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The primary objective of the research project was to determine the feasibility of utilizing phase shift phenomenon as the transducing principle of a magnetometer. The findings show that, not only is a phase shift effect magnetometer possible, but high sensitivity, low cost, low power consumption, small size, and light weight are also readily achievable. State of the art OEM off-the-shelf components were utilized to breadboard a prototype to ascertain the feasibility. A sensitivity of about 0.01 nano Teslas was achieved. Specific research was identified to quantify the phase shift phenomenon for optimization. In addition to the applicability of magnetometry to biological, physiological, geological, and oceanographic research, other areas of applicability were identified, including MRI, detection and prediction of earthquakes and volcanic eruptions, and health effects due to induced magnetic fields from transmission lines and broadcast stations.

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FINAL PROJECT REPORT
NSF SBIR 90-31 PHASE I
NSF GRANT NO. ISI-9061036

PHASE-SHIFT EFFECT MAGNETOMETER

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July 25, 1991

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Section 1 - Introduction

Written and submitted as partial fulfillment of the requirements for NSF Grant No. ISI-9061036, this final project report reflects six months of extensive research on the feasibility of utilizing a fundamental phase shift effect as the transducing principle of a magnetometer. The fundamental effect is based on the fact that a suitably phase shifted coil pair utilizing certain classes of high permeability core materials, driven to magnetic saturation by an appropriate energizing circuit, develops a uniquely shaped output which is directly related to the ambient magnetic field. The resulting phase-shifted output voltage can accurately measure the ambient magnetic field. In addition to ascertaining the applicability of this phenomenon to magnetometry, five critical features were specified: high sensitivity, low cost, low power consumption, small size, and light weight. These quantifiable features are defined in terms of the measurable specifications in section 4, Research Objectives.

Section 2 - General Conclusions

Based on the findings of this research, it is the expert opinion of the principal investigator and supporting professionals that **it is feasible and practical to utilize the phase shift effect to measure magnetic field strengths. Furthermore, the five specified features of high sensitivity, low cost, low power consumption, small size, and light weight are also shown to be readily achievable.** Supporting narratives are given in section 6, Research Findings and section 7, Technical Implications. Supporting data and documentation is presented in section 11, References. State of the art, but off-the-shelf components and materials from OEM suppliers are shown to be available for utilization in prototyping phase shift effect magnetometers that exemplify the five specified features. An unexpected but welcome feature as a result of this feasibility research project is discussed in section 6. Essentially, the phase shift effect magnetometer can be made to be highly directional sensitive. Specific research has now been identified as a result of this feasibility project. Section 7, Technical Implications, discusses the proposed specific research activities. During the course of this feasibility research, additional commercial applications became increasingly apparent. These are addressed in section 8, Potential Applications.

Section 3 - Background

Since many different types of magnetometers are currently available, this report will be limited to only those magnetometers currently capable of measuring low level magnetic fields in the range of one nano Tesla (1 nT) or smaller. Hall effect and fluxgate devices are immediately discounted along with the classical Gauss and sine galvanometers employing Helmholtz coils for magnetometry. Of the remaining magnetometers, there are only two that are most notable at this time. Both of these magnetometers are essentially based upon

the effect that a magnetic field has on charged electrons.

One of these magnetometers, classified as a "nuclear type" is probably better known as the proton precession or Larmor magnetometer. This device depends on the random magnetic resonance measurements in a fluid or gas plasma. These devices have been used by the military to detect magnetic anomalies and other magnetic signatures caused by submarines and ships. This device, even if the circuits used are solid state, is relatively large, requires a considerable amount of power, and is non-directional, measuring total magnetic field only.

Since the 60's, a new type of magnetometer has been conceived based on the pioneering work of Dr. Brian D. Josephson. This so-called "Josephson Junction" device, in essence, predicts the passage of paired electrons, so-called Cooper Pairs, through a weak connection sandwiched between superconducting materials. It was further discovered that a Josephson Junction in the presence of a magnetic field would induce a current and subsequently draw voltage across a parallel pair of Josephson Junctions. The voltage draw across the paired Josephson Junctions can be utilized as a measure of a magnetic anomaly or ambient magnetic field. Although this device is potentially extremely sensitive, it requires a cryogenic environment. Recent advances in this field have been very promising and could lead to instruments that may be of extreme benefit in certain types of laboratory research. According to Dr. John Clarke, physicist and leader of the Lawrence Berkeley Laboratory at the University of California, a superconducting quantum interference device or so-called "Squid" has been produced with relatively high temperature superconducting compounds.

However, these so-called "high temperature superconducting compounds" must still be maintained at a temperature of -196^0 C., in other words, in a bath of liquid nitrogen. Even though liquid nitrogen and liquid helium are available to maintain a near cryogenic state, packaging cost and longevity of the total magnetometer system is inconsistent with the specified parameters of a phase shift effect magnetometer.

Hence, current magnetometers, although now capable of measuring at least 0.1 if not 0.01 nT or below, have serious drawbacks in terms of the additional features specified for the Phase Shift Effect Magnetometer. Low cost, low power consumption, small size, and light weight cannot be simultaneously achieved.

The phase shift magnetometer depends on the peculiar behavior of certain high permeability magnetic materials in a magnetic field. In this research, a relatively obscure phenomenon associated with the resulting wave form distortions was investigated as the primary principle for utilization in magnetometry. Alloys having high permeability exhibit the unique hysteresis curve shown in Figure 1. If two nearly identical coils containing this peculiar high permeability material are driven into saturation by an appropriate AC power supply, then the slightly phase shifted time variance voltages from the sensing coils produce unusual shaped wave forms as shown in Figure 2. The resulting voltages, when added together, produce a very uniquely shaped voltage signal which is also indicated in Figure 2. This signal has two basic characteristics: (1) A peak voltage that is dependent on the total magnetic field strength and (2) a phase shift that is dependent on the inductance of the coil and its parallel resistance.

When the applied voltage is reversed in the paired coil, the voltage signal of the second coil will effectively cancel the signal in the first coil except for the distortion produced by the ambient magnetic field. Of paramount interest is the fact that the magnitude of the voltage signal is directly proportional to the ambient magnetic field, and extremely directional. Any change in the ambient magnetic field such as that caused by rotating the paired coil will cause these peaks to increase in the positive direction and decrease in the negative direction, or act conversely if the transducer is rotated in the opposite direction. The measurement of the difference between these phase-shifted peaks, above and below the zero line, indicates both the direction and the magnitude of the magnetic flux. A zero reference is readily established by adding the two voltages so that a net zero sum indicates zero flux.

This relatively obscure phenomenon was first described quite thoroughly by Dr. Victor Vacquier in the early 1940's. Dr. Vacquier, an employee of the Gulf Research and Development Company, filed for a patent in 1946 which was subsequently issued (Pat No. 2406870) and assigned to the Gulf Oil Company. The basic magnetometer apparatus and variations thereof are presented in the Vacquier patent. Apparently the principle reason for developing this technology and the subsequent protection of the resulting intellectual property was for oil field exploration. However, due to the apparent high degree of directionality of the apparatus, which is not alluded to in the patent description, but was discovered in this feasibility research, the system was "self locking" by saturation of the paired cores by the earth's magnetic field alone! Thus, the Gulf System had to be used in narrow areas of magnetic flux to measure anomalies, and they had to gyro stabilize the apparatus in near east-west direction to control the narrow areas of measurement and measure anomalies.

The basic system was to tow the apparatus behind a DC-3, set the transducer so that it operated in the narrow band of direction, preferably east-west, then chart an accurate position and the magnetic anomalies that show up over a geographic area. From the comparison of the two charts, it was possible to locate areas of large anomalies characteristic of underground oil deposits. Although quite accurate, the technique was time consuming and was soon superseded by other geological surveying techniques. Newer technologies using sound waves and echo pulse detection proved to be more economical for oil exploration. Also, the basic device was obviously very cumbersome in size and weight, and it used various unwieldy tube type circuits for amplification and wave form generation. The "use variations" of the tube type magnetometer described in the patent were simply too bulky and heavy for practical application.

