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Doppler Radar in the 10 GHz Amateur Band Part-1

For years, a large selection of commercial intruder detectors has been available, based on the Doppler principle and operating in the micro-wave range. We wondered whether the simple 10 GHz transceiver with Gunn elements, which was so successfully used some years ago in the amateur radio world, could perhaps be used in Doppler radar equipment, similar to that used by the police to measure vehicle speeds on the roads.

As it turned out, we were able to obtain some surprisingly accurate readings with decidedly simple circuits! If developed a little further, the equipment could even be used to track aircraft and measure their distance and speed.

If you want to, you can, for example, monitor the speed of your neighbour's car electronically at any time! So now read on!

1. THE RADAR PRINCIPLE

Radar is an artificial word made up from the initial letters of "RAdio Detection And Ranging", which points immediately to the principle involved - determining the presence and the direction of a "target" with the assistance of radio waves and measuring how far away it is. For this purpose, the radar equipment's target must be irradiated with radio waves, which should be as strong as possible (Fig.1).

A small part of the high-frequency energy reaching the target is absorbed by it. The majority is scattered in many directions, and a small part is reflected back to the radar equipment. We know this from EME radio traffic (Fig.2).

If the radar equipment receives an echo from a specific object in the area on which

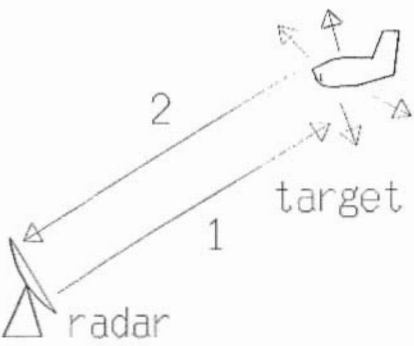

Fig.1: The Radar principle: the waves transmitted by the Radar set (1) are scattered in many directions by the target; a fraction is reflected back to the Radar

it is trained, then there must be a target in this specific direction. This is called detection.

If we now measure the time elapsing between the transmission of the radar signal and the receiving of the echo, we can calculate the distance to the object - knowing, of course, that the radio waves are being propagated at the speed of light.

$$R = c * t/2$$

where:

R = Distance from radar to target

t = Time taken for signal to travel there and back

c = Speed of light (approx. $3*10^8$ m/s)

This is called ranging.

We can distinguish between two types of radar equipment:

→ Pulse radar
→ CW radar

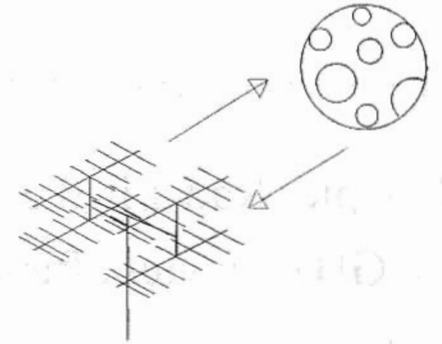

Fig.2: EME Mode, based on the same principle as Radar

1.1. Pulse radar

Pulse radar always transmits short pulses and listens to the echoes in between pulses. The pulse duration is typically in the approximate area of one per-thousandth of the reception time. For the descriptions in Fig.3, the so-called pulse-width repetition rate is thus:

$$X/(X + R) = 10-3.$$

The reception time is set in such a way that the transmission pulses have time to reach targets at the limit of the equipment's

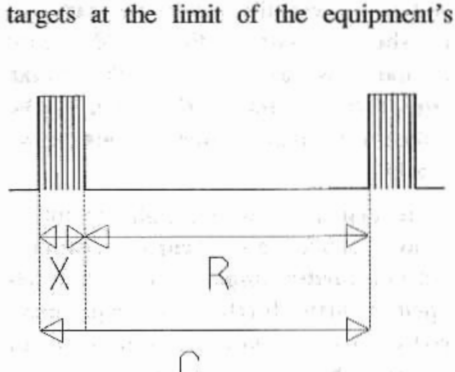

Fig.3: Pulse-width Repetition Rate: each cycle, C, consists of a Transmission Time, X, and a Reception Time, R

