PROTON MAGNETOMETER

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Archaeologists, treasure hunters and skin divers have a common problem, where to dig or dive to discover the loot. A buried metal locator would come in handy, but most are either expensive or have too limited a range. The one described here is a proton magnetometer using discoveries made in nuclear magnetic resonance first published in 1946.

Some care is required in putting together the high gain amplifier, but otherwise construction is straightforward, using standard components, and the exotic nuclear material is distilled water.

Essentially, the magnetometer measures the intensity of the earth's magnetic field at two nearby points. A difference in the intensities produces an output from the device, which can be either an audio signal or a meter reading.

The earth's field is normally uniform. but will be disturbed by local concentrations of magnetic materials, such as iron ore or just iron junk. Hence the magnetometer can only be used to search for ferrous materials or compounds. For this purpose it is extremely sensitive with considerable range.

It will, under ideal conditions, detect a one pound mass of iron at about four or five feet below one of the bottles, and larger masses at much greater distances. Typical of the latter is a twelve foot length of three inch diameter iron water pipe at twelve feet. It is difficult to give performance figures, since much depends upon the size, density and attitude of the object disturbing the field, and experiment provides the best answers.

This high sensitivity to field variations means that the magnetometer may only be used remote from known earth field disturbers, such as buildings and power lines.

ATOMIC PRINCIPLES

To understand the principles involved is easy if the cobwebs and dust are shaken off the school books and memories of atomic particles. Remember that old friend, the hydrogen atom, first in the atomic table, with just one proton and one orbiting electron, as simple a thing as any alchemist could wish.

The orbiting electron acts just like electric current in a coil of wire and sets up a magnetic field about the atom as seen in Fig. 1. The proton, the main mass of the atom, is also in motion, spinning about its centre, so that the whole atom looks like a magnetic gyroscope, whose magnetic poles are on its spin axis.

Gyroscopes have idiosyncrasies revealed to mechanical engineers, one of them being that they will precess if acted upon by an external field. In the hydrogen proton's case, its spin axis will wobble or precess about the direction of the earth's magnetic field if that is the only magnetic field acting on it. This is shown in Fig. 2. The frequency of precession will be proportional to the strength of the field and is given by

$$v = kB$$

where v = frequency of precession

$k = 4.26 \times 10^3$ Hz/weber for hydrogen

B = intensity of magnetic field.

USE OF DISTILLED WATER

If a coil of wire is wound round a small plastic bottle containing distilled water, sufficient current can be passed through the coil to set up a local field in the bottle very much greater than any external field, in this case the earth's.

A number of the spinning protons of the hydrogen atoms, remember H_2O, happily line themselves up with their spin axes along the direction of the induced field. If the current is suddenly cut off the induced field collapses, and the protons try to realign themselves with the earth's field.

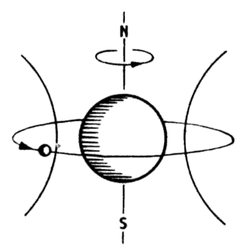


Fig. 1. Magnetic field around hydrogen proton produced by orbiting electron

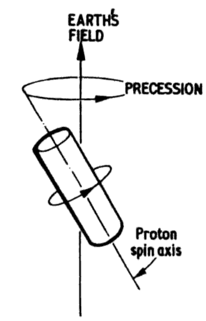


Fig. 2 Precession of proton relative to earth's field when acted upon by external magnetic influence

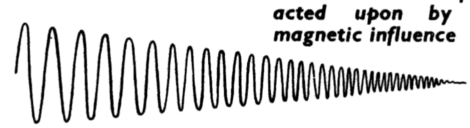


Fig. 3. Diminishing alternating voltage set up by precession frequencies from the detector coils

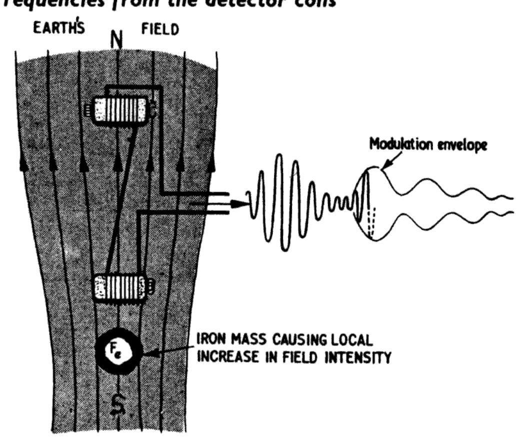


Fig. 4. Modulated output produced by mixing the two precession frequencies from the detector coils

Because they behave as gyroscopes, they cannot simply switch back but must precess back at the precession frequency. In doing so they set up a very weak alternating field in the bottle, and an alternating voltage is induced in the coil. This voltage falls to zero as realignment with the earth's field is completed. Fig. 3 shows the signal that would be seen on an oscilloscope.

BASIC MAGNETOMETER

This phenomena can now be used to make a ferrous metal detector. Two such bottles filled with distilled water are spaced about six feet apart. The longitudinal axes of the bottles lie east-west.

