Quantitative analysis of effects of Ship's Roll and Pitch on Radar Target detection performance

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Abstract - **The Radar mounted on a ship for surveillance purposes and its target detection performance is based on the parameters, Signal to Noise Ratio (SNR), probability of detection (Pd) and track confirmation and maintenance which is dependent on Track confidence level. Primarily, radar target detection, track initiation and track maintenance is dependent upon plot consistency over range and azimuth. Naval surveillance radar performance will be significantly affected due to the sea state experienced by the Ship in terms of roll and pitch parameters. The radar performance is affected due to roll and pitch of the Ship, which significantly results in degraded target detection and tracking. The Roll and pitch of ship induces a dynamic sinusoidal effect in terms of systematic azimuth offset (skew) and elevation offset, which leads to incorrect range and bearing declarations for targets apart from coverage loss.**

keywords - **Signal to Noise Ratio, Track confidence level, azimuth offset, elevation coverage, bearing**

I. INTRODUCTION

The radars mounted on board ship applications for 2-D surveillance, the tilting rotation about longitudinal axis (roll) and up/down rotation about its transverse (pitch) [1] of the ship results in offsetting the 2-D fan beam shifting as well as shifting the elevation angle of the peak of the beam in vertical plane [2] [3]. As a result, the detection capability of the radar is affected such as when the beam points into the sea or high into the air, and bearing accuracy is affected, such as when the beam tilt causes the deck bearing angle to vary from the inertial bearing angle. Because of these effects, the target detection performance of the surveillance system will degrade significantly in high sea states conditions [4].

In this paper, comprehensive experimental and numerical studies are conducted to understand the effect of Ship's roll and pitch during various sea states on the detection performance of radar fitted onboard. The sample sets of roll and pitch experienced by a medium sized Class of Ship is obtained from Cyberspace is used for this analysis. This paper analyses the effect of a medium sized ship's roll and pitch on target detection, target tracking and radar coverage loss [3]. The results and conclusions obtained from this analysis are of great significance during design of electronic beam stabilization or hydraulic beam stabilization platforms.

The terminologies involved in interpretation of Roll and pitch for Radar and the analysis of effects of roll and pitch on Radar is discussed below. To calculate effect of Roll and Pitch, few basic terminologies are used in the following equations.

a. Ship Tangent Frame

X_o - Parallel to the ship's longitudinal axis, positive in the bow direction, and parallel to the Earth's local tangent plane.
Y_o- Parallel to the ship's transverse axis, positive in the starboard direction, and parallel to the Earth's local tangent plane.
Z_o - Vertical, positive downwards, and normal to the Earth's local tangent plane.

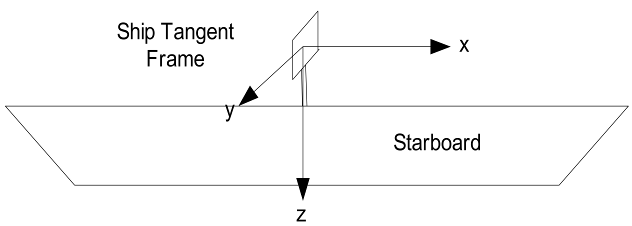

Fig 1. Ship Tangent Frame

b. Array Deck Frame

X_A - Parallel to array broadside azimuth, positive looking out from the array, in the plane of the ship's deck
Y_A - Perpendicular to array broadside azimuth, positive to the right looking out from the array, in the plane of the ship's deck

Z_A - Perpendicular to the ship's deck, positive downwards

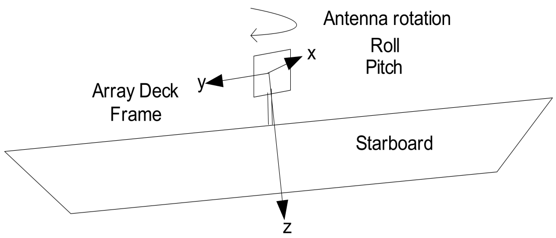

Fig 2. Array Deck Frame

c. Array Tangent Frame

X_T - Parallel to the projection of X_A onto the Earth's local tangent plane
Y_T - Perpendicular to X_T in the Earth's local tangent plane, positive to the right when looking outwards in the X_T direction
Z_T - Vertical, i.e. normal to the Earth's local tangent plane, positive downwards

