Radar Detection Evaluation Method for Sea Skimming Targets Including Effective Flight Altitude Simulations as Seen By Radar

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Summary: The objective of this paper is to show a parametric study of the difference between Real Flight Altitude (RFA) and Effective Flight Altitude (EFA) above mean sea level for sea skimming targets as seen by the radar. This is carried out by introducing a realistic sea surface in a commercial radar detection evaluation tool like Ship Air Defence Model (SADM). The radar power is adjusted so target detection takes place at a chosen range for a given RFA. Then the sea surface is removed and target flight altitude together with antenna height are adjusted until the same detection range is achieved. This flight altitude is then assumed to be the EFA. The main trend of the study shows that for long ranges the EFA is close to, but slightly lower than RFA. For shorter ranges (increased grazing angles) the EFA becomes significantly lower than RFA. Usage of EFA instead of RFA in radar detection evaluation is then assumed to give higher fidelity to obtained radar evaluation results for rough sea conditions.

1. Introduction

Detection of sea skimming targets is a huge challenge for radar mounted either on a ship or an airborne platform. A similar challenging task is developing precision simulation methods for evaluation of radar surveillance performance. The commercially available software tool SADM (Ship Air Defence Model) developed by BAE Australia is used by the authors. SADM offers a radar characterization tool with standard radar parameter inputs as e.g. frequency, PRF, pulse train strategies with corresponding Pulse Doppler/MTI processing, target RCS model, sea clutter model (GIT), land clutter model and model for propagation of electromagnetic waves from the radar e.g. APM (Advanced Propagation Model).

The objective of this paper is to show how to improve the radar evaluation fidelity of such a commercial tool for rough sea by introducing a compensation for the deviation between effective flight altitude of sea skimming target as seen by radar and real flight altitude above mean sea level.

Chapter 2 describes the methodology used for studying the effect of a generated sea surface on the RF propagation. Chapter 3 describes the sea surface model. The refractivity model is shown in chapter 4. Pattern propagation factor is introduced in chapter 5. Chapter 6 gives the parameter list for the simulations. Chapter 7 shows the simulation results.

2. The Methodology for analysing the effect of a rough sea surface on the RF propagation

This chapter addresses the RF propagation conditions near the sea surface. The RF signal return experienced by surveillance radar when illuminating a sea skimming missile is very dependent on the missile's flight height as a result of e.g. multi-path interference effects resulting from RF-reflections in the sea surface. Standardized models exist for the RF propagation over a flat sea surface, but the effects of a rough sea surface is far more challenging to model and simulate.

Simulation of effect of a rough sea surface on the RF propagation is done by generating a sea surface based on a sea surface model and running the Advanced Propagation Model (APM) over the surface. The simulations are then rerun for a flat sea surface in order to compare the results. The results are used to transfer the actual flight height of the missile over the rough sea surface to an effective flight height over a flat sea surface. This allows for simplified compensations of the propagation conditions over rough seas in later simulations, where detailed simulations over generated sea surfaces are not wanted or possible. The simulations are carried out in the Ship Air Defence Model (SADM).

The term Effective Flight Altitude (EFA) is used for the corresponding flight height over a flat sea yielding equal radar cumulative Probability of Track (requiring 2 detections out of 3 tries) as the actual flight height over the modelled sea surface. The purpose of this report is to establish knowledge about the phenomena that may influence EFA.

The relationship between EFA and the Real Flight Altitude above mean sea level (RFA) has been subject for discussions for several years. Three hypotheses for the dependence of EFA on the RFA following from these discussions are that the reference height for the EFA and the ship antenna is the height corresponding to:

1. mean sea level (EFA=RFA)
2. Significant wave height h_{sig} which is the average of the upper 1/3 of all measured wave heights (peak to peak height).
3. Some maximum wave height higher than significant wave height based on the visual impression of the sea height when viewing the horizon.

This paper brings more knowledge to the relationship between EFA and RFA over a rough sea surface.