The coils wound round the bottles are connected in series and a current passed through them. After three seconds, the current is cut off and an amplifier connected across the coils. If the intensity of the earth's field is the same at each bottle, the precession frequency at each will be the same, and the signals from both coils of equal frequency.

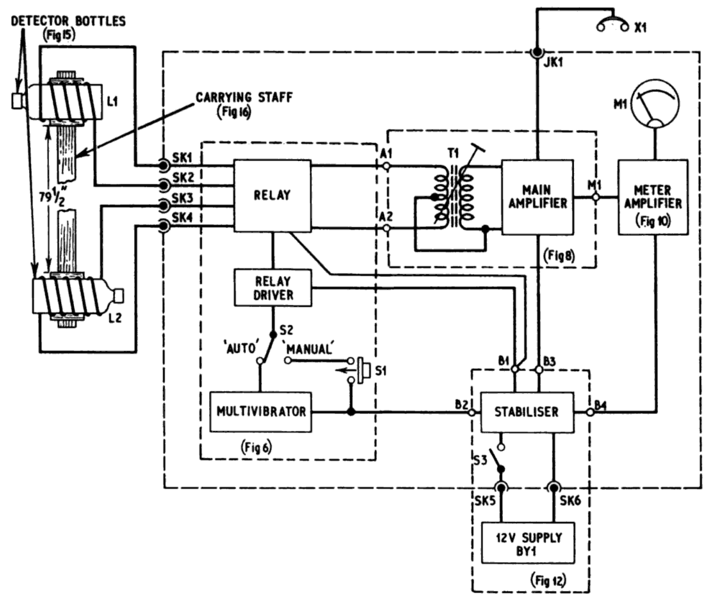


Fig. 5. Block diagram of proton magnetometer

If, on the other hand, the field intensities were different due to some local magnetic disturbance, then the signal frequencies will differ, and the difference can be detected. The amplifier input signal is then the sum of two signals of slightly different frequencies and the output will be a signal of a third frequency which is half the sum of the two input frequencies. The amplitude of this is modulated at a fourth frequency equal to the difference between the original two input frequencies. This composite output signal can be heard in a headset as a note of about 2kHz with a marked quaver. This is illustrated in Fig. 4.

The greater the difference in the field intensities between the two bottles, the faster will be the quaver. It only remains to reach for the shovel and see what is causing the magnetic difference.

CIRCUIT BLOCKS

Now look at the block schematic of the magnetometer in Fig. 5. There are in effect six units comprising: two detector bottles, relay circuit, multivibrator, main amplifier, meter amplifier, and

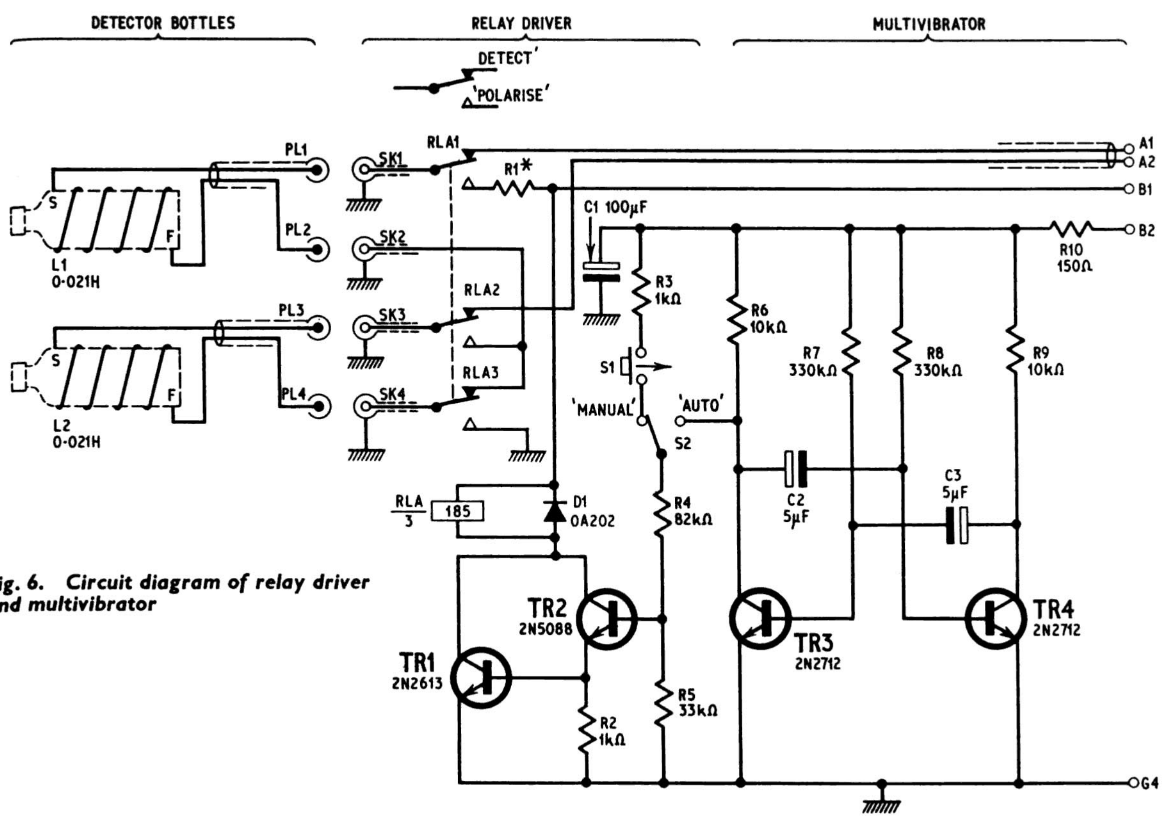


Fig. 6. Circuit diagram of relay driver and multivibrator

power supply. These form what might be called a de-luxe unit. The relay and meter circuits may be omitted if costs have to be kept down.

