Product User Manual (PUM) for the Ku-band wind data records

SeaWinds 25 km winds 2nd reprocessing (OSI-151-c)

SeaWinds 50 km winds 2nd reprocessing (OSI-151-d)

Oceansat-2 25 km winds 2nd reprocessing (OSI-153-c)

Oceansat-2 50 km winds 2nd reprocessing (OSI-153-d)

RapidScat (ISS) 25 km winds 1st reprocessing (OSI-159-a)

RapidScat (ISS) 50 km winds 1st reprocessing (OSI-159-b)

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Document Change record

Document version	Software version	Date	Author	Change description
0.9		Mar 2022	AV	First version for Delivery Readiness Review
1.0		Oct 2022	AV	Updates according to DRR RIDs
1.1		Jul 2023	AV	Corrected a few typos

Table of contents

List of tables

1. Introduction

1.1. Overview

The complete data records from the Ku-band scatterometers SeaWinds on QuikSCAT (19 July 1999 - 21 November 2009), OSCAT on Oceansat-2 (15 December 2009 - 20 February 2014) and RapidScat on the International Space Station (ISS) (3 October 2014 - 19 August 2016) have been reprocessed using the Pencil Beam Wind Processor (PenWP). ERA5 re-analysis winds from the European Centre for Medium-Range Weather Forecasts (ECMWF) have been used to initialise the ambiguity removal step in the wind processing and for validation and monitoring of the wind retrievals. The resulting Ocean and Sea Ice Satellite Application Facility (OSI SAF) wind Data Records can be obtained from the EUMETSAT Data Centre. The PenWP software is developed within the OSI SAF and can be obtained through the Numerical Weather Prediction Satellite Application Facility (NWP SAF) website.

The EUMETSAT OSI SAF produces a range of air-sea interface products, namely: wind, sea ice characteristics, Sea Surface Temperatures (SST) and radiative fluxes, Surface Solar Irradiance (SSI) and Downward Long wave Irradiance (DLI). The Product Requirements Document [1] provides an overview of the committed products and their characteristics in the current OSI SAF project phase, the Service Specification Document [2] provides specifications and detailed information on the services committed towards the users by the OSI SAF in a given stage of the project.

KNMI is involved in the OSI SAF as the centre where the level 1 to level 2 scatterometer wind processing is carried out. This document is the Product User Manual to the Ku-band wind data records. More general information on the OSI SAF project is available on the OSI SAF website: https://osi-saf.eumetsat.int/. The user is strongly encouraged to register on this website in order to receive the service messages and the latest information about the OSI SAF products. An email newsletter is available as well after subscription on https://osi-saf.eumetsat.int/newsletter. More information about these products can also be found on https://scatterometer.knmi.nl/.

The scatterometer is an instrument that provides information on the wind field near the ocean surface, and scatterometry is the knowledge of extracting this information from the instrument's output. Space-based scatterometry has become of great benefit to meteorology and climate in the past years. This is extensively described in the Algorithm Theoretical Baseline Document, see [3].

KNMI has a long experience in scatterometer processing and is developing generic software for this purpose. Processing systems have been developed for the ERS, NSCAT, SeaWinds, ASCAT, OSCAT, RapidScat, and HSCAT scatterometers. Scatterometer processing software is distributed through the NWP SAF, whereas wind processing is performed operationally in the OSI SAF.

This user manual outlines user information for the OSI SAF Ku-band wind data records from QuikSCAT/SeaWinds, Oceansat-2/OSCAT and ISS/RapidScat on 25 km and 50 km grid spacing. Detailed information on the file content and format is given in section 2. Section 3 provides the motivation and justification for reprocessing these datasets, section 4 presents a brief description of the different instruments, and section 5 gives an overview of the data processing configuration. The product quality is elaborated in the validation report to these products [4].

1.2. Acknowledgements

The QuikSCAT and RapidScat level 1b data have been obtained from the NASA JPL Physical Oceanography Distributed Active Archive Center (PO.DAAC) web portal.

ISRO has provided the near-real time Oceansat-2 level 1b data which were used as input for the OSI SAF wind products. Alexander Fore of JPL has kindly provided their archived OSCAT data record to the OSI SAF.

1.3. Disclaimer

All intellectual property rights of the OSI SAF products belong to EUMETSAT. The use of these products is granted to every interested user, free of charge. If you wish to use these products, EUMETSAT's copyright credit must be shown by displaying the words "copyright (year) EUMETSAT" on each of the products used.

The OSI SAF is much interested in receiving your feedback, would appreciate your acknowledgment in using and publishing about the data, and we like to receive a copy of any publication about the application of the data. Your feedback, e.g., directed to scat@knmi.nl, helps us in maintaining the resources for the OSI SAF wind services.

1.4. Useful links

KNMI scatterometer website: https://scatterometer.knmi.nl/

Information on OSI SAF activities at KNMI: https://scatterometer.knmi.nl/osisaf/

OSI SAF wind product documentation on https://osi-saf.eumetsat.int

NWP SAF website: https://nwp-saf.eumetsat.int/

EUMETSAT Data Centre: https://www.eumetsat.int/eumetsat-data-centre

QuikSCAT information on PO.DAAC website: https://podaac.jpl.nasa.gov/QuikSCAT

Oceansat-2 information on ISRO website: https://www.isro.gov.in/Spacecraft/oceansat-2

ISS-RapidScat information on PO.DAAC website: https://podaac.jpl.nasa.gov/ISS-RapidScat

1.5. Helpdesk and data availability

For a swift response management procedure, user requests on the OSI SAF data products should be issued at the Ocean and Sea Ice SAF website.

A BUFR reader is available at https://scatterometer.knmi.nl/bufr_reader/.

Unique Digital Object Identifiers (DOIs) are attached to the data records. A landing page containing the latest product availability information and documentation is connected to the DOI:

http://dx.doi.org/10.15770/EUM_SAF_OSI_0016 SeaWinds 25 km winds (OSI-151-c)

http://dx.doi.org/10.15770/EUM_SAF_OSI_0017 SeaWinds 50 km winds (OSI-151-d)

http://dx.doi.org/10.15770/EUM_SAF_OSI_0018 Oceansat-2 25 km winds (OSI-153-c)

http://dx.doi.org/10.15770/EUM_SAF_OSI_0019 Oceansat-2 50 km winds (OSI-153-d)

http://dx.doi.org/10.15770/EUM_SAF_OSI_0020 RapidScat (ISS) 25 km winds (OSI-159-a)

http://dx.doi.org/10.15770/EUM_SAF_OSI_0021 RapidScat (ISS) 50 km winds (OSI-159-b)

The products are available (after registration) from the EUMETSAT Data Centre. The approximate data sizes per orbit file and for the entire data set are listed in the table below.

Product	Format	One orbit file	Entire data record
QuikSCAT 25 km	BUFR	12 MB	620 GB
	NetCDF (g-zipped)	1.2 MB	65 GB
QuikSCAT 50 km	BUFR	3.0 MB	155 GB
	NetCDF (g-zipped)	350 kB	19 GB
Oceansat-2 25 km	BUFR	12 MB	220 GB
	NetCDF (g-zipped)	1.2 MB	24 GB
Oceansat-2 50 km	BUFR	3.0 MB	55 GB
	NetCDF (g-zipped)	350 kB	7.2 GB
RapidScat 25 km	BUFR	6.5 MB	56 GB
	NetCDF (g-zipped)	650 kB	6.0 GB
RapidScat 50 km	BUFR	1.7 MB	15 GB
	NetCDF (g-zipped)	200 kB	1.8 GB

Table 1: File sizes per orbit and for the entire data records.

