SeaWinds: A Scanning Scatterometer for ADEOS-II – Science Overview

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ABSTRACT

The NASA SeaWinds instrument is a conically scanning, dual pencil-beam, Ku-band scatterometer that will fly on the NASDA ADEOS-II mission in early 1999. The scanning pencil-beam approach allows σ_0 measurements and vector winds to be acquired in a continuous swath nearly 1800 km wide. The SeaWinds design has several inherent advantages over the fan-beam approach used for previous scatterometers, including greater accuracy, simplicity, more extensive coverage, easier accommodation, and scalability. This paper describes the scientific aspects of the instrument, emphasizing key differences in the measurements and processing relative to fan-beam scatterometers. A separate paper (Wu et al., 1994) provides a detailed description of the SeaWinds instrument and performance.

1. INTRODUCTION

Knowledge of near-surface winds over the ocean is critical for the investigation of many oceanographic and meterological phenomena. Satellite scatterometers are microwave radars designed specifically to acquire accurate measurements of the normalized radar cross-section (σ_0) of the ocean, from which near surface vector winds can be calculated. Although oceanic wind *speed* can be measured by spaceborne altimeters and microwave radiometers, only scatterometers at present have demonstrated capability for measuring near-surface wind *velocity* (both speed and direction).

Both Ku-band and C-band scatterometers have flown in space and are planned for future flight. The SASS instrument was a fan-beam, 14.6 GHz scatterometer that flew on the NASA SEASAT mission in 1978. The European Space Agency's ERS-1 Advanced Microwave Instrument (AMI) was launched in 1991. It operates at 5.3 GHz and includes scatterometer modes, in which 3 fan-beam antennas acquire σ_0 measurements in a single, 500 km wide swath. A second AMI instrument will fly on ERS-2 mission scheduled for launch in early 1995, and a 14 GHz, dual-swath, 6-beam fan-beam instrument, NSCAT, will be launched in early 1996 as a NASA-supplied instrument on the Japanese Space Agency's ADEOS-I mission. All previous scatterometers have used fan-beam antennas to acquire spatially extensive σ_0 measurements.

In early 1999, NASA will fly a new Ku-band scatterometer design, "SeaWinds" (SWS), as part of the NASDA ADEOS-II mission. The SWS instrument will provide crucial surface wind velocity measurements as part of the NASA/international Earth Observing System (EOS). SeaWinds will be a departure from previous instruments, as it will be a dedicated conically scanning, dual pencil-beam scatterometer. The SWS design is optimized to acquire accurate vector wind measurements over a broad, contiguous swath. Some modifications to the NSCAT data processing algorithms are required to process the SWS data and to utilize measurements from other ADEOS-II instruments (especially a broad-swath, multi-channel microwave radiometer, "AMSR"). However, the combined data aquired by the SWS and AMSR instruments will result in an oceanic vector wind data set of unprecedented coverage and accuracy.

This paper provides an overview of the SWS measurement technique, processing approach, and data characteristics. An accompanying paper (Wu et al., 1994) presents the SWS instrument hardware design in greater detail. Following a brief discussion of scatterometry in section 2, the performance requirements and overall SWS instrument design are presented in section 3. The ADEOS-II mission is briefly summarized in section 4. The baseline ground data processing, including SWS standard products and synergistic use of AMSR radiometer data for rain flagging and atmospheric correction are discussed in section 5. Conclusions are presented in section 6.

2. PRINCIPLES OF SCATTEROMETRY

Although few dedicated spaceborne scatterometers have flown, vector wind measurement using spaceborne active radars has been studied extensively. Naderi et al. (1991) provides a recent review with emphasis on the NSCAT instrument. The present summary focuses on those aspects of primary importance to the design of the SWS instrument and associated data processing.

Scatterometer measurements are highly indirect; the fundamental measurement is received power, from which σ_0 of the sea can be calculated. Sea-surface σ_0 varies as a function of radar parameters and the surface geometry. The surface geometry on centimetric scales is a sensitive function of local wind velocity (both speed and direction). Data from spaceborne and airborne scatterometers have been used to establish accurate empirical relationships between σ_0 and near-surface wind velocity (eg., Wentz et al., 1984; Wentz, 1992). At moderate incidence angles, σ_0 increases with increasing wind velocity (at fixed relative wind direction). At fixed wind speed, σ_0 varies with relative direction, with σ_0 maxima at upwind and downwind directions, and minima near crosswind. Wind velocity can thus be calculated from spatially and temporally colocated σ_0 measurements obtained from different viewing geometries, although the near-harmonic nature of the σ_0 variations with direction typically results in several potential solutions having different directions but similar speeds.

