THE DIFFERENCES BETWEEN PULSE RADARS AND FMCW ONES

Bill Mullarkey 7th December 2008

1. INTRODUCTION

Until recently the only radars available to the leisure mariner were “Pulse Radars”. One group of companies, owned by Navico, have now launched a radar that they call “Broadband” but which engineers and scientists would refer to as “Frequency Modulated Continuous Wave” (FMCW), which is not quite as snappy on a sales leaflet!

The purpose of this note is to explore some of the differences between the two technologies. It is important to hold on to the word “technologies”: the author has not had the opportunity to test the Navico products or compare them to well-established competitors. This note refers to the capabilities and relative benefits of the different technologies and not to how well a particular product has been designed to exploit those benefits.

It is important to keep in mind that practical radars have practical limitations. The pulse radars available in the market make compromises and so will the FMCW ones. The real differences between products may depend more upon the compromises than the theoretically achievable performance.

2. SIMILARITIES BETWEEN PULSE AND BROADBAND (FMCW) RADARS

It may be easier, before considering the differences between pulse and FMCW radars, to consider what they have in common. Every radar whose output is a chart-like picture has to measure the range and bearings of the targets it sees and then convert those measurements into a display that the user can understand. Figure 1 illustrates this.

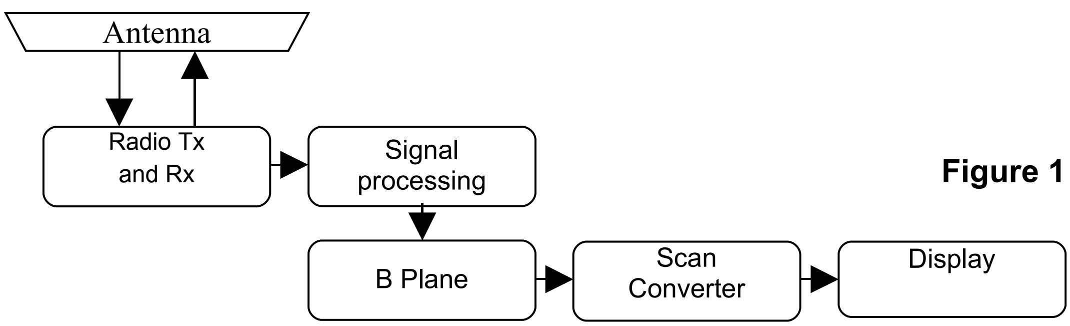

Figure 1

The B Plane is simply an area of memory addressed by range and bearing: some prefer to think of it as a “surface” on which every resolution cell has a number in it which represents the strength of the received echo. Figure 2 illustrates a single target on such a surface.

To load that B Plane, every leisure-marine radar has a radio transmitter which radiates energy via a rotating directional antenna and a receiver which listens for the echoes. Bearing is easily determined by knowing where the antenna was pointed when the echo was received. Range is more difficult because it has to be determined indirectly. This is done by measuring how long it took for the radio signal to travel from the transmitter and back again after being reflected by the target. The signal travels at a known speed of about 300,000,000 metres per second (depending upon the atmosphere’s refractive index). (Physicists

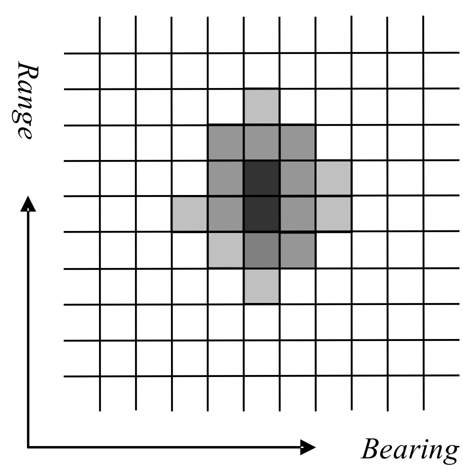

Figure 2

use the symbol "c" for this speed, which may be recognised from Einstein's famous $E=mc^2$) The range of a target falls from the high-school algebra equation

$$Range = \frac{c\, t_{return}}{2} \text{ metres}$$

where t_{return} is the time that it took the signal to travel from transmitter to the target and back again. To get a sense of the numbers involved, if t_{return} = 12.36 µs then *Range* would be 1,852 metres, which is one nautical mile.

