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Technical Note / Note technique

The advanced scatterometer (ASCAT) on the meteorological operational (MetOp) platform: A follow on for European wind scatterometers

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Abstract. The scatterometers on board the European remote sensing (ERS) satellites have proven their usefulness for weather analyses and forecasting, and operational programmes are being developed to provide routine scatterometer observations. The advanced scatterometer (ASCAT) on board the meteorological operational (MetOp) platforms is the follow on for European scatterometers. This paper describes the ASCAT system and its capabilities, including the instrument, calibration, ground processing, and products, and reviews the science associated with scatterometer measurements.

Résumé. Les diffusiomètres abord des satellites européens de télédétection (ERS) ont prouvé leur valeur pour l'analyse et prévision du temps, et on a développé des programmes opérationnels pour fournir des observations routinières de diffusiomètres. Le diffusiomètre avancé (advanced scatterometer, ASCAT) abord des plateformes opérationnelles météorologiques (MetOp) est la suite des diffusiomètres européens. Ce papier décrit le système ASCAT et ses capacités, l'étalonnage, processing au sol et produits, et aussi une revue de la science associée aux mesures des diffusiomètres.

Introduction

Atmospheric dynamics analyses show that, at sub-synoptic scales, atmospheric flow is dominated by kinetic energy. Furthermore, at synoptic and larger scales, extra-tropical atmospheric flow contains predominantly potential energy and observes geostrophic balance, whereas the tropical atmosphere is largely ageostrophic and temperature and pressure observations alone are insufficient to describe atmospheric flow. In these situations, direct wind measurements are essential. Wind measurements are therefore necessary to define the atmospheric circulation on the sub-synoptic scales and in the tropics (Stoffelen, 1998b). 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 (e.g., Stoffelen and Cats, 1991; Stoffelen and van Beukering, 1997; Isaksen and Stoffelen, 2000; Atlas and Hoffman, 2000; Candy, 2001; Atlas et al., 2001).

Table 1 summarizes the past, present, and planned scatterometer missions. The three meteorological operational (MetOp) platforms, which constitute the space segment of the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) Polar System (EPS) (<www.eumetsat.de>, Programmes under Development), will fly in polar orbit. As part of the initial joint polar system (IJPS), they will carry other instrumentation and represent a key element in weather forecasting and climate monitoring (Figa-Saldaña, 2000; Figa-Saldaña and Kerkmann, 2000).

The MetOp orbit is planned to be a sun-synchronous 29 day repeat cycle orbit with an ascending node at 21:30 and a minimum orbit height of 822 km.

ASCAT mission, inheritance from ERS scatterometers, and key features

The ASCAT mission has been primarily designed to provide global ocean wind vectors operationally. The main application foreseen is the assimilation of those winds into numerical weather prediction (NWP) models. Furthermore, its dense coverage (see **Figure 1**) makes the winds useful for direct use by operational weather forecasters when performing the necessary real-time interpretation of NWP model results to elaborate a forecast. Requirements arising from that use of the data include (1) extended coverage; (2) accuracy better than

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Table 1. Past, present, and planned scatterometer missions.

Satellite	Instrument	Radar band	Mission
Seasat	SASS	Ku	June–Oct. 1978
ERS-1	AMI	C	July 1991 – Mar. 2000
ERS-2	AMI	C	Apr. 1995 to present
ADEOS-I	NSCAT	Ku	Aug. 1996 – June 1997
QuikSCAT	SeaWinds	Ku	July 1999 to present
ADEOS-II	SeaWinds	Ku	From 2002
MetOp-1	ASCAT	C	From 2005
MetOp-2	ASCAT	C	From 2007
MetOp-3	ASCAT	C	From 2012

Note: ADEOS, advanced earth observation system; AMI, active microwave instrument; ASCAT, advanced scatterometer; ERS, European remote sensing; NSCAT, NASA scatterometer; SASS, Seasat-A satellite scatterometer.

2 m/s in the wind components; and (3) real-time data access, with a timeliness of better than 3 h from measurement.

With respect to the microwave spectrum, a recent study by Carswell et al. (2001) explores in detail the comparative performances of Ku- and C-band scatterometry, based on high-resolution airborne measurements taken during reconnaissance flights over hurricanes, thus addressing two important aspects related to operational wind scatterometry: high wind speeds (in the range of 20–60 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 the Ku band than for the C band. Furthermore, the study also shows that C-band scatterometer measures seem to be less affected by rain.

