Near-Nadiral Normalized Radar Cross Section of the SEA Surface at Ku, Ka, and W-Bands: Comparison of Measurements and Models

Ninoslav Majurec¹, Joel T. Johnson¹, Simone Tanelli², Stephen Durden²

¹ Department of Electrical and Computer Engineering
ElectroScience Laboratory, The Ohio State University, Columbus, Ohio
² NASA Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California

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Motivation

• Understanding the relationship between wind speed and direction and the near-nadiral normalized radar cross section (NRCS) of the sea surface is important in many oceanographic and atmospheric remote sensing applications:
  • wind speed retrievals in traditional altimeter systems
  • assistance in calibration and path integrated attenuation processing for atmospheric profiling radars

• The desired wind speed (and direction in some cases) retrieval requires a clear understanding of the relationship between the relevant geophysical quantities and the observed NRCS

• Such understanding is available from existing electromagnetic models, but the presence of many such models, as well as implicit descriptions of the sea surface, motivates continued evaluation of model performance.
Outline

• Ocean Surface NRCS Modeling
• Cutoff Invariant Two-Scale Model
• CloudSat Nadir Data Analysis
• APR-2 GRIP Experiment Data Analysis
• Conclusions
Ocean Surface NRCS Modeling

• Near nadiral NRCS of a rough surface can be well described at high frequencies by the Geometrical Optics (GO) method.

• GO model requires sea surface relative permittivity and the up and cross wind surface slope variances to predict the NRCS

• Slope variances of the surface can be determined:
  • through an empirical approach (Cox-Munk)
  • through an integration over the “long wave” portion of an assumed sea surface power spectral density (Durden-Vesecky or Elfouhaily sea spectra)

• A key concern in either approach is the determination of appropriate length scales over which slope variance contributions should be included.

• This issue has given rise to empirical models of the slope variance that vary with the frequency considered, or the ad-hoc selection of a “cutoff” wavenumber in the integration over the sea spectrum.
Cutoff Invariant Two-Scale Model

• Cutoff-invariant model is based on the small slope approximation of surface scattering

• Combines GO-like and “tilted-Bragg” contributions in a manner that eliminates the influence of the cutoff wavenumber.

• Appropriate for the prediction of returns at larger incidence angles, since the Bragg scatter effects that dominate at larger angles are also incorporated.

• Can be combined with any model of the sea surface spectrum, such as Durden-Vesecky or Elfouhaily

• The model requires more extensive computations than the GO-only approach
Cutoff Invariant Two-Scale Model

CTISM = GO \times e^{-Q^2 h_S^2} \left( 1 - e^{-Q^2 h_S^2} \right) + SSA

For simple spectrum, such as:

\[ w(k, \varphi) = w_0(k) + w_2(k) \cos(2\varphi) \]

calculation of NRCS requires solution of two 1D integrals:

\[ P_0 = \frac{e^{-Q^2 h_S^2}}{2\pi} \int_0^\infty \left[ e^{Q^2 h_S^2 C_0(\rho)} - 1 \right] J_0(k_0\rho) \rho \, d\rho \]

\[ P_2 = -Q^2 h_S^2 \frac{e^{-Q^2 h_S^2}}{2\pi} \int_0^\infty C_2(\rho) e^{Q^2 h_S^2 C_0(\rho)} J_2(k_0\rho) \rho \, d\rho \]

\[ C(\rho, \varphi) = C_0(\rho) + C_2(\rho) \cos(2\varphi) \]

Comparison of the NRCS calculations using Cutoff Invariant Two-Scale Model (CITSM) for radially symmetric ocean surface spectrum at W-Band
CloudSat Nadir Data Analysis

### CloudSat Data Analysis: Nadir looking data points

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Sea surface temperature: 0 to 30 °C, bin size 1 °C,

Wind speed: 0 to 30 m/sec, bin size 0.5 m/sec,

Wind direction: 0 to 360 degrees, bin size 5 deg.
CloudSat Nadir Data Analysis

Data is compared to the following model predictions:

1. Durden-Vesecky ocean surface spectrum, original amplitude \((a_0 = 0.004)\), Ellison sea water dielectric constant model,
2. Elfouhaily spectrum, Ellison sea water dielectric constant model,
3. Elfouhaily spectrum, Klein-Swift sea water dielectric constant model,
4. Durden-Vesecky spectrum, double amplitude \((a_0 = 0.008)\), Ellison sea water dielectric constant model,
5. Durden-Vesecky spectrum, 1.5 original amplitude \((a_0 = 0.006)\), Ellison sea water dielectric constant model,
6. Durden-Vesecky spectrum, 1.347 original amplitude \((a_0 = 0.00539)\), Ellison sea water dielectric constant model,
7. GO using Cox-Munk RMS slopes, Ellison sea water dielectric constant model
8. GO using Cox-Munk RMS slopes, Klein-Swift sea water dielectric constant model
CloudSat Nadir Data Analysis