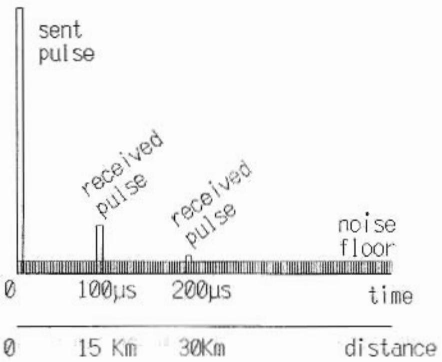

Fig.4: The echoes received from a Transmission Pulse

range and then return. A longer reception time would not make sense, as echoes coming in even later would be weaker than the receiver's limiting sensitivity. It is thus time to transmit a new pulse (Fig.4).

The pulse repetition frequency (PRF) is a very important parameter in radar technology (Fig.5). For the radar measurement of short distances, a high pulse repetition frequency is used because the echoes are already arriving shortly after the pulse has been transmitted. For large distances, on the contrary, the echoes need more time, so that a low PRF is indicated. In practise, the repetition frequencies lie between one and several kHz.

The briefer the pulse duration, the higher are the accuracy and the resolution of the distance measurement. Short pulses allow several targets close to one another to be differentiated (Fig.6a), whereas with longer pulses they appear as only one target (Fig.6b).

A magnetron is ideally suited to the generation of microwave pulses with high energy at a low pulse-width repetition rate. It has therefore been used for this since the 'forties, with a typical pulse-width repetition rate of about 1 part per thousand. The peak power can attain several megawatts.

But the transmission pulse duration can not be reduced indefinitely because, as the pulses become shorter, the reflected energy per pulse is reduced, and thus, of course, the energy of the echo. It must also be taken into account that shorter pulses have a greater signal band width.

1.2. CW radar

CW stands for continuous wave. As the name indicates, the transmitter is continuously switched on, but the frequency is switched between two or more values. The time between two frequency switchings must be sufficient for the signal to reach the target and return (Fig.7).

It has probably become clear that CW radar has nothing to do with the amateur radio meaning of "CW" as telegraphy mode.

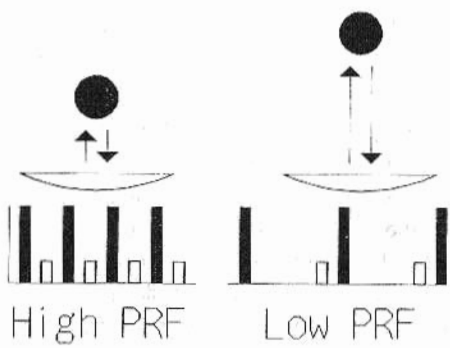

Fig.5: The Pulse Repeat Frequency must be matched to the distance to be measured: high for short range and low for long range

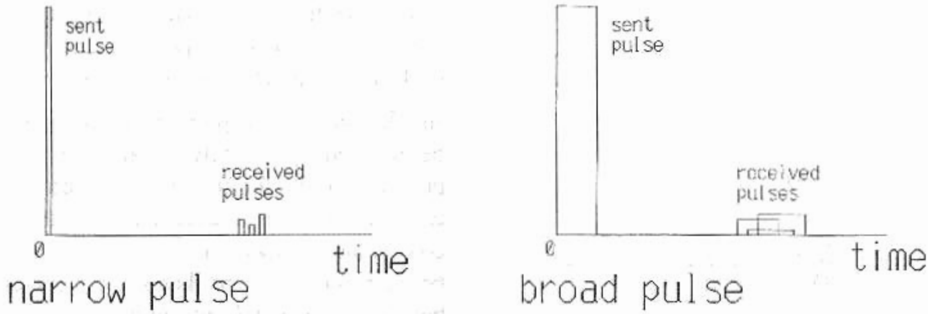

Fig.6: If the Transmission Pulse is short, targets close to one another can be differentiated. With long pulses, on the other hand, the echoes overlap

2. PRINCIPLE CONSIDERATIONS

The pulses from the classic pulse radar can be replaced by bursts on one frequency, with continuous wave transmission on another frequency in between. It is not all that simple to switch the frequency of a magnetron, except with special models. So several magnetrons must be used and must be switched at high power, which is also not a trivial matter. Although continuous magnetrons do exist (for example, those used in micro-wave ovens), using them in CW radar equipment is not easy either.

