Biofeedback Monitor

Investigate your brain's Alpha, Beta and Theta waves or just learn about instrumentation amps.

ANDY FLIND

A biofeedback system is normally used to make some normally imperceptible body function apparent to its user, often so that it can be strengthened or suppressed. The GSR (Galvanic Skin Response) monitor, which measures skin conductivity, is quite well-known. Skin surface resistance rises during relaxation, so someone who learns to increase skin resistance is in fact reducing stress.

Similarly, migraine sufferers have been taught to increase the temperature of their palms, as resulting changes in blood flow can apparently alleviate the headache. The ultimate objective for most amateur enthusiasts, however, is the construction of an EEG (for Electro-EncephaloGraph) brain-wave monitor.

EEG

The study of EEG patterns is a relatively new science. The presence of various electrical signals within the brain was first discovered in 1924 by a German scientist, Hans Berger, now generally regarded as the father of the art. Berger discovered Alpha and Beta waves with the aid of electrodes placed on the head of his son, Klaus.

Use of this knowledge was limited for many years simply to clinical diagnosis. In 1958, however, an American psychologist, Joe Kamiya, began experiments to discover whether subjects connected to an EEG machine could learn to increase production of various brain signals, especially alpha, and so the use of the EEG as a true biofeedback tool began.

In American simple, inexpensive EEG training machines were promoted as a way to instant Nirvana. Sadly, it seems they cannot achieve this for their users, but there is little doubt that Alpha training through biofeedback can assist the attainment of deep relaxation. This is valuable by itself in these stressful times, and for some it may prove a springboard into deeper meditation and spiritual progress.

Brain Activity

The brain produces various frequencies of electrical activity, most of which have been classified and named by researchers. The best known is the Alpha rhythm, about 7 to 14Hz, normally produced when the subject is awake but relaxed with eyes closed. Below this are Delta, 4Hz or less, found in sleep and in babies up to about a year old, and Theta, 4 to 7Hz.

Theta is attracting some attention, as training in it has enhanced visualization and creative abilities for some subjects. It has also been detected in some Zen masters during deepest meditation. Beta, from 14Hz upwards and usually strongest around 20Hz, is indicative of normal conscious activity. You will be producing Beta right now as you read this article.

By means of electrodes on the scalp, all these electrical signals may be detected, and displayed to the user. The only difficulty is that they are of very low voltage, typically 5 to 20 microvolts, and most users will be trying to detect them in the presence of several volts of induced 60Hz AC powerline hum.

Electronics

Until recently the electronics design was difficult, as the amplifier required a high input impedance coupled with a very low noise figure. Noise is a problem at low frequencies. Below the audio spectrum the noise generated by most semiconductors increases dramatically and op amps such as the 741, and many discrete transistors, are quite useless for the task.

One wonders how Berger coped all those years ago. Apparently he used a type of galvanometer, without benefit of amplification at all. Recently, however, the appearance of specialized low- noise op amps such as the OP-07 has made it possible to produce a simple and effective EEG monitor design for home construction.

Instrumentation Amplifier

A block diagram of the Monitor is shown in Fig. 1. The first stage is an instrumentation amplifier with a voltage gain of a thousand and a very high rejection of unwanted common-mode signals such as hum. This is followed by a notch filter to remove remaining traces of 60Hz noise, and an opto-isolator. This provides a safety if the project is coupled to mains-driven equipment such as computers or amplifiers. **With electrodes sited on the user's head safety is obviously of paramount importance.** At the same time, the isolation prevents possible entry of hum through the output. This part of the circuit is assembled on a separate PCB and carefully shielded in the finished assembly.

With the minute EEG signals now raised to useable levels and stripped of mains hum, the remaining circuitry, on a second PCB is concerned with processing and output. Three filters extract Beta, Alpha and Theta signals, which are available simultaneously. They could be interfaced to a computer for graphical screen presentation, though there are obviously many interesting possibilities. A switch selects one of them to control a VCO, for an audio output on headphones. The VCO is driven either directly or through an integration circuit that gives an output corresponding to average level. Users will quickly establish their own preference from these two outputs.

For readers not familiar with the instrumentation amplifier used for the input, a simplified diagram appears in Fig. 2. It consists of three op amps. A voltage common to both inputs will appear, unamplified, at the outputs of both A1 and A2. A voltage applied to one input appears, with a gain of (Ra+Rb)/Ra, at the output of the appropriate amp. However, the current drawn through Ra will cause an almost equal but opposite output to appear at the output of the other amp.

These signals are combined in A3, a unity-gain differential amplifier circuit. The output from this is the difference between its inputs, voltages common to both being rejected. This configuration provides differential amplification, very high rejection of common-mode signals, high input impedance (since both signals go to op amp non-inverting inputs), and a potentially high gain of, approximately, (Ra+2Rb)/Ra. The circuit is often seen in industrial applications such as electrometer amplifiers. In this project the use of OP-07 amplifiers gives the additional advantage of very low noise.

Circuit — Front End

The full circuit for the front-end board is shown in Fig. 3. The instrumentation amplifier consists of IC1, IC2 and IC3. This is similar to Fig. 2, but the inputs are AC-coupled through C1 and C2 with extra protection provided by R1 and R2. High frequency rolloff is introduced by C3 to C6 to reduce gain at unwanted frequencies. R3 and R4 provide input bias, VR1 allowing adjustment to compensate for op amp offset voltages. VR2 trims for maximum common-mode rejection.

Remaining traces of 60Hz hum are then removed by the filter constructed with dual op amp IC4. This is a modified twin- T notch filter, with active feedback to the common point to sharpen the notch. Clamp diodes D1 and D2 prevent overload of the output stage IC5, an op amp which drives opto-isolator IC6. To avoid overloading the auxiliary negative supply this stage draws all its power from the positive rail.

