A SCANNING SCATTEROMETER
FOR THE EOS POLAR PLATFORM

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Scatterometers are the only proven spaceborne instrument capable of providing all-weather measurements of near-surface wind velocity over the ocean. Because of the scientific importance of surface winds, a scatterometer is planned for flight on NASA's Earth Observing System (Eos). Two possible options for this scatterometer are being considered: a fan-beam design (STIKSCAT) based on the NASA Scatterometer (NSCAT), and a new design, known as SCANSCAT, which uses scanning pencil-beam antennas. The SCANSCAT design provides several advantages over a fan-beam scatterometer including more accurate measurements at low wind speeds and greater coverage with a single contiguous swath. This paper provides a description of the SCANSCAT instrument design developed for the polar orbiting Eos platform B. We also contrast the performance of SCANSCAT and STIKSCAT on an Eos platform.

Keywords: scatterometer, winds, Eos, radar backscatter

INTRODUCTION

SCANSCAT is a 14 GHz dual conically-scanning pencil beam radar scatterometer designed to measure surface wind velocity over the ocean. The instrument makes measurements of the normalized radar backscatter (σ^o) of the ocean's surface from multiple azimuth angles. Spatially colocated measurements of σ^o are combined to estimate near-surface wind speed and direction.

The SCANSCAT scatterometer will acquire radar backscatter measurements using two conically-scanning pencil beam antennas with different look angles. The antenna beams trace out overlapping helices as the spacecraft orbits the earth (Fig. 1). Four backscatter measurements (2 azimuth angles for each of two incidence angles) are obtained over the width of the inner scan. Two backscatter measurements (2 azimuth angles at a single incidence angle) are obtained for the remainder of the outer scan. By combining backscatter measurements for each ocean location, the surface wind velocity can be determined.

The SCANSCAT instrument represents a significant departure from earlier scatterometer designs such as the Seasat Scatterometer (SASS) and NSCAT. The SCANSCAT instrument design has several advantages over the traditional fan-beam scatterometer design:

1. High σ^o measurement accuracy: because radiation is transmitted in a concentrated pencil beam (in contrast to the diffuse fan-beam designs of SASS and NSCAT), the high gain of the antenna results in SNR values which are significantly higher than for the fan beam at similar incidence angles. This contributes directly to SCANSCAT's ability to make accurate velocity measurements, especially at low wind speeds where σ^o values are small.
2. High directional accuracy: the transmission of horizontally polarized (H-pol) radiation maximizes the azimuthal modulation and upwind/downwind asymmetry in the backscatter measurements. Additional enhancements are realized by operating at relatively high, fixed incidence angles. Finally, directional accuracy is increased because most ocean locations are viewed from four azimuth angles (as opposed to three for NSCAT-type designs).
3. Continuous swath: the incidence angle for σ^o measurements is constant for each scan, independent of cross-track distance. The SCANSCAT swath is continuous with no nadir gap as occurs for fan-beam designs.
4. Simplified model function: since SCANSCAT uses only H-pol at only two incidence angles, the empirical model function relating σ^o to winds needs only to be known over a limited range of parameter space (as opposed to a broad range of incidence angles and both V and H polarizations for traditional fan-beam designs).

The original SCANSCAT design was developed as an attached payload on the Space Station [3]. However, because of its improved accuracy relative to a fan-beam scatterometer, it is being studied for possible flight as part of Eos. We provide a description of the science requirements for SCANSCAT on Eos and a description of the instrument configuration and performance.

SCANSCAT SCIENCE REQUIREMENTS

The SCANSCAT science requirements are more stringent than those of previous scatterometers and are summarized here:

1. Wind speed accuracy:
   20% (rms) for wind speeds from 1-3 m/s
   10% (rms) for wind speeds from 3-30 m/s
2. Wind direction accuracy: 20° (rms) for the *chosen* unique vector
3. Spatial resolution: 25 km
4. Mission duration: 5 years
5. Short term coverage: 85% coverage at least once every day for all ocean areas between ±70°. 12 hour maximum spacing between revisits for at least 50% of the 2° x 2° boxes at each latitude between ±70°

The capability to accurately measure very low (1-3 m/s) winds is unique to the scanning design. The directional accuracy requirement is stated in terms of the *chosen* unique direction rather than the closest ambiguity (which is not always selected by the ground processing) This requirement will be met, in part, by the use of advanced wind retrieval techniques. The lack of a nadir gap allows SCANSCAT to achieve greater coverage and a much higher revisit frequency than is possible for a fan-beam design.