The travelling-wave tube (TWT) has many advantages in comparison. Its frequency can be varied by about 10% and it is easy to modulate because it can be used as an amplifier. So complicated forms of signal can be generated at the desired output power, even in small signal stages, and they are then much cleaner than if an attempt is made to modulate a magnetron accordingly (Fig.8).

With a travelling-wave tube, for example, coherent pulses can also be generated. Since the returning echoes are then also coherent, special filtering techniques can be used in the receiver which increase the signal-to-noise ratio or the range width. The disadvantage of the travelling-wave tube is that it can not generate the extremely high levels of power which characterise a magnetron.

For the radio amateur, of course, there is no question of using magnetrons, because in general they are much too powerful. One exception covers the types which are used in micro-wave ovens. They are cheaper than a 4CX250B, easily obtainable and also, if you buy a complete (old)

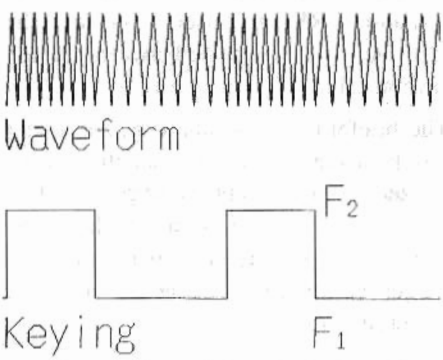

Fig.7: Waveforms of a Continuous Radar

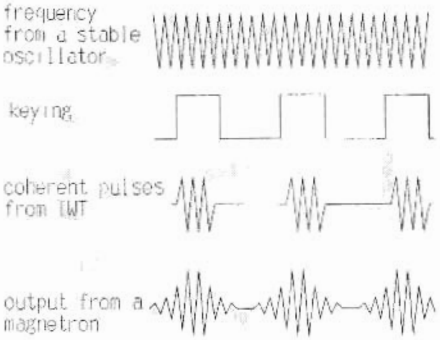

Fig.8: Comparison of Output signals from a Travelling Wave Tube and a Magnetron (only a few waves are shown out of the thousands in every pulse)

oven with them, equipped with a power supply and with cooling. With some comparatively simple modifications, the frequency can be moved to the 13cm

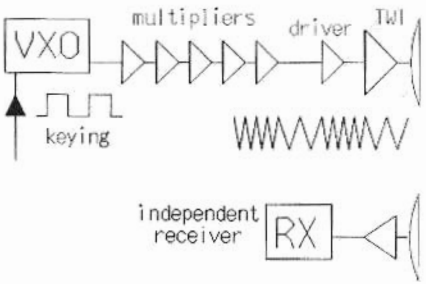

Fig.9a: Continuous Radar with FM

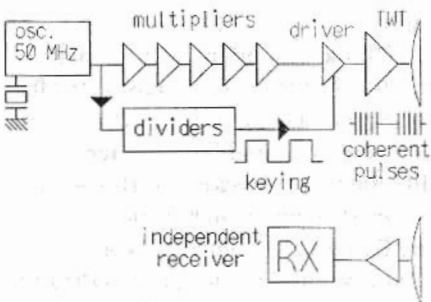

Fig.9b: Pulse Radar with Coherent PCM

amateur band and many hundreds of Watts of energy can be re-routed to an aerial. That would certainly be an interesting project (8). Switching the aerial between transmission and reception would, of course, not be exactly simple if you wanted to avoid baking the receiver input to a crisp.

Anyone who has the good fortune to get hold of a travelling wave tube amplifier can certainly also use it to carry out very promising experiments in the field of radar technology, as demonstrated by Fig's.9a and 9b.

For those amateurs who are really ''poor'' (i.e: lacking money, not spirit), the Gunn diode oscillator would seem to offer the only possibility for radar experiments. The obvious mode is CW, although we have read (1) that Gunn diodes can be forced into an intermittent high-powered mode if they are pulsed at an operating voltage which is higher than usual. But we did not investigate this type of misuse.

The lower microwave frequencies, such as the 23cm band, can be used for radar experiments, and normal ready-made FM transmitters probably can too.

The only problem would be switching the aerial between transmission and reception. You can certainly not switch a mechanical relay at a level of several kHz. So you would have to switch to a separate aerial for the receiver.

