Jean-Pierre Morel, HB9RKR and Dr. Angel Vilaseca, HB9SLV

Doppler Radar in the 10 GHz Amateur Band Part-2

3. SELECTION OF AN SHF RADAR SETUP

Several choices are open, offering varying complexity and results.

3.1 The "Gunnplexer"

This device, once widely used, is based upon a circulator (Fig.18). Power derived from a Gunn oscillator reaches the antenna via a circulator, with a small component reaching the diode mixer as a heterodyne signal. Received signals reach the mixer practically unhindered by the circulator. The desired output signal is the difference between the received and the local oscillator (LO) signal.

In this case the less than perfect directionality of the circulator is a desirable feature, since the LO works as a transmitter and at the same time makes available a heterodyne frequency. The reverse attenuation of the circulator is around 20dB so that even with several hundred mW transmit power the mixer diode is not threatened. In addition the circulator protects the LO from the outside world, which is good for stability.

A frequency drift of, for example, 10 MHz at 10 GHz is just one part in a thousand; this also means that any error in the Doppler frequency is also only 1 in 1000. There are no other errors, since the transmit and heterodyne frequencies are produced by the same oscillator.

With a 40cm dish antenna we achieved ranges of 200 metres.

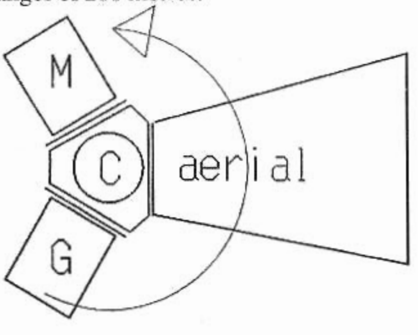

Fig.18: Practical possibility using a Circulator (i.e: Gunnplexer)

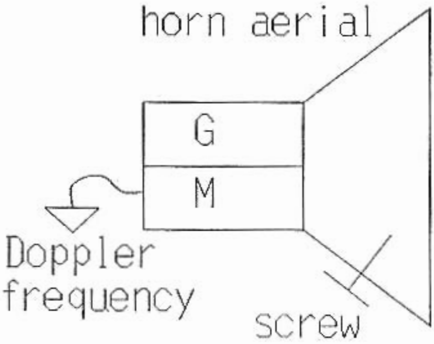

Fig.19: Another alternative: a Burglar Alarm. The minute antenna rules out large radar ranges

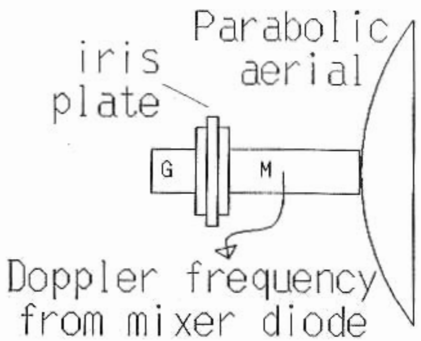

Fig.20: A 'Blast-through' Mixer for broadband FM is a good choice for Radar experiments

3.2 Burglar alarm

The setup sketched in Fig.19 was used some years back in microwave burglar alarms. Use was again made of the Gunn oscillator in the upper module, the transmitter power feeding a horn antenna. A screw in the wall of the horn radiator reflected a small part of the transmitted power into the lower module (the receive mixer). Regrettably half the receive capability was lost in the transmitter.

At the same time, the lack of isolation meant that nearby environmental influences could cause significant drifting, especially with movement directly in front of the antenna (which was what the setup was designed for). In our case the high level of drift led to inaccurate Radar measurements. Another disadvantage is that this assembly cannot be attached to standard waveguide, which makes application with a dish antenna problematic.

Using the horn antenna supplied, very short ranges are achieved and then without great accuracy.

3.3 The "blast-through" mixer

This arrangement was very popular in amateur radio circles some years back since it is easy to make at home and gives good results. A Gunn oscillator is separated from the rest of the assembly by an iris (a plate with a small round hole). According to the diameter of the hole and the thickness of the sheet, a greater or smaller part of the oscillator output reaches the antenna through the mixer (Fig.20). This (low) power is the output signal and at the same time the heterodyne signal.

Being a non-linear element, the mixer diode produces the Doppler signal - an audio frequency signal equal to the difference between the transmit and receive frequencies.

The method of operation is certainly very similar to the Gunnplexer but the transmit output is significantly lower; a few mW instead of 40mW! With an iris of 6mm to 7mm diameter made of 1mm brass sheet and a Gunn oscillator, the approx. 5mW produced is not optimal but adequate for the mixer diode. If we make the iris larger we certainly get more mixer current flowing but the oscillator also loses stability. With high powered Gunn oscillators the mixer diode can even be damaged.

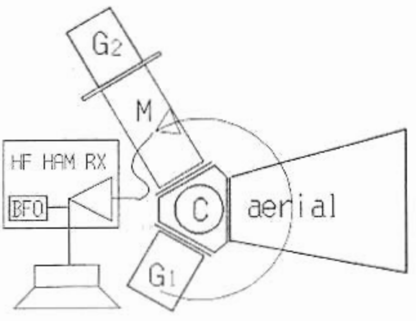

Fig.21: An attempt to increase range by using an IF of 30 MHz was abandoned due to frequency unsuitability

The transmit power will not exceed a few mW with a blast-through mixer. In the past we managed with this amount in wideband FM to span 130km and more, from one Swiss mountain top to another. Yet the range for Doppler Radar is no more than 100 to 150m, as our practical tests demonstrated.

3.4 Higher IFs

In the setups described so far the incoming signal has been converted in the mixer diode down to the audio frequency range.

Down there is also where the strongest phase noise effects of the oscillator appear, and Gunn oscillators are notorious for phase noise. The phase noise intrudes on the audio signal and reduces the sensitivity of the system.

One probable improvement would be to use a GaAsFET oscillator stabilised with a dielectric resonator (5) giving lower phase noise, whilst on the other hand it would be interesting if introducing an IF would increase sensitivity.

In our FM transceivers we used an IF of 30 MHz. So we experimented with the setup shown in Fig.21. The first oscillator G1 produces the transmit frequency f at the highest possible level, the second oscillator being adjusted to f + 30 MHz or f - 30 MHz.

