Characterization of non-Rayleigh Acoustic Scattering by Elongated Scatterers in the Water Column and on Boundaries

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LONG-TERM GOALS

To significantly reduce the probability of false alarm in Navy active sonar systems using predictive physics-based models.

OBJECTIVES

To develop and apply probability density functions (PDF's) to describe non-Rayleigh echoes from single realistic objects for eventual use in classifiers.

APPROACH

The echo statistics associated with a randomly oriented prolate spheroid randomly located in the sonar beam are modeled. The cases of a smooth and rough spheroid, both in the water column (i.e., case in which boundaries are not involved), and on a boundary are investigated. The modeling begins with the analytical physics-based expression for the scattering amplitude of a smooth prolate spheroid. The following properties are then incorporated which leads to a random echo: randomly rough outer boundary of spheroid, random orientation, and random location in the sonar beam. The contributions of each property to the echo statistics are studied both separately and collectively. Graduate student Saurav Bhatia was funded principally to conduct this research as part of his graduate research. Kyungmin Baik, a WHOI post-doctoral fellow, also participated in the research.

WORK COMPLETED

YEAR 1 (FY 11)

The tasks completed are divided between reproducing key results in the literature (#1) and advancing the field (#2 and #3):

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1. Key results of Ehrenberg (1972) involving the echo statistics of a single object in the water column and randomly located in the sonar beam.

   a) Ehrenberg's general formulation for the beampattern PDF was rederived. Here the "beampattern PDF" is defined as the random variable associated with the randomized weighting on a scatterer due to its random location in a sonar beam.

   b) The beampattern PDF was calculated for a range of beamwidths.

   c) The echo PDF as seen through the sonar receiver was calculated for the case in which the echo from the scatterer before beampattern effects is Rayleigh distributed.

2. The echo statistics (as observed through the sonar receiver) were calculated due to a randomly rough spheroid, randomly oriented, and randomly located in the sonar beam in the water column (Fig. 1). This work involved a progression of calculations of echo statistics involving the following scattering geometries (Figs. 2, 3):

   a) Smooth, randomly oriented prolate spheroid without beampattern effects

   b) Randomly rough, randomly oriented prolate spheroid without beampattern effects

   c) Randomly rough, randomly oriented prolate spheroid *with* beampattern effects

3. The echo statistics from compact mobiles, as provided by Dr. Jim Gelb of ARL:UT, were modeled using the randomly rough, randomly oriented prolate spheroid. In order to model low values of echo amplitude, a Rayleigh PDF needed to be incorporated via a two-component mixture PDF (Fig. 4).

4. All work was validated numerically, as illustrated in Fig. 2.

<u>YEAR 2 (FY 12)</u>

The tasks completed this year are divided between finalizing results from FY11 concerning a prolate spheroid in the water column, submitting a paper based on those results, and extending the results to the case in which the prolate spheroid is on a boundary:

5. The characterization of echo statistics (as observed through the sonar receiver) was finalized for the case of a randomly rough spheroid, randomly oriented, and randomly located in the sonar beam in the water column. The final work focused on numerical issues associated with singularities in the calculations and associated convergence problems. In one case, an adaptive approach was developed so that calculations were done in closely spaced intervals near the singularities. Overall, the work involved a progression of calculations of echo statistics involving the three scattering geometries given in #2 above.

6. A manuscript based on #5 was drafted, finalized, and submitted for review in a refereed journal (Bhatia et al, submitted).

7. Student Saurav Bhatia successfully completed his Master's thesis. The thesis is based on the manuscript listed in #6, but with more simulations included as well as software (Bhatia, 2012).