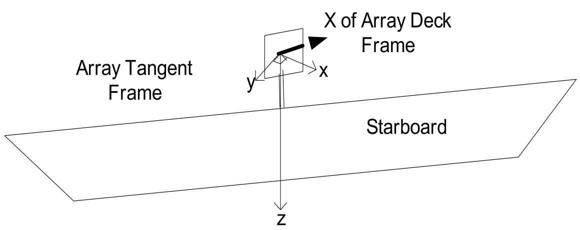

Fig 3. Array Tangent Frame

d. Positive Pitch (Θ_o)

Positive roll is termed as HULL up position of the ship.

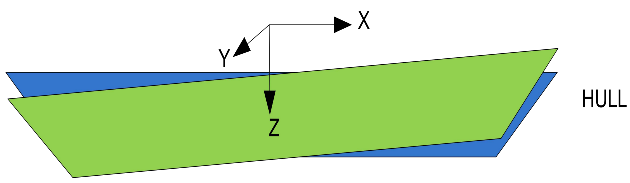

Fig 4. Positive Pitch

e. Positive Roll (Ψ_o)

Positive roll is termed as Starboard down position of the ship.

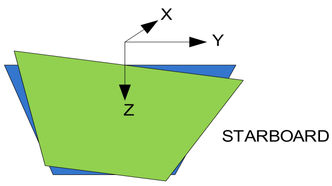

Fig 5. Positive Roll

f. Effective Pitch (Θ_A)

Inclination of X axis of Array Deck Frame w.r.t. X axis of Array Tangent Frame for given Roll, Pitch of ship and Bearing of antenna. Effective pitch is given as,

$$\Theta_A = \text{Sin}^{-1}[\text{Sin}(\Theta_o)\,\text{Cos}(\Phi_A) - \text{Cos}(\Theta_o)\,\text{Sin}(\Psi_o)\,\text{Sin}(\Psi_A)] \qquad - (1)$$

where,
Θ_o = Pitch of the ship
Ψ_o = Roll of the ship
Φ_A = Bearing of the Antenna
Θ_A = Effective Pitch of the antenna

Ψ_A = Effective Roll of the antenna

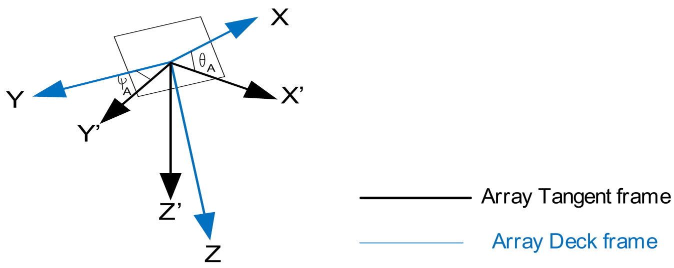

Fig 6. Effective Roll and Pitch

g. **Effective Roll (Ψ_A)**

Effective Roll is the resultant of roll, pitch of ship and bearing of antenna. It is the angle between Y axis of Array Deck Frame and X axis of Array Tangent Frame for given Roll, Pitch of ship and Bearing of antenna. Effective Roll is also equivalent of Beam skew angle (S) and mathematically it is represented as,

$$\Psi_A \text{ or } S = \cos^{-1}[\sin(\Phi_T)\cos(\Theta_o)\sin(\Theta_A) + \cos(\Phi_T)\cos(\Psi_o)\cos(\Phi_A)] \quad - (2)$$

where
Φ_T is effective bearing and given as,

$$\phi_T = \tan^{-1}\left(\frac{\cos(\psi_o)\sin(\emptyset_A)}{\cos(\theta_o)\cos(\emptyset_A)+\sin(\theta_o)\sin(\psi_o)\sin(\emptyset_A)}\right) \quad - (3)$$

Θ_o = Pitch of the ship
Ψ_o = Roll of the ship
Φ_A = Bearing of the Antenna

II. QUANTITATIVE ANALYSIS OF EFFECTS OF ROLL AND PITCH

A target of $2m^2$ is considered for entire analysis along with Track-While-Scan (TWS) radar system specifications. Because, most of the aerial targets are exhibits the RCS of size $1m^2$ to $2m^2$ towards radar. Following radar specifications are considered for simulation and analysis purposes. The radial target trajectory is used and carried out the simulation using **Matlab©** software [6] and Azimuth offset and elevation offset.

