Pg 117-126 SPIE 2001
# 4483

# Model-based ground station calibration for SeaWinds on QuikSCAT

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## ABSTRACT

SeaWinds on QuikSCAT is the latest of NASA's wind-observing scatterometer missions. It was launched in June of 1999 with the goal of accurately measuring wind fields over all the oceans. It has also proven to be valuable in monitoring ice changes in polar regions. The value of such data necessitates an extremely accurate and precise calibration of both satellite performance and instrument measurements. In order to assure optimal performance a Calibration Ground Station has been constructed, which provides direct measurements of the instrument transmissions. Each time the spacecraft flies overhead, approximately twice a day, the CGS passively captures microwave pulses transmitted from QuikSCAT. The data is then used with various processing and analysis techniques to validate the system performance and calibration. As part of the calibration analysis, a software simulation model of the instrument system has been constructed. This model is able to simulate critical instrument systems and path loss characteristics and thus predict CGS receive data for any given satellite pass. By comparing model-based simulation data with actual recorded CGS data, calibration of parameters such as system timing, power, attitude, and Doppler compensation can be accurately determined. The analysis has been able to validate the Doppler/range compensation algorithm, instrument timing, and other key system operational parameters. The major contributions of the CGS-based analysis are demonstration of pointing accuracy and overall system stability of SeaWinds. By employing a variance minimization technique between simulated and actual data, the QuikSCAT platform is shown to be extremely stable.

**Keywords:** SeaWinds, QuikSCAT, calibration, microwave remote sensing, earth observing systems

## 1. INTRODUCTION

Satellite microwave scatterometers have greatly improved global weather data over the last decade by accurately and frequently measuring marine winds. The latest NASA wind observation instrument is SeaWinds which operates aboard the QuikSCAT satellite. SeaWinds differs from past scatterometer designs by utilizing a pencil beam antenna which rotates around nadir to scan the Earth's surface, rather than the traditional collection of fan beam antennas. Additionally it uses a combination of digital Doppler compensation, linear frequency chirping, and range gating to simplify processing and improve resolution. Traditional scatterometers yield resolution of approximately 25 km by 25 km. Through the use of range gating, SeaWinds is able to resolve wind measurement cells to 8 km x 25 km. Instruments, such as SeaWinds, transmit microwave pulses which interact with the ocean surface, backscattering a fraction of the transmitted power back to the instrument. Using multiple colocated backscatter measurements, vectors of near surface wind (both speed and direction) can be determined. Near ocean wind vectors can then be directly related to global weather patterns and weather prediction. The design of SeaWinds and its orbit geometry allow it to cover over 90 percent of the Earth's surface daily. Using truth data obtained from buoys, their recorded values have been shown to be accurate to within 2 m/s and 20°.

As with any complex instrument, accurate calibration is necessary to guarantee performance. Specifically for SeaWinds, calibration of parameters such as satellite attitude, instrument timing, transmit power, and Doppler compensation are essential for accurate wind measurements. A variety of calibration techniques exist to obtain calibration parameters. One method of calibration entails the use of a Calibration Ground Station, or CGS. The SeaWinds CGS has been set up in White Sands, New Mexico to provide independent measurements of time, frequency, and power. The CGS has been calibrated to precise levels and thus is able to provide precision time and location measurements desired for SeaWinds calibration.

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**Figure 2.** Block diagram of the SeaWinds Calibration Ground Station.

**Figure 3.** Figure showing the receive antenna and RF hardware at the CGS.

is then sampled by the A/D converter and decimated for a final sample rate of 5.1875 MHz; the expected bandwidth of the signal is approximately 375 kHz. The A/D converter is controlled by a phase locked loop synthesizer which is driven by the GPS reference. The stability of the reference is within 1 part per billion. The aperture stability is better than 200 ps. Thus the A/D is time stable within strict tolerances. A block diagram of the SeaWinds CGS is shown in Fig. 2. Fig. 3 shows the antenna and associated RF circuitry.

Just before the satellite travels overhead, the CGS positions its antenna in the appropriate direction. The position is held constant during data reception for each capture. The constant antenna position is made possible by a wide main lobe on the CGS antenna, which minimizes the sensitivity to pointing errors. With a wide beam antenna, multipath of the signal is a concern. Using data collected in a careful survey of the site a numerical analysis concluded that multipath is not a concern in CGS data analysis.[1]