1.6. Limitations and remaining issues

At the time of writing this manual no limitations or issues were identified.

1.7. Reference and applicable documents

[1] OSI SAF,
Product Requirements Document,
SAF/OSI/CDOP3/MF/MGT/PL/2-001, 2021 (link)

[2] OSI SAF,
Service Specification Document,
SAF/OSI/CDOP3/MF/MGT/PL/003, 2021 (link)

[3] OSI SAF,
Algorithm Theoretical Basis Document for the scatterometer wind products,
SAF/OSI/CDOP2/KNMI/SCI/MA/197, 2022 (link)

[4] Verhoef, A., J. Vogelzang and A. Stoffelen,
Scientific Validation Report for the Ku-band wind data records,
OSI SAF report, SAF/OSI/CDOP3/KNMI/TEC/RP/415, 2022 (link)

[5] OSI SAF,
Reprocessed SeaWinds L2 winds Product User Manual,
OSI SAF report SAF/OSI/CDOP2/KNMI/TEC/MA/220, 2015 (link)

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Oceansat-2 L2 winds Data Record Product User Manual,
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Advances in Ku-band scatterometer Quality Control,
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SST Dependence of Ku- and C-Band Backscatter Measurements
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IEEE Transactions on Geoscience and Remote Sensing, **35**, 1, 115-126, 1997,
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IEEE Transactions on Geoscience and Remote Sensing, **52**, 10, 6197-6204, 2014,
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High-resolution ASCAT scatterometer winds near the coast,
IEEE Transactions on Geoscience and Remote Sensing, 2012, **50**, 7, 2481-2487,
doi:10.1109/TGRS.2011.2175001

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Improved Use of Scatterometer Measurements by Using Stress-Equivalent Reference Winds,
IEEE Journal of Selected Topics in Applied Earth O, 2017, 10, 5, 2340-2347,
doi:10.1109/JSTARS.2017.2685242

[17] Leidner, M., R. Hoffman, and J. Augenbaum,
SeaWinds scatterometer real-time BUFR geophysical data product, version 2.2.0,
NOAA/NESDIS, February 2000, available on ftp://www.scp.byu.edu/data/qscat/docs/bufr.pdf

[18] Thesis *Scatterometry* by Ad Stoffelen, 1998 (link)

[19] Thesis *Wind Field Retrieval from Satellite radar systems* by Marcos Portabella, 2002 (link)

2. Data description

2.1. Wind product characteristics

2.1.1. Physical definition

Horizontal stress-equivalent wind vector at 10 m height, obtained using the NSCAT-4DS GMF, see [3], [16].

2.1.2. Units and range

Wind speed is measured in m/s. The wind speed range is from 0-50 m/s, but wind speeds exceeding 25 m/s are generally less reliable [3]. In the BUFR products, the wind direction is in *meteorological* (World Meteorological Organisation, WMO) convention relative to North: 0 degrees corresponds to a wind flowing to the *South* with a clockwise increment. In the NetCDF products, the wind direction is in *oceanographic* convention: 0 degrees corresponds to a wind flowing to the *North* with a clockwise increment.

2.1.3. Input satellite data

The QuikSCAT and RapidScat level 1b input data [10] were obtained from PO.DAAC through their web portal. These 'Level 1B Time-Ordered Earth-Located Sigma0' data files contain both full footprint 'egg' data and high resolution 'slice' data. For QuikSCAT, the slice data were used and for RapidScat the egg data were used.

The Oceansat-2 level 1b input data [11] are provided by ISRO. The products contain geo-located backscatter measurements, each observation corresponds to a high resolution slice in a scatterometer pulse. The input data have version 1.3 until 18th May 2013 and version 1.4 after that date. It was checked that versions 1.3 and 1.4 have the same backscatter characteristics by comparing some overlapping data. The only significant difference is in the reported brightness temperatures but those are not relevant in the OSI SAF wind retrieval process. The brightness temperatures are reported though in the level 2 BUFR data.

2.1.4. Geographical definition

The swath width and orbit characteristics are different for the three missions, see section 4. The swath is composed of 76 25 km size WVCs or 38 50 km size WVCs in the case of QuikSCAT and Oceansat-2. For RapidScat, the swath is composed of 42 25 km size WVCs or 21 50 km size WVCs. Products are organised in files containing one orbit starting at the South Pole. Since the actual swath width scanned by the antenna varies with orbit height, it may be smaller than the defined swath grid width. Hence, outer swath WVCs may contain no winds due to a lack of backscatter data.

2.1.5. Output product

The level 1b input products are processed into BUFR output products including a unique wind solution (chosen), its corresponding ambiguous wind solutions and quality information (distance to cone, quality flag). The products are also available in NetCDF format; see section 8 for more details.

2.1.6. Expected accuracy

The expected accuracy is defined as the expected bias and standard deviation of the primary calculations. The accuracy is validated against in situ wind measurements from buoys, and against NWP data. Even better, the errors of all NWP model winds, in situ data, and scatterometer winds are computed in a triple collocation exercise [18]. The performance is pretty constant over the globe and depends mainly on the sub footprint wind variability. According to the OSI SAF product requirements [2] the accuracy should be better than 2 m/s in wind component standard deviation with a bias of less than 0.5 m/s in wind speed. More validation information is available in [4], showing that the actual product accuracy well exceeds the requirements.

2.2. File formats

Wind products are in BUFR Edition 4 or in NetCDF format. A complete description of BUFR can be found in WMO publication No 306, Manual on Codes.

The OSI SAF wind product is stored in exactly the same BUFR format as described in the SeaWinds BUFR manual from NOAA [17], a list of descriptors (fields) contained in each WVC is provided in section 7. Data are organised in files containing one orbit (approximately 100 minutes) of data.

2.2.1. File name conventions

The file name convention for the level 2 BUFR products is

OR2SWW025_YYYYMMDD_HHMMSS_ORBIT_QUIKSCAT.bufr (QuikSCAT 25 km)

OR2SWW050_YYYYMMDD_HHMMSS_ORBIT_QUIKSCAT.bufr (QuikSCAT 50 km)

OR2OSW025_YYYYMMDD_HHMMSS_ORBIT_OCEANSAT2.bufr (Oceansat-2 25 km)

OR2OSW050_YYYYMMDD_HHMMSS_ORBIT_OCEANSAT2.bufr (Oceansat-2 50 km)

OR1RSW025_YYYYMMDD_HHMMSS_ORBIT_RAPIDSCAT.bufr (RapidScat 25 km)

OR1RSW050_YYYYMMDD_HHMMSS_ORBIT_RAPIDSCAT.bufr (RapidScat 50 km)

- YYYYMMDD denotes the acquisition date (year, month and day) of the first data in the file
- HHMMSS denotes the acquisition time (hour, minute and second) of the first data in the file
- ORBIT is the orbit number of the first data in the file (00000-99999)

Examples of file names are

OR2SWW025_20040924_114539_27425_QUIKSCAT.bufr	for a 25 km QuikSCAT product
OR2OSW050_20120318_011356_13150_OCEANSAT2.bufr	for a 50 km Oceansat-2 product
OR1RSW025_20150911_021902_05484_RAPIDSCAT.bufr	for a 25 km RapidScat product

2.2.2. File contents

In each node or wind vector cell (WVC) 118 data descriptors are defined. In addition some extra information/alterations have been put in place:

- In the BUFR header the value for “generating centre” is set to 99, representing KNMI.
- The products contain up to four ambiguous wind solutions, with an index to the selected wind solution. After the wind inversion step, we initially store the up to four solutions corresponding to the inversion residual (Maximum Likelihood Estimator, MLE) relative minima. However, subsequently the wind speed, wind direction and MLE of the after 2DVAR-selected Multiple Solution Scheme (MSS) wind solution is put at the index of the selected wind solution. This index is set to the initial wind vector

solution which is closest to the MSS wind vector selection obtained after 2DVAR. Thus, the former wind vector is not provided in the product, but rather the MSS selected wind vector. The ‘Formal Uncertainty in Wind Direction’ does not contain the uncertainty, but the normalised inversion residual (referred to as Rn in [19]). The wind solutions (contained in BUFR fields 31 to 50) are ordered by inversion residual, starting with the lowest value.