The signal reflected by the target lies between f + 8 kHz and f - 8 kHz, depending whether it is moving towards or away from us, and at what speed. Behind the mixer the signal therefore lies between 29.992 and 30.008 MHz. In the receiver it is amplified several score times and, if we switch in the BFO, we get an audio frequency tone in the loudspeaker. We can adjust the BFO so that this tone amounts to a few Hz when the target is receding at maximum speed from the Radar device; when the target is static the audio frequency is 8 kHz, and when it is approaching fastest the tone is 16 kHz (provided the receiver bandwidth can handle this).

If the target's direction of movement is not of interest, we can adjust the BFO so that the tone is around zero when the target is static.

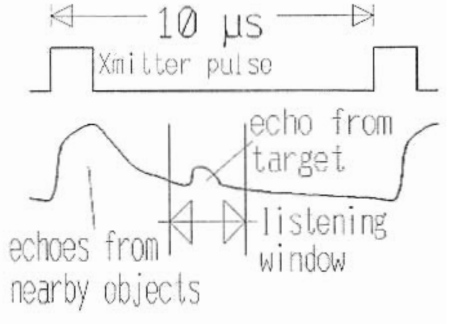

Fig.22: A Pulsed Transmitter and a brief time window can avoid receiver overload and clutter arising from reflection from nearby objects

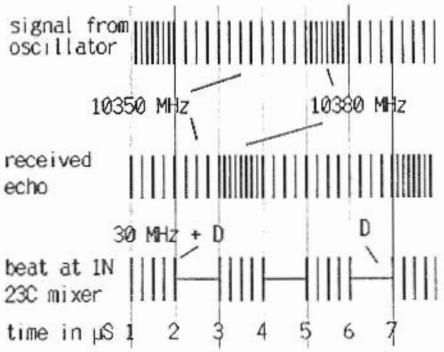

Fig.23: Frequencies in a Frequency-Inverted Continuous Wave Radar based on the 'Blast-through' Mixer. A low frequency is produced in the Mixer Diode between the received pulses: this is the Doppler Frequency

When it now moves, the audio frequency will rise in either case up to a maximum of around just 8 kHz - which corresponds already to a speed of about 450km/h.

The sensitivity of this setup should exceed that of those described previously by a wide margin and to give an example: a bird that flew away a few score metres already gave a very strong signal! We calculate that the range with this setup for a target with a Radar cross section (RCS) of one square metre is several hundred metres. Yet, as we know from our endeavours with the Radar formula, the range can barely exceed 1km - even if we had a noise-free receiver.

This setup using an IF has, however, two serious deficiencies.

Firstly there is breakthrough from the power oscillator G1 through the circulator into the receiver and, small though it is, it exceeds the receive power by several orders of magnitude. This leads to what we have come to know in VHF contests - desense. The idea of using a totally separate transmitter with its own antenna does not help either because reflections from nearby objects and/or side-lobes of the antenna will still cause sufficient coupling of transmit power back into the receiver that blocking effects arise.

Secondly there is the thermal drift of the Gunn oscillator. The calculation of the Doppler frequency depends on a precise 30 MHz difference between transmitter and receiver. This, however, is difficult if not impossible to maintain. Just breathing on one of these oscillators will cause a frequency change of a couple of kHz!

It is possible that the introduction of dielectric resonators (5) and/or PLL circuits could bring the required stability. If only we could get the two oscillators to drift at the same rate, the Doppler error could be reduced to negligible proportions, as we saw in the Gunnplexer.

3.5 Blanking the transmitter using window techniques

A further possibility for improving things lies in keying the transmitter on and off and operating the receiver when we expect an echo from the target (Fig.22). The receiver would then maintain a defined window. During this window period the transmitter would be turned off and the near-target echoes would already be dying away.

How will the Gunn oscillator react to having its power supply keyed on and off? The frequency will presumably have to stabilise each time after switching on and

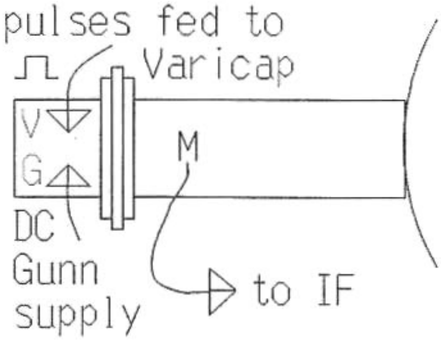

Fig.24a: Another way of avoiding Rx overload by the Tx pulse is Periodic Frequency Inversion, which would allow an IF of 30 MHz, which wouldincrease sensitivity

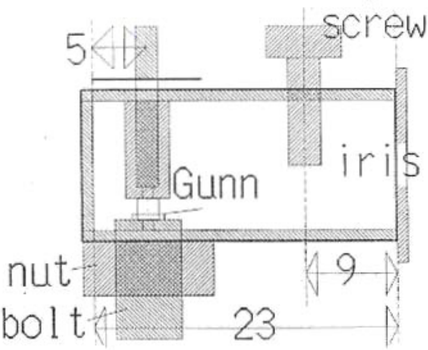

Fig.24b: Side view of a Frequency modulated Gunn Oscillator Dimensions in mm.

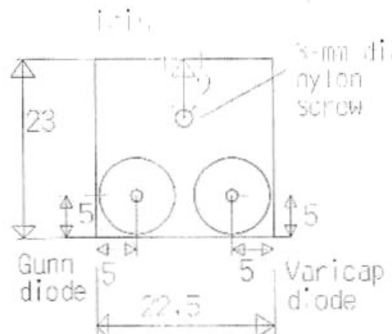

Fig.24c: Top view of the same oscillator as in Fig.24b

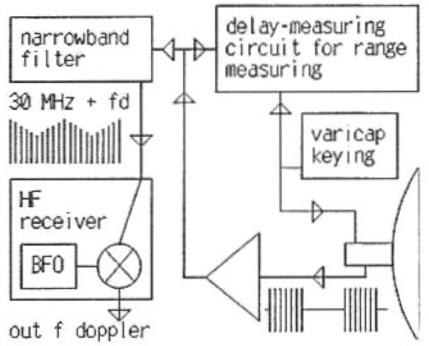

Fig.25: Block Diagram of a CW Radar with Frequency Inversion based on the 'Blast-through' Mixer

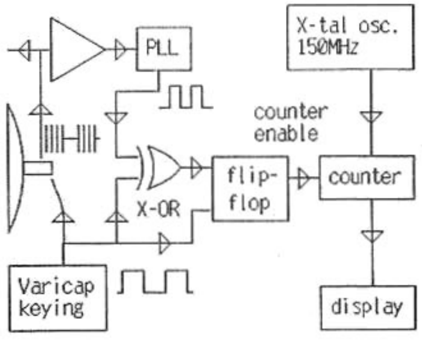

Fig.26: Distance Measurement: the Counter is started with the first Pulsed Transmitted and stopped at the beginning of the Received Pulse

would not be constant throughout the pulse. However, this will not do for Doppler measurements.

