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Title:

**The Application of High Temperature
Superconductors to Underground
Communications**

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Applications of High Temperature Superconductors to Underground Communications and Geophysical Surveys

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Abstract

The best approach for underground communication systems is low frequency electromagnetic waves that are deeply earth penetrating. Such an approach has been known for some time, but the low frequency receivers have been the limiting factor. The state-of-the-art receivers use wire wound on an air or ferrite core. These receivers are rather insensitive to low frequency magnetic fields when configured into a small package and used over a wide bandwidth. High-temperature SQUID (Superconducting Quantum Interference Device) technology is far more sensitive to low frequency magnetic fields. Receivers based on high temperature SQUID technology can be placed in small packages that can be easily carried by personnel moving in an underground environment. The receivers possess the sensitivity and bandwidth to carry voice and data in a configuration that is easier to install and maintain than hard-wired technology. The receivers may also be used with autonomous equipment such as remotely operated mining equipment or sensor systems. These receivers will increase mine productivity and worker safety.

Background and Research Objectives

Traditional radio uses frequencies above 500 kHz, but these high frequencies are weakly ground penetrating. Typically, the signals travel 1-10 meters into sedimentary rocks. Solutions of the electromagnetic wave equations in the low frequency limit show that the signal strength varies as $\exp(-x/\delta)$, where $\delta = (2\rho/\omega\mu)^{1/2}$ is known as the skin depth. Here, ρ is the resistivity, ω is the angular frequency and μ is the magnetic permeability. This relationship is depicted in Fig.1 where the relative permeability is taken to be unity. Evaluating the skin depth for actual geologies is not completely straightforward because the resistivity is variable. The table of resistivities below indicates how wide the variability is in practice. Nevertheless, examining the results for a typical material, sandstone, we have a resistivity greater than 35 ohm-m, corresponding to a skin depth of roughly one hundred meters at 1 kHz.

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Table of selected resistivities (ohm-m)					
granite	5000-10 ⁶	sea water	0.2	rock salt	10 ⁶ -10 ⁷
coal	~10 ⁴	sandstone	35-4000	galena	10 ⁻² -300
mudstones	10-100	hematite	10 ⁻¹ -100	moraine	8-4000
zinc blende	> 10 ⁴	limestone	120-400	clay	1-120
pyrite	10 ⁻⁴ -10	chalcopryite	10 ⁻⁴ -0.1	magnetite	10 ⁻² -10
pyrrhotite	10 ⁻⁵ -10 ⁻³	graphitic shale	10 ⁻³ -10		

We note that effective communications are possible over many skin depths. These results clearly imply a skin depth in common materials that would allow frequencies below 1 kHz to penetrate deep underground. We note that many of the economically valuable ores, chalcopryite for example, have a much lower resistivity, implying potential geophysical survey applications.

To receive these deeply penetrating low frequency electromagnetic waves we have introduced a high-temperature superconducting receiver. The key device is known as a Superconducting Quantum Interference Device (SQUID) and is essentially an extremely sensitive magnetometer. The underground radio uses a small liquid nitrogen dewar to provide the cryogenic temperatures necessary to operate the SQUID. The dewars will likely be industrially deployed in a 2-inch diameter. The dewars will be very light, e.g. 4-8 ounces. The liquid nitrogen is used in such small quantities that the total gas contained in the expanded cryogen is less than 0.1 cubic meters. The maximum boil-off rate produces a quantity of nitrogen that is negligible compared to the production of carbon dioxide by an individual. Thus, the boil-off will pose a negligible risk in even the smallest confined spaces. The dewars also contain a foam filler to prevent spillage. During off-hours individual users will recharge the system by plugging the unit into a combination liquid-nitrogen manifold/electrical-charging station. The battery power drawn is negligible compared to the standard miners cap lamp. A typical mine system would consist of 50-100 users each equipped with a portable unit. The infrastructure would consist of base stations on a half-mile to quarter-mile grid with a surface recharging system near the miner's entry.

In practice, a SQUID is operated with external electronics that apply current bias and flux modulation. The SQUID voltage output is fed to a preamplifier and then to a phase-lock circuit referenced to the modulation. The phase-lock output is integrated and superimposed out of phase on the modulation signal. The result is to lock the SQUID to a specific flux operating point. The feedback signal is then proportional to the magnetic flux. This circuit is known as a flux lock loop (FLL). A communications receiver requires additional electronics that demodulate the carrier signal.

At LANL, we fabricate high-temperature superconductor (HTS) electronics that are produced by successive layers of deposition, lithography, and etching on single crystals. We use both novel materials and novel processes in these steps. The device location on the crystal is not restricted.