We are studying the feasibility of adding an integral radiometer to the instrument which would permit co-located measurements of the atmospheric absorption (due to liquid water) of the scatterometer signal. These measurements would permit attenuation correction of the σ^o measurements and increase the overall wind measurement accuracy. In this paper, however, we concentrate on the scatterometer system design.

INSTRUMENT DESCRIPTION

Stringent field-of-view and accommodation requirements for

SCANSCAT on Eos have driven the configuration chosen for SCANSCAT. We have selected a dual-reflector "clam shell" antenna configuration which minimizes the antenna size and swept volume (Fig. 2). This design allows SCANSCAT to be mounted at the forward end of the Eos spacecraft without interfering with the operation of other potential instruments on the platform. The antenna reflectors are 2 m in diameter and rotate at approximately 16 rpm to produce the necessary helical scan pattern on the ocean surface at each of two incidence angles. Each 25 km resolution element in a 25 km square grid on the ocean's surface over a 1600 km swath is observed by both fore- and aft-looking antenna beams as the scatterometer moves along its ground track. The instrument transmits Ku-band (13.995 GHz) continuous wave (CW) pulses toward the ocean's surface and measures the returned backscatter power. Separate measurements of the noise-only power are subtracted from the backscattered power during ground processing and, by using the radar equation, measurements of the normalized radar backscatter (σ^o) are obtained. These σ^o measurements are then used to estimate the near-surface wind.

Figure 3 shows a block diagram of the instrument system. The flight instrument is composed of a Radio Frequency Subsystem (RFS) for generating the transmitted pulses and amplifying the received signal; a Digital Subsystem (DSS) for providing overall command processing, instrument control, digitizing baseband signals from the RFS electronics, buffering data, and interfacing with the spacecraft; an Antenna Subsystem (AS) composed of two parabolic reflector antennas mounted on a rotating assembly for generating the transmitted and received circular pencil beams; a Momentum Compensation Subsystem (MCS) which rotates the antennas and provides momentum compensation; and a Mechanical Thermal Subsystem (MTS) which provides structural support and thermal control for the other subsystems.

Most of the SCANSCAT electronics are mounted either at the antenna rotator base or on a plate on the SCANSCAT mounting bracket. RF power and control signals are passed through a rotary joint to the spinning antenna assembly. Within each of the dual RF assemblies, a frequency synthesizer generates the 13.995 GHz transmit frequency which is gated to produce 250-800 μs CW pulses. These pulses are then amplified to 120 W by traveling wave tube amplifiers (TWTAs). The output from each TWTA passes through waveguide and a rotary joint to the transmit/receive feed cluster of the offset-fed parabolic dish antenna.

The radar return echo from the ocean surface is received at the antenna by a receive feed separate from the transmit feed. This separation compensates for the rotation of the antenna during the pulse time-of-flight. After amplification, the return signal is mixed down to baseband through two intermediate frequencies to the final mixer. The final mixing frequency is selected by the DSS command processor as a function of the Doppler offset frequency of the received signal. (The return echo has a maximum Doppler bandwidth of 10 kHz with a center frequency which may vary ±600 kHz depending on orbit altitude and rotator position.) The final mix-down provides a baseband signal that is low-pass filtered to 50 kHz and then sampled digitally at 250 kHz during the time interval corresponding to the center of the returned echo. Periodically, "noise-only" measurements are made by omitting the transmit pulse and measuring only the receiver noise. The accumulated return signal and noise-only samples, together with timing and rotation position data, are transmitted to the ground for processing. During the portion of the scan which has the greatest cross-track distance, the transmitter is disabled and measurements of internal calibration sources are made to permit on-board, in-flight calibration of the receiver gain.

