Pergamon

Acta Astronautica Vol. 43, No. 7–8, pp. 397–407, 1998

Printed in Great Britain
PII: S0094-5765(97)00180-X
0094-5765/98 $19.00 + 0.00

NASA SCATTEROMETER EXPERIMENT†

J. GRAF, C. SASAKI, C. WINN, W. T. LIU, W. TSAI
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, U.S.A

M. FREILICH
Oregon State University, Corvallis, OR 97331-5503, U.S.A.

and

D. LONG
Brigham Young University, Provo, UT 84602, U.S.A.

(Received 25 April 1997)

Abstract—Satellite scatterometers are microwave radars capable of measuring near-surface vector winds (both speed and direction) over the oceans under all weather conditions. The data generated from these instruments are used in scientific studies of upper ocean circulation, tropospheric dynamics, air–sea interaction and climate change; in operational meteorology as a means to increase numerical weather forecast skill and the accuracy of storm warning predictions; and in commercial applications such as ship routing. The scatterometer wind measurement technique was demonstrated with the flight of the Seasat Scatterometer in 1978. This paper summarizes the scatterometry measurement technique, describes the design of the NASA Scatterometer (NSCAT) instrument recently launched aboard the National Space Development Agency of Japan's (NASDA) Advanced Earth Observing Satellite (ADEOS), presents first results from the NSCAT instrument, and describes the future U.S. program for measuring surface marine wind vectors.

1. INTRODUCTION

Contributing to both research, operational and commercial uses, scatterometers are a unique spaceborne instrument. The instrument measures marine surface winds, which are a critical measurement for use in scientific studies of upper ocean circulation, tropospheric dynamics, air–sea interaction, and climate change; in operational meteorology as a means to increase numerical weather forecast skill and the accuracy of storm warning predictions; and in commercial applications to enhance the safety and efficiency of ocean ship routing, sea floor drilling, and commercial fishing. With the launch of the NASA Scatterometer (NSCAT) in August 1996, the first Ku-band scatterometer in 18 years is now returning data from space. An artist's rendering of the NSCAT instrument on the Advanced Earth Observing Satellite (ADEOS) is shown in Fig. 1.

The first major collaboration in Earth remote sensing between NASA and the National Space Development Agency of Japan (NASDA), the 3 year NSCAT mission consists of a NASA-provided instrument and a NASDA-provided spacecraft and launch vehicle. The collaboration will continue with the flight of the next Ku-band scatterometer, SeaWinds, on NASDA's ADEOS II spacecraft in 1999. The SeaWinds instrument and the ADEOS II spacecraft will have a lifetime of 3 years, with a goal of 5 years of operation on orbit, and the launch is phased to produce a continuous, 6 year (or longer) time series of scatterometer data. If sufficient attitude control gas exists, the NSCAT/ADEOS combination will remain operational after the launch of SeaWinds/ADEOS II, and the overlap between the two experiments will facilitate comprehensive calibration and validation between the two instruments, increasing coverage of the oceans.

2. MARINE WIND MEASUREMENT REQUIREMENTS

The NSCAT measurement requirements for research purposes were established by NASA's interdisciplinary Satellite Surface Stress Working Group [1,2]. They are defined in Table 1 and include the ability to measure winds between 3 and 30 m/s with an accuracy of greater than 2 m/s or 10% in speed (whichever is larger) and 20° in direction, over a spatial wind vector cell resolution with 50 km; 90% or more of the oceans must be observed

†Paper IAF-96-B.3. P 103 presented at the 4th International Astronautica Congress, Beijing, China, 7–11 October 1996.

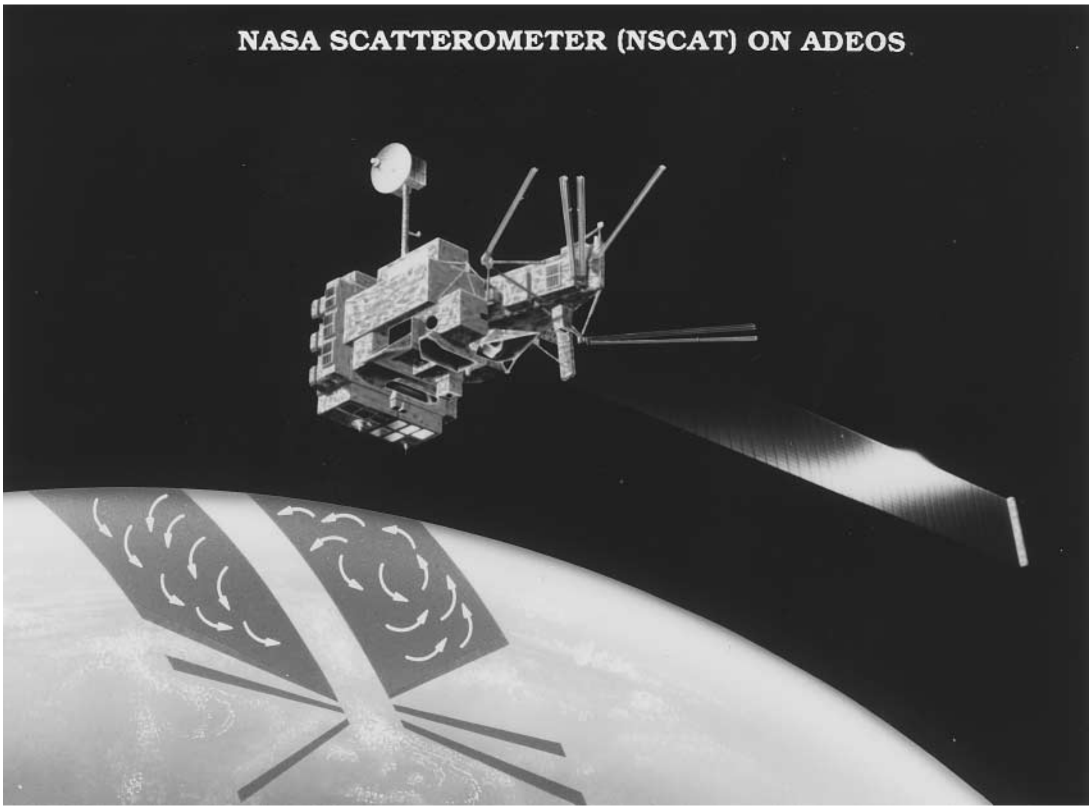

Fig. 1. NSCAT on ADEOS.

at least once every 2 days; products for non-real time research applications must be produced within 2 weeks after data is acquired at the processing center; and the instrument must be designed to acquire data for at least 3 years in order to allow the investigation of annual and interannual variability.

