ELECTROMAGNETIC UNDERGROUND POSITION LOCATION

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Abstract

The technique of electromagnetic underground position location using induction coupling (often referred to somewhat incorrectly as radio direction finding) has been tried and used with varying degrees of success by a few people over recent years. However, it appears that the full capabilities and limitations of this technique have not always been appreciated. This paper outlines the theory and problems with the technique and will attempt to show how optimum performance and full use of the techniques capabilities may be achieved. A recently constructed apparatus with the capability of accurate position location through at least 250 m of limestone will be described. This sort of range renders this instrument very useful indeed as a means of externally closing long survey loops as well as other obvious and not so obvious applications.

Introduction

One of the main purposes of underground surveying of caves is to enable the spatial relationships between passages and surface features to be determined. Electromagnetic devices which enable such relationships to be determined through solid rock without line of sight are undoubtably useful tools in the study of speleology. This paper examines the principles involved in underground electromagnetic position location (often referred to as radio direction finding or RDF) and describes new position location apparatus with a useful underground location range of 500 m.

Basic Principles

Consider two coils of wire placed side by side on a common axis. If an alternating current is passed through one of the coils, the primary, an alternating magnetic field will be set up and this will induce an alternating current in the second coil, the secondary. This principle of electromagnetic induction is of course the basis of the transformer. Now if we rotate the plane of the secondary with respect to that of the primary, the secondary coil will intercept less of the magnetic field and thus less current will be induced in it. Finally, if the secondary is rotated until it is perpendicular to the primary (though still on axis) no magnetic field passes through the secondary coil and thus no current is induced in the secondary.

Location Principles

Now consider the shape of the alternating magnetic field set up at a distance from a horizontal primary coil carrying an alternating current. Figure 1 shows the lines of magnetic flux set up in a vertical plane through the centre of the horizontal coil. Several features of this magnetic field are of particular interest.

Firstly, it is noticed that the magnetic field is vertical at any point directly above (or below) the primary coil. Thus if a secondary coil is held vertically, then at a point directly above the primary coil no current will be induced in the secondary. This forms the basis of a position location apparatus. If a detector is connected to the secondary coil, then it is simply a matter of moving the coil (held vertically) around until the null is located. As it lies on the steepest part of the sine curve, this null is very sharply defined and thus easily determined and is obviously quite independent of distance between the two coils. It should be noted that the discussion has thus far been confined to one plane. In three dimensions a null will occurr whenever the plane of the vertically held secondary coil passes through the centre of the primary coil. To pinpoint the position directly above the primary coil it is therefore necessary to find the position where a null exists independent of

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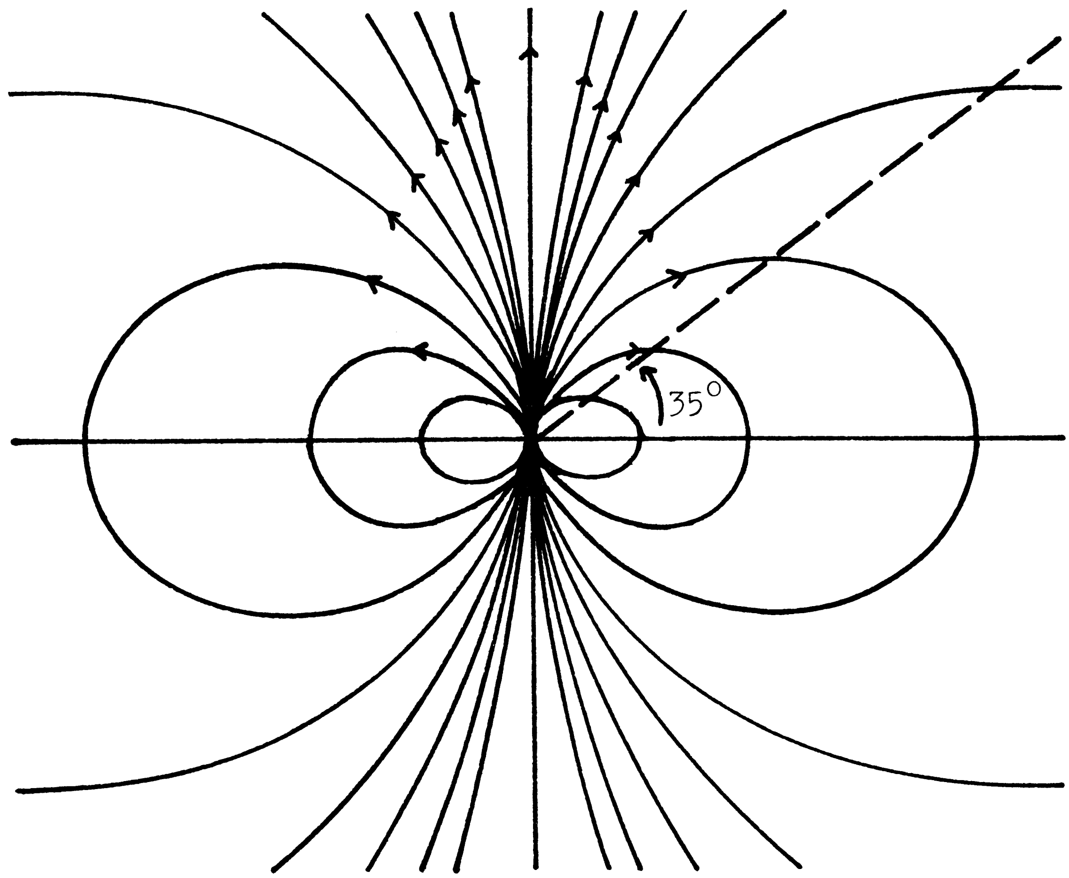