The transmit pulse repetition frequency (PRF), transmit pulse lengths and range gate lengths are constant during a single antenna rotation, but vary as a function of orbit position. The PRF and range gates are selected so that the range gates for the inner and outer scans occur between two consecutive transmit pulses. The PRF and transmit pulse length are adjusted by the DSS throughout the orbit to maintain optimum transmit/receive timing depending on the particular orbit. Uploaded tables will be used by the DSS on-board processor to determine the mix-down frequencies and timing parameters. The ground processor will use orbit predicts to determine the need for new parameters and to compute updated tables. The new tables can then be telemetered to the instrument from the ground.

The optional radiometer subsystem consists of a two-channel (19 and 37 GHz, V-pol) radiometer which uses the outer scan reflector. The radiometer subsystem will be mounted on the rotating antenna assembly. The radiometer feeds will be sized and located so that the radiometer and scatterometer receive footprints coincide.

A summary of the SCANSCAT design parameters for the baseline design is given in Table 1.

COVERAGE

The SCANSCAT inner scan look angle is set to 36° (corresponding to an incidence angle of 41°), resulting in an inner swath with 40 cells and a width of 1000 km at the Equator. The outer scan look angle is set to be 47° (an incidence angle of 54°), so that there are 24 more cells in each outer swath (12 on each side of nadir) with measurements at only 2 azimuth angles. This results in a total of 64 cells spanning a swath width of 1600 km.

Importantly, the SCANSCAT swath is continuous, while traditional fan-beam scatterometers cannot measure winds within approximately 325 km about the sub-satellite track. SCANSCAT measures wind vectors over 89% of the global oceans every day compared to 79% daily coverage for STIKSCAT. Two-day global ocean coverage is 99% for SCANSCAT and 95% for STIKSCAT.

WIND MEASUREMENT PERFORMANCE

Wind measurement performance is dependent on the accuracy of the σ^o measurements, the geophysical model function relating σ^o and the wind vector, and the uncertainty in the model function. The statistical "communication" error in the power measurements made by the instrument is characterized by K_p, a function of the signal-to-noise ratio (SNR) and the number of transmit pulses accumulated into the power measurement [2].

At most wind speeds, the signal-to-noise ratio (SNR) for SCANSCAT is sufficiently high that the errors in the measurement of the signal power depend principally on the *number* of transmit pulses accumulated into the radar return power measurement. The relatively short, frequent pulsing scheme used in SCANSCAT optimizes the measurement of the signal power and minimizes the measurement error.

The factors in the radar equation which are required to determine σ^o from the signal power include the wavelength, peak power, system loss, slant range, and antenna gain pattern. Uncertainties in the true values of these quantities result in additional uncertainties in σ^o. To achieve high σ^o accuracy, these quantities will be calibrated before launch. The normalized standard deviation of the error in σ^o due to the uncertainties in these quantities is predicted to be less than 10%. This error is known as the "retrieval error".

The geophysical model function has some uncertainty due to unmodeled geophysical effects. A normalized standard deviation of 10% is assumed for the model function uncertainty. This error is known as the "model function error".

The relationship between errors in the individual σ^o measurements and the errors in the retrieved wind vectors is highly nonlinear. Building on SASS and NSCAT inheritance, a simulation program has been written to evaluate the expected performance of the SCANSCAT instrument for determining the wind vectors. Starting with a given wind speed and direction, σ^o measurements for a given wind vector were simulated for each azimuth angle of each scan by using the SASS-2 (Wentz) model function [4], which relates σ^o at given incidence and azimuth angles to the wind vector, and adding noise corresponding to the combined effects of the communication error, the retrieval error and the model function error. The simulated σ^o measurements were coregistered and the wind vector at each cell retrieved. Three performance metrics quantitatively characterize instrument performance:

- The root-mean-square (rms) error between the input wind speed and the retrieved wind speed for the ambiguity closest in direction to the input wind vector;
- The rms error between the input wind direction and the retrieved wind direction for the closest ambiguity; and
- The "ambiguity skill", defined as the probability that the highest likelihood ambiguity is also the closest ambiguity to the input wind vector.

Using these metrics we contrast the performance of SCANSCAT with the performance of STIKSCAT. Performance is evaluated over discrete volume elements in parameter space with dimensions of 1 m/s in wind speed, 20° in wind direction, and 25 km resolution using a "compass" simulation [1]. True wind speeds and directions are assumed to be uniformly distributed within this element.