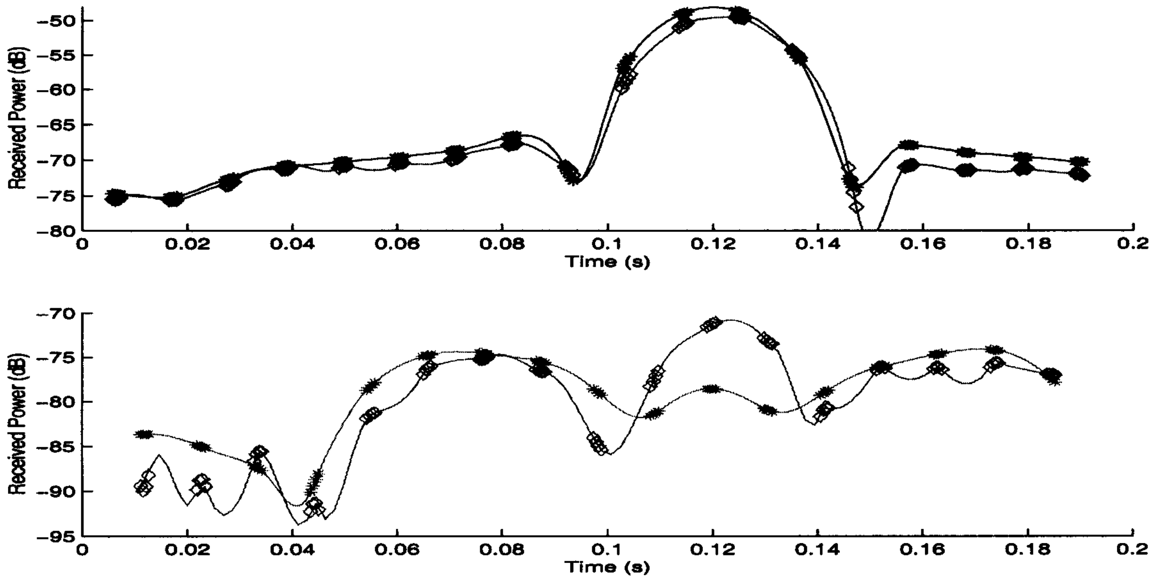


**Figure 5.** Comparison between CGS received power and model based power. The stars represent model predicted power, the diamonds are CGS determined power. (top) Outer beam (V pol). (bottom) Inner beam (H pol). The plots show the model curves before the error minimization.

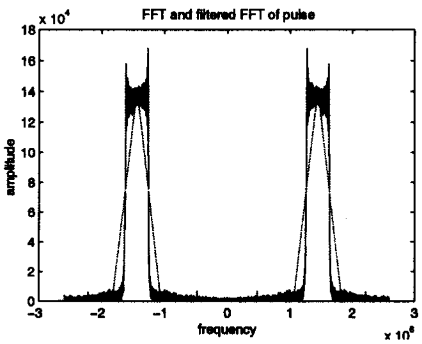


**Figure 6.** Bandwidth of one pulse received at the CGS. A plot of the window output used to find the center frequency is super-imposed over the data.

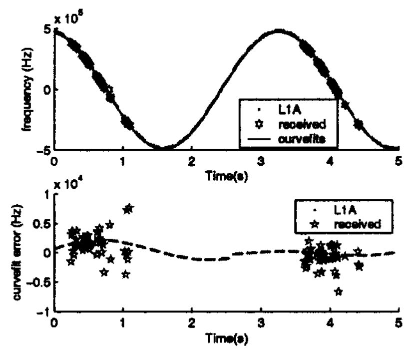


**Figure 7.** Sample results of the frequency analysis. (top) Commanded Doppler frequency with a sinusoid fit to the data. (bottom) Curve fit errors.

## 4.1. Doppler Compensation Algorithm

Once each pulse has been time located, it is subjected to a frequency analysis. The center frequency is found by computing the FFT, which is then filtered by convolving it with a 375 kHz rect, which is the bandwidth of the pulse, as shown in Figure 6. From the center frequency, the carrier and the Doppler frequency due to the velocity of the spacecraft relative to the CGS are removed. This leaves only the commanded Doppler offset frequency. The commanded Doppler offset frequency is a frequency bias added by the instrument before the signal is transmitted, designed to compensate for the Doppler shift of the pulse. This commanded Doppler varies sinusoidally with time; a result of the helical pattern which the instument's footprint traces along the surface of the earth.

