AN ENHANCED RESOLUTION SPACEBORNE SCATTEROMETER

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ABSTRACT

Spaceborne wind scatterometers are designed principally to measure radar backscatter from the ocean's surface for the determination of the near-surface wind direction and speed. Although measurements of the radar backscatter are made over land, application of these measurements has been limited primarily to the calibration of the instrument due to their low resolution (typically 50 km). However, a recently developed resolution enhancement technique can be applied to the measurements to produced medium-scale radar backscatter images of the earth's surface. Such images have proven useful in the study of tropical vegetation[3] as well as glacial[5] and sea[6] ice.

The technique has been successfully applied[2] to Seasat scatterometer (SASS) data to achieve image resolution as fine as 3-4 km. The method can also be applied to ERS-l scatterometer data. Unfortunately, the instrument processing method employed by SASS limits the ultimate resolution which can be obtained with the method. To achieve the desired measurement overlap, multiple satellite passes are required. However, with minor modifications to future Doppler scatterometer systems (such as the NASA scatterometer [NSCAT] and its follow-on EoS-era scatterometer NEXSCAT) imaging resolutions down to 1-2 km for land/ice and 5-10 km for wind measurement may be achieved on a single pass with a moderate increase in downlink bandwidth (from 3.1 kbps to 750 kbps). This paper describes these modifications and briefly describes some of the applications of this medium-scale *Ku*-band imagery for vegetation studies, hydrology, sea ice mapping, and the study of mesoscale winds.

1. INTRODUCTION

Spaceborne wind scatterometers are an important element in future remote sensing systems because of their proven ability to make all-weather measurements of vector winds over the ocean[4]. Wind scatterometry is an indirect technique in which the wind is inferred from measurements of the normalized radar backscatter coefficient (σ^o) using a geophysical model function. Current and planned scatterometer designs have σ^o measurement resolutions in the 25-50 km range which is sufficient for the study of oceanic winds but is generally too coarse for land and ice studies. Measurements over land have been primarily used for calibration of the instrument.

Recently, a new technique for generating enhanced radar images from low resolution scatterometer data has been developed[2]. This ground-based signal processing technique is based on an image reconstruction technique which utilizes the spatial overlap in independent scatterometer measurements. Applied to SASS, the resulting medium-scale images have proven remarkably useful in studies of tropical vegetation[3] and ice[5]. Thus, the technique enables more effectively use of the SASS data set as a historic measurement for studies of global change. The technique can also be used with ERS-l scatterometer data (however, since the ERS-1 scatterometer is not a Doppler scatterometer, the modifications described below are not applicable) and future scatterometers.

Since the amount of resolution enhancement is dependent on the spatial overlap of the scatterometer measurements, obtaining sufficient measurement overlap is crucial. While SASS measurements from the fore- and aft-facing antennas in a single orbit provide some measurement overlap, this overlap is insufficient to adequately apply the technique; hence, data from multiple orbits must be used. To do this, the target region must remain constant during the multiple passes (the "imaging time interval") required to obtain sufficient overlap. For SASS this required a minimum of several days to a few weeks to achieve 4-5 km resolution.

Future Doppler scatterometers, such as NSCAT and its EoS-era follow-on NEXSCAT, can, with minor modifications, provide resolutions as fine as 1-2 km in a *single pass* using the resolution enhancement technique. Thus, the technique can he used as an inexpensive "technique of opportunity" to augment the capabilities of existing and planned instruments. In particular, the wide-area, frequent coverage of the enhanced scatterometer data is particularly well suited for large-scale monitoring. In particular, the enhanced resolution scatterometer data can he used to extend the results of focused studies, possibly made in conjunction with high resolution sensors, to much larger (continental) areas. The high absolute accuracy of the scatterometer measurements and their wide incidence angle diversity can be a significant advantage for geophysical modeling studies. Further, this capability is available at little additional cost for planned missions.