It should also be mentioned that the first radar sets operated in the VHF range, which could still be done today in principle. Even the short-wave range is used for radar, because there you can see ''over the horizon'' (remember the Woodpecker!).

2.1. The Radar Equation

We shall now carry out a theoretical study to determine the range width. The range width depends on the power received - more precisely, on the signal-to-noise ratio in the radar receiver.

We shall make use of the following values:

- PE Transmission power (W)
- PR Received power (W)
- λ Wavelength (m)
- R Distance from radar to target (m)
- A Reflected wave cross-section area of target (m^2)
- G Aerial gain

The power reflected back per solid angle unit is:

$$P_1 = \frac{P_E * G}{4\pi} \text{ (W)}$$

At the target, at a distance, R, from the radar, the power density is:

$$P_2 = \frac{P_E * G}{4\pi R^2} \text{ (W/m}^2\text{)}$$

The target reflects a power, P3, which is proportional to P2:

$$P_3 = A * P_2 \quad \text{(W)}$$

A, the radar back scatter cross-section, is a measure of the target's capability of reflecting radar waves. In warplanes, this value is made as small as possible.

P4 is thus the back-scattered power per solid angle unit:

$$P_4 = \frac{P_3}{4\pi} = \frac{A * P_2}{4\pi} = \frac{P_E * G * A}{(4\pi R)^2} \text{ (W)}$$

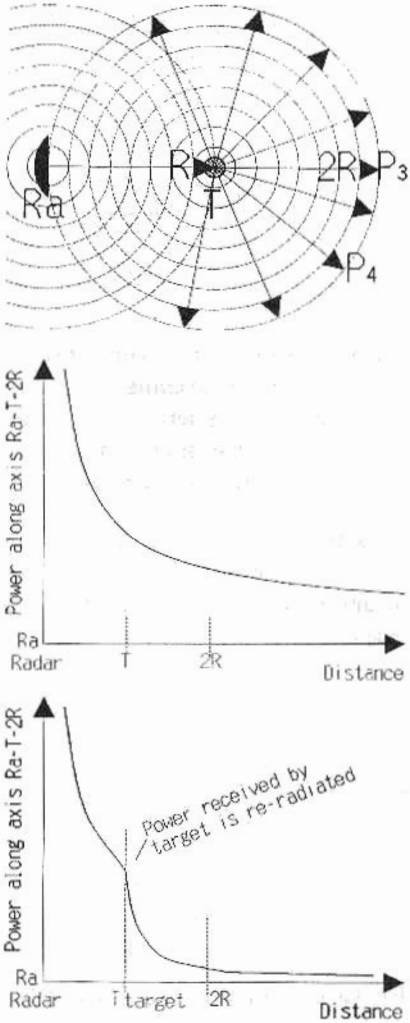

Fig.10:
The Radar Equation: only a small fraction of the energy transmitted from the Radar set, Ra, reaches the target, T, and is scattered here in many directions (a). Because of this scatter, the small signal which comes back to the Radar set is much weaker (10c) than it would be if it had travelled the entire distance - namely 2R - in free space (10b)

Finally, the following power density returns to the radar aerial:

$$P_5 = \frac{P_E * G * A}{(4 \pi R)^2} * \frac{1}{R^2} = \frac{P_E * G * A}{(4 \pi)^2 * R^4} \text{ (W/m}^2\text{)}$$

The aerial gain depends on its equivalent cross-section, Ae:

$$G = \frac{4 \pi A_e}{\lambda^2}$$

For a level wave front, the aerial therefore behaves like an absorbent aperture with a surface, Ae, of:

$$A_e = \frac{\lambda^2 * G}{4 \pi}$$

The signal supplied by the aerial to the receiver is thus P5 * Ae, which means that:

$$P_R = \frac{P_E * G * A}{(4 \pi)^2 R^4} * \frac{\lambda^2 * G}{4 \pi} = \frac{P_E G^2 A \lambda^2}{(4 \pi)^3 R^4}$$

If PR is the smallest signal usable for the radar set, then the maximum range width, R, can be read off from the following equation:

$$R^4 = \frac{P_E * G^2 * \lambda^2 * A}{(4 \pi)^3 * P_R}$$

The range width itself is thus the fourth power root of the fraction to the right of the equals sign. The problem in constructing radar sets for large range widths becomes clear here. The range width is proportional to the fourth power root obtained from the transmission power! So if, for example, you want to double the range width, then if everything else remains the same you must increase the power by a factor of sixteen!