A PLL will not lock in within the space of a couple of microseconds.

If we achieve the keying of the transmitter with a PIN diode its reverse attenuation becomes a critical factor. If we attempt mechanical keying, for example with a

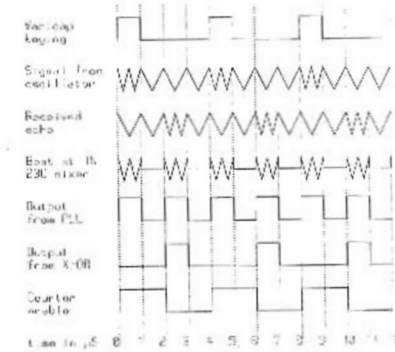

Fig.27: Timing Diagram from Fig.26

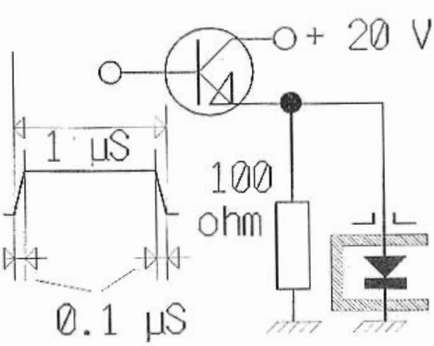

Fig.28: Pulses for the Capacity-Diode must have steep edges to enable the Microwave Frequency to be switched between the two values as rapidly as possible

propeller, the rapidly rotating rotor blades would bring about some "interesting" doppler effects.

3.6 Frequency keying

A better scheme would doubtless be to leave the transmitter G1 running all the time, but shift its frequency. It then transmits only short pulses with the frequency f and for the rest of the cycle is detuned by several score MHz by means of a varicap diode. This also avoids overloading the receiver while listening to echoes (Fig.23).

We carried these thoughts across to the blast-through mixer by equipping it with a varicap diode (Fig's.24a, b and c) supplied with keyed direct current. After this we are still left with no more than an oscillator and the problems of differential drift of the two oscillators remain.

With the knowledge that c = 300m in 1 microsecond, we know that our signal needs 2 microseconds to reach and return from a target 300m away. So in the time interval t we will switch a 20V impulse of 1 microsecond duration onto the varicap diode of the Gunn oscillator. This shifts the frequency of the oscillator by, for example, 30 MHz upwards, for one microsecond, then it reverts to its original frequency. We assume a mark-space ratio of 25 per cent.

Thus, we see on the IF side of the receive mixer a series of bursts with the frequency 30 MHz + doppler frequency. The period of the burst takes 2 microseconds which corresponds to a pulse repetition frequency (PRF) of 500 kHz.

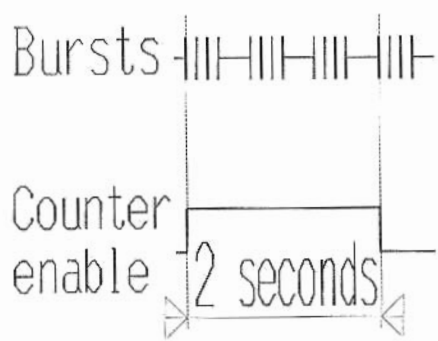

Fig.29: To increase accuracy the Counter can be enabled for several bursts

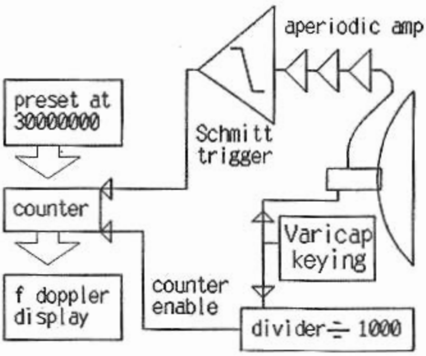

Fig.30: A Counter replaces the HF Receiver for speed measurement

This signal is now amplified in a low-noise 30 MHz amplifier, passed through a narrow-band 30 MHz filter and cleaned up in this way, is passed to the HF receiver. It is still 30 MHz + the doppler frequency with a residual 500 kHz AM, whose level depends on reflections in the filter and its bandwidth. After mixing with the BFO signal we are left for evaluation an audio frequency that is exactly the doppler frequency. Fig.25 shows this scheme schematically.

3.7 Concepts for measuring distance gand speed

With the setup described above distance measurement can be carried out by evaluating the time between the pulse to the varicap diode and the reception of echoes. The principle is shown in Fig.26.

With the leading edge of the pulse that keys the varicap diode a counter is started; it is stopped again by the leading edge of the pulse from the EXOR gate (Fig.27).