In this paper, modifications to future, planned Doppler scatterometer systems of the NSCAT-class to enable resolution enhancement to as fine as 1-2 km are described along with possible applications of the enhanced resolution data. The resolution enhancement algorithm is described in detail in *Long, Hardin and Whiting* (1993)[2]. The paper is organized as follows: First, background in Doppler scatterometry is provided. This is followed by a description of modifications to an NSCAT-class Doppler scatterometer to provide higher-resolution measurements with increased spatial overlap. Then, a description of possible applications of the enhanced resolution images is provided. Finally, a summary conclusion is provided.

2. DOPPLER SCATTEROMETRY

In this section we briefly review the NSCAT σ^o measurement scheme. NSCAT is a Doppler scatterometer scheduled to fly in 1996 aboard the Japanese Advanced Earth Observing System (ADEOS) spacecraft[4]. NSCAT will use multiple antennas to make σ^o measurements at different azimuth angles. A diagram of the NSCAT antenna illumination pattern is illustrated in Fig.1. For each orbit, these antennas will provide a 600 km wide measurement swath on each side of the spacecraft nadir track. Each antenna illumination pattern is resolved into smaller resolution cells by means of timing and Doppler filtering as discussed below. The fore- and aft-facing antennas use vertical polarization while the center antennas are dual-polarized. Thus, there are 6 antennas but 8 antenna beams.

2.1 Measurement Resolution

NSCAT achieves along-track resolution by a combination of a narrow antenna pattern and the timing of transmit pulses[1,4]. Cross-track resolution is obtained by Doppler filtering, the narrow beam pattern, and the antenna illumination pattern azimuth angle geometry.

2.1.1 Along-Beam Resolution. Doppler filtering was used to achieve along-beam resolution for SASS and is planned for future U.S. scatterometers (ERS-l uses a different technique known as range-gaging). Doppler filtering 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. This difference in Doppler shift can be exploited to filter the returned echo into cross-track (along-beam) resolution elements or "cells."

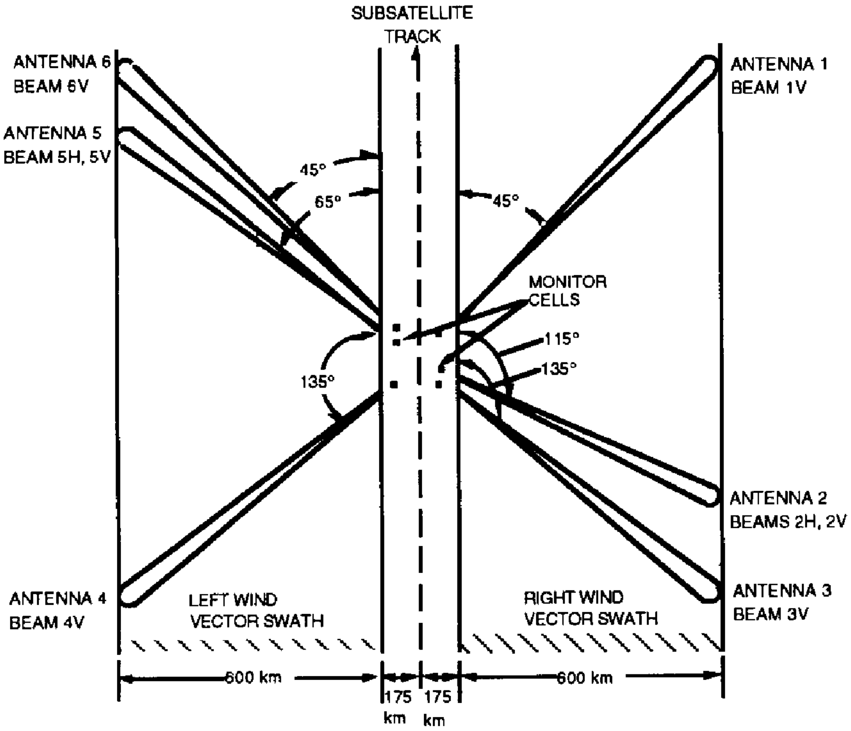

Figure 1: Illustration of the NSCAT antenna illumination pattern.