- The ‘SeaWinds Probability of Rain’ and ‘SeaWinds NOF Rain Index’ BUFR fields are not used and contain missing data values.
- The Wind Vector Cell Quality Flag (table 021109) is redefined with respect to the WMO conventions and now has the following definitions:

Description	BUFR bit	Fortran bit	Integer value
Not used	1	16	
Not enough good sigma-0 available for wind retrieval	2	15	32768
Not used	3	14	16384
VV polarised data in more than two beams	4	13	8192
Product monitoring not used	5	12	4096
Product monitoring flag	6	11	2048
KNMI Quality Control (including rain) data rejection	7	10	1024
Variational QC data rejection	8	9	512
Land presence	9	8	256
Ice presence	10	7	128
Not used	11	6	
Reported wind speed is greater than 30 m/s	12	5	32
Reported wind speed is less than or equal to 3 m/s	13	4	16
Quality Control data rejection for visualisation and nowcasting	14	3	8
Rain flag algorithm detects rain	15	2	4
Data from at least one of the four possible beam/view combinations are not available	16	1	2
Missing value	All 17 set	All 17 set	

Table 2: Definition of flag bits in the Wind Vector Cell Quality Flag in BUFR.

In Fortran, if the Wind Vector Cell Quality Flag is stored in an integer **I** then use **BTEST(I,NDW-NB)** to test BUFR bit **NB**, where **NDW**=17 is the width in bits of the data element in BUFR. The **BTEST** function is equivalent to **(I/2^NF) modulo 2** where **NF** is the Fortran bit number. The last column in the table shows the integer value if only the given bit is set.

The flag indicating that more than two beams contain VV polarised data, Fortran bit 13, is active in the outer part of the swath (generally WVCs 1-9 and 68-76 at 25 km, WVCs 1-4 and 35-38 at 50 km). It indicates that outer beam data is used to obtain four independent σ^0 values, contrary to the middle part of the swath where two beams contain VV (outer beam) data and two beams contain HH (inner beam) data. In the outer parts of the swath, the VV backscatter data present in the level 1b product are distributed to two WVC beams based on their azimuth angle such that maximum azimuth dispersion is obtained. This generally results in slightly less optimal wind retrieval; users assimilating the data into NWP models may consider to reject WVCs for which this flag is set.

If the 'product monitoring not used' bit, Fortran bit 12, is set to zero, the product is monitored. If the product is monitored and the 'product monitoring flag' bit, Fortran bit 11, is set to zero, the product is valid; otherwise it is rejected by the product monitoring [3]. This is based on a statistical check of the number of WVC QC rejections, the wind speed bias with respect to the NWP background, and the wind vector RMS difference with respect to the NWP background. The product monitoring bits have the same value for all WVCs in one BUFR output file. Since all problematic data due to instrument issues already have been removed from the input data sets, product monitoring rejection does not occur in the wind data records.

If the KNMI QC flag, Fortran bit 10, is set in a WVC, then the backscatter information is not useable for various geophysical reasons like rain, confused sea-state etc, resulting in a too large inversion residual. WVCs in which the KNMI QC flag is set, are not used in the calculation of the analysis wind field in the ambiguity removal step. However, the analysis wind is computed for all WVCs over the ocean. The wind solution (out of the available 144 MSS wind solutions) closest to the analysis field is chosen, if wind solutions are present in the WVC. This means that such a QC-flagged WVC may contain a selected wind solution, but it is suspect.

The land presence flag, Fortran bit 8, is set if a land fraction (see section 5.3) larger than zero is calculated for the WVC. As long as the land fraction is below the limit value, a reliable wind solution may however still be present so there is normally no reason to reject WVCs with the land flag set.

The 'Rain flag algorithm detects rain' flag, Fortran bit 2, is set when the inversion residual in the WVC is too large, in such cases the 'KNMI Quality Control (including rain) data rejection' is set as well.

The Bayesian ice screening algorithm as implemented in PenWP is used in the processing. The ice presence flag, Fortran bit 7, is set if the Bayesian sea ice screening algorithm calculates ice for the WVC [3]. Note that the products contain wind solutions also over sea ice regions. These bogus winds are flagged both by the KNMI quality control flag and by the ice flag. Hence it is important to reject any winds with the KNMI quality control flag set when ingesting the products. Note that WVCs that are rejected due to a large inversion residual (e.g., in case of excessive local wind variability), only have the KNMI quality control flag set. On the other hand, WVCs that are rejected due to sea ice, have both the KNMI quality control flag and the ice flag set.

If the variational QC flag, Fortran bit 9, is set, the wind vector in the WVC is rejected during ambiguity removal due to spatial inconsistency. A wind solution is present, but it may be suspect.

It is recommended not to automatically use WVCs with the KNMI quality control flag (bit 10) or the variational quality control flag (bit 9) set. See [3] for more information on product reliability. However, in visualisation, the flagged data may be inspected in their meteorological context and hence be rather useful for trained meteorologists. For visualisation applications the use of the 'Quality Control data rejection for visualisation and nowcasting' flag (bit 3) is recommended, i.e., winds with this flag set should be considered with great care. This flag rejects less data than the 'KNMI Quality Control (including rain) data rejection' but it has good skill for such use [7].

3. Motivation for reprocessing

The QuikSCAT and Oceansat-2 data records have been reprocessed before and they have been released in 2015 [5] and in 2017 [6], respectively. The RapidScat winds have not been reprocessed before in the OSI SAF hence this is the first data record based on this mission. Since the previous product releases, several algorithm and other improvements have been implemented which justify a new reprocessing.

- Implementation of improved Quality Control [3], [7] resulting in a lower rejection rate of potentially suspect winds. Two new QC flags for Ku-band wind scatterometry are implemented, a conservative (NWP QC) flag to replace the old KNMI MLE flag for NWP applications, and a new, less conservative (visualisation/nowcasting QC) flag for visualisation applications. The NWP QC flag shows a better QC skill than the old MLE flag but at the same time it rejects significantly less winds (e.g. 3.9% vs. 5.8% rejections globally in the case of Oceansat-2). The visualisation QC flag shows a comparable skill as the old MLE flag and it rejects even less winds (2.6% for Oceansat-2). In Figure 1 the lower number of rejected winds (black wind flags) in the right hand side image is obvious.

