The SeaWinds Scatterometer Instrument

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Abstract

The SeaWinds scatterometer instrument is currently being developed by NASA/JPL., as a part of the NASA EOS Program, for flight on the Japanese ADEOS II mission in 1999. This Ku-band radar scatterometer will infer surface wind speed and direction by measuring the radar normalized backscatter cross- section over several different azimuth angles. This paper presents the design characteristics of and operational approach to the instrument itself. The SeaWinds pencil-beam-antenna conical-scan design is a change from the fixed fan-beam antennas of SASS and NSCAT. The purpose of this change is to develop a more compact design consistent with the accommodation constants of the ADEOS II spacecraft. The SeaWinds conical-scan arrangement has a 1-m reflector dish antenna that provides a time shared dual-antenna beam at 40 and 46 degree look angles. The dual-beam operation provides up to four azimuth look directions for each wind measurement cell. At an orbit height of 803 km, the conical scan provides a broad and contiguous wind measurement swath of about 1800 km for each orbit paw Radiometric measurement performance from a conical scan is inherently stable because of a common antenna apparatus, a measurement cell well defined by the narrow antenna beamwidth, and only two f 1xed-beam incidence angles for the multiple azimuth looks. A tracking filter is required to accommodate variations in the Doppler shift of the echo during the scan period Key specifications 01 the SeaWinds instrument and associated tradeoffs and performance will be described.

I. INTRODUCTION

This paper describes the National Aeronautics and Space Administration (NASA) SeaWinds Scatterometer Experiment The SeaWinds instrument is a part of NASA's Earth Observing System (EOS), which comprises a family of instruments that will provide long-term monitoring of the Earth's global environment and processes. The SeaWinds Experiment will measure wind speed and direction over the ocean surface, which affects global heat transport and weather changes. It will be the latest in a series of spaceborne scatterometers, that includes the Seasat-A Spaceborne Scatterometer (SASS) launched in 1978, the Earth Resource Satellite (ERS-1) scatterometer in orbit since 1991, and the NASA Scatterometer (NSCAT) scheduled for a 1996 launch aboard the Advanced Earth Observation System (ADEOS) satellite developed by the National Space Development Agency (NASDA) of Japan. The SeaWinds Instrument is scheduled to be flown on the ADEOS 11 satellite in 1999, along with a complementary set of passive and active sensors for Earth observation.

A companion paper to this, authored by M. Freilich [1] discusses the science aspect of the SeaWinds Experiment, this paper addresses the system design parameters and the expected performance of SeaWinds.

A scatterometer is an active microwave molar that measures the normalized radar backscatter coefficient, $\sigma 0$, of the ocean surface from several different azimuth angles relative to the radar velocity. In general, $\sigma 0$ vanes as a function of the surface wind speed, the angle of incidence, and the azimuth angle between the illumination direction and the wind direction. A quantitative model of the backscatter as a function of the wind vector and the measurement geometry has been experimentally and analytically established by investigators in the past two decades [2-4]. The backscatter model generally resembles a second-order sinusoidal function of wind direction, with the overall $\sigma 0$ level increasing with the wind speed. In the wind-retrieval process, the backscattering coefficients measured over several azimuth angles arc used to estimate the most likely wind direction and speed according to the $\sigma 0$ model function. The results then form a wind field map over an extended surface

The SeaWinds science objective is to map sea-surface winds to a spatial resolution of 50 km, a wind measurement accuracy within 2 m/s meters per second or 10% of the wind speed (whichever is greater) for wind speeds from 3 to 30 meters per second, and 20 degrees in direction. The frequency of coverage should be such that more than 90% of ocean surface will be covered every two days.

Design of an active radar instrument for backscatter measurement may take several different approaches. Recent spaceborne scatterometers, SASS, ERS-1, and NSCAT [5] have employed a "fan-beam" measurement technique. These scatterometers employ several antenna beams whose footprints are narrow in azimuth and extended in range. Partitioning of the elongated antenna footprint to achieve the desired wind-cell resolution is done primarily by resolving the Doppler spectrum into cells, each corresponding to a spatial resolution cell on the surface, Physical I y, the fan-beam approach is characterized by a number of Icing antenna sticks extending mainly 4S deg forward and aft from the flight direction.