While its predecessor, SASS, used fixed-frequency analog filters for Doppler processing NSCAT will use a sophisticated digital Doppler processor (DDP)[1]. In the NSCAT DDP (see Fig. 2), the return echo is split into four processing channels of differing bandwidth. The power spectrum of each channel is then computed via a 512 point windowed-FFT. Then, in a process termed "binning", the periodogram bins corresponding to the Doppler shift of the desired 25 km resolution element are integrated to provide each signal+noise measurement[1]. This binning is repeated separately for the signal+noise and noise-only measurements and for each antenna beam. By adjusting the number (bandwidth) and location (center frequency) of each cell integration as a function of the orbit location the NSCAT DDP can insure that the resolution cells remain located at the desired cross-track positions throughout the orbit[1,4].

2.1.2 Along-Track Resolution. Measurement timing is used to achieve along-track resolution such that the centers of cells measured by each antenna beam are spaced a nominal 25 km apart in the along-track direction. The desired spacing is achieved by making measurements for each antenna beam once every 3.74 seconds, the time it takes for the subsatellite point to move 25 km[1]. Approximately 468 milliseconds are used to make a σ^o measurement for a given beam (see Fig. 3). during this interval multiple transmit pulses are issued and received for each beam in sequence.

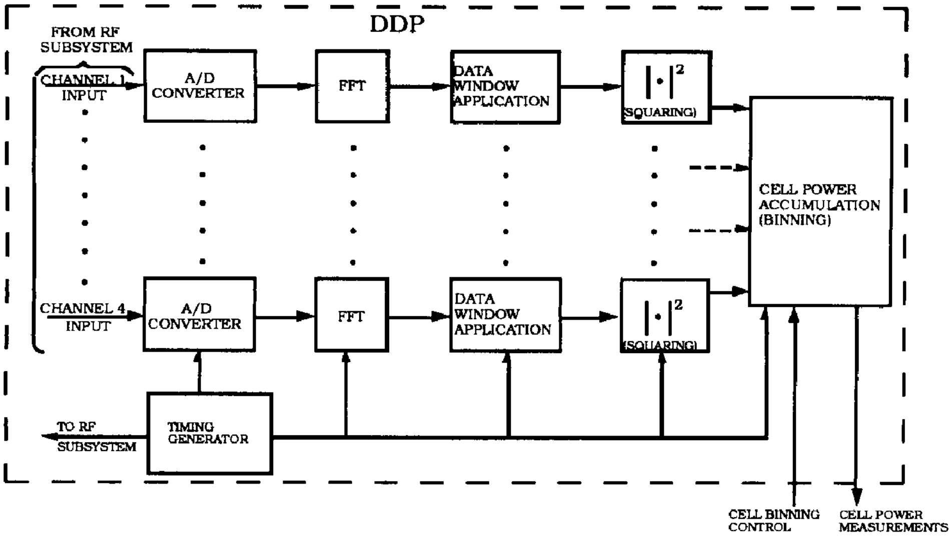

Figure 2: simplified block diagram of the NSCAT DDP.