Fitting a sinusoid through the center frequencies of the received data and the transmitted commanded Doppler as recorded in the Level 1A data allows for timing (phase shift) and frequency (amplitude shift) analysis. Fig. 7 shows the difference in received frequency between the CGS and the model prediction. As shown this difference is on the order of 500 Hz. In relation to the Doppler compensation, which is on the magnitude of 50 kHz, the measured difference is less than 1 x $10^{-3}$. Based on the pulse width, SeaWinds has a frequency resolution of 666 Hz. Thus,

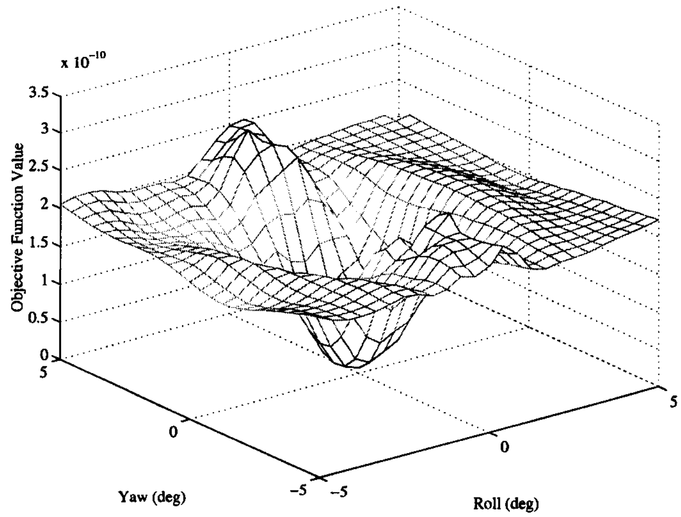


**Figure 10.** Objective function for determining the attitude of SeaWinds. The values are a function of roll, pitch, and yaw. This figure shows the objective function value versus roll and yaw with pitch held constant.

7.5 ms before it was recorded by the CGS. The variance in the pulse arrival is due to the low SNR of some of the processed pulses.

Fig. 9 shows the time difference over the length of the mission. It shows that the time difference is slightly increasing over time, with a beginning mean value of 8 ms, increasing to about 8.5 ms. The variance of the time difference is about $\pm 1$ ms.

Here we consider the effects of these time delays on actual QuikSCAT wind products. The mean bias of 8.2 ms does not effect the final wind product because it is a constant. However, the variance of each time measurement does have a small effect on the final wind product. The error in time measurement corresponds directly to an error in the azimuth direction. The SeaWinds antenna rotates at a rate of $0.108°$/s. Thus, a $\pm 1$ ms error corresponds to a $\pm 0.108°$ error in azimuth. Using a range of 1245 km, the nominal range of the outer beam, this error corresponds to a location error of $\pm 2.17$ km on the ground.

### 4.3. Attitude Perturbation

As mentioned in Section 3 the SeaWinds simulation model enables perturbation to better simulate the operation of the instrument. One of the main perturbations allowed by the model is that of spacecraft attitude, i.e. roll, pitch, and yaw. Fig. 5 shows a comparison between the model simulated data and actual CGS received data. It can be seen that there are some differences in the power level between the curves, especially around the first null. Through model perturbation these errors are minimized. Once the error is minimized, the required attitude perturbation values correspond to the calibrated attitude of the spacecraft.

The perturbation is performed by attempting to minimize the desired objective function. The minimization is implemented using a Nelder-Mead simplex algorithm. This algorithm is chosen because derivatives of the objective function are not available, thus discouraging Newtonian based methods. Additionally, each calculation of the objective function is computationally expensive.

The objective function chosen to attain attitude calibration is the combined variance of each sweep for the entire pass. As mentioned in Section 2 the CGS captures up to 12 sweeps of data for a given satellite pass. The difference in power between actual CGS received data and model predicted data for every pulse in each sweep is taken. The overall objective function value is the variance of the overall power difference. The objective function is then minimized by perturbing the attitude of the model, recalculating the power differences and subsequent variance values. Fig. 10 shows a plot of the objective function for roll and yaw, with pitch being held constant.

This variance-based objective function is chosen over a mean-squared error (MSE) objective function because a MSE function tends to accentuate yaw errors at the expense of decreased sensitivity for roll and pitch and there can

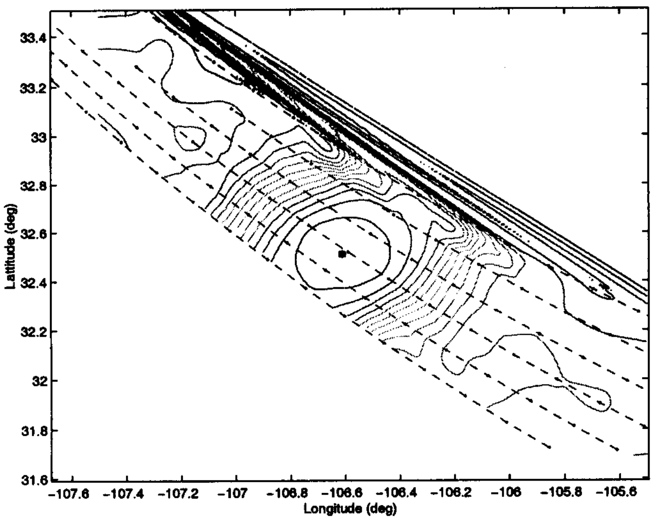


**Figure 12.** Contour plot of reconstructed antenna pattern. This plot shows the location of the CGS to be directly in the center of the illuminated area.

