PROBABILITY DISTRIBUTION OF WIND RETRIEVAL ERROR FOR THE NASA SCATTEROMETER

Daniel F. Leotta and David G. Long

Jet Propulsion Laboratory, California Institute of Technology

4800 Oak Grove Drive, Pasadena, CA 91109

Abstract - The NASA Scatterometer (NSCAT) is a spaceborne scatterometer which is scheduled to be deployed in the mid-1990s. This paper presents an analysis of the wind retrieval error distribution for wind estimates based on backscatter measurements made by the NSCAT instrument. The results are based on an end-to-end simulation of the scatterometer instrument and data processing. In general, the distribution of the wind speed error, when normalized, is independent of the true wind speed and direction. The wind speed error can be characterized by a normal distribution. The wind direction error is independent of the true wind speed, but depends on the true wind direction. Details for wind vectors with true wind speeds from 3 to 33 m/s and true wind directions from 0 to 360° are presented.

1. Introduction

Scatterometer systems may be used to infer the speed and direction of winds at the ocean's surface from measurements of radar backscatter. The NASA Scatterometer (NSCAT) is a spaceborne scatterometer which is scheduled to be deployed in the mid-1990s (Li *et al.*, 1984). It represents an evolution of the design of the Seasat scatterometer which was in operation in 1978. NSCAT utilizes six fan-beam antennas which provide backscatter measurements at three azimuth angles over two swaths of 600 km width each. Each swath is divided into 24 cross-track σ_0 cells, each with 25 km resolution. Digital Doppler filtering is included for precise location of these cells on the ocean (Long *et al.*, 1988). Measured signal power is related to wind velocity through a geophysical model function, which is a nonlinear function of such parameters as incidence angle, antenna azimuth angle, and antenna polarization. The goal of the project is to provide accurate measurements of global oceanic winds which can be of use in oceanography and meteorology.

The noisy measurements of the radar backscatter made by the scatterometer result in errors in the retrieved wind vector. Wind retrieval error is the difference between the retrieved wind (speed and direction) and the "true" wind. The characteristics of the error can impact the application of the scatterometer-derived wind estimates. This paper presents an analysis of the wind retrieval error distribution for wind estimates based on backscatter measurements made by the NSCAT instrument. Due to the non-linearity of the geophysical model function, a numerical approach using Monte Carlo methods is employed. The results are based on an end-to-end simulation of the scatterometer instrument and data processing (referred to as the "compass simulation"), using the baseline NSCAT wind retrieval algorithm. The error distribution depends on the true wind vector and the particular swath location of the measurement. Wind vectors with true wind speeds from 3 to 33 m/s and true wind directions from 0 to 360° are considered. The goal of this study is to develop a methodology for characterizing wind retrieval errors for NSCAT.

2. Compass Simulation

The compass simulation (Chi and Li, 1988) is a software package developed at JPL which simulates the performance of the NSCAT instrument over a uniform wind field. For fixed wind speeds, wind directions can be simulated for any direction from 0 to 360°, hence the name "compass" simulation. Monte Carlo methods are used to simulate measured σ_0 data from the ocean, based on instrument design parameters (Long *et al.*, 1988), the measurement geometry and the true wind vector. Modelling error is included in the simulated measurements. A geophysical model function is then used to retrieve the wind vector estimate from the simulated σ_0 measurements. In this study, the SASS-I model function (Schroeder *et al.*, 1982) has been used.

Wind speed and direction are computed from the noisy σ_0 measurements by the NSCAT baseline wind retrieval algorithm. The wind retrieval algorithm finds the minima of the maximum-likelihood objective function, which is a function of the noisy σ_0 measurements and the model function (Chi and Li, 1988). The nature of the model function results in multiple wind direction solutions; the compass simulation considers only the solution closest to the true direction. This is equivalent to using an ideal ambiguity removal algorithm. Errors in the retrieved wind vectors are a result of the noise in the σ_0 measurements. Knowing the true wind speed and direction, the wind retrieval error can be calculated.