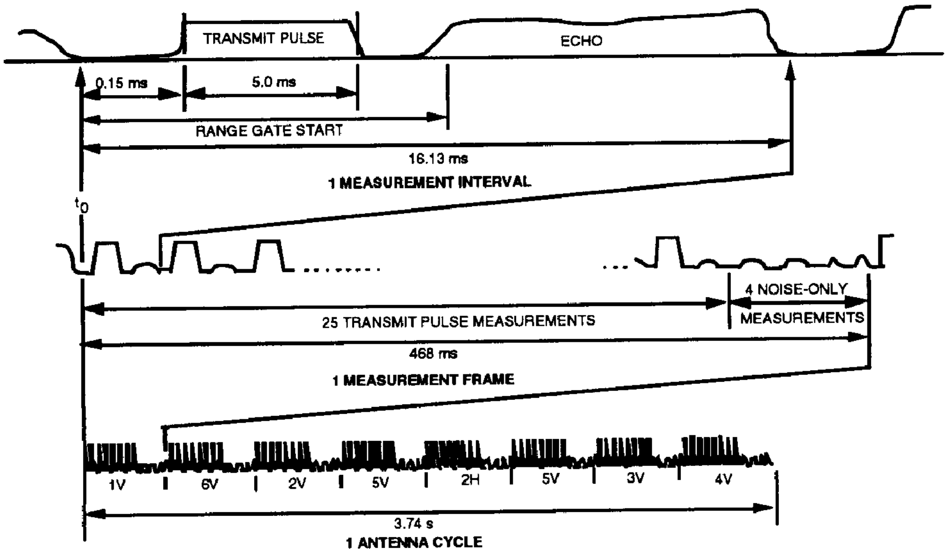

Figure 3: NSCAT timing diagram and measurement sequence.

2.2 Measurement Cell Geometry

The intersection of the Doppler filter bandwidth and the narrow antenna gain pattern define the instantaneous cell resolution for a single pulse (see Fig. 4). As previously noted, multiple echoes are summed into a single integrated σ^o measurement. Since the spacecraft is moving during these measurements, the integrated measurement cell resolution is (approximately) a six-sided polygon as illustrated in Fig. 4.

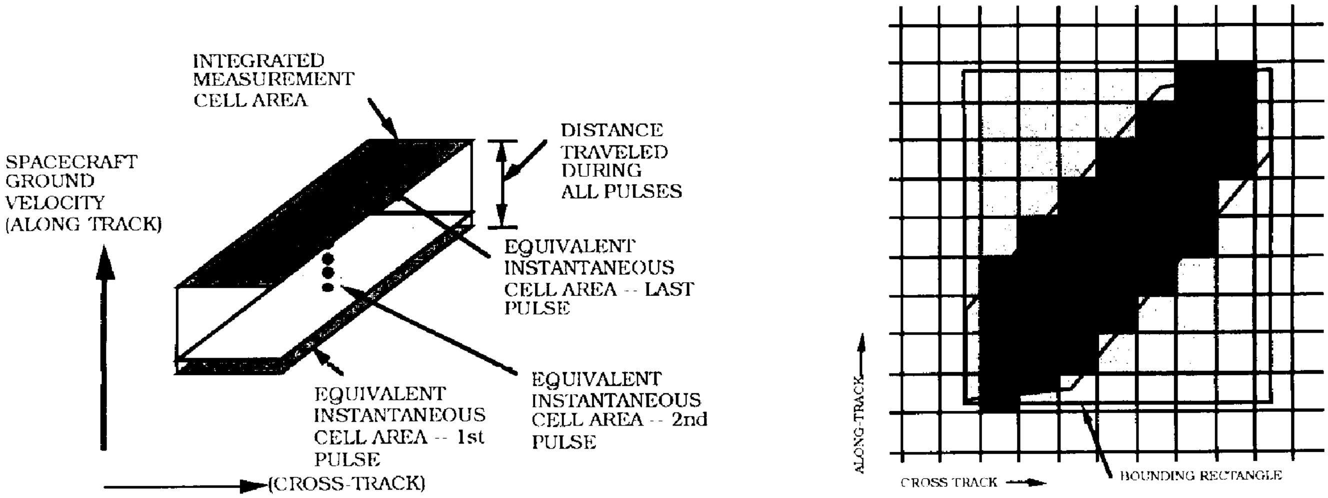

Figure 4: σ^o measurement layout cell. a) Integrated b) On enhanced resolution grid.