With the knowledge that the distance r = t *c/2 it can be calculated that a measured time period of, say, 2 microseconds implies a distance of 300m. To get a figure-perfect display we let the counter

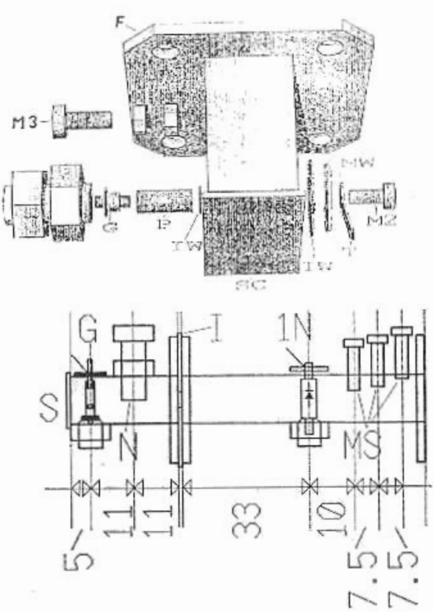

Fig.31a: The Gunn Oscillator in 3-D
Fig.31b: Dimensions of the Oscillator and Mixer

- F = Flange
- M3 = Metal or Nylon Screw, matching the bearing nuts
- G = Gunn Element with M5 nut and bolt for adjustment
- P = Metal bolt (copper or brass)
- IW = Insulating Washer, inner and outer (PTFE)
- SC = Waveguide Short-Circuit
- T = Solder Tag
- M2 = Steel Screw, M2
- MW= Metal Washer
- S = Short Circuit (on the plate soldered on the end of the waveguide
- N = Nylon Screw, 3 to 6mm in diameter
- I = Iris Plate (brass, 1mm thick with 6mm hole in the centre)
- 1N = 1N23 Mixer Diode
- MS = Matching Screws (brass, 3mm diam)

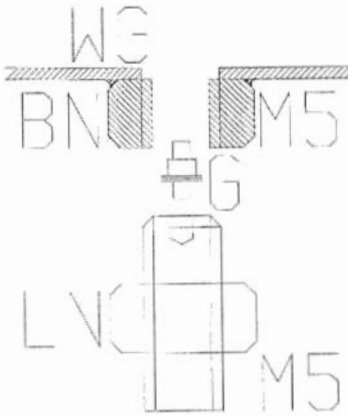

Fig.31c: Mounting details of the Gunn Element

- WG= Waveguide (inside)
- BN = Bearing Nut (M5, steel) soldered to the Waveguide
- G = Gunn Element, larger flange grounded
- LN = Nut (M5, steel)
- M5 = Support Peg (M5, steel) bored axially for the end of the Gunn Element

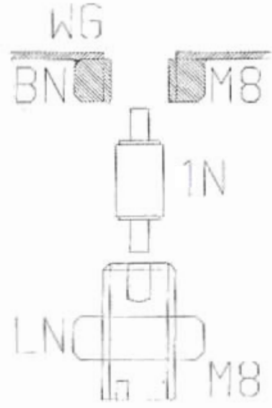

Fig.31e: Detail of the Mixer Diode inset

- WG= Inside of Waveguide
- BN = Bearing Nut (M8, steel) soldered to the Waveguide
- 1N = Mixer Diode
- LN = Nut (M8,steel)
- M8 = Support Peg (M8, steel) bored centrally for the Diode

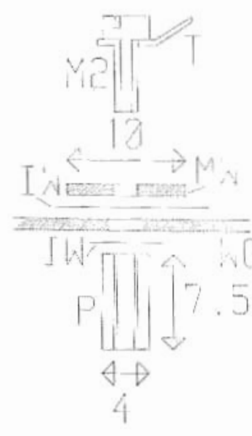

Fig.31d: Connection details of the Gunn Element

- M2 = M2 steel Screw
- T = Solder tag
- MW= Metal Washer, 10mm outside diameter
- IW = Inner/outer PTFE Insulating washers
- WG= Inside of Waveguide
- P = Round peg of brass or copper. Length 7.5mm, outer diameter 4mm, bored axially and tapped M2

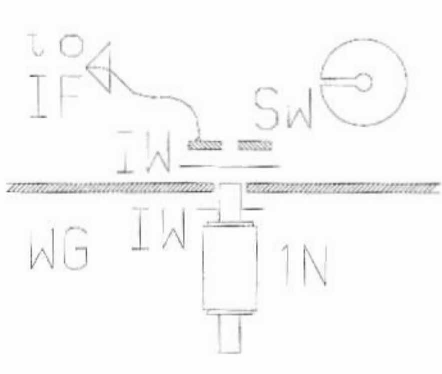

Fig.31f: Detail of the Mixer Diode connections

- WG= Inside of Waveguide
- IW = Insulating Washers (inner and outer PTFE)
- 1N = Mixer Diode
- SW = Special Washer, fastened to the Diode connection and connected to the AF or IF preamplifier

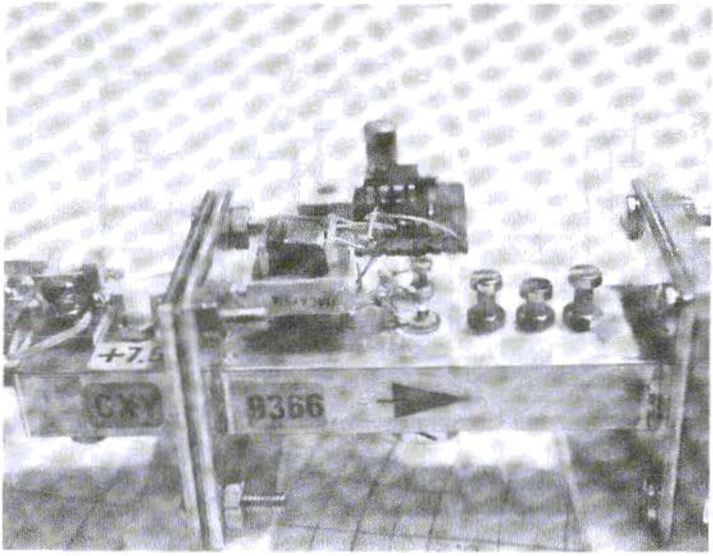

Fig.31g: Our SHF unit

count the pulses of a 150 MHz crystal oscillator: in 2 microseconds we get 300 pulses meaning that we can calibrate the counter display directly in metres.