3. HOW PULSE AND BROADBAND (FMCW) RADARS DIFFER

So there we have it. All radars need to measure t_{return} : an important difference between pulse radars and FMCW ones is how they do so. The former transmits a pulse and measures the time it takes to return. The latter transmits continuously but varies the frequency (hence the Frequency Modulated Continuous Wave). Once the signal has left the antenna its frequency obviously does not change. The further away the target is then the greater is the difference between the frequency of the received echo and the frequency that the transmitter is then using. Figure 3 illustrates the two schemes.

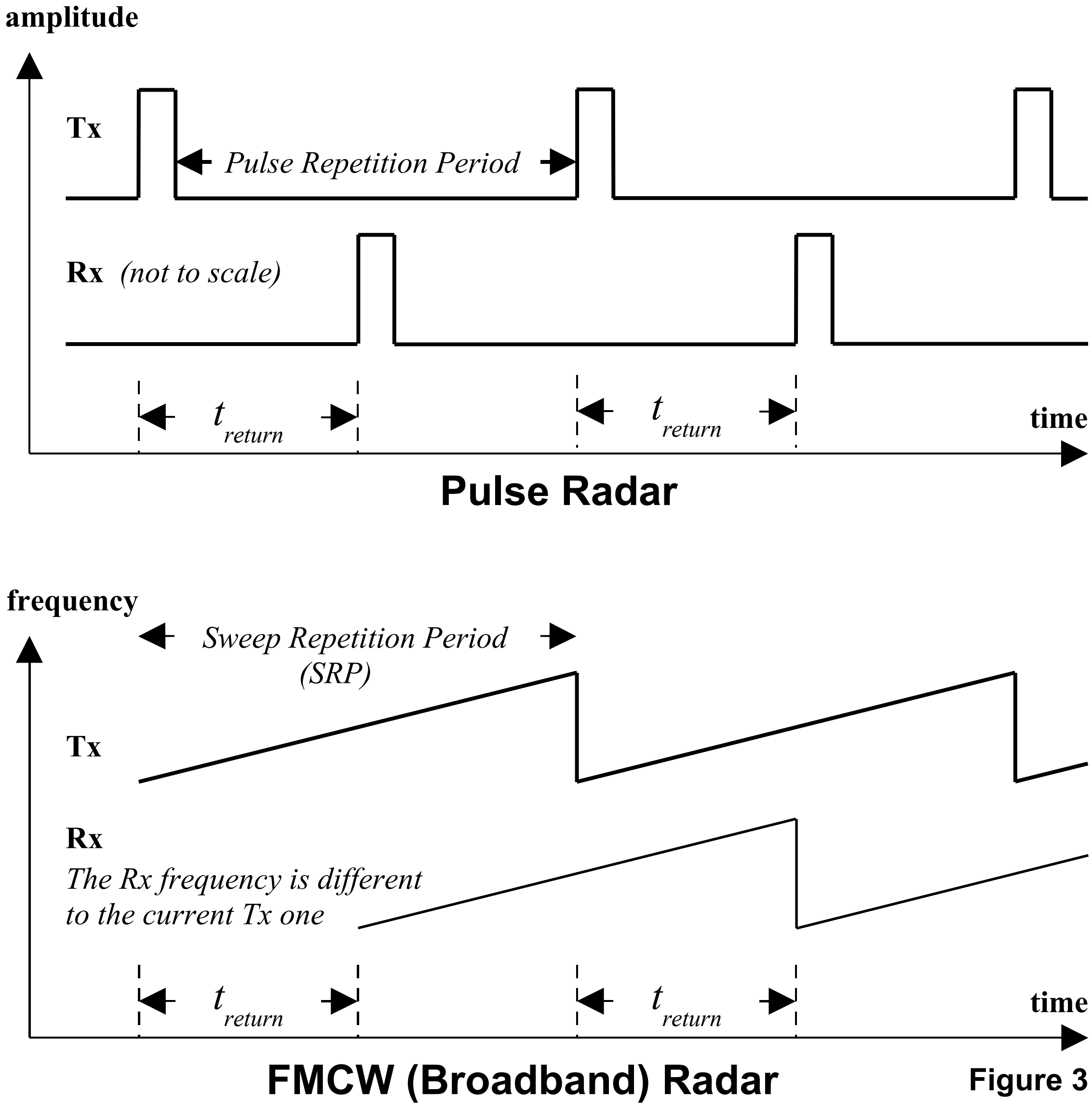

Figure 3

The main hardware difference between the two radar types is that pulse radars use magnetrons to generate the energy that they radiate whilst FMCW ones use solid state amplifiers. Another is that in the leisure-marine market pulse radars use a single antenna whilst an FMCW one uses two—one mounted on top of the other generally in the same enclosure. The difference arises because pulse radars either transmit or receive: FMCW ones do both at the same time.

If the FMCW radar sweeps through f_{sweep} Hz in SRP seconds and, within the SRP, the difference between the frequency of the echo and that currently being transmitted is $f_{difference}$, then

$$t_{return} = \frac{SRP \times f_{difference}}{f_{sweep}} \text{ seconds}$$

which plugs back into the only other equation used in this note to give *Range*. The keen eyed will observe that the frequency difference has a step in it the end of the transmitter's SRP. That, however, is relatively easily managed in a radar that has an advanced signal processing capability An alternative but less efficient approach is to leave a period of no transmission between sweeps.

3.1 Target Detection

All radar receivers generate noise of their own and for a radar to detect a target, the target's echo generally needs to have more energy than the radar's own noise. A radar receiver does not accept a single frequency but a range of them called its "bandwidth" and the amount of noise energy is proportional to that bandwidth.

In order to improve the ratio between the echo and the noise there are only three things a designer can do: illuminate the target with more energy, reduce the inherent noise and use as little bandwidth as practical.

3.1.1 Energy NOT Power