The SeaWinds scatterometer will take a different approach to accommodate the constraints in the field of view and the deployment instruments on the ADEOS II spacecraft, The approach uses a conically scanning "pencil-beam" antenna to map the sea surface. Conceptually, the pencil beam approach is close to that used in the early Skylab S- 193 scatterometer [6]. The scanning single-aperture antenna is relatively compact in physical dimension compared with the fan-beam design. Two narrow beams share one physical antenna aperture. The antenna rotates conically with respect to the nadir-looking axis of the spacecraft. The two-beam arrangement allows each spot in the primary radar mapping swath to be viewed

from up to four azimuth look directions. In detecting the echo and measuring the σ0, the pencil-beam approach corresponds to a beam-limited system, as opposed to a **pulse-limlkd** system w **here** spatial resolution is achieved by the time resolution of a radar pulse, and to a band-limited system, like a Ian-beam scatterometer that resolves by spectrum analysis with parallel Doppler filters.

II. SEAWINDS INSTRUM ENT DESIGN

Design of the SeaWinds instrument considers the orbit parameters and accommodation constraints of the host spacecraft, the heritage of previous NASA scatterometers, and issues specific to (he pencil-beam approach. The planned orbit for the ADEOSII satellite is Sun synchronous at an approximate 99 deg inclination angle. The nominal altitude is 803 km, and the orbit repeat period is 4 days. The ADEOS II Mission and the SeaWinds Experiment both have a design life of 3 years. A Ku-band carrier frequency of 13.402 GHz was selected. This frequency follows the established backscattering model function used by the SASS, and the future NSCAT.

Figure 1 is a block diagram of the instrument architecture. The three major subsystems of the instrument are the conical-scan SeaWinds antenna subsystem (SAS), the electronics subsystem (SES), and the command and data subsystem (CDS). A conceptual diagram of the SeaWinds on board the ADEOS II satellite is shown in Figure 2. Among the other instruments shown are the Advanced Microwave Scanning Radiometer (A MSR), the Global Imager (GI .1), the Improved Limb Atmosphere Spectrometer (II AS), and the Polarimetric and Directional Earth Reflectance (POLDER). The key parameters of the SeaWinds system arc given in l'able 1. Specific features of the instrument subsystems are discussed in subsequent sections.
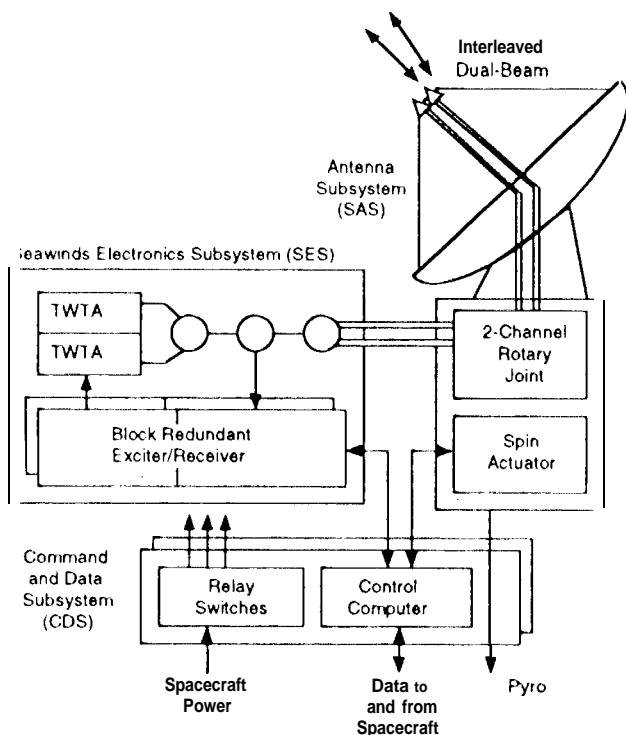

