Uniqueness of the ERS Scatterometer for nowcasting and typhoon forecasting

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***Abstract* - Since the launch of the European Remote Sensing Satellite ERS-1 in 1991, surface wind-vector observations derived from space-borne scatterometer measurements have been available over the global oceans continuously. Currently, space-borne scatterometer wind products are based on the QSCAT-1 model function for the Ku-band radar frequency (QuikSCAT) and the CMOD5 model function, recently been developed at ECMWF and KNMI, for C-band (ERS-2 and the future ASCAT series). The dynamic range of ERS derived winds now extends to at least 35 m/s. The accuracy of the wind retrieval in combination with the minimal sensitivity of the C-band frequency for rain contamination makes the ERS scatterometer an unique instrument for weather research, and the improved ambiguity removal increases the usefulness in dynamical and extreme weather conditions. The reprocessing of the entire ERS mission, combined with an anticipated overlap with the forthcoming ASCAT era will provide a 30-year long continuous and high-quality surface wind data set unique for climate research.**

The ERS-2 Scatterometer mission is currently operated on regional basis. This results in an unprecedented data timeliness of about 30 minutes. The short timeliness makes the current ERS-2 wind product suitable for operational weather now-casting and short-range weather forecasting. This offers advantages in analyzing and forecasting extreme weather events, which leads to improved predictions of these events using ERS scatterometer surface winds in numerical weather prediction (NWP).

I. INTRODUCTION

Wind measurements are necessary to estimate the atmospheric circulation on the sub-synoptic scales and in the tropics. The impact of scatterometer winds on weather forecasting and climate monitoring has been well demonstrated over the past decade during which scatterometer missions have contributed to this effort.

The first spaceborne instrument was the Skylab S-193 experiment in 1973-74, followed by Seasat-A in 1978 with the first scatterometer (SASS) actually designed to measure vector winds on the ocean surface. Unfortunately, the satellite malfunctioned after 99 days of operations. SASS had four antennae. Each set of two antennae covered a swath, one to the right of the sub satellite (ground) track and one to the left. In the horizontal plane, the fore and aft beams were pointing at respectively 45° and 135°. with respect to the ground track. The four solutions ambiguity posed a strong limitation to the usefulness of the SASS wind data.

The European Space Agency designed European Remote Sensing satellite ERS-1 included a scatterometer in the Active Microwave Instrument and was launched in 1991, and was followed in 1995 by a similar instrument on ERS-2.

The ERS Scatterometer is a three antennae radar working at C-band. This frequency is very sensitive to the sea surface roughness, which is related with the wind field by using an appropriate geophysical model function (GMF). The returned echoes are downloaded to the ground stations whenever they are in the visibility of the satellite. The processors installed at each ground station retrieve the backscattering coefficients (three sigma naught for three different azimuth angles) from the echoes with a resolution of 50x50 kilometers and sample on a grid of 25x25 kilometers. In addition, by using a wind retrieval algorithm based on the CMOD-5 GMF [1,2] and an ambiguity removal algorithm, the wind vectors (speed and direction) are computed from each sigma naught triplet. Within typically 30 minutes from sensing, backscattering coefficients and wind field estimations are provided to the international meteorological and oceanographic organizations.

In 1996, the NASA Scatterometer or NSCAT instrument, was launched onboard the Japanese ADEOS Advanced Earth-Observation Satellite. With respect to SASS for NSCAT a beam was added between the fore and aft beams to both sides of the swath. The polarization of the mid beam was VV, and HH. For the other antennae and instruments only VV polarization is used.

For HH polarization, the relationship between backscatter and wind differs from VV, and as such the HH polarization provides useful complementary information, in particular on wind direction. The addition of an antenna with two polarizations makes that at each location in the swath four independent measurements are available. This satellite only operated for nine months. This dramatic event has been a severe setback for Earth Observation, and scatterometry in particular. The United States NASA developed a "gap-filler" mission known as QuikSCAT with the instrument SeaWinds. This first flew as the only instrument on QuikSCAT in 1999, and a duplicate sensor was launched on ADEOS-II in December 2002. SeaWinds is the first scanning scatterometer. A scanning scatterometer accommodates a broad swath, but a drawback of such a design is that at the extreme ends of the swath, the earth surface is only illuminated from a single azimuth direction, Moreover, in the middle of the swath, at the so-called sub-satellite track, the ocean is only illuminated at two exactly opposite directions. The limited azimuth sampling means that wind direction can only be less well resolved at these locations. Table 1 summarizes the past, present and planned scatterometer missions.