A split supply of plus and minus 5 volts is provided for this circuit. In order to avoid a multiplicity of batteries, the output of a single 9-volt is first reduced to 5 volts by regulator IC7, then the negative supply is generated by IC8, an ICL7660 negative converter chip.

Circuit — Signal Processing

The second, signal processing part of the circuit is shown in Fig. 4. The input is developed across R1, a 470 ohm emitter load for the opto-isolator transistor. The isolator specified has a transfer ratio of about 100 percent, so in this circuit the output across R1 will about equal the input. The raw signal appears at a socket, for connection to other equipment if required. VR1 controls overall gain and is followed by buffer IC1a, one of four amplifiers in a TL064 IC The other three form two-pole bandpass filters, with Q factors of about 6.5, and center frequencies of 19.9, 9.8 and 5.4Hz for a selection of Beta, Alpha and Theta respectively.

Although EEG circuits often use a single filter with switchable frequency, there is little extra complication in providing three separate filters. The outputs are available simultaneously for recording and experiments, and switch connections are simplified. If the filter capacitor values are reasonably small some of the associated resistors will have high values, so the TL064 with FET inputs was picked for the amplifiers.

Outputs

A project intended for relaxation training should not sound harsh to the ear. The output from this circuit is a low hum, with pitch varied by the input signal. This is produced by the VCO IC3, a CMOS 4046B phase-locked loop. As the VCO output is a squarewave, the harsher components are filtered out by R23, R24 and C13, C14 before it goes to output amplifier IC4. This is a 741 op amp, which is quite capable of driving headphones at a reasonable level, especially the miniature type intended for use with personal stereos.

The filter outputs can drive the VCO either directly, or through the average level circuit around IC2, giving an output pitch that rises with overall input

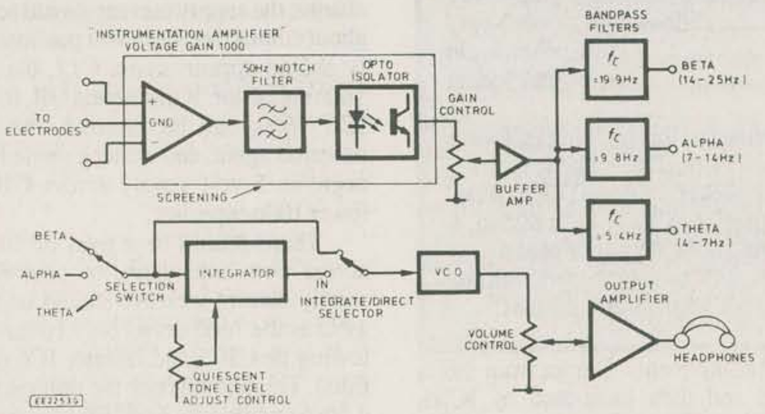


Fig. 1. Block diagram of the EEG Biofeedback Monitor.

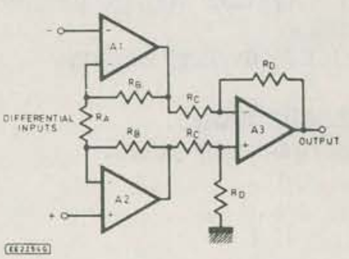


Fig. 2. Simplified diagram of an instrumentation amplifier.

Parts Lists

Front-End P.C.B.

Resistors

R1,2,20,25	10k
R3,4,23	1M
R5,6,10,11,13,22	100k
R7	1k
R8,9	560K
R12	47k
R14,16	3M9
R15,17	150k
R18	120k
R19	180k
R21	22k
R24	39k
R26	470

All metal film, 0.5W 1%

Potentiometers

VR1 100 min. hor. trim
VR2 100k min. hor. trim

Capacitors

C1,C2,C11	1u polyester
C3,C4	1n polystyrene
C5,C6	2n2 polystyrene
C7 to C10	22n 1% polystyrene
C12	1n polystyrene
C13	1000u 10V
C14,C15	100n polyester
C16	10u 25V
C17,C18	100u 10V

Semiconductors

D1,D2	1N4148 silicon diode
IC1 to IC3	OP-07C op amp
IC4	LM358 dual op amp
IC5	TLC251 LIN-CMOS op amp.

IC6 High sensitivity, high voltage opto-isolator (Maplin order code RA57M).
IC7 uA78L05 100mA positive regulator.
IC8 ICL7660 voltage convertor.

Miscellaneous

PCB; 7 x 8-pin DIP sockets.

Processor P.C.B., Case and Controls

Resistors

R1	470
R2,6,25,26	1M
R3,4,14,18,23	10k
R5	5k6
R7	12k
R8	2M2
R9,12,13	22k
R10	3M9
R11,17,20,21,24,28	100k
R15,16,22	47k
R19	150k
R27	4k7
R29	100

All metal film, 0.5W 1%

Potentiometers

VR1,VR3	10k log.
VR2	10k lin.

Capacitors

C1,10,13	1u polyester
C2-7,11,14,15,20,21	100n polyester
C8,12	10u 25V
C9,16	1u 63V
C17	1n ceramic plate
C18,19	100u 10V
C22	470u 10V

Semiconductors

D1,D2	1N4148 silicon diode
IC1	TL064C quad J-FET op amp.
IC2	LM324 quad op amp.
IC3	4046BE CMOS PLL
IC4	uA741 op amp.

