# Doppler Radar with Sense

## Portable radar showing movement direction sense and speed

*by K. Holford**

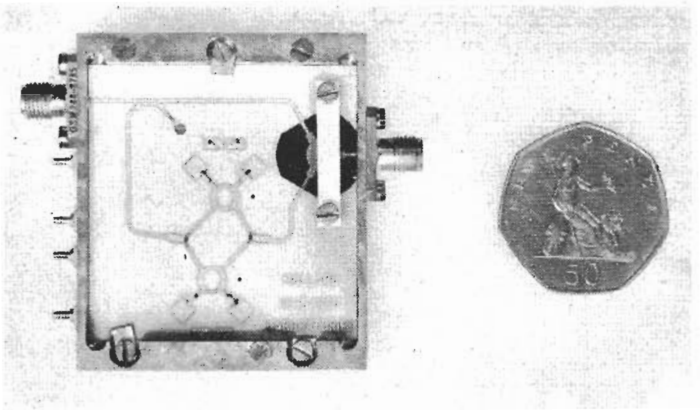

*Fig. 1. An X-band microwave integrated circuit front-end for Doppler radars having direction sense. The m.i.c. contains a circulator and two balanced mixers.*

Possible uses for Doppler radar range from measuring speeds of automatically controlled mechanical equipment to the docking of large tankers. Large tankers approach the dock at 2 metres per minute, and at that speed it is difficult to discern movement visually let alone distinguish the direction. Later on in this article a radar suitable for this purpose will be described, but as a preliminary the reader might appreciate a simple exposition of how Doppler radar works and what is required to extend existing ideas to provide the direction sense information.

The simple microwave Doppler radar speed-measuring equipment which uses just the Doppler beat rate cannot tell whether the moving object is approaching or receding. This sensing can be done using more than one detector but results in a microwave circuit which until recently has been too cumbersome and expensive, except for the few applications which demand it.

However, it is now possible to print almost the whole of the microwave part of a 'Doppler radar with sense' on a 46mm square alumina† substrate as shown in Fig. 1. The cost of such an integrated circuit will depend upon the quantities produced, but even a short production run should reduce it to half that of the waveguide version, and so perhaps the time is now ripe to look towards applications in which direction indication as well as velocity measurement is of particular advantage.

### Operating principles of Doppler radar

One of the simplest radars without sense, uses two small horn aerials as shown in Fig. 2. This arrangement forms the basis of many intruder alarms. It uses a microwave generator providing typically 5mW output. This would now normally be a semiconductor type with 7V 120mA power supply and called a Gunn source after the discoverer of the effect. Gunn sources are available in coaxial or waveguide constructions, the coaxial type usually being less prone to spurious oscillation modes but having the poorer frequency stability of the two.

The microwave power is fed from the Gunn cavity along a coaxial cable and enters the horn $H_1$ where the exposed part radiates an electromagnetic field. This radiation is in the form of a beam, the size of which depends upon the horn aperture, but is usually 25 to 60° wide, the horns being typically 8cm across when using the frequency (10.687GHz) allocated for intruder alarms. Ideally the field varies sinusoidally (since if it does not there must be other frequencies radiating) and propagates at the speed of light, $3 \times 10^8$ metres per second.

The waveforms shown are a simplified time-frozen picture of the field intensity versus distance along the lines shown, except that the power reflected to the aerial $H_2$ from target $X$ is much smaller than the size of the waves might indicate. The field in $H_2$ is coupled from the waveguide by probe $P_1$ and applied to diode $D$.

A single aerial can be used for both transmit and receive but this normally involves a non-reciprocal isolating device such as a circulator.

