# A basic radio telescope

## Portable two aerial system for detecting the sun, milky way, and sources beyond the solar system.

**by J. R. Smith**

This radio telescope is a general purpose instrument that can be used for demonstration purposes, or adapted for specific observations as required. The units making up the receiver, excluding the pen recorder, can be carried in a briefcase and two aerials can be folded to pack on a car roofrack.

THE BASIC system operates as a phase-switched interferometer between 160 and 190 MHz where a clear space in the band can be found. It can also be used in the full power, Dicke, drift interferometer and beam switching systems which are described separately. Components preceding the i.f. amplifier can be replaced for operation on other frequencies as required. The instrument consists of several self-contained blocks which can be adapted for specific experiments. A single positive 12V supply is used to simplify portable operation, and a car battery will provide a stable supply voltage for two or three weeks. The total load current is about 55mA.

Both aerials were designed for 178MHz, although at present they are being used at 182MHz. In each aerial the reflector surfaces are of a cylindrical parabolic form consisting of parallel plastic-covered steel wires spaced at approximately 0.1 of a wavelength as shown in Fig. 1. Four flat panels of the reflector are placed to within 0.1λ of a parabola where $y = x^2/1.68$ m.

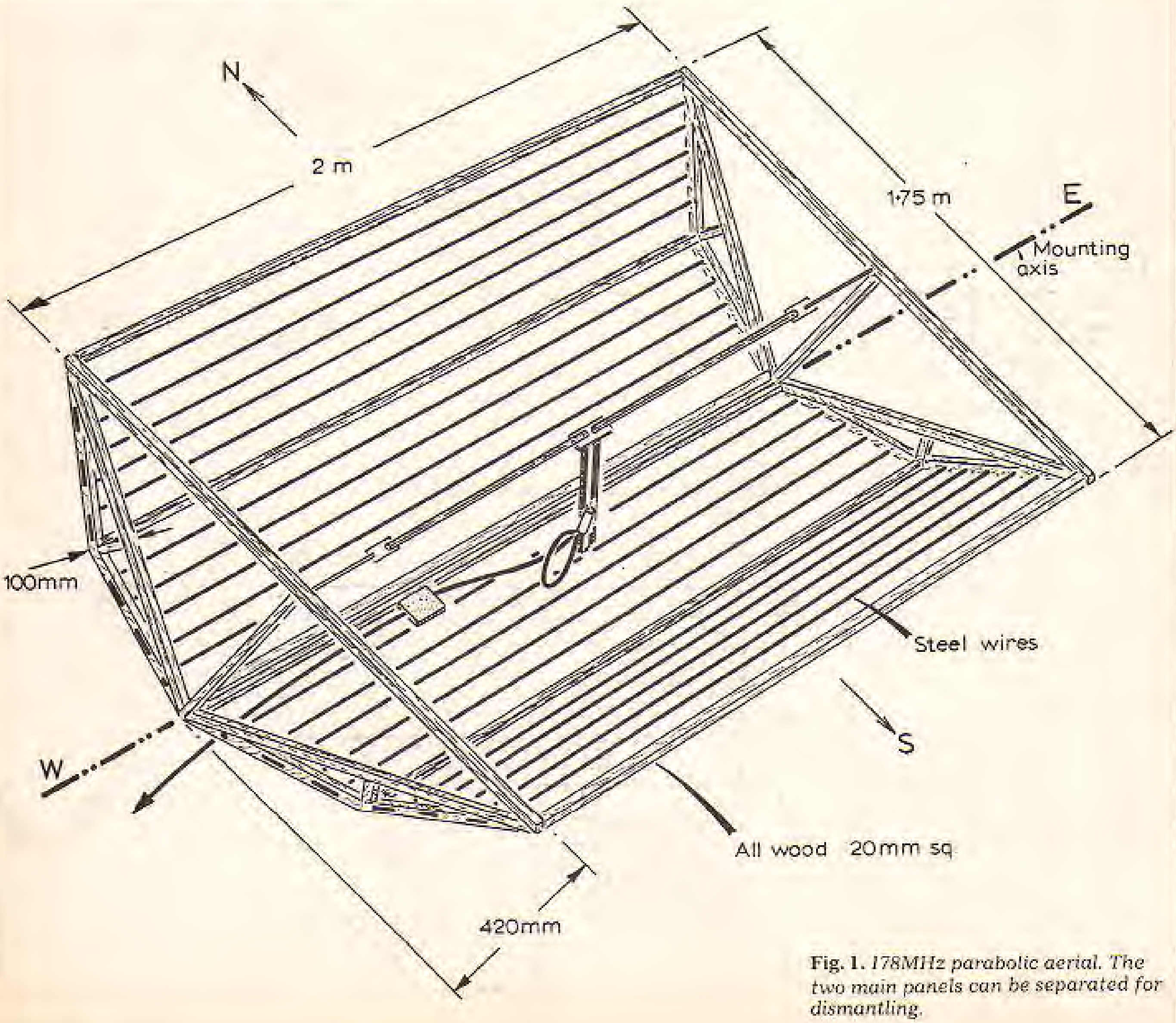


**Fig. 1.** *178MHz parabolic aerial. The two main panels can be separated for dismantling.*

R.f. switching is performed by series diodes as shown in Fig. 2. The coaxial plug arrangement permits the switch to be used as a selector between two signal inputs, or by the addition of a λ/2 length of coaxial cable, as a phase reversing switch. The two-pole, four-way switch permits phase reversal of the switching square wave, or locking of the diodes to assist in tuning and testing the complete system.