The technique that has been developed is starting with introducing a realistic sea surface in SADM as a DTED 2 map with about 30 m resolution in the horizontal plane and 1 m in the vertical axis. Since the resolution in the DTED 2 map is so poor the sea surface is scaled with a factor of 10 in all dimensions. SADM is also prepared by scaling critical parameters with the same amount to support this.

For a given choice of RFA and evaluation range the radar power is adjusted so that detection takes place at the chosen range. The next step is to remove the sea surface and inspect the detection range achieved when the surface is flat. If a shorter detection range is observed the flight altitude and antenna height are equally increased in increments until the same detection range is achieved as when the sea surface was used, and vice versa. This new flight altitude is then called the EFA.

In the simulations the significant wave height crest is used as the hypothesis for the effective zero flight height level (hypothesis 2), and thereafter adjusted to meet the performance criterion presented above. Finding the EFA is an iterative process, and a good hypothesis therefore reduces the workload needed to find the EFA. Preliminary tests resulted in that hypothesis 2 was closer to the simulation results than hypothesis 1 and 3. The simulations are carried out for C-band (5.6 GHz) over a sea surface corresponding to a sea state 4 condition.

3. Sea surface model

For generation of a realistic sea surface the Pierson Moskowitz wave height power spectral density is used. The equation of the wave height power spectral density is given by

$$S(f)=\frac{\alpha g^2}{(2\pi)^4 f^5}\exp\left[-\frac{5}{4}\left(\frac{f}{f_m}\right)^{-4}\right]. \tag{3-1}$$

The nature of the wave height spectrum is characterized by two general properties: a spectral peak at a radian frequency, ω_m (or f_m in Hz), that depends on wind speed, assuming infinite fetch (above 80 km) and a frequency tail that falls off as ω^{-5}. The major physics that it summarizes is twofold:

1. Waves having frequencies below ω_m are those traveling at phase speeds greater than the wind speed and thus they have no significant net forcing causing them to grow.
2. Waves in the high frequency region are dominated by breaking and cusp-like crests, whose frequency spectra may be shown to behave as ω^{-5}.

Here we have omitted the effects of increased peakedness of the spectral maximum and parametrization of nonlinear wave/wave scattering interactions that cause the spectrum to be more narrow and cohesive than it would be in the case of linear, independent Fourier components.

Converting the frequency spectrum to a spectrum that is a function of wavenumber $k = 2\pi / \lambda$ is carried out by substituting for the dispersion relation

$$\omega(k) = (gk)^{0.5} \tag{3-2}$$

and multiplying with the Jacobian. The spectrum then becomes

$$S(k) = \frac{\alpha g^2}{(2\pi)^4 \omega^5} \exp\left[-\frac{5}{4}\left(\frac{\omega}{\omega_m}\right)^{-4}\right]\left(\frac{g}{k}\right)^{0.5}. \tag{3-3}$$

The inverse Fourier transform can then finally be executed to give a realization of the sea surface as function of one spatial dimension and written as

$$\eta(x) = IFFT\left\{\exp(j\theta_k) S(k)^{0.5} \Delta x^{-0.5}\right\} \tag{3-4}$$

where the phase θ_k is a random variable with uniform probability density function and changes as function of wavenumber bin. For simplification no multiplicative statistics are introduced in the amplitude.

For sea state 4 the parameters for the model are as follows:

g	=	9.81 m/s^2	(gravity acceleration)
α	=	8.1*10^{-3}	
u	=	10.8 m/s	(wind speed)
f_m	=	$\frac{g}{2\pi u}$	(spectral peak)

The corresponding spectra versus wave frequency and wavenumber are given in Figure 3-1. The realized sea surface is given Figure 3-2. Only a small part is shown to give an impression of how the waves appear locally.