Wind speed sensitivity, upwind/crosswind modulation, and upwind/downwind asymmetry (the small difference between σ_0 maxima at upwind and downwind) all generally increase with increasing incidence angle, and are larger for horizontally polarized (h-pol) than for vertically polarized (v-pol) radiation. However, σ_0 magnitudes are lower at high incidence angles, and for h-pol vs. v-pol radiation. Scatterometer instrument design must therefore balance overall signal strength against the magnitude of wind-induced *variations* in the signal.

3. SWS INSTRUMENT DESIGN

Key SWS performance requirements are summarized in Table 1. These requirements are similar to those established for NSCAT. However, the SWS requirements differ in several areas: (1) the velocity accuracy requirements for SWS correspond to the "chosen," rather than the "closest," ambiguity, thus requiring that the ground processing ambiguity removal algorithm be highly accurate; (2) the SWS σ_0 measurements must be cor-

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Table 1. Key SWS Mission Requirements

Wind Speed Accuracy:	
2–20 m/s	< 2 m/s
20–30 m/s	$< 10\%$ rms
Wind Direction Accuracy:	$< 20°$ rms
Wind Cell Resolution:	50 km (desired) 100 km (max. descope)
Radiometric Compensation:	Required where AMSR data are available
Short-time Coverage:	$> 90\%$ of ice-free global oceans sampled (to accuracies specified above) at least once every 2 days
Lifetime:	3 years minimum, 5 year goal

rected for the effects of atmospheric attenuation where possible using brightness temperature measurements from the AMSR microwave radiometer on the ADEOS-II spacecraft; and (3) the resolution requirement for SWS σ_0 and vector wind measurements is 50 km, with possible relaxation to 100 km if necessitated by accommodation issues.

To achieve these requirements, the SWS instrument has been designed as a conically scanning, dual pencil-beam scatterometer, in contrast to previous fan-beam instruments. The conically scanning scatterometer concept was first proposed by Kirimoto and Moore (1985; see also Long et al., 1990 and Naderi et al., 1991). A spinning pencil-beam antenna is used to transmit and receive radar pulses. The spacecraft orbital velocity causes each beam to trace out a helical pattern on the surface. The spacecraft velocity, antenna spin rate, and instantaneous ocean footprint are coordinated so that adjacent σ_0 measurements overlap, and a continuous swath of σ_0 measurements is obtained for each beam.

Two offset feeds are used to produce twin beams having nominal incidence angles of 47° and 55° (look angles of 40° and 46° with respect to nadir). At the SWS orbital altitude of 803 km, beams have radii of 707 and 900 km. SeaWinds will operate at a frequency of 13.402 GHz (the 14 GHz band is no longer allocated primarily for remote sensing applications). A 1 m diameter parabolic antenna yields an effective σ_0 resolution of $\sim 30 \times 35$ km. The SWS antenna will rotate at ~ 18 rpm, and pulses will be transmitted at 192 Hz; see Wu et al. (1994) for a more detailed discussion of the SWS instrument design.

The SWS instrument will acquire σ_0 measurements at each swath location from up to four viewing geometries: first by the outer beam looking ahead of the spacecraft; next by the inner beam, looking ahead and later behind; and finally again by the outer beam, looking behind. Azimuth angles vary with cross-track distance as shown in figure 1. Although four measurement geometries are obtained at small cross-track distances, there are only two basic azimuth angles, $\sim 180°$ apart. At cross track distances beyond the radius of the inner beam, only two basic viewing geometries are obtained, corresponding to measurements by the outer beam. Due to the overlap of individual SWS σ_0 measurements, between 6 (at small cross-track distances) and 30 (large cross-track distances) σ_0 measurements have centers within each 50 km square wind vector cell.