The aerial amplifiers in Fig. 3 are located as close to the aerials as possible to avoid degradation of the signal. A dual gate m.o.s.f.e.t. which is equivalent to a cascoded pair of transistors is used, and is resistant to cross modulation. Because these devices are susceptible to damage by voltage surges the input and output transformers are double wound and a zener diode is placed across the

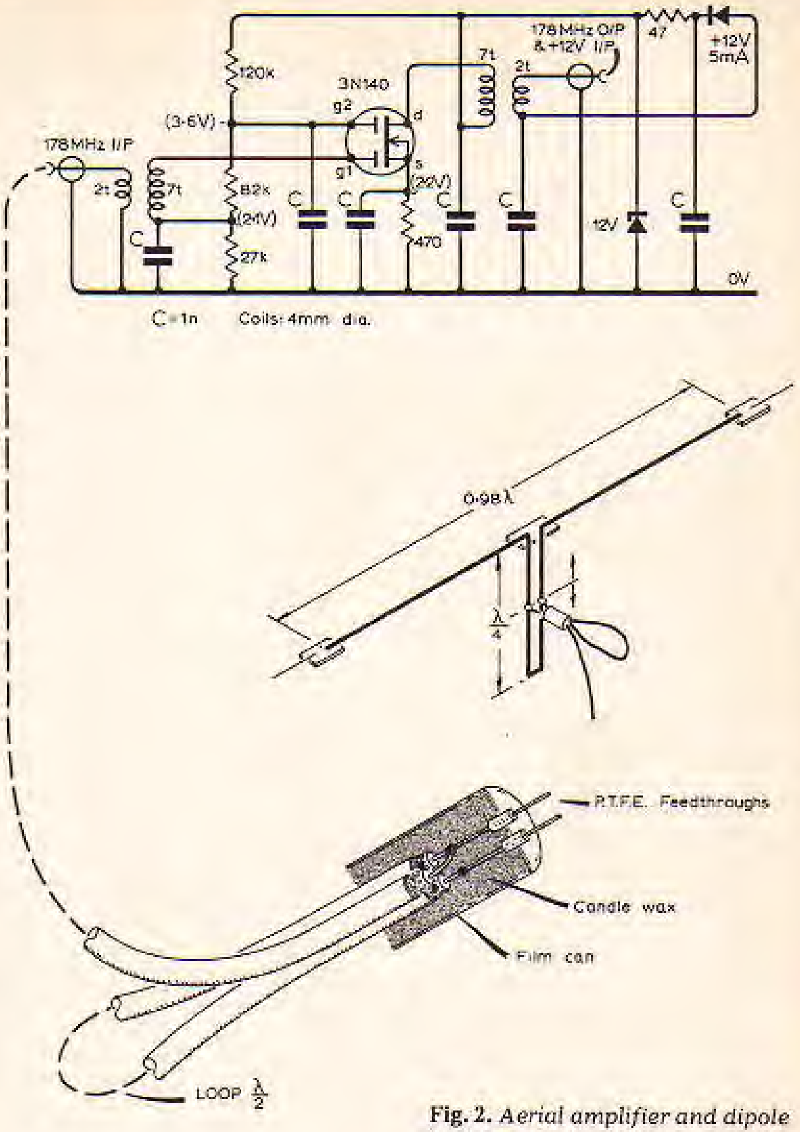


**Fig. 2.** *Aerial amplifier and dipole matching system.*

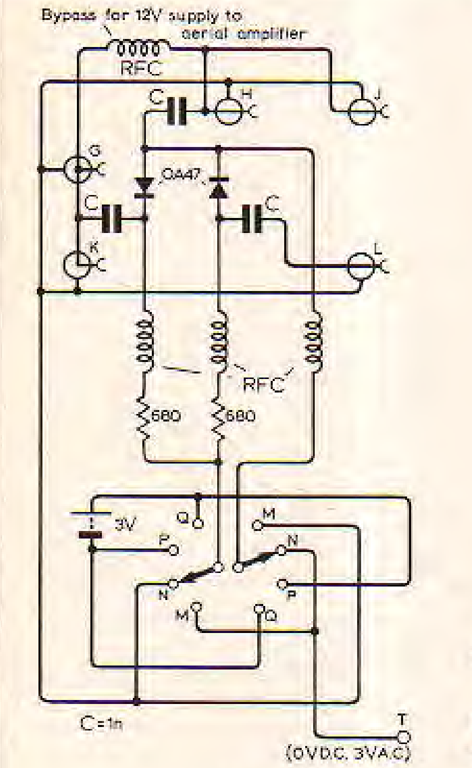


**Fig. 3.** *Aerial switch.*

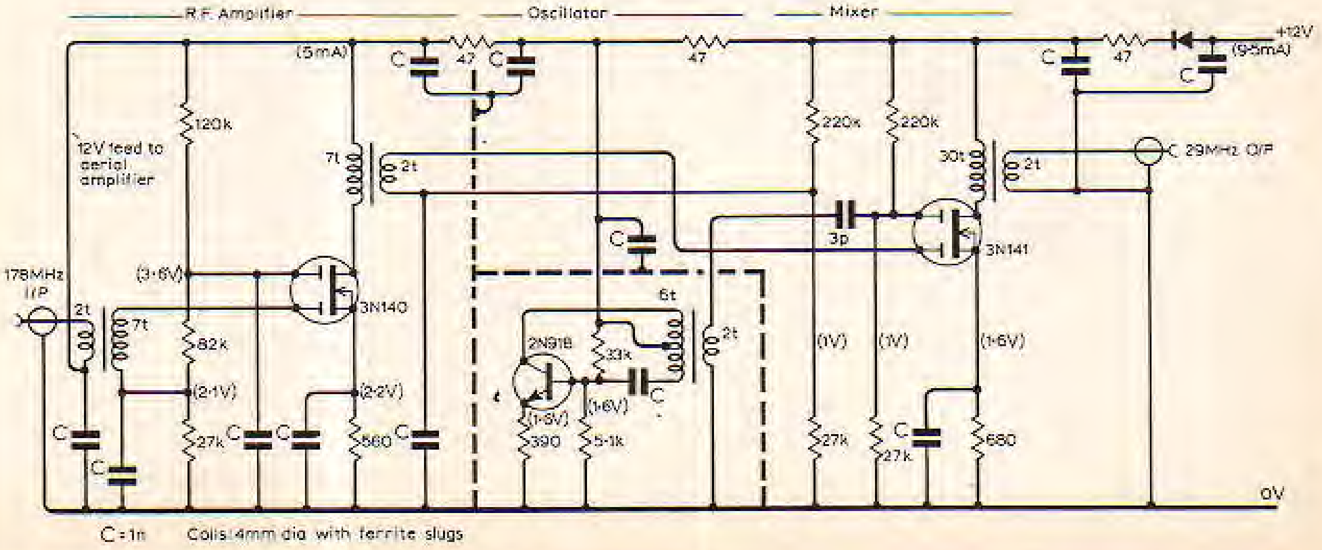


**Fig. 4.** *R.f. amplifier, oscillator and mixer.*

supply. A series diode protects the f.e.t. from reverse voltages.

The r.f. section in Fig. 4 is similar to the aerial amplifiers. A separate oscillator is used in the frequency changer, and mixing is performed by a dual gate m.o.s.f.e.t. Although a radio telescope for general purposes should have the widest bandwidth possible, it is difficult to find a clear space in the band. For this reason a narrow band filter consisting of three well-isolated parallel LC tuned circuits is used as shown in Fig. 5. Coupling is by capacitors of about 0.2pF made from two short pieces of wire twisted together. A single transistor amplifier is included to partly compensate for the insertion loss. The bandwidth is about 0.5MHz and the net

