This is the second review of this book – the first was carried in our May 2004 issue.

Detecting and Classifying Low Probability of Intercept Radar

Phillip E. Pace
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This book provides a valuable reference to current activities directed to the achievement of low probability of intercept (LPI) radar design and the intercept, detection, and classification of these radar signals. From the breadth of material covered, it is obvious the author has extensive knowledge in this field. In addition to the book's contents, a CD containing MATLAB programs for generating and processing a large class of signals is included for additional study. The book is well-suited as a text covering many details necessary for a broad exposure to the field, but the treatment could leave the student with misconceptions, and a number of questions that beg answers.

The author gives the impression that LPI radar is feasible and is being employed, but he is not clear as to how low the probability is. He also explains how to detect and classify these signals, which would suggest that low might not be very low. In all fairness, the author's point may be that a well-designed LPI radar is not detected by a badly designed intercept receiver; but a badly designed LPI radar is detected by a well-designed intercept receiver. As far as it goes, this view has some validity – but it is not the whole story.

Radar, by its very nature, is not LPI. The reasons are clear. In most applications, the radar cannot avoid illuminating the interceptor. The interceptor is passive and its location is probably unknown. It can be in the area the radar is required to observe or even on one of the radar targets. The interceptor can have a good antenna with significant receiving aperture, and a low noise amplifier; it can be at a range from the radar equal to or less than the radar range to the targets of interest. All of these factors can be more or less equal for the radar and the interceptor. What is not equal is the large reduction of the radar signal on the return path from the target. A target at a range, R, with radar cross-section, σ, has a signal return proportional to $\sigma/4\pi R^2$. For a target with a = 4π m^2 at a range of 100 km this factor is 10^{-10} (-100 dB). The interceptor receives the signal by a *one-way* path, probably with the full gain of the radar or possibly in a high sidelobe. Even if the interceptor is in the radar's side-lobes, the resulting signal reduction is usually smaller than the radar return-path loss.

On the other hand, the radar has the advantage of knowing the transmitted signal. This allows near optimum signal processing and a large gain in signal to noise ratio (SNR). This is not to say that the received signal is fully known, e.g., the time of arrival, the Doppler shift, the signal phase and polarization, as a rule, are unknown. Radar routinely deals with these unknowns but requires additional signal power to do so. Nevertheless, the radar should achieve a processing gain approaching TW, where T is the time duration of the signal processed for decisions and W is the signal bandwidth. The interceptor can also process the signal and improve the SNR, but if the input SNR is very small, the lack of knowledge of the signal imposes an unavoidable loss. Several questions arise that need answers!

How large a time-bandwidth product is practical? and *Is it large enough to offset the path loss? How does lack of knowledge of the signal hurt the interceptor?* and *How large is the penalty? What class of radar signals is best used to achieve LPI? Can LPI be achieved in general or is it limited to few very* *special types of radar?* At this point it might clarify these issues by examining a concrete example. The author analyzed a radar claimed to be LPI; this radar is a navigation radar called the Pilot MK3. The Pilot MK3 can be examined because its technical characteristics are provided in the book.

The Pilot MK3 transmits a frequency modulated continuous wave (FMCW) waveform with 1 watt of power. The FM signal with the largest bandwidth is swept through 55 MHz and repeats with a 1 KHz period. The antenna has 30 dB of gain, with a beam 1.2° in azimuth × 20° in elevation and is rotated in azimuth at 24/48 RPM. The radar wavelength is 3.2 cm so the antenna is quite small (a little over 1.5 meters in width and very narrow in height). The author correctly calculates that with a 5 dB noise figure, a 100 m^2 target at 28 km will produce a radar input signal to noise ratio (SNR) of –39 dB. The radar has a processing gain on a single FM sweep of $55 \times 10^6 \times 10^{-3}$ or 47 dB. This provides an output SNR of 8 dB, which, as the author points out, can be improved post-detection. *Is this signal LPI?* For the intercept receiver, the author seems to have in mind, perhaps it is, but let us consider an alternative.