Table 1: Past, present and planned scatterometer missions

Satellite	Instrument	Radar Band	Mission
SEASAT	SASS	Ku	Jun.'78-Oct.'78
ERS-1	AMI	C	Jul.'91-Mar.'00
ERS-2	AMI	C	Since Apr.'95
ADEOS –I	NSCAT	Ku	Aug.'96-Jun.'97
QuikSCAT	Seawinds	Ku	Since Jul.'99
ADEOS-II	Seawinds	Ku	Dec.'02-Nov.'03
MetOp-A	ASCAT	C	From 2006
MetOp-B	ASCAT	C	From 2010
MetOp-C	ASCAT	C	From 2014

In a study by Carswell et al in 2001 the performances of Ku- and C-band scatterometry were explored in detail, based on high resolution airborne measurements taken during reconnaissance flights over hurricanes, and addressing two important aspects related to operational wind scatterometry: high wind speeds (in the range of 20 to 60 m/s) and the impact of rain. The study shows that for both Ku- and C-band scatterometry, wind speed sensitivity saturation at different incidence angles occurs for very high values of the wind speed. These values are lower for Ku-band than for C-band. Furthermore, the study also confirms that C-band scatterometer measures seem to be less affected by rain. Measurement geometry is also a very important factor in the wind retrieval process. One- and two-swath multi-fan-beam scatterometers (SeaSat-A, NSCAT, ERS scatterometers, ASCAT) offer a measurement geometry that is well understood in the framework of the inversion method used to retrieve winds.
The European Centre for Medium-Range Weather Forecasts (ECMWF) has proven that the assimilation of Scatterometer data into meteorological models can improve the forecast and the estimation of the extreme weather events. The four-dimensional variational assimilation system at ECMWF allows for a dynamically consistent use of observations. In this way, information of the scatterometer surface winds is propagated to the entire troposphere [3,4]. At ECMWF scatterometer data from the ERS 1/2 platforms have been successfully assimilated from January 1996 (with an interruption between January 2001 and 9 March 2004) onwards, and QuikSCAT data from 22 January 2002 onwards.

II. ERS AND ASCAT WIND RETRIEVAL

A Geophysical Model Function or GMF relates σ_0 values to wind speed and direction. The wind retrieval is an inversion problem at each node where, given a set of three σ_0 values and the GMF, the wind vector is computed that has the highest probability of representing the true wind. Usually, two wind vectors are obtained as the most likely solutions, with directions separated by 180°. A GMF, known as CMOD5 [1,2], has been developed and will be used in the ERS-2 and ASCAT Level 2 processor. CMOD5, which takes into account the response of the system to very high wind speeds, is an improved version of the well-known C-band backscatter/wind model, CMOD4 [5].
Several quality control tools, including the powerful σ_0 measurement space visualization have been developed. Any given measured σ_0 triplet over the ocean has a unique representation in a three dimensional space defined by the axes [σ_{0FORE}, σ_{0MID}, σ_{0AFT}]. The values of the triplet coordinates in this space depend mainly on two geophysical parameters: wind speed and direction. The quality control method consists basically on plotting ocean σ_0 triplets in a three dimensional space, over-plotting the GMF on top and evaluating departures of the measurements from the theoretical surface.

III. ERS-2 COVERAGE AND TIMELINESS

Since July 2003 the ERS-2 Scatterometer mission is operated in Regional Scenario. The reason is because the two on-board tape recorders have become and therefore the payloads data set can only be directly transmitted to the ground via the X-band link at instrument acquisition time. That fact caused on one hand the loss of the global data coverage of the Earth while on the other hand it gave the opportunity to process and disseminate ERS Scatterometer surface winds within short time after the sensing. After the on-board tape recorder anomaly, the most important area for European NWP (the North Atlantic Ocean) was only partially covered.