IC5 uA78L05 5V 100mA positive regulator

Miscellaneous

S1	rotary switch, 3-pole 4-way
S2	slide switch, 1-pole 2-way
SK1	DIN socket, 5-pin
SK2	stereo jack socket

PCB; material for shielding PCB (see text); 2 x 14-pin DIP sockets; 1 x 16-pin DIP socket; 1 x 8-pin DIP socket; case, plastic box 190 x 110 x 60mm; 4 x control knobs; 4 x phono chassis sockets; 2 9V battery holders with connectors; silver sheet etc., see text.

amplitude. To avoid a rather lumpy output at the very low frequencies involved, the level detector is not the usual half-wave arrangement. Instead an absolute-value circuit is used, consisting of IC2a and associated components. Output from this is buffered and then integrated by IC2d. IC2c and VR2 provide a variable reference for threshold adjustment. In use it sets a level which the signal must exceed before the output pitch starts to rise.

This part of the circuit has its own power supply, both for safety isolation and to prevent the possibility of feedback through the power rails. With the exception of IC2 and IC4, everything operates from the 5-volt regulator IC5.

Construction — Front-End, PCB

Construction should commence with the assembly of the front-end PCB. The component layout for this is shown in Fig. 5. Both PCBs are lengthened in order to fit into the moulded slots of the specified plastic case. For different arrangements they could be trimmed short, but this should only be altered by constructors who are confident that they understand the shielding requirements.

For ease of construction, the routine of fitting the components in order of physical height should be followed. There are two links on this board. Sockets are recommended for all chips except 7, to avoid undue handling of the devices themselves and to assist testing and adjustment. Note that ICs 5 and 8 are CMOS devices so the usual precautions should be observed.

The resistors should all be one percent metal film type; these are now standard from most suppliers. Other types may result in impaired noise or hum rejection performance. The four 22n capacitors in the hum filter, C7 to C10, are 1% tolerance types instead of the usual 5%. Although opto-isolator IC6 is a 6- pin device and 8-pin socket is used as 6-pins are rare. IC6 is fitted at the top of this socket.

Front-End Checking

The front end PCB can now be checked and adjusted. It should first be powered without ICs save for regulator IC7. Following a brief surge as the electrolytics charge, the supply current should settle to about 2.5mA. and the 5 volt positive supply should appear across C17, the upper 100u capacitor. If this seems OK, IC8, the ICL 7660, can be inserted, the board powered again, and a check made for the negative 5 volt supply across C18, the lower 100u capacitor.

There should be a total of 10 volts across both capacitors, of course. The supply current increase should be negligible as the 7660 draws only 100uA. Following this, IC5 and isolator IC6 can be fitted. This should raise the drain to about 4.5mA, while pin 2 of IC6 (center, left-hand side) should have a potential of 1V.

If all seems well so far, the two inputs at the left-hand side of the board should be

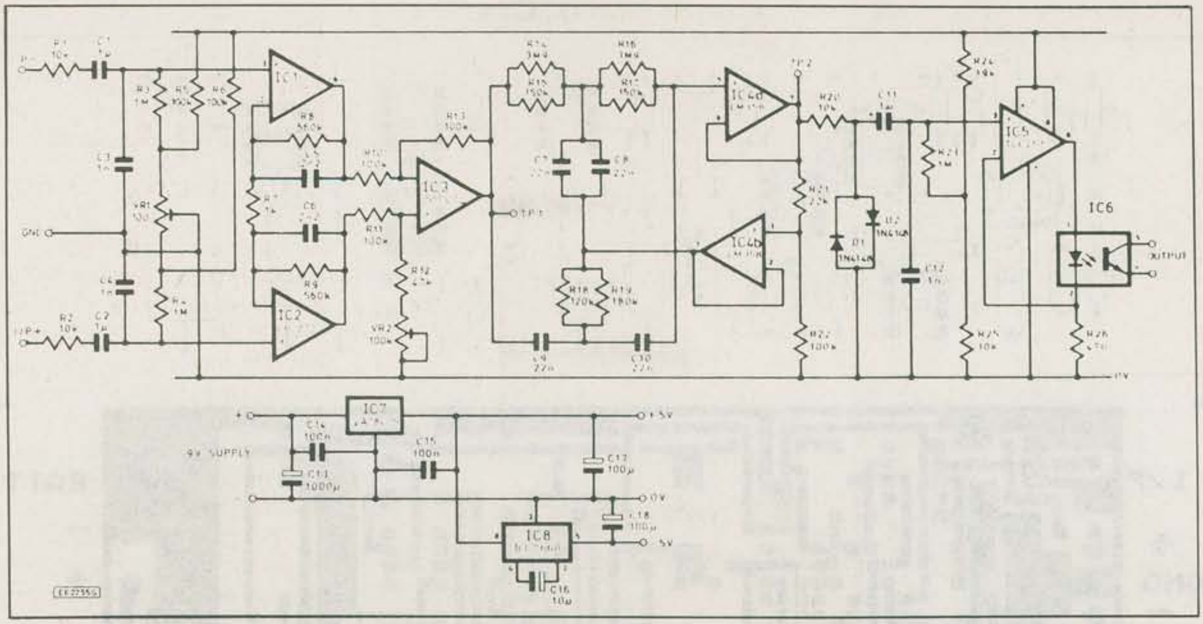
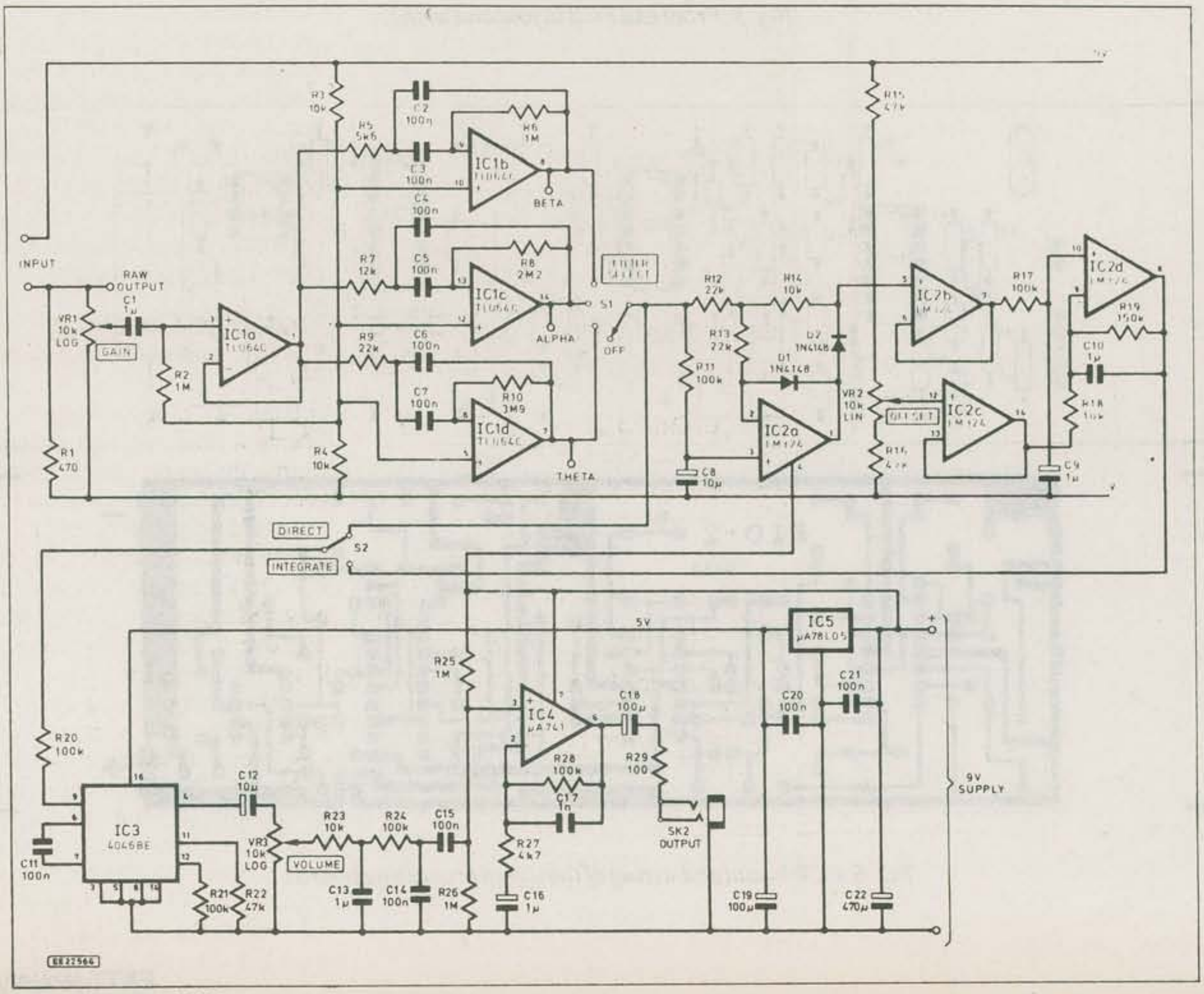


