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Measuring Directional Wave Spectra and Wind Speed with a Scanning Radar Altimeter

E. J. Walsh[1], D. Vandemark, C. W. Wright
NASA Goddard Space Flight Center, Code 972
Laboratory for Hydrospheric Processes
Wallops Flight Facility, Wallops Island, VA 23337, USA
303-497-6357, fax 303-497-6181, walsh@osb.wff.nasa.gov
[1]presently on assignment at NOAA Environmental Technology Laboratory, Boulder, Colorado

R. N. Swift, J. F. Scott, D. E. Hines
EG&G Services, Inc.
N159, Wallops Flight Facility
Wallops Island, VA 23337, USA
757-824-1019, fax 757-824-1036, swift@osb.wff.nasa.gov

Fig. 1 shows the geometry for the NASA Scanning Radar Altimeter (SRA). It transmits a 8-ns duration pulse at Ka-band (8.3 mm) and measures time of flight as it scans a 1° (two-way) beam from left to right across the aircraft ground track. The most recent configuration determines the surface elevation at 64 points spaced at uniform angular intervals of about 0.7° across a swath whose width is about 0.8 times the aircraft altitude. The system generates these raster lines of the surface topography beneath the aircraft at about a 10 Hz rate. In post-flight processing the SRA wave topographic data are transformed with a two-dimensional FFT and Doppler-corrected to produce directional wave spectra [1, 2].

The SRA is not absolutely calibrated in power, but by measuring the relative fall-off of backscatter with increasing incidence angle, the SRA can also determine the mean square slope (mss) of the sea surface, a surrogate for wind speed [3]. For the slope-dependent specular point model of radar sea surface scattering [4, 5, 6], an expression approximated by a geometric optics form, for the relative variation with incidence angle of the normalized backscatter radar cross section would be

$$\sigma^0_{rel} = \sec^4\theta \ \exp(-\tan^2\theta / mss) \qquad (1)$$

where θ is the off-nadir incidence angle.

If the logarithm of the range-corrected backscattered power is plotted against $\tan^2\theta$, the resulting curves approximate straight lines whose slope is inversely proportional to mss. But when a straight line is fitted through actual data, the resulting value of mss is dependent on the span of incidence angles used [3]. This problem can be eliminated by fitting a quadratic to the data. The ratio of the linear to the quadratic coefficient is found to be determined by the mss, so a general model for relating mss to the non-Gaussian variation of backscattered power with incidence angle can be determined. This model was used to determine the distortions expected in the SRA measurements of sea surface topography to be used in the computation of directional wave spectra.

The SRA had traditionally flown either upwave or downwave to acquire topographic data in the direction of most rapid variation. But during the 1998 hurricane season the SRA was installed on one of the NOAA P-3 hurricane hunter aircraft. The NOAA minimum height for the hurricane flights was 1500 m, significantly higher than the SRA had previously flown. And the flight patterns were such that the waves were generally propagating across the aircraft ground track rather that along it. The largest waves were generally observed near the edge of the swath during the hurricance flights.

A 3-dimensional simulation was carried out and it was determined that, even with a beamwidth as small as 1°, wave tilt modulation of the radar cross section within the antenna footprint can cause a significant, systematic increase in the apparent magnitude of wave components in the cross-track direction. The higher the altitude and the shorter the wavelength, the larger the effect.

Fig. 2 shows the geometry for a 1500 m aircraft height and ocean waves of 50 m length and 1.25 m height. The two top panels indicate the SRA 8-ns pulse approaching the sea surface