This flexibility allows step-and-repeat patterning, a manufacturing process in electronics that allows simultaneous production of numerous identical circuits on an individual crystal. If large volumes are required, the crystal is then cut into many circuits, yielding low cost per circuit.

In small magnetic fields, even those of the order of the geomagnetic field, magnetic flux can enter superconductors and introduce circulating currents that suppress the sensitivity of the device. When enough magnetic flux has entered, the SQUID ceases to function and function can only be restored by thermally cycling the device to a temperature above the superconducting transition temperature. This thermal cycle takes less than a minute, but it is unacceptable for continuous operation. The devices we fabricate at LANL have a feature (patent submitted) to make them resistant to this flux-trapping phenomena.

The underground communications program is based on applying high-temperature superconducting electronics to the reception of low frequency signals. One portion of the technical work consisted of field tests. One field test focused on establishing the functionality in a general sense - we used both our flux-trapping-resistant devices and high power transmitters indigenous to the mine. The second test focused on testing in the lowest noise floor possible with SQUIDs that need to be thermally cycled at every stop, but with low power transmitters to simulate conditions for portable systems. A second aspect of the project has been to develop components and subsystems in the laboratory. The component development has emphasized addressing stability, flux trapping and miniaturization issues associated with the high-temperature superconducting components. We have also demonstrated¹ a low frequency paging receiver subsystem and have investigated system issues related to deploying the technology. These are discussed briefly in relation to the low power data below.

Importance to LANL's Science and Technology Base and National R&D Needs

The basic research on HTS materials is part of the nuclear and advanced materials competency. The advanced surveillance program is requesting HTS electronics as tools to evaluate stockpile components. In addition, the extreme sensitivity of the HTS electronics allows new types of high performance measurements, a contribution to the complex experiments and measurements competency.

This project has developed the HTS technology necessary for other potential programs and products. A DoD agency has expressed interest in the identical problem and may be a further source of funding.

The underwater communications problem leads to a need for similar receivers, but operating at frequencies even lower than those discussed here. This need is driven by the strong attenuation of radio signals in seawater.

Beyond these communications problems, HTS electronics has been recognized by numerous agencies as a technology of the future. The major areas of application are nondestructive testing, medicine, and defense. The DOE Defense Programs Office has included nondestructive testing applications of HTS electronics in the advanced surveillance program. Nondestructive testing of critical components is also a topic of industrial interest. Medical applications are currently the largest superconductivity business. This includes magneto-cardiography, magnetic resonance imaging, and magneto-encephalography. The defense applications are detection and mapping of underground structures, detection of mines, and detection of underwater objects.

Scientific Approach and Accomplishments

The goal of this project was to develop technology for underground communication. This goal has been achieved. The technical tasks selected under this work were not selected from the point-of-view of scientific need but were organized to obtain proof-of-principle demonstrations of the technology. The experimental work was dominated by field demonstrations, using both high power and low power transmitters. Other portions of this project involved the fabrication of magnetometers and the associated thin film superconducting magnetometers. Additionally, we have demonstrated record homogeneity in critical current on very small bridges of HTS. These are important steps in the development necessary for all HTS applications, but here we reference the publications and discuss only the field tests in greater detail.

The plane waves discussed in background section are appropriate for describing electromagnetic waves from distant sources, but near-field sources such as electrical devices should be described in a multipole expansion. Electric field antennas have been investigated for similar applications and are fairly ineffective due to screening currents at the surface of the media. For a buried dipole source with magnetic moment, m , the radiation field in the plane of the dipole is given by

$$\mathbf{H} = (m/4\pi r^3)(1 + ikr - k^2 r^2)\exp(-ikr), \quad (1)$$

where k is the wave vector in the medium. At low frequencies, $k = (-i\omega\mu\sigma)^{1/2} = -(1+i)/\delta$, where σ is the conductivity of a homogeneous medium and δ is the skin depth as discussed above. The dominant term has the form $1/r \exp(-r/\delta)$.

This radiative term has a substantial effect on the field amplitudes and leads to a greatly expanded utility of the system. When considering low frequency transmitters in air, one usually requires very large high-power transmitters, but here we recognize that the strength of the radiation term is determined by the ratio of the dipole moment to the square of the skin depth, a reasonable value for modest dipole moments. This is the key to enabling portable two-way communication.