The relay is used to switch the series wound coils L1, L2 from the "polarise" condition to "detect". In the "polarise" condition the relay passes current through the coils via terminal B1 at the stabiliser. On "detect" the relay switches the precession frequencies produced at the coils to the main amplifier input terminals Al, A2. Detection of the modulation envelope is then provided for, both aurally and visually, by the headphones X1 and meter M1.

The relay can be made to operate manually by the push-switch S1 or automatically when coupled via S2 to the multivibrator; this switch does in fact select the mode.

The multivibrator switches the relay on for about three seconds and off for the same period. This continuous operation is particularly useful when searching. The manual option is used when setting up or detecting a very small frequency difference.

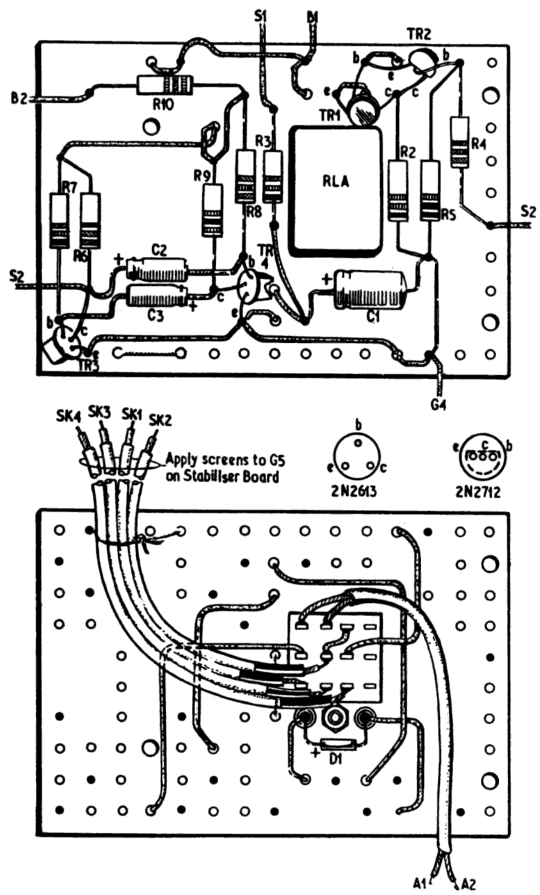
RELAY DRIVER AND MULTIVIBRATOR

The circuit diagram of the relay driver and multivibrator is given in Fig. 6. Here TR1 and TR2, in modified super alpha configuration, drive the relay. The relay contacts are shown in the quiescent state. A 1W resistor, Rl, can be inserted in the "polarise" circuit to reduce the detector coil current and so cut down on battery consumption. It follows that the higher the value of this resistance the smaller will be the signal presented to the main amplifier, so the choice of value should be made when the unit is completed and tested; 4.7 ohms is a suitable value to start with. "Cut and try" methods should provide balance between a tolerable signal and battery economy.

The multivibrator, comprising TR3 and TR4, provides an equal mark-space output of three seconds duration at the collector of TR3. This is passed via S2, when switched to the "auto" mode, to the base of TR2.

Details for assembling and wiring this circuit module are given in Fig. 7.

Fig. 7 (below). Assembly and wiring details of relay driver and multivibrator board



COMPONENTS . . .

MAIN AMPLIFIER

Resistors

R11	39k Ω	R21	68k Ω
R12	33k Ω	R22	820 Ω
R13	10k Ω metal oxide	R23	4·7k Ω
R14	2·2k Ω	R24	12k Ω
R15	15k Ω	R25	100 Ω
R16	18k Ω	R26	12k Ω
R17	22 Ω	R27	2·2k Ω
R18	47k Ω	R28	1·2k Ω
R19	4·7k Ω	R29	10k Ω
R20	4·7k Ω		

All ½ watt, 10% carbon except where otherwise stated.

