Performance Analysis for the SeaWinds Scatterometer

David G. Long
Brigham Young University
459 Clyde Building, Provo, UT 84602
(801) 378-4383 long@ee.byu.edu

Michael W. Spencer
Jet Propulsion Laboratory
4800 Oak Grove Drive, Pasadena, CA 91109 USA
(818) 354-1175 mws@shiokaze.jpl.nasa.gov

Abstract - **The difficulties of accommodating traditional fan-beam scatterometers on spacecraft has lead to the development of a scanning pencil-beam instrument known as SeaWinds. SeaWinds will be part of the Japanese Advanced Earth Observing System II (ADEOS-II) to be launched in 1999. A brief description of the SeaWinds design, signal processing, and backscatter measurement approach is given in this paper. To analyze the performance of the SeaWinds design, a new expression for the measurement accuracy of a pencil-beam system is used which includes the effects of transmit signal modulation. Performance tradeoffs made in the development of Seawinds are discussed.**

I. INTRODUCTION

A scatterometer is a radar system that measures the radar backscatter coefficient, σ^o, of an illuminated surface. Multiple measurements of σ^o from different azimuth and/or incidence angles are used to infer the near-surface wind vector over the ocean. While previous wind scatterometers have been based on fan-beam antennas, the SeaWinds scatterometer, to be launched aboard the second Japanese Advanced Earth Observing Satellite (ADEOS-II) in early 1999 as part of the NASA Earth Observation System, will employ a scanning pencil-beam antenna [2, 3, 4].

A scanning pencil-beam scatterometer offers an alternative design concept which is smaller, lighter and has simpler field-of-view requirements [2]. Further, because the antenna illumination is concentrated in a smaller area, a much higher signal-to-noise ratio (SNR) can be obtained with a smaller transmitter. Complicated signal processing is not required and the data rate is small. As a result a pencil-beam scatterometer can be more easily accommodated on spacecraft than a fan-beam.

The issues and tradeoffs encountered in optimizing a pencil-beam scatterometer system are different than those of a fan-beam system. In this paper we describe some of the details of our approach to the analysis and optimization of the SeaWinds scatterometer system.

II. PERFORMANCE EVALUATION

A metric, widely used in scatterometry, for evaluating σ^o error is the "K_p" parameter:

$$K_p = \frac{\sqrt{\mathrm{var}\{\sigma^o_{\mathrm{meas}}\}}}{\sigma^o}.$$

A general objective of scatterometer design is the minimization of K_p. K_p is a function of the signal-to-noise ratio (SNR) which depends on the wind via σ^o. Relating K_p directly to the wind measurement performance can be difficult due to the non-linearity in the wind retrieval process. As a result, we adopt the goal for SeaWinds that K_p should be less than the geophysical modeling error — the percentage variation in σ^o for a given wind velocity (17% at Ku-band). Such a criterion will insure that wind performance is limited not by the precision of the instrument, but only by our ability to relate the measured σ^o's to wind speed and direction via the model function.

The scatterometer measures the backscattered power. Unfortunately, the measurement is noisy and a separate measurement of the noise-only power is made and subtracted from the signal+noise power measurement to estimate the signal power (see Fig. 1). Ref. [3] presents a derivation of the K_p for a pencil-beam scatterometer. It has the general form

$$K_p = \left\{A + SB + S^2C\right\}^{1/2} \qquad (1)$$

where S is the noise-to-signal ratio, A is the signal variance, B is a signal-cross noise term, and C is the noise variance. For interrupted CW operation (no modulation) and a simplified geometry and antenna pattern it can be shown that $A = 1/T_pB_D$, $B = 2/T_pB_D$, and $C = 1/(T_pB_D) + 1/(T_pB_n)$; where T_p is the pulse length, B_D is the Doppler bandwidth, and B_n is the noise-only measurement bandwidth. This result is equivalent to Fisher's K_p expression [1]. When modulation is employed, A can be expressed as a weighted integral of the radar ambiguity function defined by the modulation function [3]. Proper selection of the modulation function can lead to reduced K_p for some scan angles; however, the K_p can be increased for other scan angles.

To illustrate the tradeoffs in selecting a modulation scheme, K_p for several modulation schemes is computed assuming a high SNR. The modulation schemes include Interrupted CW (ICW) (no modulation), Linear Frequency Modulation (LFM), and Minimum Shift Keying (MSK) with a maximal length pseudo-random data sequence. The results are summarized in Table 1 where values shown are normalized by the $K_p(ICW)$.