Initially, the interceptor might not know the exact frequency or bandwidth of the radar, and a search would need to be conducted (maybe surreptitiously in a file cabinet) to establish them. If the use of the correct values produces a reasonably high SNR, the search should not be difficult. To assume otherwise would be to conclude that all radars are LPI and the subject is a settled issue requiring no further discussion; however, let the discussion begin with the assumption that the frequency and bandwidth have been determined by some means.

Let the intercept antenna be the radar antenna, but orient it so that the longest dimension is vertical. With this orientation the antenna covers 20° in azimuth and 1.2° in elevation, which is suitable for receiving the signal arriving on the horizon and covers a larger azimuth to improve signal search. A signal could be received in a radar sidelobe, but this radar scans its main beam over the interceptor 24 to 48 times each minute. *So, why not use the main beam?* Also, use the radar low noise amplifier and place the interceptor 28 km from the radar. As suggested above, these choices will result in a radar input SNR that is less than the interceptor input SNR by the factor $\sigma/4\pi R^2$. For a 100 m^2 target at 28 km, the interceptor's input SNR is 80 dB above the radar's. The interceptor input SNR is 41 dB – nothing more is needed. If desired, the input signal, or perhaps its discrete Fourier transform (DFT), can be simply examined and everything worth knowing would be known.

The example makes a point, namely, LPI is not just a matter of radar design but is often a matter of interceptor receiver design. The Pilot MK3 does not pass as LPI, but there may be radars with a more difficult challenge. Apparently, the author thinks there are, and there certainly could be LPI radars that would defeat standard intercept receivers. But, to achieve a functional LPI radar against an intercept receiver designed with LPI radar in mind would be extremely difficult. Before addressing the questions raised above, some signal processing basics are needed. Since digital signal processing is popular, the processing will be explained in terms of sampled signals.

A narrow band signal with bandwidth W and time duration T can be represented by 2TW samples TW samples 1/W apart in a receiver channel in phase with a local frequency reference and TW samples 1/W apart in a channel in quadrature with the reference (the so-called I and Q channels). A signal with low input signal-to-noise would have sample values dominated by noise and reveal next to nothing about the signal. However, if each sample is multiplied by the value of the signal at that sample, the sum of these modified samples has a processing gain of 2TW. The process increases the samples with larger signal values and diminishes samples with smaller signal values. This discriminates against the noise in favor of the signal. Not knowing the RF phase of the received signal, radar with optimum processing achieves a processing gain of only TW.

If the signal is unknown and the input SNR is small, then the processing requires a different approach. With no prior knowledge of the signal and samples that reveal virtually nothing more than the value of noise at the sample points, *What can be done?* If the signal is suspected to be of known class with unknown parameters, a set of possible parameters could be tried with some prospect for success. For example, if FMCW is suspected, several linear frequency sweep rates could be tried on a set of stored samples and the signal would probably emerge.

But if the signal does not have a simple and well-known structure, then there is no practical search in signal space. This answers one of the question posed above. The signal should have sample points that are pseudo-random. If the signal samples are unknown and are not easily discovered by a reasonable number of enlightened guesses, then *What is to be done?* It is rational to multiply each sample by the best available estimate of the signal value. The only estimate available is the sample value. So square the sample and hope for the best. With a single receiver this is the best option. It is not pretty, but in times of great need one may learn to love it. The problem is that the samples are the sum of a signal value and a noise value. The square has signal × signal terms, signal × noise terms, and noise × noise terms. For large SNR, the signal × signal term dominates and the process gives a processing gain of almost TW. If the SNR is small, then the noise × noise term dominates. The result is less favorable – but still of value.