Parameters	**Value**	**unit**
Radar Frequency	L band	
Antenna Rotation	12	rpm
Instrumented Range	300	Km
Peak Power	150	KW
Antenna Gain	29.2	dB
Noise figure	3	
RCS	2	m^2
Sea State (Beufort scale)	1 - 5	
Swerling	Type 1	
PRF	500	Hz
No. of pulses	8	
Ship's speed	15	Knots
Ship's displacement	3600	Tonne
Target velocity	300	m/s
Probability of detection	0.8	

Table 1. Radar system Specification

a. Azimuth offset

Following Figure 7 presents the instantaneous offset or error in the azimuth reports as a function of target elevation angle for various target azimuth angles, ship moving with 15Knots. For any given ship's pitch and target elevation, the maximum bearing error occurs when measured target bearing is 90°, i.e, the target is at broadside. When the ship's pitch is zero, or when the target is at zero azimuth, no offset results.

The effective Azimuth offset of detected target is given as,

Azimuth offset = $Tan^{-1}[Tan(E)Tan(S)]$ - (4)

where E = Target Elevation Angle and
S = Beam Skew Angle

The effective Azimuth offset has been plotted from 0° to 360° of azimuth coverage for different sea states (roll and pitch). The potential performance risk of azimuth offset is reduction of azimuth accuracy of the target at plot and track levels.

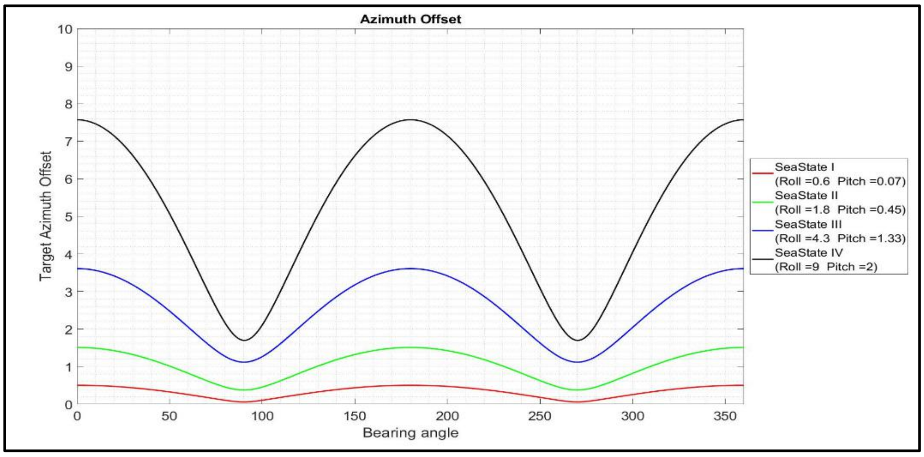

Fig 7. Azimuth offset w.r.t. sea states @ 15Knots

Estimated maximum Target Azimuth offset at sea state 5 = (+/-) 10.34°

b. Elevation offset

Elevation offset is effective pitch Θ_A of antenna at given roll and pitch of ship and bearing of antenna. The effective pitch will result in variation of elevation coverage. For example, if effective pitch is +5° at any instant, the antennal will cover from 5° to 45° instead of 0° to 40° (covers from -5° to 35° if effective pitch is -5°). Elevation offset has been plotted from 0o to 360° of azimuth coverage for different sea states (roll and pitch). The potential risks of elevation offset are:

a. Loss of high flying targets and results
b. Delayed auto track initiation/maintenance
c. Degraded track continuity