Table 1 reveals that K_p is dependent on the measurement geometry as well as the modulation. While K_p for ICW is inversely proportional to the square root of the product of the pulse length and the Doppler bandwidth (the time-bandwidth product of the echo return), K_p for MSK also depends on the bandwidth of the modulation. Though $K_p(MSK)$ is slightly increased at 0°, at 90° it is reduced with $K_p(MSK) \approx K_p(ICW)/\sqrt{B_{msk}T_c}$ where B_{msk} is the bandwidth of the MSK modulation and T_c is the differential time-of-flight over the footprint. Since MSK provides the best overall performance and can be easily generated in hardware, it was chosen for the baseline SeaWinds design [4]. Note that increasing B_{msk} arbitrarily does not always improve K_p since the receiver

Modulation	0°	90°
$K_p(ICW)$	1.0	1.0
$K_p(LFM)$	1.16	0.9
$K_p(MSK)$	1.05	0.43

Table 1. K_p for various transmit signal modulation schemes. Values have been normalized by $K_p(ICW)$.

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Parameter	Value
Transmit Frequency	13.402 GHz
Transmit Power	110 Watts
Transmit PRF	185 Hz (92.5 Hz each beam)
Transmit Pulse Length	1.5 ms
Transmit Modulation	MSK, $T_b = 15\mu sec$
Receive Gate Length	2.0 ms
System Noise Temp.	740°K
Signal+Noise Bandwidth	80 KHz
Noise-only Bandwidth	1 MHz
Rotation Rate	18 rpm
Antenna Beamwidth	1.8° × 1.6° (inner) 1.7° × 1.4° (outer)

Table 2. SeaWinds Radar Electronics Parameters

bandwidth must also be increased to accommodate the signal, requiring a tradeoff between the signal modulation and the receiver bandwidth.

III. SEAWINDS DESIGN AND TRADEOFFS

The SeaWinds measurement geometry is illustrated in Fig. 2. Figure 3 shows a block diagram of the SeaWinds radar electronics. A summary of the key radar parameters is shown in Table 3. A one meter parabolic dish antenna with two offset feeds creates both the "inner" and the "outer" beams. The inner beam makes measurements at 46° incidence angle while the outer beam makes measurements at 54°. The antenna is mechanically spun about the nadir axis to generate a conical scan. Each point within the inner 700 km of the swath is viewed from four different azimuth angles — twice by the outer beam looking forward then aft, and twice by the inner beam in the same fashion. In the outside edge of the swath, between cross track distances of 700 and 900 km, each point on the ocean is viewed twice by the outer beam only. The inner beam is horizontally polarized with respect to the ocean surface while the outer beam is vertically polarized.

Because the σ^o measurements are obtained at favorable high incidence angles over a continuous 1800 km swath, there is no "nadir gap" where wind can not be retrieved. The wide swath will cover 90% of the ocean surface within 24 hours, an improvement over previous scatterometers. The 18 rpm SeaWinds antenna rotation rate and measurement timing were chosen to obtain optimal sampling of the surface σ^o and to meet host spacecraft dynamics requirements.

Due to the motion of the satellite relative to the Earth, a Doppler shift of up to ±500 kHz is imparted to the echo signal, depending on the antenna scan position. In SeaWinds, the Doppler shift is pre-compensated by tuning the transmit carrier frequency to 13.402 GHz $-f_d$, where f_d is the expected frequency shift to be imparted to the return signal. The compensation frequency is computed by the SeaWinds on-board processor using the measured antenna position, orbit location, spacecraft velocity, and Earth rotation. Pre-compensating the transmit pulse for Doppler shift produces an echo signal that always occurs at the same center frequency, simplifying the RF down conversion and detector electronics.

A. Receive Bandwidth Tradeoffs

K_p can be decreased by appropriate modulation of the transmit pulse; however, a tradeoff between the transmit bandwidth and K_p exists due to the need to increase the receiver bandwidth which increases the effects of noise. The bandwidth of the receive signal depends on both the transmit bandwidth and the geometry-dependent Doppler bandwidth. The Doppler bandwidth results from the variation in Doppler shift over the illuminated area. For SeaWinds, the 3 dB Doppler bandwidth, B_{dop}, varies from 9 kHz to 15 kHz depending on the scan angle. We require the receive filter bandwidth B_r to be wide enough to pass at least 90% of the echo energy. A plot of the echo energy versus "filter overhead" $(B_r - B_{msk})$ is shown in Fig. 4 for $B_{dop} = 15$ kHz and various values of B_{msk}.