### Adding mixer r.f. bias to get a Doppler output

To get a Doppler signal from $D$, rather than just the detected $W_1$ signal, requires that the diode also be supplied with some microwave power directly from the microwave genera-

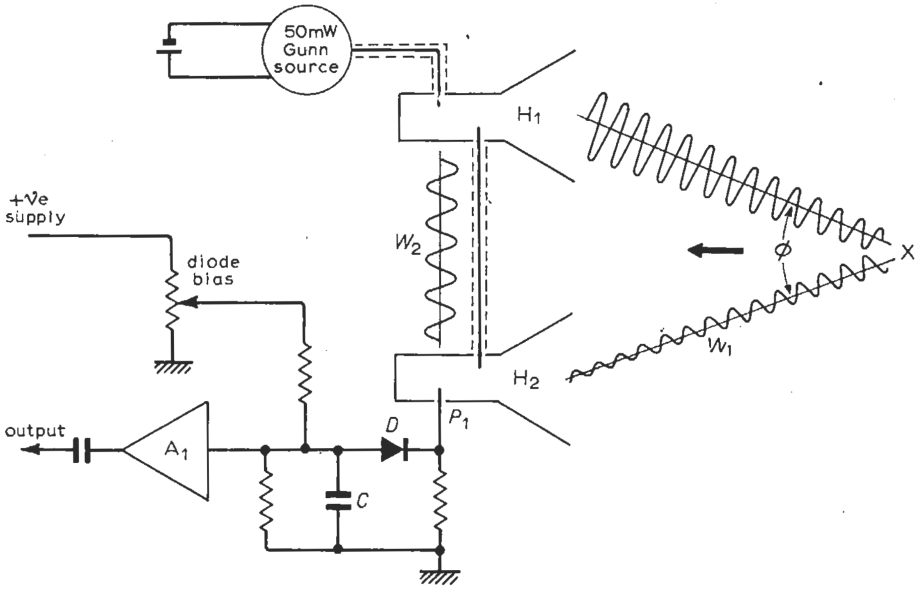

*Fig. 2. A simple Doppler radar.*

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*Mullard Research Laboratories, Redhill.

†An aluminium oxide which looks rather like opal glass.

tor and this is indicated by the wave $W_2$, flowing along the wire which has 'aerial' probes in both guides. The power of $W_2$ is typically 0.5mW, and turns out to be much larger than a normal return from a target, but even so is an amount of signal which brings the diode $D$ to its best sensitivity as a mixer.

The two signals $W_1$ and $W_2$ are added together and the diode $D$ detects the sum signal and produces a direct output voltage accordingly. The phase relationship between the two waves is important because $W_1$ could either add to or subtract from $W_2$. The point to notice about the wave diagram is that, although the fields are moving out and back at $3 \times 10^8$ metres per second, and so the field is everywhere changing sinusoidally with time, the two wave trains $W_1$ and $W_2$ have a fixed phase relationship at the mixer diode $D$, provided the target is stationary. This phase relationship changes with target movement as more or fewer waves fit into the round trip path from the radar to the target and back to the radar at $H_2$. Thus if $X$ moves continuously the diode $D$ will produce a varying amplitude direct voltage across capacitor $C$, the value at any instant depending upon whether the signal returned from the target is adding to or subtracting from the much larger signal arriving along path $W_2$.

## Calculation of Doppler frequency

Taking the larger signal as a phase reference, the target-return signal $W_1$ must be added to it on a vector basis and this is shown in Fig. 3(a). As a starting point the small vector $W_1$ is given a phase of $\theta$ relative to $W_2$. This phase changes as the target moves, and $W_1$ rotates one complete revolution each time the round trip path changes by one wavelength. The voltage applied to the diode is the sum signal $M$.

If the target moves at a steady rate, so that $W_1$ rotates at a fixed rate, the length of the sum vector $M$ changes sinusoidally with time as shown in Fig. 3(b). In practice $W_1$ is much smaller than $W_2$ and the sinusoidal variation in vector length is transferred fairly faithfully to detected d.c.