The tube type technology phase shift effect magnetic measuring system was designed in the 1950's by the Dinsmore Instrument Company under a license agreement with the Gulf Oil Company, after working with Dr. Vacquier and his assistant and collaborator, Dr. Wickersham. The system as designed by Dinsmore Instrument Company was quite different from the patented Gulf system and was used for anomaly measurement on auto and aircraft assembly lines so that compasses as produced by the Dinsmore Instrument Company could be "adjusted" against the vehicle caused anomalies while on the assembly line.

In the early 1980's, the Dinsmore Instrument Company developed and perfected a unique Hall effect sensor to produce some new and low cost compass direction sensors. This research has led to issued patents (U.S. Patent 7,402,142, Electronic Compass for Automotive Vehicle, and additional patents applied for) for a new type electronic compass which is being introduced to the market in August 1991. One of the sensing systems was just awarded one of the R & D "100 Top Products of 1991" awards.

In the never ending search for more accurate means of sensing magnetic fields, R. C. Dinsmore (Principal Investigator of this project) envisioned the possible use of modern day electronics to enhance the all-but-forgotten phase shift effect magnetometer. After a few false starts, hallmarks of any research project, Mr. Dinsmore's inquiries led to investigating if modern solid state electronics coupled with modern metallurgical techniques could effectively achieve and perfect the old phase shift principles. This led to a feasibility research project that was subsequently funded by NSF and is the subject of this report.

Section 4 - Research Objectives

The major objective of this Phase I feasibility research study was to investigate the principle of utilizing phase shifted voltages generated through the use of suitably configured and energized coils for magnetometry. The envisioned magnetometer was conditioned with the following five specified features: **high sensitivity, low cost, low power consumption, small size, and light weight.** Sensitivity was defined to mean 0.1 nT or ideally 0.05 nT. Low cost meant that the device in its envisioned form would cost less than $100 to mass produce in large quantities. Ideally, it would be preferred if the transducing element itself was no more than $2.00 to produce, and the associated off-the-shelf circuitry could be produced for $50 to $150 depending on the simplicity or degree of sophistication. The readout was envisioned as a simple modified existing LCD display, suitably calibrated. Low power consumption means that only milliwatt energy is required to drive the transducer to produce a + or - 10 V output signal. Small in size and light weight means that the transducer element should be no larger than one (1) cubic inch for a single directional unit, and not weigh over a few ounces. Ideally, the total device would take no more volume than a small match box and weigh approximately the same.

With these objectives defined, the following research questions were raised: * What type of core material is required. * In what geometric configuration. * What configurations are now available. * Of what materials. * What should the coils look like. * What windings. * How many turns. * Length. * Size of wire. * Relationship of coil pairs. * What type of circuitry for suitably energizing. * What type of wave form is best. * What is the power consumption. * How do we sense the shifted phase. * What type of signal conditioning is required and what circuitry. * Material. * Devices needed to optimally achieve the specified features of the magnetometer.

The ultimate question is what type of processing, circuitry, materials or other technology would need be investigated and/or developed in order to achieve the magnetometer as specified.

Section 5 - Research Methodology

The Phase shift effect magnetometer consists of three parts. The first is a power supply which generates a suitable wave form with sufficient power to saturate the measuring sensor. The second part is the measuring sensor. In essence it is a pair of closely matched coils with high permeability cores of suitable size and configuration so as to be easily driven into saturation. The final or third part of this magnetometer system consists of the actual measuring circuit. The output from the measuring circuit should be a shaped voltage pulse that can be conditioned to match an analog or digital readout or even used directly for microprocessing. In operation, the power supply saturates the cores of the coils which develop a very remarkable "knee" at saturation. The resultant voltage pulse can easily be translated into an understandable and useful measure of the ambient magnetic field.

Many alloys of high permeability exhibit a peculiar form of hysteresis. These materials, with suitable cross sectional areas, can be used for the cores of the miniature coils and driven into saturation without the need for large amounts of energy. In the past, materials such as Hypernik, Mu Metal, and Permalloy have been readily available since mid century. Newer alloys with much greater permeabilities have been recently developed and are currently reaching the marketplace. These materials are discussed in section 6 - Research and Findings. By taking advantage of these newer materials and their unique flux-field relationship in a suitable circuit, a very sensitive magnetometer can be is created with very low power consumption.

First we investigated the power required to saturate a given core and the type of wave form that gave the best knee in the phase shifted sensing system. To accomplish this, we first created a sensor as shown in Figure 3 based on standard design information and the teachings of the Vacquier patent. This sensor is a pair of carefully wound coils around matched Mu-metal cores. For this initial research investigation, a core of reasonable size from off-the-shelf availability was chosen. At this point we were not concerned with the formation of internal eddy currents or other problems that can lead to a so-called noisy signal. This finer detail is left to follow on research. Our intention was also to use standard commercial equipment for wave generation, adjusting the power as required for saturating the given bench type and hand wound cores. This construction proved to be quite adequate. It was determined that around twenty milliamps was needed to drive the given cores into saturation. Considering the number of wire turns and the permeability of the core, this power requirement matched well with the theoretical predictions. An internal resistance on the sinusoidal driver had to be sufficiently high (50 ohms) in order to be able to detect the back EMF of the sensing coils without using a coupling transformer.

A resistor was placed in parallel with one of the two coils to serve as the phase shifting component. With everything balanced so that each coil represented nearly a mirror image of the other, the EMF between the two coils resulted in a very sharp knee pulse saturation point of the core material. To be precise, a mathematical definition for the knee can be given as that point in a curve which exhibits an inflection or change in direction of the slope of the curve. Hence, a so-called knee also exists in the BH or hysteresis curve of high permeability core material.

In the absence of any applied magnetic field (east-west direction), the positive and negative half cycles of the sinusoid will produce pulses that have identical amplitudes but opposite polarities. After separating the positive and negative pulses from each other and passing them through a low pass filter, and then adding them together, the result will be zero. Breadboards with the amplifier and energizing circuits are shown in Figure 4. The amount of energy and polarity of the pulses depends on the EMF needed to drive the cores into saturation and on the intensity of the applied or ambient field condition. If the applied or ambient field is in the same direction as the positive half cycle of the generated sinusoid then the fluxes are additive and saturation occurs early on in the positive half cycle. This results in smaller pulses. On the negative half cycle the fluxes are subtractive and saturation occurs later resulting in a larger pulse. This combination will make the output voltage negative. If an applied field is in the opposite direction as the positive half cycle of the generated sinusoid then the fluxes are subtracted and saturation occurs later on in the positive half cycle. The net result is larger pulses. On the negative half cycle, the fluxes are additive and saturation occurs earlier resulting in smaller pulses. This combination will make the output voltage positive. These combinations are illustrated in Figures 5, 6, and 7, shown as photographs of oscillograph traces from the actual bench type laboratory prototype unit. These actual traces of the output voltages, shown in real time, substantiates the above narrative.

The net result was a very sensitive device for responding to ambient magnetic fields. It was here that we discovered another unique property of the phase shift effect magnetometer which was heretofore unknown. The measurements were linear only when the additional flux or applied magnetic field is small. Once the applied field saturates the cores, then any additional ambient or external flux has no effect on the saturated cores. In this event, one of the two pulses would be zero and the sensitivity decreases by fifty per cent. For anomalous measurements this situation may be adequate since only microscopic changes in the field are of concern and the absolute value of the magnetic field is immaterial. For continuous measurements, a compensation technique would have to be devised. This should be one of the tasks in further research.

