INCREASED UTILITY OF SEAWINDS THROUGH ENHANCED CALIBRATION

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Abstract- **Accurately measuring winds over the surface of the ocean is necessary for improving understanding of the global climate. SeaWinds, a satellite scatterometer, is designed for this purpose. Since its launch it has provided accurate and frequent estimates of near-ocean winds. Due to its success, desires to increase the utility of the data have emerged. These desires, though possible, require performance beyond designed specifications. Additional calibration of the instrument is able to improve instrument performance, allowing development of these emerging applications. Applications include high resolution wind measurement, enhanced resolution imaging, monitoring rain forest destruction, and tracking icebergs and polar ice formation. Improved calibration not only benefits current instruments, but will aid future instruments as well.**

I. INTRODUCTION

WEATHER conditions effect the decisions of every individual on a daily basis, whether it be a hurricane or just a spring shower. Weather affects business, travel, and even an outlook on life. Accurate weather prediction is important because it can save time, money, and lives by enabling appropriate preparation.

Accurately measuring the current weather over the entire world, including the ocean, is vital to predicting future weather events. Weather measurements over oceans are particularly important since more than two thirds of the Earth's surface is covered by water. Yet measurement of weather phenomena over the ocean is difficult. Previously, ocean-based weather measurements were obtained using either ships or buoys; ships are not very accurate and buoys are extremely sparse in their coverage.

Fortunately, there exists another modern method to assist in obtaining weather information over the ocean - satellites. Satellites are able to measure weather events such as near-surface winds and sea surface elevation, accurate indicators of global-scale weather patterns. Wind measurements from satellites are generally preferred over buoys and ships. Satellites are able to cover over 90% of the entire ocean surface every day, with excellent accuracy. One type of satellite sensor, a scatterometer, operates by transmitting short pulses of microwave energy which interact with the ocean surface, with a fraction of the energy reflecting back to the satellite. Based on the amount of reflected energy, the scatterometer can determine the speed and direction of the wind over the ocean.

Scatterometers, as with any space-borne instrument, are most effective when calibrated accurately and precisely. The calibration process constitutes a significant portion of instrument design. Thorough calibration, from high-level design to post-launch testing, has proven effective in ensuring accurate, reliable data to the scientific community. It continues to do so now. NASA's latest satellite scatterometer, SeaWinds on QuikSCAT, is no exception. The instrument operates well within its designed specifications, and as a result desires to increase data effectiveness have been voiced. Enhanced resolution and improved data accuracy, beyond original design, are now sought to further advanced data applications. These emerging applications seek to utilize information provided by SeaWinds to expand global climate investigation.

Achievement of these expanded objectives necessitates more stringent requirements for calibration, forcing new calibration procedures, not called for in the original design, to be developed. One available option is a Calibration Ground Station (CGS), utilized during past scatterometer missions. Its independence from the instrument, along with its own precise calibration, allows for improvement of overall instrument operation.

Improved calibration of SeaWinds has made possible the emergence of several advanced data applications. First, resolution of wind measurements has been improved. Second, alternative applications besides wind estimation have been developed. Examples include monitoring rain forest vegetation, tracking icebergs, and observing polar ice formation. These alternative applications have proven valuable in gaining a greater understanding of global climate interactions.

This paper details the emergence of new applications for scatterometer data due to its improved calibration. Section II describes the basic design and operation of SeaWinds. Next, Section III overviews the enhanced calibration effort which has improved instrument performance. Next, Section IV presents some of the latest applications that take advantage of SeaWinds data. Finally, Section V discusses future possibilities for design, calibration, and application.

II. Scatterometer Design

When microwave radiation is incident on a surface, a portion, dependent on the surfaces' physical properties, is reflected back in the same direction. Scatterometers operate on this principle; they transmit microwave pulses towards Earth's surface and measure the amount of power reflected back. This measurement allows for an estimation of the normalized radar cross section, or σ°, for the area where the pulses hit to be made. The σ° values can then be converted to wind velocity and direction values for the area measured [5].

The normalized radar cross section is computed using the radar equation

$$\sigma^\circ = \frac{(4\pi)^3 R^4 L P_r}{P_t G^2 \lambda^2 A} \tag{1}$$

where R is the range from the instrument to the Earth's surface, L represents losses in the system, P_r is the backscattered power received at the instrument, P_t is the transmitted power, G is the gain of the instrument antenna, λ is the wavelength of the transmitted pulse, and A is the area illuminated by the pulse on the surface.

