Ducting Phenomena

and their Impact on a Pulse Doppler Radar

ABSTRACT

Ducting is an important propagation phenomenon for radar operators to consider due to the effects of extending radar range beyond the maximum specified instrumented range and creating radar holes. While it may be advantageous to have the maximum radar range extended, this will impact a pulse doppler radar's sensitivity if the radar has not been adequately designed with fill pulses to take into account this phenomenon.

This article investigates ducting phenomenon in two locations – Singapore and Ajaccio. The impact of the phenomenon on the detection sensitivity of a pulse doppler radar under tropical, humid conditions is then contrasted with that of a dry, temperate environment using an example.

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INTRODUCTION

Anomalous propagation due to weather conditions leads to significant differences in the performance of radar systems compared to normal propagation. Ducting is an extreme form of super-refraction of the electromagnetic waves transmitted from radars. Super-refraction causes radar waves to bend more towards the surface of the Earth than under normal conditions. Such a phenomenon is generally caused by:

- Temperature inversion where tropospheric temperatures increase with height (e.g. warm and dry continental air may be advected over cooler water surfaces, leading to temperature inversion); and/or
- Water vapour content decreasing rapidly with height (e.g. the rapid decrease of relative humidity immediately adjacent to the air-sea interface, otherwise known as an evaporation duct) (Space and Naval Warfare Systems Center, 2009)

Ducting occurs when the bending of radar waves causes the curvature radius of the wave to become smaller than that of the Earth. The wave will either strike the Earth and undergo surface reflection, or enter a region of standard refraction and be refracted back upward, only to re-enter the area of refractivity gradient that causes downward refraction, behaving like the guided wave in a waveguide. Figure 1 illustrates the phenomenon.

EFFECTS OF DUCTING

The effects of ducting are predominant, especially in defence applications:

- **Extended radar detection.** Ducting allows the electromagnetic wave to detect objects much further away due to 'reduced' power dissipation along the 'waveguide'. However, the detection of targets too far away does not yield any practical advantage because objects often cannot be determined as threats at such distances, and even if determined, the weapons range may not support the neutralisation of such distant targets.

- **False alarms and radar desensitisation.** Ducting may cause false alarms when the radar equipment misinterprets faraway echoes to be much closer than they actually are due to range ambiguity. Ducting can also result in undesirable land clutter being detected beyond the instrumented range to be folded back to the principal range, thus decreasing the radar sensitivity within the instrumented range. Fill pulses (FP) are often required to resolve this problem at the expense of more radar time and resources. More on radar desensitisation will be elaborated on in this article.

- **Radar holes.** Extended radar detection is achieved at the expense of the volumetric coverage of the radar. An air target that would normally be detected may be missed