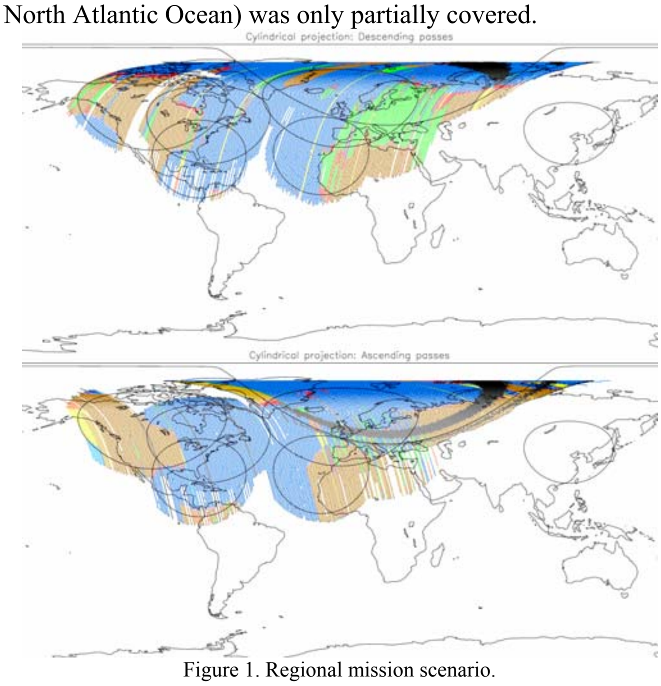

Figure 1. Regional mission scenario.
Data coverage as for cycle 103 (March 2005). The coverage of a possible new ground station in Beijing (China) is also shown. Scatterometer data are available on blue and brown segments. Green segments are related to SAR image acquisition.

In order to increase the data availability, the ESA engineers at ESOC re-configured the Instrument Data Handling and Transmission (IDHT) instrument on-board the satellite in such a way that is allows transmission of the data to the ground every time the satellite is within the visibility of an acquisition station. In addition, ESA/ESRIN improved the data coverage of the existing ground stations in Kiruna (Sweden), Gatineau (Canada) and Maspalomas (Spain) increasing the number of acquisition per day and set up new acquisition and processing facilities in the ground station located in West Freugh (UK), Matera (Italy) and Miami (USA). Currently about 40 orbits segments are daily acquired and processed in all the ground stations (for Matera data are only acquired) on a best effort basis.

Figure 1 shows the coverage as it was for the ERS-2 cycle 103 (21 February 2005 to 28 March 2005). As reported in the figure the North Atlantic Ocean is now fully covered as well as Europe, North and Central America.

That coverage allows fulfilling the needs of the monitoring of extreme weather events in Europe and USA by the meteorological community. Negotiations are ongoing to install an acquiring and processing station in Beijing (China) in order to cover part of the Chinese sea area.

The improvement in the data timeliness due to the Regional mission scenario is shown in Figure 2. On average, during one week for cycle 103, wind data from Kiruna, Gatineau and Maspalomas are now available within 20 minutes after the sensing time throughout the GTS network. Miami data are available within 40 minutes and West Freugh wind data within 70 minutes.

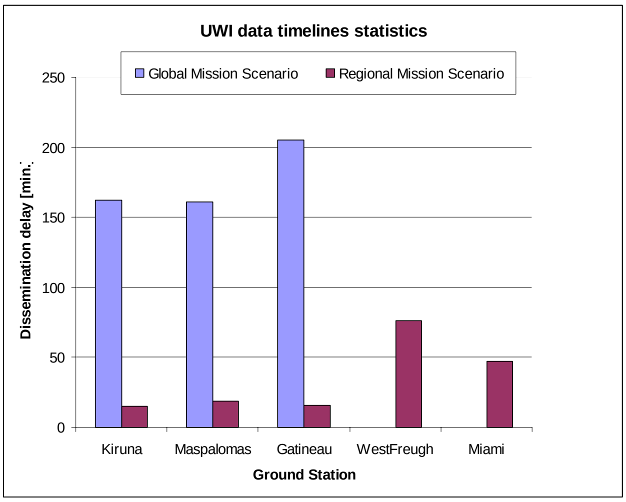

Figure 2. Timeline statistics.
Comparison of the averaged dissemination delay (difference between sensor acquisition time and user delivery time) for the User Wind Products (UWI). Statistics have been computed for one week in cycle 63 (Global Mission scenario, April 2001) and one week in cycle 103 (Regional mission scenario, March 2005).