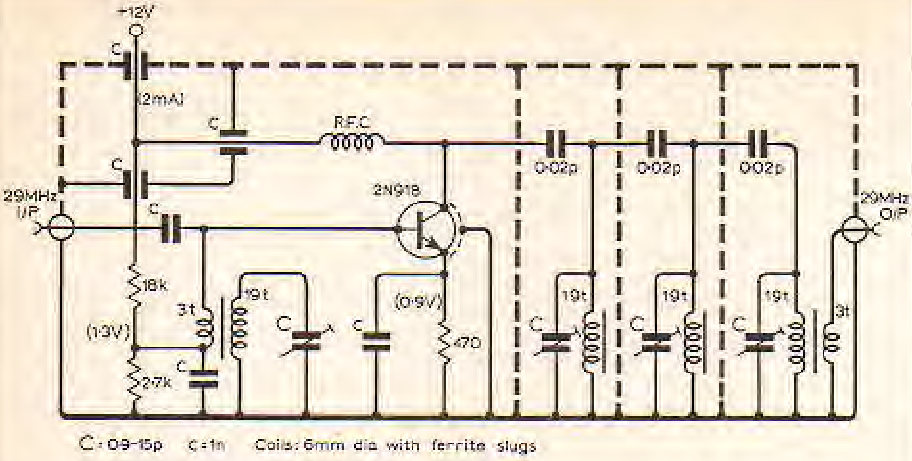


**Fig. 5.** *Narrow band i.f. filter.*

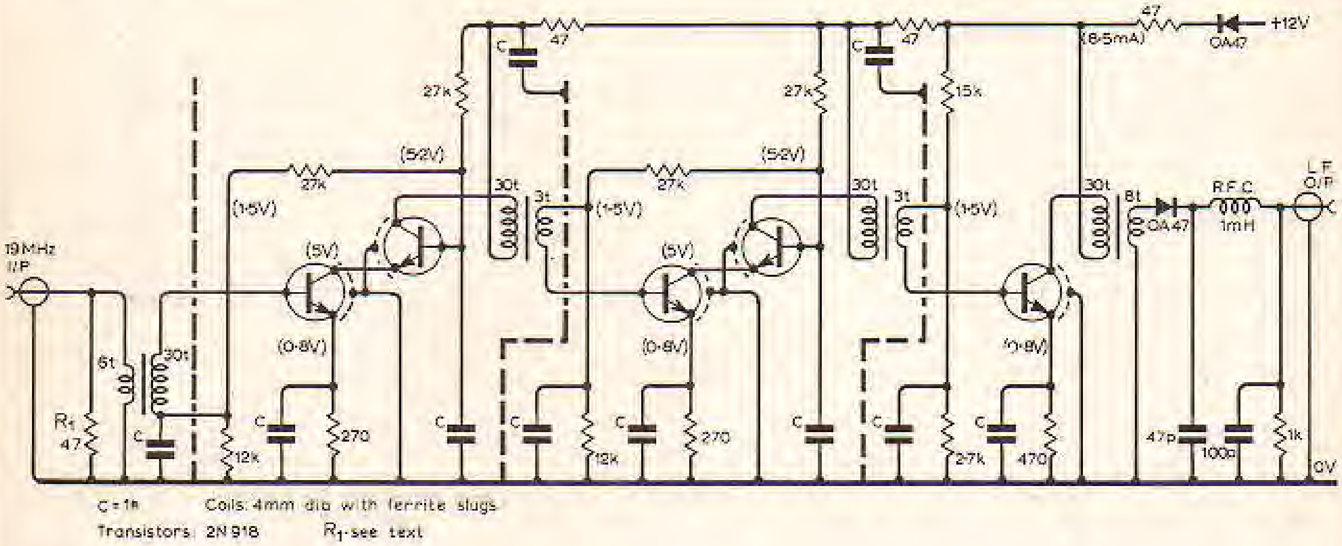


**Fig. 6.** *I.f. amplifier and detector.*

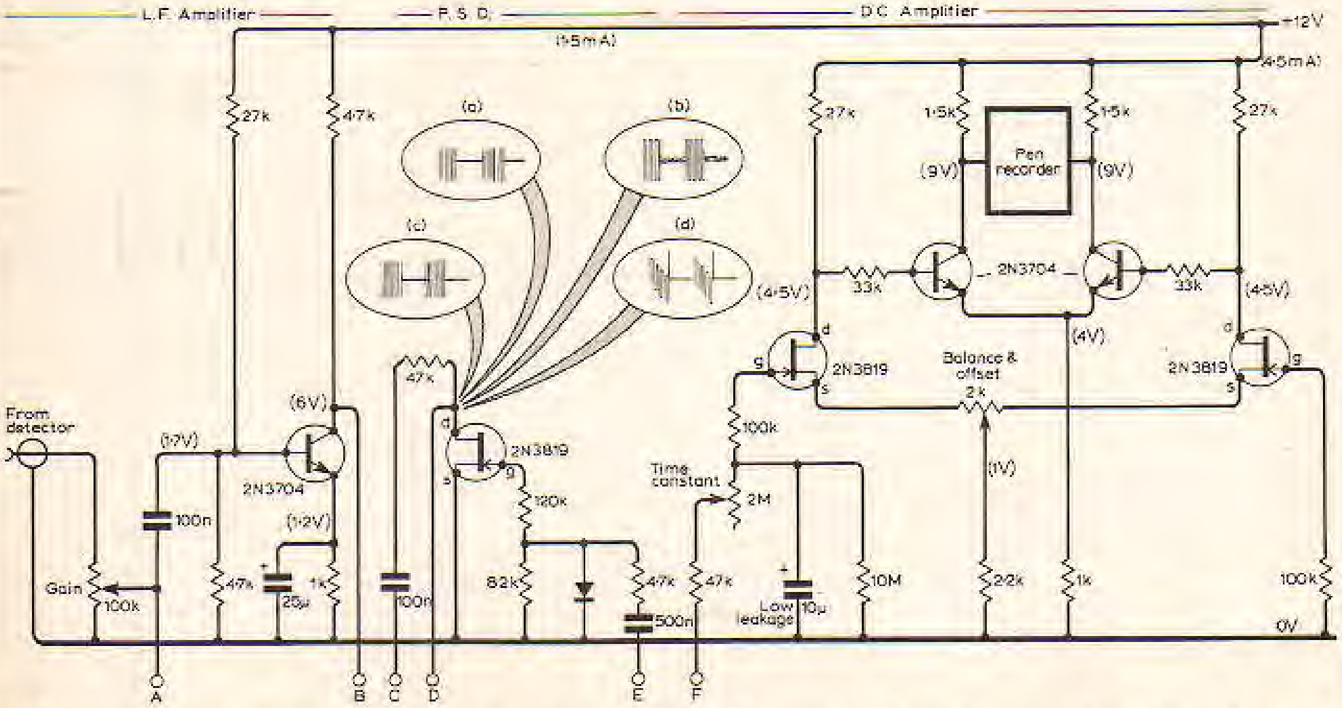


**Fig. 7.** *L.f. amplifier, phase sensitive detector, and d.c. amplifier. Oscilloscope waveforms from point D: (a) Normal signals at aerial switch unequal – d.c. output proportional to the difference. (b) Normal, both inputs equal – zero d.c. output, (c) Overload. (d) L.f. phase shift in the system, and spikes also leaking from the square wave generator.*

insertion loss is about 10dB. The i.f. amplifier and detector in Fig. 6 consists of two cascode pairs followed by a single transistor stage to give up to 2V from a 1000Ω output impedance. The original measured power gain was about 92dB, but this was reduced to 70dB by the inclusion of resistor $R_1$ across the input terminal, and some retuning to improve stability.