Measurement geometry is a very important factor in the wind-retrieval process. One- and two-swath multi-fan-beam scatterometers (SASS, NSCAT, ERS scatterometers, ASCAT) offer a measurement geometry that is well understood in the framework of the inversion method used to retrieve winds (Naderi et al., 1991; Stoffelen and Anderson, 1997a).

The design of ASCAT is based on the robust and well-understood concept of the ERS scatterometers. Among the common features are (1) fan-beam geometry with antennas oriented at 45°, 90°, and 135° with respect to the satellite track; (2) VV polarisation; (3) C-band radar frequency; (4) swath gridded into nodes, with one triplet of averaged backscatter measurements per node; and (5) generation of an operational product at 50 km resolution on a nodal grid of 25 km.

The experience acquired with nearly one decade of operations of ERS scatterometers and the use of their data have also identified areas where improvement was possible, to allow operational use of the data (Atlas et al., 2001; Isaksen and Stoffelen, 2000) and emerging scatterometer applications to develop (Wismann 2000a; Woodhause and Hoekman, 2000a). This experience has been taken into consideration by introducing a number of new key features, which are listed as follows and discussed in further detail in the paper: (1) continuous data acquisition and product generation without sharing operation time in orbit with other instruments, which would increase the data coverage; (2) increased spatial coverage via the use of a double swath; (3) higher incidence angle range towards an area that offers a higher wind direction sensitivity in the geophysical model and therefore better performance of the wind-retrieval algorithm; (4) additional generation of a research product at a higher resolution of 25 km on a 12.5 km nodal grid; (5) improved instrument design, resulting in higher stability and reliability; and (6) improved on-board processing concept, allowing for a lower data rate.

ASCAT instrument

Measurement principle and geometry

Like the ERS scatterometers, the ASCAT system geometry is based on the use of fan-beam antennas. The system covers two 550 km swaths that are separated from the satellite ground track by about 360 km for the minimum orbit height. The ASCAT incidence angle ranges from 25 to 65° (**Figure 2**). For each swath, three antennae illuminate the sea surface, measuring the backscattered signal. At such incidence angles, the main backscattering mechanism is considered to be Bragg resonance, which describes the interaction of the radar signal with short gravity waves having a wavelength of a few centimetres (Ulaby et al., 1982). The wind speed and direction near the ocean surface with respect to the antenna look angles can be determined using an empirical geophysical model function (GMF), which relates these parameters to the observed backscatter normalized radar cross section (σ^0) (Naderi et al., 1991; Stoffelen and Anderson, 1997b; 1997c). ASCAT collects data from three antennae with different look angles to retrieve a wind vector.

Instrument technical description and on-board processing

ASCAT is a real aperture radar operating at 5.255 GHz (C-band) and using vertically polarised antennae. It transmits a long pulse with linear frequency modulation (“chirp”). Ground echoes are received by the instrument and, after de-chirping, the backscattered signal is spectrally analysed and detected. In the power spectrum, frequency can be mapped into slant range provided the chirp rate and the Doppler frequency are known. The above processing is in effect a pulse compression, which provides range resolution (Gelsthorpe et al., 2000).

The contribution of the thermal noise to the radar measurement is observed within each pulse-repetition interval by monitoring the output of the receiver during a period of time when all the pulse echoes have decayed. Noise measurements are sent to the ground with echo measurements to enable measurement noise subtraction to be performed during ground processing.

It is important to point out that considerable data rate reduction is achieved by pre-processing the noise and echo measurements on board. Different averaging takes place for

