Scatterometers and Wind Retrieval Practices

Introduction

Ocean surface wind is defined as the motion of atmosphere relative to the sea surface. Typically the reference height of near surface ocean wind is 10 meters above sea level. Ocean surface vector winds, both speed and direction, play a significant role in exchanges of momentum, energy, and gases between the ocean and the atmosphere, as such they are essential climate variables for understanding the air-sea interaction.

Near-surface winds modulate centimeter-scale capillary waves on the sea surface, and in turn, directly influence the reflection of centimeter-scale electromagnetic waves at medium and/or large incidence angles through the mechanism known as Bragg scattering. Based on this principle, spaceborne radar scatterometers are designed to measure the normalized radar cross section (σ^0) accurately over the sea surface, with the objective of acquiring global mesoscale ocean surface vector winds.

At present, many satellite scatterometers are operated in orbit for the monitoring of ocean surface vector winds, soil moisture and sea ice. Hence, international cooperation is proposed to construct the virtual scatterometer constellation, in order to address observational gaps and to sustain the routine collection of wind observations. However, inconsistencies remain in the wind products from different scatterometers and producers, potentially preventing the beneficial use of multiple scatterometers for numerical weather prediction, studying air-sea interactions and/or monitoring ocean dynamical environment.

This document provides guidelines and metrics for the activities associate with scatterometer wind development, including requirements, best practices, verifications, and etc., with the aim of the errors and the inconsistencies of observation data among spaceborne microwave scatterometers. The context of this document can be used to achieve a homogenization of wind products from different scatterometers, and in turn, to improve the accuracy of weather forecasts, the understanding of air-sea interaction, and the monitoring and forecasting of ocean environment.

Guidelines on Scatterometers and Wind Retrieval Practices

1. Scope

This document defines the requirements, guidelines and verification methods for spaceborne microwave radar scatterometry, including the requirements for system design and instrument manufacturing, the best practices for wind inversion, quality control and ambiguity removal, as well as the validation references and the analyzing procedures.

2. Normative references

The following documents are referred to in the following sections. For dated references, only the cited edition applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 10795:2011, Space systems - Programme management and quality - Vocabulary
ISO 14302, Space systems - Electromagnetic compatibility requirements
ISO 22716:2007(en), Cosmetics - Good Manufacturing Practices (GMP) - Guidelines on Good Manufacturing Practices
ISO 20930:2018(en) Space systems - Calibration requirements for satellite-based passive microwave sensors

3. Terms and definitions

3.1 calibration

set of operations that establish, under specified conditions, the relationship between values indicated by a measuring instrument or measuring system, or values represented by a material measure, and the corresponding known values of a reference standard

3.2 validation

process of assessing by independent means the quality of the data products derived from the system outputs

3.3 wind vector cell

the scatterometer swath is partitioned into a set of discrete grids along and across the sub-satellite track with equal spatial distances. Each grid represent a single wind vector cell.

3.4 relative azimuth angle

the wind direction relative to the azimuth direction of radar beam. The wind blows precisely towards the radar beam is referred to as 0° (upwind), and the winds blows away from the radar beam is referred to as 180° (downwind).

3.5 geophysical model function

a look-up-table or a function describes the expected radar backscatter cross section as a function of observing frequency, polarization, incidence angle, wind speed, relative azimuth angle, and etc., representing the best fit of measured backscatter to ocean surface wind vectors at 10 m height.

3.6 level one (L1) processing

type of processing which calculates the observing geometries, converts the scatterometer measured power to the normalized radar cross section (σ^0), and correct the derived σ^0 values through a calibration procedure

3.7 level two (L2) processing

type of processing which averages the L1 σ^0s with similar incidence and azimuth angles for each wind vector cell, retrieves sea surface winds from a set of averaged σ^0 values, and then performs ambiguity removal and wind quality control procedures