The d.c. part of the rectified signal is of little interest and so in practice a high-gain a.c. amplifier is used to amplify just the perturbations. Such a signal is known as the Doppler signal because of its similarity to the acoustic Doppler effect such as the change in pitch of a train whistle associated with passing trains. To understand this it is necessary to view the system slightly differently and to observe that a target movement increases or decreases the number of waves in the round trip path. Thus, viewing the received signal from the position of $H_2$, in Fig. 2, the return signal is *seen to be* of a lower or higher frequency than that radiated from $H_1$, according to whether the target lets extra waves slip into the path or squeezes them out.

The Doppler frequency is now easily calculated. Angle $\phi$ is usually small enough to be considered zero because the target range is usually much larger than the spacing between $H_1$ and $H_2$. Thus each time $X$ moves by one half wavelength in the direction of the arrow it takes a half wavelength out of each path and there is one wavelength less in the round-trip path. If the velocity of movement is $v$ metres per second there will be a change in wavelength of $2v/\lambda$ per second, where $\lambda$ is the wavelength. The Doppler shift is therefore

$$f = 2\,v/\lambda \text{ Hz}$$

Since the propagation speed of electromagnetic waves is $3 \times 10^8$ metres per second, $\lambda$ becomes $3 \times 10^8/F$, where $F$ is the microwave frequency. Thus the Doppler frequency is given by

$$f = 2\,vF/(3 \times 10^8) \text{ Hz}$$

Taking the allocated intruder alarm frequency of $F = 10.687$ GHz and a target speed of 1 m.p.h. (0.45 metres per second) this gives the Doppler frequency $f$, as 31.8Hz.

So much for a simple Doppler radar operating in the X-band (7.5 to 12 GHz). As microwave apparatus goes it is fairly cheap and easy to set up.

The mixing signal $W_2$ is not very critical and in most applications a total radiated power of 5mW is enough to provide a useful detection sensitivity and is within the 10mW limit specified with the frequency allocation. When used in an enclosed room, however, there is not usually a radio interference risk.

## Measuring direction sense

The simple Doppler radar can be used for many movement measuring and monitoring applications, but it cannot indicate the direction of movement because a receding target produces the same sort of signal as an approaching one. However, the direction information can be got if a second detector is used, provided this is placed at a suitably different position. This is shown in

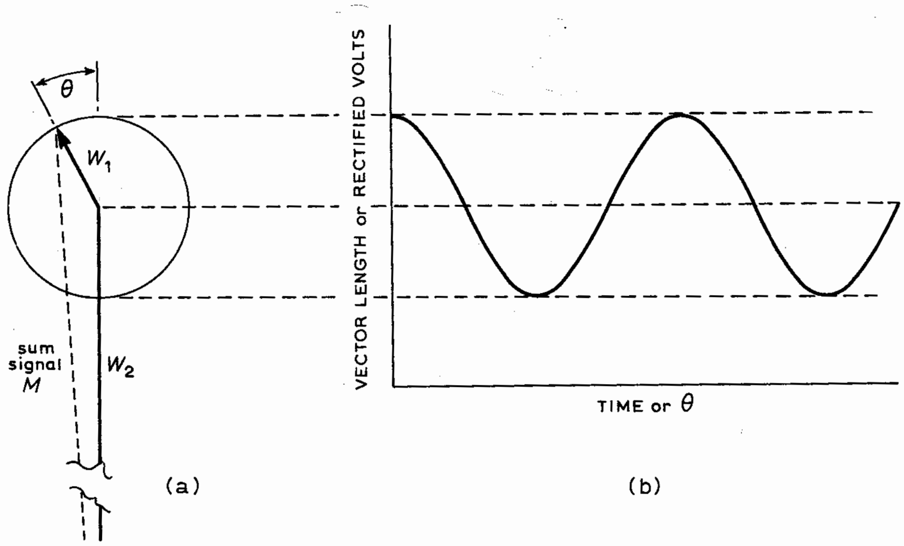


*Fig. 3. (a) Vector addition of mixer signal $W_2$ and target return $W_1$. (b) Change of length with time of $\theta$ change. (Note that in practice $W_2 \gg W_1$.)*