Capacitors

C4	0·1μF	polyester	10%
C5	0·022μF	polyester	10%
C6	5μF	elect.	6V
C7	30μF	elect.	15V
C8	25μF	elect.	6V
C9	8,200pF	polystyrene	10%
C10	5μF	elect.	6V
C11	100μF	elect.	15V
C12	50μF	elect.	15V
C13	5μF	elect.	15V
C14	5μF	elect.	6V
C15	25μF	elect.	6V
C16	10μF	elect.	15V

Transistors

TR5–TR9 2N5088 (5 off)

Transformers

T1–T2 LA2301 pot cores—Type "B" Assembly consisting of adjuster, clip, cup core, bobbin and tag board. (Gurney's Radio, 91 The Broadway, Southall, Middlesex) (2 off) (see text)

Potentiometers

VR1 20k Ω linear

Socket

JK1 Standard jack socket

Miscellaneous

Veroboard 6½in × 2¾in, 0·15in matrix, plain 40 s.w.g. wire

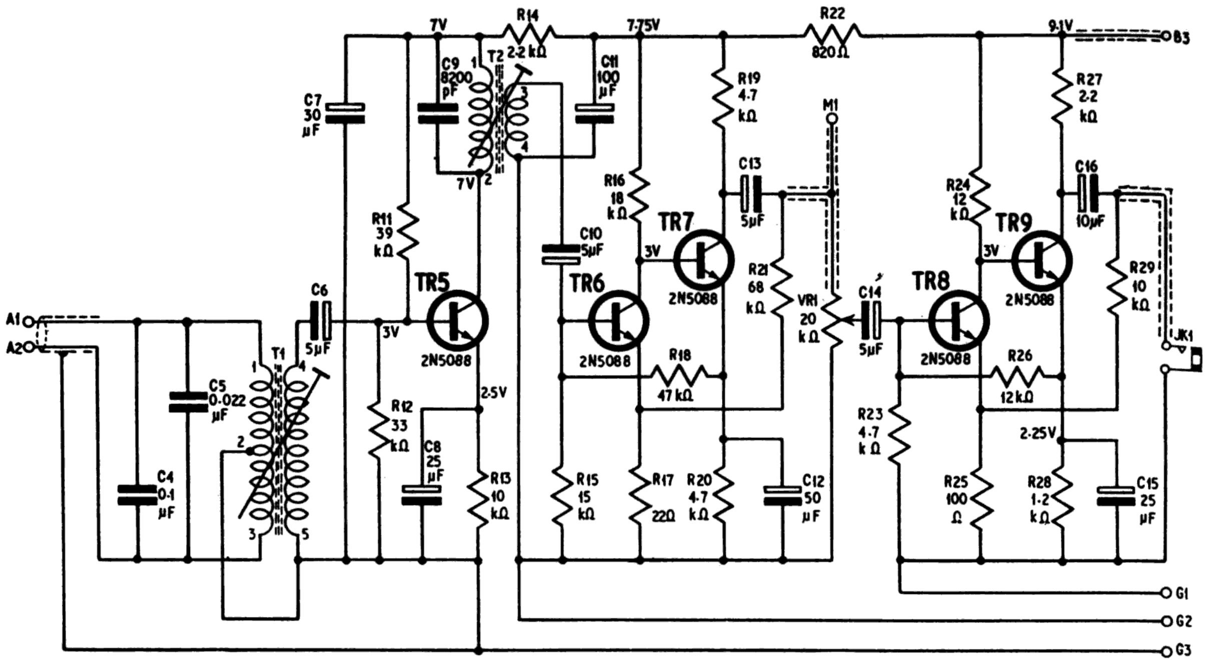


Fig. 8. Circuit diagram of main amplifier

MAIN AMPLIFIER

The main amplifier, seen in Fig. 8, serves to increase the level of the precession voltages. A ferrite cored transformer, T1, with the primary centre tapped, is tuned to the required frequency by C4 and C5. The first stage comprising TR5 has a tuned collector load resonant at the same precession frequency.

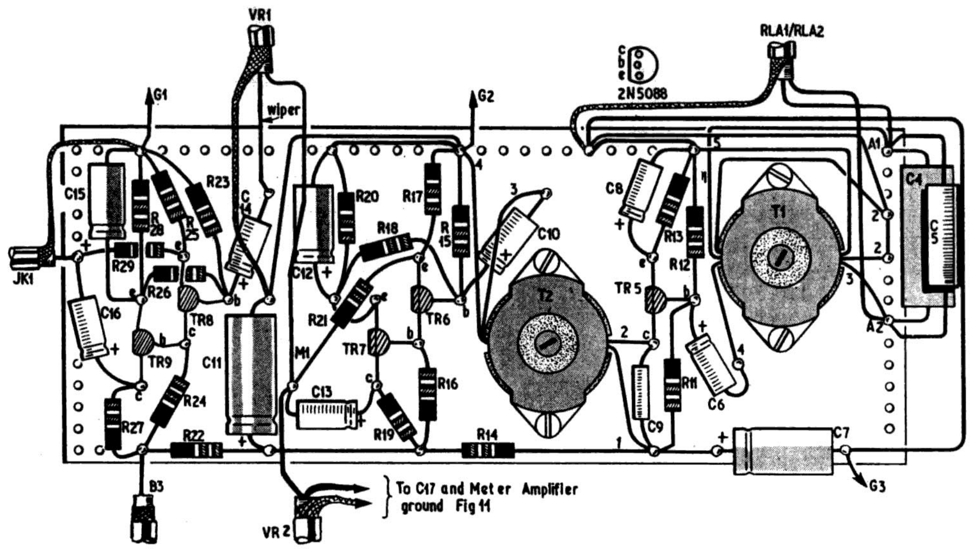


Fig. 9. Assembly and wiring layout of main amplifier board

The output from the secondary of T2 feeds the d.c. coupled amplifier TR6-TR7. This acts, in effect, as a pre-amplifier to the meter circuit, the input for this being taken from M1.