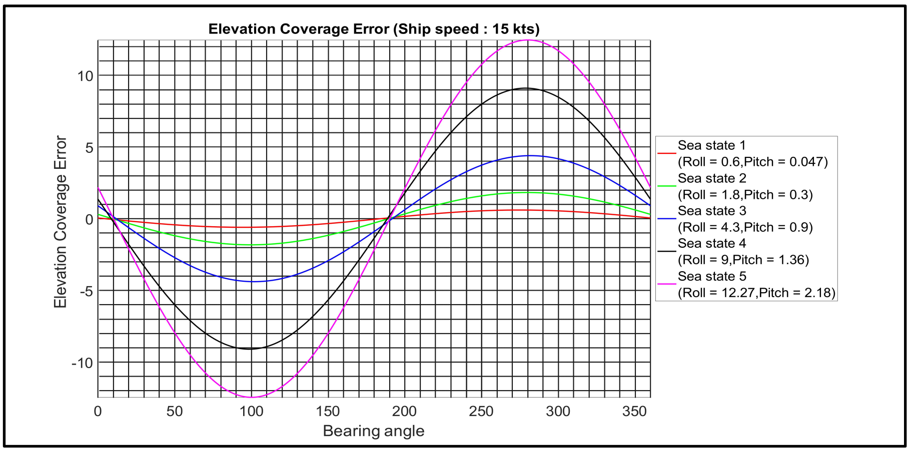

Fig 8. Elevation offset w.r.t. sea states @ 15Knots

Estimated maximum Elevation offset at sea state 5 = (+/-) 12.46°

c. Coverage Loss

The coverage error induced due to azimuth offset and elevation offsets results in volume coverage loss of radar detection. The loss in coverage is quantified and plotted from 0° to 360° of azimuth coverage for different sea states. The sea state information is used to quantify the magnitude of respective Roll and pitch which is affecting on ship platform.

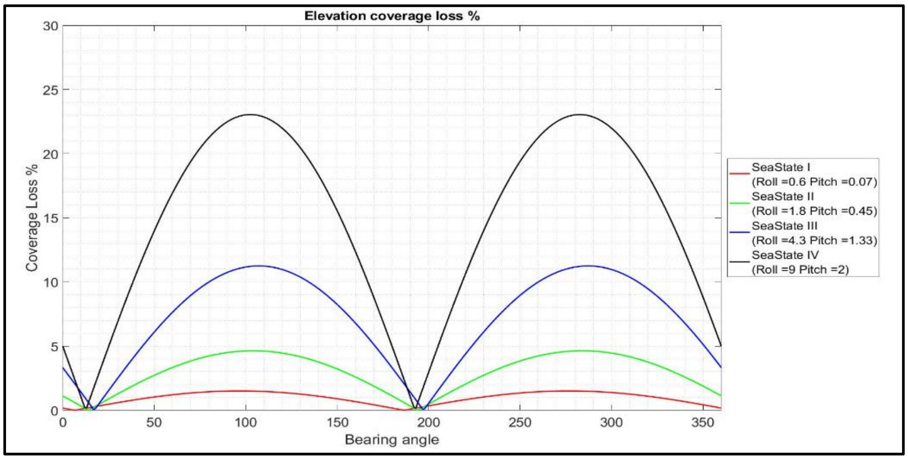

Fig 9. Coverage Loss w.r.t. sea states @ 15 Knots

d. Estimated Coverage loss (%) at different azimuth

Volume coverage loss analysis is carried out using **Carpet-2** Software. The following figures shows the typical comparison of free space coverage of with and without Roll/pitch of the platform. The results are tabulated in following table 2.

Sea State	0°	40°	80°	120°	160°	200°	240°	280°	320°
1	0.12	0.87	1.46	1.36	0.62	0.40	1.24	1.50	1.05
2	0.75	2.32	4.30	4.27	2.24	0.83	3.52	4.56	3.47
3	2.25	5.18	10.19	10.43	5.79	1.56	8.18	10.98	8.63
4	3.40	11.81	21.55	21.18	10.87	4.47	17.75	22.75	17.04
5	5.45	15.41	29.21	29.27	15.55	5.29	23.73	**31.15**	23.84

Table 2. Estimated coverage loss

Estimated maximum Coverage Loss is 31.15% at sea state 5 and peaks at bearing 100° and 280° as shown in Fig11.