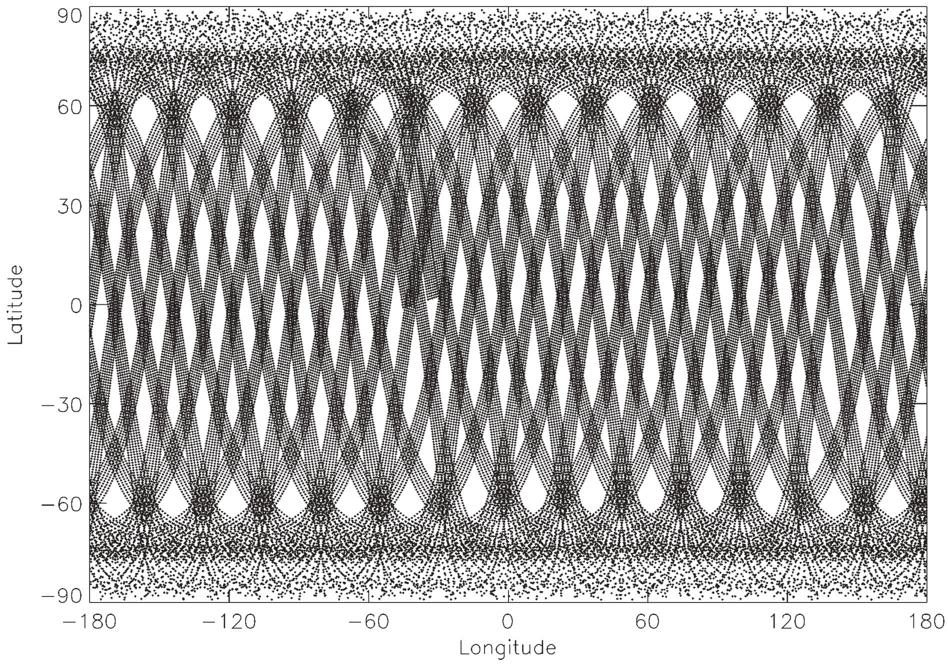

Figure 1. ASCAT coverage for 1 day. The swath coverage has been simulated by resolving the across-track viewing geometry, considering the nominal MetOp orbit of a 29 day (412 orbits) repeat cycle with ascending node at 21:30 and a minimum orbit height of 822 km.

echo and noise measurements, reducing the raw data rate by a factor of approximately 25.

Additionally, an internal calibration process is performed on board which allows the combined variation of the transmitter power and the receiver gain to be monitored. Downlinked internal calibration data are used to correct for these variations during the ground processing.

Instrument performance

The instrument performance specification has been established based on the experience with the performance of the ERS scatterometer instruments. Some of the key parameters driving the instrument design relate to the desired radiometric characteristics of the normalized backscatter determination (Gelsthorpe et al., 2000): (1) radiometric resolution (Kp) describes the uncertainty in a σ^0 estimate due to speckle and thermal noise (from 3.0% for high-speed upwind, up to 9.9% for low-speed crosswind); (2) radiometric accuracy describes the maximum uncertainty in the σ^0 estimates, once the statistical noise has been averaged out, per beam and per node, over the mission lifetime (0.57 dB), and the uncertainty is given by the maximum variation of the σ^0 estimates with respect to a reference value; and (3) inter-beam calibration stability is the maximum relative difference between the σ^0 estimates of any pair of beams within the same swath, per node, over the mission lifetime, when observing targets of the same scattering coefficient after the effects of the statistical noise has been averaged out (0.46 dB).

Parameters 2 and 3 control the variations in the absolute value of σ^0, for each of the six antennae and between them. The variations are defined with respect to a reference value, established in flight through the external calibration.

External calibration

The objective of the external calibration is to ensure that the σ^0 value measured from a target is correct (absolute calibration) for all incidence angles (relative calibration). To achieve this, the absolute gain and the pointing of each antenna need to be established in flight, and this is done with the help of ground transponders.

Transponders are active devices that, after receiving a pulse from ASCAT, send a delayed pulse back. Each transponder needs to have a well-known and stable radar cross section and response delay and its position on the Earth's surface needs to be accurately known. ASCAT receives and detects the transponder pulses from within its swath. By comparing the measured transponder echo level and its associated localization data with the expected data for each transponder, three de-pointing angles and gain correction values are estimated for each antenna. This allows a reference calibrated system to be established, against which the system performance can be evaluated and monitored. Experience with the absolute calibration and monitoring of the ERS scatterometers indicates that the external calibration accuracy that would meet the wind accuracy required by the users is 0.2 dB (Stoffelen, 1998b).

