High Resolution Scatterometry by Simultaneous Range/Doppler Discrimination

Michael W. Spencer and Wu-Yang Tsai
California Institute of Technology, Jet Propulsion Laboratory
MS 300-319, 4800 Oak Grove Dr., Pasadena CA 91109-8099
818-354-1175, mws@shiokaze.jpl.nasa.gov

David G. Long
Brigham Young University, Microwave Earth Remote Sensing Laboratory
459 CB, Provo, UT 84602

Abstract— Several spaceborne scatterometer missions have been successfully flown in the past decade. In addition to the primary mission of measuring ocean surface wind speed and direction, these measurements have proven useful in global scale climate studies of land and ice phenomena as well. A key shortcoming of the scatterometer in these measurements has been the rather coarse spatial resolution available. In this paper, the application of simultaneous range/Doppler discrimination (i.e., synthetic aperture) techniques are proposed as way of improving the single-pass resolution of conically scanning pencil-beam scatterometer systems. The unique challenges of applying the synthetic aperture approach to a conically scanning system are identified and addressed.

INTRODUCTION

A wind scatterometer is a radar instrument which measures the surface normalized backscatter cross section (σ^o) at multiple azimuth angles, with the primary objective of retrieving ocean surface wind speed and direction. Several scatterometer missions have been developed and flown in the last decade. These include scatterometer systems employing a multi-antenna "fan-beam" approach – which have included the C-Band Advanced Microwave Instrument (AMI) on the European ERS satellites, and the Ku-Band NASA Scatterometer (NSCAT) on the Japanese ADEOS-I mission – as well as those employing a single scanning "pencil-beam" approach – the NASA *SeaWinds* instrument on the *QuikSCAT* and ADEOS-II missions [2].

Scatterometer wind data has contributed significantly to the scientific study of air/sea interactions and global climate phenomena such as El Nino, as well as mesoscale phenomena such as tropical storms. In addition to ocean winds, scatterometer backscatter data is being applied to an expanding list of land and ice applications as well [1, 3]. One significant shortcoming of scatterometer data collected to date, however, has been the relatively low spatial resolution available. Current scatterometer systems have antenna beam limited resolutions of approximately 20 km [2], which is too coarse for many geophysical applications.

In previous studies, the inherent resolution limitations of scatterometers have at least been partially overcome by the application of various enhanced resolution algorithms applied as a post-processing step [1, 2]. With these techniques, multiple, overlapping σ^o measurements are used to solve for the underlying surface backscatter scene at higher resolution than allowed by the antenna-limited instantaneous backscatter measurements. A serious limitation of these "multi-pass" techniques is the fact that an assumption of scene temporal stationarity is required in order to combine multiple orbits of data to construct a higher resolution image. This assumption is clearly invalid for ocean wind measurements, and can be problematic for fast-varying land and ice events as well. It is therefore desirable to achieve high resolution with more direct and conventional "single pass" means – by sufficient sharpening of the antenna beam response on the surface for instantaneous backscatter measurements.

REAL-APERTURE AND SYNTHETIC APERTURE OPTIONS

In this analysis, we will focus on the pencil-beam scatterometer architecture where the antenna is scanned in a conical fashion to form the swath and to obtain the necessary azimuth measurements in order to perform wind retrieval [2]. This is illustrated in Figure 1a. Figures 1b and 1c illustrate the primary techniques for obtaining single-pass resolution: a real-apeture approach that employs range discrimination alone, and a synthetic aperture technique which employs both range and Doppler discrimination simultaneously. In the real-apeture case, the resolution in the azimuth dimension is governed by the azimuthal width of the antenna footprint on the ground. The resolution in the elevation dimension is achieved by range processing short or chirped pulses. Because the elevation dimension, given sufficient system bandwidth and signal-to-noise, can be processed to arbitrarily high resolution, the instantaneous resolution is primarily limited by the antenna azimuth beamwidth.

The work reported here was performed at the Jet Propulsion Laboratory, California Institute of Technology under contract with the National Aeronautics and Space Administration.