3. NSCAT MISSION DESCRIPTION

The ADEOS spacecraft is a 3-axis stabilized spacecraft weighing 3.5 metric tons, producing 4.5 kW of electrical energy at the end of life, having an engineering body dimension of $4\,\text{m} \times 4\,\text{m} \times 7\,\text{m}$, and supporting a suite of eight international instruments dedicated to Earth remote sensing. The spacecraft was launched into a 797 km sun synchronous orbit by the H-II launch vehicle on August 17, 1996, and it continues to operate nominally. Two of the ADEOS science instruments are from the USA and one is from France; the other instruments are provided by NASDA and other Japanese agencies. In addition to NSCAT, the payload includes a wide-swath ocean color and temperature scanner (OCTS), an advanced visible and near-infrared radiometer (AVNIR), a retroreflector in space (RIS), an interferometer monitor for greenhouse gases (IMG), a polarization and directionality of the earth's reflectance (POLDER), a total ozone mapping spectrometer (TOMS), and an improved limb atmospheric spectrometer (ILAS). The NSCAT instrument onboard the ADEOS spacecraft is shown in Fig. 2.

Table 1. Major NSCAT mission requirements

Measurement	Value	Accuracy/comment
Wind speed	3–30 m/s	2 m/s or 10% (whichever is larger)
Wind direction	3–30 m/s	20° (rms—closest ambiguity)
Spatial resolution	50 km	Wind cells
Location accuracy	25/10km (rms)	Absolute/relative
Coverage	90% of ice-free oceans every 2 days	N/A
Data production	2 weeks of receipt	At processing center
Mission duration	36 months	Includes check-out

The NSCAT instrument has a mass of 279 kg, including its six antennas, four antenna deployment mechanisms, three electronic units, and assorted RF waveguides, attachment fittings and electrical harness. The instrument is mounted on a 3.1 m high structure, dubbed the antenna tower, which was designed and fabricated by NASDA engineers specifically to accommodate the NSCAT instrument. The tower design enables each of the NSCAT antennas to have a clear field-of-view (FOV) and allows the electronic boxes to radiate their waste heat to deep space. The instrument uses 241 W of orbital average power and acquires data continuously over the orbit, whether over ocean, ice or land. The science data is combined into digital bins onboard the instrument, effectively reducing the

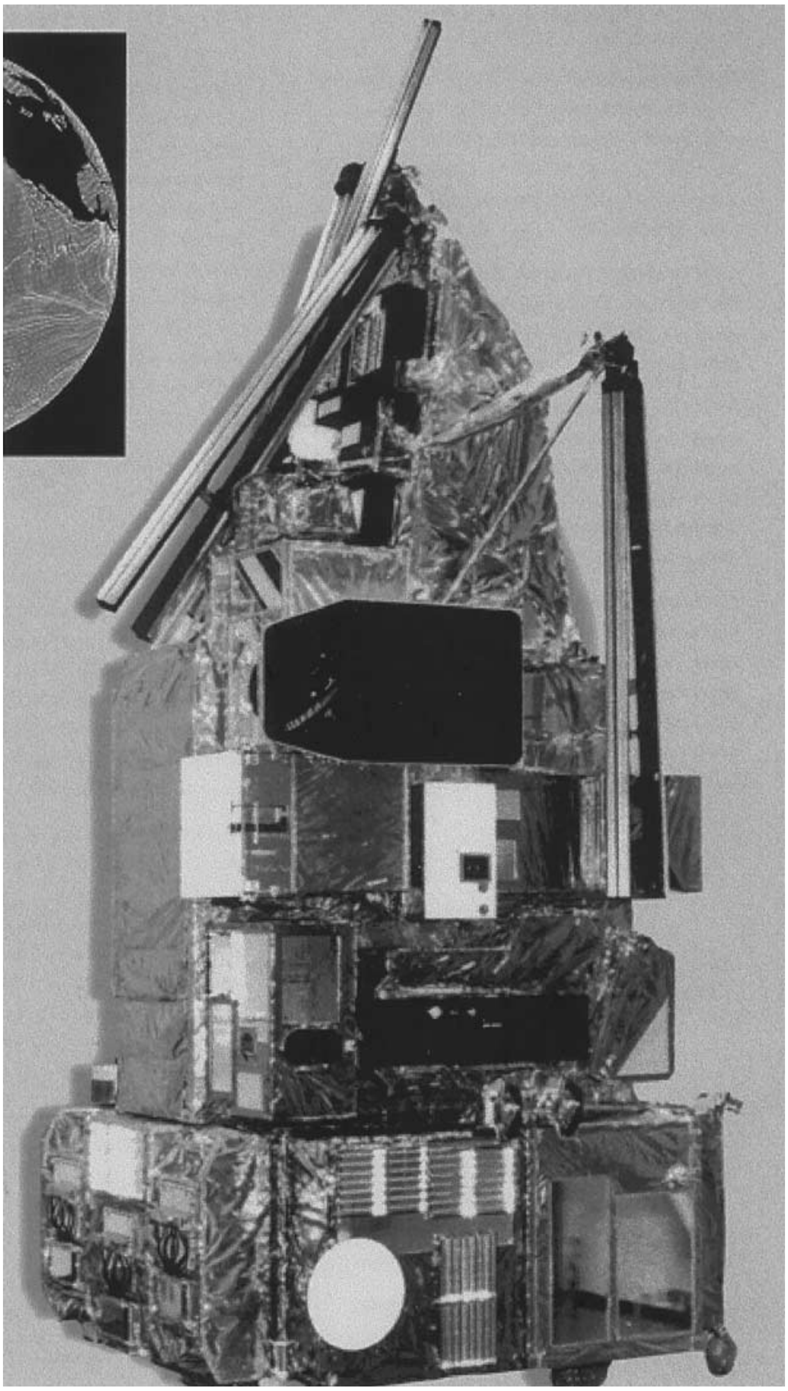

Fig. 2. NSCAT on ADEOS.

data rate by 1000 to 2.9 kb/s. The key NSCAT instrument resource parameters are summarized and compared in Table 2 to the follow-on instrument, SeaWinds, which is described later in the paper.