8. The work from #5 was extended to the case in which the prolate spheroid was in contact with a boundary (Figs. 1, 5-9). Because of the complex geometry involved, all work was numerical, although drawing from geometric-optics acoustic scattering formulas. These formulas assumed three dominant scattering rays (Fig. 5). Key tasks completed are summarized:

   a) Predicted backscattering for the full range of angles of orientation of the smooth prolate spheroid, full ranges of angles of incidence of the incident field, and three types of boundaries—soft (sea surface), rigid/hard (bedrock), and penetrable (sandy seabed) (Fig. 6).

   b) Predicted echo statistics for case of smooth prolate spheroid randomly oriented in the center of the sonar beam (i.e., no beampattern effects) (Fig. 7).

   c) Predicted echo statistics for case of smooth prolate spheroid randomly oriented and randomly located in the sonar beam (Fig. 8).

   d) Predicted echo statistics for case of *rough* prolate spheroid randomly oriented and randomly located in the sonar beam (Fig. 9).

RESULTS

Through modeling of the echo statistics of the prolate spheroid, both on and away from boundaries, we have observed there to be significant increases in the tails of the PDFs and probability of false alarms (PFAs) above the Rayleigh distribution for a wide range of important conditions. The modeling has quantified the degree to which the tails are non-Rayleigh for a variety of conditions—smooth prolate spheroid, rough prolate spheroid, range of aspect ratios of prolate spheroid, omni-directional sonar beam, directional sonar beam, and three types of boundaries.

As demonstrated in previous studies, the beampattern plays a major role in elevating the tails of the PDF and PFA. However, in this study, we have demonstrated that the scattering characteristics of the scatterer also play a major role in the tail. In general, as the spheroid becomes roughened and of higher aspect ratio, the tail of the echo distribution becomes heavier. The rough prolate spheroid predictions also compared well with the echo statistics observed in the mid-frequency sonar data (data made available by Dr. Jim Gelb, ARL:UT), providing a plausible explanation for the data.

These accomplishments represent a new capability in predicting echo statistics in the direct-path geometry: this physics-based model, which was numerically validated, is scalable to any size and aspect ratio of prolate spheroid, and thus can make predictions over a wide range of important conditions of sonar performance.

IMPACT/APPLICATIONS

The scattering by the prolate spheroid in the water column or on a boundary has a strongly non-Rayleigh tail—an effect that needs to be accounted for in ASW active sonar systems. Our new physics-based model is useful in making predictions to improve the performance of ASW active sonar systems, as it explicitly and rigorously accounts for the physics of the scattering as well as the sonar parameters (directionality). This model will be key in predicting the statistics of echoes from targets and target-like features.

RELATED PROJECTS

a. This project was inspired by a previous project (Stanton/Chu) in ONR Undersea Signal Processing (N00014-09-1-0428) in which the statistics of echoes were formulated in relation to the statistical properties of the scattering amplitude of a scatterer (before beampattern effects) and the random process associated with the scatterer being located randomly in the beam. In this current project, the echo statistics of the scattering amplitude are directly connected to the physics of the scattering of the object, hence making the overall modeling of the echo statistics *fully* physics-based.

b. This project co-funded student Bhatia with another project (Stanton/Jech/Gauss) in ONR Biology (N00014-10-1-0127) in which measurements of broadband acoustic scattering by fish were made in the ocean. In that project, fish are modeled as prolate spheroid scatterers.

c. The compact mobile data used in this project in FY11 were provided by Dr. Jim Gelb, ARL:UT, who was funded by another grant in ONR Undersea Signal Processing.

REFERENCES

J.E. Ehrenberg (1972) "A method for extracting the fish target strength distribution from acoustic echoes," in *Proc. Conf. Eng. Ocean Environ.*, **Vol. 1**, pp.61-64.