The first field system (see Fig.1) consisted of a SQUID magnetometer fabricated² at LANL, a 3-inch-diameter commercial dewar, a commercial flux-locked-loop (FLL), and a portable computer with a data acquisition card. The LANL process uses a SNS junction³ (superconductor-normal-superconductor) ramp-edge design with silver-doped $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ for the superconductor and $\text{PrBa}_2\text{Cu}_3\text{O}_{7-x}$ for the normal layer. The magnetometer was a direct-coupled⁴ design. To prevent applied magnetic field from contacting the junctions we invert the usual arrangement and place the junctions inside the transformer loop. The SQUID was mounted in the dewar with the axis of sensitivity horizontal. For the results shown here, the data acquisition was performed at 10,000 samples/sec for one-second intervals, and the resulting power spectra were averaged. The boil-off rate of the small nitrogen dewar was less than 10 cm^3 per hour. In terms of gas volume, this was a negligible hazard compared to respiration in confined spaces. We confirmed this by using an oxygen meter during the SQUID testing. Over periods of several hours in a fixed location with a curtain restricting air flow, the oxygen content of the atmosphere changed by less than 0.1%.

The SQUIDs were cooled, unshielded, outside the mine portal and transported by electric cart while cold. The system was then powered-up at various sites and used to record spectra without any thermal cycling of the SQUID. Transport of a cold SQUID in the geomagnetic field drives magnetic flux into the superconductor. If the quantized flux is localized near the Josephson junction, the resulting circulating currents can suppress the junction critical current, reduce the output voltage, and prevent the SQUID system from operating. This problem is known as "flux trapping." Thermal cycling to a temperature above the transition temperature and slow cooling usually eliminates the trapped flux. The inverted galvanically coupled design used here reduces flux trapping and allows us to perform all the measurements without thermal cycling after transport. A number of spectra were taken at three widely spaced locations. The existing transmit antenna operated in a pulsed CW mode at a frequency of 3 kHz. The pulses were of many seconds duration. This allowed us to acquire averaged power spectra with the transmitter signal on. The transmit antenna was a 14-turn, 25-meter-diameter loop wrapped around one of the mine pillars. This configuration generated a vertically polarized magnetic field in the mine.

The tests were performed at the Lake Lynn mine, which is operated by the National Institute for Occupational Safety and Health (NIOSH). The mine site is sketched in fig.3 and consisted of an older area with pillars and a new area with several tunnels extending over roughly a kilometer. The three test sites are 970m, 640m, and 320m from the transmit antenna. The first site had a noise floor of approximately 2 pT in a 1Hz bandwidth. Large peaks were observed at the power line frequency and harmonics. Above one kilohertz, the spectrum was almost featureless. The signal with the transmitter on was nearly identical to the signal with the transmitter off. The receiver is orthogonal to the transmitter fields, so signals only appear when the devices are tilted relative to the normal.

The results at 640 meters, shown in fig. 4, also indicate a noise floor of 2 pT with the transmitter off. The large peaks at low frequency are again power line fields and harmonics, with 60Hz and 180Hz dominating the spectra. When the transmitter was on the power line fields and the white background noise are unchanged, but the transmitter peak at 3 kHz is well above our noise background. The signal to noise was approximately 35 dB with the power spread over a number of frequencies. As with the previous site, the spectral region around this peak was free of any other apparent signals indicating that the transmitter, if configured for a larger bandwidth, would have several kilohertz of available spectrum for signal transmission. The standard bandwidth for telephony is 2.8 kHz, of order the available spectrum shown here.

The results at 320 meters showed that we have a noise floor well above the noise floor of the SQUID system. The wide-band noise in the spectrum likely indicated that source was a power relay box with audible clicking noises approximately 10 meters from the receiver. It may also have resulted from the FLL clipping a large amplitude signal at a lower frequency. This entry hallway contained power lines for all the ventilation and lighting systems used in the mine, but the power line signals were not larger than observed elsewhere. We have no explanation of this result at this time. The signal with the transmitter on was nearly a 1 nT, easily larger than the interference at this location. This may indicate a useful configuration of such systems, i.e. intentionally place the transmitters near known sources of wide band interference.

The SQUID noise floor for these experiments was consistently near $2\text{pT}/\sqrt{\text{Hz}}$. The SQUID had a noise floor of $700\text{fT}/\sqrt{\text{Hz}}$ in a magnetically shielded laboratory environment. This noise floor appeared to increase to about $1\text{pT}/\sqrt{\text{Hz}}$ in the geomagnetic field. The remainder of the noise appeared to come from the data acquisition equipment. At no time during the experiment were we able to determine the absolute magnetic fields. The demanding nature of the experiment, where the SQUID is cooled in one location, carried through wide field variations, and then operated in an unknown static magnetic field make it difficult to further analyze the noise floor. The devices were however, proven to be resistant to flux trapping.

We have also been studying underground signal propagation using a small magnetic dipole source. These tests were performed at the Waste Isolation Pilot Plant (WIPP) in Carlsbad, New Mexico. The source was operated at 200 mW.