Table 2. Instrument accommodations comparison

Resource	NSCAT	SeaWinds
Mass (kg)	279	198
Average power (W)	241	192
Operations	Continuous	Continuous
Data rate (kb/s)	2.9	16
Onboard actuation	4 ant. deployments	1 v-band release
Swath scan	Static using Doppler	Mechanical rotation
Antenna FOV (includes keep out zones)	6 ant. each with 50° rel. to ant. boresight	1 ant. with 51° to nadir conical scan

4. THEORY OF OPERATION

The NSCAT instrument is an active microwave radar that measures the normalized radar backscatter coefficient, σ_o, of the ocean surface from several different viewing geometries. Since wind stress over the ocean generates capillary waves which roughen the sea surface, changes in wind velocity cause changes in surface roughness. The roughness changes modify the radar cross-section of the ocean and, hence, the magnitude of backscattered power. The normalized radar cross-section itself is calculated using the basic radar equation which requires accurate measurements of the antenna gain, slant range, transmitted power, system losses, wavelength, effective illuminated area, and received back-scattered power. From each illuminated location on the earth, the total received power is the sum of the back-scattered power and a contribution resulting from instrument noise and the natural emissivity (at that frequency) from the earth-atmosphere system. In order to determine the backscatter cross-section accurately, the noise power must be estimated and subtracted from the total received power.

In general, σ_o varies as a function of the surface wind speed, the incidence angle of the illuminating radar beam, 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 over the past two decades [3,4]. The back-scatter model generally resembles a second-order sinusoidal function of wind direction, with the overall σ_o level increasing with the wind speed.

A single scalar measurement is insufficient to solve for both wind speed and wind direction. Multiple measurements obtained from different viewing geometries are required. With only two measurements taken 90° apart, the Seasat scatterometer generally had a four-fold ambiguity in wind direction. However, additional σ_o values obtained from antennas at yet other angles and/or using different polarizations provide additional information, allowing the wind direction to be uniquely defined. In the case of NSCAT, back-scatter measurements are made with an additional viewing angle having two polarizations, which substantially resolves the ambiguity.

The NSCAT design uses four antennas per side of the subsatellite track at three azimuth angles to obtain the necessary azimuthal looks (one of the stick antennas on each side is dual polarized). The antenna pattern is illustrated in Fig. 3. Each antenna produces an instantaneous footprint which is 600 km long, but only 6 km wide. These antenna patterns are further resolved into back-scatter

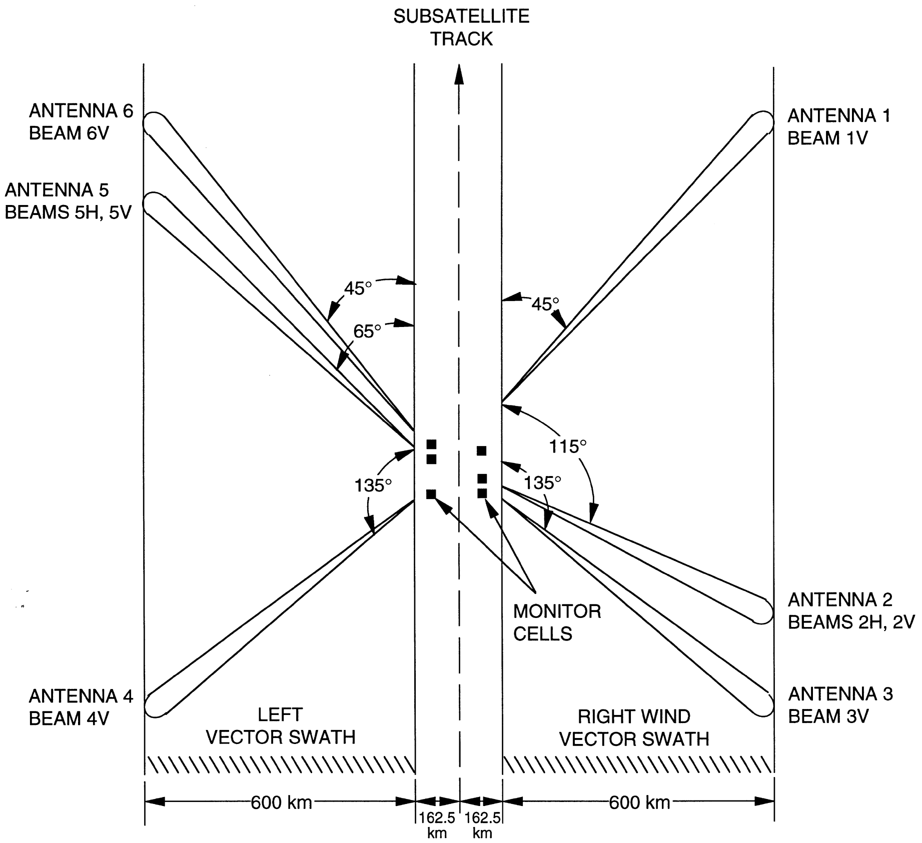

Fig. 3. NSCAT Antenna Pattern.

measurements of 25 km observation cells by means of summing pulse returns and Doppler filtering.

The technique makes use of the fact that the radar echo reflected from the ocean surface is Doppler shifted, due to motion of the spacecraft relative to the earth's surface. The return echoes from different portions of the antenna footprint have different Doppler shifts, with a larger shift at far swath and a smaller shift at near swath. By processing the returned signal with a number of bandpass filters of unequal bandwidth, NSCAT can resolve the 600 km wide swath on each side of its sub-satellite track into 24 σ_o cells, each having 25 km spatial resolution. This 600 km swath enables over 95% of the Earth's oceans to be viewed at least once in every 2 day period. Several σ_o cells are combined in the ground processing to obtain wind velocity estimates having spatial dimensions of 50×50 km.