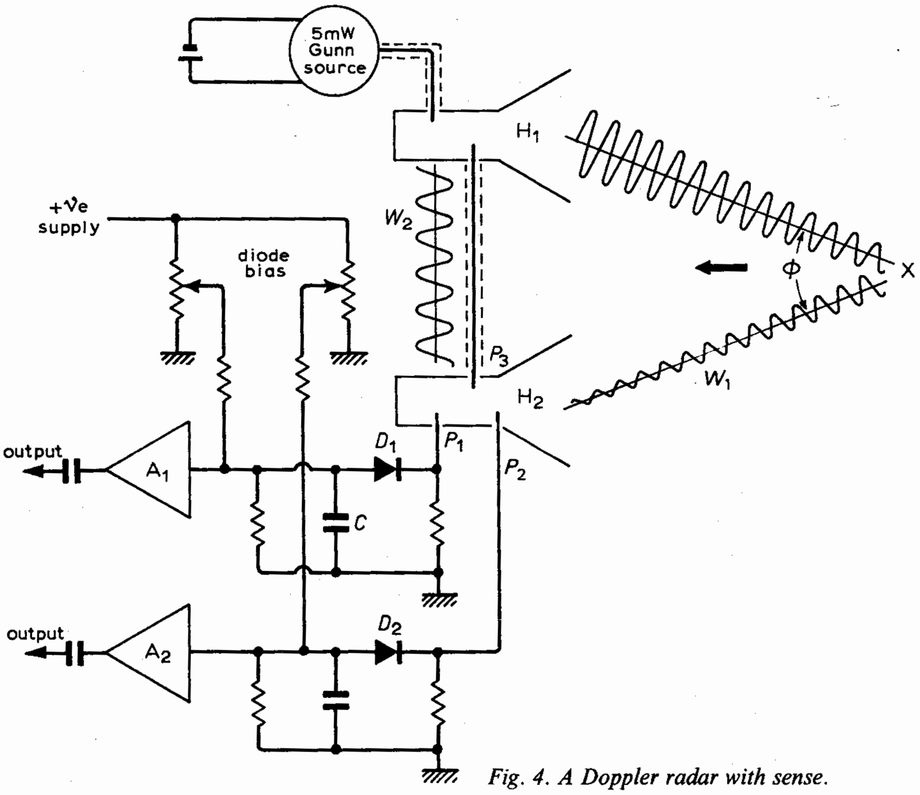


*Fig. 4. A Doppler radar with sense.*

Fig. 4 where the second probe $P_2$ is up-stream by a suitable part of a wavelength distance.

To simplify matters consider that the spacing of the probes is such that both $P_1$ and $P_2$ receive the same phase of $P_3$ signal and that $P_2$ is a quarter-wave (90° phase) distance up-stream from $P_1$. When target $X$ moves towards the radar and passes through the position which makes the waves $W_1$ and $W_2$ sum to a maximum at $P_2$, the maximum at $P_1$ is about to occur a little later when the $W_1$ path length has shortened by another quarter wavelength. In other words the Doppler amplitude modulation of the sum signal at $P_1$ lags $P_2$ by a quarter wavelength (90°), where the wavelength is being measured at microwave frequency, but the Doppler is normally being produced at audio frequency. If the target is now considered for the case where it is moving away from the radar, then the maximum at $P_2$ follows a quarter wavelength behind the maximum at $P_1$. These phase relationships are shown in Fig. 5 in which the wave from $P_2$ ($A_2$) is used as the reference wave.