Nominally, the Doppler shift is perfectly pre-compensated and the echo spectrum is centered in the signal+noise filter. However, antenna position uncertainty and spacecraft attitude uncertainty lead to errors in Doppler tracking. The signal+noise filter bandwidth B_r must be sufficiently wide to accommodate the echo center frequency. The worst-case Doppler pre-compensation error is 10 kHz. Assuming the worst-case error, a plot of the resulting error in the energy detection versus the "filter overhead" is shown in Fig. 5. To minimize Doppler-precompensation induced errors in the measurement of echo return energy, we require the error to be < 0.15 dB.

Applying these criteria to Figs. 4 and 5, we see that they are satisfied for a filter overhead of between 30 kHz and 50 kHz, depending on B_{msk}. Thus, in our trade-off analyses to find the optimum B_{msk} we have used $B_r = B_{msk} + 40$ kHz.

B. Transmit Signal Modulation Tradeoffs

To select B_{msk}, the parameters A, B, and C are computed numerically as a function of antenna scan angle. To optimize K_p over the range of wind speeds, the swath location dependent SNRs corresponding to low wind speeds (3 m/s), moderate winds (8 m/s), and high winds (20 m/s) are used.

In Fig. 6 K_p vs. azimuth angle for a range of B_{msk} is plotted for each beam at three representative wind speeds. Only the azimuth range between 0 and 90 degrees is shown since the performance is symmetry around the scan. Transmit modulation significantly reduces K_p for most of the swath, but offers little improvement for scan angles pointed forward or aft of the spacecraft — near 0 and 180 degrees. At the high wind speeds where S is small (high SNR), the "A" term in Eq. (1) dominates, and a larger B_{msk} leads to lower K_p. Thus, in a high SNR environment, measurement accuracy can be improved by modulating the signal and consequently increasing the effective number of independent samples. At lower wind speeds (which have lower SNRs), however, K_p can actually increase for larger B_{msk}. This is particularly evident for the inner beam. This occurs because the benefit derived from modulating the signal is overcome by the deleterious effect of increasing B_r and passing more thermal noise to the detector.

An evaluation of the curves in Fig. 6 led to the selection of $B_{msk} = 40$ kHz and $B_r = 80$ kHz for SeaWinds. This significantly improves K_p performance over most of the swath and for most wind conditions. Lower values of B_{msk} produced inferior performance at high and moderate wind speeds, in general failing to meet the performance goal of $K_p < 0.17$. Higher values of B_{msk} were judged to produce undesirably large K_p at low speeds. Due to the greater scientific importance of high wind measurements, a degree of performance degradation at low wind speeds, such as that experienced with $B_{msk} =$ 40 kHz for the inner beam at 3 m/s, was deemed acceptable. Unfortunately, for the values of S achievable with the SeaWinds design parameters, the goal of $K_p < 0.17$ is not possible at the very lowest wind speeds for any modulation bandwidth. Nevertheless, despite being "K_p limited" rather than "model function limited" in the less critical low wind speed regime, SeaWinds performance simulations indicate that the desired measurement accuracies will still be met [2].

IV. SUMMARY

Because SeaWinds employs a compact dish antenna rather than multiple fan-beam antennas, the instrument is more easily accommodated on spacecraft than previously flown scatterometers. Tradeoffs to select the transmit modulation scheme and filter bandwidths have been described. Modulating the transmit signal results in improved K_p which will result in improved wind measurement accuracy.

REFERENCES

[1] R. Fisher, “Standard Deviation of Scatterometer Measurements From Space,” *IEEE Trans. Geosci. Electron.*, Vol. GE-10, No. 2, April 1972.

[2] M.H. Freilich, D.G. Long, and M.W. Spencer, “SeaWinds: A Scanning Scatterometer for ADEOS II – Science Overview,” *Proceedings of the International Geoscience and Remote Sensing Symposium*, Pasadena, California, August 8-12, pp. 960-963, 1994.

[3] D.G. Long and M.W. Spencer, “Radar Backscatter Measurement Accuracy for a Spaceborne Pencil-Beam Wind Scatterometer with Transmit Modulation,” submitted to the *IEEE Trans. Geoscience and Remote Sensing*, 1995.

[4] M.W. Spencer, C. Wu, and D.G. Long, “Tradeoffs in the Design of a Spaceborne Scanning Pencil-Beam Scatterometer: Application to SeaWinds,” submitted to the *IEEE Trans. Geoscience and Remote Sensing*, 1995.

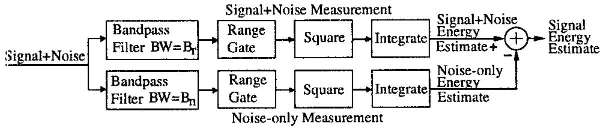

Figure 1. Measurement flow diagram.