For NSCAT (and SASS) there is no overlap in the σ^o cells from a single beam in a single spacecraft pass, though there is overlap between the fore-facing, center, and aft-facing beams. This overlap, in which the same region of the ocean's surface is observed at several different azimuth angles (and two polarizations) is used to estimate the wind at the overlap point. This overlap, however, is insufficient to directly apply the resolution enhancement technique. However, every few orbits, the spacecraft passes over the same region again on either a north-bound (ascending) or a south-bound (descending) ground track. This produces criss-cross measurement swaths with multiple overlapping measurements. The overlap is exploited to enhance the effective resolution by assuming the target does not change between orbit passes.

2.3 NSCAT Downlink Telemetry

For each antenna cycle (468 ms) NSCAT generates a frame of telemetry data. Each 1728 bit frame contains of 896 bits of science data with the remainder being engineering data. An 8-bit A/D converter in the DDP digitizes the radar signal from the radio frequency (RF) subsystem while the FFT is computed using 16 bit arithmetic. A 28 bit accumulator is used to prevent overflow in the power accumulation binning. Then, to minimize the science telemetry data volume while maintaining dynamic range, the 28 bit accumulator is coded into a 16 bit pseudo-floating point value with a 12 bit mantissa and a 4 bit exponent. A total of 26 cell signal+noise power measurements and 26 noise-only power measurements are included in each downlink telemetry frame. Four channel noise-only power measurements are also included[1]. The engineering telemetry contains status information, temperature and voltage measurements, and measurements of the transmitter power. These are required to convert the power measurements made by the instrument to σ^o measurements and to monitor the instrument health.

3. MODIFICATIONS TO FUTURE SCATTEROMETERS

The resolution enhancement method provides estimates of the radar backscatter characteristics on a rectilinear grid. For example Fig. 4b illustrates a six-sided σ^o cell imposed on this small-scale grid of high-resolution elements. Assuming a noise-free measurement, the value of σ^o observed by the scatterometer will be a weighted average of the σ^o's of the individual high-resolution elements covered by the measurement. Noting this, a matrix equation relating the observed σ^o measurements and the σ^o values of a high-resolution grid can be formulated. This equation can then be iteratively solved using a modified algebraic reconstruction technique and involves a tradeoff between resolution and image noise which is considered fully in[2] .

The resolution enhancement algorithm is based on measurement cell overlap. For SASS (or an unmodified NSCAT), overlap is obtained by combining multiple orbits over an extended period of time. Increasing the number of orbits combined results in improved resolution and reduced estimate noise. However, the target's radar characteristics must remain constant over the data acquisition interval. This represents a serious limitation for rapidly changing regions such as polar ice.

For future Doppler scatterometers such as NSCAT and its follow-ons, additional resolution ehancement can be obtained by modifying the measurement sequence. This permits high-resolution imaging with only a single spacecraft pass, relaxing the target constancy requirement. The required instrument modifications are relatively minor and affect only the digital subsystem (DSS). The modifications consist of 1) changing the beam sequence timing and 2) downlinking the periodogram data. These increase the data rate from 3.1 kbps to approximately 700 kbps but does not affect the wind measurement capability. If desired, the higher-rate data need only be collected over land and ice.

3.1 Instrument Modifications

The NSCAT DDP processes each of its four return channels into many periodogram "bins" (effectively very narrow bandpass filters). Individually, these bins constitute a very high resolution measurement. When the bins are integrated ("binned") into the cell power measurement, this additional resolution information is, in effect, discarded. Binning reduces the downlink data rate because only the accumulated powers for each of the 25 resolution cells per beam are downlinked to the ground rather than all the periodogram bins. While the periodogram bin frequency resolution (i.e., Doppler bandwidth) is different for each channel, each periodogram bin bandwidth corresponds to approximately 2.5-3.5 km along-beam distance on the ground (refer to Fig. 5). The narrow antenna illumination pattern which defines the cross-beam resolution varies from approximately 7 km at the near swath to approximately 15 km at the far swath. Thus, for a single transmit pulse each periodogram bin corresponds to a four-sided "resolution area" on the ground which is 2.5-3.5 km along-track by 9-25 km cross-track (see Fig. 5).