The bandwidth of the tuned circuits is about 300Hz, which has proved adequate on field trials.

VR1 is the volume control for the headphone amplifier, TR8-TR9, the output being taken via JK1.

The headphones used should preferably be high impedance crystal, since magnetic ones can cause feedback trouble if brought too close to the detector bottle, and so cause the amplifier to oscillate.

(In field trials magnetic phones were used and proved trouble-free provided they were maintained in the plane of the detector bottles.)

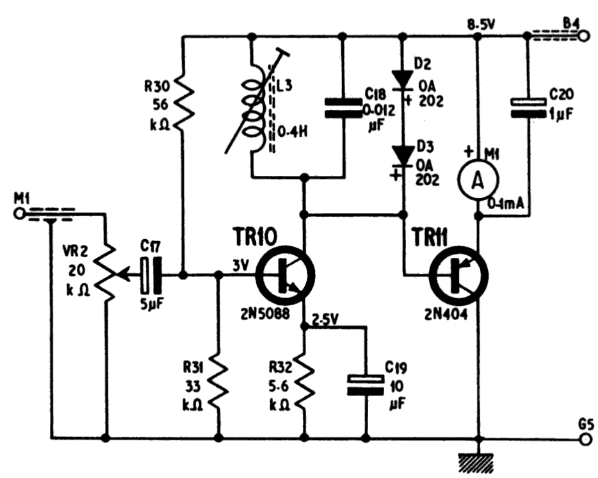


Fig. 10. Circuit diagram of meter amplifier

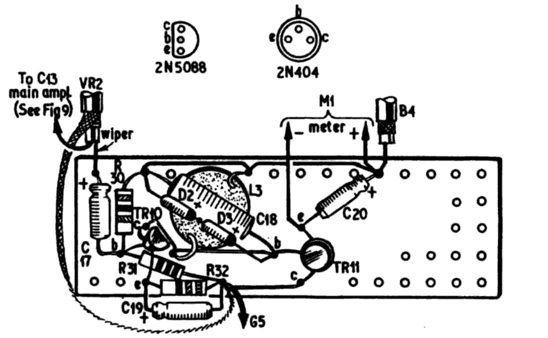


Fig. 11. Assembly and wiring layout of main amplifier board

AMPLIFIER CONSTRUCTION

Since the amplifier provides high gain, the wiring layout and constructional details of Fig. 9 should be adhered to, to prevent instability.

Both of the transformers are contained in Vinkor adjustable pot cores. To wind T1 use 40 s.w.g. enamel covered wire. Slip a couple of inches of fine sleeving over the start to protect the leadout, then wind on seven hundred and fifty turns. Put on another piece of sleeving over the finish leadout and wrap a layer of cellotape round the winding.

Put on two more windings of three hundred and seventy-five turns each and identify the starts and finishes with different coloured sleeving. Wind a layer or two of plastic electrical tape around the completed winding then very carefully assemble the bobbin in the ferrite core. Ensure that nothing gets trapped between the two halves of the core, preventing them mating.

If test equipment is at hand, the inductance of the seven hundred and fifty turn winding should be 0.196H, and its resistance about 56 ohms. The resistance of each of the other winding will be 28 ohms.

COUPLING TRANSFORMER

The coupling transformer T2 is built in the same way. Its primary winding has 1,076 turns of 40 s.w.g. and the secondary 258 turns of 40 s.w.g. When finished the primary inductance should be 0.4H and its resistance about 88 ohms. The secondary resistance will be about 26 ohms.

Since final tuning of the amplifier is made during field trials, the capacitors C4, C5 and C9 should be temporarily connected using crocodile clips.