5. DESCRIPTION OF THE NSCAT INSTRUMENT

Four major physical subsystems comprise the NSCAT instrument. The radio frequency subsystem (RFS) contains the transmitter and receiver chains; a digital data subsystem (DSS) provides instrument control, data formatting, digital Doppler processing and telemetry; the antenna subsystem (Ant) consisting of six identical, dual-polarization fan beam antennas deployed by four mechanisms; and the system waveguide and harness.

The basic function of the RFS is to generate the transmitted pulses at 13.995 Ghz and route them to the antenna subsystem through a switch matrix; to receive the returned signal, down convert and pass the signal to the DSS; and to provide a noise source for onboard calibration of the instrument and accurate measurement of transmitter power.

The DSS consists of two processors: a command and control processor which controls the operations of the instrument, collects housekeeping data and formats downlink telemetry; and a digital Doppler processor which achieves along-beam resolution utilizing the spatially varying Doppler shift of the returned signal and integrates multiple pulses for each along-beam cell.

To achieve the desired fan beam illumination pattern on the Earth's surface, the individual NSCAT antennas are approximately 3.1 m long and have a 15×15 cm cross section. Electrically, the feed horns each produce a fan beam with a 25° beamwidth in elevation (along-beam) and a very narrow 0.4° beamwidth in azimuth (cross-beam). Each antenna assembly consists of two end-fed waveguide arrays in a horn (one for v-pol and one for h-pol radiation) supported by a graphite–epoxy structural member. While each of the antennas has both vertical and horizontal horns, only the vertical polarization is used for antennas 1, 3, 4 and 6 (refer to Fig. 3), while antennas 2 and 5 use both polarizations.

The antenna deployment design employs a pyro-activated launch restraint bolt to release the antennas after launch and an aluminum hinge mechanism using viscous-damped springs for the actual deployment. A more complete description of the instrument can be found in Ref. [5].

6. NSCAT GROUND SYSTEM

The NSCAT ground system is shown in Fig. 4. The data from the NSCAT instrument is returned via two independent communication paths: one for high-quality science and one for near real-time operational uses. The science data stream is collected by the Earth Receiving Station at NASDA's Earth Observation Center (EOC) in Hatayama, Japan. Tapes with the processed level zero data (i.e. time-ordered, non-redundant raw data) are sent weekly to the Jet Propulsion Laboratory (JPL) for higher level processing. After processing at JPL by the NSCAT Project, a suite of higher level products will be distributed weekly to users by the Physical Oceanography Distributed Active Archive Center, also located at JPL. The NSCAT science products will be distributed approximately 3 weeks after acquisition of data and will be the most accurate and complete product suite produced by the NSCAT Project.

Separately from the science stream, the operational data streams will be collected by US ground stations in Alaska and Virginia and the EOC, and processed by the National Oceanic and Atmospheric Administration (NOAA) within 3 h of acquisition. NOAA will distribute the products both domestically and internationally for use by other meteorological agencies.

The standard data products that will be generated include: *σ_o wind vector cell product*—Earth-located σ_o cells in subtrack wind vector cells with quality flags over ocean; *vector wind product* (or winds in swath)—wind speed and direction in the instrument swath and containing the number of σ_os used for wind retrieval, quality flags, the multiple wind vector solutions, and the selected vector; and *global wind map product*—time-averaged, space averaged wind vectors on a global grid. The standard products are described further in Fig. 5. Special products will also be generated, including: *a high resolution merged geophysical data product*—Earth-located σ_o and vector wind measurements collocated in 25×25 km wind vector cells; and a *σ_o beam product*—σ_o organized by beam. Both special products provide coverage over land and ice, as well as oceans. Both the standard data products and the special products are available through the Physical Oceanography Distributed Active Archive Center at JPL and NASDA's Earth Resources Observation Center.

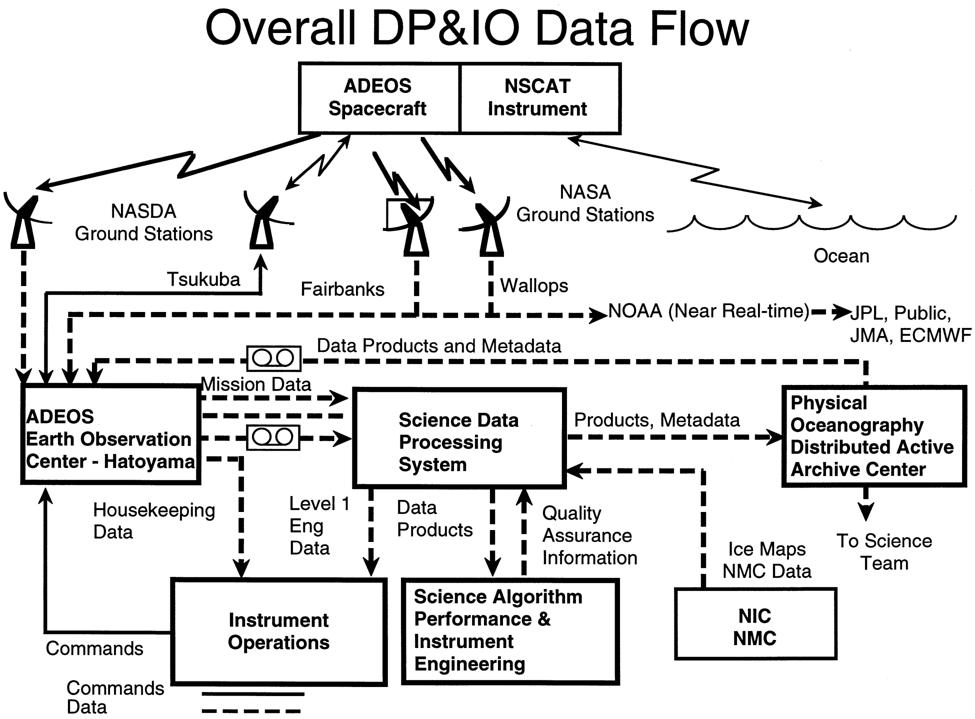

Fig. 4. Overall DP&IO data flow.