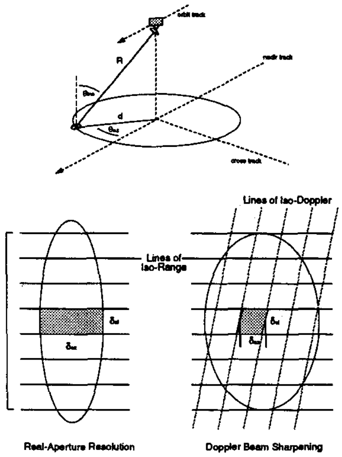

Figure 1: *Resolution methods for real aperture and Doppler sharpening systems.* x_{el} *is the elevation width of the antenna footprint, and* δ_{el} *and* δ_{az} *are the range and azimuth resolution of the* σ^0 *cell respectively.*

The limitations of the of the range-only approach are apparent when we consider the antenna size required to obtain higher resolution. To achieve an instantaneous azimuth resolution of 1 km, for instance, a rotating antenna operating at Ku-Band and at the *SeaWinds* scan geometry would have to be over 15 meters long, and would clearly be a spacecraft accommodation challenge. The application of synthetic aperture radar techniques, which allow resolution in Doppler as well as in range, are a well known remedy to the limitations of the real-aperture approach.

SYNTHETIC APERTURE TECHNIQUES

At the most fundamental level, synthetic aperture techniques achieve resolution by transmitting a periodic pulse train and then applying a correlation operation to the echo return to extract the surface response from a specific point in range/Doppler space. This same general approach is applicable to the pencil-beam scatterometer case, but there are two significant differences from traditional SAR systems that arise from the conically scanning geometry. First, with the pencil-beam system, the azimuth angle of the measurement is continuously changing. From a SAR perspective, this is equivalent to the squint angle varying over the swath, and will produce a distortion of the resolution cell shape. A second major difference is the fact that the scanned footprint of the pencil-beam case is moving much faster over the surface of the Earth than the traditional SAR case where the footprint simply moves at the speed of the spacecraft. This dramatically reducing the dwell time of the footprint on the target area and consequently places significant limits on the azimuth resolution that can be achieved. The implications of these unique aspects are discussed in turn.

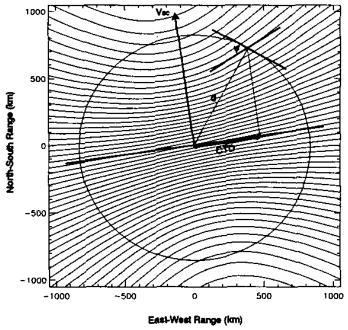

Figure 2: *Lines of iso-Doppler for 800 km sun-synchronous orbit at ascending equator crossing. Line spacing is 20 kHz. Also shown is 1200 km iso-range line corresponding to scan at off-nadir angle of* 45°.

Continuously Varying Squint

The effects of the continuously varying squint associated with the pencil-beam system are illustrated in Fig. 2. Shown are the hyperbolic iso-Doppler lines on the Earth's surface, calculated for an 800 km altitude, sun-synchronous orbit near the ascending equator crossing. Also shown is the line of iso-range corresponding to the antenna boresight. When simultaneous range and Doppler processing is employed, the resolution cell is delineated by the iso-Doppler and iso-range lines projected on the surface, where the spacing between the lines is the achievable Doppler or range resolution respectively. Note that when the antenna is scanned to the side-looking location, the angle formed between the iso-Doppler and iso-range lines, ψ, is 90°. As the beam is scanned (or squinted) away from the side-looking direction, ψ decreases and the Doppler and range contours ultimately become parallel towards the forward or aft directions. As the contours change from perpendicular to parallel, the shape of the resolution cell is elongated by a factor of $\frac{1}{\cos\psi}$ in the azimuth dimension. Note also that as θ_{az} approaches the forward or aft case, the iso-Doppler lines become spaced farther apart, also elongating the measurement cell relative to the cross-track case. We term the combined effects of the angular and Doppler spacing effect "squint elongation." Squint elongation is the degree which the azimuth resolution is degraded as the beam is scanned away from the side-looking case. The significance here is that, unlike the traditional SAR or real-aperture case where azimuth resolution is essentially unrelated to the location of the measurement within the swath, the achievable azimuth resolution for the synthetic aperture pencil-beam case is highly dependent on cross-track position.

Available Dwell Time

A pulsed radar echo return signal, filtered for scatterers with specific range and Doppler, has associated with it ambiguous returns from elsewhere in range/Doppler space.