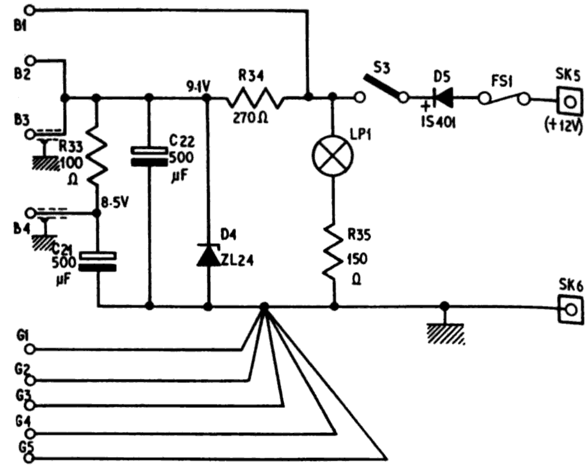


Fig. 12. Circuit diagram of stabiliser circuit

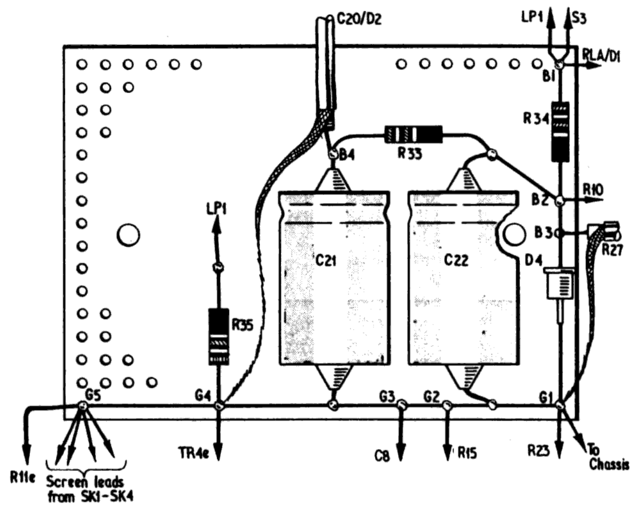


Fig. 13. Assembly and wiring layout of the stabiliser board

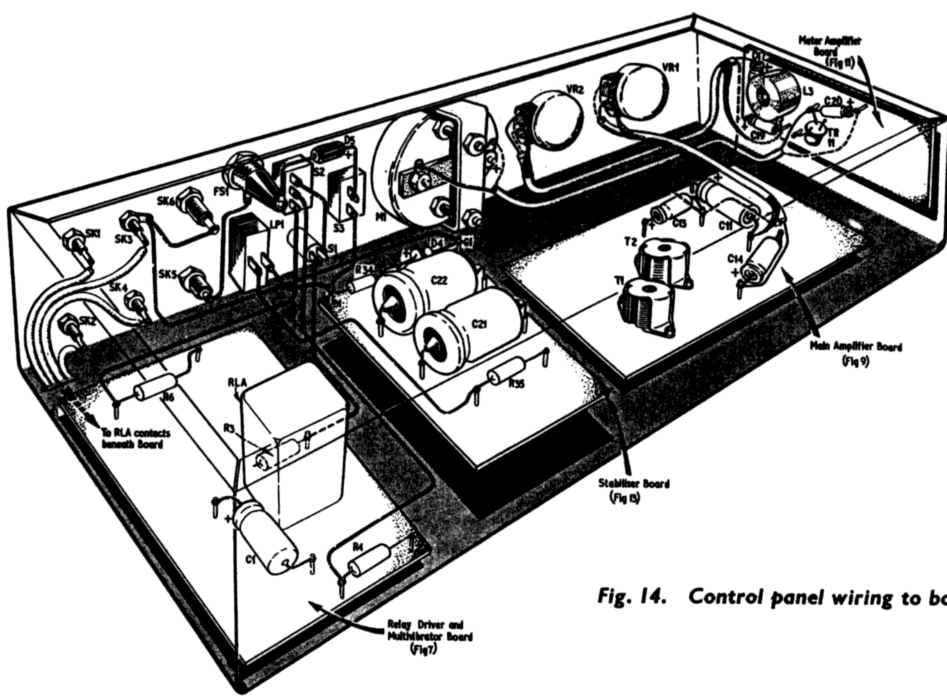


Fig. 14. Control panel wiring to boards

METER AMPLIFIER

The circuit for the meter amplifier is given in Fig. 10. Here VR2 acts as a sensitivity control in feeding the complementary pair TR10 and TR11.

The meter circuit can be used in conjunction with, or to replace the headset.

The meter needle follows the amplitude of the amplifier output which varies at a rate equal to the difference between the two input frequencies. It is particularly useful with very low difference frequencies.

Constructional details of this module are given in Fig. 11.

The inductor L3 is contained in an adjustable pot core, the type being the LA2301, the same as used in the main amplifier. To achieve the specified inductance, 1,076 turns of 40 s.w.g. enamel covered wire should be wound on the bobbin. With the winding complete the free ends should be cleaned and the bobbin assembled in the cup cores.

The mating surfaces of the cores should be fixed together with an adhesive such as Araldite, and the whole stuck to the Veroboard.

POWER SUPPLY

The power supply stabiliser circuit is shown in Fig. 12. Here the diode D5 will prevent damage if incorrect connection to the power source is made.

The supply to the main amplifier and multivibrator is taken from the Zener diode D4, and that for the meter circuit is additionally decoupled by R33 and C21.

Three separate chassis connections, G1-G3, are made between the main amplifier and stabiliser to prevent the possibility of oscillation.

The supply lead from the 12V battery must be screened. The centre wire is positive and terminates at SK5; the negative screen at SK6. Constructional details are given in Fig. l3.

Since the magnetometer draws about 750mA during “polarise”, an adequate heavy duty power source must be used.

CHASSIS ASSEMBLY

Assembly details of the modules on the chassis and front panel interwiring is given in Fig. 14. It should be emphasised that the chassis must he aluminium, and contain as few iron parts as possible, ideally none.

DETECTOR BOTTLES

The detector bottles are plastic, 1-5/8 in. outside diameter and 4 in long. The bottle caps must be plastic.