PUBLICATIONS

Refereed

Bhatia, S., T.K. Stanton, and K. Baik (submitted), "Non-Rayleigh scattering by a randomly oriented elongated scatterer randomly located in a beam," submitted to IEEE J. Ocean. Eng. [submitted, refereed]

Dissertation

Bhatia, S. (2012). "Non-Rayleigh scattering by a randomly oriented elongated scatterer", M.S. thesis, MIT/WHOI. [published]

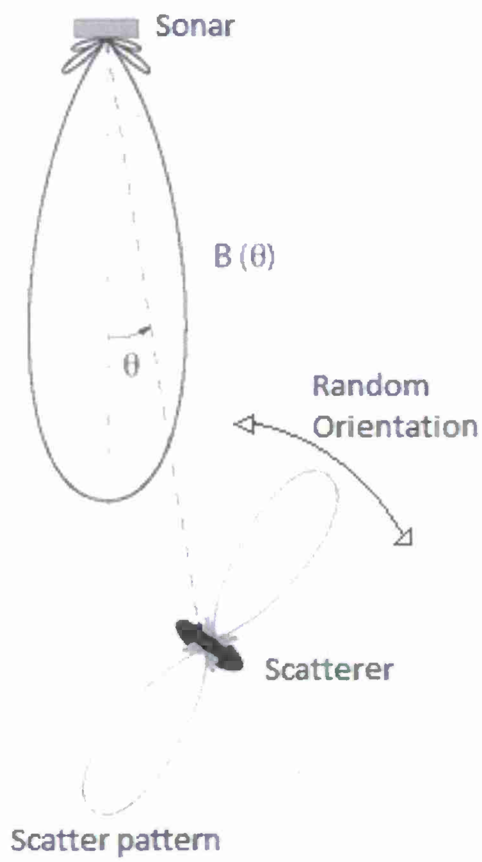

Figure 1. Scattering geometry for a prolate spheroid randomly oriented and randomly located in an active sonar beam. This geometry applies to both the case of the prolate spheroid being away from a boundary (water column) or on a boundary (top view) with a horizontally-looking sonar.