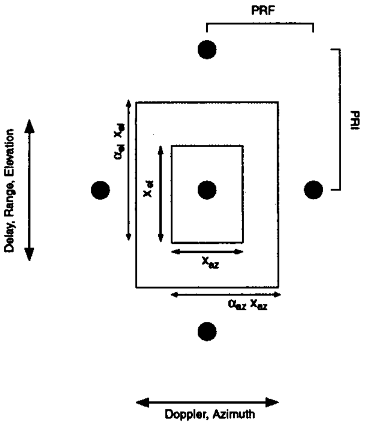

Figure 3: *Spatial ambiguity diagram. Dark spots represent Doppler/range ambiguities for side-looking case. Concentric squares represent antenna pattern with shaded region as the ambiguity "keep out" zone and the center "clear" region.*

To isolate only the returned energy from the desired point, the antenna pattern roll-off is used to suppress energy from the ambiguous regions. The situation is conceptually illustrated for the side-looking case in Fig. 3. Here the black dots represent the location of the desired resolution cell (center), as well as the location of ambiguous returns in range/Doppler space. The ambiguities are spaced at intervals of the PRF in Doppler and the PRI (pulse repetition interval) in the delay or range dimension. The concentric squares are an idealized representation of the two-way antenna pattern projected on the surface. The small inner square of dimension $x_{az} \times x_{el}$ represents the ambiguity "clear" region of the footprint – meaning scatterers on the surface may be unambiguously resolved only while they dwell within this clear region. The outer square of dimension $\alpha_{az}x_{az} \times \alpha_{el}x_{el}$ is the ambiguity "keep-out" region, where the α's are greater than one and are termed "keep-out factors." As with traditional SAR design, there is a trade-off between the PRF and the available values of x_{az} and x_{el}.

For the simultaneous range/Doppler case, the fundamental limit on azimuth resolution is determined by the target "dwell" time – i.e., the length of time a given scatterer is observed. The relationship between the Doppler resolution, δ_{dop} and the dwell time, τ_{dwell}, is $\delta_{dop} = \frac{1}{\tau_{dwell}}$. Employing well known approximations to calculate Doppler shift we obtain an expression for the achievable azimuth resolution, δ_{az}, to be

$$\delta_{az} = \frac{R\lambda}{2v_{sc}\tau_{dwell}} f(\theta_{az}) \qquad (1)$$

where the factor $f(\theta_{az})$ is the azimuth elongation factor due to squint effects as discussed previously.

The maximum available dwell time is the total time that a given scatterer resides in the azimuth width of the ambiguity clear footprint, or $\frac{x_{az}}{\gamma}$, where γ is the speed of the footprint moving over the ground. In the traditional SAR case the footprint speed over the ground is simply given by v_{sc}. In the scanning pencil-beam case γ is constrained to be

$$\gamma \geq \frac{2\pi d v_{sc}}{N_b x_{el}}, \qquad (2)$$

where N_b is the number of independent elevation beams employed. Because, for a reasonable value for N_b, we have that $\gamma \gg v_{sc}$, the dwell times for the scanning scatterometer case are much shorter and the achievable azimuth resolution is much coarser. This may be viewed as the price paid to obtain such a wide swath.

DESIGN EXAMPLE AND CONCLUSIONS

Employing the above considerations discussed above with traditional SAR theory, a concept analysis study was performed to explore how the *SeaWinds* scatterometer architecture could be modified to perform simultaneous range and Doppler resolution improvement. After expanding the antenna to 2 m diameter from 1 m diameter to allow sufficient suppression of ambiguities, the theoretical limit on azimuth resolution via (1) was determined to be 0.5 km for the sidelooking case at the outermost edge of the swath. According to Fig 2, this resolution would then degrade to about 1 km at mid-swath, and then to about 4 km within 200 km of the nadir track. Despite the degradation in resolution near nadir, there are two 400 km wide swaths on either side of the ground track where better than 1 km resolution is obtained. Such a system has the potential to significantly extend the utility of scatterometer measurements to applications which require higher resolution.

REFERENCES

[1] D.G. Long and M.R. Drinkwater, "Cryosphere Studies Using NSCAT Data," *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 37, No. 3, pp. 1671-1684, May 1999.

[2] M.W. Spencer, C. Wu, and D.G. Long, "Improved Resolution Backscatter Measurements with the *SeaWinds* Pencil-Beam Scatterometer," *IEEE Trans. Geosci. Remote Sensing*, Vol. 38, No. 1, pp. 89-104, Jan 2000.

[3] V. Wisman, "Land Surface Monitoring with Spaceborne Scatterometers" *Proceeding of the ESA Workshop on Emerging Scatterometer Applications*, Noordwijk, The Netherlands, 5-7 October, 1998.