COIL FORMERS

The coil formers for the bottles are made to be a sliding fit. One way to do this is to roll each bottle in a couple of thicknesses of paper, cover that with a layer of thin plastic

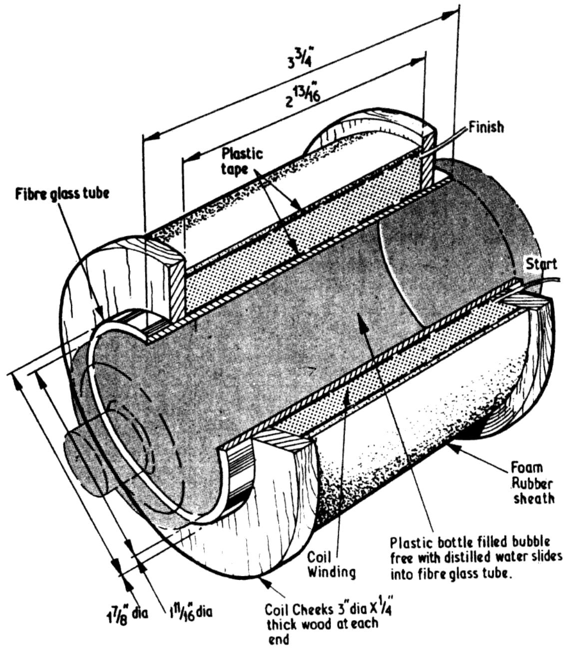


Fig. 15. Constructional details of detector coil former

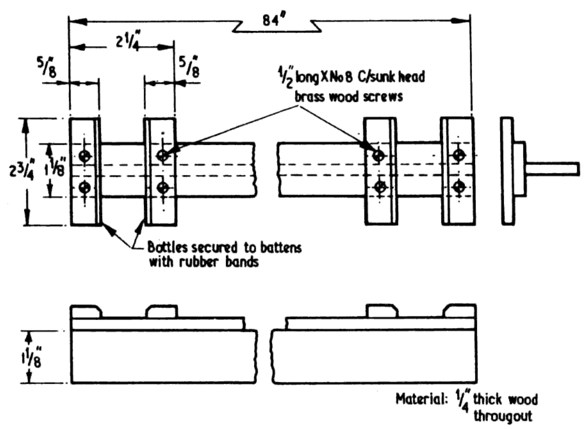


Fig. 16. Constructional details of carrying staff

sheet, such as is used for food wrapping, and then wind on two or three layers of glass cloth as shown in Fig. 15.

The glass cloth is impregnated with epoxy resin and left to cure. The final thickness of the former wall should be about 5/64 in. Once the epoxy has hardened, the outer surfaces should be sanded smooth, and two wooden cheek pieces epoxied on. This gives a very rugged former. Two small holes are drilled in one cheek, one close to the bottom, the other near the top to bring the ends of the coil out through. The former is then covered with a layer of insulating tape.

WINDING THE DETECTOR COILS

Carefully solder an eight inch length of fine plastic covered multistrand wire to the start of the coil wire and insulate the joint with thin sleeving.

Three inches of the multistrand wire are passed out through the bottom hole in the cheek to make the wiring connections to. Seven hundred and fifty turns of 24 s.w.g. enamelled coil wire are now wound on The winding should be as neat and even as possible.

If a lot of rough use is foreseen in the future, it might be prudent to spend a little more and use coil wire with a tougher coating. A suitable coating is armoured polythermaleze. With the winding completed the free end is joined to another piece of multistrand, the joint insulated and the wire taken out through the remaining hole in the cheek.

The complete winding is covered with a couple of layers of plastic insulating tape. For further protection put on a layer of thin foam rubber or plastic. At this point take a break to steady the hands and then make the second coil in exactly the same way.

Now if it is possible to measure the coils, the inductance of each should be 0.021H and the resistance about 7.9 ohms.

CARRYING STAFF

Details of the carrying staff construction are given in Fig. 16. This is of wood, the cross members being attached with brass wood screws.

D.C. CHECK OUT

Give the wiring and all solder joints a final careful check, making sure that all semiconductors are connected correctly. Set all controls to minimum and connect to a 12V power source. Switch on and check all given d.c. voltages with a test meter (20,000 ohms per volt).

Operate the press switch S1 which should energise the relay when the switch S2 is at “Manual”. Switch the latter to “Auto”; the relay should now cycle on for three seconds and off for three seconds.

If the periods are unequal try substituting different electrolytics for either C2 or C3 in the multivibrator. These capacitors have a very wide manufacturing tolerance which may affect the timing. Once the meter circuit is cycling correctly, connect the test meter across the detector input sockets SK1 and SK4. The meter should read 12V when the relay is closed, and zero volts when it is open. Switch the supply off.

Check that the meter reads about 43 ohms across the input sockets SK1 and SK3. This ensures that the relay is switching the two inputs to the input transformer.

METER AND FIELD CHECK

Connect up the detector bottles and turn the supply on again.

If an oscillator is available, make a loop of wire across its outputs and set it near the end of one of the bottles.

Turn up the amplifier gain control slightly and a loud note should be heard in the headsets if the oscillator is adjusted between 2,000Hz and 2,500Hz. At this frequency turn up the meter gain control until the meter reads about half scale. Turn the oscillator off whereupon the note should disappear, and the meter needle fall to zero.