The scanning pencil-beam design of SeaWinds has many advantages compared with traditional fan beam scatterometers:

1. σ_0 measurement accuracy: The large pencil-beam antenna gain results in much higher signal-to-noise ratios than for fan-beam systems at the same incidence angle and transmit power. This yields more accurate wind velocity measurements, especially at low wind speeds; alternatively, lower power transmitters can be used.
2. Continuous swath: The incidence angle for σ_0 measurements is nominally constant for each beam, resulting in a continuous swath in which all σ_0 measurements are sensitive to wind velocity. Classical fan-beam approaches have incidence angles that vary systematically across the swath; as σ_0 is insensitive to wind direction at small incidence angle, dual-swath fan-beam scatterometers have "nadir gaps" of several hundred km between swaths. The continuous SWS swath results in increased coverage and simplified science processing.
3. Fixed incidence angle: The model function relating σ_0 to wind velocity must be known only near the (two) incidence angles at which measurements are acquired, rather than the broad range of incidence angles required for fan-beam systems. By operating at relatively large incidence angles (47° and 55°), the wind velocity sensitivity of the instrument is improved. In the baseline SWS design, the inner and outer beams will be h-pol and v-pol respectively, further increasing the wind velocity sensitivity without sacrificing signal-to-noise ratios.
4. Processor complexity and data rate: Fan-beam scatterometers require complicated on-board Doppler or range-gating schemes to achieve along-beam resolution and reduce data rate. The pencil-beam design requires neither a sophisticated on-board processor nor a high data rate.
5. Accommodation and scaling: The SeaWinds design is substantially more compact than fan-beam instruments with similar performance, greatly easing spacecraft accomodation issues. To further decrease instrument size, reduced spatial resolution can be achieved with no loss of coverage simply by decreasing the antenna diameter.

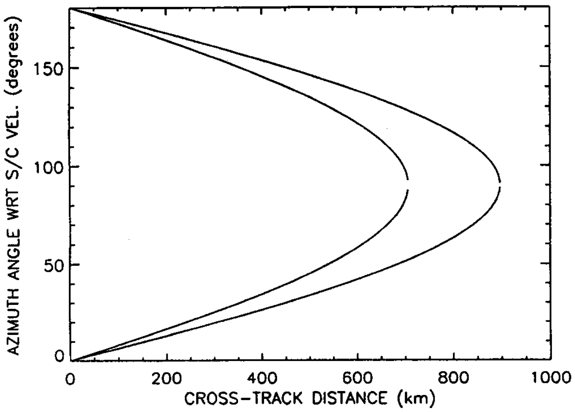

Figure 1.
Azimuth angles vs. cross-track distance
for SWS look angles of 40° and 47°

4. ADEOS-II MISSION

The NASDA ADEOS-II mission, scheduled for launch in early 1999, will be a dedicated earth observation mission carrying a variety of complementary instruments. ADEOS-II will be placed in a 4-day (57 rev) sun-synchronous near-polar orbit with nominal 803 km altitude and 98.6° inclination. Although the full instrument complement for ADEOS-II has not yet been finalized, it is anticipated to include, in addition to SWS: (1) GLI, a multi-frequency (visual/near, short-wave, and thermal infrared) imager with 2000 km swath width and 1 km spatial resolution; and (2) AMSR, a scanning multi-channel (6.6, 10.7, 18.7, 23.8, 36.5, and 89 GHz) microwave radiometer with 1500 km swath width, 49° incidence angle, and frequency-dependent spatial resolutions of 60–5 km. The microwave instruments will allow all-weather measurements of many atmospheric and oceanic parameters, while the GLI will acquire data related to clear-sky sea-surface temperatures and ocean color. Ground-based analyses will combine ADEOS-II data with other earth-observing measurements to be acquired by an international suite of co-orbiting spacecraft.

5. SWS PRODUCTS AND PROCESSING

The SWS ground data processing will produce three products of broad geophysical utility:

1. Global Backscatter Cross-section: Time-ordered, earth-located, global (land, sea, and ice) σ_0 measurements and associated incidence/azimuth angles and SWS radar information/quality flags. This product also includes earth-located, processed brightness temperature data from the AMSR radiometer, for subsequent use in determining rain flags and atmospheric absorption corrections to the SWS σ_0 data.
2. Ocean Vector Winds: Time-ordered, earth-located, 50 km resolution near-surface wind velocities over the open ocean within the measurement swath of the SWS instrument, based where possible on radiometrically corrected σ_0 data. Up to four ambiguous solutions are reported at each location, with a flag identifying the unique wind velocity selected by the ambiguity removal processing algorithm.
3. Wind Maps: Temporally and spatially averaged vector winds and associated statistics on a regular grid (typically 1° x 1° x 1 day).