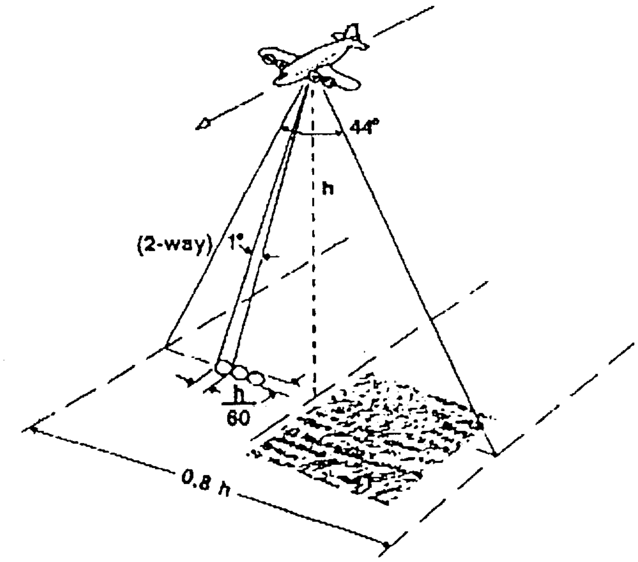

Fig. 1. NASA Scanning Radar Altimeter (SRA) geometry.

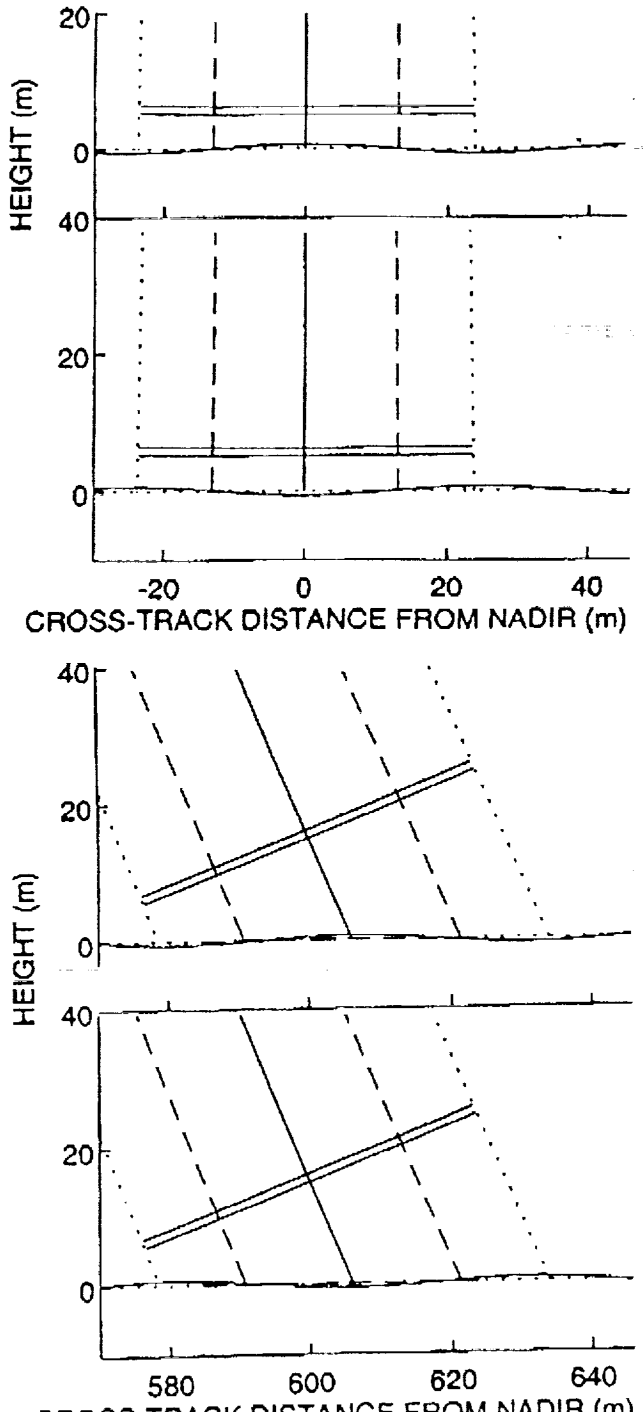

Fig. 2. SRA 8-ns pulse approaching sea surface from 1500 m height at nadir (top two panels) and 22° off-nadir (bottom two panels) for waves of 50 m wavelength and 1.25 m height propagating in the cross-track direction.

with the two-way half-power antenna beamwidth indicated by the dashed lines and the 0.1 power beamwith indicated by the dotted lines. The solid line indicates the boresight, with a wave crest at the boresight in the top panel and a wave trough in the second panel. Spatial filtering by the antenna footprint would be expected for waves this short.