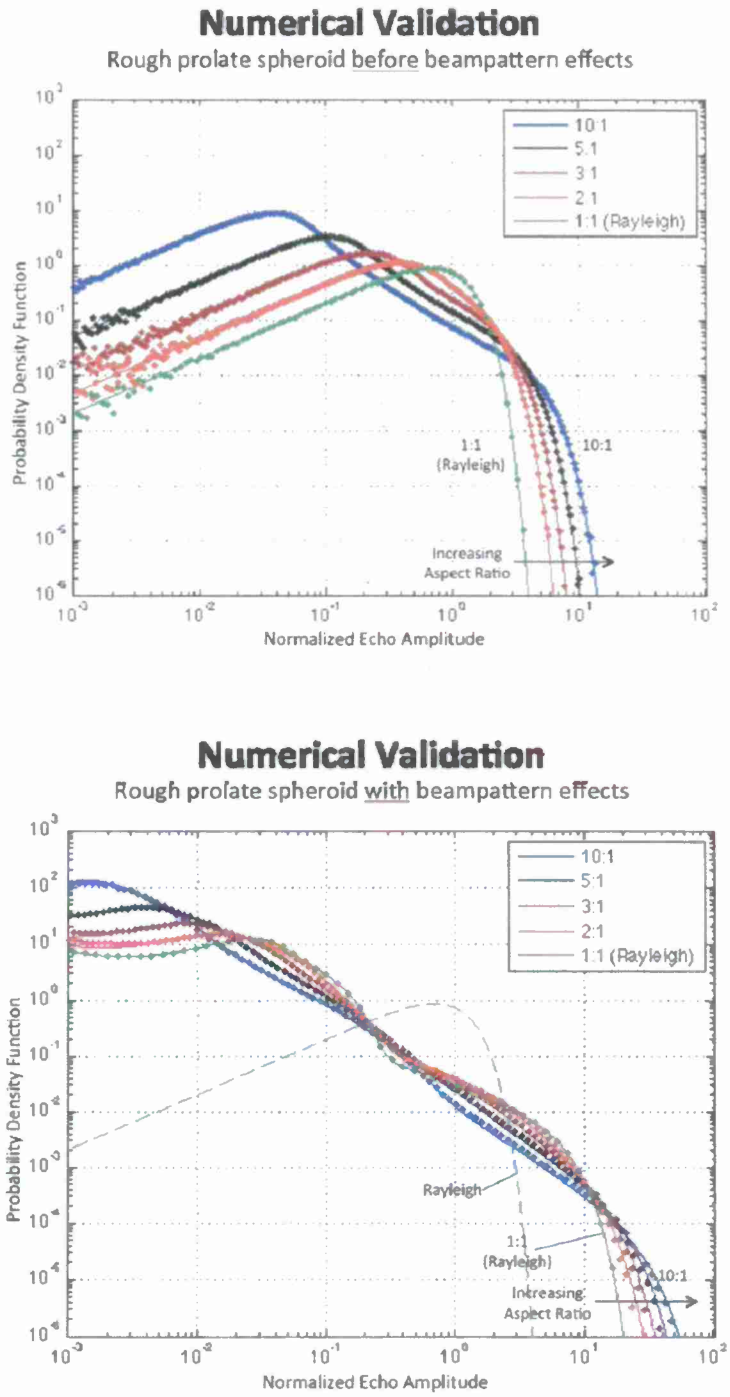

Figure 2. Theoretical predictions (curves) and numerical validation (symbols) of PDFs of the echo from a randomly rough, randomly oriented prolate spheroid of various aspect ratios (ratio of length to width = 1:1 to 10:1). Upper: no beampattern effects (i.e., omnidirectional beam). Lower: with beampattern effects. The 1:1 Rayleigh curve in each panel corresponds to a rough sphere with an echo that is Rayleigh distributed before beampattern effects.

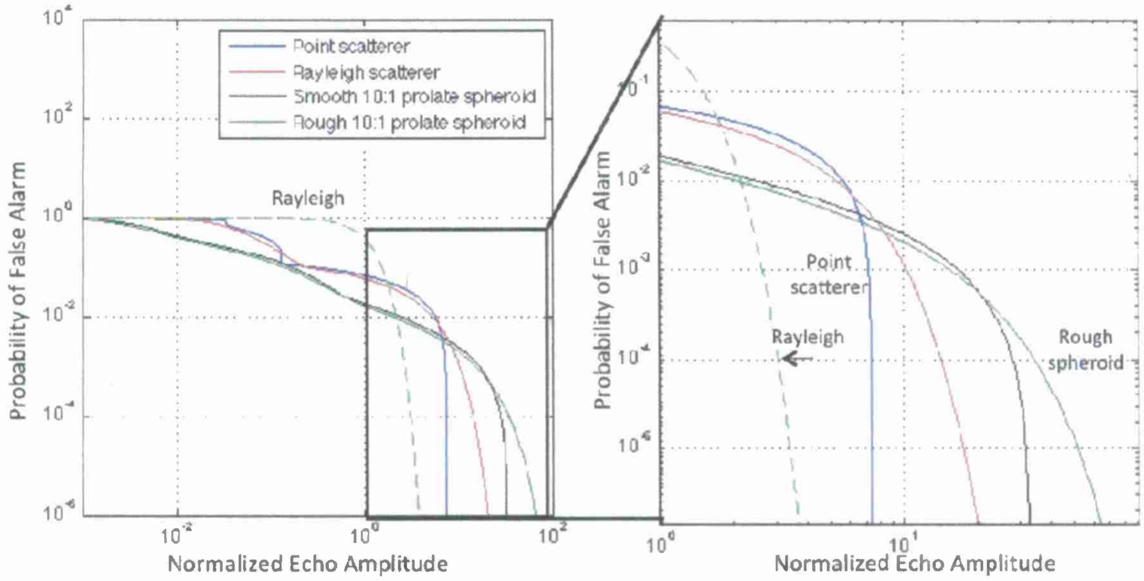

Figure 3. Probability of false alarm for various types of scatterers that are randomly located in the sonar beam. The spheroids are randomly oriented.

