new approach and what we think is a state-of-the-art methodology in (electro)magnetic measurements for earthquake research. Existing methods have met with limited success due to limited sensitivity and long-term stability of instruments, imperfect elimination of environmental noise, and in the case of induction coils, to limited low frequency features and the skin effect for their bandwidth of measurements.

We analyzed dipolar magnetic fields and their gradients generated by earthquakes with emphasis on their strongly local character. The magnetic moments of two measured precursors are calculated as well as the maximum distances at which those earthquakes can be detected with both present methods and a new proposed method (i.e. short base Potassium gradiometer).

Due to the extreme sensitivity of the Potassium SuperGradiometer, the new method is at least one order of magnitude more sensitive than presently used induction coils. SuperGrad features and installations are described.

INTRODUCTION

Magnetics has played a significant role in Earthquake studies for several decades. Based on the theory of piezomagnetism and/or electrokinetics, it offers a possibility of detection of precursors to earthquakes due to gradual pressure build-up, microcracking of rocks and water flow in the process. Three typical limiting factors include sensitivity, long-term stability of instruments and a need to eliminate environmental noise (diurnals, ionospheric and anthropogenic noise).

Early monitoring systems with sensitivities in the nT range and long base differential measurement produced in a few cases, startling precursors that however, happened so rarely and sometimes under semi-mysterious circumstances that their credibility as precursors stayed very low. In some of the more recent work induction coils with an improved sensitivity (25pT) have been employed. Even with their limited long term features (bandwidth down to 0.01Hz) the results have been somewhat better as the anomalies down to few tens of pT could be detected.

However detection of precursors was only possible when the detectors found themselves very close to earthquake hypocenters. At larger distances, the skin effect severely limits the detectability by induction coils.

Skin effect is the tendency of a high frequency electric current to flow mostly near the outer surface of a solid electrical conductor (earth), at frequencies above the audio range. It is proportional to the square root of the resistivity and the square root of $1/\varpi$ where ϖ is the frequency. As discussed later, the skin depth (depth of penetration) for a superconducting coil is approximately 30km (based on a frequency of 10 MHz) as compared with that of the SuperGradiometer which has significantly greater skin depth (based on a frequency of 0.1 MHz).

Piezomagnetic anomalies vary substantially with the earthquake intensity, composition of rocks that come under pressure, geometry of pressure etc. Assuming that they are of dipolar character (3), their fields vary with the cube of distance (i.e. their detectability will be limited to a proximity to epicenters - or better, to hypocenters).

More systematic results can only be obtained if the measurements can be done with substantially increased sensitivity and long-term stability. When assessing the results of measurement one must consider very local character of dipolar magnetic field, and large interfering time variations of magnetic field (diurnals and ionospheric effects). Anthropogenic noise is another formidable barrier that must be overcome.

Both magnetometers, and to a lesser extent, induction coils need to work in differential mode to reach the best sensitivity - free of interfering time variations of magnetic field. Reference instruments that measure only temporal variations of the magnetic field are usually placed away from active zones, (long base), resulting often in imperfect elimination of interfering environmental noise.

Main diurnal “anomaly” of 10–30nT travels around the globe once every 24hrs and any east-west, non-meridian offsets of the reference magnetometer will show a part of this “anomaly” daily.

DETECTABILITY OF EARTHQUAKES BY GRADIOMETERS

If we assume that earthquakes create a dipolar type of magnetic anomaly, we can calculate the detectability of earthquakes of given magnitude. The magnetic induction B of a magnetic moment M is defined as:

$$\boldsymbol{B} = \frac{\mu o\, M\, (1 + 3cos^2\alpha)^{1/2}}{4\pi\, r^3} \qquad \mathbf{1}$$

where μo is magnetic permeability of a vacuum,

$$\mu o = 4\pi \;\; x\; 10^{-7}\, Vs/Am \qquad \mathbf{2}$$

and α is the angle between radius vector **r** and dipole directon.

Since

$$1 \;\le\; (1 + 3cos^2\,\alpha)^{1/2} \;\; \le 2$$

we can assume $cos^2 = 0$ for simplicity. Then:

$$\boldsymbol{M} = \frac{4\,\pi\, r^3\, B}{\mu o} \qquad \mathbf{3}$$

In extending these results, we should look first at the spectacular data from the Loma Prieta earthquake[(8)] of 1989. As shown in Figure 1, this earthquake clearly illustrates precursor phenomena. Measurements were made with a nearby induction coil that had been set up fortuitously[(8)].

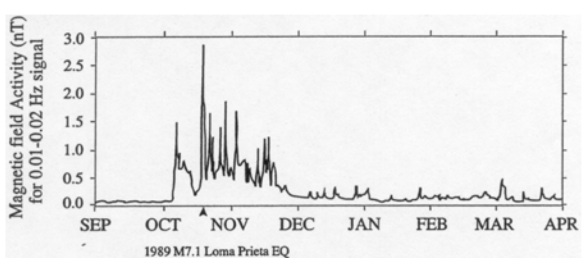

Figure 1: Example of magnetic data preceding and following the Loma Prieta earthquake in California, 1989.