A better result can be achieved with two identical antennas pointed in the same direction, with identical receivers. The receivers would output the same signal, but their noises would be independent. The sample points of one receiver would multiply the corresponding samples of the other. This technique has the advantage of having independent noise samples in the noise × noise terms. Consequently, the processor output has zero average when the signal is not present and assumes a value proportional to the signal energy when the signal is present. Thus, the presence of a signal is more apparent and the output SNR is also improved. The approximate result for either technique (the two antenna technique is 3dB better) is conservatively given by:

$$\mathbf{SNRout = TW\ (SNRin)\ if\ SNRin >> 1,}$$
$$\mathbf{SNRout = TW\ (SNRin)^2\ if\ SNRin << 1,}$$

where SNRin is the input SNR and SNRout is the post-processing SNR.

The conclusion: that the Pilot MK3 fell far short of being LPI. *What can be done, if anything, to make it LPI?* The interceptor input SNR was 41 dB. Since the interceptor has losses if the SNRin << 1 we need to lower the interceptor SNRin by at least 51 dB. *How can this be done?* The 80 dB path loss cannot be reduced since it is determined by radar requirements. The only thing we can improve is the time bandwidth product.

The bandwidth used was 55 MHz. Suppose we try to increase the bandwidth to 1000 MHz. *This would buy almost 13 dB, or would it?* This bandwidth has 15 cm range resolution, which is small when compared with the size of targets having a radar cross section of 100 m^2. This bandwidth would resolve most targets into scattering center with radar cross-sections much smaller than 100 m^2. Since there is no obvious way to combine the returns from these scattering centers, we could lose more than we gain; not to mention the problems incurred with more than 10% bandwidth. Nonetheless, assume, by some clever means, we achieve 1000 MHz and it provides 11 dB.

We have only 40 dB more to achieve, and the only thing we can achieve it with is the signal time duration. Very well, increase T from 10^{-3} sec by 40 dB. This is signal time duration of 10 seconds. This seems like a very long time! *What are the problems it presents?* First, there is the issue of covering 360° of azimuth in a reasonable time. Our azimuth beam is 1.2° so there are 300 azimuth cells in 360° and the post-detection integration requires 8 sweeps while the beam is on the target. Consequently, we have a refresh time of $300 \times 8 \times 10 = 24{,}000$ seconds or 6 hours and 40 minutes. This will never sell! We need a three-face planar array antenna to form multiple beams, and it will require time delay steering because of the 1000 MHz bandwidth. There are a few remaining problems. Targets returns are not constant; targets have six degrees of motion freedom and exercise all of them. A typical aircraft has a bandwidth of 10 Hz. The radar return from such a target is coherent for about 0.1 seconds. This implies that 10 seconds of coherent integration on such a target will suffer substantial losses. Targets also exhibit radial accelerations, which produce large quadratic phase excursions in 10 seconds. The TW of this new waveform is 10^{10}, which means that return signals from moving target are no longer simply Doppler-shifted; they are subjected to major time dilation. They are expanded or compressed in time by amounts that exceed the reciprocal bandwidth. So the signal processing must accommodate both acceleration and time dilation.

The resulting radar is an expensive nightmare which might not be practical, *But is it LPI?* No it is not! Using the formula above, the SNRout, despite all of the effort, is extremely large. By driving SNRin down to –10 dB, we have denied the interceptor the ability to examine signal details, but signal energy is still available for detection. The radar must have signal energy if the radar is to see targets.

Of course, the resulting radar is absurd and I seriously doubt that anyone would contemplate it. That is the point. The Pilot MK3 radar is not LPI and it is not about to become so.

Dr. Pace has written a fine book, but it does not begin to make clear the extreme difficulty of achieving LPI radar for most radar functions.

If there is a determined adversary that wishes to detect the radar, as a rule, it is highly probable that it will be detected. There are exceptions to this rule but they are few and far between. One such exception is radar altimeters. The reasons for this exception will be left as an exercise for Professor Pace's students.

– Edwin L. Key
15 Berkley Drive
Chelmsford, MA 01824