Assessment of ERS-1 SAR wind-speed estimates using an airborne altimeter

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Ocean-surface wind speeds that are estimated from SAR imagery could benefit both coastal meteorological and oceanographic research. However, ERS-1 SAR wind-speed estimation is not well validated due to the small number of collocated in-situ wind measurements. We present wind-speed measurements from airborne Ku-band altimeter flights under the ERS-1 SAR. Wind speeds were estimated from the altimeter data for direct comparison and assessment of those estimated from the SAR. The large comparison dataset shows that, within noted limitations, properly calibrated ERS-1 SAR data can provide valid wind-speed estimates. Such aircraft observations may be an effective approach for future SAR validation activities.

Introduction

Synthetic Aperture Radar (SAR) ocean imagery presents an opportunity to obtain high-resolution information related to ocean-surface winds, curents, bathymetry, biological activity, and oceanic precipitation. Virtually all SAR ocean studies require the wind-related impact on the image because to first-order, ocean SAR backscatter is caused by the wind-generated short waves. For example, interpretation of features such as current fronts, surface eddies, or internal waves must account for the possibility of the wind impacting the feature identification. More directly, accurate SAR wind retrieval is essential for the successful use of SAR as a high-resolution wind scatterometer. In this application, spatial wind information is derived from scales as small as 100 m, as compared to the much coarser 25-50 km cell size of satellite wind scatterometers.

The objective of this study is to assess wind-speed estimates from ERS-1 SAR backscatter. Similar studies have been done using *in-situ* observations of wind vectors [e.g. *Vachon & Dobson*, 1996; *Fetterer et al.*, 1998; *Wackerman et al.*, 1996]. These efforts demonstrated the feasibility of wind retrieval by examining imagery near moored meteorological buoys. However, inherent limitations of these studies include the limited number of comparison data points (< 30 in all cases), and that the image assessment is restricted to single point buoy sites preventing evaluation along and across the SAR swath.

Here we present an alternative ERS-1 SAR wind-speed validation dataset. Wind-speed data for comparison with SAR estimates are derived from aircraft altimeter measurements collected within the SAR scenes near the time of the satellite overpass. More than 2000 comparison data points are available with exact spatial co-registration and within one hour of overpass times.

Approach

Airborne altimeter data can provide wind speed estimates at continuous spatial scales comparable to those measured by the SAR. This approach offers several benefits over buoy winds:

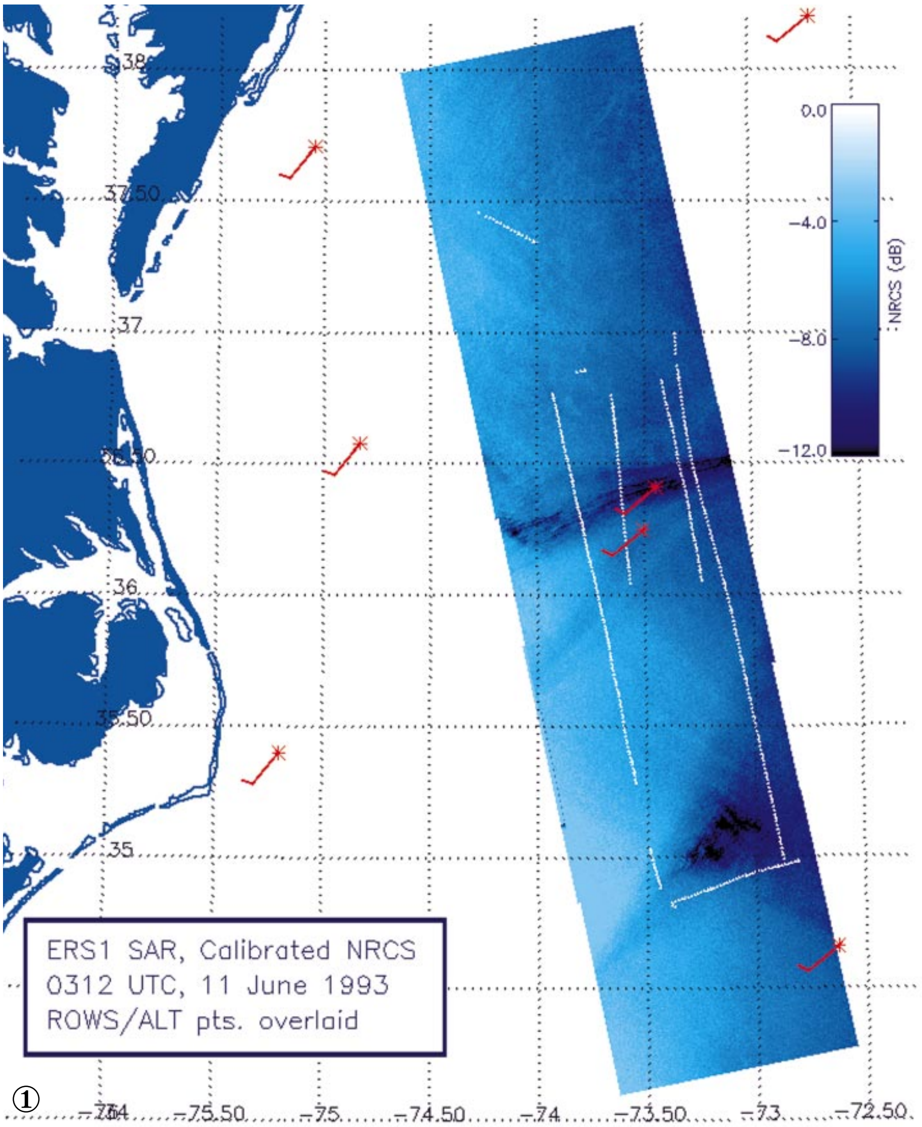
1) evaluation of SAR wind retrieval at a continuum of incidence angles across the swath (19.5 to 26.5° for ERS-1)
2) evaluation of SAR wind retrieval for several spatial resolutions (e.g. from 0.1 to 10 km)
3) a large comparison data population with exact spatial collocation
4) the ability to evaluate SAR wind retrieval in regions of operational or geophysical interest.