From reports[(5,7)] on the Loma Prieta M7.1 earthquake (maximum magnetic anomaly B = 2.8nT at 7km distance to epicenter and 17km depth of hypocenter) and San Juan Bautista M5.1 earthquake (20pT anomaly at 2km distance to epicenter and 9.2km depth of hypocenter), one can calculate the magnetic moments:

For Loma Prieta $B_{max} = 2.8nT$ $r = 18.38km$, and $M_{LP} = 1.74\ 10^{11}\ Am^2$

For San Juan Bautista $B=20$ pT $r = 9.41km$, and $M_{SJB} = 1.67\ 10^{8}\ Am^2$

Those measurements were made at 0.01 Hz. If we take into account skin effect (skin depth in this area[7] is about 30km at 0.01 Hz). The magnetic moments are corrected to:

$$M_{Lps} = 3 \times 10^{11}\ Am^2$$

$$M_{SJBs} = 2.6 \times 10^{8}\ Am^2$$

San Bautista magnetic moment is about 1000 times less than Loma Prieta magnetic moment. Considering the uncertainty of the M_{SJB} measurement, and our approximation of dipolar magnetic fields, one can conclude that the moments of earthquake magnitudes follow energy dependence (i.e. $10^{1.5}$ for a unit difference of the Richter scale).

From the above results it is possible to assess expected magnetic moments from the earthquakes of various magnitudes (Table 1) and the distances to hypocenters at which they will produce anomalies equaling magnetometer / induction coils noise levels. From equation (3) and B = 25pT sensitivity of induction coils:

$$r = \left[\frac{\mu o\ M}{4\pi\ B} \right]^{1/3} = 15.874\ M^{1/3} \qquad \textbf{4}$$

Returning to the potential field theory, the gradients of the magnetic moment are:

$$\frac{dB}{dr} = -\frac{3\mu o\ M}{4\pi\ r^4} \qquad \textbf{5}$$

And the distance, r, at which the magnetic moment M will produce a gradient dB / dr is:

$$r = \left[\frac{3\mu o\ M}{4\pi\ \frac{dB}{dr}} \right]^{1/4} \qquad \textbf{6}$$

For gradiometer sensitivities of 1fT/m and 0.1fT/m, $r = 131M^{1/4}$ and $r = 233\ M^{1/4}$ respectively.

Table 1:
Comparison of different types of sensors. Nominal magnetic moments and the maximum distances they can be detected by various magnetometers and gradiometers are shown.

Mag-nitude	Mag Moment Am^2	Detectable Distance [km]			
		Mag 1nT	Mag 0.1nT	Induction coils 25pT Skin Depth 30 km	SuperGrad 0.1 fT/m
9	1.2×10^{14}	228	492	150	771
8	3.8×10^{12}	60	130	90	325
7	1.2×10^{11}	18	39	46.6	137
6	3.8×10^{9}	6	13	20.0	57.8
5	1.2×10^{8}	1.8	3.9	7.2	24.4

SHORT BASE (GRADIENT) MEASUREMENTS

True gradiometric (i.e. Short Base) measurements place stricter requirements on the instrument sensitivity (or placement of sensors closer to hypocenter of the earthquake) in comparison to electromagnetic and long base magnetic measurements.

This effect is due to the faster decay of dipolar magnetic gradients with distance:

$$\frac{dB}{dr} = \frac{-3B}{r} \qquad \mathbf{7}$$

where dB / dr is a measured gradient, B is the magnetic induction produced by earthquake at the measurement site and r is the distance to the hypocenter.

The advantage of Short Base Measurements is a possibility of deep suppression (if not complete elimination) of the influence of diurnals, ionospheric and anthropogenic noise. For this to occur, it is important to ensure that the two gradient sensors record strictly synchronous readings.

POTASSIUM SUPERGRADIOMETER

The extreme sensitivity required for the Short Base method of Earthquake Research is delivered by the Potassium SuperGradiometer from GEM Advanced Magnetometers. SuperGrad was developed in cooperation with Professor E.A. Alexandrov and his research group and (late) Dr. Arthur Green of the United States Geological Survey.

The background noise of the magnetic gradient of SuperGrad is 0.05pT or 50fT for 1 reading per second. Spacing of sensors 50m to 100m from each other produces a gradient sensitivity of 0.5fT/m to 1fT/m.

For a 10km distance between sensors and the earthquake hypocenter, this is equivalent to detecting some 1.6pT to 3.3pT of the earthquake's local magnetic field at 1 reading per second (or a minimum magnetic moment of 16 – 33.10^6 Am^2). At 100km distance to a hypocenter, the detectability becomes 16 – 33pT (or a minimum magnetic moment of 16-33. 10^{10} Am^2).

This is comparable to induction coil sensitivity, although induction coils, measuring relatively high frequencies, suffer from severe skin effect at comparable distances. For example, if we consider the skin depth at 0.01Hz and average conductivity of soil of 0.01 S/m at 30km [(7),] , we find that at 100km, this translates into attenuation of over 20 times.