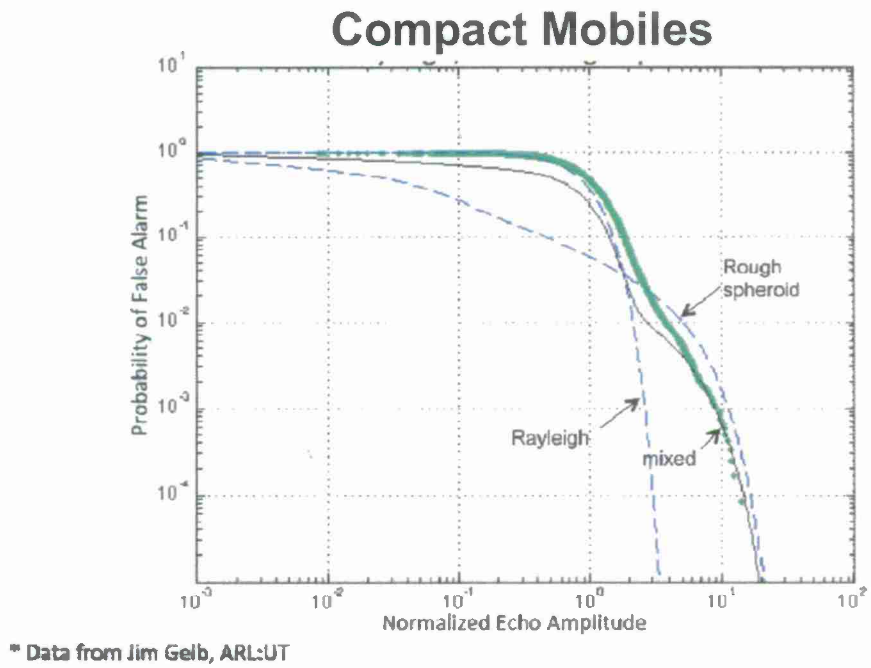

Figure 4. Modeling a compact mobile as a randomly rough, randomly oriented prolate spheroid. The corresponding PDF is mixed with a Rayleigh PDF in a two-component mixture PDF. Data are in green.