If everything functioned perfectly - which of course it won't do - we could use this

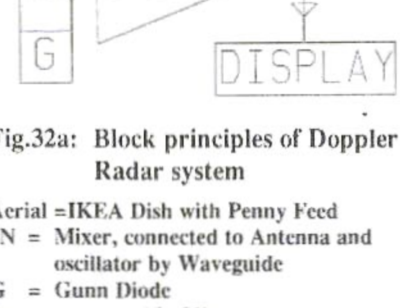

Fig.32a: Block principles of Doppler Radar system

Aerial =IKEA Dish with Penny Feed
1N = Mixer, connected to Antenna and oscillator by Waveguide
G = Gunn Diode
Preamp = see Fig.32b
Display = see Fig.35

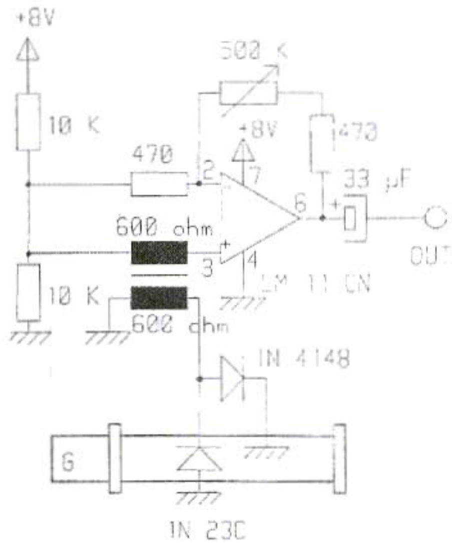

Fig.32b: Circuit of the Audio Frequency Preamplifier. The 1N23 is very sensitive to static electricity and is protected by the Switching Diode.

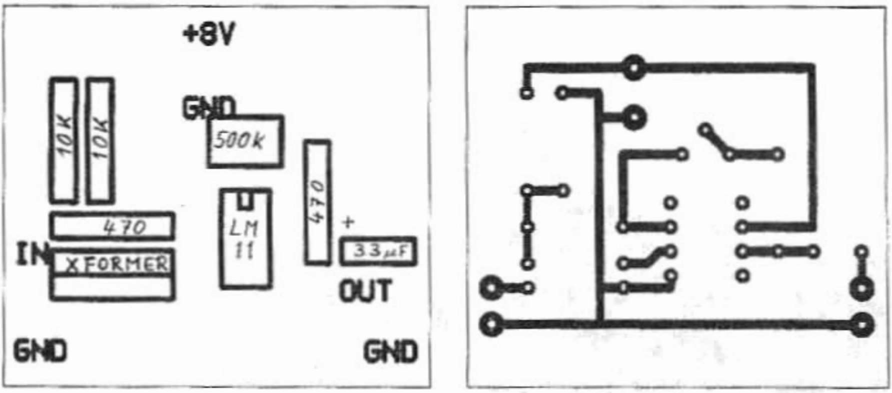

Fig.32c:Printed Circuit Board and Component Layout of the AF Amplifier

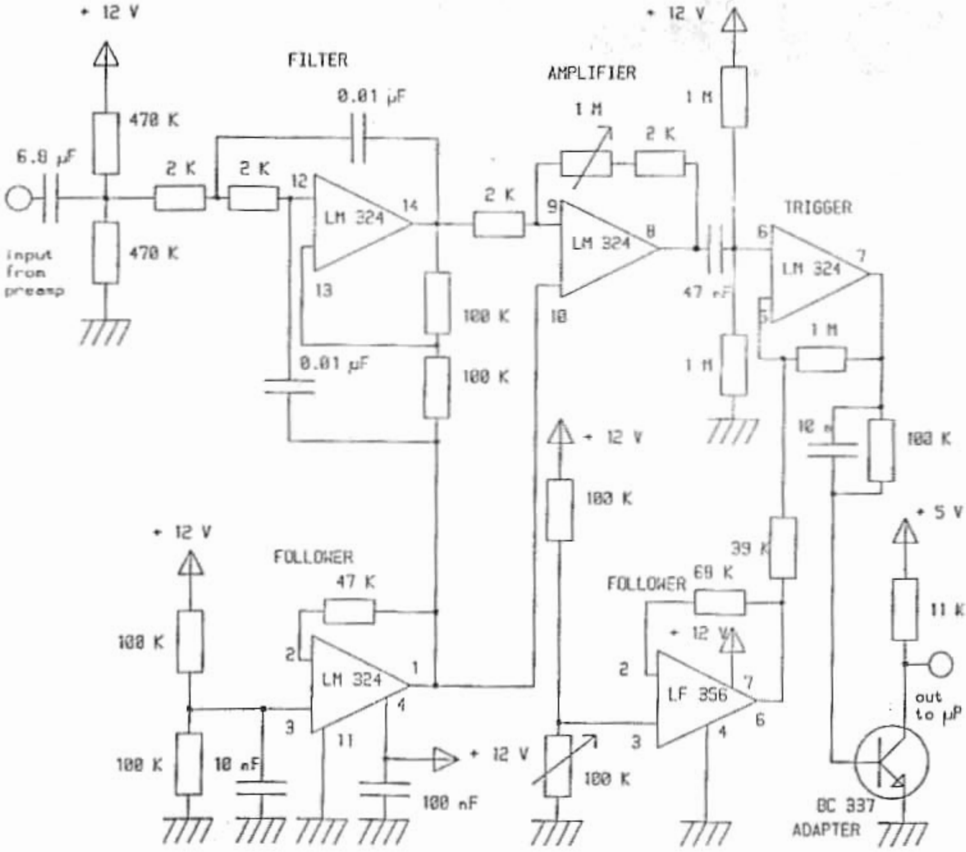

Fig.33a: Filter and Trigger Circuit

setup to measure distances from zero up to 500 metres. A lower pulse repetition frequency would probably give no additional range, even with a better 30 MHz IF unit barely more than 500 metres could be expected.

What we need to investigate now is how fast we can achieve frequency switching at 10 GHz. The 20V, 1 microsecond pulse for the varicap diode must have an internal resistance as low as possible in order that the pulse edges are as steep as possible (Fig.28).

We hope then that the 10 GHz oscillation (that's still 10,000 oscillations in one microsecond) follow on directly from the change in capacity, so that bursts as clean as possible are sent. During reception, when the signal is mixed down to 30 MHz, we shall only be counting 30 oscillations in 1 microsecond; 30 is not many.

The amplifier and filter circuit must be optimised with care if accurate results are to be achieved. We could spread out the frequency count over several periods, to increase the accuracy. The count result must be multiplied by two then, in order to compensate for the 1µs gaps between the 1µs bursts (Fig.29).

This measure would make the critical filter between IF preamp and HF receiver superfluous (Fig.30). The aperiodic amplifier with a necessary amplification of 100,000 to 1,000,000 would not be entirely uncritical, however. The frequency counter would count for 2 seconds and each time be preset by 30,000,000.