3. Error Distribution Calculation

In order to characterize the wind retrieval errors in scatterometers, distributions of the errors over many runs of the compass simulation have been computed. Wind speeds from 3 to 33 m/s have been simulated over wind directions from 0 to 360°. The compass simulation was used to generate 500 Monte Carlo realizations for each of 180 true wind vector bins (10 wind speed bins and 18 wind directions spanning 3 to 33 m/s and 0 to 360°). The results were combined to give the histograms of Figures 1 and 2. Figure 1 shows histograms of wind retrieval error (speed and direction) versus true wind speed averaged over 18 wind directions (every 20° from 0 to 340°). Each true wind speed bin includes 9000 points. The wind speed error has been normalized by the true wind speed. Figure 2 shows wind retrieval error histograms versus true wind direction averaged over the 10 wind speed bins (3 m/s in width from 3 to 33 m/s). Each true wind direction bin includes 5000 points.

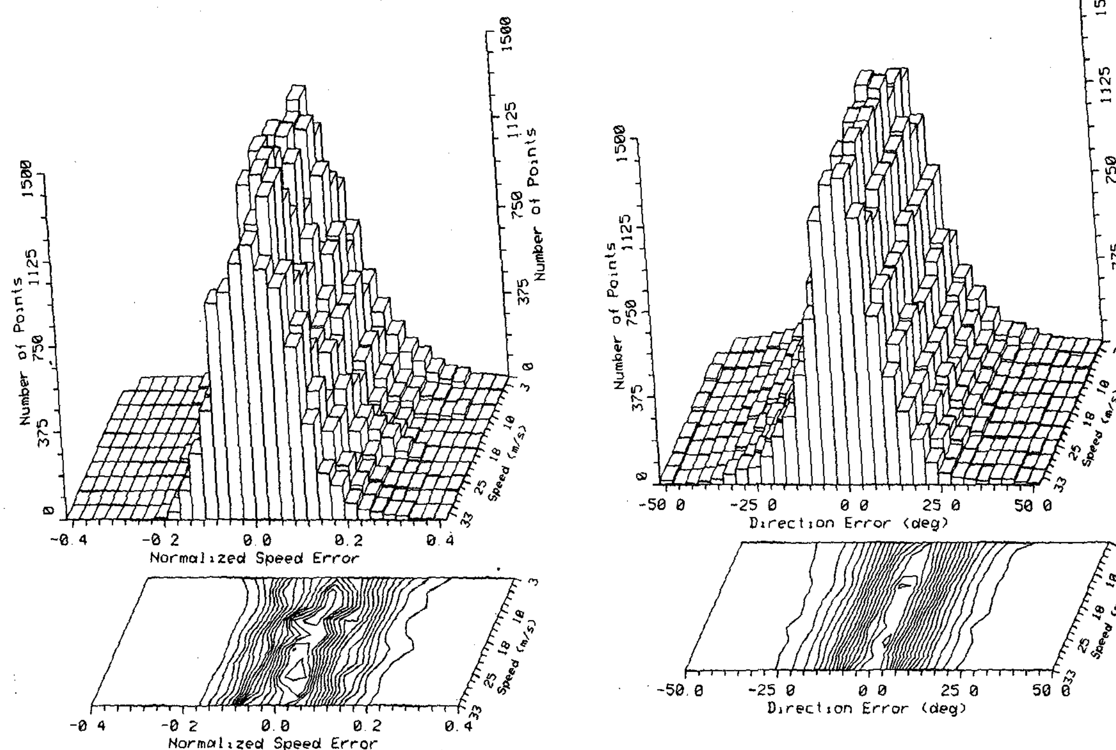

Fig. 1. Histograms of normalized wind speed error (left) and wind direction error (right) versus true wind speeds from 3 to 33 m/s.