IV. Forecasting and Nowcasting

The main application of scatterometer ocean winds is the assimilation in NWP models. Since the main limitation for this application is the problem of the wind direction ambiguity, the impact and the benefits of the assimilation of scatterometer winds in NWP models were clearly improved when variational data assimilation was developed. These schemes can ingest the wind direction ambiguities and perform the ambiguity removal within the assimilation process, by weighting each wind direction to the information provided by the background field and to other observations used in the assimilation. Scatterometer ocean winds can also be used also in nowcasting and forecasting of extreme events. An example of each is presented below. The added value of the scatterometer data in these applications is twofold. First, the scatterometer measurements are available in data-sparse oceanic regions where extreme weather events such as typhoons are generated, and they are available in cloudy and rainy conditions. Secondly, scatterometer winds contain much sub-synoptic scale information that, though difficult to assimilate into NWP, is vital for nowcasting applications. Moreover, the increased timeliness of the ERS-2 derived winds facilitates the use of scatterometer data by operational weather forecasters.

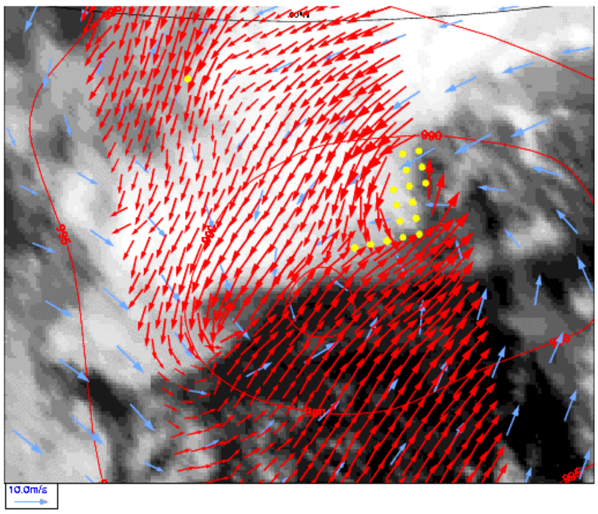

Figure 3. Nowcasting.
Comparison between ERS-2 scatterometer (red) and KNMI HiRLAM surface winds (blue) around 00 UTC, 23 April 2004, west of Ireland.

Around midnight 23 April 2004, a complex low was developing west of Ireland. Real-time ERS-2 scatterometer winds (Figure 3) showed two cyclonic centres, separated by a line of shear flow. This detailed picture was missed by even the 3-hour forecast from the High-Resolution Limited Area Model (HiRLAM) run operationally at KNMI, the Netherlands. The scatterometer winds, therefore, clearly provided a handle to the operational forecaster.

In Autumn 2000, two typhoons hit the Korean Peninsula within three weeks time. Typhoon Prapiroon (category 2 at maximum) led to substantial damage due to severe winds. Just prior to its landfall on 31 August 2000, the Korean Meteorological Administration measured wind gusts up to record values of 130 mph. In the evening of 15 September 2000, super-typhoon Saomai hit the South-Korean coast. A 6-meter storm surge pushed a 40,000-ton Indonesian cargo ship onto rocks just outside Pusan port, breaking the vessel in half. Although at landfall Saomai had weakened to category 1, severe rainfall led to considerable flooding in the South. Both typhoons led to several casualties.

Prapiroon and Saomai were captured four, respectively three times by the ERS-2 scatterometer. Details may be found at the ERS archive (http://earth.esa.int/pcs/ers/cyclones/archive).

In Figure 4, two ERS-2 tracks for Saomai are plotted, along with the typhoon track information (red squares; source: http://weather.unisys.com/hurricane). As can be seen, the structure of Saomai is well observed up to near its center.