Many different shaped input wave forms were tested including the standard sine wave, square waves, sawtooth waves, triangular waves, and combinations thereof. This was done in order to determine if any one wave was better than any other for creating the phase shifted pulse. After trying all the various combinations, it was determined that no wave form or shape or combination thereof was better than a standard sinusoid. Once this was determined, the standard commercial wave form generator was shelved and the power supply was downsized by constructing the subminiature sinusoidal power supply shown in Figure 4. A TLC555 was used as a stable multivibrator. We used the 555 because the oscillator frequency is independent of the voltage of its supply and part of this research investigation was to look at the feasibility of small power input as might be supplied by a miniature battery. Frequency was adjusted to about 727 Hz using a fifty per cent duty cycle.

We fed this voltage into a CMOS square wave generator and then through a simple Op Amp to buffer and isolate the output of the square wave generator from the active filter stages. We then used a Sallen-Key two pole low pass filter. With the input being a fifty per cent duty cycle we set the cut off frequencies on the filter to filter out all the third, fifth, seventh, ninth -- in other words --all of the fundamental odd harmonics, making the output a pure sinusoidal signal.

The next stage of the power driver consisted of two small power amplifiers. The first stage is a non-inverting amplifier with a gain of two. The companion stage is an inverting amplifier with a gain of -1. This power amplifier could supply two hundred milliamps, which is sufficient for this investigation. Obviously, this could be considerably reduced since the ultimate sensor would be smaller in size and consume less power. By feeding the coils with the input of the companion stage from the output of the first stage we achieved a balanced dual output driver without the use of any transformers.

A pair of balanced resistors on the outputs were placed before the coils so that the back EMF reflected the condition of the coils and not the output of the driver. Next we used a summing amplifier to eliminate the common mode signals and then amplified the final signal. The output from this low gain amplifier was fed to an experimental circuit to eliminate the unwanted near zero signals. By sharply separating the positive signal from the negative, we achieved extremely sharp pulses with little noise in the output. We were consequently able to use a buffer amplifier system with a gain of only 5.7 and a high input impedence.

If the sensor system has no outside magnetic flux flowing through it, the negative and positive outputs from the buffer's amplifier will be in balance. These are fed to a last stage summing amplifier with a gain of around 100. With some circuit adjustments, we could then have a zero output reading for a zero flux. Consequently, we only need to calibrate the display device to various flux densities to accurately measure magnetic flux. The readout or display of output information can be analog, digital, or microprocessor based since the output voltage is compatible with any of these systems.

The above comprehensive but condensed narrative covers and completes the basic work of this feasibility research project. The circuitry which may appear complex is, in fact, relatively straight forward and can be manufactured in volume at low cost and in extremely small size. The circuitry in the laboratory was designed with many adjustments so it could be used in further identifying the response characteristics of the sensor, the core, the display, the magnetic field, and any other possible variation that could be theorized and subsequently, quantified. A final circuit, would of course, not have any of these elaborate adjustments. There is no doubt that the device, in its final configuration, could be extremely light weight and low cost.

The current circuitry was designed to develop sufficient power, for what we would consider to be an extremely oversized coil sensor. The core section of the sensor as shown in Figure 2 has an H_C that runs from two to five. Many modern high permeability materials have an H_C below .010. For example, Carpenter technology Corporation produces high permeability nickel alloys with an H_C of .01 to .008. Hence, our requirements for a practical unit should theoretically be reducible by a factor of a hundred, if not a thousand, based on the results of this feasibility research project. The circuitry, as depicted in Figures 3 and 4, was designed as a bread board unit and handwired to a PC board measuring only 3 X 5 inches. However, 80 percent of this board is open space for reason of the ability to make adjustments to the circuit in order to determine the effects of various parameters or components on total performance. Even with the current components, it is easily conceivable that the PCB could be reduced to 1.5 X 2 inches and/or possibly even smaller. Thus, the feasibility of light weight and small size is verified.

Based on the given data that the Vacquier system had a resolution of .5 nano Teslas, then it is felt that our configuration will easily measure .05 nT. Our experimental laboratory bench type unit was at least ten times more sensitive than the Vacquier model. However, the optimum material or circuitry has not even been closely achieved. It is therefore very conceivable that this sensitivity could be increased by some twenty or fifty times with current state-of-the-art technology. In fact, as discussed in Section 6 - Research Findings, new alloy materials that are apparently an order of magnitude higher in permeability have been identified. The data on this material has not yet been published.

The research methodology undertaken essentially paralleled the twelve step research plan given in the original proposal. Step one and two involved the design of an appropriate bench type laboratory prototype sensor; step three and four required the construction of a wave form generator from off-the-shelf components; step five required appropriate signal conditioning; step six and seven resulted in configuring and breadboarding the entire system; step eight required a series of tests; step nine analyzed the output data from the breadboard unit; step ten determined the power requirements; step eleven quantified the necessary signal conditioning and readout characteristics; step twelve is in essence the final report.

Section 6 - Research Findings

Based on the fabrication of a bench type prototype phase shift effect magnetometer and subsequent laboratory experimentation, the following five findings were made:

(1) It is absolutely feasible, as demonstrated from the results of this project, to utilize the obscure phase shift phenomenon originally proposed by Dr. Vacquier in the early 1940's to measure magnetic field strength.

(2) With the utilization of state of the art electronics and newly processed materials, it is not only possible to fabricate a phase shift effect magnetometer, but to incorporate highly desirable features that are not available in any other type of magnetometer either currently in existence or in development. **All of the five featured specifications: low cost, low power consumption, small size, light weight, and adequate sensitivity to low level magnetic fields are conclusively shown to be feasible.** In fact, the prototype bench model conclusively shows that low cost, in terms of only a few dollars, *even if the sensing element is appropriately configured as a smart transducer*, is indeed realizable with current, state-of-the-art, off-the-shelf technology.

(3) Low power consumption, in terms of a few milliwatts, as originally specified, is also possible. Weight and size, in terms of a few ounces, and a fraction of a cubic inch in volume, are also readily obtainable.

(4) The question of sensitivity is also affirmatively answered since it can be conclusively shown that .01 nano Teslas is measurable with the crude prototype model, using current state-of-the-art and off-the-shelf technology.

The absolute minimum sensitivity may, in fact, be in the order of magnitude of milli nano Teslas. Evidence of sensitivity is easily determined from a simple experiment. As shown in Figure 8, a slight movement of around 1^0, will cause the amplifier circuit to become completely saturated, producing a maximum output of 11 volts. Since the earth's magnetic field at this location is around 37,000 nT, then a shift of 1^0 corresponds to change of 654 nT (i.e., 37,000 times the tangent of 1^0). Assuming a half millivolt is the least easily measurable signal then the corresponding field strength is .0116 nT. Yet another demonstration of the magnetometer's sensitivity is shown also in Figure 8. At a distance of around 1 meter, the magnetometer is reading around 5 volts for a simple, 1.0 inch long by 1/8 inch diameter magnet. By turning the magnet 180^0 , the output voltage changes to around -5 volts.

Cost, power requirement, weight, and size are readily assumable through the process of deductive extrapolation based on state-of-the-art technology. The question of ultimate sensitivity, however, will have to depend upon further research and experimentation. It would be tempting to anticipate the lower level may be in the order of micro nano Teslas. However, there is really no concrete evidence other than optimism based on the findings of this feasibility research study that such a low level magnetic sensitivity is achievable. If it were, there is no doubt that it would also be the most rugged type of magnetometer scientifically developed.