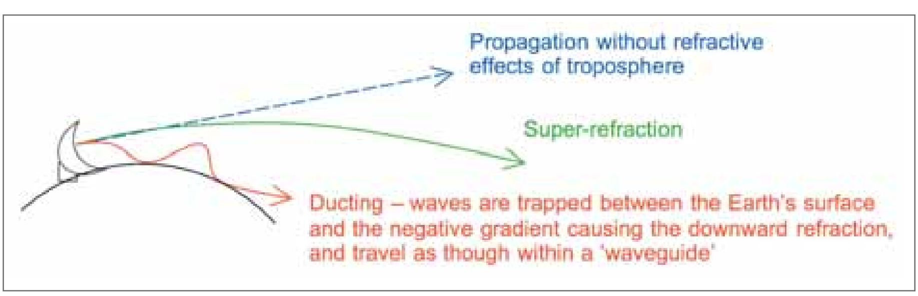

Figure 1. Propagation of electromagnetic waves from a radar

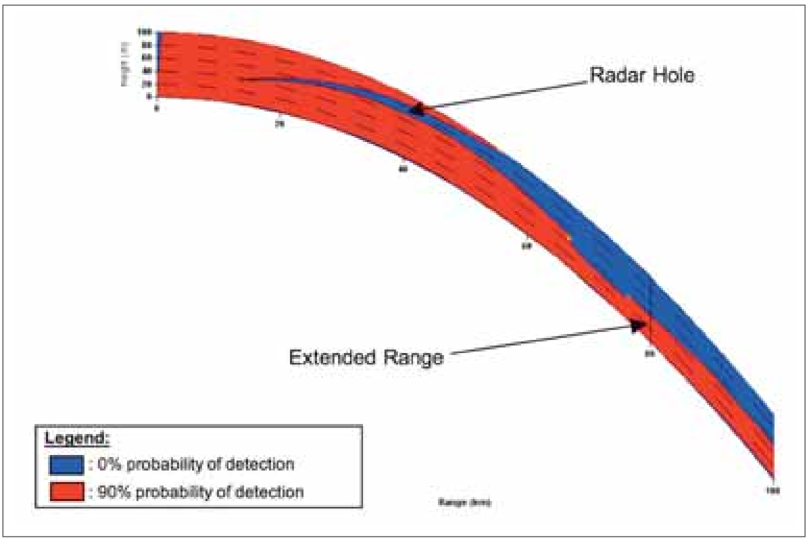

Figure 2. Effects of ducting

if the radar is within or just above the duct and the target is just above the duct (Space and Naval Warfare Systems Center, 2009). This area of reduced coverage is known as a radar hole or shadow zone. A simulated example is shown in Figure 2.

As such, it is important to understand ducting and the meteorological parameters that shape such a phenomenon.

APPROACH

Published literature has broadly defined conditions that encourage ducting. In the following sections, an investigation of ducting phenomena in two locations, Singapore and Ajaccio, was examined for a year from July 2007 to June 2008. The two locations were chosen as an example. The exact coordinates of the weather stations are:

- **Singapore Changi Airport, Singapore**
  Station latitude: 1.37
  Station longitude: 103.98

- **Ajaccio, South of France**
  Station latitude: 41.92
  Station longitude: 8.80

The two timings were obtained from a meteorological website where year-round weather reports could be obtained.

- **0000z (Zulu time)** – corresponding to 0100hrs / 0200hrs in Ajaccio (GMT +2 in the summer, GMT +1 otherwise) and 0800hrs in Singapore (GMT +8).

- **1200z (Zulu time)** – corresponding to 1300hrs /1400hrs in Ajaccio and 2000hrs in Singapore.

Simulation Process

The meteorological data obtained was entered into the Advanced Refractive Effects Prediction System (AREPS). AREPS is a radar refraction simulation programme which calculates the refractivity of the tropospheric layer using upper air atmospheric soundings, and translates these refractivity readings into the maximum radar range using ray diagrams and radar range equations. AREPS then determines the radar's probability of target detection at certain heights and ranges, and plots the results.

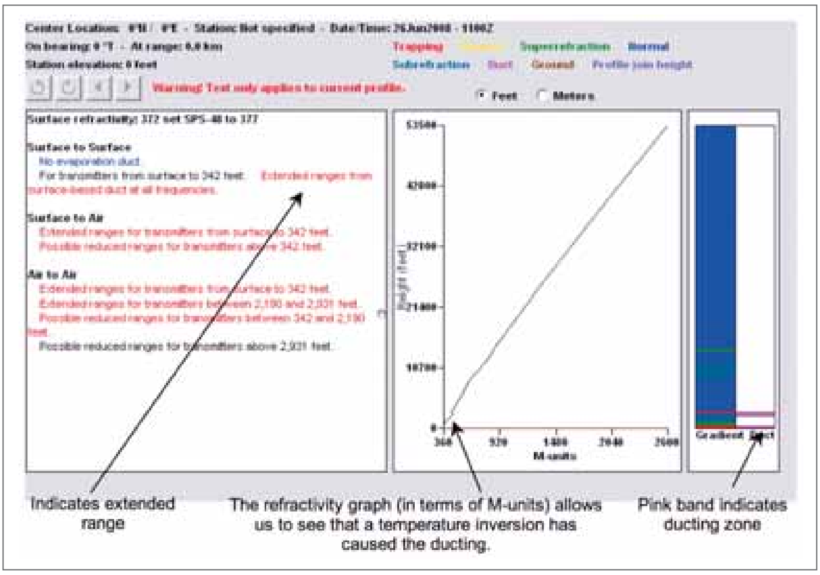

Figure 3. Summary page of AREPS propagation condition

Decision Process

The detection of ducting is based on a two-fold decision process.

First, the propagation condition summary (as shown in Figure 3) for a particular meteorological data set needs to indicate that there is a band of surface-to-surface trapping zone, and that there are extended ranges for the operation of transmitters in that region.