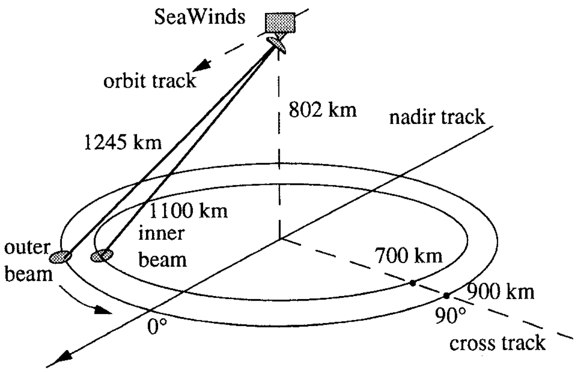

Figure 2. SeaWinds geometry.

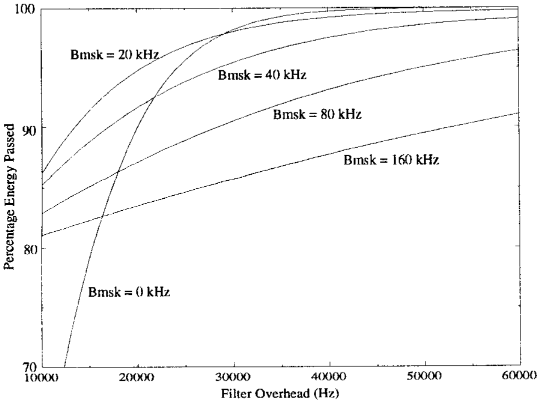

Figure 4. Doppler bandwidth induced energy detection error versus “filter overhead” $(B_r - B_{msk})$.

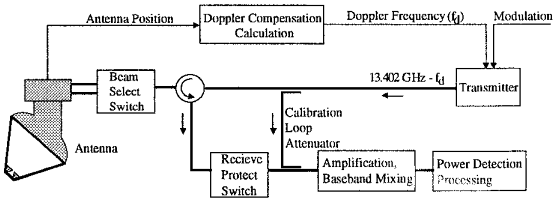

Figure 3. SeaWinds block diagram.

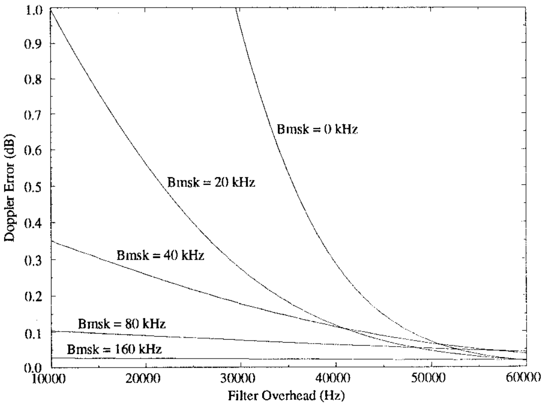

Figure 5. Energy measurement error due to Doppler compensation error versus “filter overhead” $(B_r - B_{msk})$.

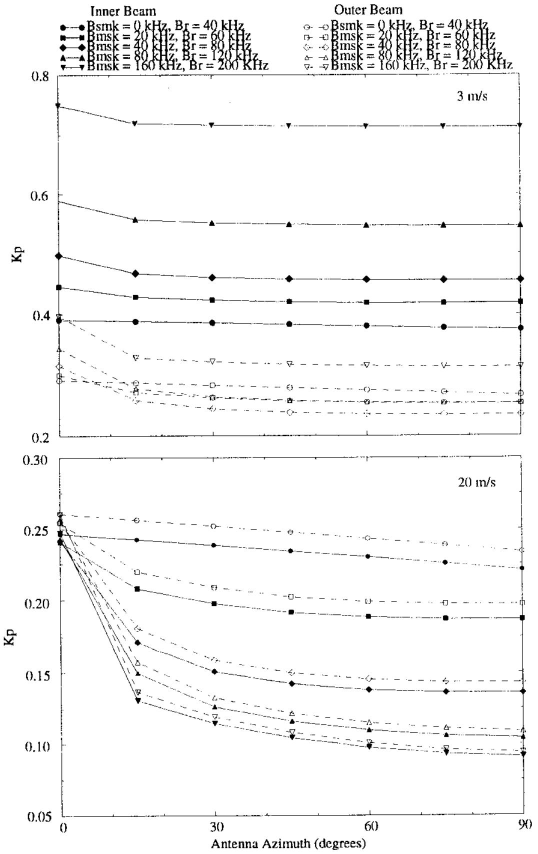

Figure 6. SeaWinds K_p versus scan angle for various B_{msk} and wind speeds.