The first major design requirement for SeaWinds is to maximize coverage of σ° measurements, accomplished using a combination of an effective orbit and wide swath. SeaWinds operates in a near-polar orbit, completing 14.4 revolutions per day. It uses a rotating pencil beam antenna to create a swath of 1800 km, as shown in Fig. 1. To obtain additional information, SeaWinds uses two beams, or polarizations, horizontal (H-pol) and vertical (V-pol). This is accomplished by using two feeds to the antenna, with each consecutive pulse alternating polarization, creating an inner beam (H-pol) and outer beam (V-pol).

The other major design requirement for SeaWinds is resolution. The effective resolution of a scatterometer is given by the 3 dB footprint of the antenna on the Earth's surface. This is generally defined by the size of the antenna; a larger antenna improves resolution. Yet antenna size is severely constrained by the requirements of global coverage and the capability of the launch vehicle. The combination of orbit, antenna rotation, and maximum allowable antenna size limits the possible resolution. The design of SeaWinds has been optimized to maximize the resolution of the instrument given these constraints. The antenna used is a 1 meter parabolic dish and gives an elliptical footprint of 25 km x 35 km.

In the final stages of SeaWinds' design, it was recognized that resolution could be enhanced by separating the power backscattered to the instrument according to the surface range from the instrument. This method is called range-gating, or slicing, because the instrument footprint, termed an egg, is cut into several slices based on the range delay of each section [6]. The effective resolution of the slices is 5 km x 25 km, as shown in Fig. 2.

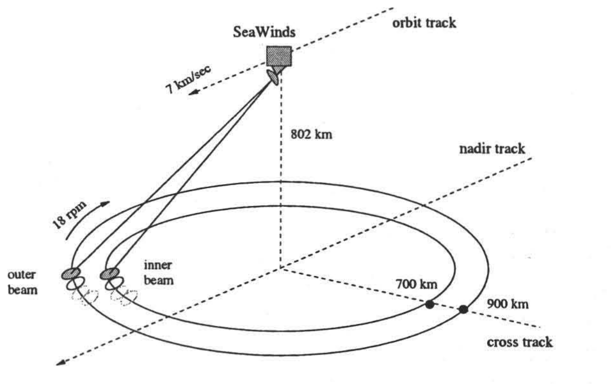

Fig. 1. Scanning geometry of SeaWinds. The outer beam creates a swath of 1800 km, the inner beam has a diameter of 1400 km [6].

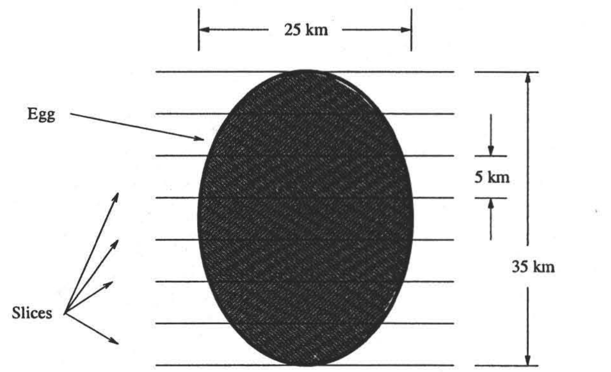

Fig. 2. Creating slices from the egg. Each slice is created by range-gating the returned echo power [1].

III. Instrument Calibration

The ability to slice the egg measurements has motivated the development of applications which utilize this unique ability. Improving the calibrated accuracy of σ° and slice locations of the surface is now desired to support these new applications. This is accomplished in part by improving accuracy of pulse power, transmitted frequency, and instrument timing. Pulse power includes transmitted and received power by the instrument. Frequency includes the center frequency and frequency modulation. Instrument timing is related to the coordination between the system components of the instrument. Calibration options such as the Calibration

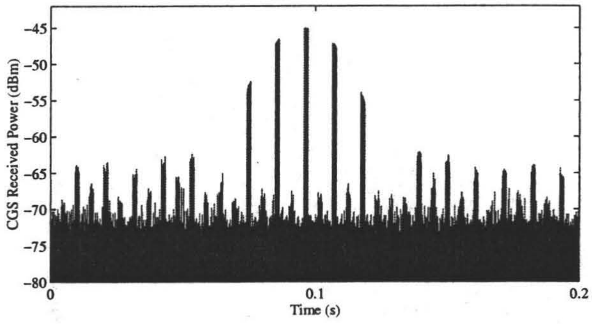

Fig. 3. Power received at the CGS vs time. The individual pulses can be clearly identified above the noise.