Please note that it is the energy that matters when considering target detection not the peak power. In the past, radar manufacturers have sold against each other on the basis of their radar transmitter's power: 4kW was better than 2kW and 12kW was better than both. In physics, the unit of energy is the "Joule" and one Joule is one Watt of power delivered for one second. When making comparisons between pulse radars and FMCW ones we need to think in terms of Joules not kilowatts. It could be argued that if we are to consider Joules per second that is just the mean power so compare mean powers. Take your pick but choose one and forget peak power. As the antenna rotates it will illuminate the target with energy for a few milliseconds which is why the author prefers to think in terms of energy.

A conventional 4kW radar will typically use a 100ns pulse on the short ranges with a Pulse Repetition Frequency of about 3kHz: multiplying the numbers together establishes that it radiates 1.2J of energy per second.

A 2W FMCW radar will typically sweep the frequency over a period of about 1ms, which corresponds to a pulse width of 1mS and have a PRF of 1kHz. That is, it transmits all of the time and radiates 2J of energy in every second. For practical reasons, it may not have the processing power to radiate continuously but the principle remains.

On longer ranges, a pulse radar may have a 1us pulse and a PRF of about 1kHz: that provides 4J. The energy from the FMCW radar is independent of the radar's selected range.

3.1.2 The effect of "bandwidth" on target detection

A less obvious difference between the radar types is the receiver bandwidth they require. A pulse radar requires a bandwidth that is inversely proportional to the pulse width. That is, it requires a wider bandwidth on the shorter ranges than it does on the longer ones. An FMCW radar has the opposite requirements. The shorter the range, the less the difference between the transmitted and received frequencies and the less bandwidth is required. The less the bandwidth, the less the receiver noise energy that the target energy needs to exceed for reliable detection.

FMCW radars have a further difficulty at longer ranges because their performance tends to be determined by the spectral purity of the transmitted signal rather than the receiver's noise.

Having regard to the transmitted energy, the receiver noise and spectral purity, it will be seen that a pattern is emerging. An FMCW radar is inherently capable of having better target detection than a pulse one at short ranges and worse at long ranges.

3.2 Target Resolution

This is a measure of how close two targets can be to each other and still be resolved as two targets. FMCW and pulse radars use similar antennae so, all things being equal, their angular resolution will be the same. As an aside, Raymarine do have a range of open array radars, which they call "Super HD", that uses advanced signal processing to get much better angular resolution than the antenna would otherwise deliver but they have no dome-radar equivalent.