We shall now try to understand the mathematics intuitively. As Fig.10a shows, the wave front is strongly curved at point Ra. As the distance grows, the radius of the curve becomes larger and larger, i.e. the wave front becomes flatter and flatter. If a wave front is strongly curved, the power diminishes very rapidly, which is shown by the steep sections of the curve in Fig.10b. If the wave front now becomes flatter and flatter, the power diminishes less and less, and thus the curve in Fig.10b becomes less and less steep.

At a great distance from the transmitter, the wave front is almost perfectly flat, so that the wave can cover great distances while losing almost no power. The power which transports the wave moves in only one direction.

Now what happens if an obstacle (radar target) is in the way? Right - the target scatters the waves in all directions again (Fig.10a), so that once again the propagation behaviour seen at point Ra returns. There is again a very steep fall in the (small reflected) power (Fig.10c). The power which strikes the target is proportional to ÖR. The power which reaches the radar receiver is thus proportional to √√R, or to ⁴√R. In certain cases, this very high attenuation can be circumvented by building a transponder into the target. Whenever the transponder receives a signal from the radar, it amplifies it and loads it with information - such as identification and flying height - and then transmits the signal back to the radar set. The power received is then proportional to the fourth power root derived from R (Fig.11). It is clear that we can not make use of this possibility.

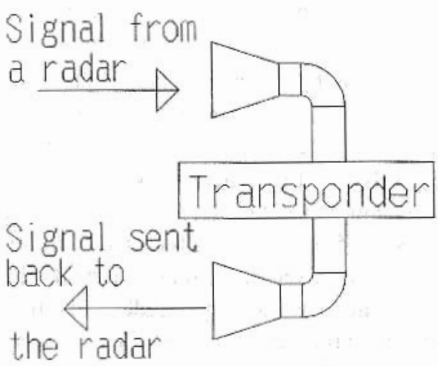

Fig.11: The Transponder Principle

The radar equation also shows that the 4th power also applies to the receiver sensitivity. The sensitivity has to be improved by a factor of 16 if the range width is to be doubled.

The smallest signal which the receiver can evaluate can also be expressed as the input noise power, N, for a given signal-to-noise ratio, SNR:

$$P_R = N * SNR$$

The radar equation then becomes:

$$R^4 = \frac{P_E G^2 \lambda^2 A}{(4\pi)^3 N * SNR}$$

The noise power, N, contains a fraction received from the aerial and a fraction generated in the receiver. The latter has many sources, among others the thermal noise. This can be very closely approximated by using the thermodynamic law:

$$N = k * T * B$$

where:

k is the Boltzmann constant: $1.374*10^{-23}$ W/Hz/K or Joule/K
T is the temperature of the object (K)
B is the receiver noise band width (Hz)

Now, we still haven't got the noise factor, n, which expresses the factor by which the receiver noise exceeds the minimum noise power established by the thermodynamic law. The total noise power is thus

$$N = n * k * T * B$$

Now we can write out the radar equation in a more comprehensive form:

$$R^4 = \frac{P_E G^2 \lambda^2 A}{(4\pi)^3 * SNR * nkTB}$$

The numerator still contains the reflected power, PE, and the received power, PR, has been resolved in the denominator.

As the final factor, we would now like to introduce the power losses between the generator and the aerial, as well as between the aerial and the receiver. The sum of these losses, L, comes into the denominator of the radar equation:

$$\boxed{R^4 = \frac{P_E G^2 \lambda^2 A}{(4\pi)^3 * SNR * nkTB * L}}$$

This should suffice for our purposes, and we shall now use this radar equation to estimate the range width of our experimental radar set-up (Fig.12). Let us assume the following values for our 10 GHz blow-through mixer with Gunn elements:

P =	$10mW = 10^{-2}W$
G =	20dB (or more) = $100 = 10^2$
	thus: $G^2 = 10^4$
λ =	$c/f = 3 * 10^8/10 * 10^9 = 30mm$
	thus: $\lambda^2 = 10^{-3}$
A =	$1m^2$
$(4\pi)^3$ =	$1.98 * 10^3$
SNR =	10dB = 10
n =	20dB = 100
	(not exactly state of the art!)
T =	$290 = 2.9 * 10^2$ K
B =	8 kHz = $8 * 10^3$ Hz

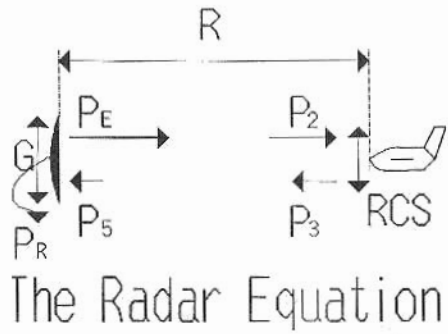

Fig.12: The most decisive values from the Radar Equation

This is an adequate band width, for if the Doppler frequency reaches 8 kHz, that corresponds to a target speed of 459km/h.

$$L = 6dB = 4$$

We now introduce this value into the above radar equation and we get: R = 140m.

That might appear somewhat optimistic for the minuscule transmission power, but we shall find out by practical experiments. Initially we want to try and increase our range width on paper. If we had a hypothetical receiver without noise and without losses, only the thermal noise would remain and, with SNR = 1, we would obtain n = 1 and L = 1 from our radar equation, if the other parameters remained unaltered, giving R as 1.12km!

With a modern receiver and small power losses, the range width will thus lie somewhere between the extremes 140m and 1km.

We can now lay the receiver aside and juggle with the other parameters instead:

a) Increasing Aerial Gain

With a reflector diameter of 160cm, we would obtain a gain of about 40 dB, i.e. a hundred times the earlier figure, so that the range width is multiplied by ten: R = 1400m. Disadvantage: targeting with a large aerial is very much more difficult.

b) Using lower frequencies

This makes the wavelength bigger - for example about 10 times as big if we use the 23cm band. The range width is increased by the square root of 10 = 3.16. Thus R = 440m. Disadvantage: as we are still calculating on 20dB gain, the aerial becomes correspondingly larger!

c) The last possibility - increasing the transmitter power

Unfortunately increasing the transmission power by ten only increases the range width by the fourth power root of 10, which is 1.77. So a range width of 140m becomes 249m at a transmission power of 100mW, or 442m at 1W, or 787m for 10W, and so on.

A super 3cm radar set with a transmission power of 10W from a travelling-wave tube and a 1.6m parabolic antenna could have a range width of between 7km and 30km, depending on the quality of the receiver.

A 23cm radar set with a transmission power of 100W and an antenna gain of

20dB (super long Yagi) would have a range width of between 4km and 30km.

So we can see that it is theoretically possible to track aircraft - especially large aircraft - and measure their speed. Now it's time to deal with the radar backscatter cross-section (RCS).

2.2. Radar Backscatter Cross-section (RCS)

The higher the RCS value, the greater the range width. All range widths given above are based on an RCS value of $1m^2$. It is clear that, for example, a Boieng 747 has a much higher RCS value. Moreover, it is immediately clear that the RCS value is always variable, depending on the orientation of the target relative to the wave front of the radar signal (Fig.13).

The RCS value is also dependent on the shape of the target. Flat surfaces act like mirrors and reflect the waves very well. Sharp edges, slots and points can act as aerials and reflect the microwave energy received. Multiple reflections take place in cavities or intersecting surfaces, and the incoming wave can be reflected to the radar set (Fig.14).

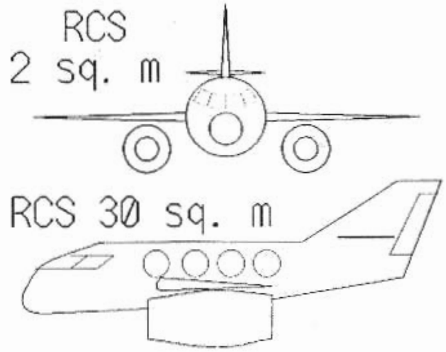

Fig.13: The Radar Backscatter cross-section, RCS, depends, among other things, on the orientation of the target

But the RCS value is not dependent on the size and shape of the target alone. The material it's made of also has an influence. Metal reflects much better than, for example, plastic or composite materials. Certain materials which absorb microwaves are used to reduce the RSC value of warplanes, as is special shaping (remember the stealth bomber). Some aircraft optimised in this way should allegedly have an RCS value no greater than that of a seagull!