Fig. 1. Magnetic field shape.

angle of rotation of the coil about a vertical axis. The direction in which to move to get to this complete null may always be determined by rotating the coil until a null appears at one particular angular orientation. The plane of the coil then points in the direction of the primary coil below.

It will also be apparent from figure 1 that the magnetic field lines are also vertical anywhere in the horizontal plane containing the (horizontal) primary coil. Thus we may use a similar procedure to detect when the two coils are at the same level.

Finally, figure 1 shows that the magnetic field lines will be *horizontal* at any point such that the angle of inclination between the two coils is approximately 35 degrees. Thus by holding the secondary coil horizontally and locating a null, the distance between the two coils may be found with the aid of a little rudimentary surveying between this null and that found directly above (or beside) the primary coil.

Many other procedures to accomplish specific tasks may be devised involving different orientations of one or both of the coils, however, those described above form a most useful basic set of underground position location procedures.

One interesting further feature of the magnetic induction field should be noted. It will perhaps be apparent from figure 1 that if the primary coil is not placed exactly horizontally (i.e. levelling error) then the point where the field lines are vertical is not now directly above the primary coil. However, the point is not on the axis of the primary coil either. The null in fact will occur on a line at an angle from the vertical equal to 1/3 the levelling error angle for small (less than 30 degree) angles. The primary coil may thus be considered to be partially self-levelling (or "2/3 self-levelling" perhaps).

Electronic Design Considerations

The aim of any good design of electromagnetic position location apparatus is to gain maximum useable range at maximum accuracy and precision. Unfortunately many factors make the achievement of these objectives difficult.

The first problem lies in the fact that the medium through which we wish to transmit an electromagnetic signal is conductive. This means that any signal suffers attenuation, particularly at high frequencies. In order to minimize attenuation and eliminate the guiding or channelling of the signal through cracks, voids and other discontinuities in the inherently non-homogeneous medium, it is necessary to choose an operating frequency in the mid audio range. At such frequencies a directional antenna has undesirably immense dimensions and thus we are forced to use the induction principle previously outlined. This has the unfortunate disadvantage that the received signal strength is inversely proportional to the cube of the distance between transmitter and receiver. Thus any improvement that doubles transmitter output or receiver sensitivity gains only 25 percent improvement in usable range.