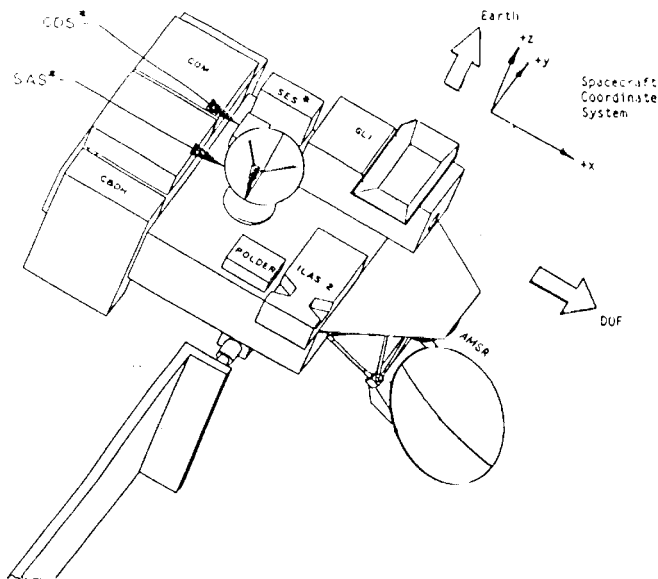Figure 1 Block Diagram of the SeaWinds Instrument

Figure 2 Conceptual Diagram of the SeaWinds Subsystems (*) Onboard the ADEOS 11 Satellite

Table 1. SeaWinds instrument Key Parameters

Parameter	Value
instrument frequency	13.402 +/- 0.5
Expected sigma-O range	-37 to -2 dB
Number of Beams	2
Look angle to nadir	40 and 46 degrees
Antenna beam width	1.6 (el) x 1.8 (az) at 40 deg.
	1.4 (el) x 1.7 (az) at 46 deg.
Polarization	H at 40 deg beam, V at 46 deg.
Antenna spin rate	18 rpm
Antenna gain	>39 dB
Antenna peak sidelobe	-15 dB or below
Transmitter power	110 W TWTA
Transmitter pulse width	1.5 ms
Transmitter pulse rdtc	192.3 Hz
Instrument 10ss	< 3 dB
Receiver sensitivity	< -135 dBmW
Receiver dynamic range	4S dB
Equivalent noise temperature	700 deg K
Echo detection filter	Doppler tracking to 2kH 17
Doppler tracking range	+/-500 kHz
Absolute prelaunch gain knowledge	< 1 dB
Gain uncertainty and drift (6 month)	< 0.5 dB
Telemetry accuracy	< 2 %
Test equipment calibration	0.15 dB

2.1 Antenna Parameters and Scanning Approach

The SAS contains an antenna dish of about 1 m in size with two separate feeds for two slightly elliptical radiation beams, electronic controls, and the spin actuator . A rotary waveguide coupler will be used to transfer radiation energy between the rotating antenna aperture assembly and the stationary radio- frequency electronics,

The elevation or look angles of the two antenna beams are 40 and 46 deg with respect to nadir. At the planned orbit height of 803 km, the incidence angles of the beams are about 46 and 54 deg respectively. The beams are electrically polarized in the horizontal (perpendicular to the incidence plane) for the inner or 40-deg beam, and in the vertical for the outer, or 46 degrees, beam.