Fig.3. Circuit diagram of the "front end" of the EEG Monitor.

Fig.4 Circuit diagram of the signal processing section of the Monitor.



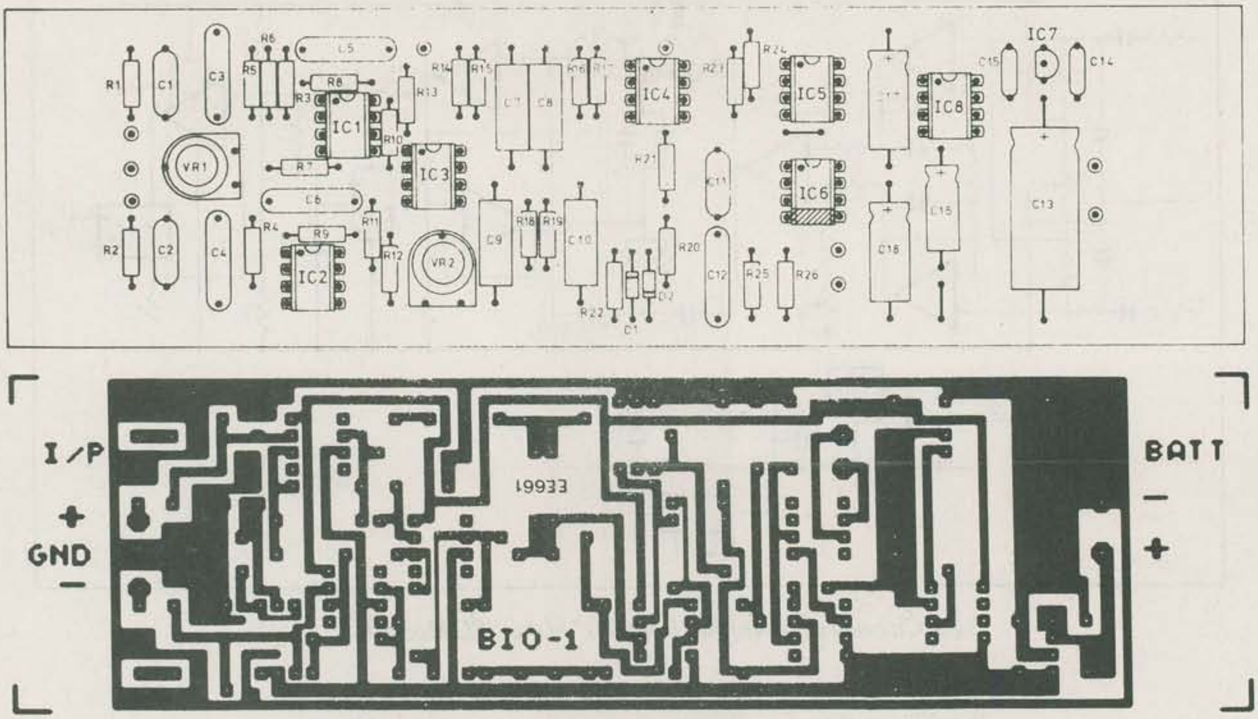


Fig. 5. Front end PCB layout and wring.