4. Abbreviated terms

AR	Ambiguity Removal
ECMWF	European Centre for Medium-Range Weather Forecasts
GMF	Geophysical Model Function
MLE	Maximum Likelihood Estimator
NWP	Numerical Weather Prediction
NOC	NWP Ocean Calibration
QC	Quality control
SE	Singularity Exponent
2DVAR	Two-Dimensional Variational Ambiguity Removal
T/R	Transmit/Receive
WVC	Wind Vector Cell

5. Satellite scatterometer wind retrieval overview

5.1 Mission and system

Satellite based scatterometers transmit microwave radiation with a wavelength of typically a few centimeters towards the Earth, and measure the properties of the reflected signal after absorption, reflection and/or scattering by the Earth's surface or the atmosphere. The most common measured property is the amplitude, while the polarization and the frequency measurements may be also applied for certain purposes other than regular wind observation, such as sea ice, extreme winds, sea surface current, and etc.

The scatterometer backscatter signal from the sea surface is dominated by Bragg resonant mechanism, so the backscatter power is proportional to the density of surface elements whose size is comparable to the incident wavelength. Over sea surface, these elements are gravity-capillary waves that respond instantaneously to the strength of the local wind. Consequently, following the relationship between the sea surface wind and such waves, people can retrieve sea-surface wind vector information from the a set of measured radar backscatters.

Operationally, the ground segment, which consists of L1 and L2 processing, is used to estimate the sea surface radar backscattering coefficients from the raw measurement data of satellite scatterometers, and to retrieve sea surface vector winds from the estimated radar backscatters, respectively. Eventually, the wind data are delivered to the wind users.

5.2 Types of microwave scatterometers

According to the observing geometry, satellite based scatterometers are generally categorized as follows:

1) fan-beam scatterometers with multiple fixed antenna orientation;
2) pencil-beam scatterometers with conically scanning antennas;
3) fan-beam scatterometers with conically scanning antennas.

The fan-beam This document covers the requirements for the above three types.

5.3 Concept and scope

Satellite scatterometers receive weak reflected signal from the Earth. Knowledge among the instruments would affect the accuracy of the estimated radar backscatters, and in turn, impact on the retrieved wind quality. Therefore, it is necessary to understand the instrument characteristics in both pre-launch and on-orbit phases, and to develop algorithms for compensating the potential biases before the wind inversion. The concept of satellite wind scatterometry and its scope are as follows:

1) Pre-launch activities: measure accurately the parameters that may affect the estimation of radar backscatters, including the antenna gain pattern, the transmit power, the receiver gain, the system loss, and the antenna pointing angles.
2) On-orbit operation: operate the instrument in different modes to meet the mission requirements, including regular T/R mode, noise measurement, internal calibration, and ground station calibration mode.
3) Ground processing: estimate the radar backscattering coefficients based on the onboard measurements, calibrate the raw σ^0s using the active radar calibrator or the extended surface targets, such as sea surface, amazon rainforests, homogeneous ice surface etc., and retrieve the sea surface vector winds from the calibrated σ^0s.

6. Requirements for pre-launch phase

6.1 General

In the pre-launch phase, the characteristics of scatterometer instruments shall be precisely specified and verified, and such characteristics should be recorded in the ground segment for the ground processing purposes. This section explains the requirements for designing, manufacturing and ground testing. The parameters and their values acquired through the pre-launch ground test should be disseminated to the ground processing system for accurate calibration and wind inversion.

6.2 Design and manufacturing

This subsection defines the requirements for the sensor instrument, the spacecraft and the ground segment. The following requirements shall be considered throughout design, manufacturing and ground test phase.

6.2.1 Instrumental requirements

The requirements for the sensor instrument, especially for the following subsystems are described.

a) Transmitter (Tx) sub-system;
b) Receiver (Rx) sub-system;
c) Internal calibration unit;
d) Antenna sub-system (ANT); and
e) Data processor.