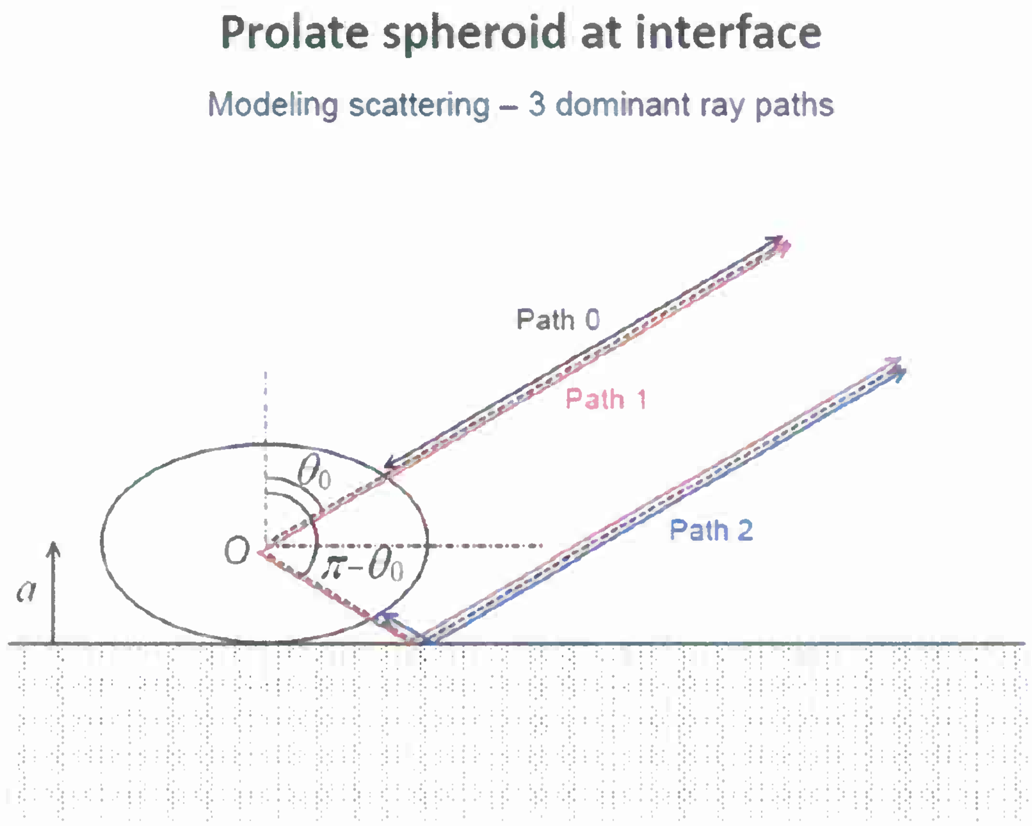

Figure 5. Side view of prolate spheroid on a boundary. The scattering is modeled by using the three dominant rays (paths 0, 1, and 2).

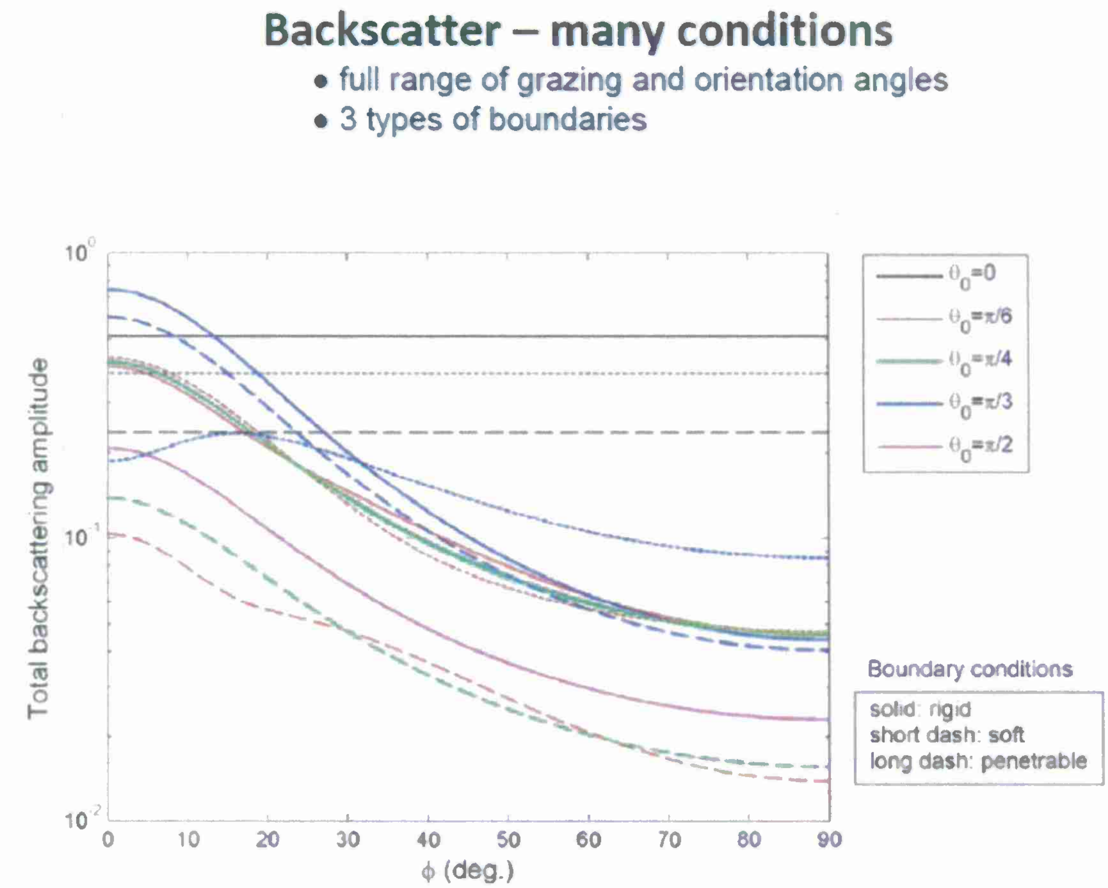

Figure 6. Backscattering by a smooth prolate spheroid on a boundary versus angle of orientation (ϕ). The calculations were done for a range of angle of incidence ($\theta_0 = 0°$ for normal incidence through $\theta_0 = 90°$ for horizontal-looking) and for three types of boundaries-- soft (sea surface), rigid/hard (bedrock), and penetrable (sandy seabed).