The choice of a probe spacing of quarter wavelength can now be seen to be very convenient, because when $A_2$ is crossing zero, in say the positive-going direction, the sign of the $A_1$ wave indicates the target direction. But $A_1$ is also sitting nicely equally each side of the $A_2$ zero and so allows maximum circuit errors before any logic would give a wrong answer. One way of processing the signals would be to use the $A_2$ wave to produce a pulse or edge each time it crossed zero in the positive-going direction, for instance using a Schmitt trigger which triggered each time the wave became minutely positive. This pulse can then be applied to a circuit which has the output polarity controlled by the sign of the $A_1$ signal. Such a circuit is shown in Fig. 6. The $A_1$ waveform controls which of the $Tr_2$ or $Tr_3$ transistors conducts, but neither can conduct except during the time that $Tr_1$ is turned on by the pulse which is applied to input (1). The $A_1$ wave controls the $Tr_2$–$Tr_3$ pair, by making one of the two bases, $b_1$ or $b_2$ more positive than the other during the time that $Tr_1$ conducts, and so determines which of the two resistors, $R_1$ and $R_2$ has voltage developed across it. This voltage causes the appropriate $Tr_4$ or $Tr_5$ transistor to conduct and so causes meter $M$ to deflect left or right.

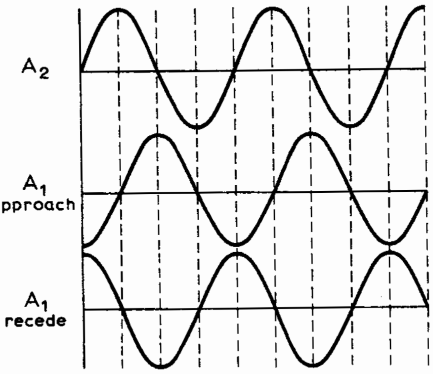


*Fig. 5. Phase relationship between $A_1$ and $A_2$ for (1) an approaching target and (2) a receding one.*

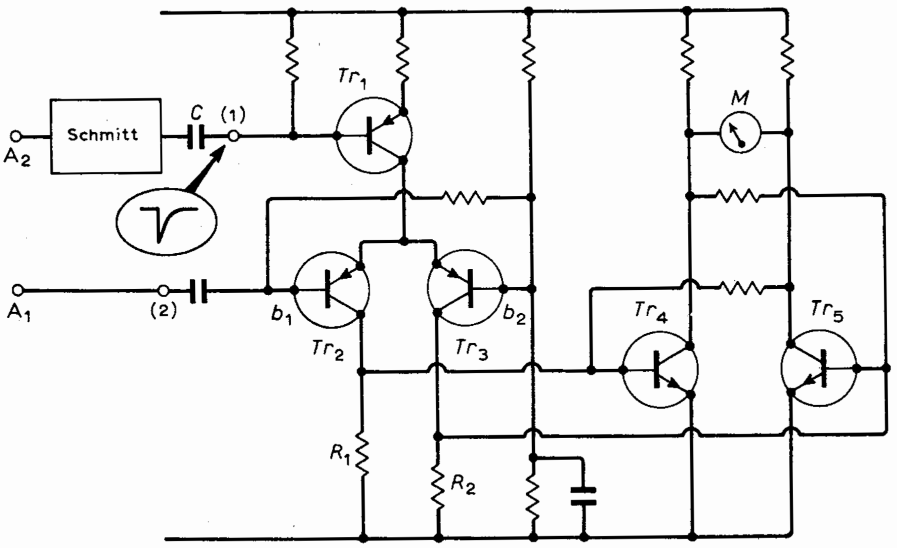


*Fig. 6. Type of circuit which will indicate sense.*

Ideally no further change in $M$ occurs after the first setting unless the phase relationship between $A_1$ and $A_2$ changes due to a change in target direction.

Although the above circuit contains the basic workings of a system and can be developed, it is hardly worth doing so since integrated circuits can be found which will do the complete job and decode the $A_1$, $A_2$ waves if they are connected to the appropriate terminals.