(5) Another finding based on laboratory testing of the bench type prototype is the fact that a phase shift effect magnetometer, as originally envisioned and described by Dr. Vacquier, is highly directionally sensitive. This inherent directionality characteristic has some uniquely distinct possibilities. It should be realized that with all instrumentation it is always easier to desensitize a transducer than it is to increase sensitivity. Increasing sensitivity is usually limited by signal to noise ratio. In this instance, all of the apparent noise that was even detectable was very easily suppressed with the filtering system introduced in the circuitry explained in the previous section. From extensive library and technical publications research, and subsequent technical contacts, including an overseas visitation, it was also determined that new high permeability alloys have been developed. Others are apparently even being developed at this time. These materials will obviously play an important role in the phase effect magnetometer. With every percent increase in permeability, there should be a corresponding decrease in size and power consumption. A second finding from the trade research was that a number of companies already exist that design and fabricate miniature coils for thin film applications. The adaptation of this technology to the construction of an appropriate sensing coil using basic photolithographic processes should be immediately investigated.

Section 7 - Technical Implications

Based on the findings of this feasibility research project, the following technical implications become evident. Although applicable, these technical implications are not necessarily all inclusive. There may be other implications. These will probably come about after introduction of the phase shift effect magnetometry.

(1) Because of the high sensitivity of our bench type prototype, it is difficult to measure anything but a weak field. In order to make an instrument that has both range and sensitivity, a servo or compensating system should be investigated. Means to cancel the field being measured can then be utilized as a measure of the ambient field under investigation. Also, it will prevent the current instrument from being locked up by saturation. This condition would then provide a linear measurement of nearly all magnetic field strengths. Ideally starting from zero field strength.

(2) To further increase the sensitivity of the magnetometer, other ways to sample the pulse amplitude should be investigated. A slope limiter circuit, peak detector circuit, or sample and hold circuit, for example, should be investigated. The sensitivity could conceivably be increased some twenty to perhaps fifty times without sacrifice or other trade offs. Noise at the low level of the signal would be removed, allowing only the peak value to be utilized in the measurements.

(3) Separation of DC magnetic field strengths from an AC magnetic field should be investigated. The envisioned magnetometer could possess these capabilities.

(4) The addition of a microprocessor to manage the output data stream could enhance the instrument's range and usefulness.

(5) Additional coil configurations should be researched to even further reduce size and drive power requirements. While this does not seem like a difficult task, it is probably one of the biggest challenges, even though there are now some very unusual possibilities for coil and core miniaturization. Photolithography, for example, is a viable technology for sensor miniaturization.

(6) Acquire, test, and quantify many of the new extremely high permeable materials, some of which are still in the laboratory stages of development. Many of the new high nickel materials are currently used in toroid coils or as circuit shields for EMI and other disturbances. The new complex alloys which have been developed in the last few years appear to have significantly higher permeabilities while maintaining inherent resistance to change in permeability as a function of frequency. Such improved core materials could very conceivably add at least another order of magnitude to the magnetic measurement capabilities of the phase shift effect magnetometer.

(7) Investigate methods to configure the coils so as to make the device orthogonally sensitive without any one coil or sensor being influenced by any other coil or sensor in a two or three axis system.

(8) Investigate microprocessor programming to integrate orthogonally separated inputs for indicating the total magnetic field. Thus, the ability to indicate total field magnitude as well

as vector components separately would be achieved.

(9) Evaluate commercially available IC's and other components to achieve maximum value and economy of production. For example, for a simple type instrument, it may be economically wise to use readily available or off-the-shelf IC's in place of radiation hardened IC's which are excessively costly. Different uses, in fact, may require different IC's or it may be that substitute IC's will be a better value.

Section 8 - Potential applications

In addition to the applications cited in the original proposal which included the use of magnetrometry for medicine, biology, physiology, geology, oceanography, and even archimagnetism and peliomagnetism, a number of specific utilizations have since been identified as a result of this feasibility research investigation. The most notable area of applicability, as cited in the original proposal, stems from the work cited by Y. A. Kbolodob, member of the USSR Academy of Sciences, who is the late 60's and early 70's reported that various animal vertebra clearly showed changes in motor activity as a result of short term exposure to high magnetic fields. Humans exposed to continuously or semi-continuously high magnetic fields, especially those carried by high tension wires, may in fact be already suffering physically adverse health effects. Additional commercial applications include the potential use as the sensing element in a compass, magnetic resonant imaging system and health effects due to electromagnetic fields around power lines and broadcasting stations. Also, measurements could be made prior, during, and after volcanic eruptions or earthquakes. In particular, the following applications are noted:

(1) The need, in high volumes, for a directional measuring device having low cost and high capability is extensive. Based on the demands for the current flux gate system, which is both relatively costly and inaccurate, a device with an accuracy of no better then about twelve degrees is currently being mass produced for automotive use, including military. The recent occurrences in the Middle East and the inability of our military in vehicles to maintain certain directions because of the lack of landmarks and other reference points in the desert day or night necessitates the use of a good compass. The current principle, because of its unique features could be configured into a good, highly directional and low cost compass which could be on every military vehicle and most private automobiles.

(2) Commercial requirements for accurately measuring low level directional magnetic flux is also apparent when one considers such devices as dipping needles, pipeline locators, buried mine locators, bore hole controls, mineral lode indicators, and similar devices. The newly developed magnetic resonance imaging system where a human is subjected to large magnetic flux and then returned to randomness requires nearly instant measurements of the magnetic field at a point. Currently, the Larmor type of magnetometer is used in this configuration.

With the phase shift effect magnetometer it is conceivable to produce faster measurements that are more sensitive and accurate than the Larmor magnetometer and at considerably less cost. Conceivably, this could reduce the cost of medical procedures involving MRI and associated computer-aided tomography. Also, if the phase shift magnetometer proves to be orders of magnitude more sensitive and less costly than the current Larmor magnetometer then conceivably less severe magnetization may be utilized to produce the same medical image results.

(3) Recent public attention has been focused to either real or imagined effects of a varying electro magnetic field, such as those produced by power lines or broadcasting areas. No accurate methods exist for measuring a low level alternating electro magnetic field. There will, conceivably, be a requirement for such an instrument, especially for determining long range effects of these low frequency electromagnetic radiation.

(4) It is well known that geophysical changes occur prior to, during, and just after volcanic eruptions or earthquakes. For example, volcanologists in Hawaii would like to measure the total field, especially in areas an active volcano. However, current devices are not expendable or not directionally sensitive enough to be able to detect and transmit changes in the magnetic field surrounding the sensor that is next to an active volcano. The envisioned size, low cost and low power consumption of the phase shift magnetometer would make it possible to continuously monitor this type of activity, even during a volcanic eruption; and should the device survive, it would be able to continue to monitor and transmit data via a transponder. The signals could be analyzed for certain characters or signatures which would enable the geologist or volcanologist to be in a position to predict eruptions or earthquakes. Even the prospect of having the sensor destroyed during this activity is of no concern if its cost were low enough. An inhibiting factor for geologists or other scientists is cost.

(5) Photolithography, currently available, could be utilized to micro-miniaturize the envisioned magnetometer. It may be possible then to use magnetic brain scans in place of skin resistance measurements, in vivo measurements of muscles and tissues and bones, opening up a whole new field of low level, small spaced, magnetic sensing transducers for a number of medical research activities.

High nickel alloys, complex in composition, have made the so-called flux gate instruments possible because of their very unique and desirable properties; namely, low H_C and high permeability. However, there are new alloys (complex amorphous alloys of iron, cobalt, vanadium, silicon and boron, with measured H_C of 0.003 Oe) that have been developed and are currently being promulgated that may, in fact, offer even greater advantages than the high nickel alloy materials. Thus, it may be possible to measure lower and smaller magnetic fields, such as, for example, those caused by IC's.

(7) We need not only to measure the strength of the magnetic field at a point but also

determine the total vector. This becomes increasingly important in such areas as aircraft and space craft navigation. With a three axis phase shift magnetometer it would be actually possible to accurately map magnetic fields on earth or in space. Perhaps even the profile of a given anomaly could be deduced from this type of three dimensional measuring instrument.