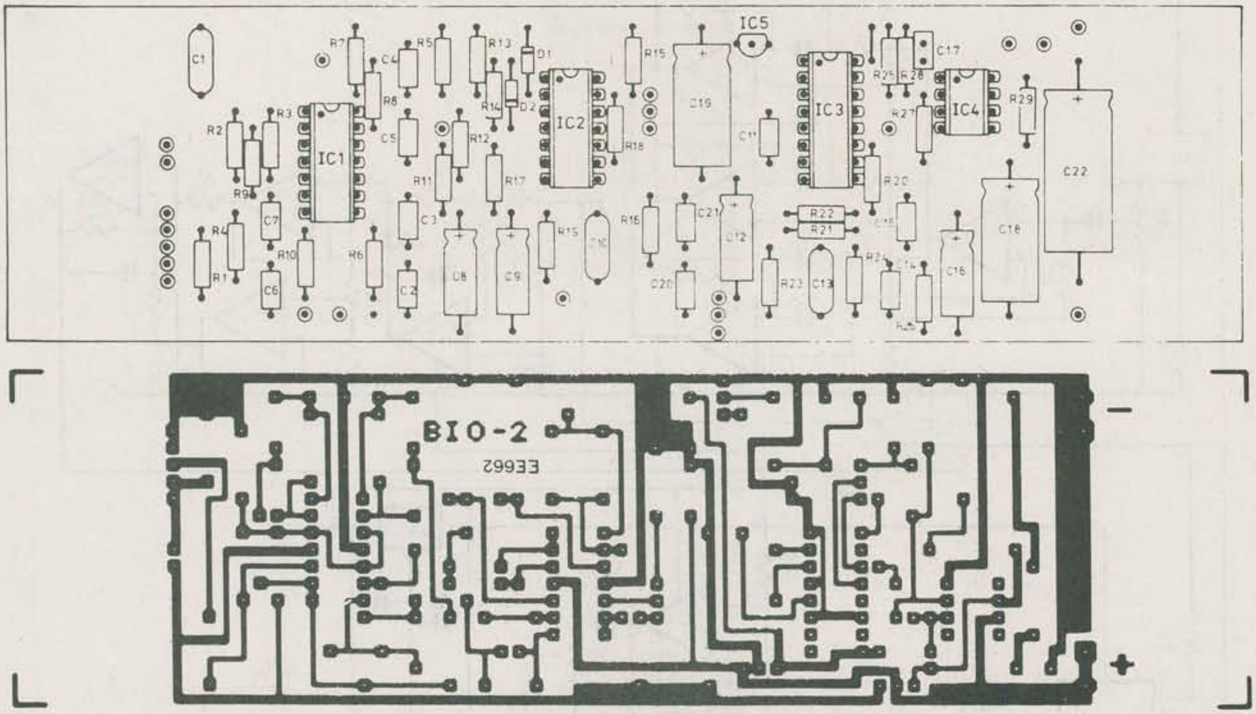


Fig. 6. PCB layout and wiring of the signal processing board.

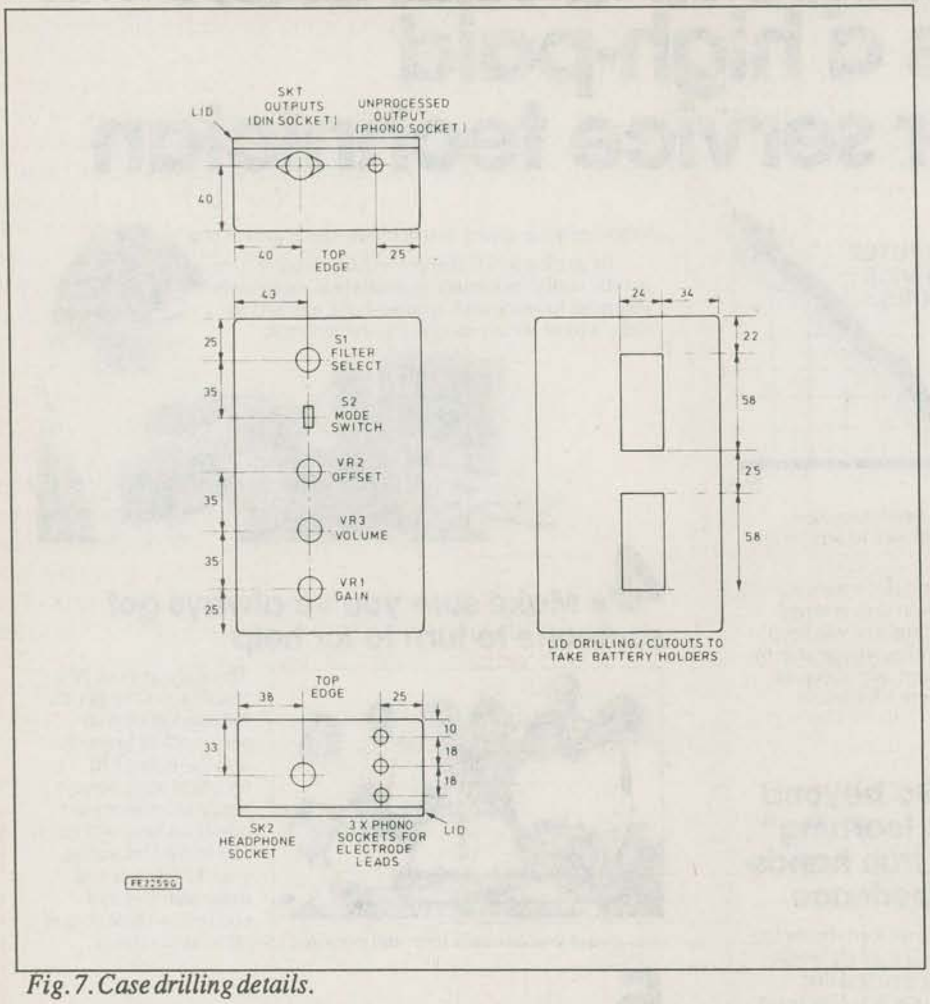


Fig. 7. Case drilling details.