The approximate 1.6 deg beam width (l'able I), will produce a two-way antenna footprint on Earth's surface of approximately 30 by 40 km. This footprint pattern defines the basic surface resolution cell dimension for measuring the radar back scattering coefficient. The diameters of the helical circles formed on the surface by the two scanning beams arc 7(K) and 900 km, respectively. Figure 3 depicts the viewing geometry of [he SeaWinds. Wind speed and direction measurements between 250 and 800 km cross-track on each side of nadir track are the most accurate and are expected to meet the science requirements in speed and direction, as well as the coverage frequency. Data acquired near nadir and the edge of the 900 km circle are also useful and provide the potential for extending full coverage to 1800 km per orbit track.
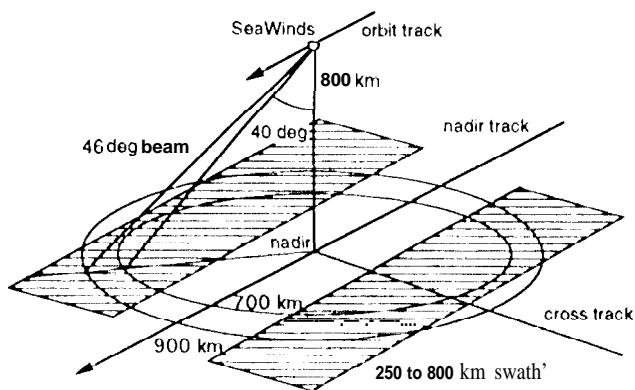
' 250 to 800 km swath contains data that meet wind accuracy requirements when averaged over all wind directions

Figure 3 SeaWinds Conical Scan Geometry

The radar timing design has a pulse width of 1.5 ms and a pulse repetition interval of 5.2 rns. The corresponding radar pulse repetition frequency is 192.3 Hz. The two beams operate in an interleaved manner, and the effective pulse rate for each beam is one half of the 192.3 Hz composite rate. The rotation rate of the conical scan antenna is nominally 18 revolutions-per-minute (rpm). This rate is chosen (1) to produce a beam-sarnplc spacing of approximately one-half of the beam footprint size cm the surface, (2) to provide a possible 640 pulses per revolution at a 5.2-ms pulse interval, and (3) to accommodate a mechanical constraint set by the spacecraft. At this rate, the spatial sample spacing is approximately 22 km along-track and 14 and 18 km in azimuth for the inner and outer beams, respectively. The 00 adjacent measurement cells will appropriately overlap. In the ground processor, the σ0 samples will be further manipulated spatially as well as radiometrically for gain compensation and registration to form wind vector cells.

2.2 SeaWinds Electronics Subsystem

The SeaWinds electronics subsystem (SES) provides the active measurement of the σ0 over a surface area defined by the antenna footprint. The dominant sources of statistical uncertainty in

measuring σ0 include the electronics noise, the Rayleigh scattering noise, spatial Interference due to antenna and filter sidelobes, and the variability in the radiometric gain of the sensor. To accommodate such error sources, the SeaWinds electronics design incorporates the following features:

- A 110 W peak power TWT amplifier (TWTA) with 1.5-ms pulses and a 30% duty cycle,
- A transmitter with a 40 kHz modulated bandwidth to provide frequency diversity to reduce the narrowband Rayleigh effect in detecting [he received echo,
- A receiver that tracks the Doppler shift of the echo to maximize the signal-to-noise ratio (SNR).
- A design for low sidelobes and self-generated spurious noise.
- A calibration scheme for the radiometric gain of the Instrument.

The TWTA is of NSCAT heritage and uses a coupled cavity design 10 generate a nominal peak power of 110 W. The constraints on total power consumption and thermal design limit the transmitter duty cycle to within 30%. The nominal radar pulse width is 1.5 ms over a pulse interval of 5.2 ms. The pulses are modulated to increase the frequency diversity for noise reduction. The receiver design contains a Doppler tracking filter to reject as much noise as possible, The tracking filter has a narrow bandwidth compatible with the echo spectrum. The total range of Doppler frequency shift over al I orbit and scan positions is +/- 500 kHz.

Accurate estimation of the echo return requires that the noise bias be subtracted from the narrow band echo filter. A second filter in the receiver covering the 1-MHz Doppler range is specified to estimate the noise density. The. detected prover samples from the echo and the noise filters form the major part of the science telemetry.

2.3 Command and Data Subsystem

The Command and Data Subsystem (CDS) serves the following functions: provides the command and data interface to the spacecraft, controls of the subsystem configuration and operation mode, provides real-time generation of Doppler trucking parameters for SES, provides real-time sense of the antenna spin position, and processes and formats the science and engineering telemetry for downlink.