In addition to the two aforementioned data streams which will be widely disseminated, a near real time data stream (< 24 h since acquisition) is generated by the EOC Processing Center and sent electronically to the NSCAT Project at JPL for processing. This data is used for monitoring instrument health and, during the early portion of the mission, for performing initial calibration and validation of the data products.

The real time spacecraft and instrument operations are performed by NASDA engineers at the Tracking And Control Center (TACC) in the Tsukuba Space Center in Tsukuba, Japan. The NSCAT Project performs engineering trend analysis and command generation at JPL. Commands are transferred electronically from JPL to EOC, and are merged with other instrument and spacecraft commands and sent to TACC for transmission to the spacecraft.

NSCAT STANDARD DATA PRODUCTS

Level 1.7 Data Files
- Oceans only, in 24-cell rows of 50km wind vector cells
- Up to 24 Sigma0s per cell (typically ~16)

Level 2 Data Files
- Rev-based files organized by wind vector cell row (50km cells)
- Each row has 12 cells on each side (600km swaths)
- Each cell contains up to 4 wind combinations of speed and direction (in likelihood order) and selected solution after ambiguity removal.

Level 3 Data Files
- One day average global map gridded at .5 degree resolution from +75 to -75 latitude (720 cells by 300 cells)
- Each cell contains ten averaged parameters (e.g. avg wind vectors, avg speed, rms speed, wind vector std dev, map day fractions)

Fig. 5. NSCAT standard data products.

7. EARLY RESULTS

The NSCAT instrument was launched successfully on August 17, 1996 from Tanegashima Space Center in Tanegashima, Japan aboard an H-II rocket. Although initially 20 km too high, NASDA successfully commanded the spacecraft to lower its orbit to the operating 797 km, sun synchronous orbit. Eleven hours after launch, the NSCAT antennas were successfully deployed. Power was applied to the heater elements of the electronic units to maintain required temperatures until electrical turn-on on September 10, 1996.

After turn-on, the instrument stepped through each of its operating modes, spending several hours in each. All temperatures and modes have been nominal to date.

The first science data was returned to JPL on September 10, 1996. The data consisted of a single revolution with primary ocean coverage over the North Atlantic. The data was processed successfully by ground computers within 2 h. Typical results include wind vectors in swath (Fig. 6) and global averaged wind vectors (Fig. 7). During the 5 day, checkout period, the instrument performed both calibration measurements and experimental high

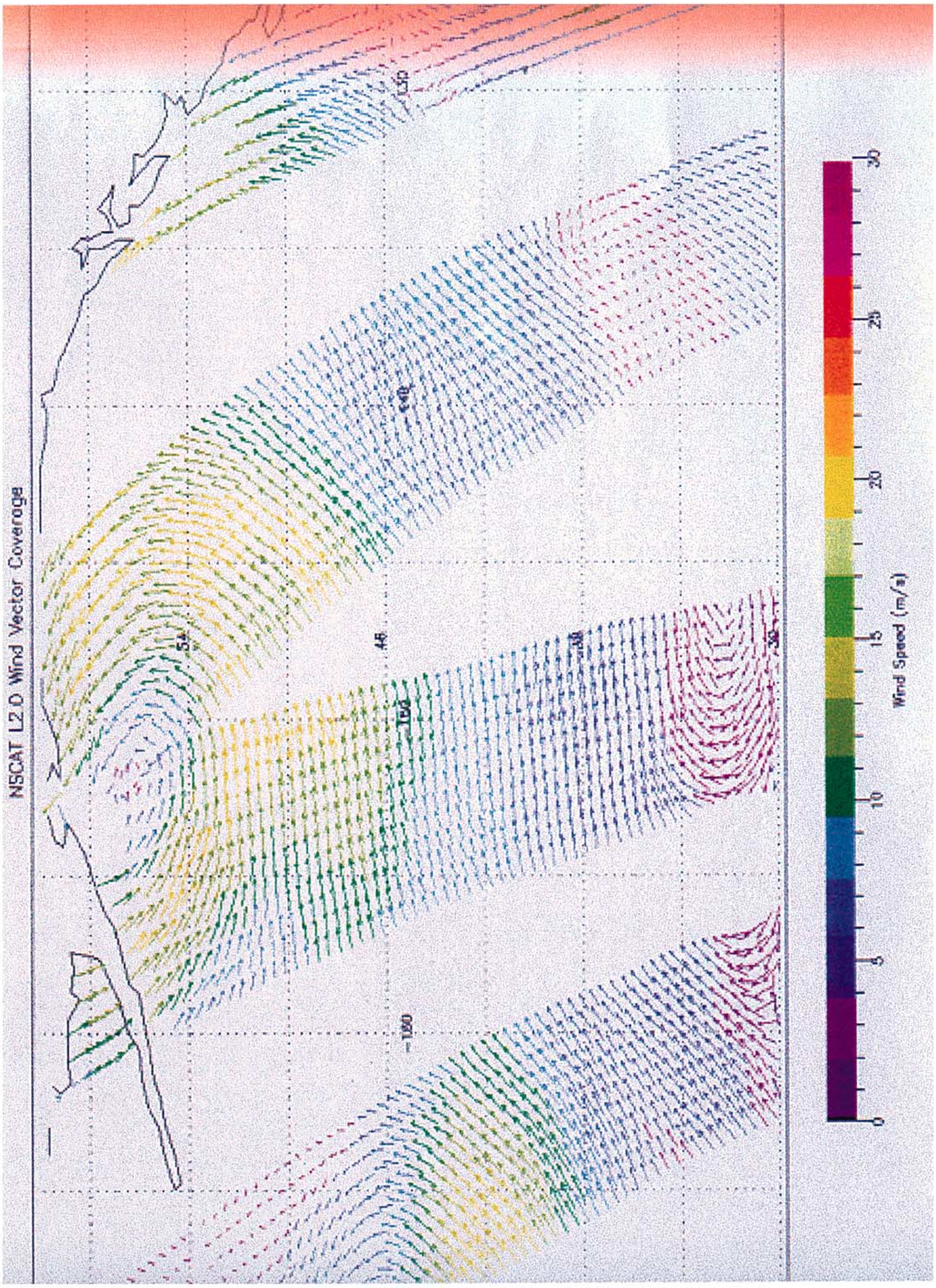

Fig. 6. Wind vectors in swath.