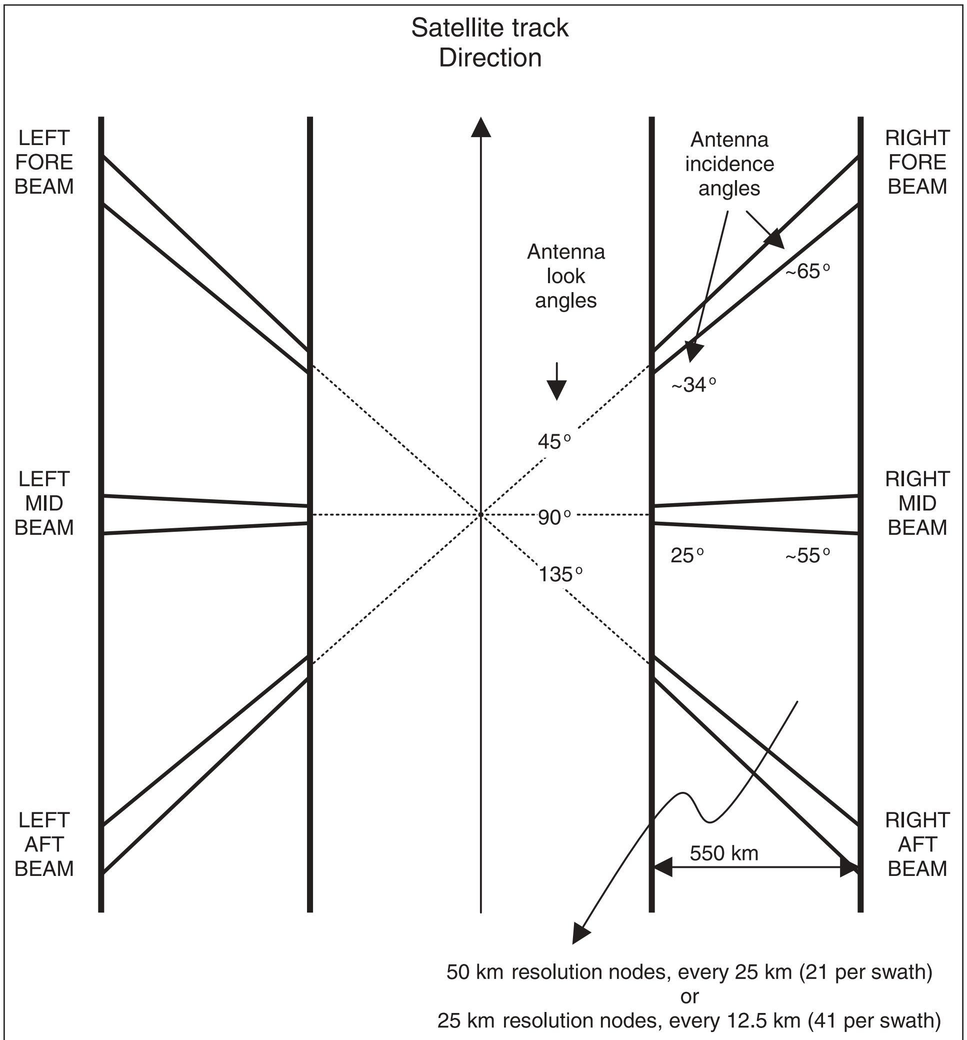

Figure 2. ASCAT swath geometry. Dimensions are given for the right swath, and the left swath is symmetric with respect to the satellite ground track.

The three transponders used for the ASCAT external calibration will be placed in an east–west line, separated by approximately 150 km. For the planned MetOp orbit, over a period of 1 month, this will allow transponder measurements to be obtained for each antenna beam over the full range of incidence angles, with cuts at approximately 10 km intervals in ground range. This is the sampling needed to be able to reconstruct each antenna gain pattern over the whole range of incidence angles and therefore achieve an appropriate relative calibration.