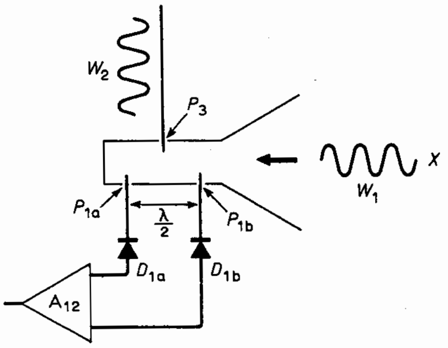


*Fig. 7. Amplitude-modulation noise rejection using a pair of diodes.*

## Combating noise from the microwave source

One other aspect of Doppler radar needs describing before an engineered arrangement can be considered, and that is to do with noise. Since the larger part of the signal received by the diodes is supplied directly from the microwave generator, any noise from this can have a very significant effect on performance. With a short range radar the noise amplitude variations will be more important than frequency changes. The amplitude noise will be detected and in a simple system is largely indistinguishable from a target signal of similar strength. This can set the limit to the sensitivity of a radar and therefore its ultimate usefulness. The effect of this noise can be reduced by about a factor ten in voltage terms, at the expense of doubling the number of diodes used, and the principle is demonstrated using the probe arrangement in Fig. 7.

It is assumed that the probe arrangement is such that probe $P_3$ delivers equal power at the same phase to both $P_{1a}$ and $P_{1b}$. Since $P_{1a}$ is a half wavelength down-stream from the target, compared to $P_{1b}$, the Doppler signals produced by these two probes will be 180° out of phase; because a moving target, which is, say, approaching, will produce a peak signal amplitude at $P_{1a}$ a half wavelength later than it produces it at $P_{1b}$. For a receding target, similar phase relationships occur again because a Doppler delayed by 180° looks similar to the previous one which was advanced 180°, there being 360° between the two which is just one cycle of Doppler difference.

The two antiphase Doppler signals produced by diodes $D_{1a}$ and $D_{1b}$ can be summed to give a double strength signal by applying them simultaneously to a differential input amplifier which inverts the signal applied to one of its inputs ($A_{12}$, Fig. 7).

This type of amplifier rejects signals that are of the same amplitude and polarity by the common mode rejection capability. And it will now be shown that amplitude noise on the mixing signal $W_2$ has the same effect on both $P_{1a}$ and $P_{1b}$. The amplitude noise to be rejected is caused by low-frequency variations in amplitude of the microwave signal supplied directly as $W_2$. Since it is mainly in the audio frequency range, there must be many hundreds of thousands or even millions of cycles of microwave frequency between each noise peak. And since the $W_2$ signal supplied to the two probes $P_{1a}$ and $P_{1b}$ differs by only a fraction of a cycle in the arrangement shown in Fig. 7, or perhaps a few cycles in some arrangements, it follows that both $D_{1a}$ and $D_{1b}$ receive the amplitude variations, for all practical purposes, at the same time. Thus $D_{1a}$ and $D_{1b}$ will produce the same phase and amplitude of noise signal provided they are supplied with the same amount of $W_2$ signal, and are matched diodes. (The amount of $W_2$ signal could be adjusted to take account of the different diode sensitivities but in practice it is often easier to choose matching diodes.) Having both diodes the same way round is very convenient for portable equipment because only a single polarity battery supply is required for diode d.c. bias. However, it is also possible to get noise rejection by reversing one of the diodes and using a single input amplifier. The noise currents then subtract, but the two Doppler signals are of the same phase and constitute a combined power signal by virtue of their lower impedance signal source. This has previously been the more common arrangement, but there seems to be no great difficulty in using the differential $A_{12}$ arrangement in Fig. 7.

The f.m. noise becomes significant if the radar is receiving signals from (stationary) unwanted targets which are stronger than the wanted signal, provided the receiving distance is sufficient. The mixer then receives two 'frequency' different signals due to the time delay and the frequency shifting nature of the microwave source. As far as is possible this should be avoided. Additional cavities can be added to a microwave source to reduce f.m. noise provided the expense is justified.