It is when considering range resolution that the FMCW radar tends to come out on top. Without a lot of processing, the best that a pulse radar can deliver is determined by the pulse width. For reasons beyond the scope of this note, it corresponds to a return of approximately twice that pulse width: a 100ns pulse will give a range resolution of about 30 metres. The resolution of an FMCW radar has no lower theoretical limit. Rather the resolution comes from the engineering implementation and, practically, could be as low as 5 metres or so. That also makes the FMCW radar less susceptible to sea clutter because it is less likely to join the waves together into a single mass.

Forgive a bit of deep theory. From an information-theoretic viewpoint, both technologies use similar energy to discover information about a target or group of targets. There ought to be a different mathematical approach to both that would produce similar results from both. The difference lies more in the implementation than the underlying theory. For example, it is known that Raymarine's Super HD open array radars deliver twice the angular resolution than might be expected from the antenna by a naive look at its polar diagram. Similar techniques could greatly improve the range resolution of pulse radars. The simple fact is that until FMCW came on scene there was no motivation to do so. PLEASE refer to the "boxed" paragraph in the introduction.

FMCW has a further advantage over pulse radars and that is the shortest distance that can be seen. A pulse radar has to turn off the receiver for a period of about three times the width of the transmitted pulse and a 100ns pulse leaves the radar blind for about 45 metres.

3.4 Other Differences

FMCW does not get all of its own way. There are two things that it inherently does much less well than a pulse radar.

The first is that it is easily overwhelmed by interference from pulse radars. That is one reason why FMCW radars are not generally used by the military for surveillance or weapons control: they are easily jammed by aiming high power pulses at them. Time and testing will tell how well the Navico products have dealt with this problem.

The second is that they potentially get confused by onboard reflectors such as masts and satellite antennae.

The author expects that much will be made of the different power requirements of the two technologies but care is needed when considering any claims. In physics as in business there are no free lunches. Target detection requires transmitted energy and, as will have been seen above, there is not much of a difference between the two technologies: in one second, the pulse radar radiates between about 1.2J and 4J, depending upon the selected pulse width, whilst the FMCW one radiates about 2J. They do differ in the ratio of peak to mean power and energy but it is the mean that has to be taken from the vessel's batteries.

Where there may be a difference between the mean power of the Navico products and those of competitors is not in their transmitters but in the rest of the electronics. Generally speaking, the more computationally intensive a design is the more power it will use. From which it follows that a radar that uses less advanced signal processing (but which might still deliver all the capability the mariner wants) will generally use less power.

The author chooses not to get involved with the health and safety issues of different peak and mean powers.

Finally, a pulse radar's magnetron takes time to warm up whilst, in principle, an FMCW radar one can be switched on instantly.

4. IN SUMMARY

Inherent differences between the technologies		
Characteristic	**Broadband (FMCW)**	**Pulse**
Short range target detection	Better	Worse
Long range target detection	Worse	Better
Visibility of close in targets	Better	Worse
Target resolution in azimuth	Same	Same
Target resolution in range	Better	Worse
Sea clutter suppression	Better	Worse
Power requirements	Similar	Similar
Requires standby period	No	Yes
Vulnerability to interference from other radars	Difficult to solve	Easy to solve
Vulnerability to onboard reflectors	Potentially a problem	Not a problem
Potential for future development	Only just begun	Mature technology

Author Biography
Professor Bill Mullarkey is an experienced leisure mariner who has spent most of his working life associated with radar systems, whether repairing them as a Merchant Navy Radio Officer or designing them as Managing Director of dB Research. He earned his PhD in 1993 for research concerned with the information contained in radar and similar images. Whilst he enjoys the theory behind engineering, he is not an ivory-tower type as may be deduced by the title of that PhD Thesis – *"A Practical Theory of Communication"*. His research continued after the PhD and the professorship followed a few years later.

Latterly his radar interests have been in shore-surveillance and leisure marine radars. With colleagues, he contributed to the design of Raymarine's HD digital radars and led the team that designed their Super HD version.

He continues as MD of dB Research (www.dbresearch.co.uk) but, in response to the downturn in the leisure marine industry, has also joined Denbridge Marine as Research Fellow so that he can contribute to the design of the next generation of shore-surveillance systems.