An excellent method to provide an independent assessment of the quality of the transponder external calibration in a very short time is the validation of the measured σ^0 values over the ocean. In this method, σ^0 values measured over the ocean are compared with a reference data set of σ^0 values derived from NWP model winds (Stoffelen, 1999). Additionally, the experience with the ERS scatterometers has provided knowledge about the properties of σ^0 measurement spaces over natural targets such as tropical rain forest and ice sheets; this knowledge will be exploited to validate the ASCAT level 1b product and its calibration. The scatterometer backscatter response from the rain forest is explained basically by volume scattering. This type of response is typically isotropic and its variation depends on the incidence angle through a parameter, γ_0, which is related to the biomass (Woodhause et al., 1999). Monitoring over time the peak value of γ_0 histograms over an area of the rain forest (sufficiently homogeneous in backscatter response) allows monitoring the stability of the absolute calibration. High-altitude snow and ice areas have a fairly stable backscatter response. This additional means of monitoring the absolute calibration of the ASCAT over time is being explored.

Generation of ASCAT products

The processing of ASCAT measurements leads to the generation of two main products: (1) ASCAT level 1b consists of rows of nodes along-track, containing σ^0 estimates (three values, one from each beam within a swath), with a fixed node grid across the swath; and (2) ASCAT level 2 is the wind product, containing values of wind speed and direction retrieved on a node by node basis from the σ^0 triplets.

ASCAT level 1b processing overview

Level 1b processing for ASCAT is the generation of the radiometrically calibrated backscatter product, namely σ^0 values. In the EUMETSAT core ground segment facility, the ASCAT power echoes are subject to front-end processing, namely internal calibration and noise corrections. Calibrated power is then normalized into 256 σ^0 values along every antenna beam projection on the ground.

Spatial averaging (smoothing) in the along- and across-track directions is further applied per beam over all available σ^0 values, with the objective of obtaining a set of three σ^0 values (one from each beam) for each grid node of each swath at the desired radiometric resolution (also called Kp). The weighting function used to carry out the spatial filtering is a two-dimensional Hamming window centred at every node position, which is based on a cosine function and designed to peak in the centre of the samples and taper to zero at the ends (Hamming, 1977). Its width determines in effect the spatial resolution of the σ^0 averaged values, which is defined in the principal cut in each of the along- and across-track directions, as the distance around the centre of the spatial filter when its intensity reaches 50% of the peak value. The averaged σ^0 values at two different horizontal scales and spatial grids are generated this way, leading to two smoothed σ^0 products with 50 and 25 km horizontal resolution on grids of 25 and 12.5 km, respectively.

ASCAT level 2 processing overview

Level 2 processing takes the radiometrically calibrated backscatter product to derive the geophysical product, namely winds near the ocean surface (at a nominal height of 10 m). ASCAT level 2 products will be produced and distributed by the Ocean and Sea Ice Satellite Application Facility (OSI SAF). The OSI SAF <http://www.meteorologie.eu.org/safo> is part of the EUMETSAT geographically distributed applications ground segment (<www.eumetsat.de>, Programmes Under Development). A consortium of institutes from EUMETSAT member states, led by Météo-France, develops ocean and sea ice products from EUMETSAT and other space-borne instruments. The Royal Netherlands Meteorological Institute (KNMI) and the French Research Institute for Exploitation of the Sea (IFREMER) are responsible for the development, generation, and distribution of the ASCAT wind product.

Prototyping of the methods to be used in the processing of ASCAT level 2 products is at present done using ERS-2 and SeaWinds scatterometer data. The system performance in terms of timeliness and product quality is demonstrated by means of a pre-operational system based on currently available scatterometer measurements. The following activities are and will be carried out within the OSI SAF in preparation for the operational retrieval, quality control, and distribution of ASCAT winds.

The OSI SAF will produce and distribute near-surface ocean wind vectors derived from ASCAT level 1b data by using a GMF, which 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. An inversion problem presented in these probabilistic terms is usually equivalent to the minimisation of a cost function. Usually two wind vectors are obtained as the most likely solutions, with directions separated by 180°. The measurement noise and the harmonic nature of the GMF result in this wind direction ambiguity, as two equal-probability minima occur in the cost function.

A GMF, known as CMOD5, is being developed for use in the 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 current C-band backscatter – wind model, CMOD4 (Stoffelen and Anderson, 1997b). Moreover, the role of other sea surface parameters in the sea surface backscatter response (e.g., sea-state effects, sea surface temperature) will be evaluated, and CMOD5 may be modified to take these into account. It is also necessary to optimize the wind retrieval and quality monitoring and extend CMOD5 to the ASCAT incidence angle range.