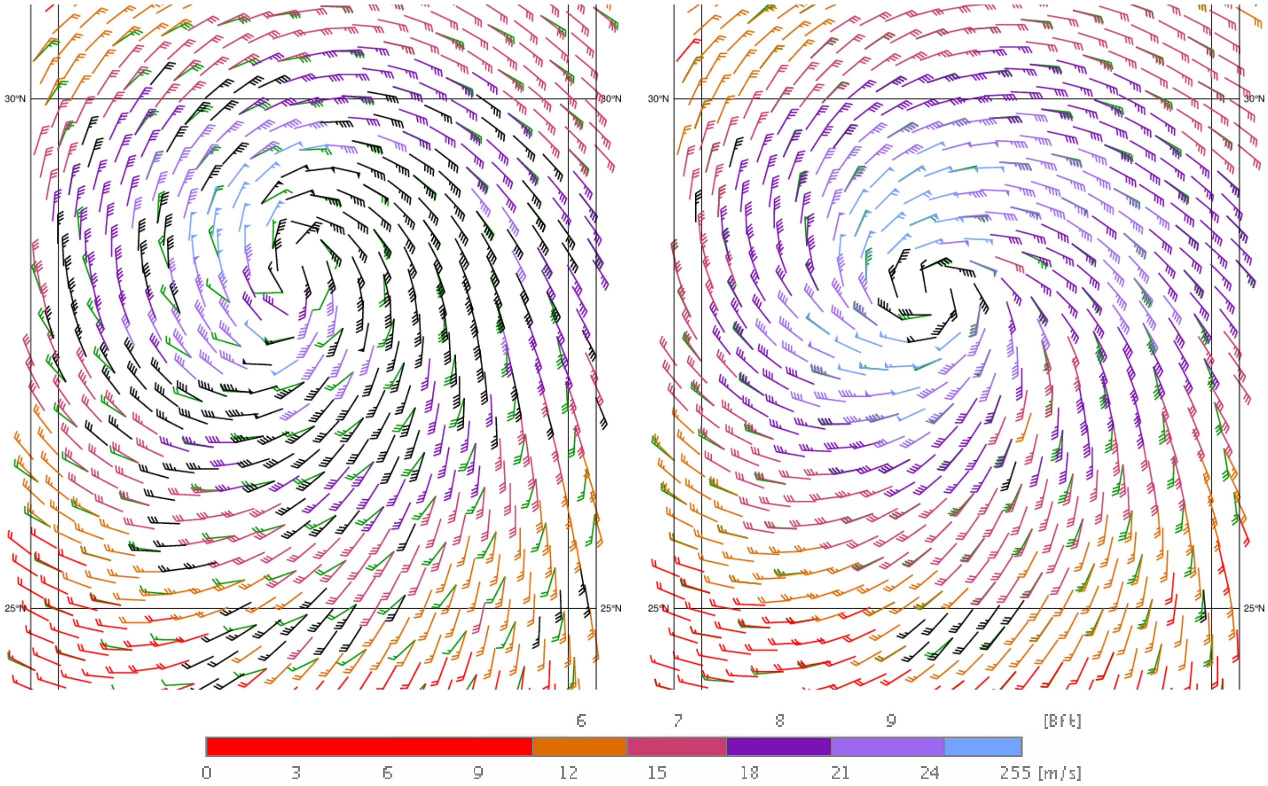

Figure 1: Oceansat 2/OSCAT wind field of hurricane Katia retrieved in the western Atlantic (28° N, 68° W) at 25 km Wind Vector Cell (WVC) spacing on 7 September 2011, approximately 4:15 UTC. Left hand side: product from the first reprocessing, right hand side: product from the current, second reprocessing. The scatterometer wind flags are coloured according to their Beaufort force, the ECMWF ERA-Interim (left) or ERA5 (right) NWP winds are plotted in green. Black flags indicate Wind Vector Cells flagged by the Quality Control due to e.g. heavy rain or confused sea state.

- The ECMWF ERA5 reanalysis winds are used instead of ERA-Interim winds to include in the products and to initialise the ambiguity removal step. ERA5 has been generated with a newer version of the

ECMWF Integrated Forecasting System and on a much higher resolution. In Figure 1 it is clear that in the ERA Interim NWP wind field (left, green wind flags) the cyclonic structure is too weak and located at the wrong position, in the ERA5 NWP wind field (right) this is much improved.

- Coastal processing is implemented for QuikSCAT and Oceansat-2, see section 5.3. This results in significantly more retrieved winds closer to the coast and between islands as can be seen in the right hand side of Figure 2.
- A Sea Surface Temperature (SST) dependent correction has been applied to the backscatter data in order to reduce systematic wind speed biases in colder and warmer areas [3], [8]. Figure 3 shows significantly reduced speed biases in the right hand side.

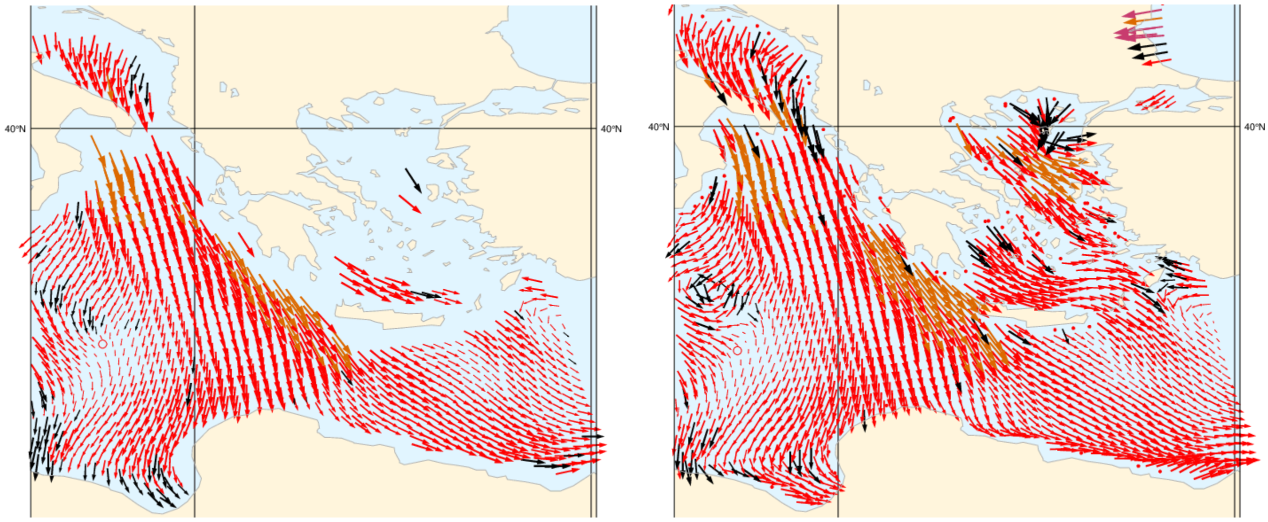

Figure 2: QuikSCAT/SeaWinds wind field retrieved in the eastern Mediterranean Sea (36° N, 23° E) at 25 km Wind Vector Cell (WVC) spacing on 2 January 2008, approximately 4:30 UTC. Left hand side: product from the first reprocessing, right hand side: product from the current, second reprocessing. The colour scale is the same as in Figure 1.

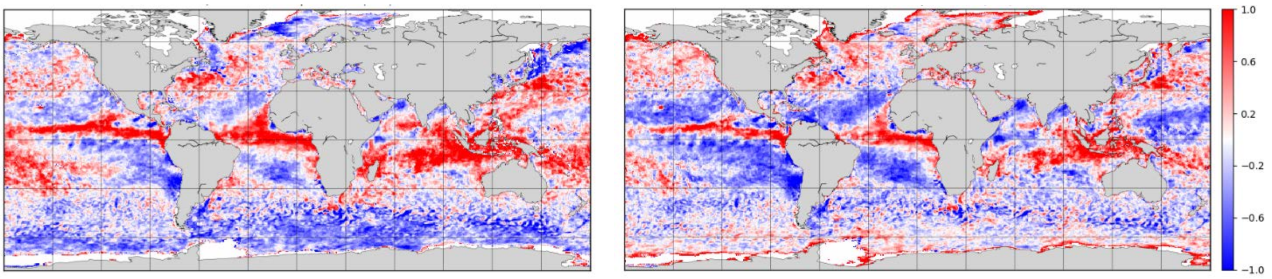

Figure 3: Average QuikSCAT/SeaWinds wind speed bias with respect to ERA5 stress-equivalent forecast winds for January 2001. Left hand side: product from the first reprocessing (ERA-Interim model winds in the products have been replaced by ERA5 winds for this image), right hand side: product from the current, second reprocessing.