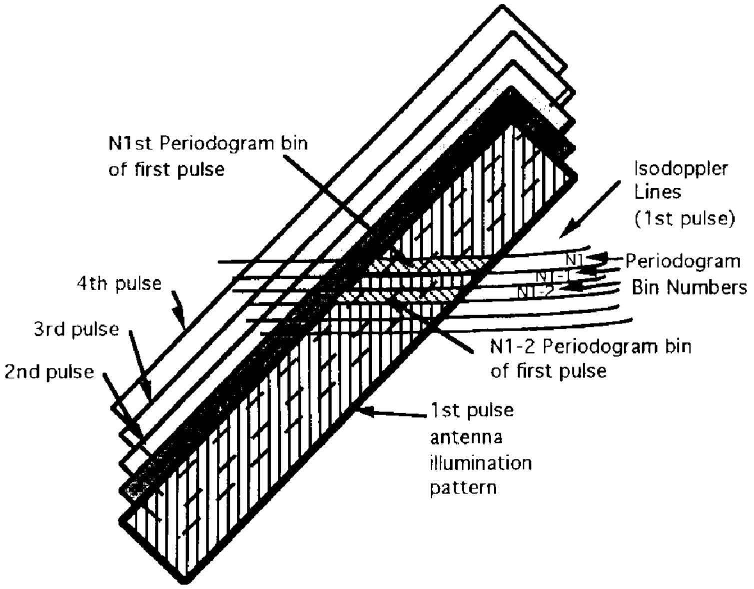

Figure 5: Diagram illustrating the σ^o measurement scheme of the proposed modifications for an NSCAT-class scatterometer (see text).

In the baseline NSCAT timing, twenty-five consecutive transmit pulse/receive cycles (468 ms) constitute the signal+noise measurement for a given beam. This is followed by four additional noise-only "pulses" to obtain the noise-only measurement for that beam. This beam cycle is repeated for each beam in sequence before returning to the first beam. While the spacecraft moves ~ 25 km between the measurements on a single beam, it only moves approximately 110 m between individual pulses.

To improve the distribution of the along-track overlap of the periodogram "resolution areas," the transmit timing can be modified to interleave the transmit/receive cycles among the different beams. In the modified scheme, one transmit/receive pulse cycle from each beam is made (cycling through all eight beams in sequence) before returning to the same beam. Then, between the individual transmit pulses on a given beam, the spacecraft will have moved approximately 860 m (refer to Fig. 5). Hence, the "resolution areas" of the periodogram bins will be on 860 m along-track centers. Since they are 2.5-3.5 km wide in the along-track direction they have significant overlap in the along-track dimension. They will have a similar amount of overlap in the cross-track dimension where they are 10-25 km long.

To further improve the resolution for imaging over land/ice, the antenna beam sequence can be changed so that only a single beam is used. In this case, the along-track spacing between periodogram bins is reduced to approximately 110 m, resulting in more measurements with more overlap between the measurements and, hence, improved ultimate resolution. This can not be done for wind measurement over the ocean, since multiple azimuthal measurements of σ^o are required to retrieve the wind. With the modifications described above the ultimate resolution of the scatterometer with the ground processing is estimated to be approximately 1-2 km over land/ice (single beam operation) and 5-10 km over the ocean (multiple beam operation).

3.2 Telemetry Modifications

These changes discussed above affect only the NSCAT digital subsystem (i.e., the timing and the downlink control). Even after modification, 25 km resolution-compatible measurements can still be made; however, we note that if the periodogram data is collected continuously, the onboard cell "binning" can be eliminated and can be performed more accurately on the ground.

A possible implementation of the proposed changes is to maintain the existing 3.2 kbps 25 km resolution interface and add a higher rate interface for the periodogram bin data. Since only unique the periodogram bins which are not affected by per-digitization filter rolloff, only approximately 180 bins of periodogram per channel need to be down1inked at 16 bits per periodogram bin. Thus, there are approximately 10 kbits per pulse to downlink (there are four channels). Since each pulse period is 16.13 ms, the downlink data rate is approximately 700 kbps not including frame synchronization bits. Approximately 14% of the "pulses" will, of course, be noise-only but are required to compute the σ^o of signal+noise measurements.