The second propagation condition depends on the actual simulation of the radar. In the investigation, the dependent variable used is that of the maximum distance (measured in kilometres) for a predetermined 100m^2 Radar Cross Section (RCS) target to be detected at a probability of 90% and at the height of 30m. For ducting to affect the radar performance, the simulation must show that this visibility distance is sufficiently large as compared to normal propagation visibility distance. In this investigation, a decision threshold of at least twice the mean visibility distance (in this case, 35.0 x 2 = 70.0km) is chosen.

Using this set of criteria, ducting occurrences were counted and duly recorded.

ANALYSIS

Ducting Occurrences

Figure 4 summarises the percentage of ducting occurrences from July 2007 to June 2008.

As seen from Figure 4, Singapore (represented by the blue line) had little to no ducting occurrences for the entire year. On the other hand, Ajaccio (represented by the orange line) had significant ducting from April to August and little to no ducting during the other months.

It is also interesting to note that the majority of ducting occurrences in Ajaccio took place

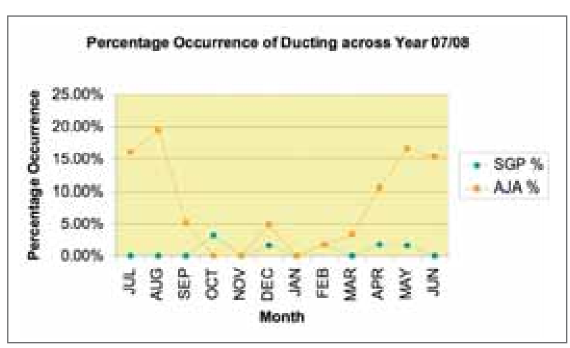

Figure 4. Percentage of ducting occurrences

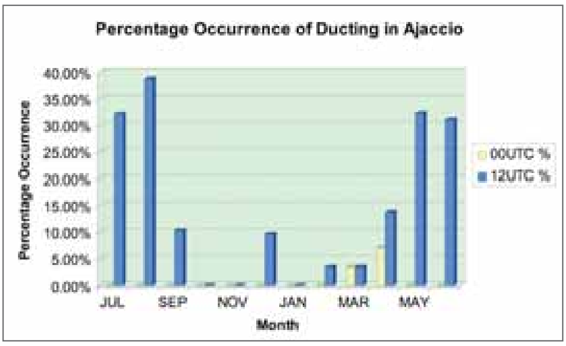

Figure 5. Percentage of ducting occurences in Ajaccio

at the 1200 UTC observation, rather than at the 0000 GTC observation. Figure 5 shows the percentage occurrences in Ajaccio at the two different times.

Effects of Ducting on Radar

Table 1 shows the average radar range for days with normal propagation as well as for days with ducting.

As shown in Table 1, ducting does increase the radar range by a large amount. However, this is not altogether useful as explained earlier.

Location / Type of Day	Normal Propagation (km)	With Ducting (km)
Singapore	33.0	367.1
Ajaccio	35.0	349.4

Table 1. Average radar range for Singapore and Ajaccio

SUMMARY OF RESULTS

The results obtained from the investigation confirmed several observations about ducting, but also raise several points that seem at odds with the literature.

Correlation of Average Temperature with Ducting Occurrence in Ajaccio

Figure 6 shows a comparison of the monthly average temperature of Ajaccio and the percentage of ducting occurrences. (EuroWEATHER).

The correlation factor between the two sets of readings is 0.727. This shows a strong likelihood that there is a correlation between the average temperature of the month to the percentage of ducting occurrences.

This seems plausible as higher sea-level temperatures would lead to higher levels of evaporation close to the sea surface. As discussed earlier, higher levels of water vapour i.e. higher partial pressure of water vapour would lead to an increase in refractivity N (as shown from the following refractivity equation) which in turn increases the likelihood of ducting:

$$N = (n-1)10^6 = \frac{77.6p}{T} + \frac{e_s 3.73 \cdot 10^5}{T^2}$$

where n is the index of refraction, e_s is the partial pressure of water vapour in millibars, p is the atmosphere's barometric pressure in millibars and T is the atmosphere's absolute temperature in degrees Kelvin.

In considering refractive gradients and their effect on propagation, a modified refractivity M, defined as:

$$M = N + 0.157h$$

where h is the altitude in metres, is used.