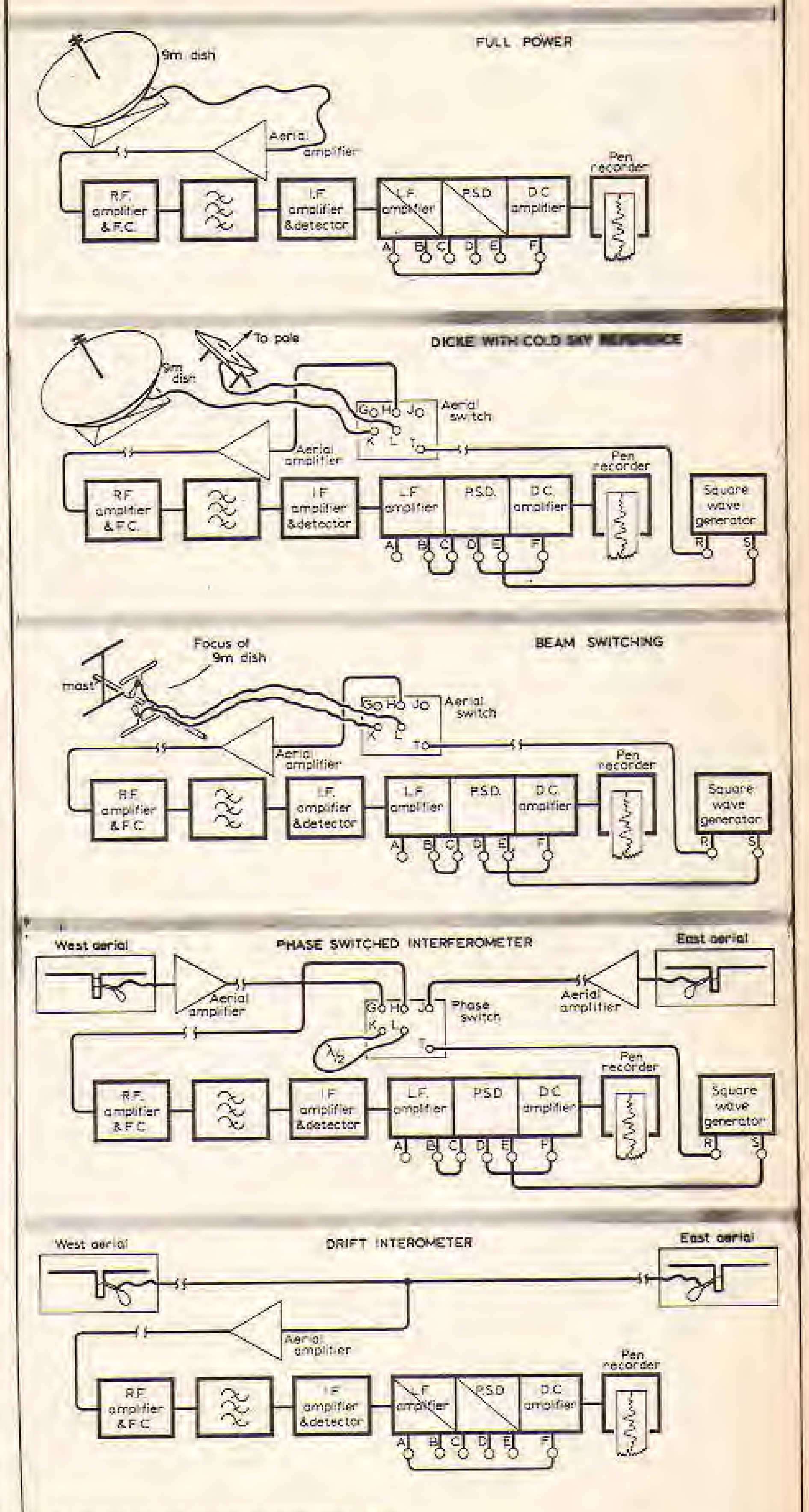
## Construction

The aerial framework is constructed from 25 x 25mm timber, and the two main panels are joined by removeable wire pegs to permit easy dismantling. A full wave dipole is used as this conveniently fills the aperture. The dipole high impedence is transformed to a low impedance to match the balun by a short circuited λ/4 line. The position of the tap to the balun is found by trial and error. The dipole and λ/4 matching stub is made from one piece of 3.18mm diameter aluminium or copper wire and the insultors are cut from perspex sheet with holes at 25mm spacing. Brass connectors to the aluminium, and soldered connections to the balun are greased to prevent corrosion.

Each balun consists of a λ/2 section of 50Ω coaxial cable which gives a 4 to 1 impedance transformation as shown in Fig. 2. The coax and feed-through connections are housed in a 35mm film can which is subsequently filled with candle wax to form a hermetic seal. Similar baluns made eleven years ago and exposed to the weather are still working satisfactorily. The components are mounted on p.t.f.e. insulated studs or ceramic stand off tags attached to copper clad insulating board. The boards are bolted to the inside of diecast-box lids. All external connections pass through holes in the boards and lids. This method permits easier access for construction and maintenance. The transistors are located in holes which are drilled in the boards, and their screen leads are cut a short as possible and soldered to the copper cladding. All leads are kept as short as possible, particularly for the decoupling capacitors. Vertical screens cut from copper clad board are placed between stages, and where possible they are cut to bridge the transistors to provide electrostatic and electromagnetic isolation between the bases and collectors or gates and drains. The coils are wound on 4 or 6mm diameter formers with ferrite slugs. In the r.f. circuits the number of turns required is affected by the circuit layout and variations in the transistors.

As the detector output level is fairly high the l.f. amplifier in Fig. 7 is very simple. For some observations it can be omitted. In the phase sensitive detector of the same circuit the f.e.t. acts as a simple switch driven by the square wave generator.

*To be concluded.*



*Techniques of radio astronomy that can be used with the telescope as shown above are summarized over the page.*

## Radio telescope systems

Most natural signals from space are in the form of white noise and are similar in character to the noise generated in a receiver. Factors affecting the overall sensitivity of a radio telescope are receiver system noise, gain fluctuations, aerial collecting area, aerial efficiency, aerial feeder loss, receiver bandwidth $B$, and receiver output time constant $T$. The minimum detectable signal at the receiver is roughly equivalent to the noise recorded on the pen recorder. The system noise fluctuations and hence the minimum detectable signal level can be reduced by using a wide bandwidth and a long time constant which produces an improvement proportional to $\sqrt{BT}$. Bandwidths greater than 1MHz and time constants greater than 10 seconds are desirable but unfortunately the bandwidth often has to be reduced to find part of the spectrum clear of man-made transmissions. This causes a loss of sensitivity. The output time constant needs to be between 0.1 and 2.5 seconds for recording rapid bursts from the sun, and from about ten seconds to several hours for galactic sources. This choice often depends upon the presence and type of interference.