Several quality-control tools, including the powerful σ^0 measurement space visualization, are also developed and implemented. Any given measured σ^0 triplet over ocean has a unique representation in a three-dimensional space defined by the axes σ^0_{FORE}, σ^0_{MID}, and σ^0_{AFT}. The values of the triplet coordinates in this space depend mainly on two geophysical parameters: wind speed and direction. A two-parameter representation within a three-dimensional space is by definition a surface. The shape of this surface is determined by the GMF, which in this case defines a two-sheet conical surface (Stoffelen and Anderson, 1997a). The properties of this cone can also help validating certain system performance parameters, such as the radiometric resolution (related to the measurement noise) or the inter-beam stability. The method to do this consists basically of plotting ocean σ^0 triplets in a three-dimensional space, overplotting the GMF, and evaluating departures from the measurements from the theoretical surface.

Sea ice screening methods based on scatterometer data and sea ice history information are also being developed, implemented, and validated. In particular, the idea of developing a sea ice GMF based on the properties of the sea ice scatterometer measurement space is being explored (de Haan and Stoffelen, 2001). Improved wind direction ambiguity removal methods are also being developed, with particular attention to those based on variational meteorological analysis, thereby relying on prior NWP model information. In 2D-VAR, a cost function is minimised. The cost function is formulated in terms of wind increments and penalises deviations from both a background wind field and the ambiguous scatterometer wind solutions obtained from scatterometer wind retrieval. De Vries and Stoffelen (2000) developed a new 2D-VAR procedure for the OSI SAF that can be applied effectively in real-time

ASCAT messages. The method uses the known spatial structure of the wind field, as used in meteorological analysis, to improve ambiguity-removal skill. One of its main features is the use of a discrete grid that extends beyond the scatterometer swath to incorporate wind increments generated outside the swath due to scatterometer observations at or near the edge of the swath. The wind increments contribute to the cost function and help to obtain a realistic and meteorologically consistent solution.

Lastly, wind-validation and error-analysis tools are being developed, including the gathering of necessary validation data, which would allow a final assessment of the quality of the ASCAT winds. The accuracy target for ASCAT winds generated by the OSI SAF is 2 m/s root mean square difference and 0.5 m/s bias with respect to a reference wind data set (e.g., NWP winds) for all speeds below 25 m/s. Above 25 m/s the accuracy gradually decreases with an increase in wind speed due to poorer sensitivity (Carswell et al., 2001). A practical solution to deal with the uncertainties related to the measured and reference data sets is known as the triple collocation method (Stoffelen, 1998*a*), which produces error estimates for all three data sources involved in the comparison. To use this method to validate ASCAT winds, two reference data sets are needed, collocated in time and space with the scatterometer measured winds (i.e., NWP winds and buoy wind data).

In addition to the development of ASCAT winds, the NWP SAF <http://www.metoffice.com/sec5/NWP/NWPSAF> develops improved and new observation operators for the use of ambiguous scatterometer winds (both wind direction ambiguities), together with associated information to improve the assimilation of these data. The European institutes involved in the NWP SAF scatterometer work are the KNMI, the Met Office (United Kingdom), and the European Centre for Medium-range Weather Forecasts (ECMWF). To fulfill the data requirements for NWP applications, the two wind direction ambiguities (and flag pointing at the selected solution from the ambiguity-removal scheme) will be provided within the ASCAT level 2 product.

Apart from the ASCAT level 2 product generation, sea ice information contained in the scatterometer data is further used within the OSI SAF by the Norwegian Meteorological Institute (DNMI) in a multi-sensor multivariate sea ice detection and classification method (Breivik et al., 2000).

ASCAT product description

Two level 1b products will be derived in the EPS central processing facilities at EUMETSAT. These will give σ^0 estimates at 50 and 25 km horizontal resolution on grids of 25 and 12.5 km, respectively, and will be distributed within 2 h 15 min from acquisition and archived in the Unified Multi-mission Archiving Facility at EUMETSAT (U-MARF) in Darmstadt, Germany.

The OSI SAF will be generating and distributing the level 2 wind products corresponding to the spatial resolutions and sampling grids given in the previous paragraph. Distribution is intended to take place within 2 h 30 min from acquisition, and archiving will be performed in the U-MARF. The format intended for the distribution of ASCAT winds is the World Meteorological Organization code BUFR (binary universal form for the representation of meteorological data).