2.4 Physical Accommodations

The SeaWinds instrument is being implemented with the three major subsystems described above. The three subsystems are physically separated, and thermally isolated from the spacecraft. Each subsystem contains block dual redundancy to enhance the operation reliability. The mass and power estimates for the flight instrument are approximately 200 kg and 2.50 W, respectively.

III. IMT1MATION AND CALIBRATION

3.1 Noise and Interference

Rayleigh noise is associated with narrow-band scattering from distributed scatters, which randomize the amplitude and phase of the return echo. For SeaWinds design, a transmitter modulation of 40 kHz is specified. The associated tracking filter bandwidth is specified as 80 kHz, which includes a margin for pointing and

tracking uncertainty. The pulse modulation arrangement provides net reduction in detection variance, even though [he noise bandwidth is increased.

In this paper, Inference refers [o σ0 error caused by interference response from the adjacent σ0 cells. It originates from various sidelobes, such as those from the antenna pattern, modulation, and Inter response. Interference adds additional bias to [he detected σ0 samples. One way to reduce interference is to design the system with low sidelobes. 1 he degree to which the antenna sidelobes can be suppressed is affected by the the dual- beam antenna arrangement. The two feeds cannot both be at the focus of the aperture, thus adding difficulty to the sidelobe suppression. The antenna sidelobe is currently specified at -15 dB or below with respect to the peak of the corresponding main lobe. Spatial Inverse filtering may be applied in the ground processor to reduce the estimation bias due to interference. The requirements and approach will be further analyzed.

3.2 Radiometric Gain Calibration and Verification

The estimated echo return power of a beam-limited molar like SeaWinds relates to the σ0 by a rather standard radar equation:

$$\hat{\sigma}_0(x\ y) = \frac{\int [G_1(u,v)\sigma_0(x+u,y+v)G_2(u,v)F(u,v)/R^4(u,v)]\,du\,dv}{\int [G_1(u,v)G_2(u,v)F(u,v)/R^4(u,v)]\,du\,dv} \quad (1)$$

where

$$\int \frac{G_1(u,v)\sigma_0(x+u,y+v)G_2(u,v)F(u,v)}{R^4(u,v)}\,du\,dv = \frac{(4\pi)^3 P_r}{P_t.G_r\lambda^2} \quad (2)$$

G], and G2 are the antenna transmit and receive gain
    patterns projected to the surface during scan
F(u,v) is the effect of the Doppler tracking filter
R is the slant range
λ is the wavelength
Pr is the power at output of the receiver
Pt is the transmit power
Gr is the receiver gain
1. is the two-way path attenuation caused by atmosphere

The equation above relates the sensed echo power Pt to σ0 centered at location (x, y). The domain of the σ0 measurement is defined by the normalization integral at the denominator of E-4(1. Error sources of the σ0 estimate now include (1) the inherent uncertainty in estimating the Pr caused by noise and interference, (2) error in the knowledge of Pt Gr, and L, and (3) error in evaluating the normalization integral, which involves the antenna pattern, scan rate, filter response, and surface projection of these quantities based on the orbit and attitude knowledge. **When σ0 cells of multiple azimuth look angles are registered in the ground processor for wind** retrieval, attempts shall also be made to minimize error related to mis-registration.

Based on **analysis of error sources and their impacts on the** wind detection **accuracy, the SeaWinds Experiment calls for** a calibration or radiometric accuracy of the mean value of 00 to be within 1 dEt absolute at the launch of the instrument and 0.S dB relative throughout the mission period. The absolute error is [he difference **between the best** knowledge and its true value. The relative error is defined as a change or drift of the absolute error over the entire mission period that is subjective to the space environment. 1 he SeaWinds performance model [o verify compliance with the science objectives includes a third major error, which is the uncertainty of the wind related σ0 model function.