If we now target a large (civilian) aircraft with an RCS value of $50m^2$, the theoretical range width of our radar will be multiplied by the fourth power root of 50 = 2.6. So the original range width of 140m becomes about 400m.

Now here are a few examples of RCS values:

Human being:	$0.1 - 1.9\ m^2$
Seagull:	$0.01\ m^2$
Fly:	$0.00001\ m^2$
Aircraft:	$0.5\ m^2$ (head-on)
	$20\ m^2$ (sideways-on)

A more precise RCS value can be calculated only for simple surfaces (flat surfaces, spherical surfaces and the like). A multiform object can be seen as a combination of many simple shapes. Some of them will be good reflectors, others bad. To the radar set, such objects appear as a collection of bright spots between dark spots.

Depending on whether the waves from the various reflecting part-surfaces finally reach the radar receiver more in phase or more in opposite phase, the target is bright or dark, the RCS value large or small. If any of the structures of the target at all is in

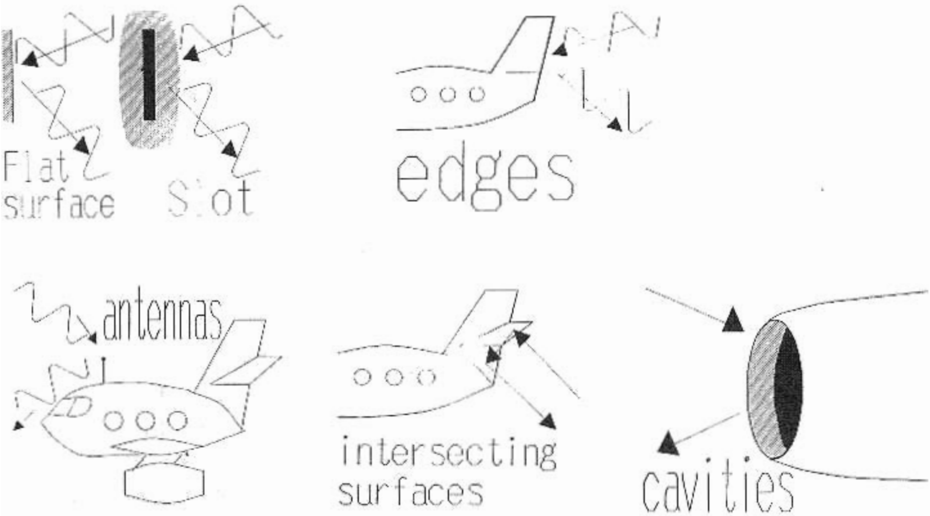

Fig.14: Certain structures of a Radar target can reflect particularly well, especially if their dimensions are of the order of magnitude of the wavelengths used; this creates particular;y bright spots in the Radar image

resonance with the radar wavelength, this produces a particularly bright spot, because the reflection is particularly effective.

It should now no longer come as a surprise to find that the RCS value of a moving target is continually varying in practise, because the phases of the wave fractions reflected are continually being superimposed on each other. Variations in the propagation conditions in the atmosphere, which are expressed as fading with changing strength and time constants, also play a part. Each individual radar echo will thus have a different intensity. There will be an average value, with a random scattering around it.

Thus, when signals are processed in the receiver of a pulse radar, a number of successive echoes must be determined in order to increase the accuracy of the process.

2.3. The Doppler effect

The Doppler effect is familiar to everyone since rail and road traffic became widespread. This effect has become very important in astronomy (Fig.15), as the so-called red shift of spectra, on the basis of which their speeds and distances can be calculated on the cosmic scale.