Many position location apparatuses in the past have suffered from inadequate range due to a lack of appreciation of the optimum design procedures. I shall start by considering the transmitter end. The most important aspect of transmitter design lies in the design of the coil. The transmitter itself should consist simply of a square wave oscillator and fully driven class B power amplifier. The coil should be connected to the transmitter output via a series capacitor such that the combination forms a series resonant circuit at the operating frequency. The design of the coil is based on three constraints. These are maximum permissible weight, maximum permissible size and maximum permissible battery drain. The strength of the transmitted magnetic field is proportional to the number of turns times the current times the area of the coil (NIA). If we wish to maximise this product it is easy to show that for a given allowed weight of copper we want a circular coil of as large a diameter as possible wound with as heavy a gauge of wire that transmitter current drain will allow. (For a given area of coil it should be obvious that doubling the wire cross-sectional area and halving the number of turns will leave the weight unchanged but will reduce the coil resistance by four times thus increasing current by four times and doubling the NIA product.) The maximum current drain is in turn based on the maximum weight and hence capacity of battery allowed and the minimum operating time required. Most of these constraints are based upon what the underground party is prepared or is able to carry through the cave.

Design of the receiving (or search) coil is based on the same principles. In order to intercept as much of the magnetic field as possible the coil should be as large as possible. To further maximize the induced signal voltage we want a maximum number of turns. The limit to the number of turns possible is determined by the self resonant frequency of the coil. As the number of turns is increased, both the inductance of the coil and the capacitance between turns increases thus lowering the self resonant frequency. We want a coil whose self resonant frequency is just above the system operating frequency so that the coil may be tuned to resonance at the operating frequency with a small tuning capacitor in the receiver. Finally, the gauge of wire will be determined by the total copper weight that can be tolerated; bearing in mind that the coil must by easy enough to support in one hand for reasonable periods of time. It is important that as heavy a gauge of wire as possible be used as the copper losses have a significant effect on the magnitude of the received signal.

The receiving coil designed as above will have a considerable peak in its response at its resonance frequency thus providing a useful degree of pre-selectivity. In order to preserve this selectivity and sensitivity the coil Q must not be damped significantly by the input resistance of the receiver front end. The receiver should thus consist of a high gain, low noise, high input impedance amplifier plus a band-pass filter to remove noise outside the narrow band of interest. It is of paramount importance that the input stage of the receiver be painstakingly designed for minimum noise as it is receiver input noise which ultimately limits the detection range of the equipment.

One major problem with high gain, high input resistance amplifiers lies in their susceptability to capacitive feedback. This problem can only be solved by very careful shielding of the input from the output and requires considerable attention to system layout.

A Practical Design

Figure 2 shows a block diagram schematic of an electromagnetic underground position location apparatus designed along the above lines.