AREPS calculates the M and N values and also considers the effective Earth radius factor

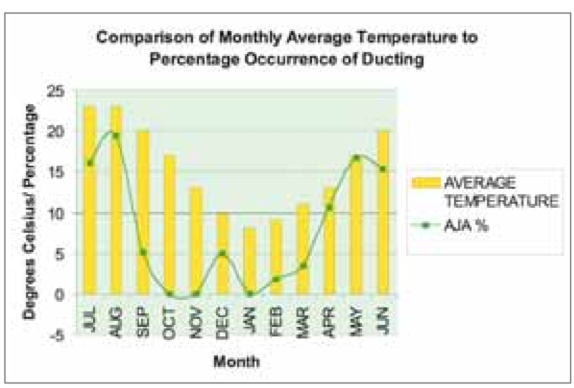

Figure 6. Comparison of the monthly average temperature to the percentage of ducting occurrences

before employing ray-tracing diagrams to determine the percentage probability of detection.

The Lack of Ducting in Singapore

While warmer temperatures seem to be able to explain the ducting pattern in Ajaccio, the results for Singapore contradict this observation. In fact, the literature also mentions that 'surface-based ducting is associated with fair weather, with increased occurrence of surface-based ducts during the warmer months and in more equatorial latitudes' (Space and Naval Warfare Systems Center, 2009). However, the results do not seem to support this.

One possible conjecture would be the wind factor. One would assume that Singapore would have a well-mixed troposphere with high wind conditions due to the monsoon seasons. It is known that 'any time the troposphere is well-mixed, such as with frontal activity or with high wind conditions, surfaced-based ducting is decreased' (Space and Naval Warfare Systems Center, 2009). Ajaccio, on the other hand, does not seem to have any strong wind activity, and can be assumed to have fair weather during the hot, humid months of summer.

Another possible conjecture would be the relative locations of Ajaccio and Singapore as shown in Figure 7. Ajaccio is situated near mountains and has considerably larger land masses surrounding it as compared to Singapore. Therefore, the possibility of dry continental air being advected over the cooler water surface in the summer is more likely as compared to Singapore.

RADAR DESENSITISATION DUE TO DUCTING

The investigation has provided an indication of the occurrences of ducting phenomenon at different places and also some of the factors that would possibly affect the presence of ducting. What is more important is to have a better understanding of how ducting phenomenon would affect radar performance.

For a typical pulse doppler radar, there is a need to consider increasing the number of FPs as the radar instrumented range is increased. This is to take care of N-time-around echo returns while operating near coastal areas or land masses. Unfortunately, it is not practical to have unlimited FPs to cater for N-time -around echo returns from distant land masses under ducting environment. This section attempts to illustrate by example the effect of 'missing' FPs on N-time-around echo.

Fill Pulse on N-Time-Around Echo

Pulse Doppler (PD) radars can be categorised as low Pulse Repetition Frequency (PRF)[1], medium PRF and high PRF. For a specific

Figure 7. Location of Ajaccio (left) and Singapore (right)
(Source: 2009 Cable News Network)

PRF, there is a corresponding maximum unambiguous range (R_u) and velocity (V_u) and is determined as follows:

$$R_u = ct_r/2 = c/2f_r$$
$$V_u = \lambda f_r/2 = \lambda/2t_r$$

Where t_r is the pulse (repetition) interval;
f_r is the pulse repetition frequency;
λ is the transmitted RF wavelength (Assuming f=3GHz, λ=0.1m);
c is the speed of light ($3\text{x}10^8$m/s).

Generically, the level of PRF is determined by range and velocity ambiguity i.e. low PRF is unambiguous in range but ambiguous in velocity; medium PRF is ambiguous in both range and velocity; and high PRF is ambiguous in range but unambiguous in velocity.

Table 2 provides examples of the relationship of a specific Pulse Repetition Interval (PRI)[2] and its unambiguous range (R_u) and unambiguous velocity (V_u) as follows:

PRF (Hz)	PRI (μs)	R_u(km)	V_u(m/s)
1872	534	80.1	93.6
2940	340	51	147
5320	188	28.2	266

Table 2. Relationship between PRI, Ru and Vu

It can be observed that the lower PRF PD radar will have a larger unambiguous range as compared to medium and high PRF. However, even a low PRF radar may not have a PRF low enough to avoid the second or N-time-around clutter from rain, chaff echoes or even land clutter in the presence of ducting in the atmosphere. This will in turn affect the doppler processing and clutter attenuation performance, resulting in potential radar desensitisation.