These low powers are intended to simulate possible portable transmitters. In addition, we used a commercial SQUID that was thermally cycled every time it was transported. During broadband data acquisition we have observed additional sources of noise intrinsic to mining operations.

The range dependence of a typical 3 kHz signal transmission is shown in Fig. 3. The fit is to the dipole model (Eq. 1) with one fit parameter, the skin depth, or two fit parameters, the skin depth and moment. The dipole moment is measured independently in the laboratory. At ranges up to more than 100 meters the signal amplitude is larger than expected from the one-parameter dipole model.

The two-parameter fit implies a larger dipole moment than can be explained and does not fit very well. The most likely explanation is that these results are due to multi-mode effects where the inhomogeneity of the actual environment introduces other modes not included in the dipole model. These modes typically involve TEM quasi-coaxial field configurations, where the inner conductors may be power lines, telephone lines, etc. and the outer conductor is the rock mass. This type of signal propagation has been extensively discussed in the mine communications literature. Generally one can obtain attenuation values of well under 1 dB/meter with such modes. Corners in the tunnel result in tens of dB additional loss. Applying this interpretation to Fig. 5 the data points near 125 meters result from quasi-coaxial propagation for a distance of 10-20 meters to a right-angle corner and then down a section of tunnel approximately 125 meters long. The results at 180 meters involved propagation around two corners and two long sections of tunnel, where the quasi-coaxial contributions must be small. In that case, the results are near what is expected for the through-the-earth propagation from a dipole source.

In the course of examining underground signal propagation we have measured the background signals due to other electrical devices in the mine environment. When examining the harmonics of power frequency one distinctive signature belongs to fluorescent lights. In Fig. 6a we display a magnetic field power spectra taken in a lighted underground tunnel. One bank of fluorescent lights was directly over the magnetometer. There is no other apparent draw of current in the tunnel at this time. Many harmonics are observed in the frequency range above 1 kHz due the highly nonlinear load. The pattern between 1.5 kHz and 3.5 kHz is typical of an isolated florescent light. The next spectra, shown in Fig.6b, were taken in a tunnel 70 meters from the lighted tunnel. This parallel tunnel was unlighted and had much lower harmonic noise, but still well above the noise floor of the magnetometer. The harmonics in Fig. 6a must be filtered to fully utilize the very low noise floor of the SQUID technology. The harmonics near the center of Fig. 6b have a lower integrated noise power than broadband SQUID noise, so they are in fact negligible for audio communications applications.

The above results allow one to fully plan for the noise environment expected with small signals. Two features are immediately evident: one is that to use the full performance and bandwidth we need to include digital filtering in the design. The peaks in the spectra in Figs. 6a and 6b consist almost entirely of signals with harmonic content at integer multiples of 60 Hz. The signals at other frequencies are several kilohertz apart. This defines a direction that is important to future radio projects. One must include a digital filtering algorithm to eliminate these multiples. Typically, this is called comb filtering and implemented with an inexpensive digital signal processor. The significant bandwidth remaining is available for audio communications at the noise floor of the SQUID. We note that the total power in the power frequency harmonics, see Fig. 6a, is small in the kilohertz frequency range. Filtering this will require only modest filter performance (20 dB rejection).

These results indicate that we will be able to install low frequency communications systems in mines and will be able to send signals over meaningful distances with modest power levels. Mine-wide coverage should be obtained with a network of base stations and portable low power radios.

Publications

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2. Jia, Q. X., Reagor, D., Mombourquette, C., Fan, Y., Decker, J., and D'Alessandris, P., "Stability of dc superconducting quantum interference devices fabricated using ramp-edge superconducting/normal-metal/superconducting technology," *Appl. Phys. Lett.* **71**, 1721-1723 (1997).
3. Jia, Q. X., Fan, Y., Mombourquette, C., and Reagor, D., "Directly coupled direct current superconducting quantum interference device magnetometers based on ramp-edge Ag:YBCO/PrBCO/Ag:YBCO junctions," *Appl. Phys. Lett.* **72**, 3068-3070 (1998).

Figure captions:

- Fig. 1. The skin depth for various resistivities in the frequency range of interest.
Fig. 2. Block diagram of the test system.
Fig. 3. Sketch of the Lake Lynn test location.
Fig. 4. Wide band magnetic field power spectra at site B.
Fig. 5. Range dependence with a low power source.
Fig. 6a. A magnetic field power spectra taken under florescent lights in a mine.
Fig. 6b. The magnetic field power spectra in the unlit tunnel discussed in the text.

References

¹ Pub. #1.

² Pub. #3.