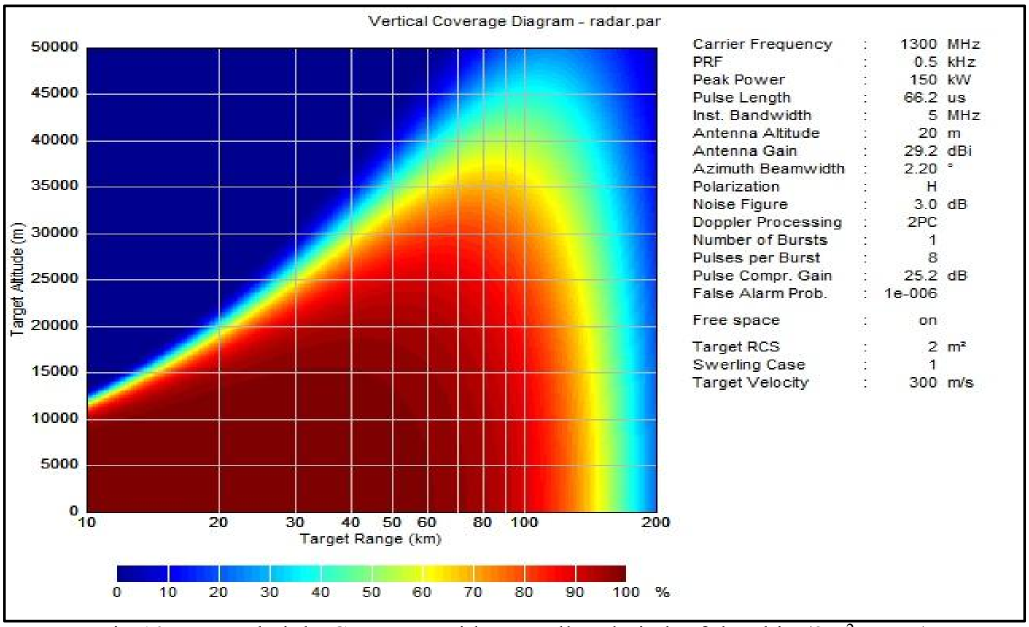

Fig 10. Range-height Coverage with no Roll and pitch of the ship (2m^2 target)

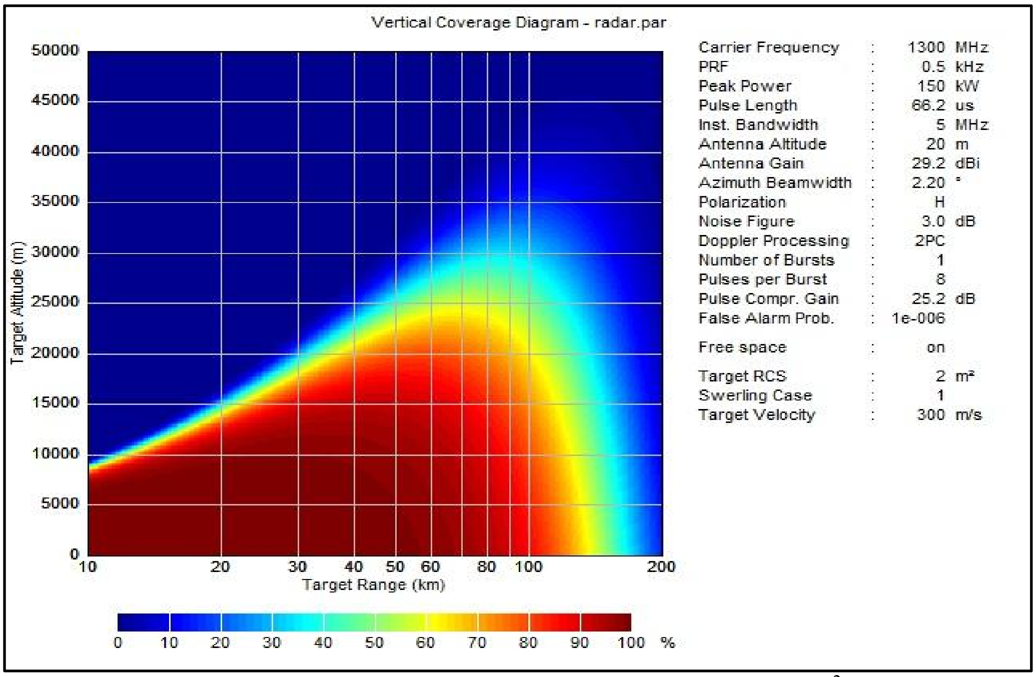

Fig 11. Range-height Coverage with Roll and pitch of the ship ($2m^2$ target)