- Ku-band pencil beam winds often have wind direction retrieval errors in the nadir swath due to poor beam azimuth separation. This leads to wind direction 'attractors' in the retrievals and hence biases. As compared to products from the previous reprocessing, the modulations have been considerably reduced due to improvements in the NSCAT-4DS Geophysical Model Function and refinements in the backscatter calibration [3] (Figure 4). NSCAT-4DS was derived using direct ScatSat-1 and ASCAT collocations, in order to bring the Ku band wind direction distributions closer to those from ASCAT and to match the wind speed probability distribution functions.

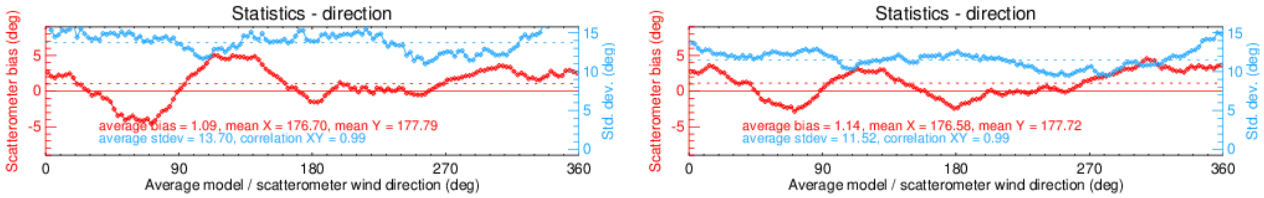

Figure 4: SeaWinds wind direction bias and standard deviation with respect to ERA5 stress-equivalent forecast wind direction as a function of average scatterometer / model wind direction, for 1 and 2 January 2001. Left hand side: product from the first reprocessing (ERA-Interim model winds in the products have been replaced by ERA5 winds for this image), right hand side: product from the current, second reprocessing.

4. Ku-band scatterometer missions and instruments

This document covers the wind data records from three missions which will be briefly described in this section.

The SeaWinds scatterometer is carried on-board the QuikSCAT polar satellite. It was launched on 19 June 1999. The QuikSCAT mission was a ‘quick recovery’ mission from the National Aeronautics and Space Administration (NASA) to fill the gap created by the loss of data from NSCAT, when the ADEOS-1 satellite lost power in June 1997. The QuikSCAT nominal mission ended on 23 November 2009 due to problems with the SeaWinds instrument antenna spinning mechanism. The 1800 km-wide swath covers 90% of the ocean surface in 24 hours. A similar version of the instrument (SeaWinds-2) flew on the Japanese ADEOS-2 satellite, launched in December 2002, which was regrettably lost in October 2003. For detailed information on the instrument and data we refer to [9] and [10].

The OSCAT scatterometer is one of the three instruments carried on-board the Oceansat-2 polar satellite, launched and operated by the Indian Space Research Organisation (ISRO). It was launched on 23 September 2009. The mission ended on 20 February 2014 due to an unrecoverable instrument anomaly. The daily coverage of the swath is comparable to QuikSCAT. For detailed information on the OSCAT instrument and data we refer to [11].

The RapidScat scatterometer instrument is a speedy and cost-effective replacement for the QuikSCAT satellite. QuikSCAT's measurements were essential and when the satellite stopped collecting wind data in late 2009, NASA was challenged to quickly and cost-effectively conceive of a replacement. NASA's Jet Propulsion Laboratory and the agency's station program came up with a solution that uses the framework of the International Space Station (ISS) and reuses hardware originally built to test parts of QuikSCAT, to create an instrument for a fraction of the cost and time it would take to build and launch a new satellite. RapidScat was launched on 20 September 2014 and mounted on the ISS. The mission ended on 19 August 2016 due to an unrecoverable instrument anomaly. The observation swath covers the majority of the oceans between 56° north and south latitude in 48 hours. The orbit, which is not sun-synchronous, gives different overpass times for each day and as such allows cross-calibration with other instruments on polar satellites, like ASCAT and HY-2A. For detailed information on the RapidScat instrument and data we refer to [9] and [10].

The three missions all have a conically scanning pencil-beam scatterometer on board. Some mission-specific information and numbers are collected in the table below. The radar instrument uses a rotating dish antenna projecting two “spot” beams on the ground: a horizontal polarisation beam (HH) and a vertical polarisation beam (VV) at different incidence angles. They sweep the surface in a circular pattern as depicted in the OSCAT example in Figure 5. Due to the conical scanning, a WVC is generally viewed when looking forward (fore) and a second time when looking aft. As such, up to four measurement classes (called “beam” here) emerge: HH fore, HH aft, VV fore, and VV aft, in each wind vector cell (WVC). The egg-shaped beam footprints are divided into slices by applying a modulated chirp signal for QuikSCAT and Oceansat-2. Since the International Space Station provides a less stable orbital platform, it was decided to use the lower resolution footprint (‘egg’) data for wind processing rather than the ‘slice’ data for RapidScat. Since the beam footprints are larger than the slices, they will slightly overstep the Wind Vector Cell borders leading to a slightly lower effective spatial resolution.

	QuikSCAT SeaWinds	**Oceansat-2 OSCAT**	**ISS RapidScat**
Orbit inclination (°)	98.6	98.2	51.6
Repeat cycle (days)	4	2	N/A
Local time at ascending node	6:00 AM	0:00 AM	varying
Orbit altitude (km)	810	720	375 – 435
Antenna dish size (m)	1.0	1.0	0.75
Antenna rotation speed (rpm)	18	20	18
Swath width (km)	1800	1800	1100
Footprint size on ground (km)	25 × 55	46 ×52 (HH) 31 x 65 (VV)	25 × 35
HH beam incidence angle (°)	46	49	49
VV beam incidence angle (°)	54	57	56

Table 3: Mission and instrument characteristics.

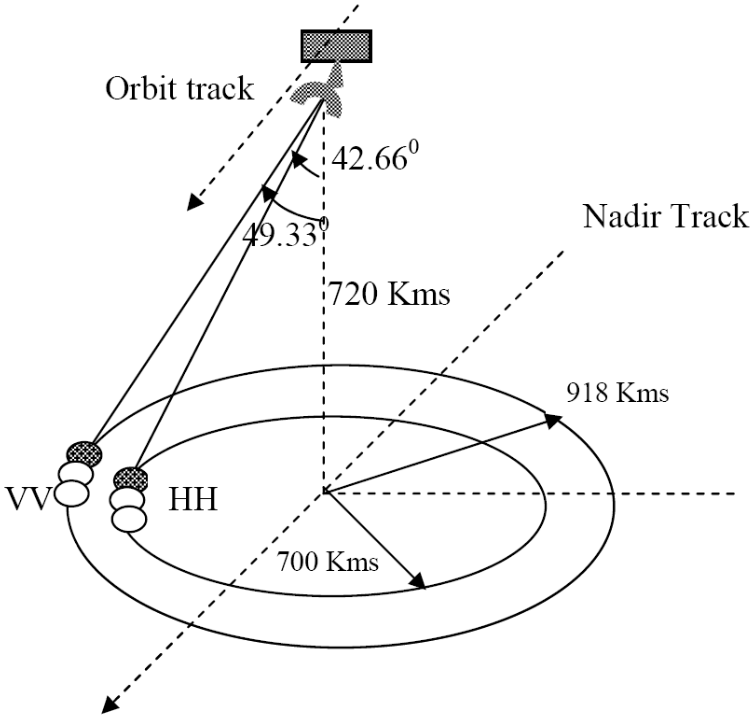

Figure 5: OSCAT pencil beam geometry (source: [11]).