Granules 06446-06912 (Group 2), SST 10 to 11 C
Granules 06446-06912 (Group 2), SST 20 to 21 C
Granules 06446-06912 (Group 2), SST 27 to 28 C

CloudSAT Data

Granules 14253-14703 (Group 9), SST 20 to 21 C
Granules 14253-14703 (Group 9), SST 10 to 11 C
Granules 14253-14703 (Group 9), SST 27 to 28 C

Sigma0 [dB]

Wind Speed [m/sec]

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CloudSat Nadir Data Analysis: Conclusions

• The results showed that the cutoff-invariant model could reproduce CloudSat measurements to a reasonable agreement (using wind speed “ground truth” from other satellite measurements)

• The Elfouhaily spectrum model was found to produce the best prediction of measured data on average

• GO model with Cox-Munk slope variances provided a reasonable match to measured data, indicating that the relevant sea slope variances at W-band are nearly identical to the optically determined values.
APR-2 GRIP Experiment Data Analysis

• The APR-2 is a Ku and Ka-band radar system observing in a cross track scanning configuration

• Data at the incidence angles ranging from ~ 4 to ~ 25 degrees are available

• Several APR-2 deployments are considered:
  • NASA African Monsoon Multi-Disciplinary Analyses (NAMMA, 2006)
  • Tropical Composition, Clouds, and Climate Coupling (TC4, 2007) mission,
  • Genesis and Rapid Intensification Processes Experiment (GRIP, 2010)

• Only data in “clear air” was utilized in the comparison

• Standard APR-2 calibration processes were utilized to determine the observed sea surface NRCS, including path integrated attenuation corrections obtained from atmospheric observations

• Wind speed and direction ground truth information was obtained from dropsonde measurements.
APR-2 GRIP Experiment Data Analysis

- Dropsondes used in analysis
- Dropsondes that stopped responding more than 40 m above sea surface
APR-2 GRIP Experiment Data Analysis
**APR-2 GRIP Experiment Data Analysis**

Ku-band, Method 3: Clear-Air mean Ku < -75 dBZe

Ka-band, Method 3: Clear-Air mean Ku < -75 dBZe

- Elf – Elfouhaily Spectrum
- DV – Durden-Vesecky ($a_0 = 0.004$)
- DDV – Durden-Vesecky with double amplitude ($a_0 = 0.008$)
- CM – Cox-Munk

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APR-2 GRIP Experiment Data Analysis

- mean value of the dB difference
APR-2 GRIP Experiment Data Analysis

• standard deviation of the dB difference
APR-2 GRIP Experiment Data Analysis

- Strong impact of both, temporal and spatial proximity of the wind speed ground truth
- More reliable data set can be extracted using weight value assigned to each dropsonde

\[
W_d = e^{-\frac{ds\text{ point } d^2}{2\sigma_d^2}}
\]

\[
W_t = e^{-\frac{ds\text{ point } t^2}{2\sigma_t^2}}
\]

\[
W = W_d \cdot W_t
\]

where, \( \sigma_d = 50 \text{ km} \) and \( \sigma_t = 20 \text{ min} \)
Ku-band: Weight value > 0.8

Ku-band: Weight value > 0.832
Conclusions

• The statistical results show that the considered models produced generally similar predictions

• Significant uncertainties in wind truth are important in these comparisons, particularly at lower wind speeds

• Somewhat smaller mean errors were achieved by the Elfouhaily spectrum. The average bias absolute value of \(\sim 1.276\) dB was obtained with Elfouhaily model for Ku-band (DV \(\sim 2.037\) dB, DDV \(\sim 1.472\) dB, and CM 2.169 dB). The Ka band values are 1.227 dB (Elf), 1.662 dB (DV), 1.651 dB (DDV), and 1.758 dB (CM).

• Bias is fairly uniform in incidence angle suggests that other factors in addition to uncertainties in the sea spectrum may be contributing to these differences

• More reliable data subset can be extracted using the weight values as an indicator of the valid data points:
  • aside from a general improvement in standard deviation, the Elfouhaily model seems to exhibit the improvement in bias as well.

• Models seem to work even at the high wind speeds