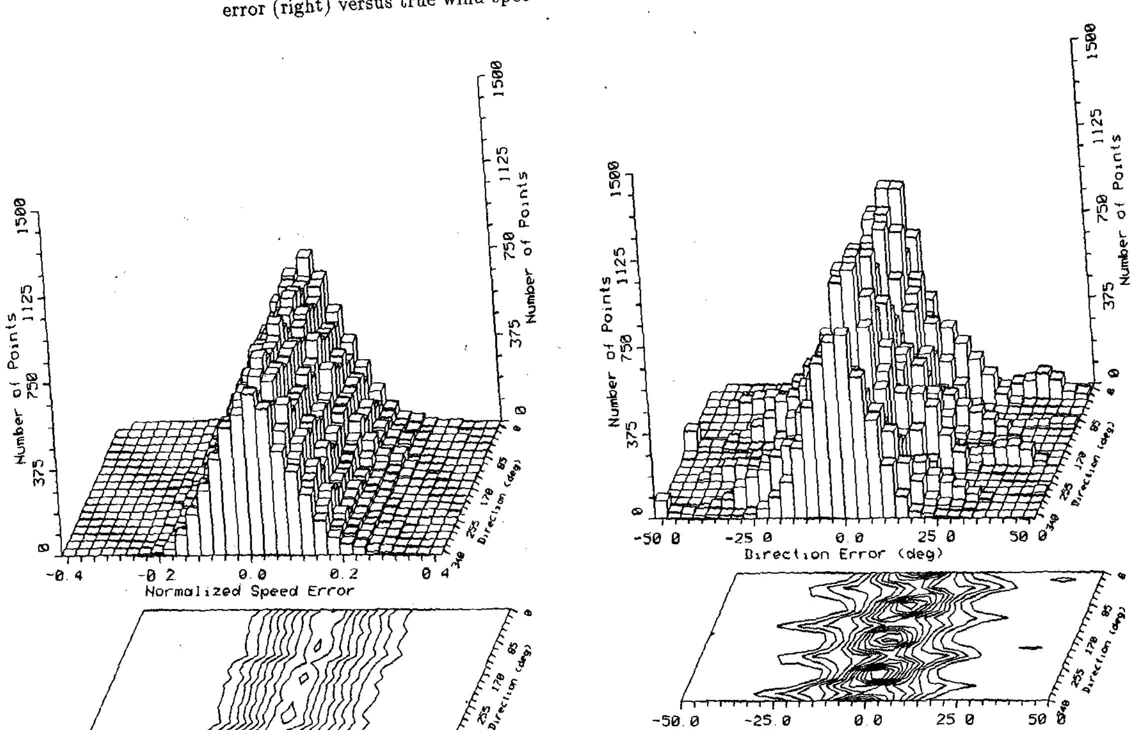

Fig. 2. Histograms of normalized wind speed error (left) and wind direction error (right) versus true wind directions from 0 to 340°.

All results are for 50-km resolution cells at the near swath location (closest to the spacecraft).

Figure 3 shows plots of the variance of the wind retrieval error. Each point in Figure 3a corresponds to one true wind bin from Figure 1; Figure 3b corresponds to the bins of Figure 2. The left-hand plots of Figure 3a show the variance of each of the 10 true wind speed bins of Figure 1; the right-hand plots show the variance for the 18 individual directions before averaging. Similarly, Figure 3b shows the variance for each of the 18 true wind direction bins of Figure 2, along with the results for the 10 individual wind speed bins before averaging.

Histograms of the wind retrieval error for all of the 90000 data points of Figures 1 and 2 are shown in Figure 4. The normalized wind speed error distribution has a mean of 0.02 and standard deviation of 0.08 (or 8% of the true wind speed). The wind direction error has a mean of -0.17° and standard deviation of 11.6°.

4. Error Distribution Characteristics

From the plots of Figures 1 through 4, some generalizations about the scatterometer wind retrieval errors can be made. Figure 4 shows that, for a large number of samples, the distribution of errors approaches a normal distribution. The plots of Figure 3 provide details of the error distributions for speed and direction.

From the upper plots of Figure 3, the wind speed error, which increases with increasing wind speed, is nearly constant across true wind speed when the error is normalized by the true wind speed. The wind speed error is also independent of the true wind direction. The only exception is for true wind speeds in the 3-6 m/s bin, for which the wind speed error is relatively high. The variance for these low wind speeds corresponds to the first point in Figure 3a and the curve which lies above the other wind speeds in Figure 3b. This may be due to significantly higher noise levels in σ_0 measurements for low wind speeds.

From Figures 1 and 2, the wind speed error distributions of individual true wind bins are approximately normal. Figure 3 shows that the variance of these distributions is nearly constant across both wind speed and wind direction. Wind speed error, therefore, can be characterized by a single distribution, represented by Figure 4. From Figure 4, the overall distribution of wind speed errors is nearly normal, with a mean slightly greater than zero and standard deviation of 8% of the true wind speed at near swath location for winds from 3 to 33 m/s.

From the lower plots of Figure 3a, the wind direction error, when averaged over all wind directions, is nearly constant over the range of true wind speeds examined. The spread of the curves in the right hand plot of Figure 3a, however, shows that the retrieval error is dependent on the true wind direction. This is also evident in Figure 3b. Depending on the true wind direction, the standard deviation of the error (averaged over wind speeds) ranges from 6.9 to 14.3°. Again, low wind speeds (3-6 m/s) show higher errors.