Clutter Attenuation

The Clutter Attenuation (CA) is used to determine the performance of the PD radar. It is defined as the ratio of the input $(C/S)_i$ ratio to the output $(C/S)_o$ ratio for a target at a specific velocity (v_t) as follows:

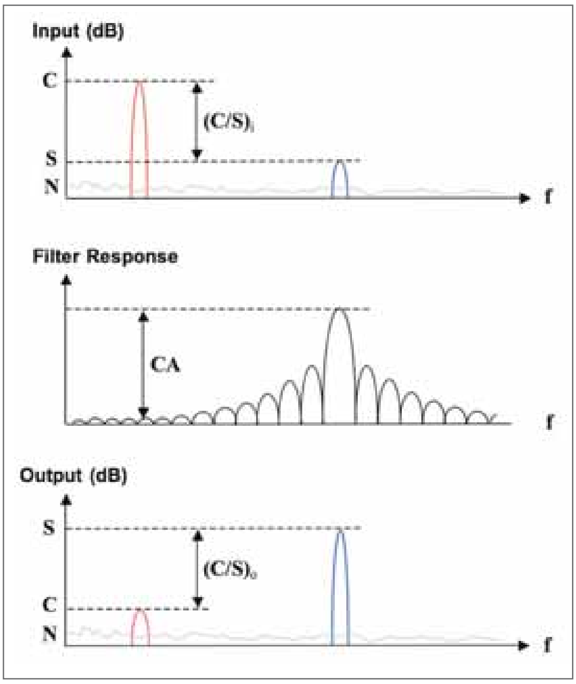

Figure 8. Illustration of CA terminology

$$CA(v_t) = (C/S)_i / (C/S)_o$$

Where $(C/S)_i$ is the clutter to signal ratio at the input;
$(C/S)_o$ is the clutter to signal ratio at the output.

As illustrated in Figure 8, the input clutter and signal powers can be measured on a single-pulse basis in the wideband portion of the receiver. Output levels are measured after the signal passes through the narrowband filter.

Therefore, with the target doppler filter integrated, the signal power would be amplified through the response of the doppler filter for the target velocity (v_t). For the clutter power, the clutter velocity is normally low and will be reduced by the sidelobe response of the doppler filter corresponding to v_t. In other words, the CA is determined by the filter response (for velocity v_t) and is equal to the sidelobe rejection level between the

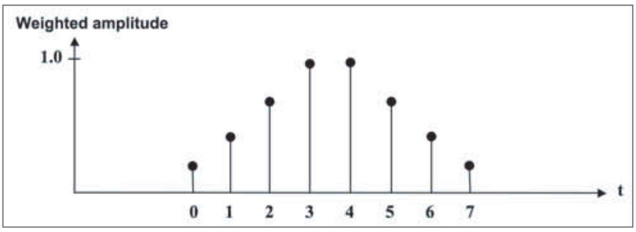

Figure 9. Unambiguous echo pulses, R < Ru

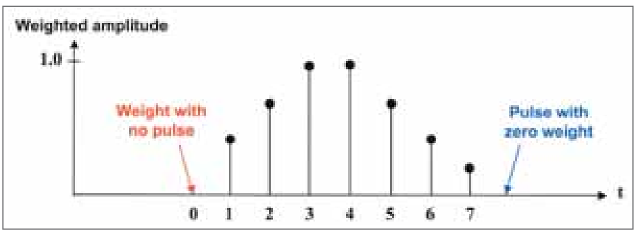

Figure 10. Pulses from Ru < R < 2Ru

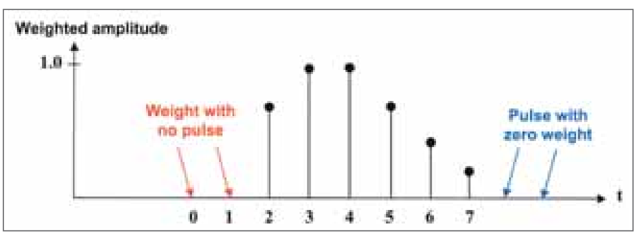

Figure 11. Pulses from $2R_u < R < 3R_u$

level corresponding to the target doppler and clutter doppler. Therefore, a higher CA will result in a better performance of PD radars.