Ground-based scatterometer processing is discussed in detail in Naderi et al. (1991). Accurate calculation of σ_0 requires subtracting measurements of signal return power from estimates of instrumental and environmental noise. In the case of SWS, the return power (signal+noise) and noise-only data are acquired simultaneously by passing the received signal through both a narrow (80 kHz) "signal" and a broad (1 MHz) "noise" filter. The radar equation, in conjunction with known antenna gains and antenna/spacecraft geometry information, is used to calculate σ_0.

The σ_0 measurements are grouped for wind retrieval on a fixed, 50 km square grid aligned with the local along- and cross-track directions. All open-ocean σ_0 measurements with centers falling within a given 50 km wind vector cell are used. Prior to wind retrieval, available AMSR brightness temperature data and sea-surface temperature estimates from AMSR and/or climatologies will be used to calculate excess attenuation due to cloud and rain droplets (cf. Moore et al., 1982; Wentz, 1983; and Wentz et al., 1986). Although correction of SEASAT scatterometer data was difficult owing primarily to the low resolution of the SEASAT SMMR radiometer, the ADEOS-II AMSR spatial resolution is comparable to the SWS resolution, the AMSR swath covers nearly the entire SWS swath, and the incidence angles of the two instruments are similar.

Wind retrieval will utilize a maximum likelihood estimation technique as described in Chi and Li (1988) and Naderi et al. (1991). The technique as implemented is model function independent and does not require fixed viewing geometry. Wind retrieval will be carried out using only open-ocean σ_0 cells (no ice or land contamination) corrected for atmospheric attenuation where possible. Cells flagged as contaminated by rain will not be used for wind retrieval.

As noted above, the near-harmonic nature of the model function, coupled with instrumental and model function errors, result in several potential wind velocity solutions at each location. An ambiguity removal algorithm is required to select a unique vector from among the potential solutions. In the baseline processing, a modified version of the circular median filter algorithm (Schultz, 1990; Shaffer et al., 1991) will be used. While the circular median filter is effective when instrument skill uniformly exceeds $\sim 65\%$, the algorithm can fail when large spatial areas are initialized with incorrect directions. Simulations suggest that accurate ambiguity removal will not be possible based on SWS data alone. A limited initialization using surface analyses from operational numerical weather prediction (NWP) models will therefore be used. In this technique, which is presently being used to process ERS-1 scatterometer data (Freilich and Dunbar, 1993), interpolated NWP data are used to select initial directions only from among the first- or second- most likely ambiguities at each location. Following this initialization, the median filter is applied until convergence. Importantly, *all* ambiguities are used for the median filter, although only the top-ranked ones are used in the initialization. Tests with simulated SWS and actual ERS-1 data show that the limited initialization results in higher final skill than a full initialization; in the latter case (where the closest ambiguity is used, regardless of rank), spatially correlated errors in the NWP analyses remain in the final median filter solution. The limited initialization combines the NWP information with streamline directional information contained in the scatterometer solutions themselves, thus resulting in correct convergence of the median filter even in the presence of most NWP errors.

6. CONCLUSIONS

The NASA SeaWinds instrument is a conically scanning, dual pencil-beam, Ku-band scatterometer that will fly on the NASDA ADEOS-II mission, planned for launch in early 1999. The scanning pencil-beam approach allows σ_0 measurements and vector winds to be acquired in a continuous swath nearly 1800 km wide. Detailed simulations (to be described elsewhere) indicate that performance requirements will be achieved over large portions of the swath, and the coverage requirements will be met with margin. Even at near- and far-swath locations where wind velocity accuracy may be worse than specified, considerable information on the vector wind field is present in the data, due to the large, uniform incidence angles of the SWS beams.

The SeaWinds design has several inherent advantages over the fan-beam approach used for previous scatterometers, including potentially greater accuracy, simplicity, more extensive coverage, easier accommodation, and scalability. Some modifications to the NSCAT ground processing algorithms will be necessary to accommodate the SWS design and the use of AMSR microwave radiometer data for radiometric correction. In particular, an ambiguity removal approach based on median filtering with a limited initialization by operational surface wind analyses will be necessary to achieve the high ambiguity removal skill required for the SWS data. This approach is presently being used successfully to process ERS-1 data, and simulations suggest that it will be extremely effective when applied to the SWS data. The SeaWinds data set, in conjunction with other ADEOS-II and co-orbiting data sets, will play a crucial role in the study of the ocean's role in weather and climate.

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