**The full power system** consists of a single aerial connected directly to the receiver. The detector output is measured by a d.c. amplifier and a pen recorder. Often the d.c. component due to receiver noise is backed off by a stable bias supply. The full power system is very susceptible to receiver gain variations due to changes of temperature, supply voltage and component characteristics. These changes vary the output due to receiver noise and mask the output due to the signal. In the case of the Crab Nebula, the signal seen by the receiver is only $10^{-21}$ watts/Hz and will be lost in the smallest of receiver gain variations.

**In the Dicke system** the signal is continuously compared with the thermal noise produced by a high quality resistor that has been matched to the system input impedance. The receiver is switched alternately to the aerial and the resistor at about 500Hz and the detector output polarity is also switched synchronously so that over a complete cycle the system output is

$$\propto \frac{(s+n)-(r+n)}{2} \propto \frac{s-r}{2}$$

where $s$ is the signal, $r$ is the resistor noise and $n$ is the receiver noise. Because $s$, $r$, and $n$ are all randomly varying quantities, the output still needs to be averaged by the output time constant and wide bandwidth.

A disadvantage of the Dicke system is that the temperature of the reference resistor is different to the equivalent temperature of most celestial sources, and therefore these signals can differ considerably. Any variations of system gain will be modified by this difference and show up as drift on the pen recorder.

**The cold sky reference** is a simpler system where the resistor is replaced by an aerial pointing at a cold part of the sky which will have an equivalent temperature of a few degrees above absolute zero. If the aerial is pointing to the celestial pole, it will always see the same portion of the sky in spite of the Earth's rotation.

**In the drift interferometer** two aerials are set up on an East West base line facing a selected point in the sky on the meridian. The aerials are connected in parallel through two equal lengths of feeder and the rotation of the Earth scans the aerial beams across the sky at a fixed declination. When a radio source is on the meridian, the path lengths through each aerial to the receiver are equal and the signals collected by each aerial add together. The pen recorder responds to the sum of the signals plus the receiver noise. When the Earth has rotated so that the path length through the West aerial has shortened by a quarter of a wavelength, and increased through the East aerial by a quarter of a wavelength, the signals will be 180° out of phase and will therefore cancel. At this point the pen recorder trace will fall to the receiver noise level. After the path lengths have each changed by half a wavelength the signals are again in step and add together.

A sinusoidally varying multi-lobe or fringe pattern is recorded above the receiver noise bounded by an envelope corresponding to the overall beam-width of the two aerials.

One advantage of this system is that the signals from a celestial source can often be distinguished from unwanted signals.

**In the phase switched interferometer** the advantages of the Dicke, drift interferometer and cold sky reference systems can be combined. If the connections to one of the aerials of the drift interferometer system are reversed the fringe pattern is shifted sideways by half of a fringe width. A source located at a fringe maximum will then be located at a fringe minimum. Therefore, at any one moment the system is seeing the source, and in the next moment the cold sky alongside it. Reversal of the aerial polarity can be by two germanium diodes acting as r.f. switches to alternately insert or remove half a wavelength of the aerial feeder. Separation of the signal from the receiver noise is accomplished by feeding the receiver output to a synchronous detector as in the Dicke system.

When the source is on the meridian, the output is

$$\frac{(2s+n)-n}{2} \propto -s$$

where $s$ is the signal due to one aerial and $n$ is the receiver noise. When the source has moved by half a fringe, the output is

$$\frac{n-2s+n}{2} \propto -s$$

Unwanted signals reaching one aerial only or both aerials incoherently are treated as receiver noise unless there is gross overloading.

# A basic radio telescope — 2

## Construction, performance and testing

**by J. R. Smith**

WHEN NO SIGNAL coherent with the square-wave generator is present the noise blocks are symmetrical about the zero line and the mean d.c. output is zero. If the signal and the square-wave are coherent the noise blocks are not symmetrical about the zero line and the d.c. output appears with a polarity dependent upon the phase of the noise blocks with respect the square wave. Integration of the output signal is carried out by a RC circuit. The time constant is adjusted by a variable 2MΩ resistor and the capacitor is selected for low leakage. The maximum time constant obtainable is 20 seconds. The d.c. amplifier consists of a bootstrapped pair of transistors with some carefully matched devices to provide an acceptable temperature stability. Field effect transistors are used for the input stage to provide a high input impedance which permits a long time constant. To obtain an equal mark-to-space ratio, an asymmetrical astable multivibrator is used to drive a divide-by-two monostable multivibrator, see Fig. 8. Buffer transistors provide low impedance outputs, and normal or inverted square-wave outputs at 1kHz are available as required. Early trials showed that these outputs require filtering to prevent radiation of r.f. fields. Values for r.f. chokes and capacitors are best found by trial and error, but excessive filtering degrades the shape of the square wave. The 12V power supply must be stable to within 5mV. As the total load current is about 55mA dry batteries can be used for short periods or a car battery for longer periods. With the last mentioned the voltage should be stable, after a charge, if it is partially discharged before use by about 5%.

The values of most of the components are not critical although high stability resistors are used in potential divider circuits and the d.c. amplifier. Radio frequency chokes are made by winding between twenty and thirty turns of enamelled wire on polythene tubing of 5mm in diameter. The i.f. chokes consist of twenty to thirty turns