The ASCAT 50 km resolution products will continue with the more than a decade long time series of ERS-1 and ERS-2 scatterometer data at the same spatial resolution. For applications with a need for higher spatial resolution data and a slightly more relaxed requirement in terms of radiometric resolution (Kp), the instrument design allows for the generation of equivalent products at 25 km resolution with acceptable values of random noise for wind retrieval.

Near-real-time ASCAT winds will be disseminated via the global telecommunication system (GTS) or (in Europe) the regional meteorological data communication network (RMDCN) to national meteorological services in BUFR format. Alternatively, the data and a visual presentation will be available on the Internet at <http://www.knmi.nl/scatterometer>.

Science and applications

A number of operational applications of scatterometer data have been developed in meteorology and climate monitoring after the success of the recent scatterometer missions. The main operational product from scatterometers remains the wind over the ocean surface, and the main operational application is the use of scatterometer winds in weather analysis and forecasting. Scatterometer winds are used routinely to track tropical and extra-tropical cyclones.

A second group of operational applications, based on the use of scatterometer σ^0 estimates, has been developed recently, such as sea ice edge detection and monitoring, where maps of sea ice coverage based on scatterometer data are routinely produced. Besides the operational use of scatterometer data, there are a number of scatterometer applications at various levels of maturity, in the fields of oceanography and for monitoring sea ice, snow cover, and land surface parameters (European Space Agency, 1998; IEEE, 2000).

Scatterometer ocean wind applications

Ocean winds assimilation in weather forecasting

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 benefits of the assimilation of scatterometer winds in NWP models were clearly improved when variational data assimilation was developed (Stoffelen and Anderson, 1997c). These schemes can ingest the two wind direction ambiguities and perform the ambiguity removal within the assimilation process by weighting one wind direction or another according to the information provided by the background field and the other observations used in the assimilation (Figa and Stoffelen, 2000). After demonstrating the impact of assimilating scatterometer winds in NWP models (Isaksen and Stoffelen, 2000; Candy, 2001), ERS and SeaWinds data have been and are operationally assimilated in global models at ECMWF and the Met Office (United Kingdom); regional NWP models use scatterometer data following similar principles (Stoffelen and van Beukering, 1997).

Now-casting and forecasting of extreme events

Scatterometer ocean winds can be used also in now-casting and forecasting of extreme events. The added value of the scatterometer data in this particular application is twofold. First, the scatterometer measurements are available in data-sparse oceanic regions where extreme weather events such as tropical cyclones are generated and in cloudy and rainy conditions (Carswell et al., 2001). Second, scatterometer winds contain much sub-synoptic-scale information (e.g., Stoffelen et al., 2000) that, though difficult to assimilate into NWP, is vital for now-casting applications. Moreover, the increased coverage and timeliness of ASCAT with respect to ERS winds will facilitate routine use of scatterometer winds by operational weather forecasters.

Winds forcing ocean models

The main limitation in the interpretation of the results obtained by ocean models is considered to be the uncertainties in the surface wind fields, especially in tropical areas, where the ocean reacts strongly and quickly to the atmosphere's variability. Again in this case, conventional instrumentation data are generally sparse in these areas. While the TAO/TRITON buoy array in the tropical Pacific provides information with high temporal resolution, the scatterometer data have proven to provide a key contribution because of the dense spatial resolution. The main parameter of interest in this case is ocean surface wind stress, related to the near-surface ocean winds, and a major challenge still remaining is the validation of this parameter as provided by the scatterometer with other observations used in the model (Quilfen et al., 2000).

The scatterometer winds also play an indirect role in operational ocean wave forecast models, as most of these models are driven by an atmospheric model wind analysis that has assimilated scatterometer winds (e.g., the ECMWF model).