The wind retrieval from rotating pencil beam instruments is not trivial. In contrast with side-looking scatterometers like ASCAT, the number of measurements and the beam azimuth angles vary with the sub-satellite cross-track location. The wind retrieval skill will therefore depend on the position in the swath. A detailed discussion is provided in [3]. Here we only summarise some issues specific to this type of instrument.

In the outer swath (where only VV beam data are available), the individual backscatter measurements (‘eggs’ or ‘slices’) contributing to the fore or aft beam in a specific WVC are ordered by their azimuth angles. Two groups with the same amount of measurements are formed with lower and higher azimuth angles. These groups are accumulated and averaged separately to form two independent WVC views. This is done separately for the VV fore and aft data, resulting in a total of four independent WVC views. The outer swath winds have slightly reduced quality control skill, but they are still very well usable, depending on the application. These winds are flagged in the product and can be filtered out easily if requested, see section 2.2.

The instruments operate at a Ku-band radar frequency (13.3 GHz corresponding to ~2 cm wavelength). The atmosphere is not transparent at these wavelengths and in particular rain is detrimental for wind computation. In fact, moderate and heavy rain cause bogus wind retrievals of 15-20 m/s wind speed which need to be eliminated by a Quality Control (QC) step. Wind-rain discrimination is easiest to manage in the sweet swath, but still performs acceptably in nadir and outer swath, see the figure in Section 2 of [3] for the definition of swath regions. The QC skill for Ku-band wind retrievals has been improved recently due to the use of the so-called J_{oss} parameter which is computed from the analysis wind field in the 2DVAR ambiguity removal step [7].

The algorithms for the wind processing are quite generic. When calibrated geophysical backscatter measurements are available, the wind processing of the different Ku-band pencil-beam scatterometers is very similar. The wind processing software which is used, the Pencil beam Wind Processor (PenWP), is the successor of the SeaWinds Data Processor (SDP) and the OSCAT Wind Data Processor (OWDP). PenWP is capable to process data from SeaWinds, OSCAT, RapidScat and HSCAT scatterometers and replaces all former pencil beam Ku-band wind processing software packages.

Differences between the various rotating pencil beam scatterometers are to a great extent on a technical (data formats and handling) level. Moreover, due to different orbits and antenna geometries, incidence angles differ. PenWP utilises the NSCAT-4DS Geophysical Model Function (GMF) [3], which is available for all prevailing incidence angles. In order to handle instrument differences well, particularly noise characteristics, some parts of the processing were re-tuned, mainly the normalisation of the Maximum Likelihood Estimator (MLE) and the tuning of the Quality Control [3].

5. Processing scheme

Figure 6 shows the system architecture to generate the wind data sets. The processing environment consists of a set of software components to do data conversions, collocate scatterometer data with ECMWF model data, to generate the wind data and to convert the output BUFR data into level 2 NetCDF data. General information about the scatterometer wind processing algorithms can be found in the Algorithm Theoretical Basis Document (ATBD) [3]. The PenWP [12] software version used is 2.2.08.

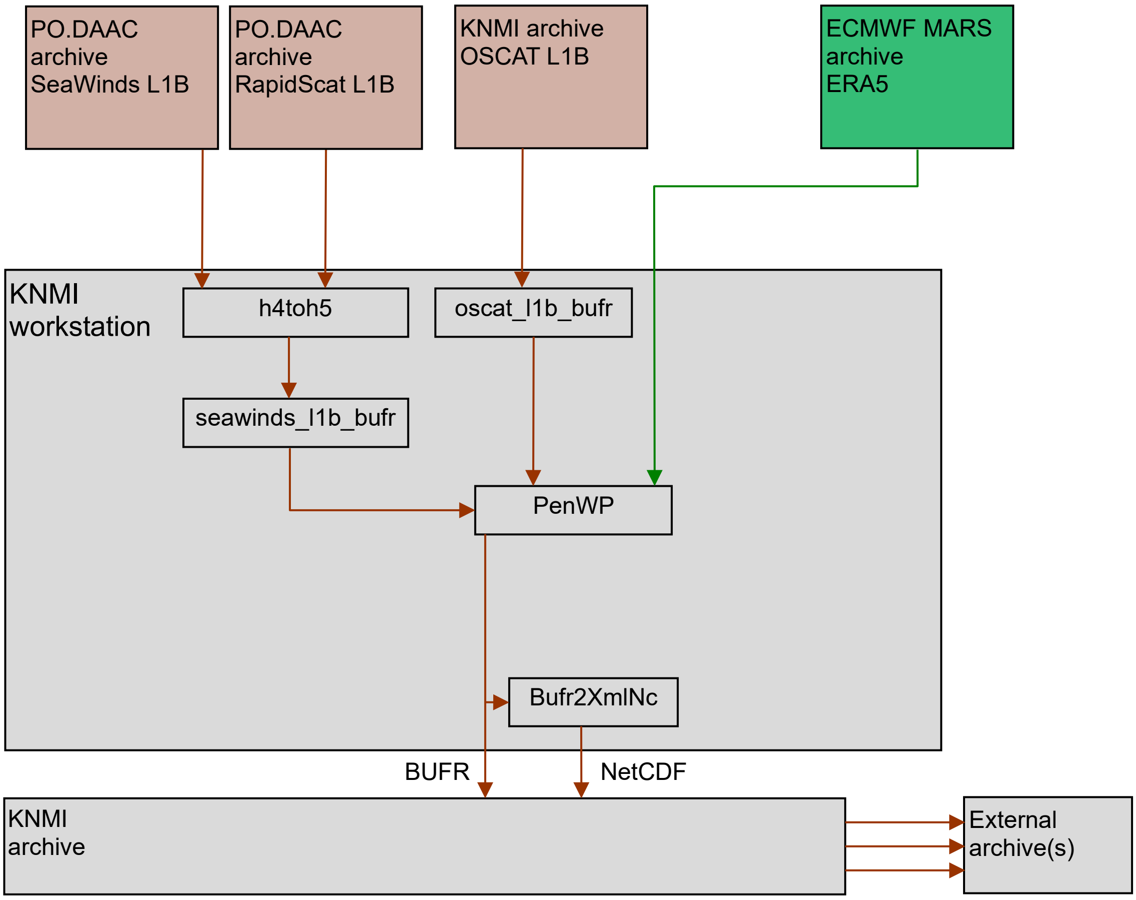

Figure 6: System architecture of reprocessing chain.

5.1. Backscatter data averaging

The SeaWinds and RapidScat level 1b backscatter data from JPL are organised in eggs and slices, both are available in the same input file. Each egg σ^0 is based on the sum of the echo energies measured among the eight centre high resolution slices in a single scatterometer pulse. The slices (eggs in the case of RapidScat) are beam-wise accumulated to a WVC level by program seawinds_l1b_bufr before wind inversion is done. The observation weights are proportional to the estimated transmitted power contained in that observation, i.e., inversely proportional to the K_p value. The Sigma0 Quality Flag present in the level 1b data is evaluated and data with one of the following flags set are skipped:

- Bit 0: Measurement not usable
- Bit 1: Signal to Noise Ratio level low

- Bit 3: Data outside acceptable range
- Bit 4: Pulse quality unacceptable
- Bit 5: Location algorithm does not converge
- Bit 6: Frequency shift beyond range
- Bit 7: Temperature outside range
- Bit 8: No applicable attitude records
- Bit 9: Ephemeris data unacceptable

For the Oceansat-2 level 1b data from ISRO the same approach is used. The Sigma0 Quality Flag present in the level 1b data is evaluated and slice data with one of the following flags set are skipped:

- Bit 4: Sigma0 is poor
- Bit 5: K_p (noise value) is poor
- Bit 6: Invalid footprint
- Bit 7: Footprint contains saturated slice

It was discovered that the beam azimuth angles reported in the Oceansat-2 level 1b data are not correct. In particular at high latitudes, significant deviations from the expected values occur. The azimuth angles were re-computed from the WVC location and sub-satellite point using formula (5.23) in [11]. These re-computed values replace the original azimuth level 1b angles.