One limitation is that the SAR acquires its data in less than one minute; the time difference between the aircraft and SAR observations must be considered.

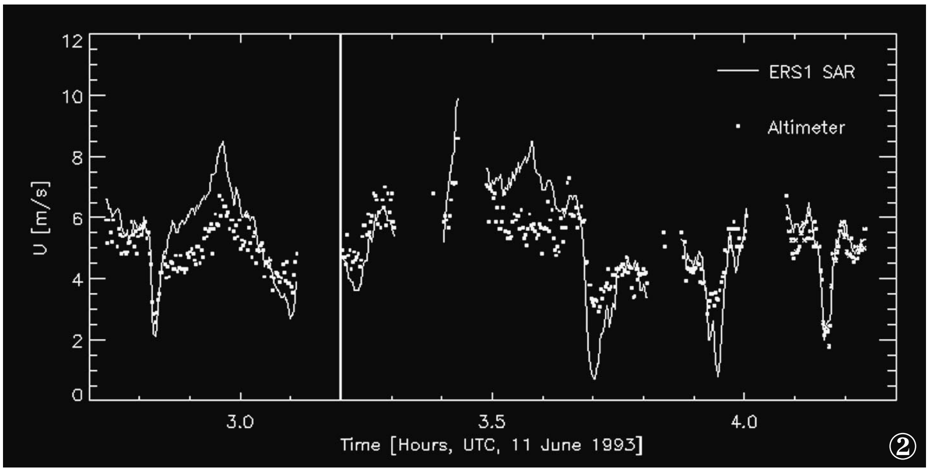
Aircraft altimeter and altimeter wind speed

The altimeter data were acquired by NASA's radar ocean wave spectrometer (ROWS). This airborne Ku-band radar provides interleaved ocean directional swell spectra and radar altimeter measurements [Vandemark *et al.*, 1994]. The ROWS is usually operated from altitudes above 7 km from a NASA Wallops Flight Facility P-3 or T-39 aircraft. From this altitude, the altimeter's surface footprint for near-surface wind speed estimation is of the order of 2 x 2 km. Altimeter estimates are provided at a nominal 2 km spacing along the aircraft flight track.

Derivation of wind speed from the ROWS altimeter is based on the measured decrease in radar backscatter with increasing incidence angle as the radar instantaneously samples the power returned from near-vertical incidence angles. This measurement may be directly related to the absolute value of vertical backscatter measured by satellite altimeters such as Topex/Poseidon. Hence, ROWS altimeter data is converted to a 10 m height wind-speed estimate using the operational satellite



Composite image made from five ERS-1 SAR frames acquired in the vicinity of the Gulf Stream during Hi-Res, 11 June 1993. Superimposed in white are the locations of ROWS altimeter wind-speed estimates. Note the significant imprint of the Gulf Stream from the north wall near 36.5° N and the south wall, 35.5° N to 34.5° N. The calibrated SAR imagery is in NRCS. The red wind barbs are in-situ measured wind vectors at the overpass time.