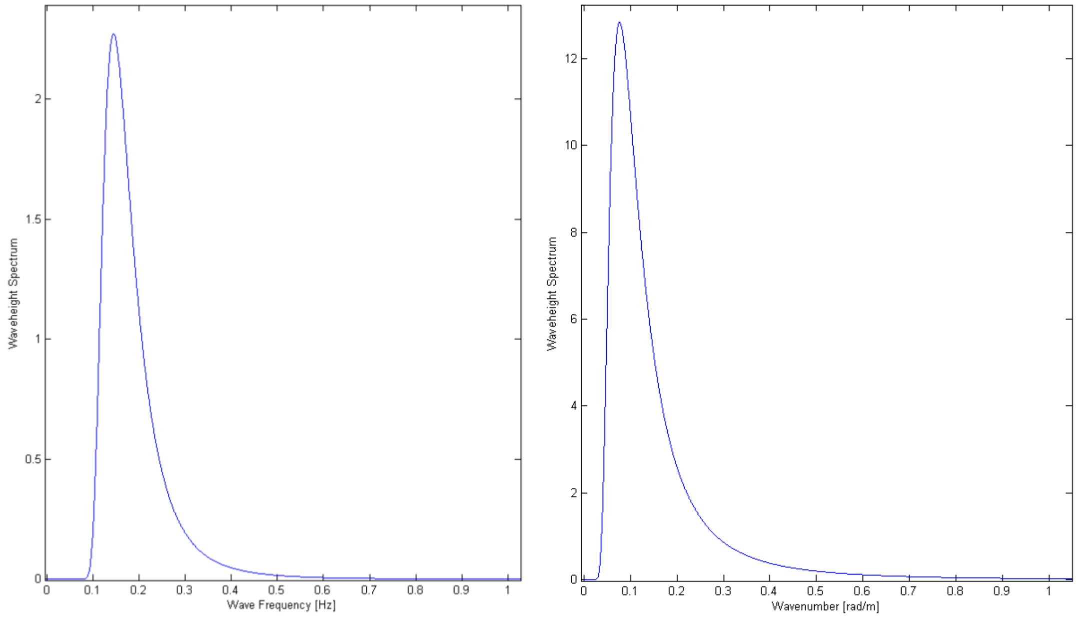

Figure 3-1: Pierson Moskovitz waveheight spectrum versus wave frequency (to the left) and versus wavenumber (to the right).

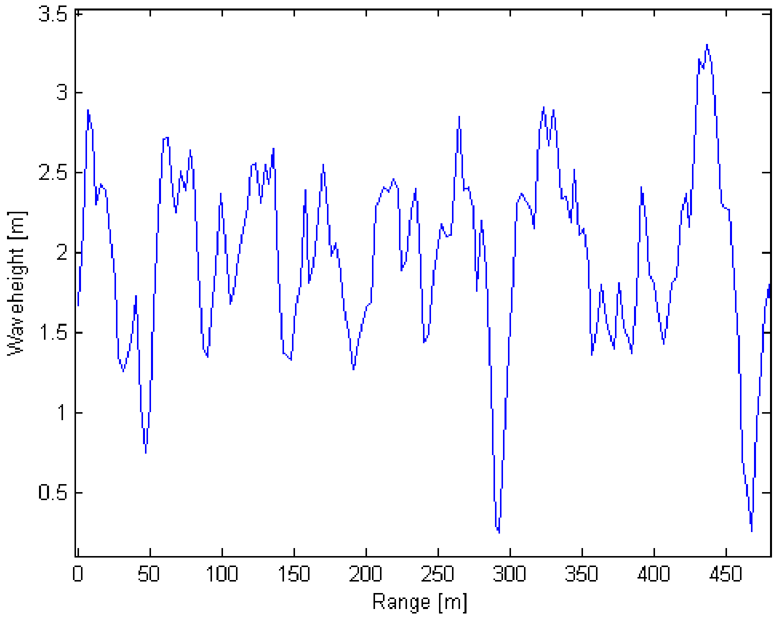

Figure 3-2: Realization of the sea surface for sea state 4. The mean sea level is offset to avoid negative values.