Although the wind direction error depends on the true wind direction (from Figure 3), averaging over wind directions gives the expected error when the true wind is not known, assuming that the global distribution of wind directions is uniform. Figure 3a shows that this distribution is independent of wind speed. The distribution of Figure 4 predicts that this overall wind direction error is normally distributed with mean slightly less than zero and standard deviation of 11.6°.

Unlike the wind speed error, the direction errors for individual wind direction bins in Figure 2 are not, in general, normally distributed. Not only does the variance change (as seen in Figure 3), but for a given true wind direction, the distribution may be skewed either positive or negative.

The variations in wind direction error with true wind direction are related to the model function used in wind retrieval. The wind retrieval algorithm finds the minima of an objective function, which is a function of the difference between σ_0 measurements and the model function. The solutions can be thought of as "valleys" in the objective function. Plots of the objective function derived from noise-free σ_0 measurements reveal that the shape of these valleys varies with true wind direction. Narrow, steep valleys in the objective function correspond to cases with low wind direction errors, while wide valleys correspond to cases with large errors. This can be quantified by measuring the "width" of the valley near the

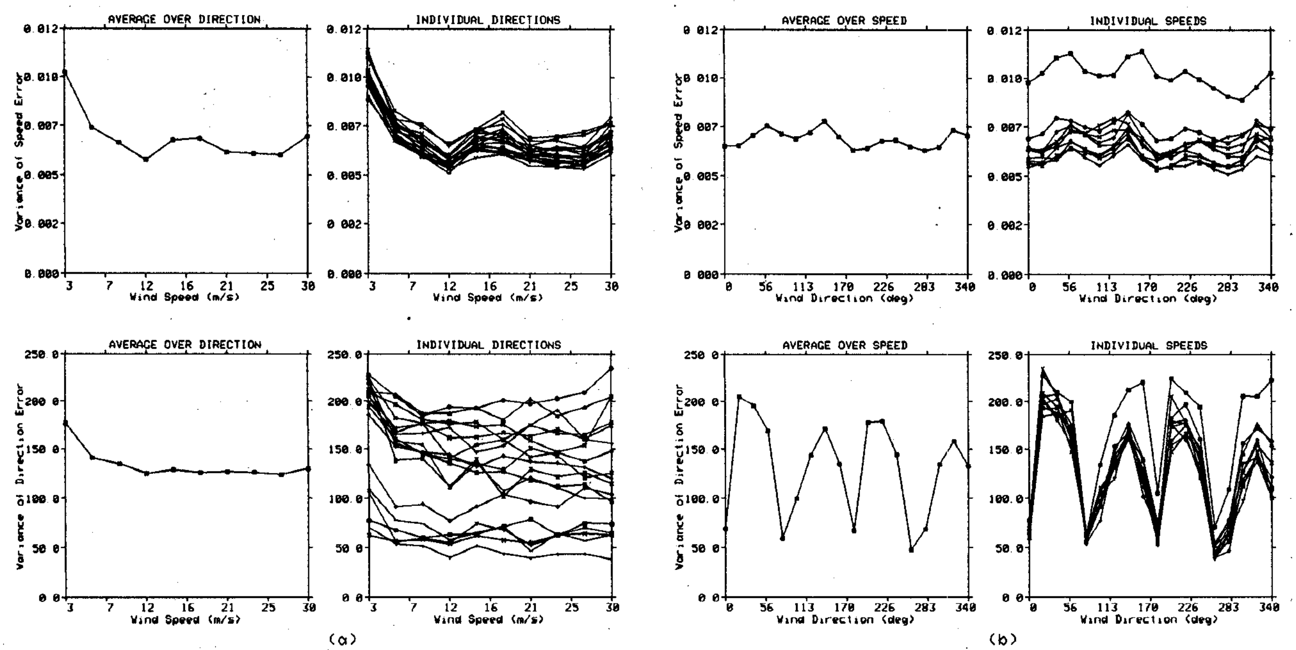

Fig. 3. Variance of wind retrieval error versus (a) true wind speed and (b) true wind direction.