(8) Since the device could be self-contained on an integrated circuit with all solid state components, it is possible to envision one square inch of PC board or other suitable substrate. The device would be virtually indestructible to high G forces and consequently could be utilized as mine detonators or artillery fuses or torpedo and rocket guidance systems.

(9) A three dimensional magnetometer would have distinct advantages over the current Larmor or proton procession magnetometer utilized in location of metallic devices especially in military applications. It would not be necessary, for example, to make point by point measurements but rather a unique single measurement at a distant point to measure not only the anomaly but the direction of the anomaly.

(10) It is conceivable that the transducer itself could be separated from the circuitry that is used to either detect or to respond to certain magnetic anomalies or total magnetic fields. The configuration of the envisioned phase shift magnetometer would make this possible. Hence, the sensor itself could be no bigger than an eraser tip and located at some innocuous place or in some hostile environment. An example of this type of application could be easily in the nuclear industry.

Section 9 - Recommendations

Based on the results of this investigative feasibility research project, it is my belief, as principal investigator, and unanimous consensus of my supporting researchers, Professor Shih and Dr. Kowalski, **that we should earnestly and swiftly pursue an extensive Phase II research project.**

Section 10 - Acknowledgements

On behalf of the Dinsmore Instrument Company and myself, I wish to express a profound thanks to NSF for making possible the realization of a Phase Shift Effect Magnetometer. Without the Phase I grant, these findings and implications may not have been realized. I would also like to thank Professor Kelvin Shih of Lawrence Technological University for making available his vast resource of knowledge on analog circuitry, and Dr. Henry Kowalski of GMI Engineering and Management Institute for his tremendous aid and

support on quantifying and organizing this project.

Section 11 - References

(1) **R. C. Dinsmore, SBIR-Phase I Research Proposal, "Phase Shift Effect Magnetometer", NSF June '90.** (Extensive bibliography on magnetometry is given on pages 13 and 14)

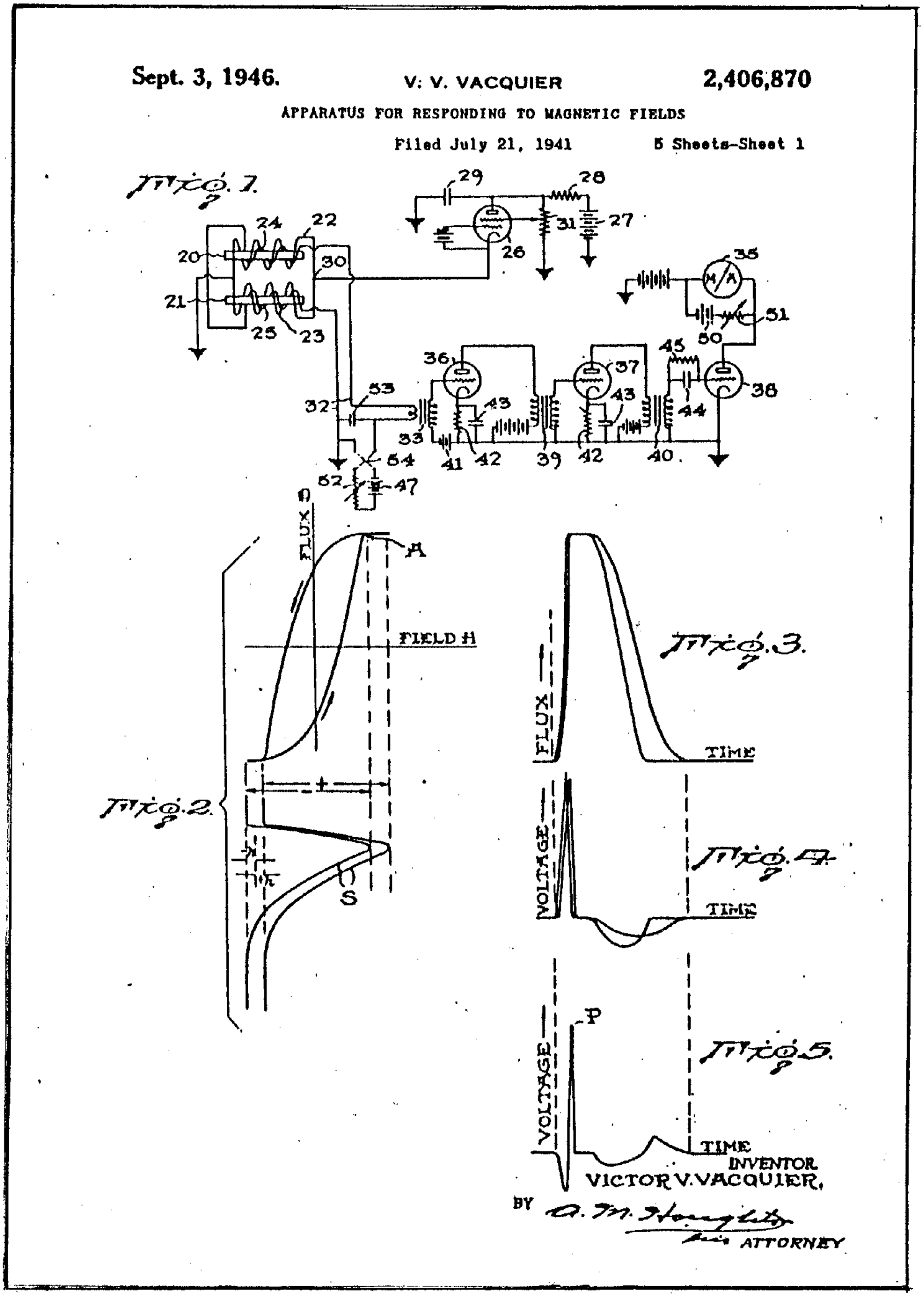
(2) **John Clarke, "SQUID Magnetometer Project", UC/LBL, Department of Energy, Berkeley, CA.** (Comprehensive research program on alternate magnetometry technology)

(3) **Carpenter Technology Corporation, Car-Tech Alloy Data Bulletin 11-8815M, Reading, PA.** (An exclusive processor of high permeability alloys)

(4) **Analog Devices, Linear Products Databook, 1990/91, Norwood, MA.** (A suitable OEM supplier of electronic components for use in a magnetometer circuit)

(5) **National Semiconductor Corporation, Linear Applications Handbook, 1991, Santa Clara, CA.** (A suitable OEM supplier of pertinent electronic components.)

Section 12 - Appendices: Figures 1 through 8



Sept. 3, 1946. V. V. VACQUIER 2,406,870

APPARATUS FOR RESPONDING TO MAGNETIC FIELDS

Filed July 21, 1941 5 Sheets-Sheet 1

INVENTOR
VICTOR V. VACQUIER,

BY O. M. Haughton
His ATTORNEY

Figure 1. First page of Vacquier Patent, illustrations depicting the state of the art at that time. Middle left drawing of hysterisis phenomenon of high permeability core material, (Figure 2), illustrates the characteristic "knee" (Pt. A).