4. Refractivity model

The index of refraction is defined as

$$n = \sqrt{\varepsilon_r} \tag{4-1}$$

where ε_r is the dielectric constant of the troposphere. The scaled index of refraction, N, is more practical to use and defined as

$$N = (n-1)10^6 . \tag{4-2}$$

In order to examine the N gradients the modified refractivity index is used and defined as

$$M = \left(n - 1 + \frac{h}{a} \right) 10^6 \tag{4-3}$$

where h is height above sea level and a is earth radius, this to take into account the earth curvature.

Standard refractivity as function of height in SADM is shown to the left in Figure 4-1. The refractivity profile that results when the earth radius is scaled with a factor of 10 is given to the right. The file for this scaling has to be loaded into SADM when preparing SADM for simulations with sea surface.

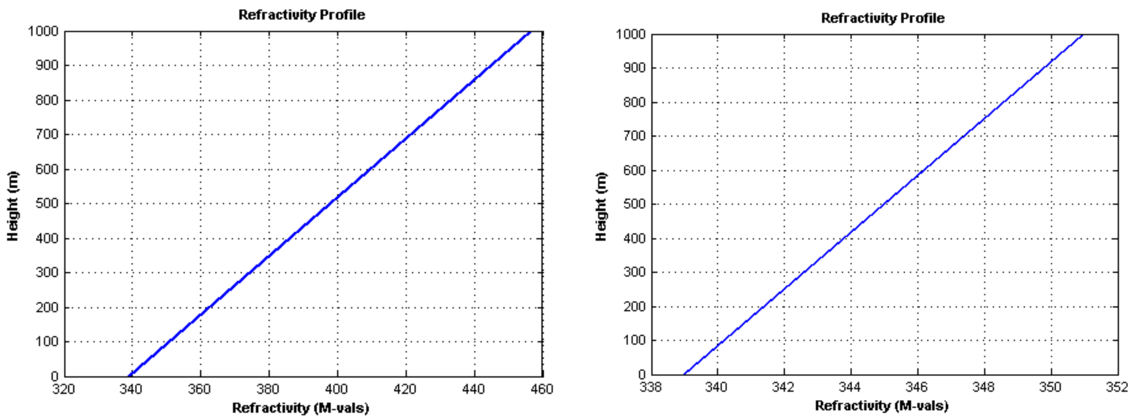

Figure 4-1: Standard refractivity height profile is given to the left. The refractivity profile for earth radius scaled by a factor 10 is given to the right.

5. How Pattern Propagation Factor (PPF) is modeled in SADM

Pattern Propagation Factor is defined as the difference in dB between the signal strength received at a point and the signal strength that would be expected at that point due to free-space propagation only. As such, it incorporates the effects of multipath, diffraction, ducting, troposcatter, terrain profiles, etc. The Radio Frequency (RF) Propagation Model calculates the 1-way PPF in dB for a path between any specified transmitter and receiver, considering the locations of the transmitter and receiver, frequency, polarization, environmental conditions, multipath, diffraction, terrain height profiles, etc.

The RF Propagation Model APM, created by Atmospheric Propagation Branch of the SPAWAR Systems Center, San Diego, is a hybrid model, using different calculation methods in different height / range regions. It can cope both with terrain and with arbitrary refraction profiles. APM returns an entire array of PPF values versus target height and range when it performs its calculations. This is a result of the parabolic equation methodology used within the model.

The work presented in this report uses APM in SADM. Figure 5-1 left shows a typical PPF diagram in SADM before scaling. A comparison between a proper slice and the same slice when SADM is simulated with all necessary parameters scaled with a factor of 10 is given to the right in Figure 5-1 and to the left in Figure 5-2. The two plots show good agreement.

When the sea surface realization given in Figure 3-2 is incorporated in SADM the surface is implemented in the DTED map. The resulting PPF diagram is given right in Figure 5-2. The characteristic finger lobe structure is seen, but it is disturbed by the underlying surface. Another apparent feature is that the PPF shows significant diffraction effects over the wave crests. This may result in that a higher amount of energy is bent so that close to the crests it is more energy than in the flat sea surface case. This may be the reason that the radar is experiencing longer detection ranges for low ASM flight height than what is expected when compared with the flat surface.