## Radar construction

Engineering a radar with multiple probes presents problems, because if the probes are individually designed to extract as much signal as possible by having good coupling into the waveguide, they interact. However, to use less coupling means a loss of efficiency. Thus in practice a better engineered power-splitting arrangement is preferred. This can be done in waveguide construction but it is expensive and bulky. One radar at present in use has about a cubic foot of metal waveguide components, as well as the aerial, and this arrangement is hardly portable.

## Printing the microwave circuit

It is possible to print most of the microwave circuit in the form of interconnected thin film transmission lines etc., using nichrome and gold and a 46mm square alumina substrate as shown in Fig. 1. This has a double diode balanced mixer for each Doppler output to reject oscillator noise as just described. Each pair of diodes is connected to a transmission line ring known as a hybrid ring and the path length differences required to produce the correct Doppler phase are built in. The signal path and the mixer path lengths are both used, since adding length to one path has a similar effect to shortening the other, as far a achieving a particular phase difference is concerned. The width of the conductor is varied to get the desired power splitting ratio and this is particularly noticeable for the rings.

## Microwave i.c. in tanker docking radar

The microwave integrated circuit (m.i.c.) shown in Fig. 1 includes a circulator which enables the use of a single aerial for both transmission and reception. A block diagram of a Doppler radar, with direction sense, using this m.i.c. is shown in Fig. 8. The circulator is a power routing device having non-reciprocal properties based upon current flow over a polarized magnetic material. Microwave power entering port 1 flows out of port 2, except for reflections due to aerial impedance mismatch and leakage due to device imperfections. Power entering port 2, including the reflection, is routed to port 3. Reflected power is typically held to less than 4% at which it is small enough not to alter substantially the diode microwave "bias" signal ($W_2$ in previous figures) or upset the working of the Gunn oscillator which tends to be sensitive to reflected power greater than about 4% (1.5:1 v.s.w.r.).

It is beyond the scope of this article to go into greater detail in describing the design of the m.i.c. and the system, but the device can be assumed to produce the two phase-related Doppler signals as required which are individually amplified in the $A_1$ and the $A_2$ channels. The phase detector has already been described, leaving the speed meter and audio monitoring to be covered.

## Speed meter

A suitable speed meter which could be used with this or any other Doppler radar is shown in Fig. 9, and is based upon generating pulses of fixed height and width, one or two, for each Doppler cycle. The circuit is a monostable and the average voltage across the 10kΩ collector load of $Tr_1$ is proportional to the number of pulses per second, i.e. proportional to speed. The input trigger pulses must be shorter than the length of the output pulses, which in turn is controlled by the value of $C$. The pulse length must also be about 5% or more shorter than half the repetition time at the highest intended speed, if ambiguity is to be avoided with off-scale input frequencies.

## Audio monitor

The audio monitor presents a problem when the Doppler frequency is very low, because of the difficulty in making this frequency audible. For the tanker docking radar the Doppler frequency ranges from approximately 1 kHz to 1 Hz. The latter corresponds to a movement speed of 1 metre per minute, and even lower speeds could be monitored if the direction sense is not important. The solutions considered included modulating the audio onto a carrier such as 1 kHz, either as f.m. or a.m. but this became indistinct at the higher audio frequencies. The solution adopted was to generate 0.2ms pulses, one for each half cycle of the Doppler. Thus at low frequencies clicks are emitted, but these blend and change to a tone as the speed increases. The scheme works well over the complete range and the note at higher speeds is not all that different from a normal clipped Doppler wave which would be given by the Doppler amplifiers directly.