In the bottom two panels of Fig. 2, the boresight incidence angle is 22° off-nadir, the nominal edge of the SRA swath. In this instance the simulation indicated that the measured wave height would actually be enhanced. The waves shown are propagating in the cross-track direction, and when the antenna boresight is at a crest (third panel), the near side of the crest backscatters more power because the incidence angle is smaller than for the far side of the crest. The centroid of the

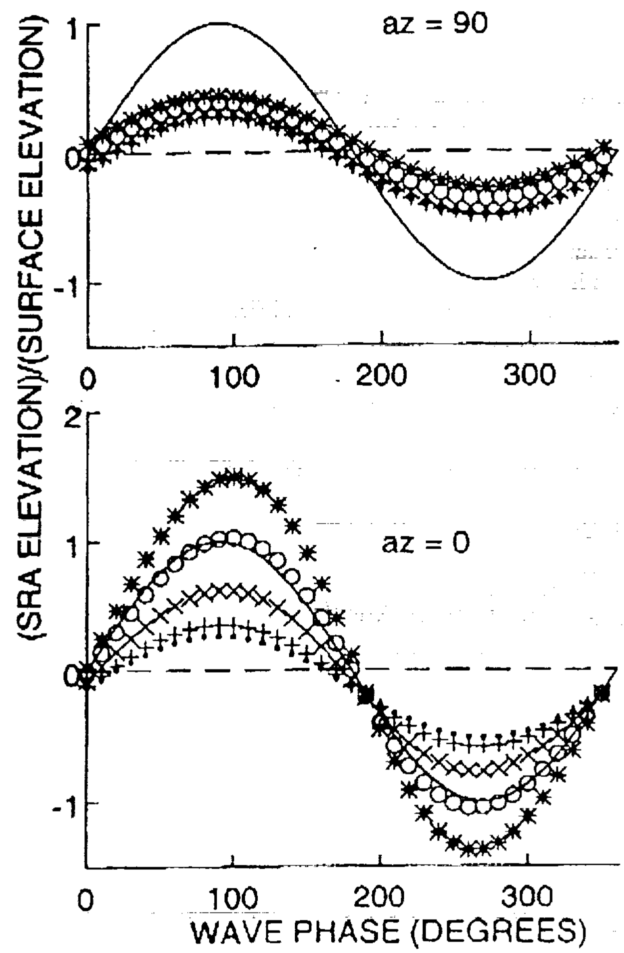

Fig. 3. Sea surface elevation measured by the SRA at nadir (.) and 4°(+), 8°(x), 12°(o), and 16°(*) off-nadir, normalized by the peak of the actual surface elevation for waves of 50 m length and 1.25 m height propagating in either the along-track direction (azimuth = 90°, top panel) or the cross-track direction (azimuth = 0°, bottom panel) for various phase angles of the wave train at the SRA antenna boresight. The assumed sea surface height variation is indicated by the solid sinusoidal curve, which has been normalized by its 0.625 m amplitude.