If we now measure the speed of a car travelling at 100km/h, it will have moved on 56 metres during the 2 seconds measuring time. It would be advisable then to select a shorter measurement window. In the deliberations that followed, an opportunity for this occurred.

Our setup can be simplified in two ways:

a) If the doppler frequency lies between

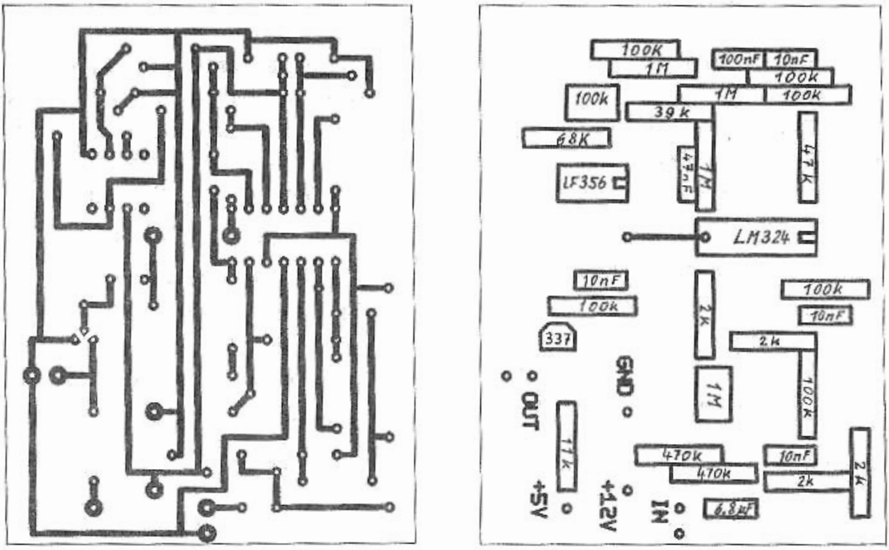

Fig.33b/c: Printed Circuit Board and Component Layout for Counter Display

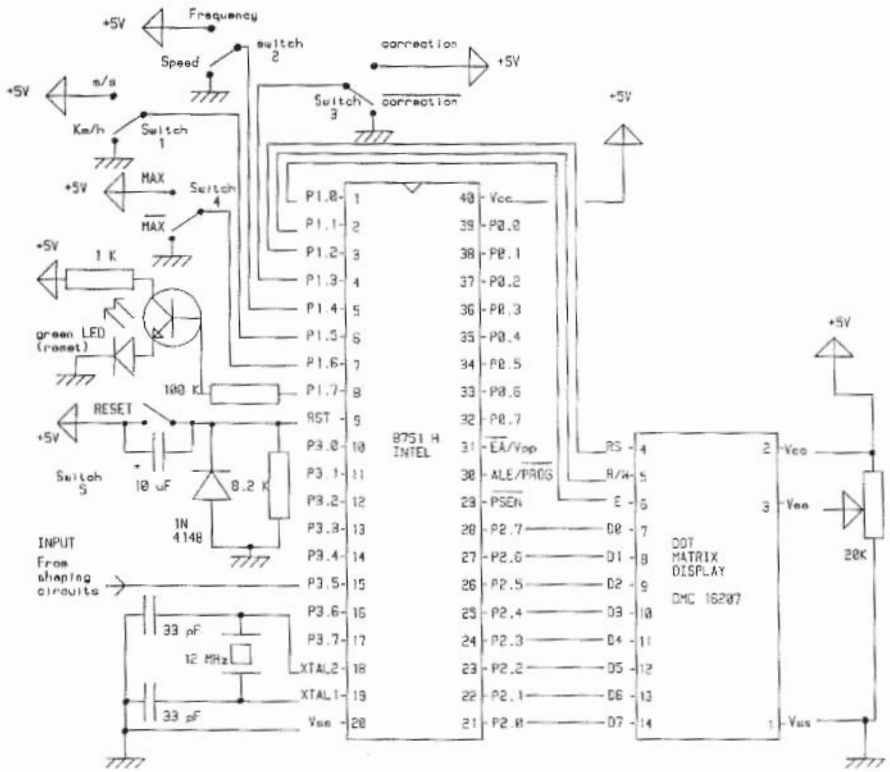

Fig.34a: Processor/Counter Display

30.000000 and 30.018000 GHz we can omit the three left-hand positions of the display. Our display, which only has to cover the five remaining digits, doesn't even have to be preset any more.

b) As we have seen that the doppler frequency and speed are directly proportional to each other, we can count the number of periods during an intentionally chosen time window and multiply the result by a constant, so as to produce the speed in the desired unit of measurement. The constant is:

$1.463 * 10^{-2}$ for a speed in metres/second

or:

$5.266 * 10^{-2}$ if km/h are desired.

If the counting period now measures 2 seconds we get the frequency in Hz and this gives the simplification that we can multiply this 2 seconds by one of the factors mentioned above. We count:

$$2s * 5.266 * 10^{-2} = 0.1053s$$

and the display gives us the result directly in km/h! During this short period the car driving at 100km/h has only moved 2.9 metres, and this is quite acceptable.

If we wanted the display in metres per second, the counter would need a gating time of:

$$2s * 1.463 * 10^{-2} = 0.029626 \text{ seconds.}$$

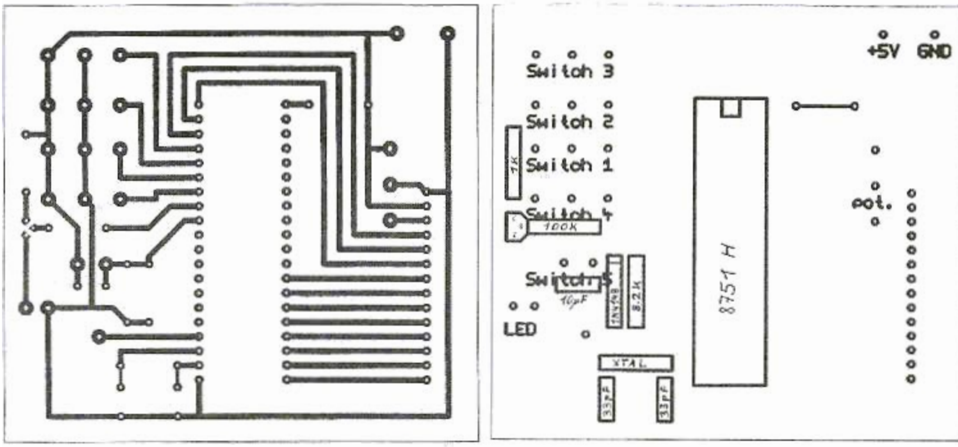

Fig.34b/c: PCB and Component Layout for Counter and Display

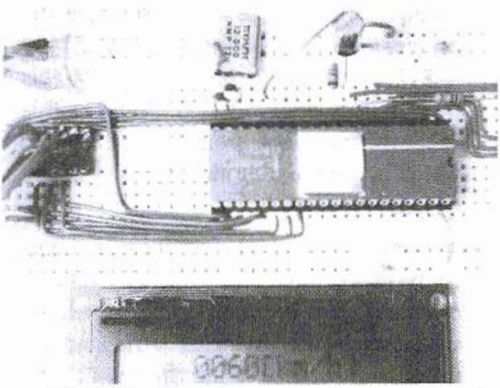

Fig.34d: Doppler radar processor and Display

4. CALCULATING SPEED

The dot-matrix LCD used (Fig.34a) needs to be driven by ASCII commands such as CLEAR, cursor position and others. For the calculating tasks we use an Intel 8751 microprocessor, which works with 8-bit words. With 8 bits we can count up to 255 (decimal), meaning that a doppler frequency of, say, 2000 Hz would be

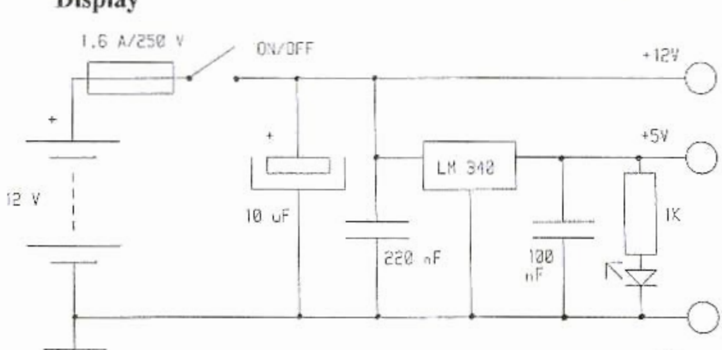

Fig.35a/b/c: The simple PSU for Fig.34a and overleaf the PCB and Layout

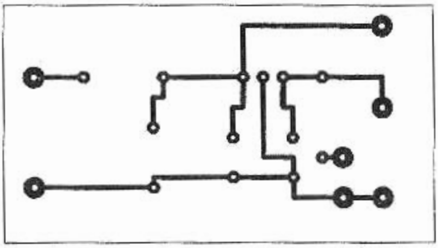

Fig.35b

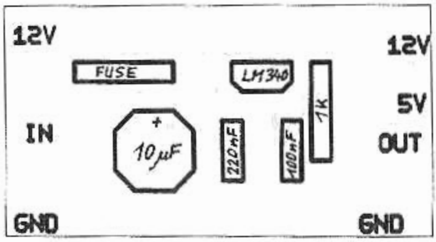

Fig35c

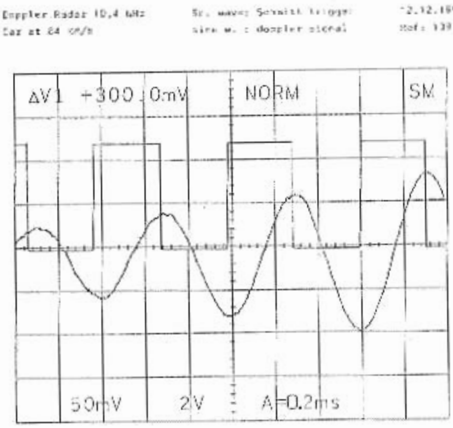

Fig.36: I/P and O/P signals of the Schmitt Trigger

too large. Fortunately, however, the timer embedded in the microprocessor uses 16-bit words.

The selected algorithm counts the incoming doppler pulses over a predetermined time span. With a Radar transmit frequency of 9.4 GHz (without doppler shift) the gate period is 15.947ms if we require speed in metres per second. If we use a different transmit frequency, the program must be modified for the new gate times.

The timer in the processor must be loaded with the complement of the gate time to 65536 ($=2^{16}$). That means, taking an example of gate time = 57409us, that the counter must be loaded with 65536 - 57409 = 8127. It then counts during 57409us from 8127 to 65536. When it reaches this value the processor produces an interrupt which is used to stop the counting of the doppler impulses.

To increase accuracy, eight measurements are taken and from these the mean value is calculated and displayed. The maximum values of all measurements carried out are stored and recalled if the time is insufficient for eight measurements. We assume that the highest value is the best and display this.

F input (Hz)	Display (km/h)	Calculated value (km/h)	Display (m/s)	Calculated value (m/s)
10	0	0.52	0	0.14
50	2	2.59	0	0.72
100	5	5.18	1	1.44
500	25	25.9	7	7.20
1000	51/52	51.8	14	14.40
5000	259	259.1	71/72	71.97
10000	518	518.2	143/144	143.95