Switch S2 to “Auto”, the coils will now be energised each time the relay is closed. This can be checked by holding a compass near each one and seeing that a field is produced.

No further testing can be carried out indoors. The unit must be taken to some spot at least a quarter of a mile from all wires, buildings, and possible sources of electrical or magnetic interference and ferrous junk.

TUNING

The resonant circuits have now to be tuned to the exact precession frequency produced by the earth’s field at the site chosen for the test. This will be between 2kHz and 2.5kHz.

Once so tuned the magnetometer can be used within a radius of a hundred miles or so of the test site. At greater distances the tuning should be checked, and corrected if necessary.

The staff with the bottles should be set with the bottle axes pointing east-west, that is the staff points north-south (see Fig. 4). The chassis should be somewhere along a line east-west through the middle of the staff.

With S2 switched to “Manual”, turn the audio gain full up. There should only be some noise in the headset, and no trace of oscillation. Now turn the gain down to about half.

Place a pound mass of iron - pair of piers or hammer - about two feet below one of the bottles and switch S2 to “Auto”.

QUAVERING NOTE

A note with a marked quaver should be heard on the “detect” portion of the relay cycle. Adjust the gain to give a convenient output in the headset.

Vary the distance between the iron mass and the bottle until the note peaks about five times during “detect”.

Try going up or down a few preferred values on the tuning capacitors to get the loudest signal. Then fine tune by adjusting the tuning core in the ferrite cores. If the gain of the meter circuit is turned up the meter should follow the amplitude of the detected signal, the height of the peaks shown falling over the detect period.

All is now in order, heave a sigh of relief, the magnetometer is ready to go to work.

USING THE MAGNETOMETER

It is probably obvious by now how the device can be used. The area to be searched should be traversed, moving so that the coil axes point east-west; this gives maximum sensitivity.

Move fairly slowly, remember that it takes six seconds for one polarise and detect cycle, so do not overshoot small objects.

Alternatively, walk a couple of steps, let the device cycle and then move on a few more. Once something is detected, move around until the quaver reaches its fastest, when the “something” should be somewhere beneath.

DETECTION CAPABILITY

The size of that something and how far down it is will only be resolved by digging. As a rough and ready guide as to what to expect, a one pound mass should be detectable at about five feet below one of the bottles, and a one ton mass at around forty feet.

Size, distribution of metal and the attitude of the object all affect the magnetometer's ability to detect it; the best way to evaluate its performance is by experiment with a number of different objects.

In Fig. 17 is shows the traverse pattern that should be employed for overland searches.

When working from a boat it is simpler to keep the bottles near the surface, rather than make an elaborate underwater housing to get it near the bottom. Using this method, some idea of a wreck size and depth can be more easily estimated. A typical arrangement for aquatic search purposes is given in Fig. 18.

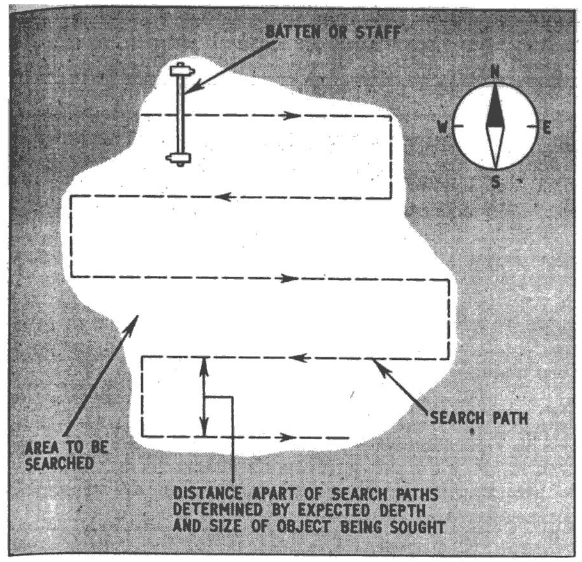


Fig. 17. Search pattern that should be followed when using the magnetometer

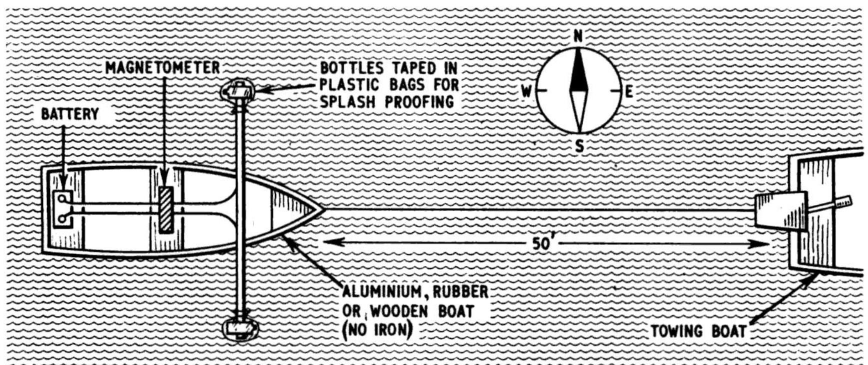


Fig. 18. Arrangement of magnetometer equipment in a boat