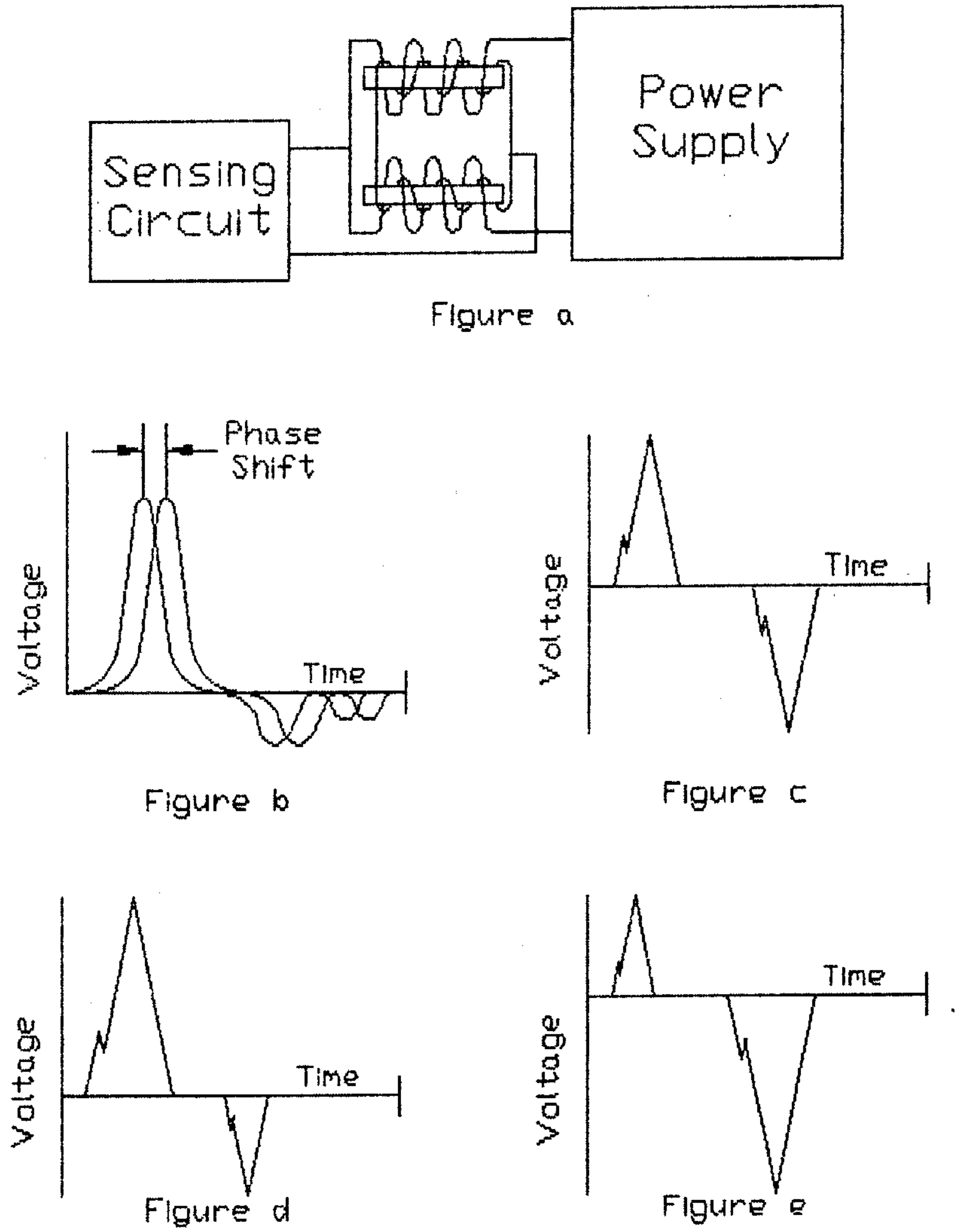


Figure a

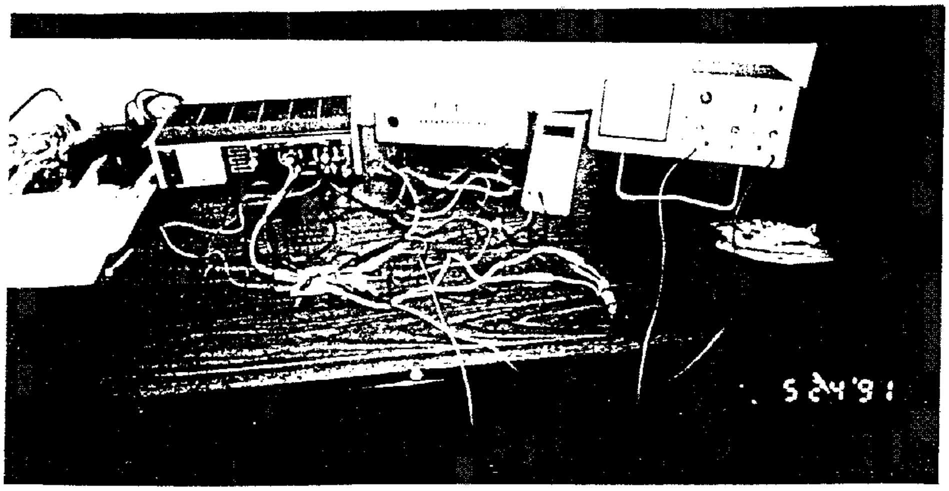
Figure b

Figure c

Figure d

Figure e

Figure 2. Schematic representation of Phase Shift Effect Magnetometer. Output voltages from a pair of bifilar coils, Fig. a, appropriately driven to saturation is illustrated in Fig. b for a typical half cycle. The "phase shifted" voltage, when added, produce the spiked voltage outputs illustrated in Fig. c for a full cycle. For a balanced or zero state magnetic field, the wave forms are symmetric. An anomaly or change in magnetic field strength provides unequal voltages as shown in Fig. d and e. The difference in positive and negative voltage values is a measure of the field strength. The highest peak, positive or negative, indicates the field direction.



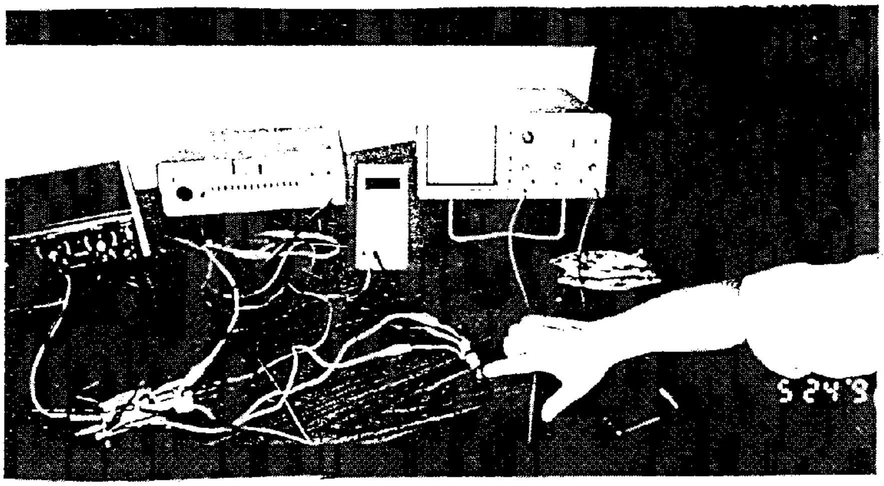


Figure 3. Overall perspective of laboratory bench test set-up and close-up identification of the sensor, a pair of coils encapsulated in an epoxy shell. The hand made PCB with all the test clips attached, to the left of the sensor, is the remainder of the circuitry.