6.2.1.1 Transmitter sub-system

The transmitter sub-system mainly consists of Radio Frequency Unit (RFU) and High Power Amplifier (HPA).

a) The RFU is designed to generate the low level transmit signal, which drives the HPA. It also generates the calibration signal and provides the reference signal for down-conversion within the receive module. The modern satellite scatterometers usually adopt chirped signals for the transmitter.
b) The RFU shall provide chirps with desired start frequencies and chirp slopes with high stability during the measurement phase.
c) The main design requirements of the HPA are to generate sufficient output power at as high efficiency as possible with a constant output level over the pulse's duration.
d) Moreover, the harmonic and spurious outputs from the HPA shall be controlled tightly in order to be compatible with other instruments on the satellite.

6.2.1.2 Receiver sub-system

a) The receiver sub-system are mainly designed to provide the echo amplification and down-conversion within the receive module.
b) Moreover, it digitizes the analogue echo data and the transmitted and reflected power data using analogue-to-digital converters.
c) A important element of the receiver sub-system is the low-noise amplifier, which as the first active element of the receive chain has an important role in determining the system noise figure, hence shall have a very low noise figure.

6.2.1.3 Internal calibration unit

The internal calibration unit gives an indication of how the combination of transmitter power and receiver gain is varying and allows changes in these parameters to be compensated. It consists of a measurement of the output power during the transmit pulse, the injection into the receiver of a signal proportional to the transmit pulse at a point in the inter-pulse period, and monitoring of the magnitude of this signal at the receiver output.

a) The injected signal should be much larger than the system noise to ensure a high signal-to-noise ratio, but would not cause saturation in the receiver output.
b) Loss of the internal calibration coupler shall be accurately measured, and have a high stability to minimize the internal calibration errors.

6.2.1.4 Antenna sub-system

a) The main requirements for the antenna sub-system are to design antennas with high gain to ensure an adequate link budget, and low gain slopes, high gain stability and high pointing accuracy to minimize radiometric errors. Side-lobe performance has driven the antenna design in order to minimize the reception of echo signals from outside the desired measurement cells, notably the scattering from the satellite.

b) High antenna gain stability shall be acquired through a combination of low antenna-temperature variation over the orbit and low antenna-gain sensitivity to temperature. As such, it usually requires careful design of the antennas' passive thermal-control elements and its thermal stability, which latter can be achieved by covering the aperture surface with a combination of aluminum tape and silver paint in a carefully selected ratio.

6.2.1.5 Digital Data Processor

The digital data processor (DDP) shall be designed to process and output the observation data, the noise measurements, and the internal calibration data, together with the information of the sensor status and the ancillary data required for high level data processing.

a) All the output data shall be specified in accordance with the design of the ground processing system.

b) The main processing flow of DDP is: windowing of the digital samples, Fourier transformation, squared-modulus detection, data compression and finally formatting of the data, together with time stamps and further auxiliary data, into data packages.

6.2.2 Spacecraft requirements

The spacecraft bus shall be designed and manufactured carefully, especially considering the following interface items with the sensor instrument:

1) RF interface;
2) Spacecraft attitude; and
3) Data downlink.

6.2.2.1 RF interface

The design of RF interface shall meet the following requirements:

a) The RF interface shall comply with the interface control specification to avoid excessive RF radiative emission which may interfere with the satellite scatterometer. ISO_14302 or similar standards shall be referred to with the objective of obtaining the design criteria for interference and damage level.

b) Interface design requirements shall be specified to avoid muilt-path RF interference due to the Tele-communication, tele-command devices, and/or data transmission devices, in order to avoid a degradation of sensor performance.

6.2.2.2 Spacecraft attitude

a) The spacecraft attitude shall be accurately measured and delivered to the data processor of scatterometer, in order to determine the observation geometry in the ground segment.

b) Errors of spacecraft attitude shall be specified in the interface control specification, considering the accuracy requirements of observing σ^0 and geo-position.

6.2.2.3 Data downlink

The observation, noise measurement and calibration data, together with the information specified in 6.2.2.2, shall be delivered to the ground processing system at certain time slot determined in the interface control specification between the spacecraft, the sensor instruments and the ground segment.