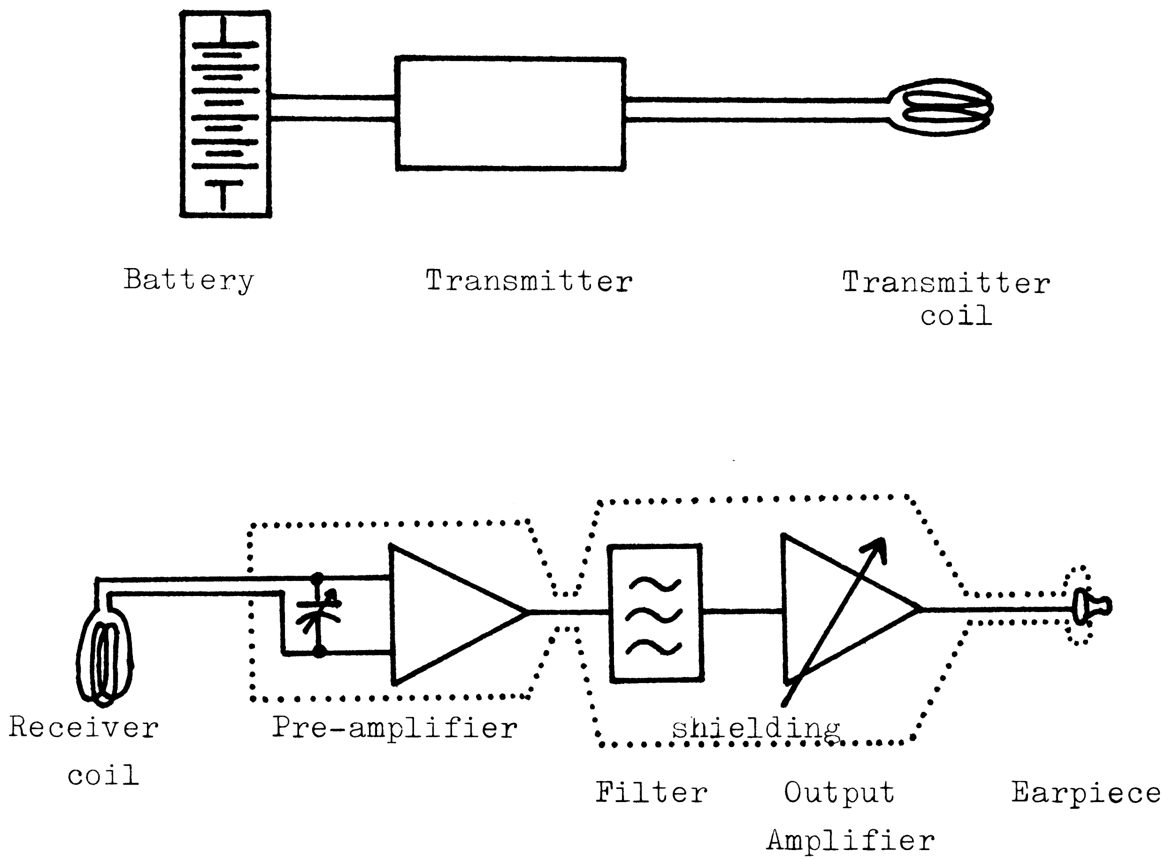

Fig. 2. Block diagram of a practical system.

The transmitting coil consists of 230 turns of 15 B&S gauge wire wound around a wooden former 35 cm in diameter. The former is supported on three brass bolts which function as levelling legs. Levelling is achieved with the aid of a surveyors bubble level mounted on the coil former. The transmitter is a simple square wave oscillator and fully driven power amplifier driving the coil via a series capacitor. A fine tuning control is provided to tune the transmitter frequency to the resonant frequency of the load. To aid tuning, a Light Emitting Diode (LED) level indicator is incorporated to detect maximum coil current. The whole unit is powered by a 12 volt motorcycle battery. Resonance occurs at about 2 KHz with about 600 volts peak-to-peak developed across the coil. The battery drain is about 1 amp and this allows about 6 hours of continuous operation. The total transmitting system weight of 9.7 kg is made up predominantly of 5 kg for the coil and 4.5 kg for the battery.

The receiving coil consists of 2200 turns of 33 B&S gauge wire wound on a 55 cm diameter wooden former. The coil, which weighs 4 kg, is suspended from a handle by two cords such that it hangs perfectly vertically. The receiver consists of a low noise pre-amplifier with a gain of 500 and an input resistance greater than 50 megohms. A tuning capacitor is incorporated at the input to tune the coil to resonance at the transmitter frequency. The pre-amplifier is followed by a band-pass filter with 2 KHz bandwidth and 18 dB/octave cutoff slopes. A final variable gain stage with a maximum gain of 1500 is used to drive a shielded crystal earpiece which constitute the detector. The receiver is powered by two pairs of 9 volt transistor batteries which provide for a battery life of about 30 hours of continuous operation.

The set-up has been tested and used successfully at Yarrangobilly. It has a maximum usable range of 500 m through limestone. With the transmitter 60 m below the surface, position location precision was plus or minus 5 cm, at 170 m precision was ±50 cm. This range and precision is considered quite adequate for use in any Australian mainland caves, however, improvements are being developed to further enhance performance. An experiment in level detecting in the Yarrangobilly tourist caves was considerably less successful due to the presence of high levels of interference from the locally generated power for the cave lighting. This remains the main bugbear with this type of equipment. At reasonable distances the magnetic induction signal is very small and sensitive receivers are easily overloaded with any extraneous signals such as invariably occur near civilization. This is no problem in the isolated caving areas that hold most of our interest, however, significant areas do occur close to interference sources and in these areas this severely limits the effectiveness of position location apparatus of the type described. But then, life wasn't mean't to be . . . . !!

In response to several requests, a complete constructional description of the unit described will be published at a later date.