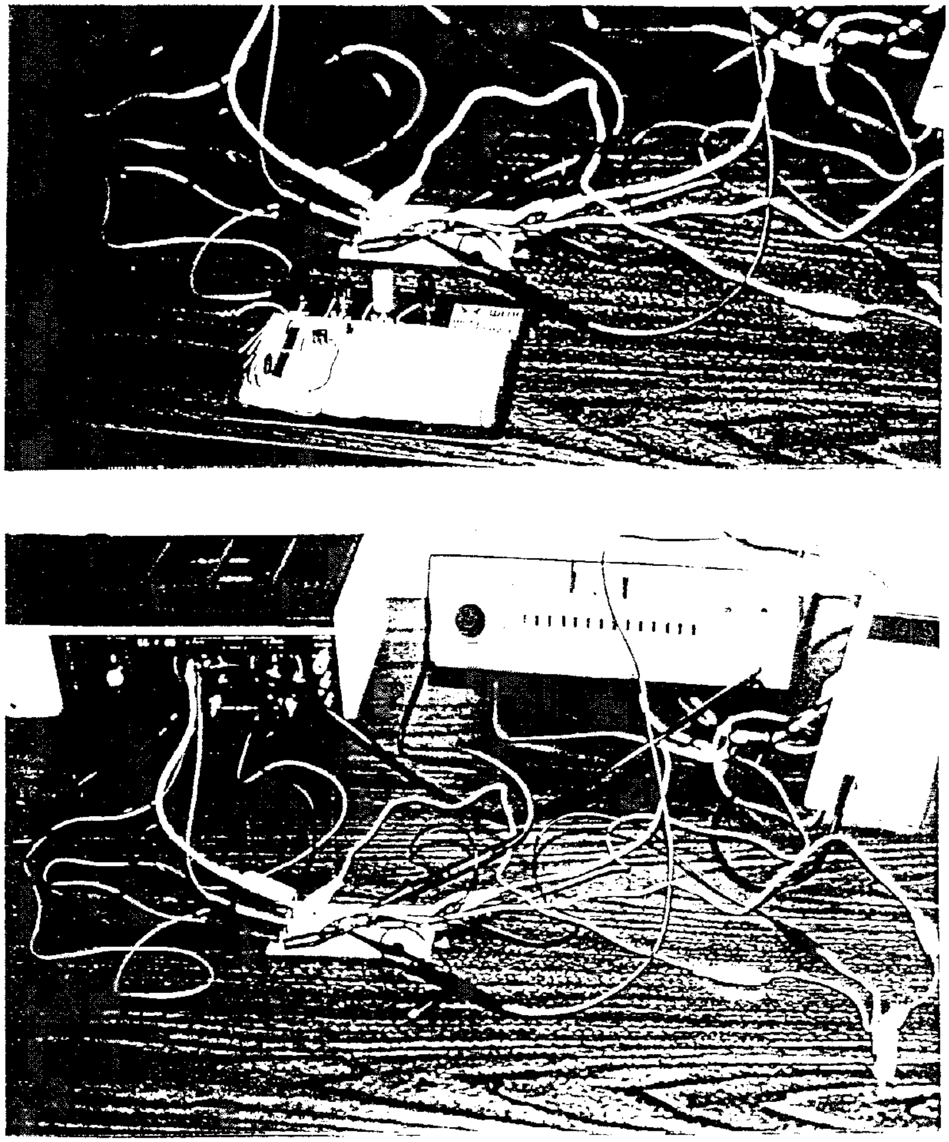


Figure 4. Laboratory bench top view of power supply, amplifier circuitry and sensor Breadboard system with various readout and monitoring systems attached.

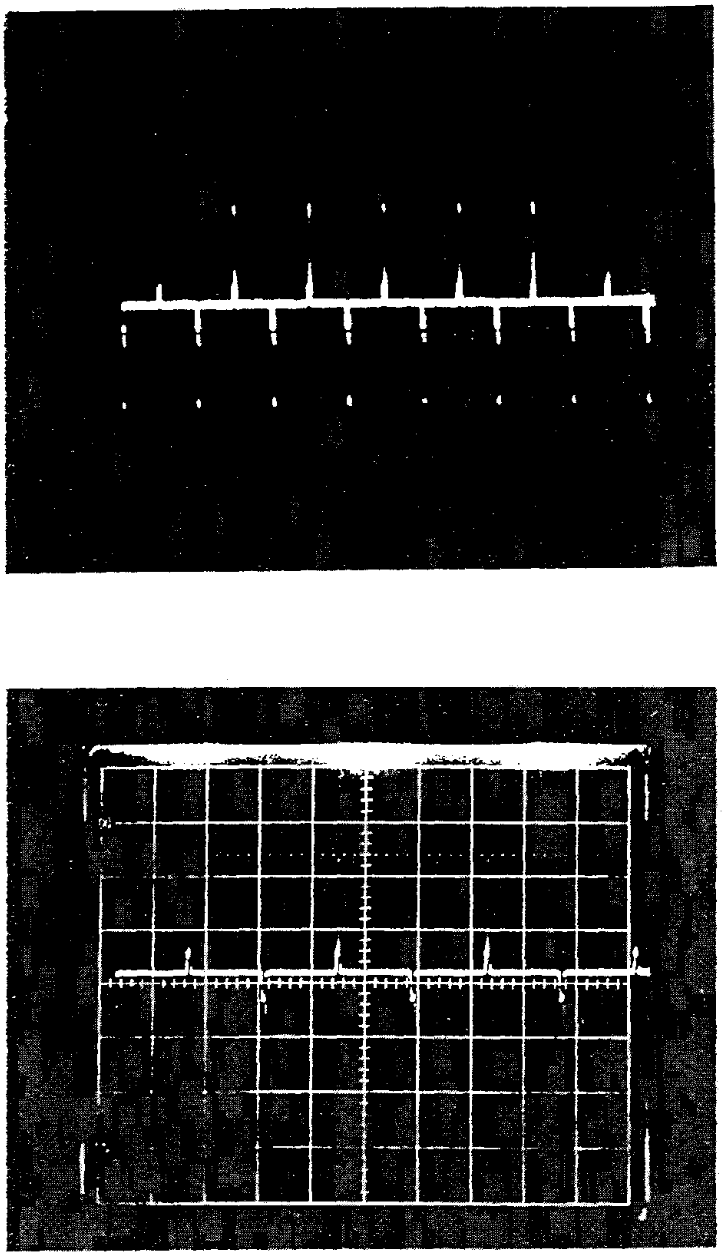
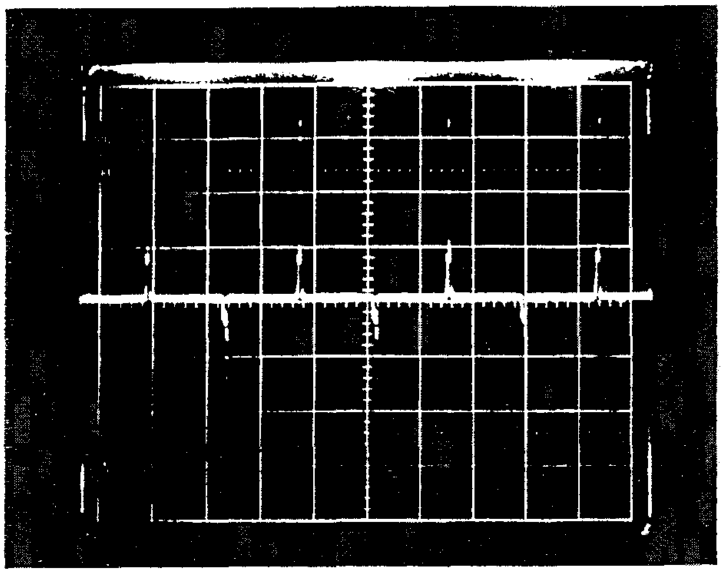


Figure 5. Photocopied reproduction of Polaroid Oscillograph traces of output voltages for a balanced or zero referenced magnetic field. This shows the positive and negative voltage peaks are equal.