shorted to the ground point between them, the 100ohm trimmer VR1 set to about half-travel, and the first two OP-07s, IC1 and IC2 inserted. This will raise the supply current to about 7.5mA. Their output voltages (pin 6) can be checked, and the effect of VR1 noted. It should be possible to zero both outputs with VR1, though allowance should be made for the slow response. (This check initially failed on the prototype, revealing a faulty OP-07).

After this IC3 can be fitted, raising the current to about 9.5mA. With a meter connected to test point 1, IC3 output, VR1 should be carefully adjusted for zero voltage. Inserting IC4 should raise the supply current to the final value of about 10.5mA, and the test point 2, IC4a output, should also be at 0V.

A fairly tricky adjustment follows, the setting of VR2 for best hum rejection. To avoid problems of spurious hum pickup during this adjustment the board should be placed on an insulated conductive surface, to which its ground rail must be connected. A sheet of kitchen foil overlaid with cardboard will suffice. The inputs should be disconnected from ground but coupled together and a 60Hz input applied to them.

If a signal generator is available this input should be about one volt RMS — if not, a finger placed on them will probably inject about the right level in most workshops. A means of monitoring test point 1 is required, ideally an oscilloscope, though a millivoltmeter will do. Most DVMs have a suitable range (no serious constructor today should be without one). VR2 should be trimmed for minimum AC output at the test point. If the optimum adjustment is difficult to find, hum is probably still being induced into the circuit from some external source.

This adjustment proved almost impossible on the prototype until the grounded conductive sheet was set up as described, when it became easy. If a scope and generator are available, test point 2 can be monitored while the frequency is varied and the effect of the filter observed, although this is not essential. A final check on the adjustment of VR1 is advisable.

The completed front-end PCB may be used on its own for experiments if desired, though the comments on shielding, given in the description of final assembly, should be noted.

Construction — Second PCB

Assembly of the second PCB is simpler than that of the first. The layout is gien in Fig. 6. Again the sockets should be used for the ICs, and CMOS handling precautions observed for IC3. Since testing requires most of the controls to be connected, it is as well to complete it and assemble the entire project into the case, an ABS box, size 190 X 110 X 60mm, before commencing.

As the layout is fairly compact full case drilling details are given in Fig. 7. The layout of controls, sockets and PCBs is shown in Fig. 8, while their connections appear in Fig. 9. The Delta/Alpha/Theta switch S1 has a fourth position, Off, which controls battery supplies to both printed circuit boards. The front-end PCB has shields placed to either side and connected to the input ground point. Spare pieces of PCB material, with the copper facing outwards, are ideal, but suitably insulated sheet metal or even stiff card and kitchen foil could be used.

Note that when boards and controls are placed as shown, there is room for the two snap-in battery holders to fit between them. Four stick-on rubber feet keep these holders clear of surfaces on which the unit is placed.

Testing — Second PCB

Testing of the second PCB can proceed as follows. First it should be powered up by itself, without ICs except for the regulator IC5. Following an initial surge the supply current should settle to about 5mA. The presence of 5 volts across C19 can be checked. IC4 should now be fitted, raising the drain by a couple of milliamps. With a 9 volt supply the voltage at IC4's output, pin 6, should be about 4.5 volts.

If the headphones are connected and a finger placed on the bottom of the 100n capacitor C15, a loud hum will probably be heard. The same finger on the top of the 10uF capacitor C12 (or pin 4 of IC3's socket), should cause a softer hum, adjustable with volume control VR3. IC3, the 4046B chip, can now be fitted and S2 switched to integrate. This should produce a horrible noise, half hum and half tone. Connecting pin 8 of IC2's socket to negative supply should produce a clear, steady, low frequency tone, while taking it to the 5 volt positive supply will result in a higher tone, slightly more than an octave up.

Next the TL064, IC1, can be fitted, and

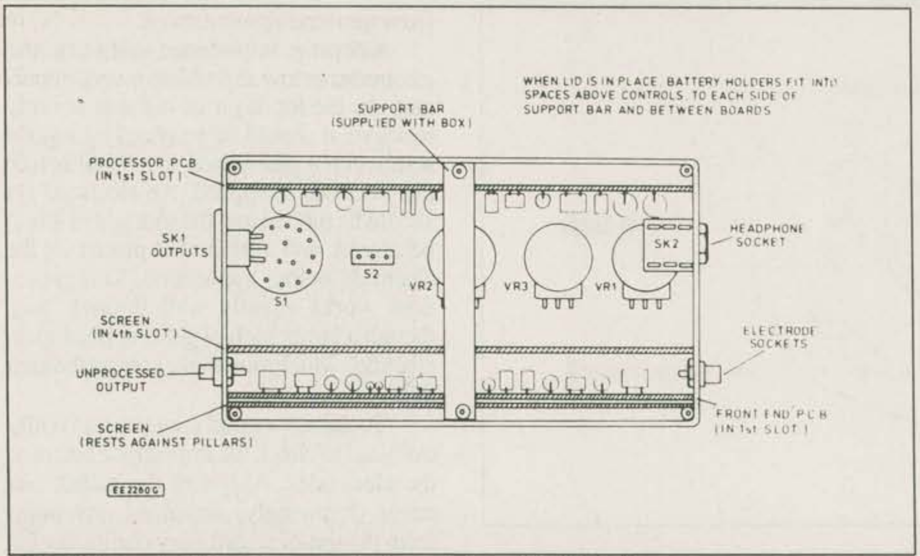


Fig. 8. Layout of the various controls, sockets and PCBs in the case.