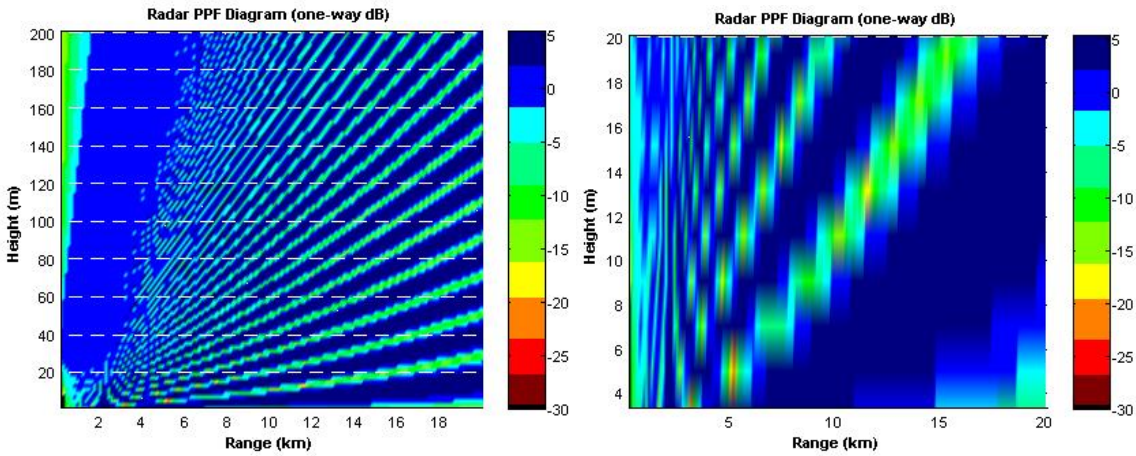

Figure 5-1: Typical PPF diagram for APM in SADM when a flat surface is used is given to the left. The color scale represents the one way power gain or loss relative to free space in dB. A suitable slice is given to the right.

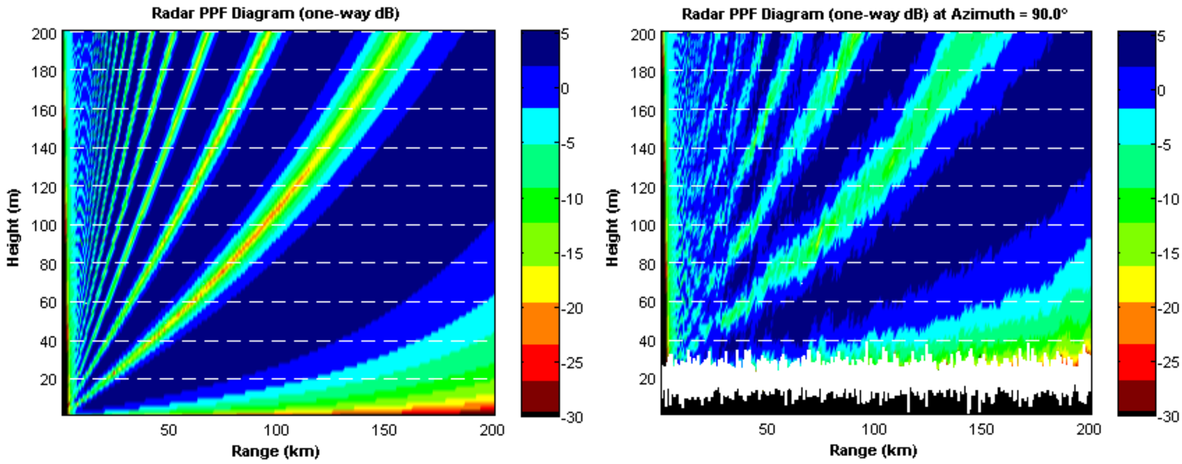

Figure 5-2: The same slice is simulated when SADM is fully prepared for surface simulation with all necessary parameters scaled with a factor of 10 is given to the left.