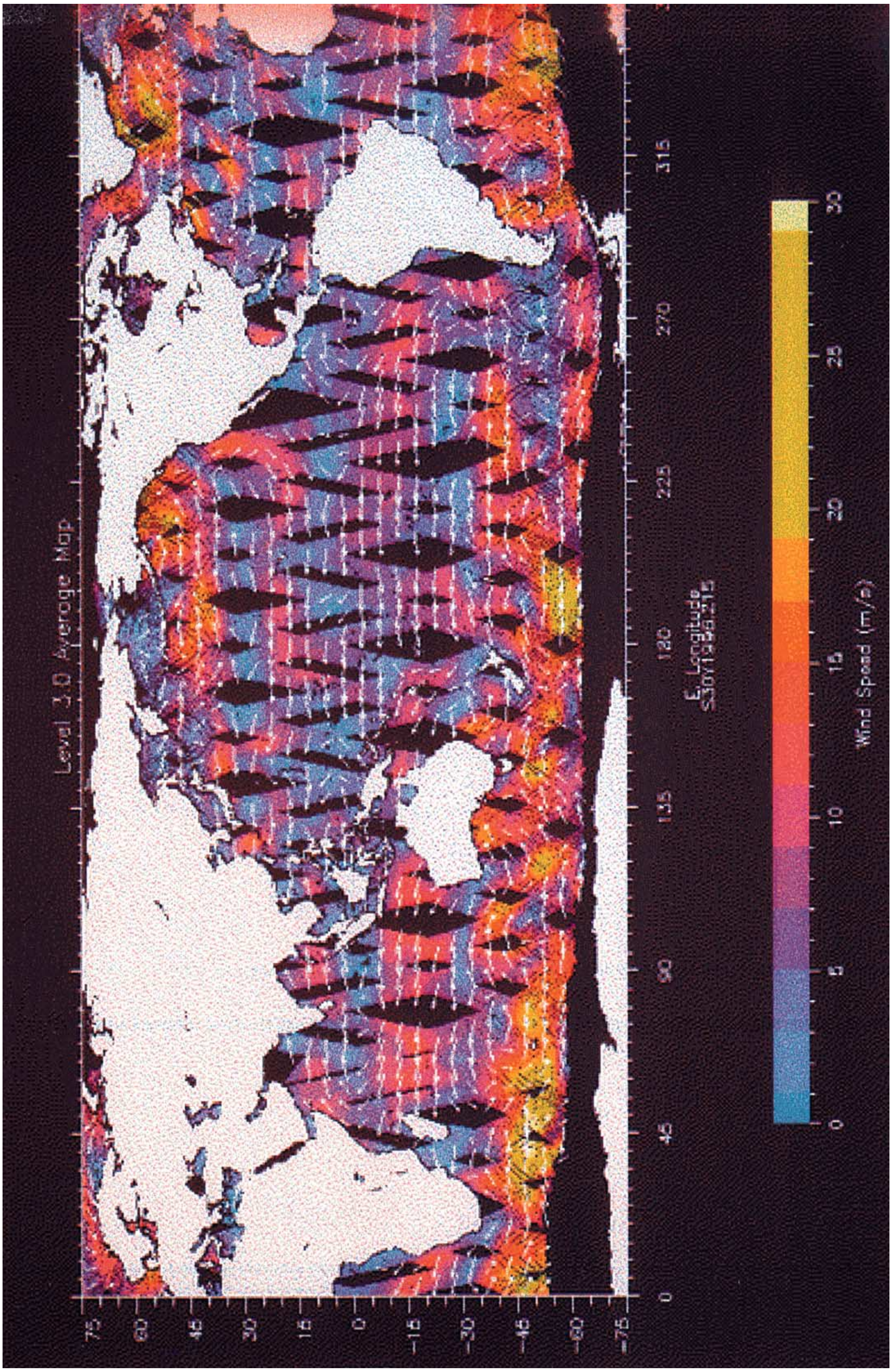

Fig. 7. Global averaged wind vectors.