**Measured performance of various stages**

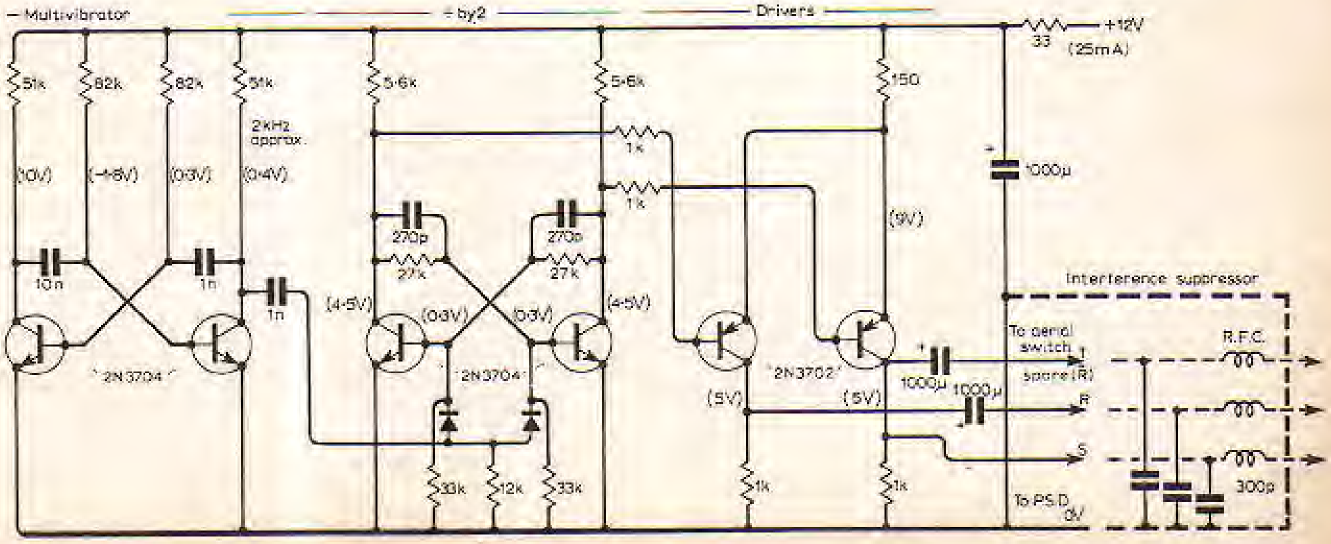
| Stage | $V_d$ when $I$ is 0 | $I$ to double $V_d$ | Noise factor | Noise figure | $\frac{I_a}{V_d}$ | $\frac{dI_a}{dV_d}$ | Stage gain | |
|---|---|---|---|---|---|---|---|---|
| | V | mA | No | dB | $\frac{\text{mA}}{\text{V}}$ | mA per V | Absolute | dB |
| Aerial amplifier and coax | 0.37 | 4.7 | 5.7 | 6.7* | $\frac{0.8}{0.1}$ | 8 | 16.2 | 12* |
| Frequency changer | 0.15 | 14 | 15 | 11.5 | $\frac{13}{0.1}$ | 130 | 11.3 | 10.5 |
| Filter | 0.12 | – | – | – | $\frac{38}{0.03}$ | 1270 | $\frac{1}{28}$ | −14.5 |
| I.f. amplifier | 0.12 | 5 | 6 | 7.7 | $\frac{4.5}{0.1}$ | 45 | $1.05\times10^{7}$ | 70.2 |

* A 3N140 f.e.t. should achieve a noise figure of 4dB. Some improvement in gain should also be possible.

$V_d$ is the detector voltage. Output power is assumed to be proportional to $V_d$ because a square law detector is used.

$I_a$ is the diode anode current. The diode resistor is 50Ω and the voltage gain of the d.c. amplifier is 18.5 (absolute).

Fig 8. *Square-wave generator*



wound and glued onto OBA ferrite slugs. A 1mA recorder that can be centred or end-of-scale zeroed is used with a chart speed of one inch per hour for most observations.

## Noise diode

A valuable piece of test equipment is the valve noise diode, Fig. 9, which produces signals of a similar character and strength to a celestial radio source. The diode is modulated by supplying 240V a.c. to the anode while the detector output is fed to the Y plates of an oscilloscope. The X plates are fed from 240V a.c. through a phase adjuster. With the diode connected to the input of the correctly tuned aerial amplifier or i.f. amplifier a display similar to that shown in Fig. 9 is obtained. The left side of the trace corresponds to the receiver noise, and the right side to the receiver and diode noise. The system is adjusted to produce the largest difference between the two. The noise diode can also be connected to a dipole aerial which in turn can be placed near an aerial which requires adjustment for best performance. In this case, a pair of headphones is connected to the detector. The modulated noise can then be heard and adjustments made to produce the loudest buzz.

Because the noise diode operates at a high voltage, all exposed metal, including the dipole, must be correctly earthed. As the centre point of the folded dipole is at an r.f. voltage node, this point can be bonded to the earthed box without affecting the r.f. performance. All mains earthing leads must be made as secure as possible, and a one amp fuse should be placed in the mains line lead. Similar precautions are necessary for the transistor equipment when running from a mains operated power supply. Fig. 10 shows some typical results. The voltages given in the circuit diagrams were measured with a meter having a 100kΩ resistance. The i.f. amplifier gain was determined from the noise diode output corrected for the difference of the i.f. 4MHz bandwidth and the 0.5MHz filter bandwidth, divided into the change of the detector output power. ☐