The colour scale represents the one way power gain or loss relative to free space in dB. The resulting PPF diagram is shown when DTED 2 map with a sea surface introduced is given to the right.

6. Parameter settings and simulation with DTED map of sea surface in SADM

This study involves transformations of object heights to be used in the simulations. These transformations are described when simulating over the generated the sea surface and when simulating over the flat default sea surface in the following:

6.1 Object heights used in the simulations over the sea surface

In order to introduce a DTED map in SADM it is advisable to avoid negative terrain height values. Offsetting the zero level of the sea surface in the map-data avoids negative values. The height of the radar and missile must be offset by the same amount before the size scaling.

The height values used in the simulations are:

Antenna_Height1 = (Antenna_Height_Ship + offset)*10

Flight_Height1 = (RFA + offset)*10

For the sea state 4 sea surface generated offset = 2 m was used.

Antenna_Height_Ship = 30 m was used in the simulations.

6.2 Object heights used over the flat sea surface

The height values used in the simulations are:

Antenna_Height2 = (Antenna_Height_Ship – EZL)*10

Flight_Height2 = (RFA – EZL)*10

where EZL is the Effective Zero Level with meter as unit.

The significant wave height crest (H_Significant/2) is used as the initial EZL hypothesis. EZL is thereafter adjusted affecting both Antenna_Height and Flight_Height until the same detection range is achieved as over the sea surface. When agreement is obtained EFA is found from the equation:

EFA= RFA – EZL

The simulations are carried out for C-band using the SADM default radar model (5.6 GHz carrier frequency) at sea state 4. The cumulative Probability of Track Initiation (Ptrack) curve (black) goes through 0.8 at e.g. 120 km (scaled) range, as given to the left in Figure 6-1 for Flight_Height1 = 79 m (5.9 m RFA).

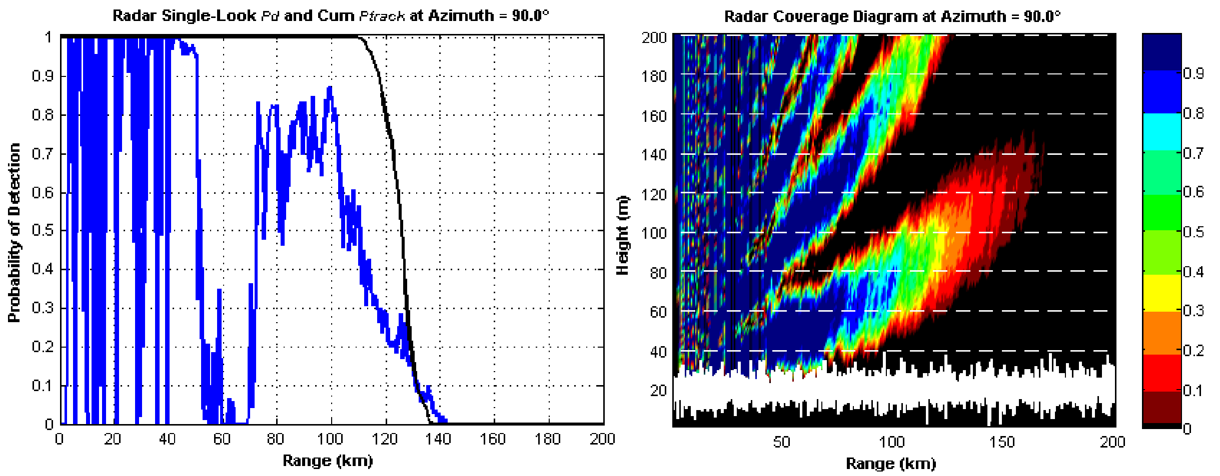

Figure 6-1: Probability of single scan detection (blue curve) and cumulative probability of track (black curve) when transmitted power is adjusted to give cumulative Ptrack of 0.8 at 120 km range for Flight_Height1 = 79 m (5.9 m RFA) is given to the left. The corresponding Coverage diagram for the radar is given to the right.