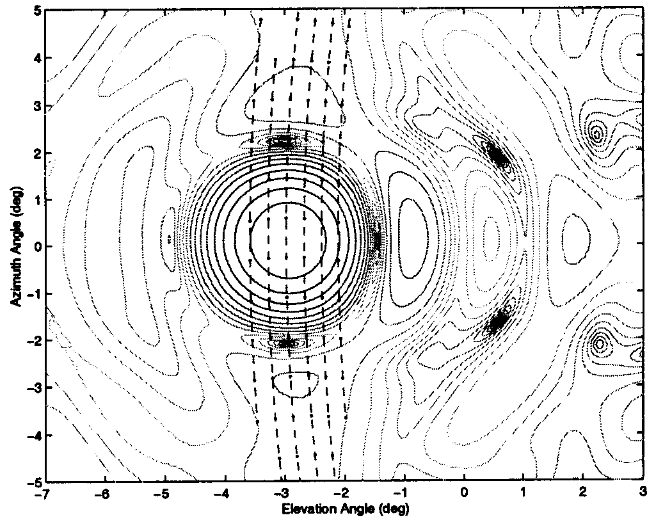


**Figure 13.** Actual transmit antenna pattern for SeaWinds. The dashed curves are included for reference to Fig. 12.

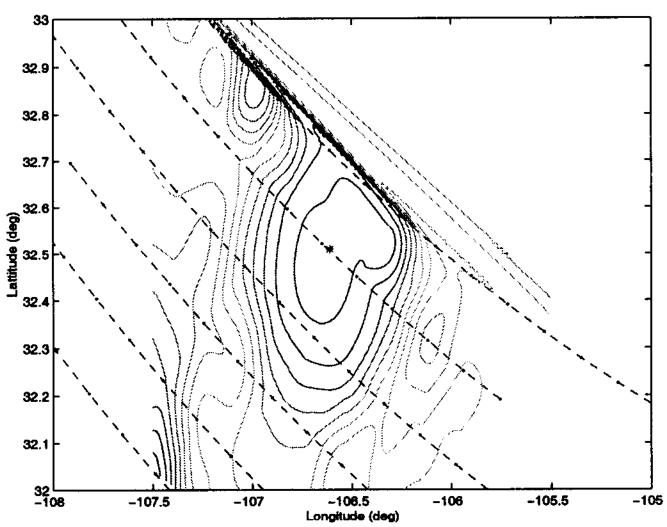


**Figure 14.** An example of a breakdown of the pointing estimation algorithm. The boresite contour is poorly defined, thus mislocating the center of the contour.

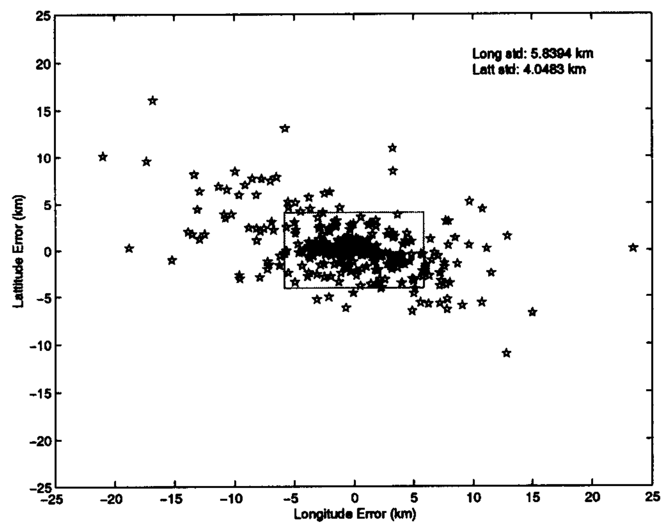


**Figure 15.** Determined location error of QuikSCAT for several passes. Each point symbolizes the location difference for a given pass. The CGS is located at the point (0,0).

## 5. SUMMARY

Over the past two years of operation SeaWinds has proven to operate well within specifications. As part of the calibration effort the Calibration Ground Station provides independent calibration information. It shows that the Doppler tracking algorithm is operating as expected. It also shows that there is a slight timing offset of about 8.2 ms, though overall timing is well within specification. Attitude is excellent, allowing that the variability in the CGS attitude analysis is due to noisy CGS data. Ground pointing is also shown to be excellent, for most cases within 1 km. Overall, SeaWinds is well calibrated and provides excellent data for use in ocean wind estimation.