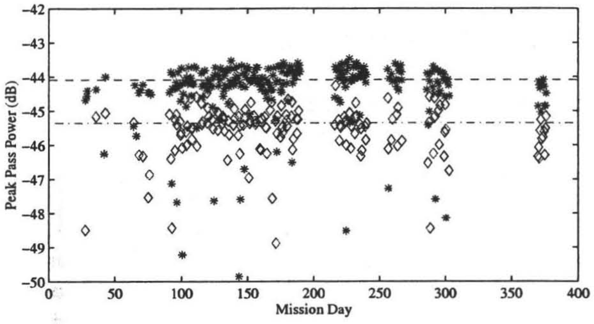

Fig. 4. Peak received power at the CGS for each beam as a function of SeaWinds mission day. The stars (∗) represent the outer beam, and diamonds (◇) represent the inner beam.

Ground Station (CGS) are designed to measure precisely these parameters.

The SeaWinds CGS, which is located in White Sands, New Mexico, operates by passively recording the transmissions of SeaWinds when it passes overhead. A sample recorded data set is shown in Fig. 3. The figure shows the power received at the CGS as a function of time. By determining the pulse power, frequency, and time of arrival of each pulse, operational properties of SeaWinds can be inferred.

One example of power calibration is beam balancing. SeaWinds alternates polarization as it transmits pulses, resulting in two beams. Ideally the peak power transmitted by one beam should equal that of the other beam. By capturing SeaWinds data over the span of more than a year, it can be shown by the CGS that a bias exists between the two beams. Figure 4 shows the maximum received pulse power for each CGS capture over the length of the mission. It shows that a mean bias of 1.27 dB exists between the inner beam and outer beam. This bias negatively effects accuracy of the σ° calculations made by SeaWinds. By compensating for this existing bias, the accuracy of σ° can be significantly improved.

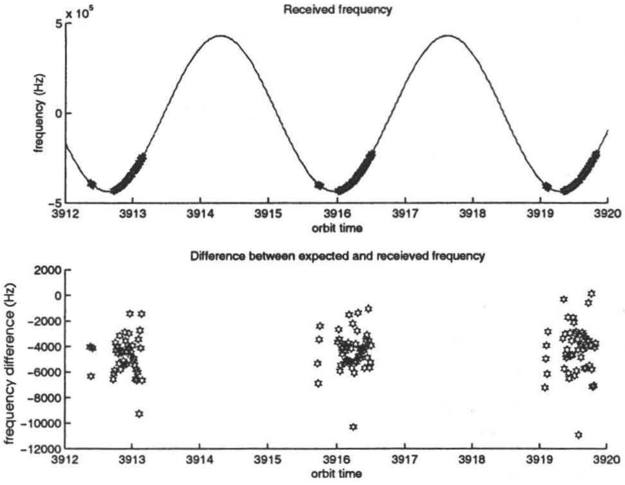

Fig. 5. (top) Frequency of pulses received at the CGS, a sinusoidal curve has been fit to the data. (bottom) Difference between the received data and the expected frequency. The mean error is 4 kHz [1].

The SeaWinds CGS is also able to measure the frequency of received pulses. Each pulse that is received by the CGS has a different frequency, dependent upon the transmitted frequency from SeaWinds and the frequency shift that results from the movement of the instrument, called the Doppler frequency. The Doppler effect is governed by the speed of the satellite, and the geometry between the satellite and the CGS. It can be described mathematically and calculated for each pulse. Figure 5 shows the received frequency of pulses by the CGS along with the difference between expected and received frequencies. The average difference for this data set is 4 kHz. This difference represents a bias between the oscillator aboard the instrument and the oscillator at the ground station. Knowing the offset is necessary to accurately separate the return echo power of each pulse into slices.

A final example of CGS-based calibration is estimating pulse timing. SeaWinds' main internal clock is related to the interval between pulses, nominally 5.4 ms. By determining the arrival time of each pulse at the CGS, an estimate of the pulse repetition interval, or PRI, can be made. It is important to monitor the stability of the PRI over the length of the mission because it is an indicator of overall stability for SeaWinds. Figure 6 shows the stability of the PRI over the length of the CGS mission for SeaWinds. The points represent the average PRI for each CGS capture, with error bars of standard deviation also shown. The figure shows that overall SeaWinds PRI has remained quite stable over the length of the mission, varying by less than 10 parts per million. This helps ensure data quality and ensures

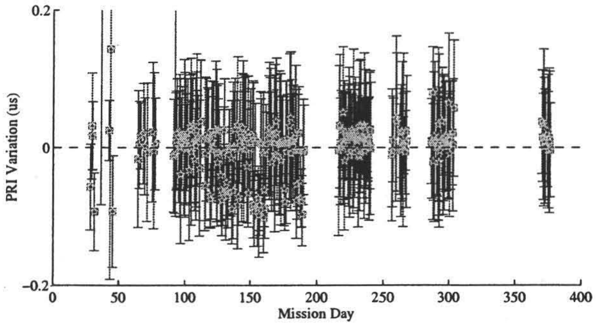

Fig. 6. Stability of the PRI over the length of the CGS mission. The points represent the average PRI for each CGS capture. Error bars represent the standard deviation of the measurements.

the ability to relate data sets recorded over different time periods.