Gain performance monitoring and verification during the instrument flight period include (1) onboard monitoring of the transmitter power and receiver gain, (2) systematic dithering of the Doppler [racking parameters in the echo filter to verify the antenna boresight pointing, and (3) acquisition of the radar transmission pattern by a ground calibration receiver placed near the cross-track edges of the **scan** circles. The in-flight calibration telemetry will be applied **to** the ground processor for gain compensation. SeaWinds design also defines a set of 'super cells" for wind cells located at the cross-track boundaries. The span of the azimuth viewing angle from the sensor exceeds 40 deg over the super cells. They are therefore useful in acquiring the wind dependent σ0 model function. These locations will also receive the most frequent hits by the radar pulses, and will be the site for ground calibration receiver..

IV. SEAWINDS DATA PROCESSING

The SeaWinds ground data processing system will be a part of the EOSDIS. The ground system will acquire the science and engineering telemetry associated with the SeaWinds as well as ancillary data required to process the SeaWinds data Selected radiometer data acquired by the Advanced Microwave Scanning Radiometer (AMSR) onboard the ADEOS II spacecraft will also be requested. The AMSR data will be used to estimate the atmospheric attenuation for SeaWinds calibration and to define σ0 cells affected by rain. Land and map and seasonal ice and sea boundaries will also be input to the ground data system to flag those cells affected by land or ice. Another type of input will be the routinely available numerical weather products. A low resolution **wind trend derived from the pressure field will serve as a reference to guide the solution of** wind direction **from a detected streamline,**
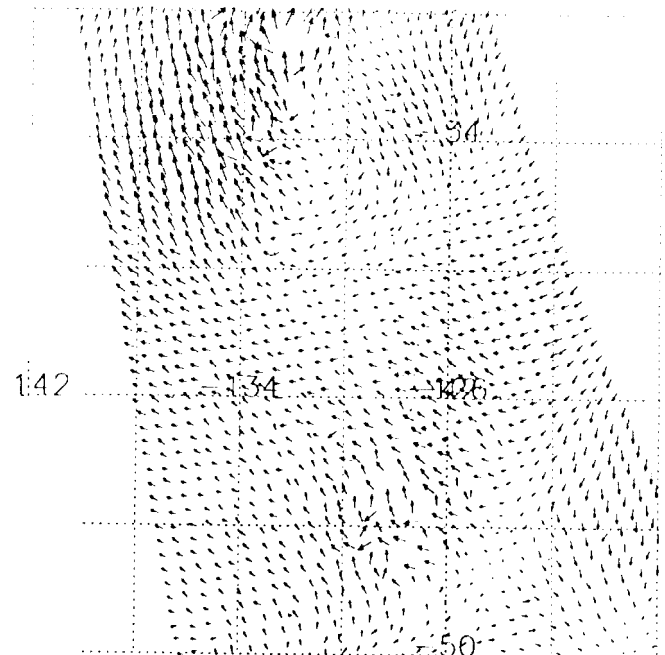
SeaWinds standard data products are summarized in the following three categories: (1) level 1.5, global σ0 map over sea, land, and ice, radiometrically calibrated based on engineering telemetry and radiometer derived atmospheric attenuation, (2) level 2, chosen wind vectors and the associated set of ambiguous solutions, and (3) level 3, global wind map. Special data products, such as the intermediate coregistered σ0 cells of level 1.7, may also be available upon request. The turnaround time for wind-data products is mainly driven by the time to assemble all the input data. The data products and requirements for SeaWinds are being defined.