6.2.3 Ground segment requirements

The ground segment is designed to receive the satellite downlinked data, acquire ancillary data for L1 and L2 processing, calculate Earth surface radar backscatter coefficients and perform wind inversion.

a) The ground segment shall process both observation and internal calibration data to eliminate the effects of potential fluctuations associated with the transmitted power and the receiver gain;
b) The ground segment shall acquire ancillary data that are needed to perform external calibration, and in turn, to mitigate the potential biases associated with the antenna gain pattern.
c) The ground processing system, including the L1 and L2 processors, shall be designed to comply with the interface control specification.

7. Data processing and verification

7.1 Level one processing

7.1.1 Noise subtraction

The observation data and the noise measurements are split into two different streams. Noise measurements are used to estimate the shape of receiver-chain spectral-transfer characteristic and also to compute and subtract receiver noise power. These items must be determined before the relevant procedures of observation data can be processed.

a) The observation data is first corrected to compensate for the shape of the receiver-chain spectral transfer characteristic.
b) An estimate of the receiver noise power is then subtracted to acquire the “pure” Earth reflection signal.

7.1.2 Internal calibration

a) The resulting signal of section 7.1.1 is divided by the power-gain product, which compensates for variations in transmitted RF power and receiver gain. The power gain products are computed for each echo using various power measurements made by the instrument for internal-calibration purposes.
b) The resulting signal is then divided by a normalization function accounting for slant range, antenna gain pattern and orientation, incidence angle, instrument configuration, etc., in order to convert the signal-power values to σ^0 values. This function varies with cross-track position, observation azimuth angle and orbital position, which is essentially determined by summing up the contributions to the power at a particular discriminator frequency from all elemental areas on the surface of the Earth.

c) The normalization function is computed as a function of signal frequency, azimuth angle and orbit time, and is then stored as a look-up table for the sake of computational efficiency. If any of the various contributing elements are changed, the look-up table has to be recomputed.

7.1.3 Geo-location

After the internal calibration and the normalization processes, spatial coordinates in terms of latitude and longitude are associated to the σ^0 values. The essential requirements are as follows:

a) First, establish the relation between slant range and discriminator signal frequency.
b) Then, retrieve the corresponding position from the slant range and orbital position using an Earth model and a model of the satellite's orbit and attitude.

7.1.4 External calibration

The external calibration is designed to estimate the in-flight antenna patterns. Basically, the external calibration is performed using the ground calibration stations and/or the extended surface targets, such as sea surface, amazon rainforests, homogeneous ice surface, etc.

a) In case that the ground calibration stations are used, the satellite scatterometer shall be operated in the calibration mode during certain limited periods in the satellite's lifetime specifically assigned to the observation of external calibration transponders.
b) During overflight of a transponder, only a few samples cutting through the antenna gain pattern are obtained. The overall in-flight antenna gain pattern can be only determined when a sufficiently large number of cuts have been acquired.
c) In case that the extended surface targets are used, the satellite scatterometer shall be operated in the nominal measurement mode. Since this method is based on comparing the probability density function of the measured backscatter data with the known backscatter data from the extended surface targets, it also requires large amount of samples accumulated during certain periods. Moreover, the radar backscatter characteristics of the extended surface targets shall be well-known or modeled.

7.2 Level two processing

7.2.1 Grid generation

Following the processing philosophy, the observing swath of satellite scatterometers is artificially separated into a set of nearly equidistant grids across and along sub-satellite track. The grids are defined based on Keplerian elements or the satellite position and velocity vectors included the L1 data.

a) Use the orbit propagator to compute the sub-satellite positions and the ground velocities.
b) The line for the cross-track grids is computed as the intersection of the plane with

normal to the ground-velocity vector and the earth ellipsoid. The intersection is an ellipse.

c) The grids are finally computed by variation of the angle between the ellipse semi-major axis and the vector to the grids' center position.
d) The definition of grid size shall take the number of independent measurements within a certain area, as well as the user requirements, into account.
e) The grids, which are usually named as wind vector cells, are normally numbered from the left-most side to the right-side of the swath.