S2 set to direct. All three on positions of the selector switch S1 should produce clear, steady tones. IC1's outputs, pins 1, 7, 8 and 14, should be checked as being about 2.5 volts; being the four corner pins they're easy to locate. Touching the top of 1u capacitor C1 to +5 volts on any range should produce a sharp rise in pitch, followed by a return to the original output tone during which ringing at the selected Brainwave frequency should be clearly audible.

Finally IC2, the LM324, can be fitted, S2 set to integrate, and the effect of offset control VR2 tried. About halfway around its travel this should start to increase the output frequency. Set just below this point, a finger touched to the top of C1, to inject hum, should produce a rise in pitch. The total current drawn by the complete board should be around 7 to 8mA, though this will depend to some extent on output volume.

Finally, the front-end board should be powered, the gain control VR1 turned right down, and the voltage across R1 (and VR1) checked as being about one volt DC. If the circuit is set to integrate, advancing VR1 should cause a rise in output pitch as noise finds its way into the open-circuit inputs. A finger placed over them should increase this output. The final supply current drawn by the output board should be about 10mA, the increase being due to the current drawn by the opto-isolator and R1.

The project is now operational and can be put to use as soon as suitable electrodes have been prepared.

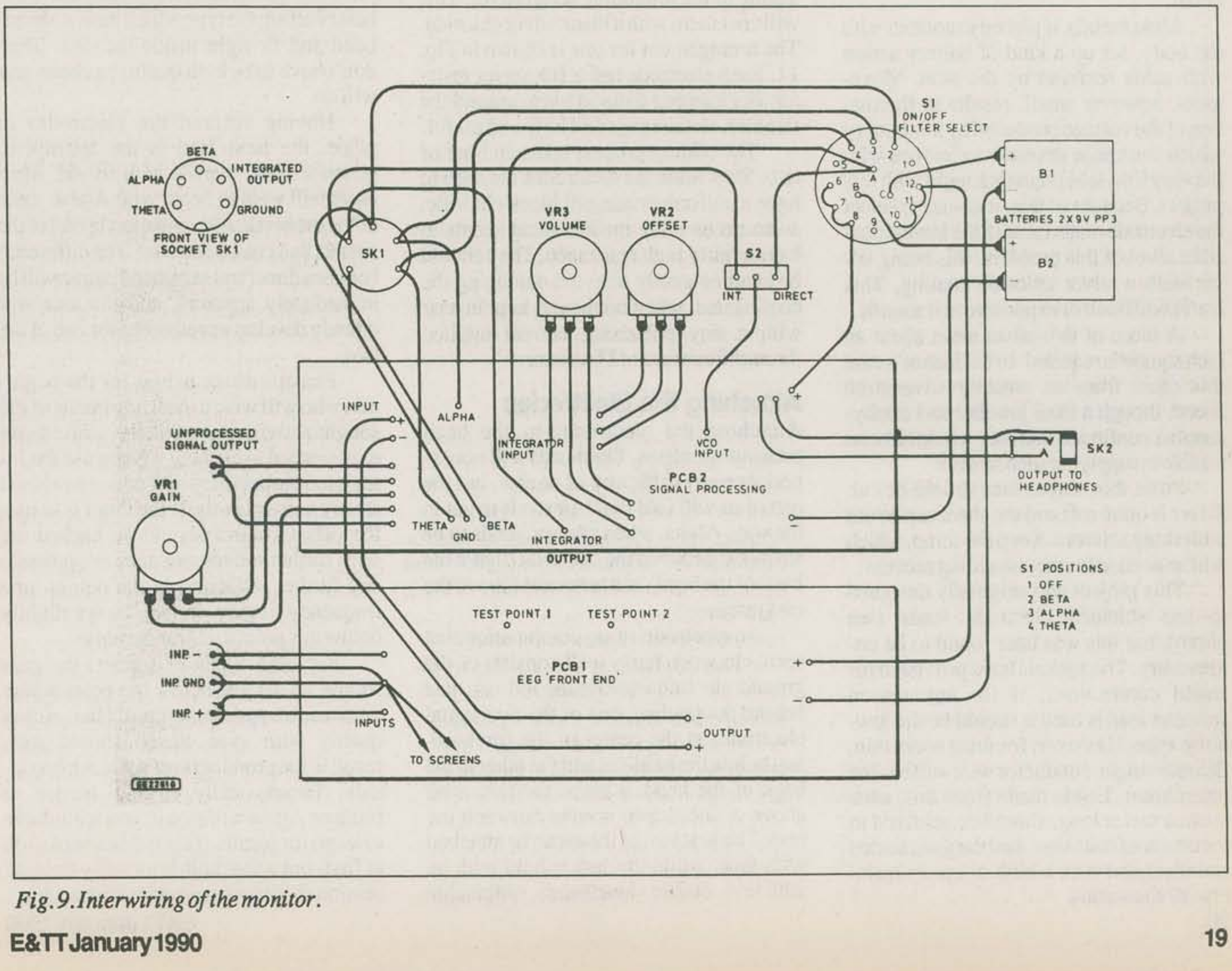


Fig. 9. Interwiring of the monitor.