While this high rate data can be continuously collected, a "targets of opportunity" approach could be used instead. In this approach, the data is continuously generated by the instrument but is collected by the spacecraft only when commanded from the ground. This will minize the total downlink data volume. If desired, by scheduling the high-rate data transfer, the operational requirements can be minimized

4. APPLICATIONS OF ENHANCED SCATTEROMETER DATA

Although the best obtainable resolution with this method is significantly better than the intrinsic resolution of the scatterometer, it is only medium-scale and remains relatively coarse compared to such sensors as a synthetic aperture radar (SAR). However, the scatterometer provides a wider swath with more frequent global coverage. Thus, the enhanced resolution scatterometer images are well-suited for large-scale global monitoring to augment high resolution sensors. Based on preliminary studies[2,3,5,6], the medium-scale resolution scatterometer images have significant potential in many areas of geophysical research including vegetation, ice, and wind measurement.

4.1 Land Imaging

while *Ku*-band (14 GHz) radar signals have very little surface penetration, *Ku*-band σ^o is very sensitive to vegetation, surface water, and land surface type. In a recent paper[3] the utility of the scatterometer data for discriminating between broad vegetation groups was demonstrated. Given the very high accuracy of this classification, it may be possible to make precise areal measurements of the global tropical rainforest extent from SASS data taken in 1978. Such measurements can then be compared with measurements from NSCAT in 1995 to evaluate tropical deforestation. The greater resolution possible with suitably modified future scatterometers will permit more detailed studies. The frequent, broad-area coverage afforded by the scatterometer may also allow for daily vegetation and surface water monitoring as well as studies of diurnal variation of vegetation over large regions.

4.2 Ice Imaging

Recently, Long and Drinkwater[5] extensively studied the radar response of ice and snow for the Greenland ice sheet using SASS data and the resolution enhancement technique. Their results indicate that the enhanced resolution images can be used to map the ice facies in the Greenland ice sheet. The data may also be useful for mapping sea ice. A scatterometer with the proposed modifications would provide a good measurement platform for polar ice data since it provides 1) frequent coverage and 2) multiple incidence angle observations. From the latter it may be possible to infer ice-age as well as snow cover and ice motion. We are currently investigating the use of our technique for ice studies of Arctic and Antarctic sea ice[6]. Preliminary results dramatically illustrate the capability of the enhanced resolution scatterometer data to map sea ice.

4.3 High Resolution Wind Measurement

With some limitations the technique can also be applied to oceanic wind measurement. Because of the high variability of the ocean and the limited orbit sampling of the scatterometer, *global* measurement of high (better than 25 km) resolution winds may not be appropriate; however, "target of opportunity" diagnostic studies of interesting meteorological conditions can be used to improve local forecasts and for mesoscale studies of air/sea interaction with a resolution of 5-10 km.

5. CONCLUSION

Traditionally, spaceborne scatterometers have been low resolution radar instruments designed to measure winds over the ocean. Because of their low resolution, the scatterometer measurements made over land have been used primarily to calibrate the instrument. However, studies of scatterometer measurements over land have hinted at their sensitivity to vegetation and ice coverage. A new resolution enhancement method for obtaining enhanced resolution radar images from low resolution holds forth the promise of additional scatterometer applications. For traditional Doppler scatterometers, resolution enhancements of up to 10 times have been achieved (to 3-4 km). With relatively inexpensive modifications, future NSCAT-class scatterometers may achieve effective resolutions as fine as 1-2 km with a moderate increase in downlink telemetry bandwidth. Thus, the modified scatterometer can provide significant additional science return with only a limited budgetary impact. This relatively inexpensive enhancement of planned missions may yield significant contributions to future studies of global change.