## The complete radar

A picture of the prototype tanker docking radar is shown in Fig. 10. It is a low power X-band c.w. Doppler radar able to measure

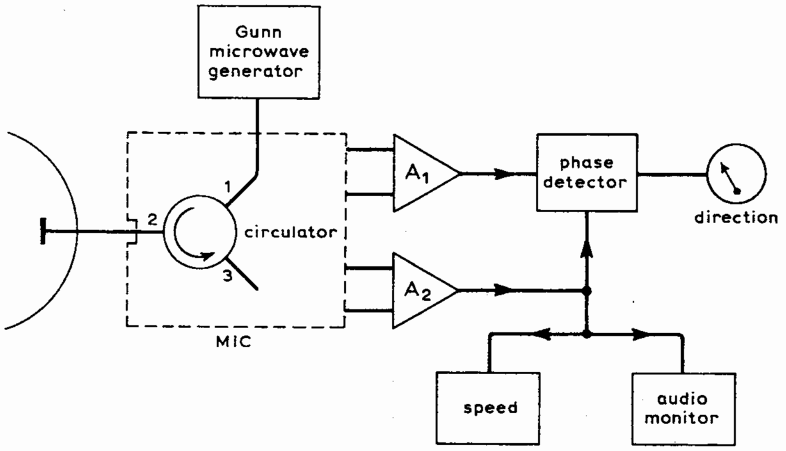
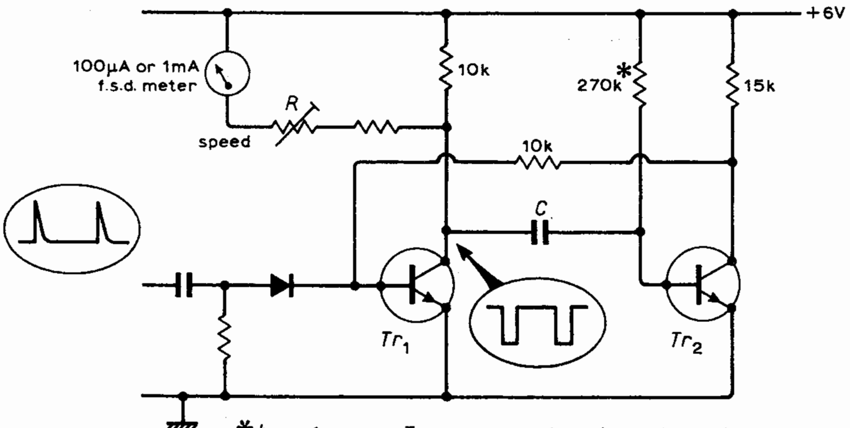


*Fig. 8. Block diagram of Doppler radar with sense using Mullard m.i.c.*



*$h_{FE}$ ≤ 150 for $Tr_2$ for easy triggering by input signal

*Fig. 9. Speed/frequency meter based upon a monostable.*

both the speed of an approaching ship (over the range 1 yd per minute up to 30 knots) together with the sense of movement i.e. approach or recede. The sense indicator is useful for aiming the radar. The fluctuations of the direction meter pointer due to noise begin to change their pattern when a weak target enters the radar beam and before it is strong enough to give a speed reading. It also shows that a good target signal had been acquired. An audio signal is also provided for these preferring to monitor the radar aurally. The audio pitch changes smoothly speed and works over the total speed range. At the lower speed the tone becomes a series of clicks.

Optimal automatic protection of the speed meter against false readings with weak signals has been provided; the speed meter can be switched to read only when a single, clear signal is present. The range of the equipment depends upon the type of target, the amount of microwave power radiated and the size of the aerial dish. The demonstration model radiates 6mW of power and should be usable to detect most vessels of 80ft (24 metres) or more in length at 1 mile, and a larger tanker at 1½ miles. Used on land it can indicate the speed of most cars and lorries at about 300 yards. With a smaller aerial the equipment might be useful in the automation of machine control.

The equipment can be mains or battery powered and has a built in rechargeable battery which provides 4 to 5 hours continuous use. Total current consumption is only about 0.2A.

## Acknowledgement

The m.i.c. referred to in this article was designed by Mr. L. W. Chua. There have also been useful discussions with Dr. P. Bulman, of R.R.E.