e. Height coverage loss for various sea states with roll and pitch

The instantaneous height coverage is reduced by maximum of 14km for sea state 5 with Ship's Roll and Pitch as simulated and shown in Fig 12.

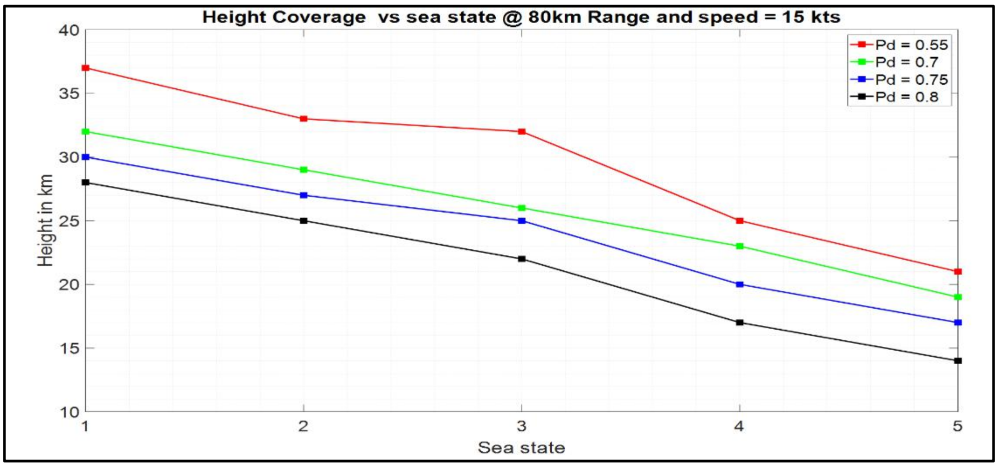

Fig 12. Height Coverage Vs Sea State

It is verified that, the instantaneous height coverage is reduced by maximum of 14km for various sea states at different Probability of detection.

III. Future work

This study is restricted only to derive the magnitude of azimuth and elevation offset for the given Ship's Roll and pitch. Further, the study can be expanded to derive the direction of azimuth and elevation offsets.

IV. CONCLUSION

It is evident that the roll and pitch of ship is severely affects the target's probability of detection. The detected targets are not only identified with azimuth angle offset but also because of change in elevation coverage, targets beyond the specified coverage area of radar are detected. The severity of wrong detections is depending on sea states which results in ship's roll and pitch. Hence it is imperative to compensate the roll and pitch of the antenna to get the right target detection parameters in the affected coverage volume.

Specifically, at sea state 5, a significant loss of 31.15% in total area coverage. The detection probability and accuracy at plot and track level will be reduced due to this coverage loss, and by increased nearby clutter level (more false alarms). The tracking function correlates the plots from scan to scan, and hence the plot correlation and track maintenance will be severely impacted. Also, the course and velocity accuracy at track level is affected due to targets missing from scan to scan.

The Clutter background of the radar is depending on the proportion of the radar energy projected on the surface. The amount of energy projected is depending on the inclination (tilt) of the antenna. Due to the ship's effective roll and pitch, there will be a change in the main beam illumination and results in instability of the background clutter from scan to scan (Reduced clutter in upward elevation coverage and increased clutter in downward elevation coverage) and hence the degradation in track maintenance.

V. ACKNOWLEDGMENT

The authors would like to thank Sri. Umesh K.S, General Manager, NS2, BEL, for giving us the opportunity to work on this requirement. He provided the motivation through his vast knowledge and experience in BEL Radars. It was a good learning experience for us to work with his vast experience in Radars installation onboard Indian Naval ships.

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