Time series of ROWS altimeter (symbols) wind speed for the aircraft flight tracks of Figure 1. The solid trace represents collocated wind speeds estimated from the ERS-1 SAR images. The solid vertical line marks the ERS-1 overpass time. The four significant wind-speed drops are associated with repeated crossings of the Gulf Stream's north wall.

wind-speed algorithm of Witter & Chelton (1991) and a well-validated ROWS altimeter to Topex conversion [Vandemark *et al.*, 1997; Jackson *et al.*, 1992]. The root-mean-square (rms) wind-speed difference between satellite or ROWS altimeter and *in situ* validation data is of the order of 1.8 m/s. However, an altimeter has limitations: it provides wind speed but not wind direction since its surface scattering measurement is omni-directional; furthermore, the wind speeds are a remote sensor inference, not surface truth.

For this study, we use ROWS altimeter data acquired under ERS-1 to provide comparison wind estimates. Figure 1 shows an example of aircraft data gathered within five contiguous ERS-1 SAR scenes. Airborne altimeter data were collected on three occasions during a SAR wave validation experiment on the Grand Banks of Newfoundland in November 1991 and on five occasions during the High-Resolution Remote Sensing (Hi-Res) experiment off Cape Hatteras in June 1993.

ERS-1 SAR wind speed retrieval

A SAR wind-speed estimate was made at each ROWS measurement location using ERS-1 images processed to resolution cell sizes of 200 and 2000 m, the latter matching the altimeter resolution. SAR wind retrieval requires calibrated normalised radar cross section (NRCS), the SAR geometry, and the wind direction. Our ERS-1 SAR data were processed to the ESA Precision Image (PRI) standard on a workstation-based SAR processor at CCRS. The calibration procedures involved compensation for analogue-to-digital converter (ADC) power loss based on a saturation analysis of the raw signal data, and use of a calibration constant derived from observations of calibration transponders over a time period of several years [*Vachon & Dobson*, 1996].

The wind speed was estimated from NRCS data using the CMOD-Ifremer C-band wind scatterometer retrieval algorithm [Bentamy, 1994]. A robust method to derive wind direction directly from SAR images is not yet available. In this study, we relied on wind direction information gathered during the field campaigns. For the Grand Banks cases a hindcast wind field on a 40-km grid was used for the wind direction. For the Hi-Res cases, buoy and ship observations were combined with surface synoptic charts to deduce a wind direction on a SAR frame-by-frame basis.

Results

Figure 2 shows a one-day subset of our wind-speed estimates from ERS-1 SAR and the ROWS altimeter for the case shown in Figure 1. High correlation between the SAR and altimeter wind speeds is apparent. The absolute magnitude and the dynamic changes in wind speed at spatial scales smaller than 2 to 5 km are seen to be in agreement along most of the transects. Note that the aircraft track covered a range of incidence angles within the SAR swath and that the data continue to agree even when the time difference between acquisitions extends beyond one hour.

Figure 3 shows a scatterplot comparison of the full SAR/altimeter wind dataset, composed of eight separate dates and 35 SAR images. The surface wind conditions ranged from calm to 12 m/s, while the significant wave height ranged from 0.5 to 4.5 m. The spatial collocation of the wind-speed estimates is exact while the maximum time between the SAR and altimeter estimates was limited to one hour. The sample population is 2315 points. The SAR wind speeds were estimated on 2 x 2 km resolution cells, resulting in an rms difference of 1.6 m/s with a correlation coefficient of R^2=0.89. When using 200 x 200 m SAR resolution cells, the rms difference became 1.8 m/s.

Conclusion

We provide a comparison of ERS-1 SAR and airborne altimeter wind-speed estimates for 2 x 2 km resolution cells on the ocean surface. The excellent agreement between the two wind speeds suggests that SAR wind retrieval using the CMOD-Ifremer algorithm is accurate; the measured rms difference was 1.6 m/s. An essential part of ERS-1 SAR wind retrieval requires accounting for ADC saturation power loss. In our case, this calibration correction was based on a saturation analysis of the raw SAR signal data.

Several factors contribute to the residual scatter between the SAR and altimeter wind speed estimates in our dataset. These include residual errors in the SAR calibration, inherent differences between the SAR and altimeter scattering processes, and most importantly, uncertainties in the surface wind direction. Spatially dynamic events such as atmospheric fronts require wind direction estimates with high spatial resolution to completely separate the wind speed and direction effects on the normalised radar cross section measured from a SAR image. Further investigation of these issues is planned using case studies drawn from the present dataset.