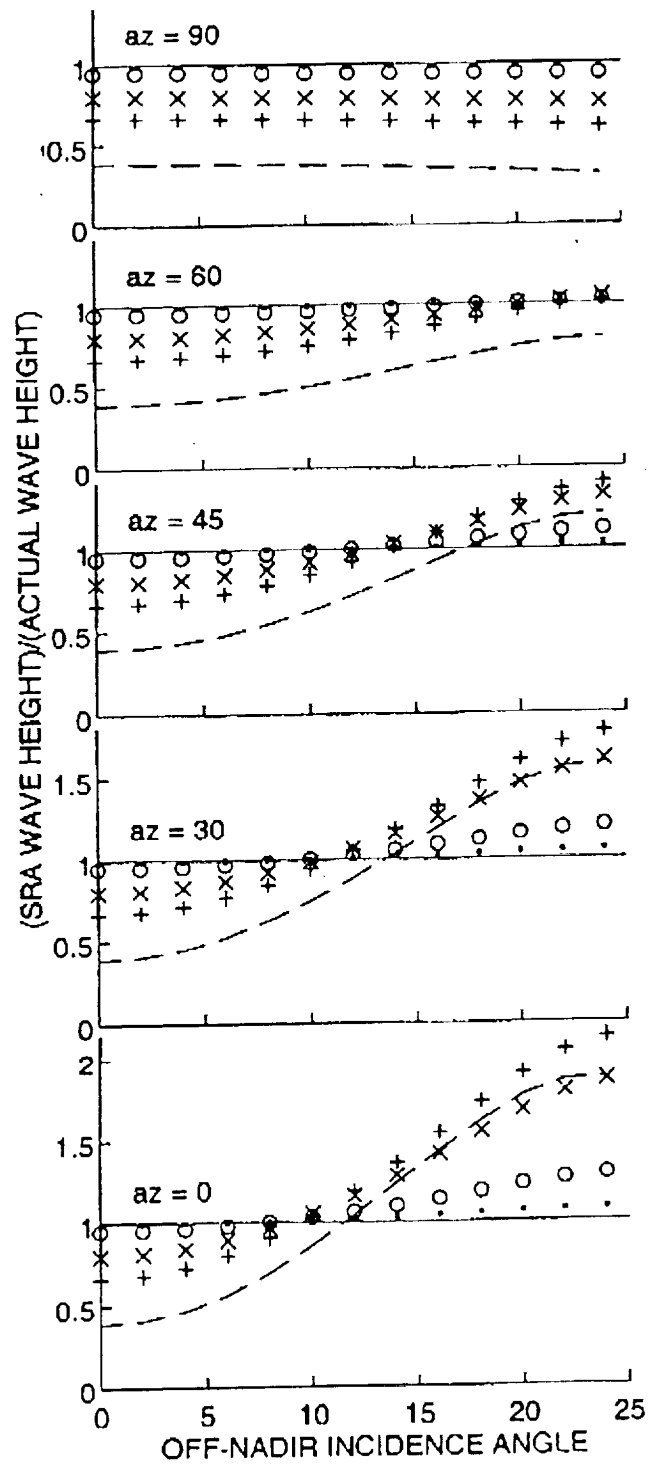

Fig. 4. Wave height measured by the SRA, normalized by the actual wave height, for various propagation directions of the wave train from along-track (azimuth = 90°, top panel) to cross-track (azimuth = 0°, bottom panel) for ocean wavelengths of 50 m (dashed), 75 m (+), 100 m (x), 200 m (o), and 400 m (.) for various incidence angles of the SRA antenna boresight.

backscattered power is biased to shorter range. The short range is ascribed to the boresight angle and the resulting calculated crest position is higher. The reverse occurs at wave troughs (Fig. 2, bottom), where the erroneously larger range, ascribed to the antenna boresight, makes the trough appear deeper.

Fig. 3 summarizes wave topography distortions for various phase angles of the ocean waves at the antenna boresight and various off-nadir angles for 50-m waves propagating in the along-track (top panel) and cross-track (bottom panel) directions. An mss of 0.08 was assumed, corresponding to ~25 m/s wind speed. The situation worsens at lower wind speed.

Fig. 4 summarizes (for mss = 0.08) the variation of the ratio of measured to actual wave height for various ocean wave lengths and azimuth propagation directions relative to the cross-track plane of incidence. All wave lengths are assumed to be 40 times the respective wave heights, for constant wave steepness approximately corresponding to full development.

At nadir, waves propagating in all directions have amplitudes reduced by the same amount. The reduction is over 60% for 50 m wavelength and negligible for 400 m wavelength.

For waves propagating in the cross-track direction, shorter waves are significantly enhanced at the edge of the swath. In general, the off-nadir incidence angle for the transition between wave amplitude reduction and enhancement depends on both the wavelength and the azimuthal direction of propagation.

Because the SRA simultaneously measures the backscattered power variation when it measures the wave topography, these distortions can be corrected in the directional wave spectra.

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