³ Q.X. Jia, X.D. Wu, D. Reagor, S.R. Foltyn, C. Mombourquette, and D.E. Peterson, "High temperature superconductor edge-geometry SNS junctions with engineered normal-metal layers," *Electronics Lett.* **32**, 499, (1996).

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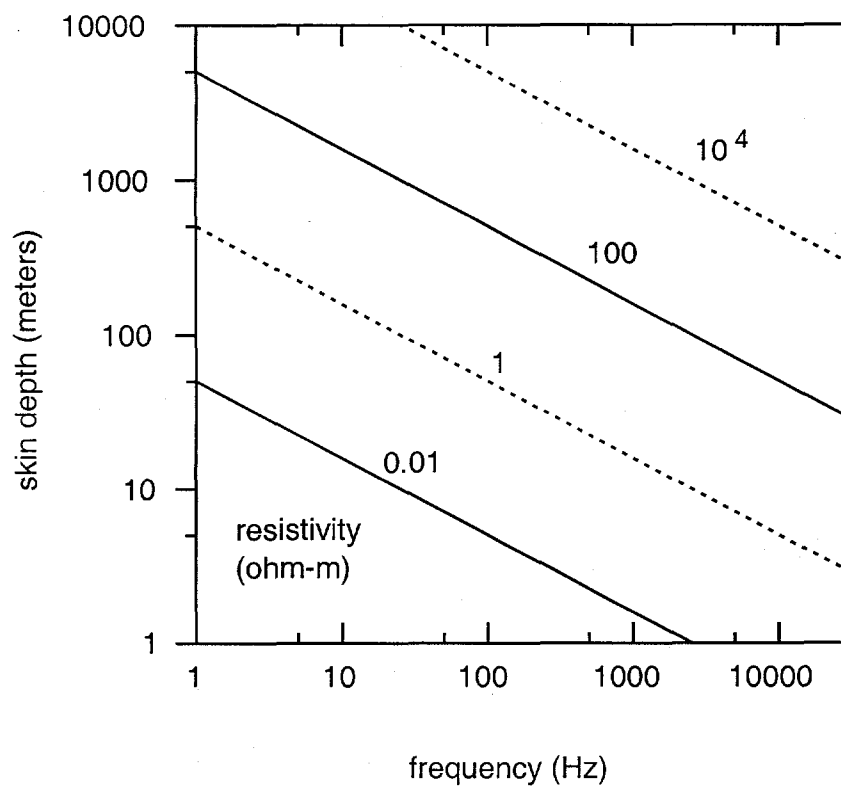