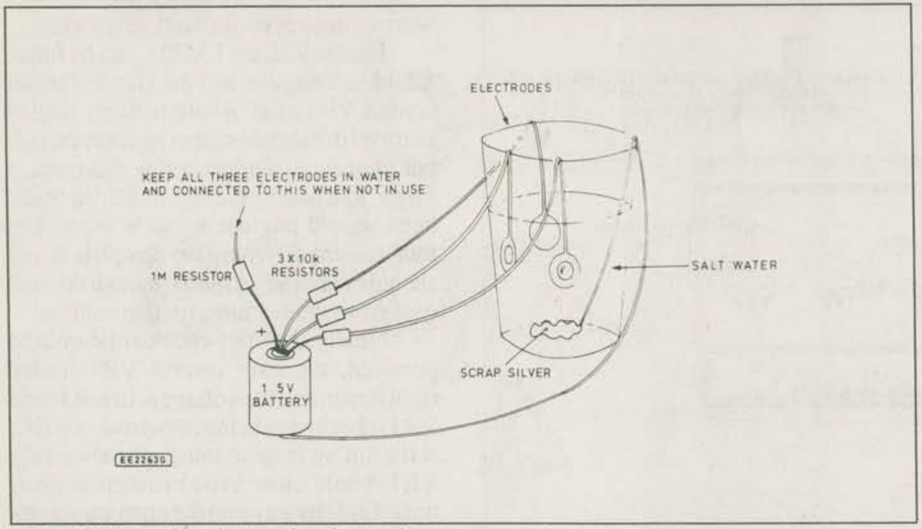


Fig. 10. Setup for plating the electrodes.

Electrodes

A large factor in the successful operation of this project is the manner in which its electrodes are made and used. It follows that considerable care should be taken with these, so they will be covered in some detail.

Most metals, if placed in contact with the body, set up a kind of battery action with acids secreted by the skin. Movement, however small, results in fluctuation of the voltage produced by this battery which can cause severe interference with the very low-level signals sought with this project. Because of this, it is wise to select the electrode material with the lowest possible level of this problem, this being silver with a silver chloride coating. This isn't as difficult or expensive as it sounds.

A piece of thin silver sheet about an inch square is required. In the author's case this came from an amateur silversmith friend, though a local jeweller and trophy-supplier confirmed that they would have no trouble in supplying such an item.

From this, three discs should be cut. Silver is quite soft and the sheet can be cut with sharp scissors. Keep the scrap, which will be needed for the chloriding process.

This project was originally designed to use shielded electrode leads (see photo), but this was later found to be unnecessary. The sockets have provision for shield connections; if for any reason shielded lead is used it should be the low-noise type. However, for most users thin, flexible single-conductor wire will be fine (see photo). Leads made from this, each about a metre long, should be soldered to the center of each disc, and the joint sealed and insulated with a blob of epoxy resin. Fig. 10 shows this.

The other side of each disc should be thoroughly cleaned before the chloriding process. This consists of placing them in a tumbler of water containing a teaspoon of dissolved salt, and passing a small current through them to a common electrode consisting of the remaining scrap silver. This will coat them with a black silver chloride. The arrangement for this is shown in Fig. 11. Each electrode has a 10k series resistor. For keeping them in place around the tumbler, clothes pegs will be found useful.

The plating process takes an hour or two. Stop when the electrodes are seen to have a uniform coating of black chloride, as an excessively thick coating seems to have a fairly high resistance. They should be handled gently to avoid damaging the coating and, when not in use, kept in a jar with a tiny polarizing current applied through a common 1M resistor.

Attaching the Electrodes

Attaching the electrodes to the head presents problems. Skinheads will not experience any difficulty of course, but the rest of us will find that hair tends to get in the way. Alpha, when present, tends to be strongest between the occipital (that's the back of the head) and temporal (above the ears) areas.

An electrode siting combination that seems to work fairly well consists of the ground electrode below the left ear, just behind the jawline, one of the two signal electrodes at the center of the forehead, just below the hairline, and the other at the back of the head, a bit to the left, a bit above a line drawn around between the ears. The first two of these can be attached with tape, while the last is held with an athlete's elastic headband, obtainable from sports equipment shops.

Keeping impedance between the electrodes as low as possible is very important. As the top layer of the skin is fairly resistive, it should be prepared by a good scrub with a pad dipped in alcohol before the electrode is applied. An electrode gel should be rubbed into the spot where it is to be placed, and a blob of it placed on the electrode before application. This procedure works equally well through hair, though a larger blob of gel is applied to an electrode which must make contact through this.

To ensure a good contact, it is really essential to check the impedance between the electrodes. Although the author has never (knowingly) sustained any harm from the use of an ordinary ohmmeter for the job, this is not going to be recommended here.

In Use

Ordinary headphones can be used with this project, but may tend to get caught up in the electrode leads. The miniature type supplied for personal stereos are better, but best of all are the type which have no headband and fit right inside the ears. They don't have to be high quality; a cheap pair will do.

Having secured the electrodes in place, the next step is the attempt to generate some signals with its aid. Most users will wish to begin with Alpha, since this is the best known and most useful of the signals that can be detected. The difference between direct and integrated output will be immediately apparent, and the user will quickly develop a preference for one of the two.

Perhaps direct is best for the beginner, who will wish to hear any bursts of the sought activity immediately, while more experienced users may wish to use the integrated output to try to produce sustained steady output levels. If the latter is in use, the offset control should be backed off until further movement does not produce any further reduction in the output tone frequency. It may, in fact, be set slightly below this point to eliminate noise.

For both types of output, the gain should be set just below the point where noise causes spurious output. Then, sitting quietly with eyes closed should soon result in the production of some Alpha signals. Paradoxically, trying harder to produce Alpha will stop it; you really have to let go for results. This is quite hard to do at first, but a few half-hour daily training session should soon produce the knack ■