The Doppler effect affects all electromagnetic waves, and this includes microwaves. Here it can even be measured quite handily. The frequency shifted by the Doppler effect can be calculated using the following formula - with the proviso, of course, that the speed of the object is small in comparison with the speed of light:

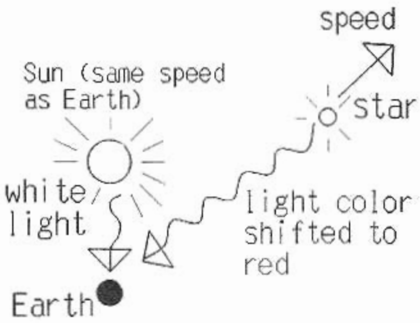

Fig.15: The Doppler effect in Astronomy

$f' = f * (1 - (v/c))$

- f' = the frequency received
- f = the frequency transmitted
- v = speed of object
- c = speed of light

But we must remember that this formula is based on the assumption that the frequency, f, is generated by the moving object itself, not by the observer.

2.4. Doppler radar

In a Doppler radar system, the output frequency, f, is generated, not by the moving object, but by the radar set. When it encounters the moving object, a Doppler frequency shift has already taken place. This displaced frequency, f', is reflected back to the radar set and undergoes a second Doppler shift. The reception frequency, f'', thus includes a double frequency shift (Fig.16).

$f'' = f * (1 - (2\,v/c))$

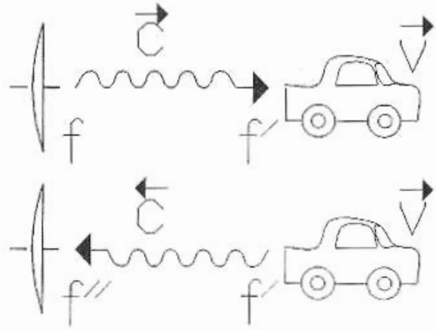

Fig.16: The Doppler effect in its dreaded form. With Doppler Radar the Doppler Effect is doubled when the return signal is received

The Doppler frequency, fd, is the difference between f and f'', i.e. the total value of the frequency shift which the original frequency, f, has undergone due to the Doppler effect.

$f_d = f * 2\,v/c$ oder $v = f_d * c/2f$

As we can see from this formula, the speeds of the target, v, and the Doppler frequency, fd, are directly proportional to

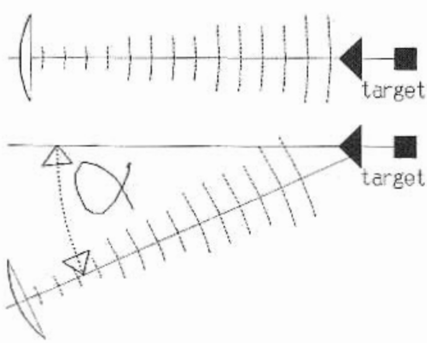

Fig.17: The Alpha Angle must be taken into account in the calculation of the speed

Doppler Frequency Hz	Speed m/s	Speed km/h
0	0	0
10	0.146	0.526
50	0.731	2.633
100	1.463	5.266
200	2.956	10.532
500	7.315	26.33
1000	14.63	52.66
2000	29.26	105.32
5000	73.15	263.3

Table.1: Doppler Frequencies and Speeds for a Transmission Frequency of 10.25 GHz

one another. We can also see why it is particularly easy to deal with the Doppler effect in the micro-wave range. For speeds which arise in practise, Doppler frequencies are in the low- frequency range. able 1 gives some examples of this, based on the assumption that the transmission frequency of our radar set is 10.25 GHz.

As we see, an interesting speed range can be covered using a handy receiver range width. The Doppler formula was averaged to obtain the figures for the table. Multiplying the frequency by $1.463*10^{-2}$ gives the speed in m/s. The factor for the speed in km/h is $5.266*10^{-2}$.

So far we have been assuming that the target is moving directly towards or away from the radar set. But in practise this is extremely rare. There is almost always an angle, alpha, between the direction of propagation of the radar waves and the direction of motion of the target (Fig.17).

The Doppler equation must therefore be expanded as follows:

$$f_d = \frac{f * 2v}{c} * \cos\alpha$$

or

$$v = \frac{f_d * c}{2f * \cos\alpha}$$

If the radar set is standing at the side of the road and the target is picked up when it is a few tens of metres away, cos alpha is so close to 1 that the term can be ignored for practical purposes. If the alpha angle is 33.5°, cos alpha = 0.83. The speeds listed in Table 1 would need to be multiplied by 1.2 in such a case.