Figure 1

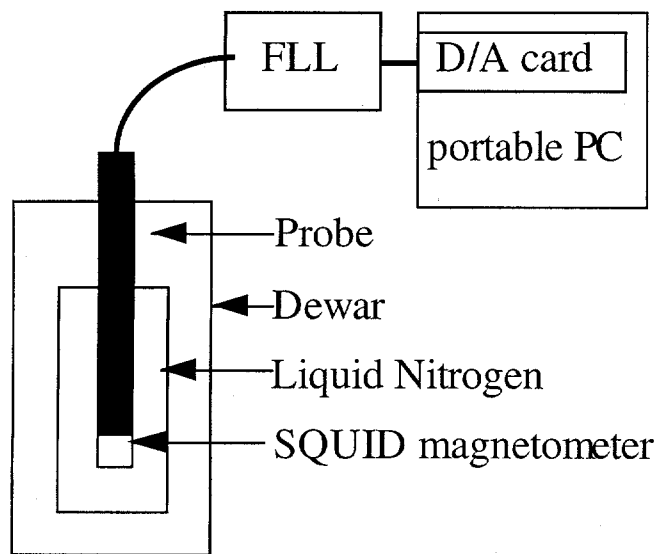


Figure 2

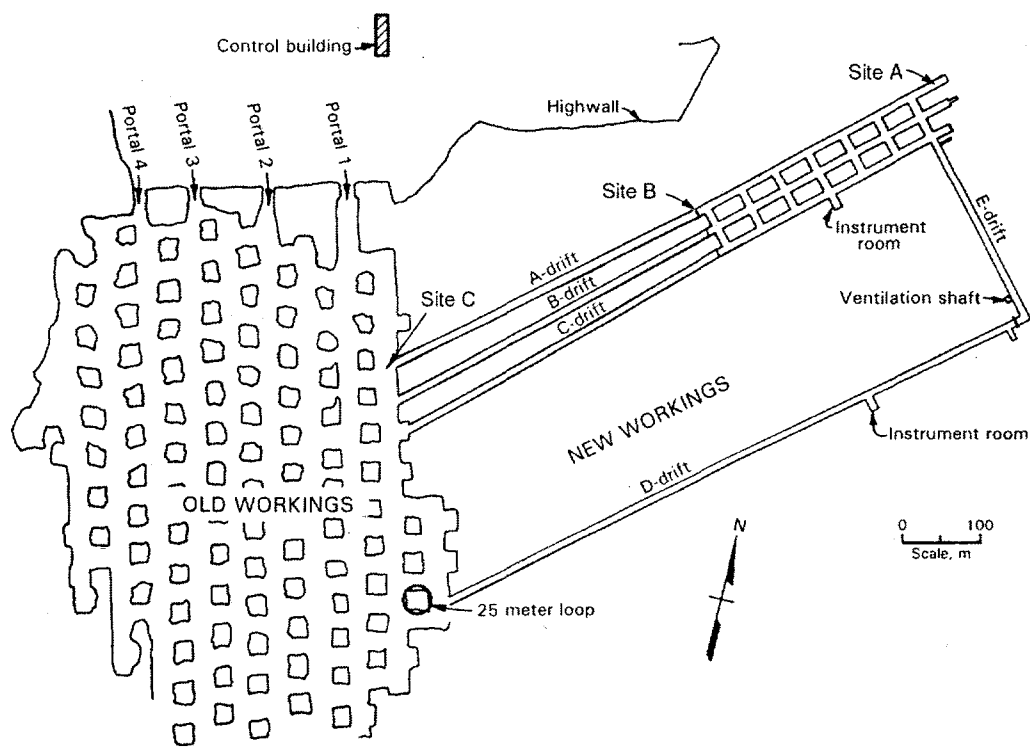