Effect of N-time-Around Echo on Doppler Filter Response

N-time echo is defined as the number of times (a multiple of the unambiguous range, R_u) it takes for the echo to return. A higher N-time echo would result in a lower CA and also a 'flatter' response filter spectrum. To illustrate, consider a Doppler waveform having a burst of eight pulses and a PRI of 340µs. In this case, R_u would be 51km. For simplicity, three scenarios are presented as follows:

a. Ideal scenario ($R < R_u$). For any echo return which falls within the unambiguous range of 51km, the PD radar is able to detect the target against background clutter as there will be a good CA. This is because the echo will arrive within the PRI (340µs) before the next pulse is transmitted. This implies that each of the weighted amplitudes[3] (as shown in Figure 9) for each of the transmitted pulse returns will receive an echo return. After doppler filtering e.g. Fast Fourier Transform (FFT), this will result in a good doppler filter response.

b. Second-time-around echo ($R_u < R < 2R_u$). For an echo return which falls within a range greater than 51km but less than 102km, the second-time-around echo will arrive with an extra time delay. In other words, the first echo returning from the first transmitted pulse will receive the second weight, and the last echo will be lost (or included with the incorrect delay in the next processed burst) as shown in Figure 10.

c. Third-time-around echo ($2R_u < R < 3R_u$). For an echo return which falls within a range greater than 102km but less than 153km, the third-time-around echo will arrive with an even larger time delay. In other words, the first echo returning from the first transmitted pulse will receive the third weight and the last two echoes will be lost (or included with the incorrect delay in the next processed burst) as shown in Figure 11.

Thus, this results in a filter response higher than intended and a lower CA as shown in Figure 12. With increasing N-time-around echoes, the response approaches a 'flatter' response filter spectrum with zero CA. This results in a poor PD radar performance.

Effect of Fill Pulses on N-time-Around Echo

As seen earlier, the effect of the N-time-around echo will result in the echo arriving after a certain delay, which in turn results in an 'imperfect' doppler filter response and thus a lower CA.

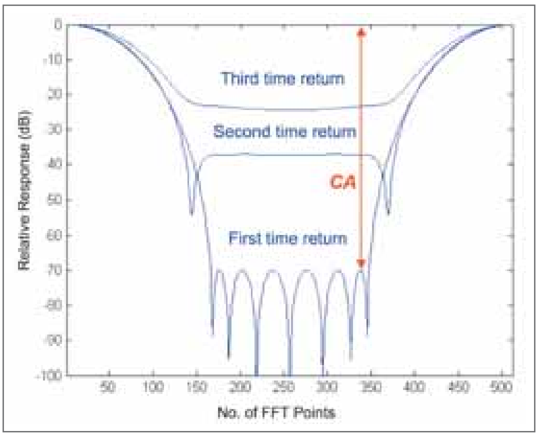

Figure 12. Response of eight pulse filters (with 512 FFT points)

In order to compensate for the delay after which the echo will arrive, FPs are transmitted prior to the pulses to be processed in each burst. To illustrate, scenario (a) in Figure 13 shows that without FPs and assuming that the echo returns for the third time round (e.g. >102km for a PRI of 340μs pulse), the first and second weights will have no echo return. This results in a poorer CA performance as explained earlier.

In scenario (b) of Figure 13, there are two fill pulses transmitted prior to the eight processed pulses. These first two FPs will not be processed at the processing end i.e. there will not be any weights with no echo return. Assuming that that the echo returns for the third time round (e.g. >102km for a PRI of 340μs pulse), the first echo return will be between the first and second processed pulse transmission. At the doppler processing end, the first weight, and subsequently the rest of the weights, will now have echo returns. This will result in optimal doppler processing and hence the doppler response will have a good CA. This will in turn desensitise the radar detection performance, especially against low RCS targets. For a larger RCS target, this radar desensitisation may not be apparent to the operator.

In order to have a better performance of the PD radar and to minimise the effect of N-time-around echoes, it is necessary to ensure significant clutter attenuation on the ambiguous echoes by transmitting FPs prior to the pulses to be processed in each burst. The number of FPs (N_{fill}) required for a specific instrumented (or processing range) is determined as follows:

$$N_{fill} = (R_{instr} / R_u) - 1$$

where (R_{instr}) is the instrumented range and R_u is the unambiguous range.