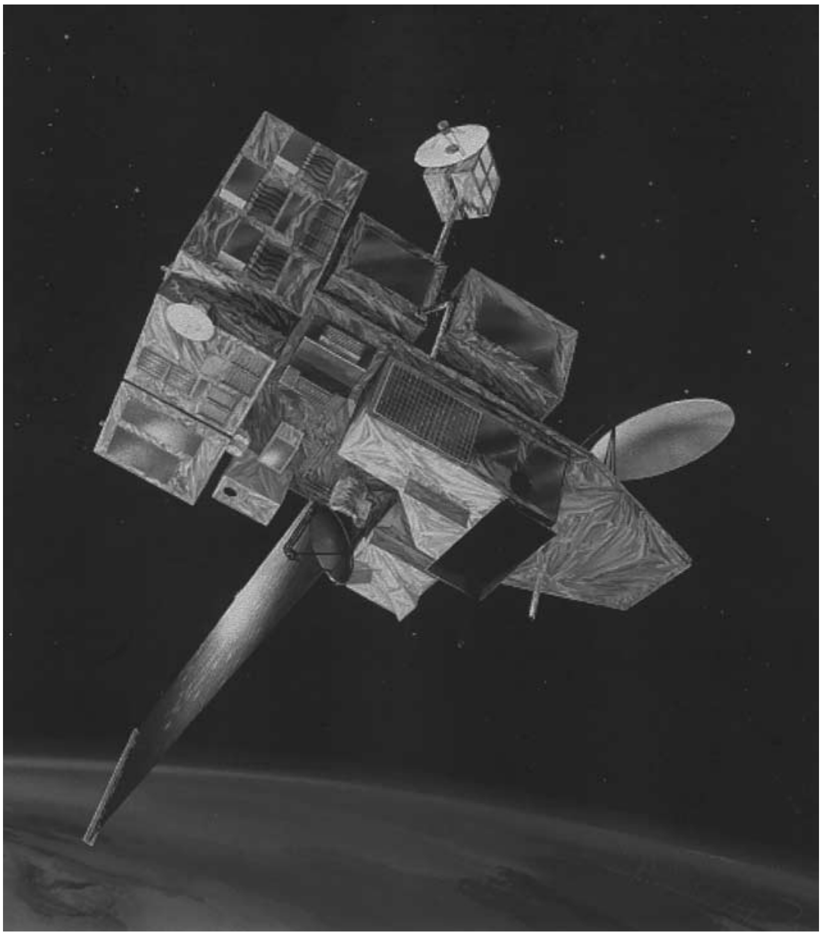

Fig. 8. Sea Winds on ADEOS II.

resolution wind measurements of 6 × 6 km. Upon conclusion of the checkout activities, the instrument was commanded into the wind observation mode, in which it will remain until the end of mission. Also during the checkout period, the communication paths to the ground stations were verified, as was the ability to process the science and operational data streams.

8. DESCRIPTION OF THE SEAWINDS INSTRUMENT

The SeaWinds scatterometer represents a different approach to the spaceborne scatterometer design. SeaWinds will use a conically scanning "pencil-beam" antenna to map the sea surface. The scanning single-aperture antenna is used to form two narrow beams, yielding an instrument that physically is significantly more compact than the fan-beam design. The SeaWinds antenna will rotate conically with respect to the nadir-looking axis of the spacecraft. The scanning design imposes less stringent FOV constraints than the fan beam design; allows for a reduction in spacecraft power requirements; reduces the overall mass of the instrument; and eliminates the need for deployment mechanisms, although a release v-band is required. Conversely, the design requires the antenna to be rotated at 18 rpm, and the σ_o resolution size is dependent on the real aperture of the antenna, i.e. antenna dimensions.

The planned orbit for the ADEOS II satellite is, again, a sun synchronous (99°) inclination angle but at 803 km altitude. The resulting orbit repeat period is 4 days vs the ADEOS spacecraft's 41 days. The ADEOS II Mission and the SeaWinds Experiment both have a design life of 3 years, with a 5 year goal. A Ku-band carrier frequency of 13.402 GHz was selected for SeaWinds to satisfy both the scatterometer objectives and recent changes in spectrum allocations. A conceptual diagram of the SeaWinds onboard the ADEOS II satellite is shown in Fig. 8.

The three major subsystems of the instrument are the conical-scan SeaWinds antenna subsystem (SAS), the SeaWinds electronics subsystem (SES), and the command and data subsystem (CDS). Figure 9 shows a photograph of the SeaWinds engineering model units now in integration and testing. The CDS provides the command and data interface to the spacecraft, controls the instrument configuration and operation mode, provides real-time generation of the Doppler 2nd-range tracking parameters for the SES, and processes and formats

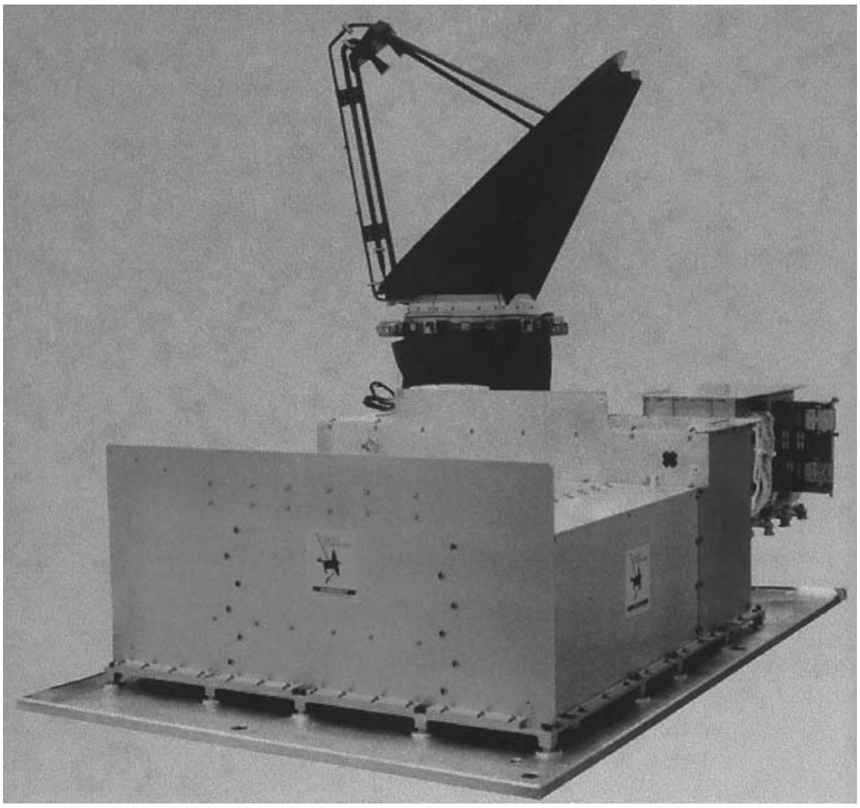

Fig. 9. SeaWinds engineering model.