Coverage Diagram showing single-Look Probability of Detection (PD) is given to the right. The characteristic finger pattern due to multipath can be seen in the figure. The coverage diagram is appearing as given in Figure 6-2 left when the sea surface is turned off. Single- and cumulative Ptrack curves are plotted as to the right, here for Flight_Height2 = 47 m (EFA = 4.7 m). In this example the cumulative Ptrack is also passing through 0.8 for 120 km (scaled) range. Any further adjustment of EFA is then not needed to match the 120 km (scaled) detection range. This means that the initial EZL hypothesis for this example gave a very good agreement. If the cumulative Ptrack=0.8 range occurred closer than 120 km Antenna_Height2 and Flight_Height2 had to be increased in small increments until the cumulative Ptrack=0.8 occurred at 120 km (scaled) range. Vice versa, if the cumulative Ptrack =0.8 occurred for beyond 120 km, the heights had to be decreased in similar manner. This experiment is then carried out for other detection ranges to obtain an EFA as function of range.

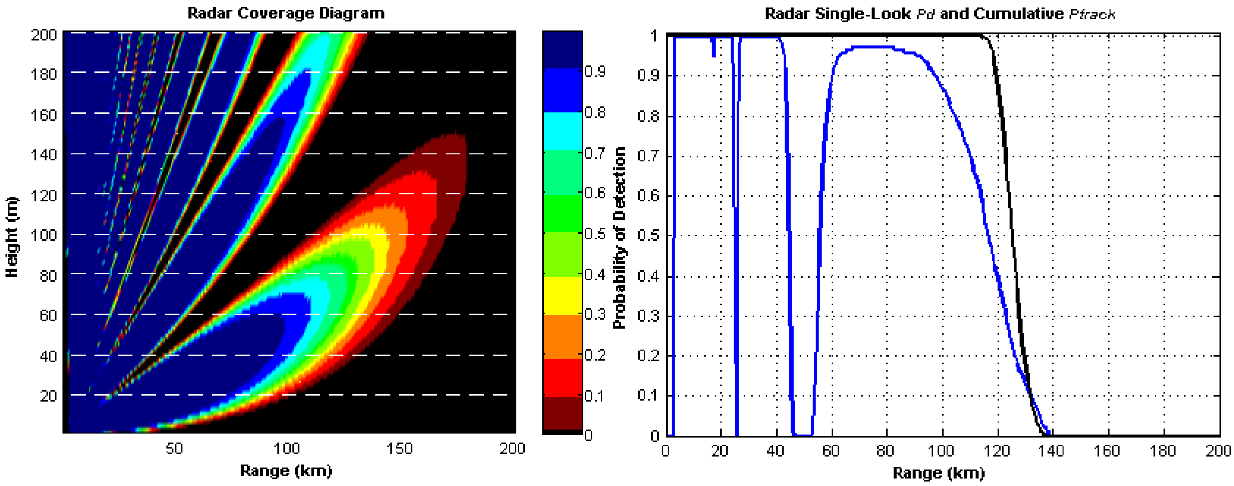

Figure 6-2: Coverage diagram for the radar tuned as given in Figure 6-1 when the sea surface is removed and Flight_Height2 is set to 47 m is given to the left.

Similarly single look PD (blue curve) and cumulative Ptrack (black curve) are given to the right. The cumulative Ptrack goes through 0.8 at 120 km (scaled) range for Flight_Height2 = 47 m resulting in EFA = 4.7 m.

7. Simulation results and conclusions for estimation of effective flight altitude as seen by radar

Figure 7-1 shows a parametric presentation of the relationship between RFA and EFA for generic low real flight altitudes (RFA solid lines). The flight height has a start value and is increased in small increments until the same detection range, as given when the sea surface is applied, is achieved. This flight height is then the EFA. Figures 6-1 and 6-2 shows an example of how to establish EFA for RFA = 5.9 m (green solid curve). EFA is then 4.7 m (green dashed curve) at 12 km range to radar.