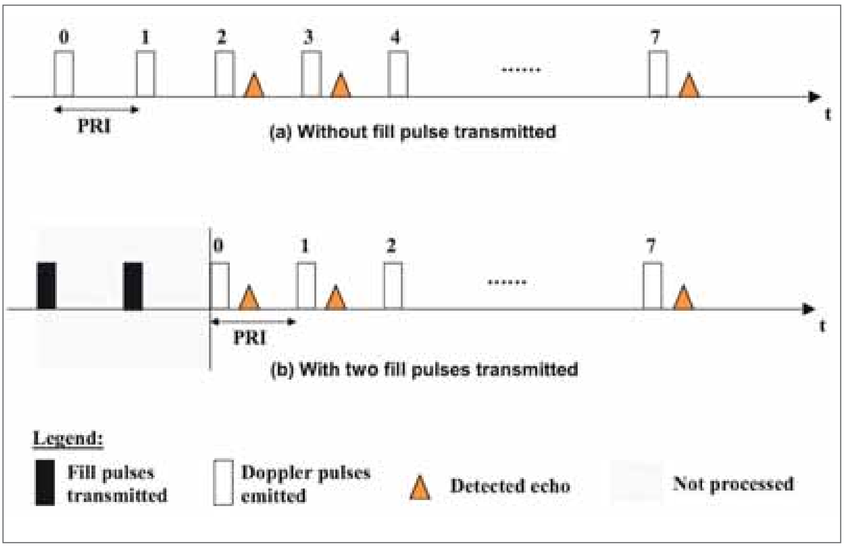

Figure 13. Eight pulse filters (with and without FPs)

CONCLUSION

The first part of this article investigates the ducting phenomenon in two locations. It has been found that Ajaccio has significantly more ducting during the warmer months from April to August, with the majority of the ducting observations occurring during the 1400hrs observation as compared to the 0200hrs observation. On the other hand, Singapore has relatively little to no ducting in the times sampled regardless of month or time of day. This difference in the two locations could be due to the windy, unsettling upper air conditions from the monsoon seasons and proximity to the ocean.

The second part examines the specific effect of ducting on radar sensitivity. Ideally, the number of FPs needed should mitigate N-time-around echoes even under ducting conditions. However, it is not practical to add FPs indefinitely, especially for medium or high PRF waveforms. This is because it will take up radar time budget and there is usually a compromise to be made (e.g. adding a FP up to the instrumented range), depending on requirements and operating environments. As the FPs cannot be 'filled' indefinitely, strong ground clutter returns beyond the instrumented range could still enter and affect the doppler processing and corresponding CA in extreme ducting conditions. Thus, this degrades the detection of low RCS target i.e. radar desensitisation. However, such extreme ducting conditions are rare. The clutter returns would suffer from more severe propagation loss due to the long range and hence, the effect on detection may not be significant for larger RCS targets.

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ENDNOTES

1 Pulse Repetition Frequency (PRF) is defined as the number of pulses transmitted per second by the pulsed doppler radar.

2 Pulse Repetition Interval (PRI) is the reciprocal of PRF which is the elapsed time from the beginning of one pulse to the beginning of the next pulse.

3 In order to have a good doppler filter response (i.e. low side lobes for clutter rejection), it is necessary for the echo returns (corresponding to each of the transmitted pulse) to be weighted. Any echoes received outside this weight during the expected doppler coherent pulses will affect the doppler filter response (in particular the side lobes). For an optimal doppler filter response, it is necessary for each weight to be 'matched' with an echo return.

BIOGRAPHY

Young Kin Chuan is Head Engineering (Naval Systems). He is involved in the development of sensor system applications for naval platforms and facilities. Kin Chuan was awarded the Defence Technology Prize (Team Award) in 2001 and 2007 and the National Day Award (Commendation Medal) in 2006. A recipient of the Defence Technology Training Award Scholarship, he graduated from the National University of Singapore (NUS) with a Bachelor degree in Electrical and Electronics Engineering in 1993.

Loke Mun Kwong is a Programme Manager (Naval Systems). He has vast experience working on sensor system applications for air and naval platforms and facilities. Mun Kwong assists the Programme Centre in the technical competency development of radar applications. He was appointed as Senior Adjunct Fellow of Temasek Defence Systems Institute at NUS in 2006 and has since been lecturing on radar systems to Master's level graduate students. Under the Defence Technology Training Award (Overseas), he received a Master of Engineering degree (First Class Honours) from Imperial College London, UK in 1995.

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Frank Chen Liheng is a recipient of the DSTA Overseas Undergraduate Scholarship in 2004. He is currently pursuing his degree in Electrical and Electronics Engineering (with a double degree in Psychology) in Cornell University, USA. During his study break from May to August 2007, he was attached to DSTA Naval Systems Programme Centre to work on a ducting study assignment.