7.2.2 Slice aggregation

The high-resolution σ^0 measurements with similar incidence and azimuth angles are averaged in a defined swath grid in order to reduce the noise effect and to improve the inversion efficiency. Regarding a swath grid of 25-km resolution, the slices used in the aggregation are normally with incidence difference less than 2° and with azimuth difference less than 6°. Typically, more than two views are acquired at each WVC. A weighted average is performed to estimate the following variables for each WVC view:

a) σ^0;
b) Signal-to-noise (SNR) ratio;
c) Latitude;
d) Longitude;
e) Incidence angle;
f) Azimuth angle;
g) The normalized measurement error coefficients (K_p).

7.2.3 Wind inversion

A set of aggregated σ^0 measurements in each WVC is inverted into a set of ambiguous wind solutions using a geophysical model function (GMF) that relates wind vector and radar backscatter measurements for a certain observing geometry, polarization, and radar operating frequency. The main factors of wind inversion are as follows:

a) Geophysical model function. Since the interactions between long and short waves are not trivial, and phenomena such as breaking waves, foam, formation of slicks, etc., contribute in different ways, not yet well understood, to the density of the gravity-capillary waves, the theoretically modeled GMF is not satisfactory for the wind inversion. Hence, the empirical GMF is widely used and highly recommended for sea surface wind retrieval from radar backscatter measurements. Several GMFs are available and tuned for different radar instruments. However the basic formulation is common to all satellite scatterometers.
b) The number of independent σ^0 from the same WVC is of particular importance for a successful inversion of the two unknowns. Two or more views with good azimuth diversity among views are required to well determine the ambiguous wind solutions, notably the wind direction ambiguity.
c) The point-wise technique called Maximum Likelihood Estimation is widely used to invert winds. The Maximum Likelihood Estimation (MLE) can be interpreted

as a measure of the distance between a set of σ^0 measurements and the solution lying on the GMF surface in a *N*-dimensional space.

7.2.4 Quality control

Quality control (QC) is required to discern between good- and poor-quality winds, such that the latter can be filtered out. The recommended QC method is developed by analyzing the characteristics of certain quality-sensitive indicators derived from scatterometer data itself, and by optimizing the thresholds of these indicators in order to filter (preserve) as many poor (good) quality winds as possible. Several quality-sensitive indicators are proposed as follows for the QC purposes:

a) A commonly used QC indicator is the inversion residual or maximum likelihood estimator (MLE), which depicts the minimum distance between the backscatter measurements and the scatterometer GMF. A large inconsistency with the GMF results in a large MLE, which indicates geophysical conditions other than those modeled by the GMF, such as for example rain, confused sea state, or ice.

b) The singularity exponent (SE), derived from an image processing technique, called singularity analysis, depicts the degree of local regularity (spatial gradient) around a given point *x* for a given scalar signal *s*. Negative SE values correspond to less regular behavior of the function, while positive SE values indicate a more regular behavior.

c) J_{oss}, which is defined as the difference between the 2-Dimensional Variational Ambiguity Removal (2DVAR) analysis wind speed and the selected observational wind speed, is also an indicator representing the spatial heterogeneity due to the scale difference between rainy and non-rainy wind fields.

The above three QC indicators are complementary in terms of identifying the non-wind geophysical phenomena, such that it is recommended to combine them for the scatterometer wind QC.

7.2.5 Ambiguity removal

Ambiguity removal (AR) is the process of selecting a unique wind solution out of a set of ambiguous wind vectors at each WVC. There are two AR techniques commonly used in scatterometry, i.e., median filter and variational analysis.

1) Median filter:
    a) The wind field over an entire orbit of scatterometer data is initialized with the help of a reference wind, e.g., NWP forecasts. For each particular WVC, the first rank or the second rank wind vector solution, whichever is closer to the NWP field, is selected as first guess wind. The number of ranked solutions used for initialization does not necessarily need to be two.
    b) The wind vectors in a *N* x *N* filter window determine a median vector for the center WVC. The ambiguous solutions in that WVC are compared with the median vector, and the closest ambiguity to the median is selected for use in the next iteration. All the WVCs are filtered in that way. The process continues until it converges.