Other scatterometer applications

Sea ice monitoring: mapping and analysis

Sea ice detection and discrimination from open water using scatterometer data is mainly based on two characteristics of the backscatter response from sea ice. First, sea ice surfaces have an isotropic backscatter response, in contrast with the strong anisotropic response from open water (Early and Long, 1997). Second, the dependency of the backscatter response with respect to incidence angle is smaller for sea ice than for open ocean (Gohin and Cavanié, 1994). Based on these properties, and on available in situ validation sea ice data (Carsey, 1992; Drinkwater et al., 1995; Drinkwater, 1998), models describing the scatterometer sea ice backscatter signatures have been developed, which point to one key sea ice characteristic modulating the backscatter response: sea ice age–thickness (Gohin, 1995; Ezraty and Cavanié, 1999; Drinkwater, 1998; Drinkwater et al., 2001). A comprehensive analysis of the ERS backscatter measurement space over sea ice results in an improved sea ice model and ice parameter retrieval (de Haan and Stoffelen, 2001). Other developments include detecting seasonal transitions accompanied by surface melting or refreezing, such as the onset of melting (Forster et al., 2001; Drinkwater and Liu, 2000) or the autumn freeze-up (Drinkwater and Lytle, 1997).

Based on these results, multi-sensor sea ice detection and classification algorithms relying on multivariate analysis with microwave (active and passive), infrared, and visible data as input have been developed in which the sea ice information contained in the scatterometer measurements plays a key role (Remund et al., 2000; Breivik et al., 2000). Additional multi-sensor synergetic methods exploiting decision rules have also been explored as a means of accurate sea discrimination (Grandell et al., 1998).

The significance of these sea-ice applications is largely in their maturation to the point where operational ice centers such as the Canadian Ice Centre (de Abreu et al., 2002) and the U.S. National Ice Centre (Long et al., 2001) are presently evaluating the use of scatterometer data for operational sea-ice monitoring.

Snow accumulation over large ice sheets

To understand the relationship between global warming and changes in large ice sheets, it is necessary to quantify mass balance and the time and space scales of variability in snow accumulation and ablation. Microwave backscattering depends on both the roughness and the physical characteristics of the snow and ice (Mätzler, 1987). This provides an efficient means of monitoring backscatter changes, which accompany diagenetic changes in the ice sheets forced by seasonal accumulation, densification, temperature cycling, ablation, and (or) metamorphic processes (Bingham and Drinkwater, 2000; Drinkwater et al., 2002; Forster et al., 1999; Wismann, 2000b).

Scatterometry over land surfaces

Radar backscatter from land corresponds to a mixture of surface and volume scattering associated with the radar penetration depth. The surface roughness, vegetation cover, and terrain dielectric properties play an important role in determining the dominant backscatter regime. The response of the land surface to the radar with respect to incidence angle (slope) is different for both regimes. Hence examining not only the backscatter intensity but also the backscatter slope allows assessing surface type, vegetation cover, and soil moisture content (Wagner et al., 1999; Wagner and Scipal, 2000; Woodhause and Hoekman, 2000a; 2000b; Wismann, 2000b).

Summary and conclusions

The ASCAT on MetOp is optimized for the operational routine observation of winds near the ocean surface. ASCAT is a C-band fan-beam scatterometer system with a design based on the robust and well-understood concept of the ERS scatterometers, including important enhancements such as continuous operations, increased spatial coverage thanks to a double swath, higher wind direction sensitivity, and the generation of higher resolution σ^0 and wind products. The σ^0 values estimated from ASCAT will be absolutely calibrated with the help of ground transponders. The radiometric performance and the stability of the calibration will be monitored with the help of natural targets such as rain forest and ice sheets.

Levels 1b (σ^0 values) and 2 (10 m high ocean wind vectors) will be generated at 50 and 25 km horizontal resolution on grids of 25 and 12.5 km, respectively. The distribution timeliness associated with levels 1b and 2 products will be 2 h 15 min and 2 h 30 min respectively, via the GTS–RMDCN network or the Internet (ftp).

Continuing with the very valuable contribution of the ERS scatterometers, the most important benefits from ASCAT will be in weather forecasting and climate monitoring by helping to improve the definition of the atmospheric circulation on the sub-synoptic scales and in the tropics. Other operational applications, based on the use of scatterometer measurements of σ^0, include sea ice edge detection and monitoring. These applications will significantly benefit polar logistics and ship operations in ice-infested waters, in particular because of the advantage of the high revisit frequency which the satellite offers at high latitudes. Many other additional scientific applications will benefit from the ASCAT data, such as in the fields of oceanography and climatology, in the study of terrestrial ecosystems and land-system processes, and for monitoring sea ice, snow cover, and land surfaces.

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