Simulation results for the baseline SCANSCAT instrument design vs. wind speed are presented in Fig. 4. The performance has been averaged over all wind directions. STIKSCAT performance is included in both figures for comparison. All results are for the starboard side of the spacecraft. SCANSCAT coverage extends 800 km, with the inner 500 km covered by both scans. SCANSCAT performance has been averaged over the inner and outer scans separately. Figure 4a shows the rms value of the wind speed error. The rms wind speed errors for SCANSCAT are lower than those for STIKSCAT at all swath locations. The simulation results for the rms value of the wind direction error are shown in Fig. 4b. SCANSCAT directional accuracy is significantly higher than STIKSCAT at low wind speeds.

From Fig. 4c, the SCANSCAT alias skill at all wind speeds is higher than the STIKSCAT skill for the inner swath, and lower for the outer swath. At near-nadir, the SCANSCAT alias skill falls as low as 40% but the first plus second skill remains reasonably high (above 70%) so that high-quality ambiguity removal is possible.

SUMMARY

We have developed a viable design for a scanning scatterometer on the Eos polar platform. Compared to fan-beam instruments such as SASS, NSCAT, and STIKSCAT, the SCANSCAT design will result in significantly more accurate measurements of the near-surface wind vector. The higher ambiguity removal skill of SCANSCAT relative to STIKSCAT, coupled with advanced wind retrieval techniques, is expected to eliminate the traditional difficulties associated with the ambiguities occurring in scatterometer wind measurements.

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REFERENCES

[1] C-Y Chi and F.K. Li, "A Comparative Study of Several Wind Estimation Algorithms for Spaceborne Scatterometers," *IEEE Trans. on Geosci. Remote Sensing*, Vol. GE-26, No. 2, pp. 115-121, March 1988.

[2] D. G. Long, "K_p Equation for SCANSCAT," JPL Internal Memo 3343-89-146, Dec. 5, 1989

[3] R. K. Moore, R. G. Kennett, and F. K. Li, "Performance of a Scanning Pencil-Beam Spaceborne Scatterometer for Ocean Wind Measurements," *Proc. Int. Geosci. Remote Sensing Symp.*, pp. 563-564, Edinburgh, Scotland, Aug. 1988.

[4] F. J. Wentz, S. Peteherych, and L. A. Thomas, "A Model Function for Ocean Radar Cross-sections at 14.6 GHz," *Journal of Geophysical Research*, Vol. 89, pp. 3689-3704, 1984.

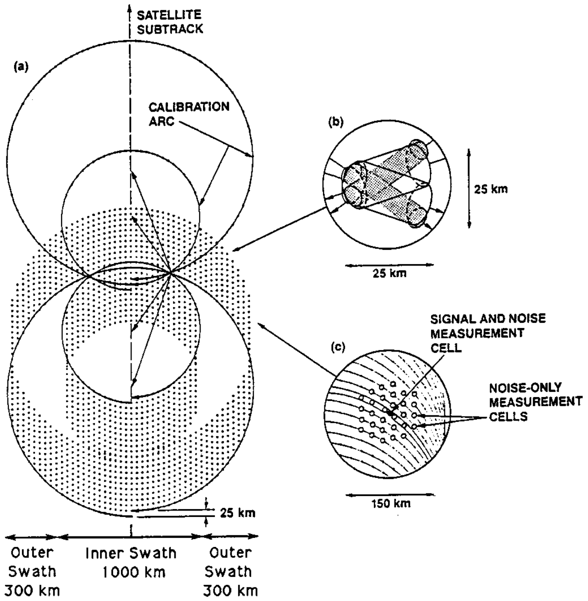

Figure 1. Diagram of the SCANSCAT swath and spatial sampling scheme. (a) σ^o sample locations during the first few antenna rotations illustrating how a 25 km grid point (from which arrows emanate) is observed from four azimuth angles with the two scans. (b) Enlargement of the area around this grid point showing the integrated σ^o measurement cells. (c) A lower-scale enlargment showing the signal+noise measurement and near-by noise-only measurements used to compute σ^o.