Echo statistics (no beampattern effects)

- Randomly oriented smooth prolate spheroid on rigid boundary
- Shallow grazing angle

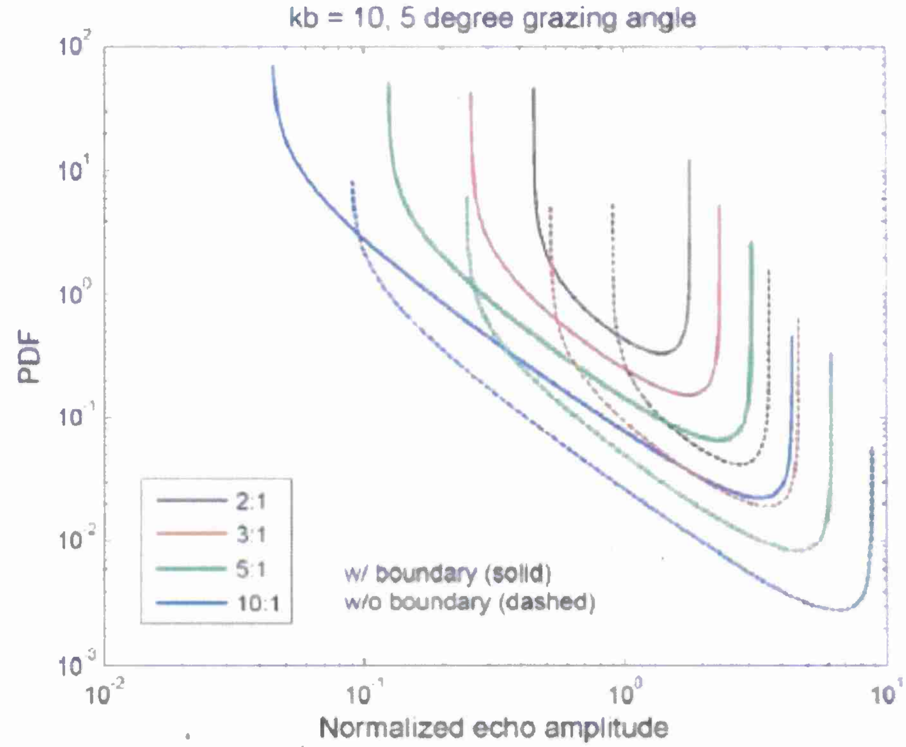

Figure 7. Echo amplitude PDF (probability density function) from randomly oriented smooth prolate spheroid on a rigid boundary. The prolate spheroid is located in the center of the sonar beam (i.e., there are no beampattern effects). The sonar is at 5° grazing angle (i.e., 5° between direction of incident field and boundary).

Echo statistics (with beampattern effects)

- Randomly oriented smooth prolate spheroid on rigid boundary
- Shallow grazing angle