5.2. Backscatter calibration

No absolute instrumental instrument calibration exists for Ku-band pencil-beam scatterometers. Ku-band pencil-beam backscatter distributions should however be matched to achieve wind intercalibration of all space-borne scatterometer instruments. We thus developed methods that calibrate the winds of each scatterometer effectively to the mean winds at collocated moored buoys. No significant signs of azimuth (or WVC) dependent instrument biases have been found for SeaWinds and RapidScat (contrary to Oceansat-2, see below). Also the beam incidence angles are constant and hence we have chosen to apply backscatter corrections that are only dependent on the beam polarisation. The goal of applying backscatter corrections is to minimise wind speed biases between scatterometer winds on the one hand and buoy and NWP winds on the other hand. With this in mind, the calibration correction for VV has been obtained by looking at the outer swath data (where no HH data are available) and choosing a calibration amount that yields minimum wind speed biases. Subsequently, the swath part containing both HH and VV was considered. It appears that in this region the wind direction biases are slightly dependent on the ratio between the VV and HH corrections, i.e., changing the VV and HH corrections in opposite directions will change the wind direction biases without affecting the wind speed biases significantly. In this way, within a few iterations the two calibration coefficients can be obtained which yield minimal wind direction and wind speed biases.

For Oceansat-2 an instrument calibration change occurred between 19th and 20th August 2010, which was also reported in literature [13]. For an unknown reason, the σ^0 values dropped by approximately 0.5 dB. On top of the NOC corrections, an extra constant correction of 0.47 dB on HH and 0.56 dB on VV was applied both for 25 km and 50 km data from before 20th August 2010 to correct for this.

RapidScat underwent several changes in signal levels during its lifetime which resulted in different signal-to-noise (SNR) ratios and different calibration corrections. Three periods can be distinguished (with the corresponding orbit numbers between brackets), see also the information on the PO.DAAC website: https://podaac.jpl.nasa.gov/dataset/RSCAT_L1B_V1.3:

Data from 10 Oct 2014 (00161) to 15 Aug 2015 (05063) are high SNR, level 1b v1.1

Data from 19 Aug 2015 (05127) to 11 Feb 2016 (07871) are low SNR period 1, level 1b v1.2

Data from 11 Feb 2016 (07873) to 19 Aug 2016 (10827) are low SNR period 2, level 1b v1.3

Product	HH	VV inner swath	VV outer swath
QuikSCAT 25 km	0.44 dB	0.24 dB	0.37 dB
QuikSCAT 50 km	0.31 dB	0.29 dB	0.34 dB
Oceansat-2 25 km	0.68 dB	0.22 dB	0.42 dB
Oceansat-2 50 km	0.47 dB	0.28 dB	0.37 dB
RapidScat 25 km high SNR	0.54 dB	0.40 dB	0.57 dB
RapidScat 50 km high SNR	0.38 dB	0.52 dB	0.56 dB
RapidScat 25 km low SNR 1	1.25 dB	0.40 dB	0.78 dB
RapidScat 50 km low SNR 1	0.79 dB	0.60 dB	0.69 dB
RapidScat 25 km low SNR 2	1.80 dB	0.65 dB	1.00 dB
RapidScat 50 km low SNR 2	0.95 dB	0.85 dB	0.96 dB

Table 4: Calibration coefficients per product and per beam category.

The table shows the calibration coefficients per product and per beam category. Note that the calibrated backscatter values are only available within the wind processing software; the σ^0 data in the BUFR wind product are uncorrected values.

For Oceansat-2 the situation is more complicated since the OSCAT instrument flies at a 9° yaw off-angle with respect to the flight path. This leads to a skew antenna azimuth (and WVC) dependency of the backscatter calibrations. This issue was successfully corrected by a sigma0 correction dependent on antenna azimuth. The correction is zero in the left part of the swath, starts when the antenna is looking forward, is at maximum when the antenna is looking to the right, and then decreases again to zero when the antenna is looking aft. The maximum correction is 0.30 dB for HH and 0.54 dB for VV in the outer right swath. These antenna azimuth dependent corrections are included in the σ^0 data in the BUFR wind products.

5.3. NWP collocation

The scatterometer data have been collocated with ERA5 re-analysis Numerical Weather Prediction (NWP) data from ECMWF [14].

NWP model sea surface temperature (SST) data are used to support the Bayesian sea ice discrimination [3]. The SST values of the four surrounding model grid points around the WVC location are bi-linearly interpolated. Note that the ECMWF model data do not contain SST values over land; if one or more of the four surrounding grid points has missing SST data, the SST value of the grid point closest to the WVC is taken. WVCs with a sea surface temperature above 5 °C are assumed to be always open water. The Bayesian ice screening procedure may sometimes assign rainy WVCs erroneous as ice; using the extra SST criterion, WVCs in areas warmer than 5 °C will never be labelled as ice. Due to its rather ‘warm’ threshold value, the NWP-based SST ice screening will only be active in regions far away from the ice extents.

Land presence is determined by using the land-sea mask available from the model data. For QuikSCAT and Oceansat-2, a coastal processing scheme is used comparable to the processing of ASCAT coastal data [15]. The weighted mean value of the land fractions of all model grid points within a certain distance of the slice centre is calculated. The weight of each grid point scales with $1/r^2$, where r is the distance between the WVC centre and the model grid point. If this mean land fraction value exceeds a threshold of 0.02, the slice is excluded for wind processing. In this way, the slices too close to the coast are excluded which will reduce the land contamination. It will also lead to a slight displacement of the WVC location away from the coast since slices near or over the coast are excluded from the spatial averaging in the WVC; the WVC lat/lon location is computed from the used backscatter data locations that fall within that WVC. For RapidScat (since the ISS provides a less stable orbital platform), only full resolution egg data are used and the land fraction is computed in the WVC centre location. Again, if this mean land fraction value exceeds a threshold of 0.02, the WVC is excluded for wind processing.

NWP forecast wind data are necessary in the ambiguity removal step of the processing. Wind forecasts are available twice a day (06 and 18 GMT analysis time) with hourly forecast time steps of +3h, +4h, +5h, …, +30h. The model wind data are quadratically interpolated with respect to time and bi-linearly interpolated with respect to location and put into the level 2 information part of each WVC (see section 2.2). The ECMWF ERA5 winds stored in the wind products are stress-equivalent winds [16] which have been computed from the equivalent neutral model winds.

It is important to note that scatterometer winds are being assimilated into the ECMWF model and therefore the wind field used for ambiguity removal (i.e., a forecast) is taken to be independent from the scatterometer observation. In ERA5, observations are assimilated in the model up to 3 hours after the analysis time. Therefore, in the processing of scatterometer winds, only forecast winds starting from 3 hours after analysis time are used. In this way the independence between the scatterometer and the ECMWF model winds, used to guide the wind direction ambiguity removal, is guaranteed.

5.4. Quality control and monitoring

In each WVC, the σ^0 data is checked for quality and completeness and the inversion residual [3], called MLE, is checked. On top of that, the difference between analysis wind and scatterometer wind in the 2DVAR ambiguity removal step is evaluated and this information is used to refine quality control [7]. Degraded WVCs are flagged; see section 2.2 for more details.