2) 2D variational analysis scheme (2D-Var):
    a) The probability of each ambiguos solution is derived empirically and used explicitly in this AR technique.
    b) A conjugate gradients method is used to solve the minimization problem of the 2D-var cost function. After convergence, the control variable vector of wind increments is added to the background field to obtain the wind analysis.
    c) At each WVC, the ambiguous solution which is closest to the wind analysis is selected as the final wind solution.

7.3 Verification

It is relevant to verify the characteristics of scatterometer winds for providing useful guidance to wind users in terms of most appropriate product for their application. Moreover, it is significant for understanding product fort further development and advanced analysi.

7.3.1 Reference winds

Scatterometer wind vectors are conventionally validated using collocated in-situ observations (e.g., buoy) and numerical weather predictions (NWP) winds, such as from the European Centre for Medium range Weather Forecasting (ECMWF).

1) Buoy winds:
    a) It is highly recommended to use the moored buoy data, including the National Data Buoy Center (NDBC) moored buoys off the coasts of U.S.A., the Ocean Data Acquisition System (ODAS) buoys in the north-east Atlantic and British Isles inshore waters, the National Oceanic Atmospheric Administration (NOAA) Tropical Ocean Atmosphere (TAO) buoy arrays in the tropical Pacific, the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) Triangle Trans-Ocean Buoy Network (TRITON) buoys in the western Pacific, the Prediction and Research Moored Array in the Atlantic (PIRATA), and the Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction (RAMA) at the tropical Indian Ocean.
    b) The buoy winds should be quality controlled, and be converted to winds at 10-m height above the sea surface using the Liu-Katsaros-Businger model or other similar model of height conversion.
    c) The collocation criteria for buoy winds are 30 minutes and 25 km distance from the scatterometer measurements.
2) NWP winds:
    a) The NWP forecast winds or re-analysis winds are usually used in the verification of scatterometer-derived vector winds.
    b) The NWP winds are collocated with the scatterometer measurements by interpolating both spatially and temporally to the scatterometer data acquisition location and time.

7.3.2 Direct comparison

A direct comparison is performed by calculating the mean and the standard deviation values of the difference between scatterometer and reference wind components, e.g., speed, direction, zonal wind component *u*, and/or meridional wind component *v*, respectively. For wind direction, the mean and SD values are estimated by taking the circular characteristics of wind direction into account, e.g., using the Yamartino method.

The Pearson correlation coefficient between scatterometer and reference wind components is also used to verify how close the scatterometer winds match with the reference winds.

7.3.3 Wind spectra

The Spectra of wind vector components are important for assessing the spatial characteristics of atmospheric motions, and for estimating representation errors in the triple collocation method. Given a sample of *N* wind measurements at regular distances, the spectrum is calculated as the periodogram of the sample. This can be done in two equivalent ways:

a) The sampling method: Fourier transform the sample with an FFT algorithm and take the square of the absolute value of each frequency component.
b) The moments method: Calculate the mixed second order moment (or autocorrelation) and Fourier transform with an FFT algorithm.

The dimension of wind spectra is m^3/s^2, which is generally presented as a function of the spatial frequency.

7.3.4 Spatial variance

The variance associated with wind fields at different scales plays a essential role in various branches of geophysics and meteorology. In wind scatterometry, spatial variance gives an accurate estimate of the Kinetic energy variance as a function of spatial scale for wind fields.

Spatial variances are sample variances averaged over all samples as a function of sample length. In terms of numerical calculation, spatial variances are usually defined through first and second moments. In practice, the data set can be divided into samples each containing $n+1$ points that are of interest, the variance over each sample is calculated, and all variances are averaged.

7.3.5 Triple collocation analysis

Triple collocation (TC) analysis is a technique for estimating the unknown error standard deviations (or RMSEs) of three mutually-independent measurement systems, without treating any one system as perfectly-observed “truth”.

Given a set of collocated measurements from the above mentioned three different sources, choosing one data source as calibration reference and assuming that linear calibration suffices to calibrate the other two relative to the reference, one can estimate the random measurement errors as well as the relative calibration coefficients for each wind data source independently.