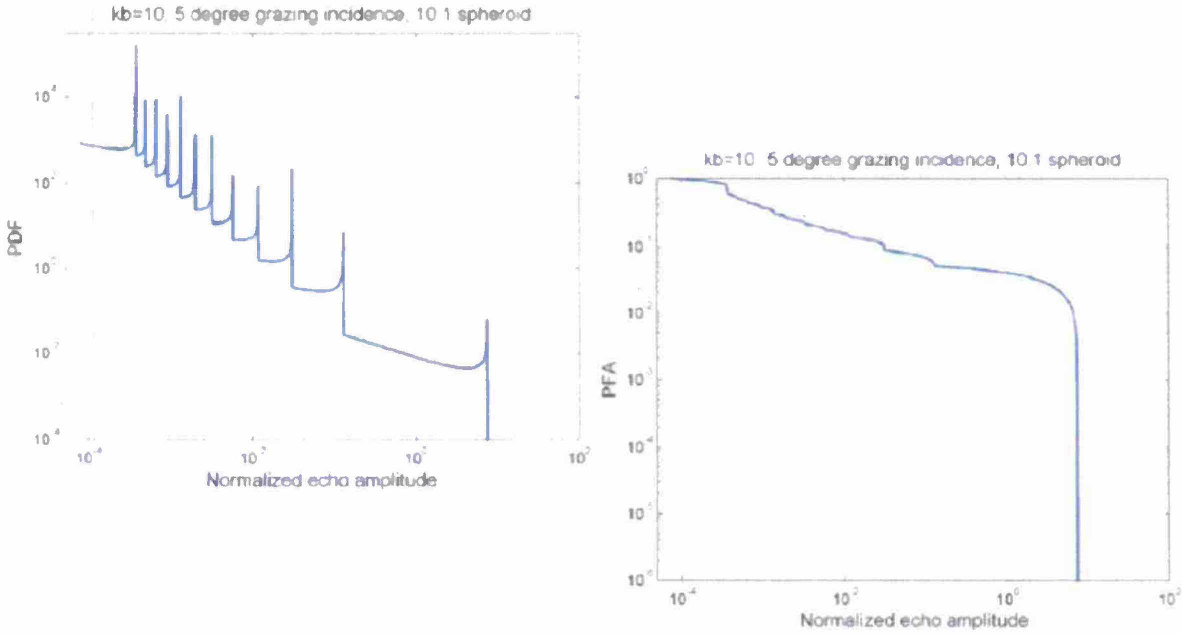

Figure 8. Echo PDF and PFA (probability of false alarm) for geometry listed in Fig. 7, but now the smooth prolate spheroid is randomly located in the sonar beam. This adds more variability to the echo.

Echo statistics (with beampattern and roughness effects)

- Randomly oriented rough prolate spheroid on rigid boundary
- Shallow grazing angle
- With beampattern effects

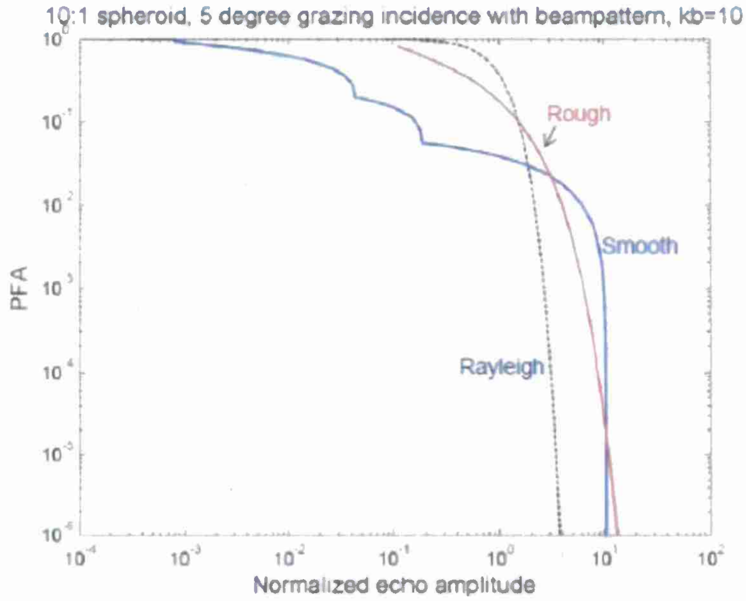

Figure 9. Echo PFA for geometry in Fig. 8, but now using a randomly rough prolate spheroid. This adds even more fluctuations to the signal. The PFA for a smooth spheroid is shown for comparison.

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