These three examples along with several other individual CGS data analyses have been performed to help enhance the calibration of SeaWinds. These analyses show that overall the instrument is operating well within its designed specifications. They have also helped to characterize the operation of the instrument and enhanced the quality and accuracy of the data generated.

IV. EMERGING APPLICATIONS

Improved calibration along with the slicing technique have allowed for new application to emerge. These application not only improve on the standard wind measurements but also provide additional global climate information.

The most straightforward application enhancement for SeaWinds is high resolution wind estimation. As SeaWinds' antenna rotates, the footprint of the individual slices overlap each other. The oversampling of σ° allows for the creation of wind measurements on the scale of 2.5 km [3]. This is significantly improved over the nominal wind estimation resolution for SeaWinds of 25 km. The tradeoff with this improvement is that the measurements are noisier. This suggests that for global ocean wind measurements, the standard and more accurate, 25 km wind estimates are more appropriate. For coastal areas and specific events, such as determining the eye of a hurricane, the high resolution winds provide a significant benefit. Figure 7 shows an example of improved resolution wind. The top figure shows wind speed at 25 km resolution, the bottom at 2.5 km resolution. The noise in the data is apparent, but the resolution greatly enhances understanding.

Wind estimation only requires σ° values for ocean regions; operationally, SeaWinds measures σ° over the entire surface of the Earth. Values of σ° recorded over

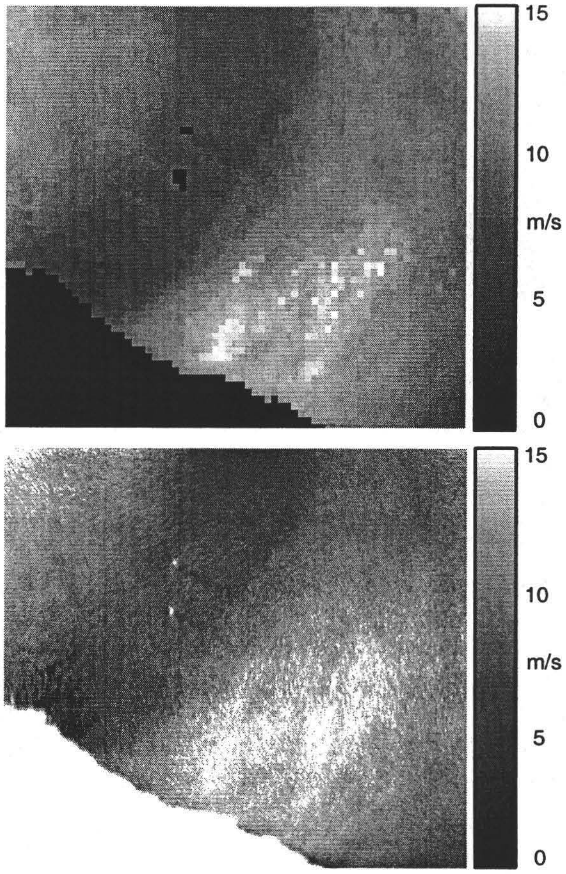

Fig. 7. Images of wind speed; black area represents land. (top) 25 km SeaWinds wind speed estimates. (bottom) 2.5 km high resolution wind speed estimates [3].

land and ice can be used for other applications without any modification of the scatterometer design.

One example, related to high resolution wind development is enhanced resolution imaging. SeaWinds, by providing σ° values and associated surface locations, allows images of the Earth's surface to be constructed. σ° is a strong function of water content. This property is particularly valuable when monitoring rain deforestation. σ° values for heavily forested areas are higher than those of Savannah regions. This difference allows for simple and accurate monitoring of rain forest destruction. Figure 8 shows an image of the Amazon region. The forested areas appear light in comparison with the dark Savannah regions. Areas which show significant change over time are highlighted.