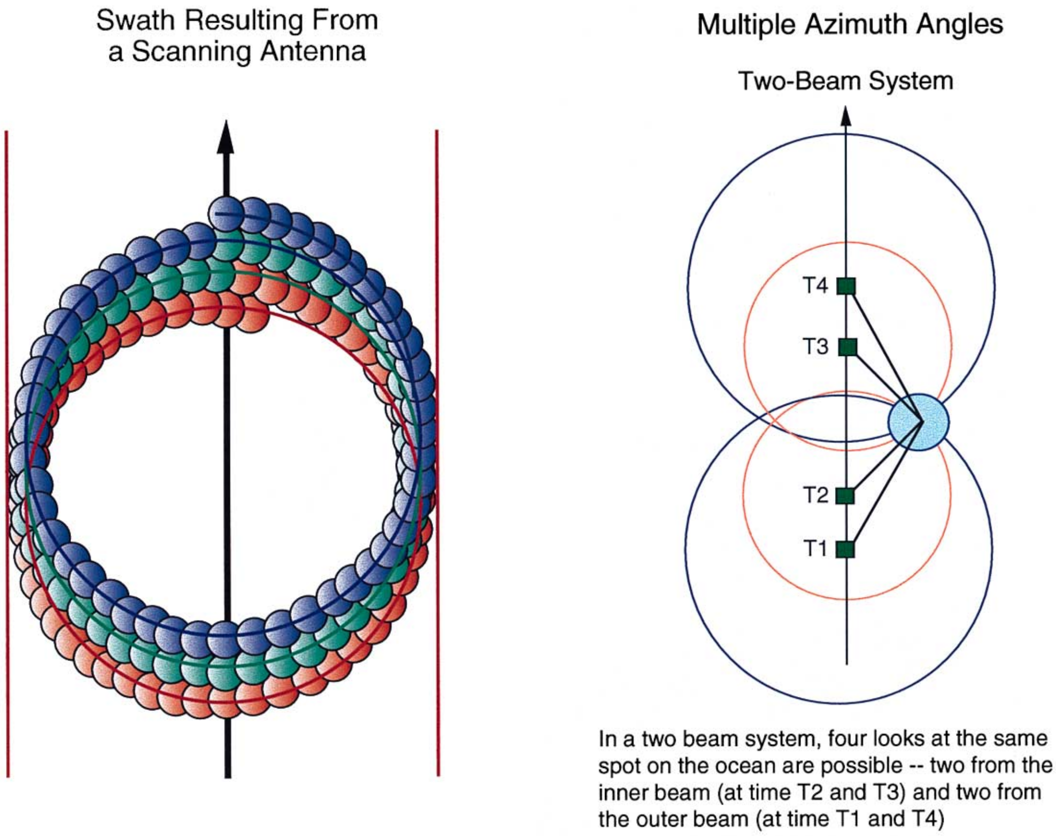

Fig. 10. Ground geometry created by the SeaWinds antenna patterns.

the science and engineering telemetry for downlinking. The SES contains the transmitter chain, including a coupled-cavity 110 W traveling wave tube and the receiver chain, and also digitizes the RF signal before transmitting it to the CDS.

The SAS contains an antenna dish of about 1.1 m in diameter; two separate feeds producing two slightly elliptical microwave beams; electronic controls; and the spin actuator. A rotary waveguide coupler is 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° with respect to nadir. At the planned orbit height of 803 km, the incidence angles of the beams are about 46 and 54°, respectively. The beams are electrically polarized in the horizontal (perpendicular to the incidence plane) for the inner, or 40° beam, and in the vertical for the outer, or 46° beam. Reference [6] describes in greater detail the SeaWinds design.

The antenna beamwidth will produce a two-way antenna footprint on the Earth's surface of approximately 25×35 km. This footprint pattern defines the basic surface resolution cell dimension for measuring the radar backscattering coefficient, σ_o. The σ_os are combined on the ground, as in the NSCAT processing, to achieve 50×50 km wind vector cells. The radius of the helical circles formed on the surface by the two scanning beams are 700 km and 900 km, respectively. Figure 10 depicts the ground geometry created by the SeaWinds antenna FOV.

The SeaWinds scatterometer will cover more than 90% of the Earth's surface in only 1 day. However, the SeaWinds viewing geometry results in three distinct regions in the instrument swath of differing wind vector quality based on present ambiguity removal techniques. The middle region of the swath satisfies the science requirements and is comparable in size to the NSCAT coverage. The 2 beam arrangement allows each spot in the primary radar mapping swath to be viewed from up to four azimuth look directions.

With looks separated by approximately 180°, the innermost region has relatively poor azimuthal diversity and, consequently, requires new ambiguity removal techniques to satisfy the directional accuracy. The outermost region has coverage from only one beam, has little angular separation between measurements, and also has poor azimuthal diversity. Consequently, it also requires new ambiguity removal schemes. Studies by the SeaWinds science team members are presently underway and show promise in removing the directional ambiguities and may make data from the entire SeaWinds swath satisfy the science requirements.

9. SUMMARY

The NSCAT instrument is presently in orbit and returning high quality data†. The SeaWinds instrument is under full-scale development and is planned for launch so as to generate a continuous time-series of scatterometer extending over 6 or more years. The scatterometer products are actively being used by the research, operational and commercial communities.

Acknowledgements—The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. The authors would like to thank Chialin Wu for help with the SeaWinds description, Steve Gunter for review assistance, and Janis Taylor for manuscript preparation.

REFERENCES

1. O'Brien, J. J. *et al.*, *Scientific Opportunities Using Satellite Wind Stress Measurements Over the Ocean*, N.Y.I.T. Press, Fort Lauderdale, FL, 1982.
2. NASA Scatterometer Mission Requirements, JPL, D-2676, Rev A, July 1998 (Internal document).
3. Wentz, F. J. *et al.*, *Journal of Geophysical Research*, 1984, **89,** 3689–3704.
4. Jones, L. *et al.*, *Journal of Geophysical Research*, 1982, **89,** 3297–3317.
5. Nadesi, F., Freilich, M. and Long, D., *IEEE Proceedings of the IEEE*, 1991, **79,** 850–866.
6. Wu, C. *et al.*, Proceedings of the International Geoscience and Remote Sensing Symposium, Pasadena, CA, August 8–12, 1994.

†On 30 June 1997 the ADEOS spacecraft failed and the data stream from the NSCAT instrument ceased. The launch of the ADEOS II spacecraft was delayed until fall 2000. To restart the data stream as quickly as possible, a new mission, called the Quick Scatterometer Mission (Quick SCAT) is planned for a launch in the fall of 1998. Quick SCAT will fly a SeaWinds-type scatterometer.