V. EXPECTED PERFORMANCE

Simulation **models** and tools for the fan-beam NSCAT **were** adapted **to analyze the SeaWinds instrument performance. Based on** the Instrument operation **parameters. simulated σ0 measurements are** processed to retrieve **the original wind vectors. The difference between the input and the retrieved Vectors are examined. Statistics** are compiled **and plotted and referenced to several key parameters,** such as wind speed, swath location, and signal-to-noise ratio. Two figures that show **the wind field input to simulation and results** after the retrieval process are given in Figure 4.
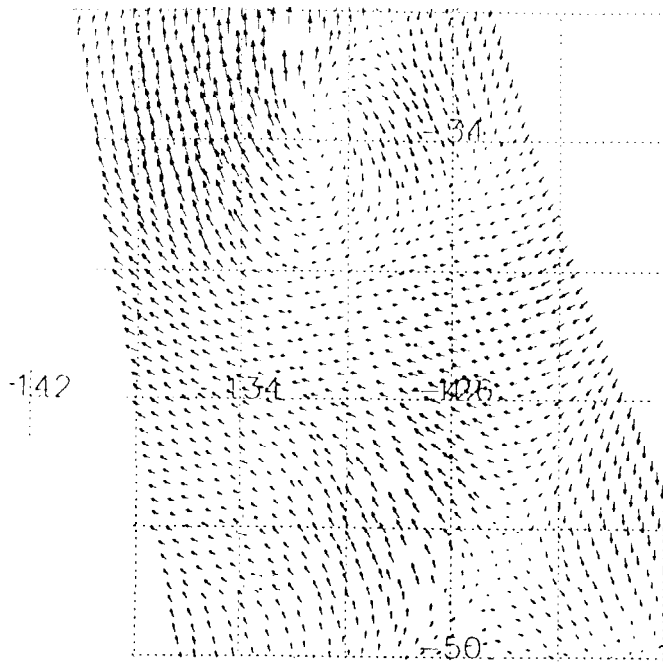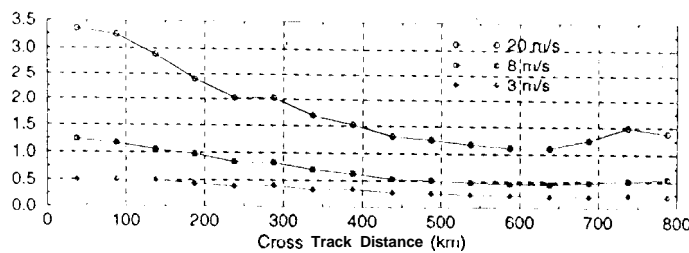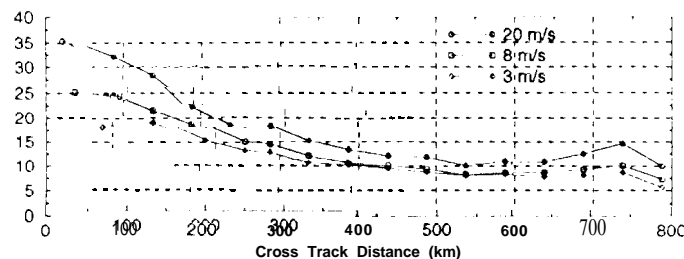
(a) original Wind Field   (b) Simulation of the Retrieved Winds

Figure 4 Simulation of the original and the retrieved Wind Field (1600 km swath **including nadir** gap)

(a) rms wind speed error (m/s) vs cross-track distance (km)

(b) rms wind direction error (degrees) vs cross-track distance (km)

Figure 5 Expected Wind Retrieval Performance of the Sea Winds

The expected performance is best summarized in Figure 5. The expected rms speed and direction error over al I possible wind directions, for three wind speeds, 3, 8, and 20 m/s, are plotted versus the cross-track distance, The science requirements for the wind speeds evaluated is within 2 m/s for wind speed error, and within 20 degree for wind direction. It is observed that the wind detection performance in the swath from 250 to 800 km cross-trick will meet **the** science requirements. Global coverage in two days, for the 2.50 to 800 km swath, exceeds 96% versus [he requirement of 90%. Cover.ige over any 4-day orbit repeat cycle reaches 100%, leaving no systematic gaps.

V]. SUMMARY

The pencil-beam SeaWinds scatterometer is characterized by simplicity in signal processing and limited beam incident angles. The SeaWinds instrument is being developed now according to the architectural design desenbed herein, The implementation approach has strong heritage from the current N. SCAl' and other related satellite programs. The expected performance meets **the** science requirements, and the extended data acquisition swath indeed offers a potential for global wind mapping on a nearly daily basis.

ACKNOWLEDGEMENT

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