Enhanced resolution images are of additional value when applied to remote locations such as the polar regions. Enhanced resolution images are especially applicable to these areas since the boundary between ice and water, which also exhibits a high σ° contrast, is constantly in flux. Images help monitor formation of

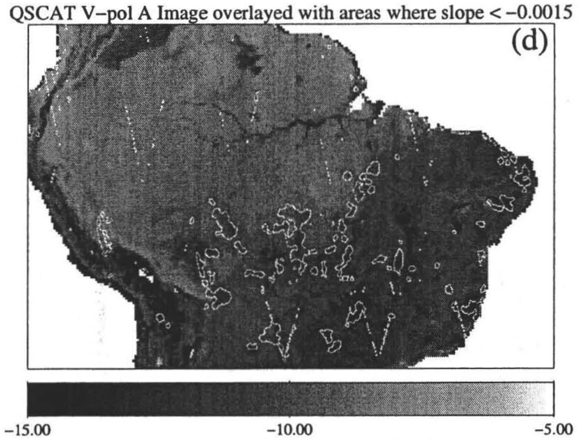

Fig. 8. SeaWinds image of the Amazon rain forest region using σ° values. Areas with significant change over time are highlighted [7].

snow and ice in Greenland and Antarctica. Snow and ice formation in these regions is a strong indicator of long term variations such as global warming. Figure 9 shows a sample σ° image of Greenland. The contrast allows discrimination between snow water content and monitoring of seasonal melt cycles.

Another application associated with ice formation is the tracking of icebergs. Icebergs frequently detach themselves from the ice pack and migrate into the open ocean. They range in size from a few meters to some which are larger than the state of Rhode Island. Tracking icebergs is crucial for the safety of oceanic vessels. Scatterometers are of value because they can operate effectively regardless of weather or time of day [2]. The improved calibration of SeaWinds aids in tracking icebergs, especially those which are smaller than 25 km, yet still large enough to effect shipping lanes.

A final example of the value of scatterometer data is the recent establishment of the NASA Scatterometer Climate Record Pathfinder (SCP) [4]. This project has been established to provide near real-time images and data from scatterometers. The images feature the entire globe, and are updated daily. In addition, raw σ° values are provided. Improved calibration of SeaWinds has allowed the SCP project to provide enhanced resolution images to the scientific community.

V. Future Considerations

SeaWinds on QuikSCAT was launched in June of 1999. It was planned as a quick recovery mission, providing valuable data after the failure of the previous instrument, NSCAT, and before the launch of the next mission, SeaWinds on ADEOS II. Initially ADEOS II was scheduled to launch in 1999, but due to multiple delays, it has not yet been launched. It is currently slated to begin operation early in 2003. The effective operation of QuikSCAT has limited the disappointment. It has provided exceptional data quality, as evidenced by the multitude of emerging applications.

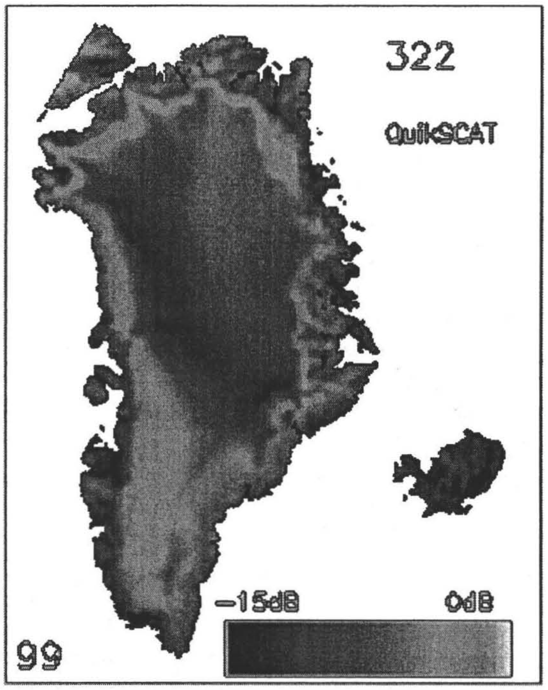

Fig. 9. A sample SeaWinds image of Greenland. The dark areas show areas of limited melt, the white areas represent snow with high water content.

The improved calibration of QuikSCAT bodes well for ADEOS II. The instrument, SeaWinds, is identical on both satellite platforms. All calibration work performed for QuikSCAT will be transferable to ADEOS II. This should enable a shorter calibration period and improved data quality for ADEOS II. The opportunity to have two simultaneously operating scatterometers is highly anticipated. Cooperation between the two instruments, once calibrated, will allow for further utilization of scatterometer data.

While awaiting the launch of ADEOS II, further calibration tests for QuikSCAT are being performed. These tests continue to improve the performance of QuikSCAT, and will be easily applicable to ADEOS II, enabling additional application of scatterometer data.

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