SuperGrad sensitivity is about an order or magnitude better than reported sensitivities of induction coils in all circumstances. For example, a simple calculation shows that the San Juan Bautista earthquake which was barely detected by induction coils (signal to noise ratio of 1:1) would have been detected by Supergrad with signal to noise ratio of 22:1.

In contrast to induction coils, the SuperGradiometer 1/f noise can be (theoretically) limited to some 1pT long-term i.e. 10fT / m could be maximum long-term noise. This is also close to our preliminary measurement of ionospheric noise. Potentially, magnetic moments weaker than 10^8 Am^2 (M5) could be detectable at 10km distance to a hypocenter of the earthquake.

The final limiting factor is possibly the long-term drift of the magnetometer / gradiometer – a factor which is currently being evaluated. Elimination of anthropogenic noise is also promising. At the distance of 1km and the sensitivity of 1fT/m, a large anomaly of $1000Am^2$ related to man made effects becomes undetectable.

INSTRUMENTATION

GEM's special gradiometer is a system based on the Optically Pumped Potassium – a unique technology that can produce very high volumes of data, taking 20 readings per second.

Figure 2:
SuperGrad console with three sensors.

The system is specially designed for sensitivity, high absolute accuracy, minimal heading error and reliability based on the principles of Potassium optical pumping theory. In practice, the system has 3 sensors and measures gradients in two perpendicular directions in a horizontal plane as shown in Figure 3 below.

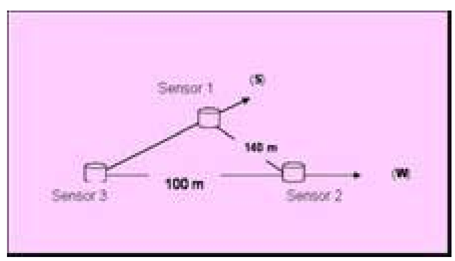

Figure 3: Sample SuperGrad Array showing two horizontal sensors
(W, S) referenced to sensor (3) for horizontal gradient measurement in two directions.

EXAMPLES

The SuperGrad is currently being employed for earthquake studies in the vicinity of the Dead Sea Rift, Israel in combination with an integrated radon measuring system. The Integrated SuperGrad / Radon (ISGR) system was developed in conjunction with SOREQ Nuclear Institute of Israel, the Geological Survey of Israel and the Survey of Israel.

The SuperGradiometer was installed in mid 2002 in Amram tunnel near Eilat in Israel. This site is in the vicinity of numerous weak earthquakes and the goal is to learn more about the earthquakes and possibly detect precursors. Radon monitoring performed by Geological Survey of Israel supplements magnetic measurement.

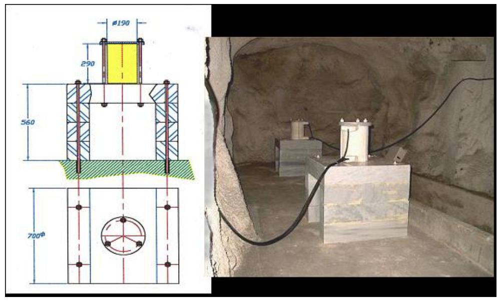

Figure 4. SuperGrad sensors installed in Amram tunnel
with a sketch of a marble sensor-mounting platform

The SuperGrad measures magnetic fields at 3 sensors 20 times per second with 50msec (10Hz Nyquist bandwidth) and 1 second integration times. Six channels of data measured to 1fT resolution (11 digits) are transferred to Survey of Israel automatically on an hourly basis for analysis. A GPS receiver provides precise Universal Time.

The noise background of the data is about 0.1pT for 1second integration giving about 2fT/m sensitivity at 50m-sensor spacing.

The gradiometer has now been in operation for more than two years, and more than 8 billion individual readings – likely the largest volume magnetic dataset of this type ever collected – have been acquired. Based on these results, the system shows excellent long-term reliability. A second 3 sensor SuperGradiometer has been built and will be deployed on magnetically quiet new site near the same rift within a year.

Another SuperGrad has been deployed at a site operated by the National Research Council (NRC) in Ottawa, Canada. However, another installation is planned in an area that is more earthquake-prone with the anticipation of additional results and case histories.

By extension, the principles of gradiometry described here may apply to other types of applications, such as airborne gradiometers with very short (0.3m) baselines or extremely sensitive measurements of remnant magnetization of paleomagnetic samples. The SuperGrad has good potential with respect to other systems (ex. SQUIDS) due to its reliability, low cost, and relative ease of operation. Work is ongoing in this area.

CONCLUSIONS

We can conclude that magnetometers of 1nT sensitivity can detect only the strongest earthquakes (M = 7 and 8), and induction coils earthquakes of magnitude M = 6 or more, and the Supergradiometer in “fast” and “slow” modes M = 5 or more. Note that this analysis is approximate, as it does not take into account geometrical factors. If these are taken into account, we may expect some, but not very essential variations of the above result.

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