Table 2

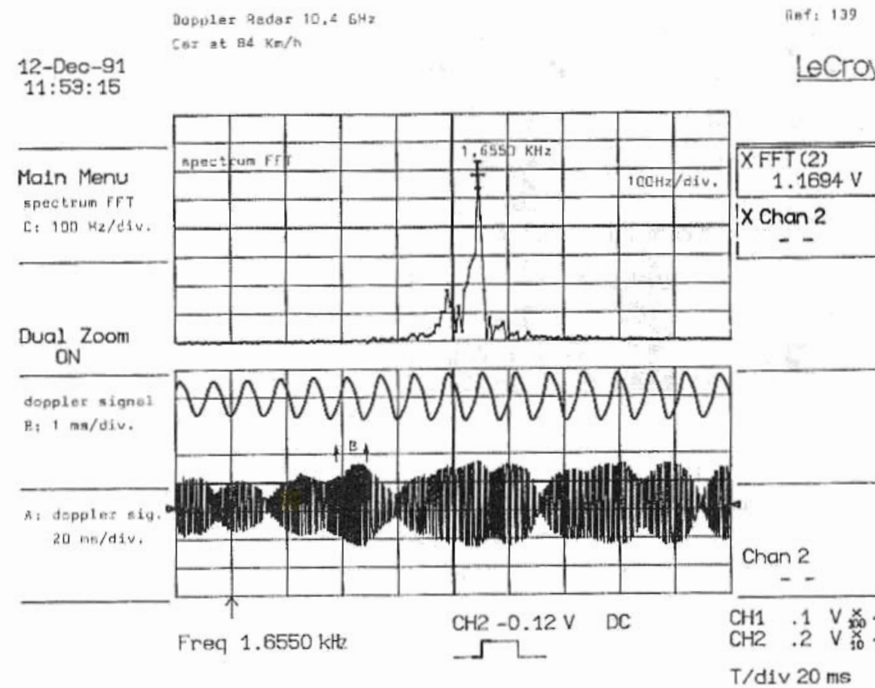

Fig.37: Lower curve shows Doppler signal of a car at 86km/h. Signal variations are clearly visible. Above this is represented extract B; the signal is deviating from a sine wave format. The upper display shows Fast Fourier Transform with a main frequency of 1.6550 kHz

5. PRACTICAL CONSTRUCTION

For our practical trials we wanted to use something simpler. An unkeyed blast-through mixer, very similar to the broad-band FM Gunn transceiver we already had, turned out to be good enough for a range of up to 100 metres.

Figures 31a to 31f show sufficient mechanical details for radio amateurs with some experience of these techniques to see what we have in mind.

The basis is a piece of R100 waveguide with internal measurements 22.86mm x 10.18mm. The Gunn element employed in the oscillator is a CXY11C. Adjoining this but separated by an iris window is the receive mixer with a 1N23C (Fig.31g).

The dish antenna used is by Sivers Lab and has a diameter of 36cm. This should give an antenna gain of 25dB at 9.5 GHz.

Fig's.32a to 32c show the entire electrical arrangements and the low-noise audio frequency preamp in circuit and layout. An LM11CN is used here.

Fig's.33a to 33c show the following stages: filter and amplifier, again in circuit and layout. After adequate amplification

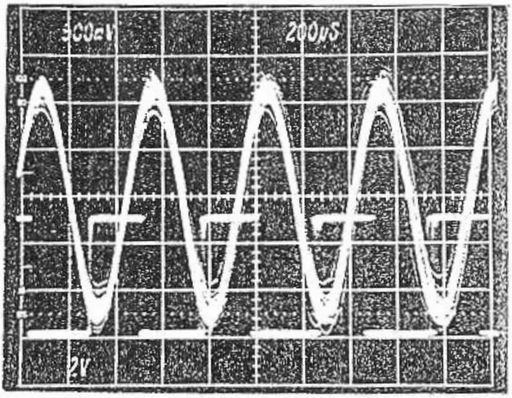

Fig.38: Doppler signal of a train 2030 Hz / 105,2 km/h The high Radar cross-section value produces a steep (900mV/division) and low-noise Doppler signal; the pulses from the Schmitt Trigger are correspondingly clean

the signal is transformed into a rectangular form in a Schmitt Trigger. Finally this signal is passed to pin 15 of an Intel microprocessor which carries out the counting and calculation (Fig's.34a to 34d). The circuitry for the stabilised power supply is shown in Fig's.35a to 35c.

5.1 External connections

Five switches and one LED provide the user interface. They have the following operations:

Frequency (Hz)	Amplitude (mV_{pp})
3200	1.4
7000	2.0
8400	3.0
11000	10
14000	100
20000	1000

Table 3

Switch 1: toggling the display between km/h and m/s.

Switch 2: toggling between displaying doppler frequency and speed. When frequency is displayed switch 1 has no effect.

Switch 3: switches in a correction that takes into account the 33.6 degrees angle between the road and the Radar direction. If this is angle is neither zero or 33.6 degrees, then the software must be modified.

Switch 4: puts the highest value of the series on the display.

Switch 5: resets the microprocessor.

The LED is illuminated each time the micro is reset.

6. PRACTICAL TESTS

On the laboratory bench we were feeding in known frequencies directly into the low-frequency evaluation circuitry and obtained the speed results indicated in Table 2. As we can see, the accuracy of the counter is within plus or minus 1km/h.

6.1 Sensitivity

Table 3 shows the minimum input voltage needed at the preamplifier to produce a stable signal at the output of the Schmitt Trigger (Fig.36).

As can be seen, our direct conversion receiver is fairly deaf! Of course higher receiver sensitivity would increase the range of our Radar - this has been discussed already.

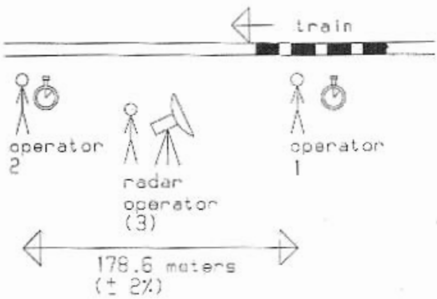

Fig.39: Free space test and Calibration setup

The screen shots (Fig's.37 and 38) show how the system works in practice. In addition the doppler signals produced by trains and cards are recorded at audio level on tape and later shown on an oscilloscope in the laboratory. It is particularly interesting to note here that real doppler signals are not as clean as the ones produced artificially in the lab, but on the other hand, they are not spurious readings.

Practical checking of accuracy and range was achieved as in Fig.39. When a train comes operator 1 signals the exact time the locomotive passes and operators 1 and 2 start their watches. When the locomotive passes operator 2, he gives a signal and they both stop their watches. The average of the two times is taken and operator three reads off the Radar display.

In three tests with varying speeds we found inaccuracies of from 4 to 6 per cent, the variations in the stopped time included. The maximum distance at which we could measure the train was around 100 metres. Possible improvements have already been discussed. If there is no Radar signal on the input, amplifier noise reaches the trigger stage and the display shows spurious readings. This spurious display could of course be suppressed with further software development.

To close we would like to offer cordial thanks to Pierre-Alain Glardon for his intensive and excellent co-operation in this project.

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