The figure shows a trend going from that EFA is just a little lower than RFA at long ranges (lowest grazing angles) to be significantly lower at shorter ranges (some higher grazing angle). The former observation may be a result of diffraction being strong close to the wave crests so that the radar appears to be "looking through" the wave crests for targets at long ranges. The latter may result from that the multipath constructive interference is not so pronounced at shorter ranges when the sea surface model is introduced.

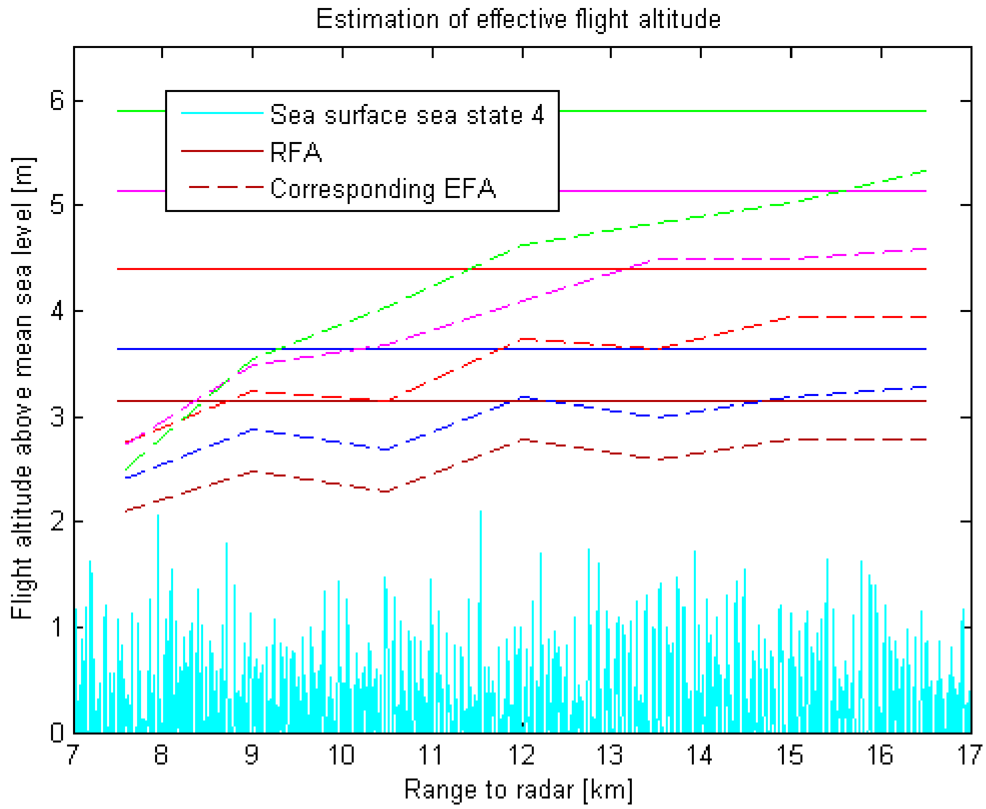

Figure 7-1: A parametric presentation of EFA and generic low RFA versus range to radar for sea state 4.

Referenced Documents

Author and Title	Doc ID	Rev./Date	Publisher
[1] J. R. Apel, "Principles of Ocean Physics"	-	1988	Academic Press, London
[2] S. Chapman, "SADM-AE Users Guide"	-	-	BAE Systems Australia

8. Acronyms and Abbreviations

APM	Advanced Propagation Model
EFA	Effective Flight Altitude
EZL	Effective Zero Level
PPF	Pattern Propagation Factor
Ptrack	Probability of Track
PD	Probability of Detection
RFA	Real Flight Altitude
SADM	Ship Air Defence Model