References

Bentamy A, Y Quilfen, P Queffeulou & A Cavanie, 1994: Calibration of the ERS-1scatterometer C-band model, Ifremer Tech. Rep. DRO/OS 94.0.1.

Fetterer F, D Gineris & CC Wackerman, 1998: Validating a scatterometer wind algorithm for ERS-1 SAR, *IEEE Trans. Geosc. Remote Sensing* **36**, 479-492.

Jackson FC, WT Walton, Walter WT & CY Peng, 1992: Sea-surface mean square slope from Ku-band backscatter data, *JGR* **C7**, 11441-11427.

ROWS altimeter compared with ERS-1 SAR estimated 10 m/s wind speed. The dashed line is the best linear fit through the data.

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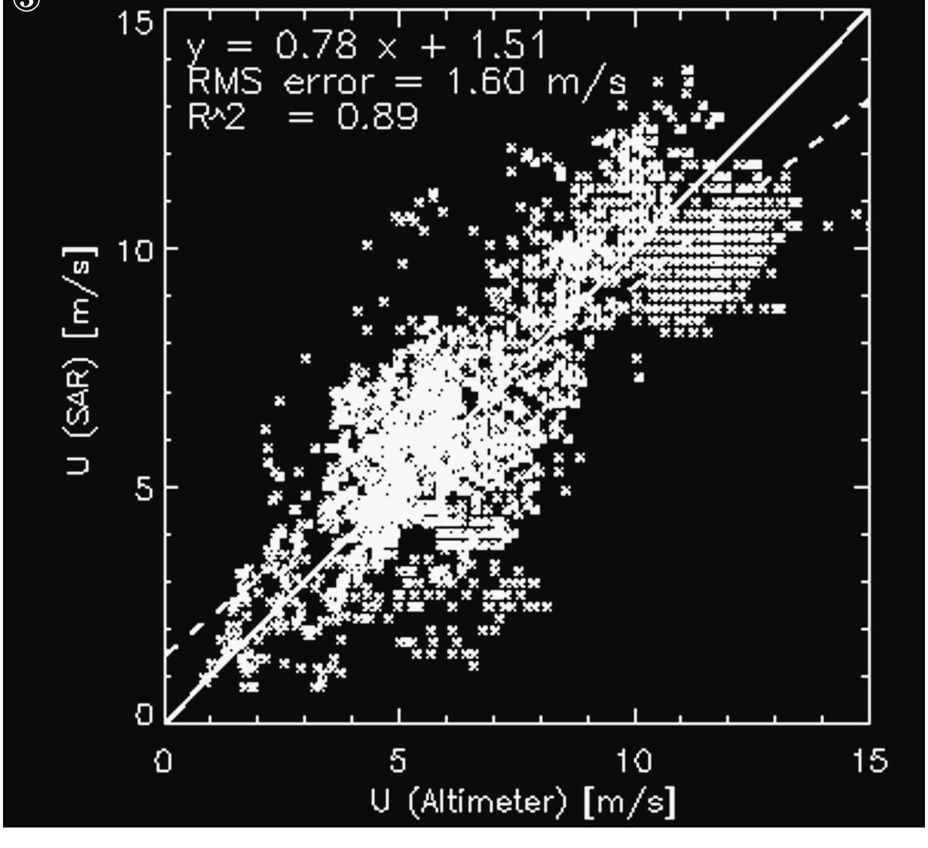

Vachon P & FW Dobson, 1996: Validation of wind vector retrieval from ERS-1 SAR images over the ocean, *Global Atmos. Ocean Sys*. **5**, 177-187.

Vandemark D, FC Jackson, EJ Walsh & B Chapron, 1994: Airborne radar measurements of ocean wave spectra and wind speed during the ERS-1 SAR wave experiment, *Atmosphere-Ocean* **32**, 143-178.

Vandemark D, JB Edson & B Chapron, 1997: Altimeter estimation of sea-surface wind stress for light to moderate winds, *J. Atm. Oceanic Tech*. **14**, 716-722.

Wackerman C, C Rufenach, R Shuchman, J Johannessen & K Davidson, 1996: Wind vector retrieval using ERS-1 synthetic aperture radar imagery, *IEEE Trans. Geosc. Remote Sensing* **34**, 1343-1352.

Witter DL & DB Chelton, 1991: A Geosat altimeter wind-speed algorithm and a method for altimeter wind-speed algorithm development. *JGR* **96**, 8853-8860.

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