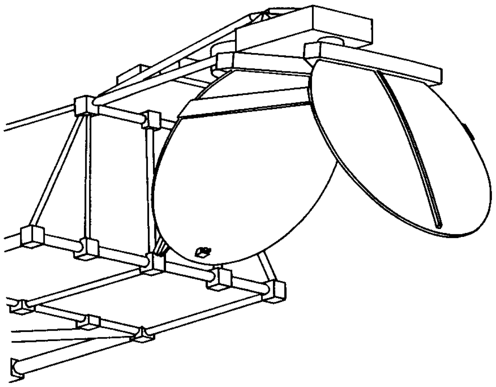

Figure 2. SCANSCAT on the Eos-B platform.

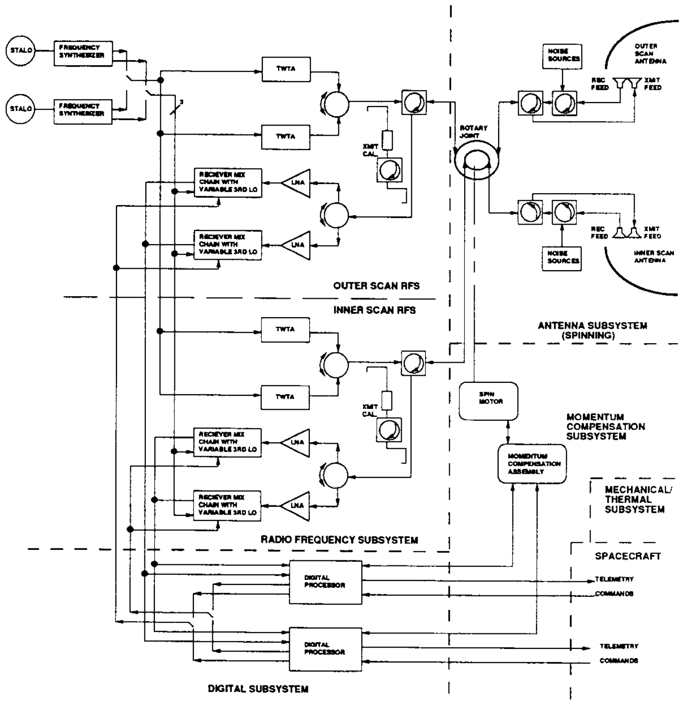

Figure 3. SCANSCAT instrument block diagram

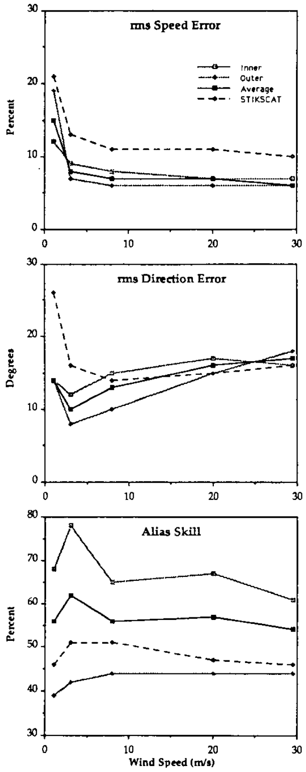

Figure 4. SCANSCAT vs STIKSCAT performance.

		Inner Scan		Outer Scan	
PARAMETER	unit	Equator	S. Pole	Equator	S. Pole
(a) Orbit					
Orbital altitude	km	705			
Inclination angle	deg	98.186			
(b) Antenna					
Rotation rate	rpm	16.4			
Half-power beamwidth	deg	0.61		0.61	
Antenna gain	dBi	47		47	
Look angle (fixed)	deg	36		47	
Xmit/Rec separation	deg	0.590		0.767	
(c) Geometry					
Incidence angle	deg	40.8	41.0	54.3	54.6
Slant range	km	900	933	1112	1154
Max Doppler shift	kHz	415		518	
(d) Swath					
Resolution	km	25			
Full cross-track width	km	1000	1050	1600	1650
Cross-track cells		40	42	64	66
Global ocean coverage	%/24 hrs	69		89	
Global ocean coverage	%/48 hrs	95		99	
(e) Radar Parameters					
Transmit Power	W	110		110	
Receiver Noise Figure	dB	3		3	
(e) Timing					
Pulse time-of-flight	msec	6.0	6.3	7.3	7.6
PRF	kHz	0.71-0.74			
Pulse length	μsec	643-696		684-792	
Range gate length	μsec	545-597		499-609	

Table 1: SCANSCAT Baseline Design Parameters.