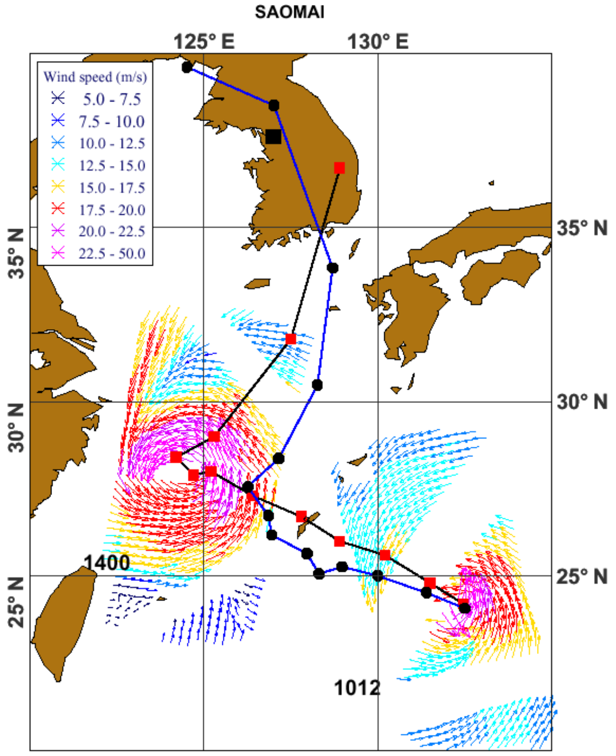

Figure 4. ERS-2 scatterometer winds observed around 12 UTC 10 September 2000 and 00 UTC 14 September 2000. Red squares (black bullets) indicate the observed (by ECMWF forecasted) position of typhoon Saomai, at 12-hourly time intervals from 12 UTC 10 September 2000. Only ERS-2 winds within a radius of 550 km from the observed typhoon center are plotted.

Both ERS-2 tracks displayed in Figure 4 were used in the ECMWF system (having at that time assimilation/forecast components with a combined T319/T63 spectral horizontal resolution (~55/250 km), and 60 levels in the vertical). For the first ERS-2 swath (13h44m UTC, 10 September 2000) Saomai was at maximal strength. The ERS-2 winds as assimilated at ECMWF (based on CMOD4 plus off-line determined bias corrections) showed a maximum of 30 m/s. Although this is much lower than the maximum observed wind (70 m/s), one should realize that these latter only occur near the eye wall. The winds observed by ERS-2 represent an average over a larger area. Given the general knowledge of the wind distribution in a tropical cyclone, scatterometer winds can be post-processed to obtain more realistic, local extremes [6]. This route was, due to the resolution of the assimilation system, not followed at ECMWF. Figure 5 shows the wind data that entered the assimilation along with resulting increments in mean-sea level pressure (contours) and the final analysis wind field (streamlines). Note that at ECMWF the ERS-2 product is thinned to 100km in order to represent a better match to the resolution at which the assimilation is performed. The analysis has led to a slightly deeper central pressure (from 988 hPa to 986 hPa) and a correction in position of 30 km to the Northeast. Larger increments would have been found in case of larger initial position errors.

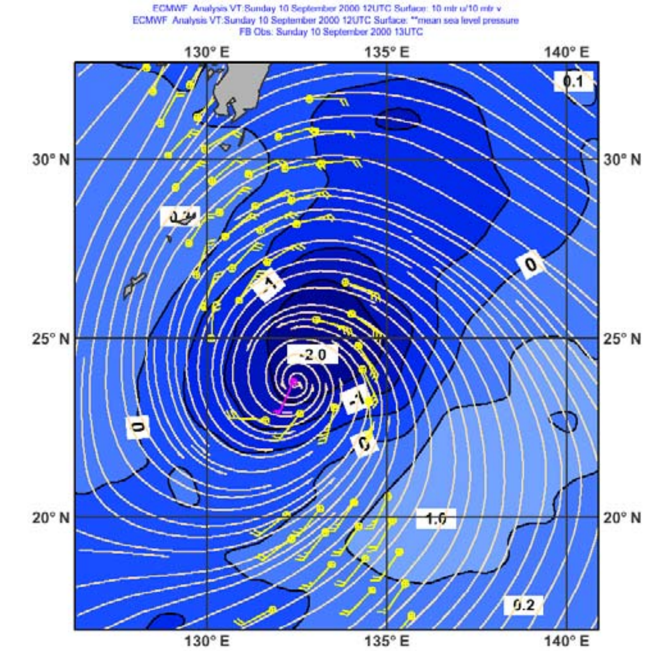

Figure 5. ERS-2 scatterometer winds as assimilated at ECMWF for the analysis of 12 UTC 10 September 2000 (yellow accepted; red rejected). Contours indicate the increments in mean-sea level pressure, while resulting analysis wind field is presented by the cream streamlines.

Examples may be found in [3]. The forecast starting from the analysis is displayed in Figure 4 as well (black bullets). Although the recurving point is too far to the East, its timing was correct. At forecast day 5.5, landfall on the South-Korean coast was, besides a 6-hour error in timing, correctly predicted. Maximum wind speed was predicted to be 24 m/s, which, taking in consideration the 55 km resolution of the ECMWF model at that time, indicated a likely scenario for an extreme event to occur.

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