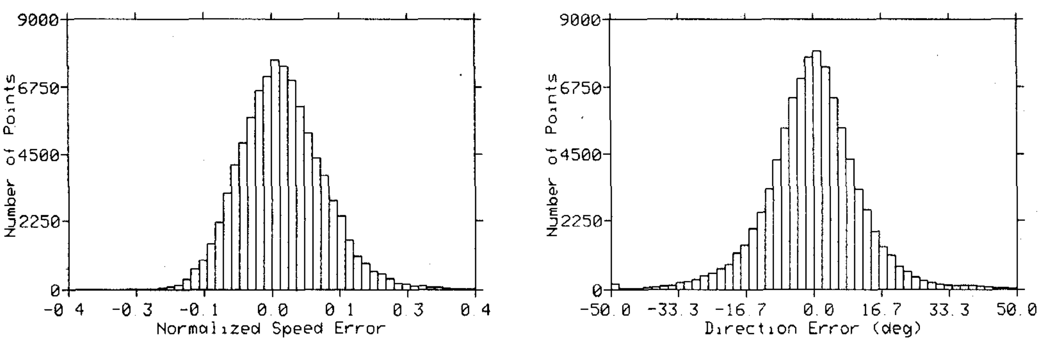

Fig. 4. Histograms of normalized wind speed error (left) and wind direction error (right) for all wind speeds and directions.

closest wind direction solution. A plot of the width as a function of true wind direction follows the wind direction error variation seen in Figure 3b. This plot of valley widths can be used to predict which true wind directions have maximum and minimum retrieval error.

5. Prediction of NSCAT Performance

A goal of this study is to develop a methodology which can yield accurate estimates of scatterometer performance without relying on cpu-intensive simulations. Using the above results, simulations can be run for only a few selected true winds, and performance for other winds can be inferred. As an example, this concept has been applied to predict the performance of the NSCAT instrument with a change in orbit parameters. For example, flight on the Japanese satellite ADEOS involves a reduction in altitude of 20 km, and changes in eccentricity, inclination angle, and antenna roll angles. Compass simulation results for this new orbit will be compared to performance predictions based on the above error distribution study.

From the above generalized results, near-swath rms wind speed error may be estimated by simulating performance at only one true wind speed. A quick estimate of NSCAT performance is then provided by running the compass simulation only twice, using the true wind directions with the maximum and minimum variance. From the widths of the objective function minima, the true wind direction with maximum error is 200°, and the true direction with minimum error is 260°. Running these two cases for a true wind speed of 10 m/s with 500 samples each yields an rms wind speed error of 10% of the true wind speed, and maximum and minimum rms wind direction errors of 15.2° and 8.4° respectively. This simulation therefore predicts that the wind speed error will increase from 8% of the true wind speed to 10% for the new orbit. The expected rms wind direction error is about 1 degree higher than the error for the original orbit.

The near-swath results based on a full compass simulation run for the old and new orbit parameters agree with the above predictions. For three wind speeds (8, 25 and 30 m/s), the wind speed error increases by 2% for the new orbit, and the average increase in wind direction error is 0.5°. The estimate of overall NSCAT performance based on the error distribution results requires 20 minutes of cpu time. The compass simulation, using the same number of realizations, requires 6 hours of cpu time for each wind speed.

6. Conclusion

Errors in retrieved wind speed for NSCAT can be characterized by normal distributions. If the wind speed error is normalized by the true wind speed, the variance of the distribution is independent of wind speed for true wind speeds from 6 to 33 m/s. Wind speeds from 3 to 6 m/s were found to have higher errors, and wind speeds greater than 33 m/s were not included in this study. The wind speed error is also independent of the true wind direction. For the near swath location, the NSCAT wind speed error is 8% of the true wind speed.

Although retrieval errors for individual wind directions are not identically distributed, when the true wind vector is unknown, the direction error can be characterized by a normal distribution. Wind direction error averaged over true wind directions is normally distributed with variance independent of the true wind speed. At the near swath location, the average wind direction error is approximately 12°.

This paper has focused on NSCAT wind retrieval errors at the near swath location. For middle and far swath locations, the overall error distributions (analogous to Figure 4) are also normal distributions, characterized by different means and variances. However, not all of the generalizations made for the near swath apply. For instance, at the far swath location, the wind speed error shows some dependence on the true wind direction, and the wind direction error increases with increasing wind speed. The study of the dependence of wind retrieval errors on swath location is continuing.

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