Figure 3

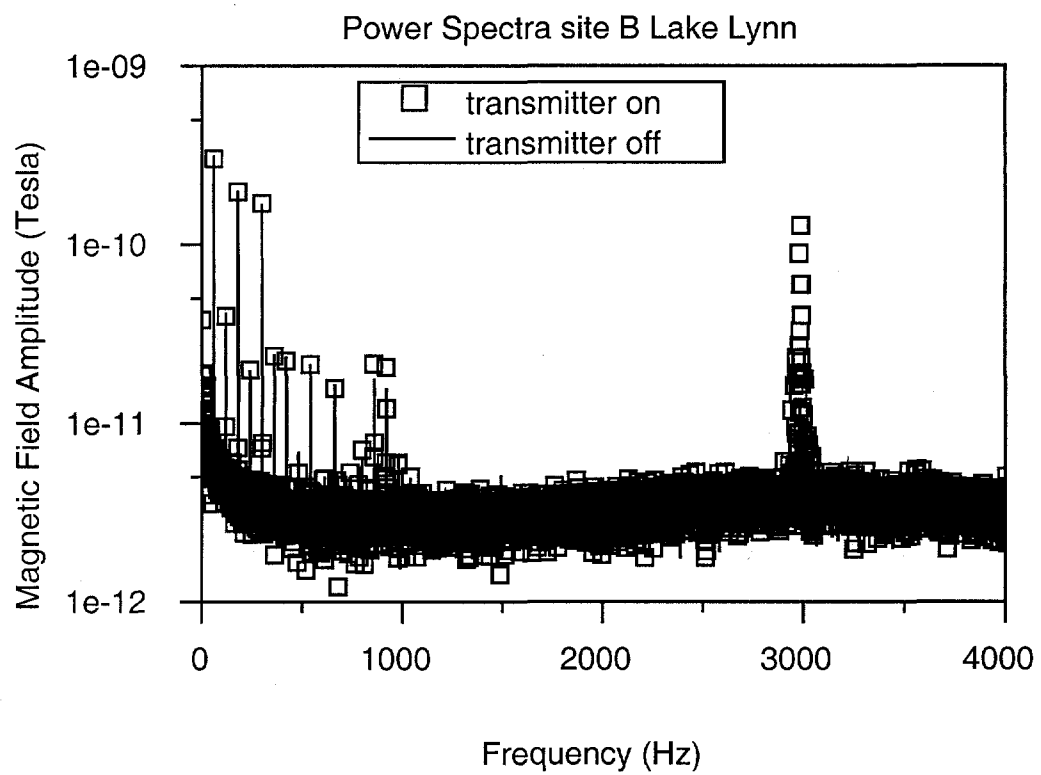


Figure 4

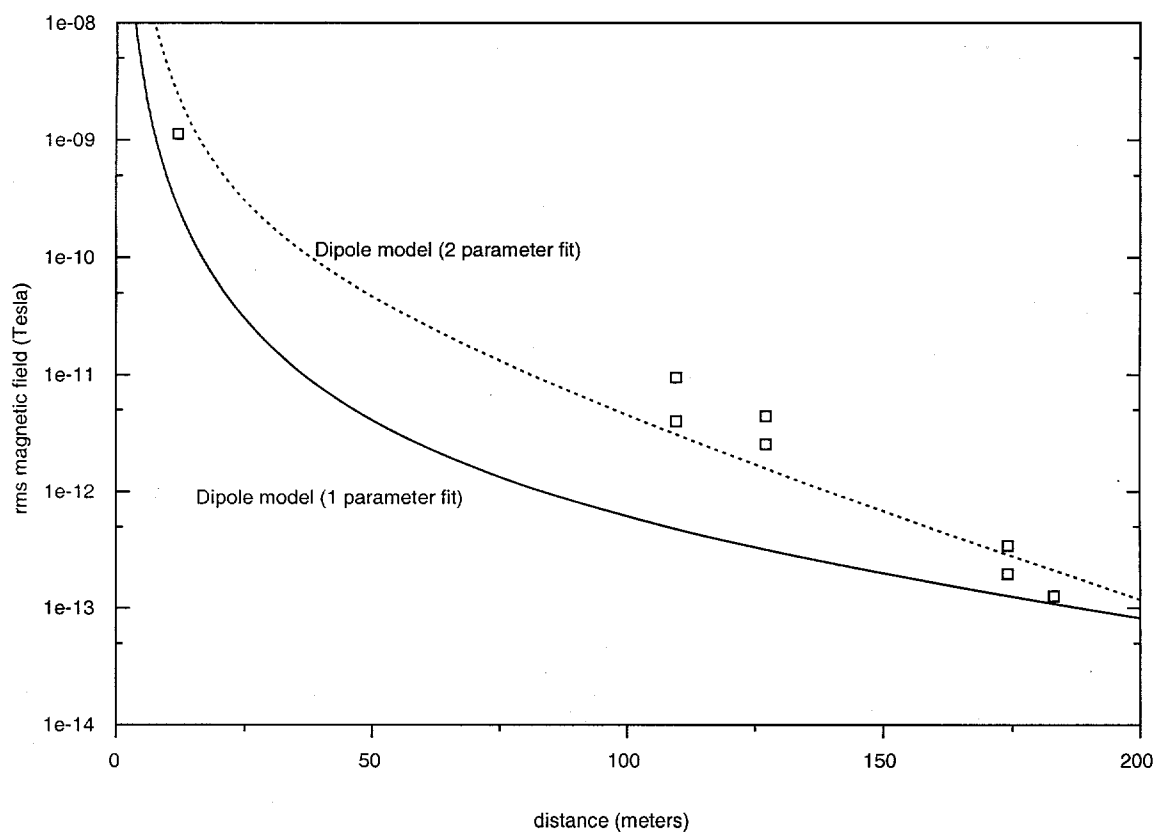


Figure 5