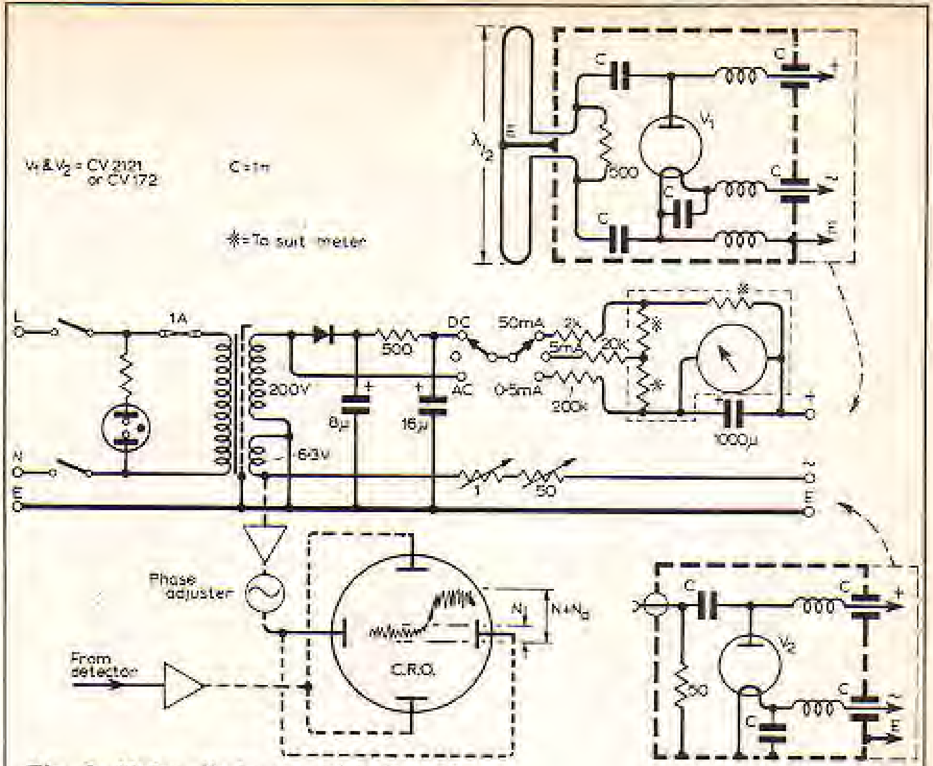


**Fig. 9.** *Noise diode test circuit and typical oscilloscope display of a.c. modulated noise.*

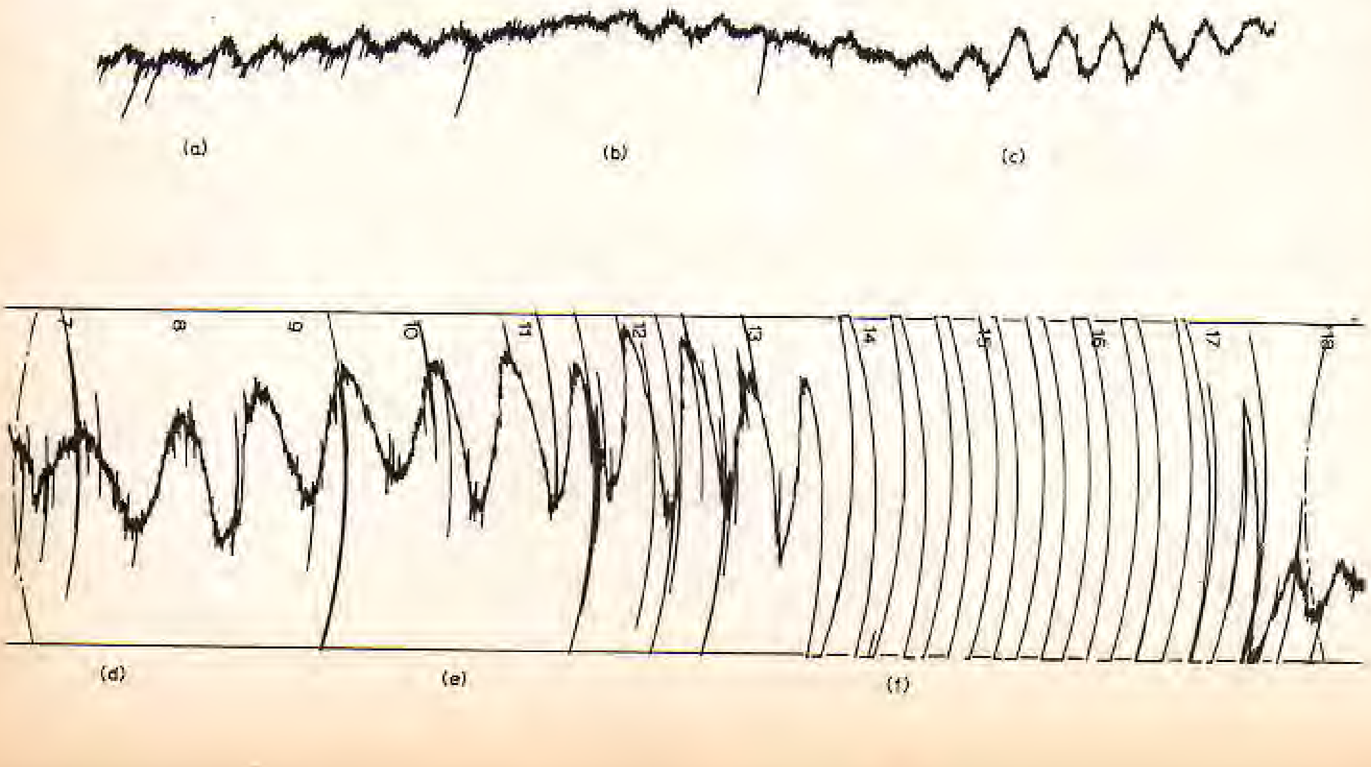


**Fig. 10.** *Pen recordings from the telescope used in the phase switched interferometer mode. Portion (a) shows Virgo A, galaxy M87. (b) Hercules A, a galaxy 1500 million light years distant. (c) Taurus A, Crab Nebula. (d) Cassiopeia A, a super nova reminent. (e) Cygnus A, a galaxy 600 million light years distant. (f) active sun.*