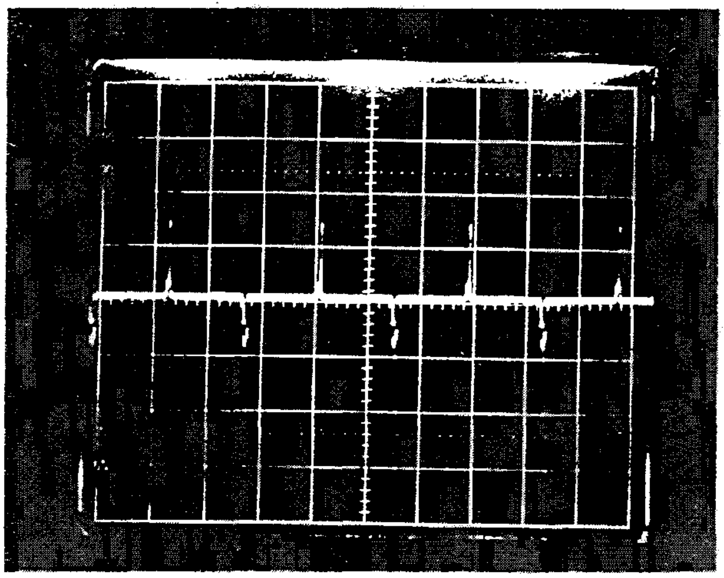


Figure 6. Photocopied reproduction of Polaroid Oscillograph traces of output voltages for an anomaly or induced magnetic field. Differences in voltage peaks (positive and negative) is a measurement of field strength. Positive or negative bias is an indication of field direction.

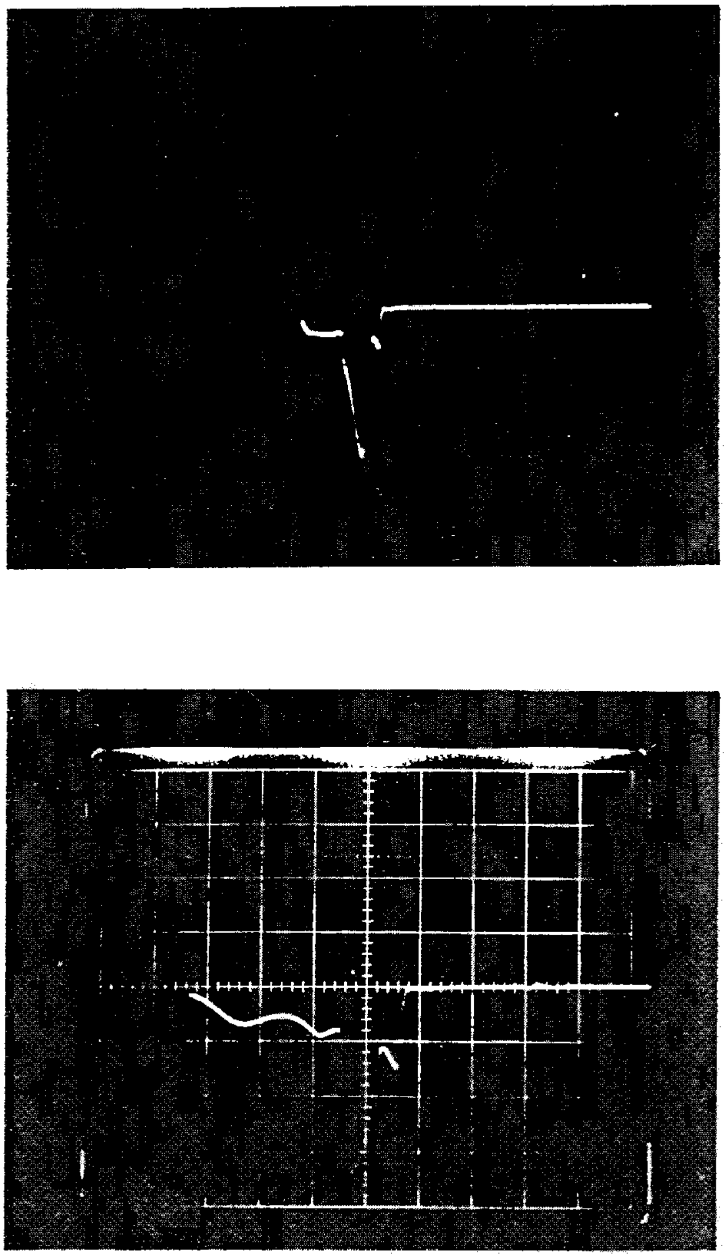
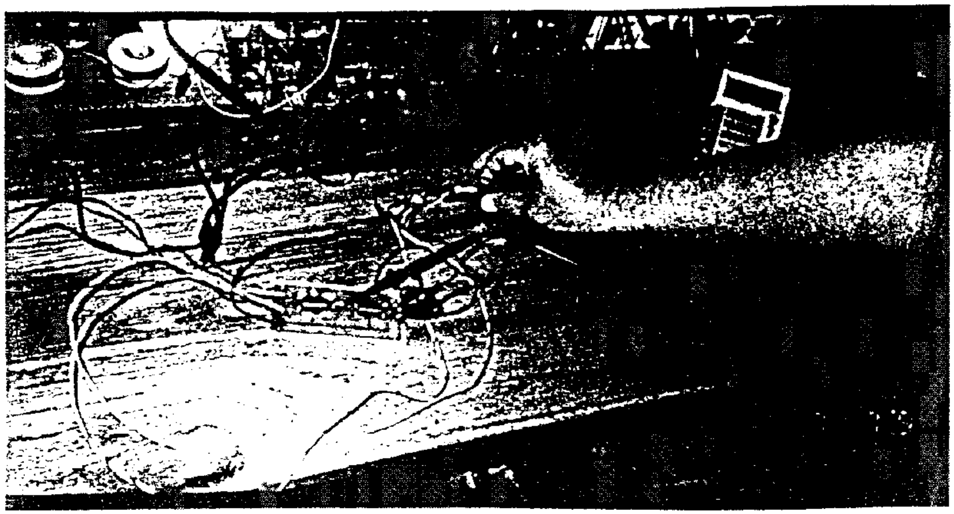


Figure 7. Photocopied reproduction of Polaroid Oscillograph traces of typical voltage signal (wave form) highly magnified. This shows the system noise at the base of the voltage peak.



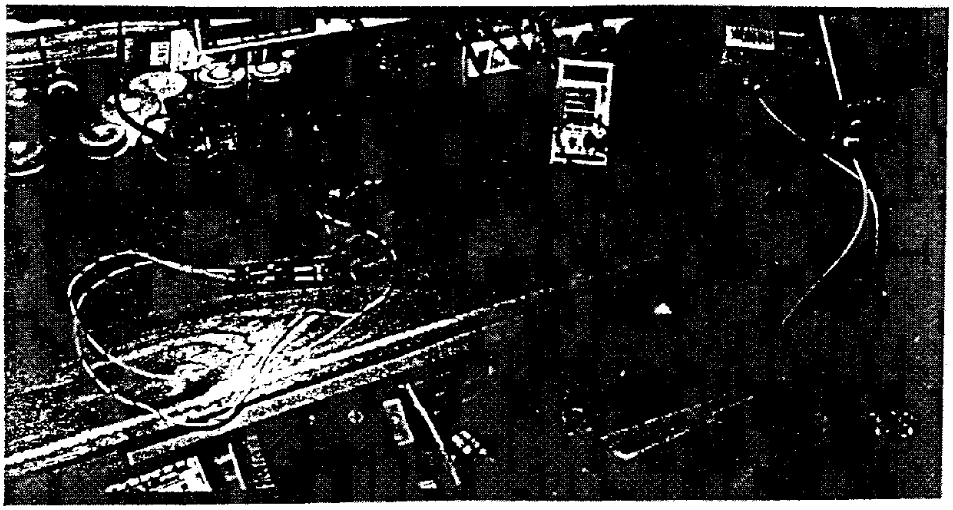


Figure 8. Photocopied reproduction of photographs illustrating two of the basic experimental methods to ascertain the sensitivity of the Phase Shift Effect Magnetometer. Top photo illustrates the 1^0 movement for sensor saturation. Bottom photo illustrates the voltage flip-flop for a 180^0 turn of a simple bar magnet held in the hand (at right) at a distance of one meter from the sensor. Both driver and amplifier are on the 3 x 5 PCB graphically demonstrating the possibilities of downsizing and miniaturization.