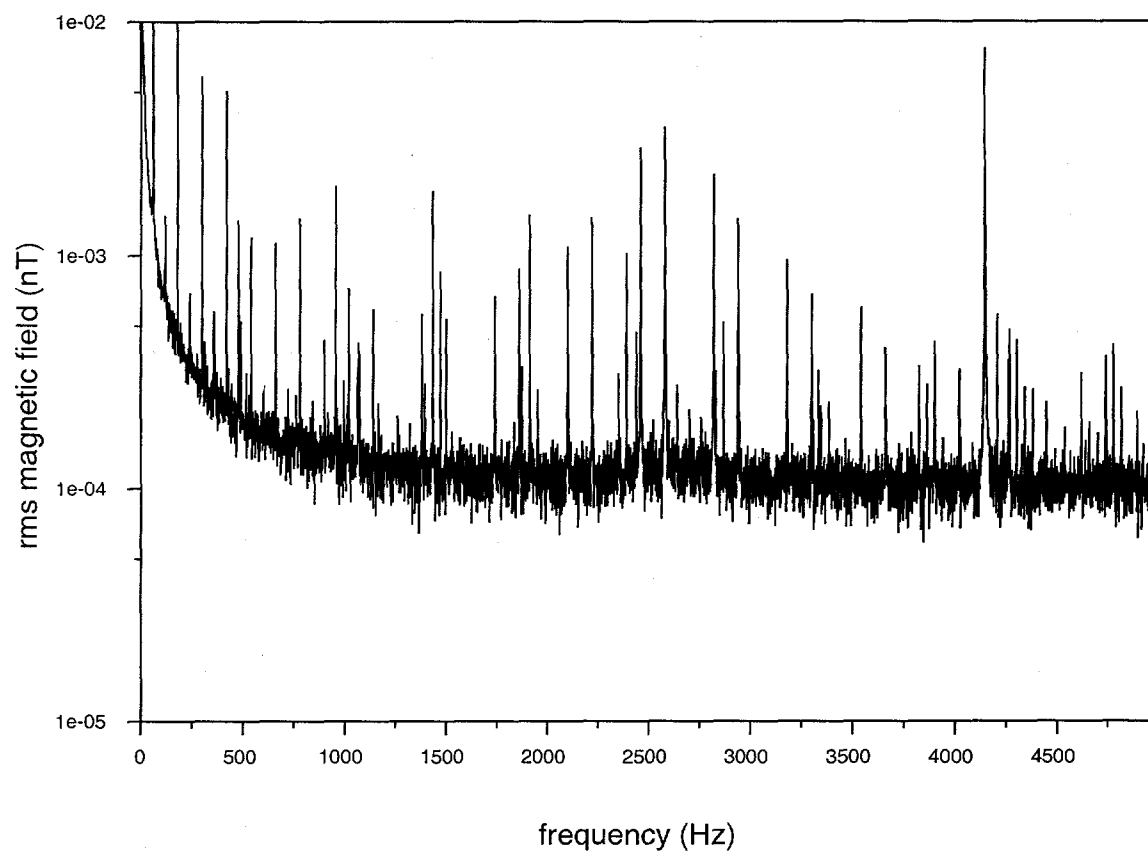


Figure 6a

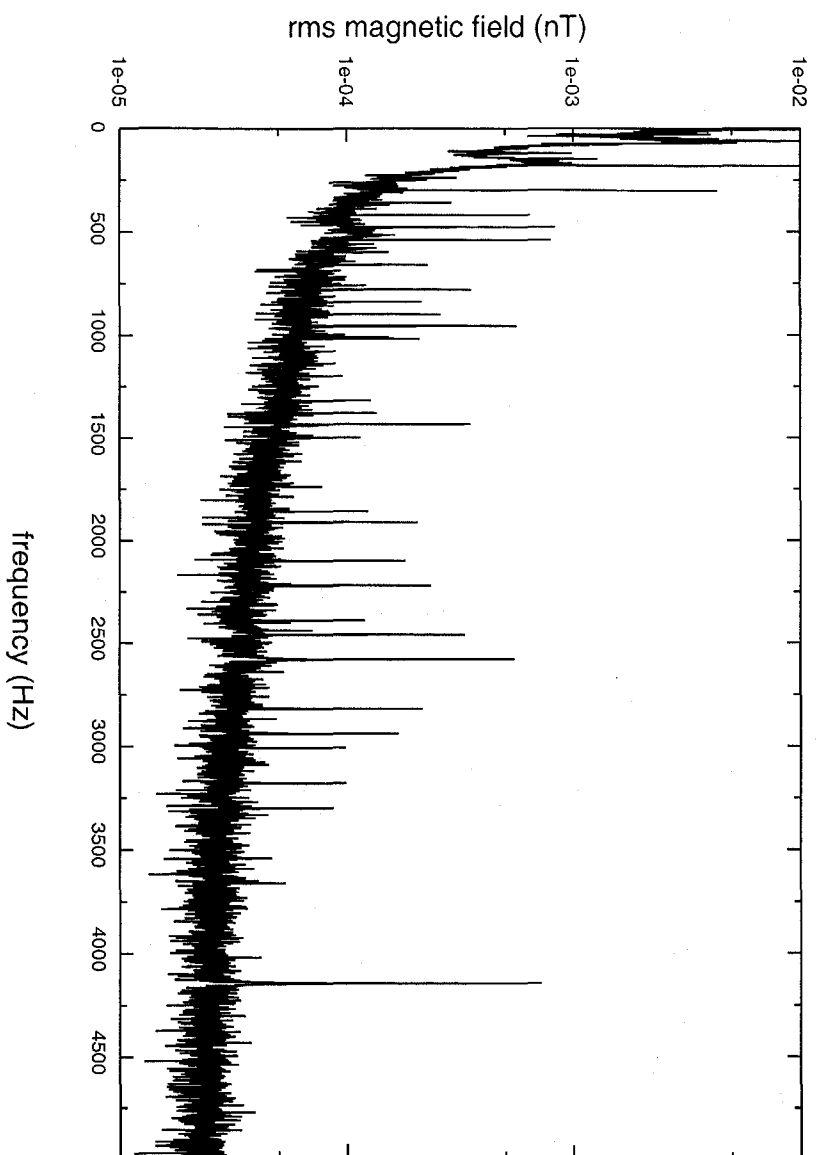


Figure 6b