An information file is made for each product. The content of the file is identical whatever the product and results from a compilation of all the global information concerning this product. From these files, various graphs are produced to visually display the confidence levels of the products and their evolution with time. Any deviations from nominal behaviour will be immediately visible as steps in these graphs. Data and overall product quality is also available to the users within the products; see section 2 for a description of quality flags.

6. Abbreviations and acronyms

2DVAR	Two-dimensional Variational Ambiguity Removal
ATBD	Algorithm Theoretical Basis Document
AR	Ambiguity Removal
ASCAT	Advanced Scatterometer
BUFR	Binary Universal Format Representation
DLI	Downward Long wave Irradiance
ECMWF	European Centre for Medium-Range Weather Forecasts
ERS	European Remote-Sensing Satellite
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
GMF	Geophysical Model Function
HDF	Hierarchical Data Format
HH	Horizontal polarisation of sending and receiving radar antennas
HSCAT	Scatterometer on-board the Haiyang 2 series satellites (China)
ISRO	Indian Space Research Organisation
ISS	International Space Station
JPL	Jet Propulsion Laboratory
KNMI	Royal Netherlands Meteorological Institute
K_p	Backscatter measurement noise estimate
MLE	Maximum Likelihood Estimator
MSS	Multiple Solution Scheme
NASA	National Aeronautics and Space Administration (USA)
NetCDF	Network Common Data Form
NOAA	National Oceanic and Atmospheric Administration (USA)
NSCAT	NASA Scatterometer
NSOAS	National Satellite Ocean Application Service (China)
NWP	Numerical Weather Prediction
Oceansat-2	Indian Scatterometer mission carrying an OSCAT scatterometer
OSCAT	Scatterometer on-board the Oceansat-2 and ScatSat-1 satellites (India)
OSI SAF	Ocean and Sea Ice SAF
OWDP	OSCAT Wind Data Processor
PenWP	Pencil beam Wind Processor
QC	Quality Control

QuikSCAT	US Quick Scatterometer mission carrying the SeaWinds scatterometer
RapidScat	US scatterometer on-board the International Space Station
SAF	Satellite Application Facility
SDP	SeaWinds Data Processor
SeaWinds	Scatterometer on-board QuikSCAT platform (USA)
SSI	Surface Solar Irradiance
SST	Sea Surface Temperature
u	West-to-east (zonal) wind component
v	South-to-north (meridional) wind component
VV	Vertical polarisation of sending and receiving radar antennas
WMO	World Meteorological Organisation
WVC	Wind Vector Cell

7. Appendix A: BUFR data descriptors

Number	Descriptor	Parameter	Unit
001	(01007)	Satellite Identifier	Code Table
002	(01012)	Direction of Flight	Degree True
003	(02048)	Satellite Instrument Identifier	Code Table
004	(21119)	Wind Scatterometer GMF	Code Table
005	(25060)	Software Identification	Numeric
006	(02026)	Cross Track Resolution	m
007	(02027)	Along Track Resolution	m
008	(05040)	Orbit Number	Numeric
009	(04001)	Year	Year
010	(04002)	Month	Month
011	(04003)	Day	Day
012	(04004)	Hour	Hour
013	(04005)	Minute	Minute
014	(04006)	Second	Second
015	(05002)	Latitude (Coarse Accuracy)	Degree
016	(06002)	Longitude (Coarse Accuracy)	Degree
017	(08025)	Time Difference Qualifier	Code Table
018	(04001)	Time to Edge	Second
019	(05034)	Along Track Row Number	Numeric
020	(06034)	Cross Track Cell Number	Numeric
021	(21109)	Seawinds Wind Vector Cell Quality Flag	Flag Table
022	(11081)	Model Wind Direction At 10 M	Degree True
023	(11082)	Model Wind Speed At 10 M	m/s
024	(21101)	Number of Vector Ambiguities	Numeric
025	(21102)	Index of Selected Wind Vector	Numeric
026	(21103)	Total Number of Sigma0 Measurements	Numeric
027	(21120)	Seawinds Probability of Rain	Numeric
028	(21121)	Seawinds NOF Rain Index	Numeric
029	(13055)	Intensity Of Precipitation	kg/m**2/sec
030	(21122)	Attenuation Correction On Sigma-0 (from Tb)	dB
031	(11012)	Wind Speed At 10 M	m/s
032	(11052)	Formal Uncertainty In Wind Speed	m/s
033	(11011)	Wind Direction At 10 M	Degree True
034	(11053)	Formal Uncertainty In Wind Direction	Degree True
035	(21104)	Likelihood Computed for Wind Solution	Numeric
036	(11012)	Wind Speed At 10 M	m/s
037	(11052)	Formal Uncertainty In Wind Speed	m/s
038	(11011)	Wind Direction At 10 M	Degree True
039	(11053)	Formal Uncertainty In Wind Direction	Degree True
040	(21104)	Likelihood Computed for Wind Solution	Numeric
041	(11012)	Wind Speed At 10 M	m/s
042	(11052)	Formal Uncertainty In Wind Speed	m/s
043	(11011)	Wind Direction At 10 M	Degree True
044	(11053)	Formal Uncertainty In Wind Direction	Degree True
045	(21104)	Likelihood Computed for Wind Solution	Numeric
046	(11012)	Wind Speed At 10 M	m/s
047	(11052)	Formal Uncertainty In Wind Speed	m/s
048	(11011)	Wind Direction At 10 M	Degree True

Number	Descriptor	Parameter	Unit
049	(11053)	Formal Uncertainty In Wind Direction	Degree True
050	(21104)	Likelihood Computed for Wind Solution	Numeric
051	(02104)	Antenna Polarisation	Code Table
052	(08022)	Total Number w.r.t. accumulation or average	Numeric
053	(12063)	Brightness Temperature	K
054	(12065)	Standard Deviation Brightness Temperature	K
055	(02104)	Antenna Polarisation	Code Table
056	(08022)	Total Number w.r.t. accumulation or average	Numeric
057	(12063)	Brightness Temperature	K
058	(12065)	Standard Deviation Brightness Temperature	K
059	(21110)	Number of Inner-Beam Sigma0 (fwd of sat.)	Numeric
060	(05002)	Latitude (Coarse Accuracy)	Degree
061	(06002)	Longitude (Coarse Accuracy)	Degree
062	(21118)	Attenuation Correction On Sigma-0	dB
063	(02112)	Radar Look (Azimuth) Angle	Degree
064	(02111)	Radar Incidence Angle	Degree
065	(02104)	Antenna Polarisation	Code Table
066	(21105)	Normalized Radar Cross Section	dB
067	(21106)	Kp Variance Coefficient (Alpha)	Numeric
068	(21107)	Kp Variance Coefficient (Beta)	Numeric
069	(21114)	Kp Variance Coefficient (Gamma)	dB
070	(21115)	Seawinds Sigma-0 Quality Flag	Flag Table
071	(21116)	Seawinds Sigma-0 Mode Flag	Flag Table
072	(08018)	Seawinds Land/Ice Surface Flag	Flag Table
073	(21117)	Sigma-0 Variance Quality Control	Numeric
074	(21111)	Number of Outer-Beam Sigma0 (fwd of sat.)	Numeric
075	(05002)	Latitude (Coarse Accuracy)	Degree
076	(06002)	Longitude (Coarse Accuracy)	Degree
077	(21118)	Attenuation Correction On Sigma-0	dB
078	(02112)	Radar Look (Azimuth) Angle	Degree
079	(02111)	Radar Incidence Angle	Degree
080	(02104)	Antenna Polarisation	Code Table
081	(21105)	Normalized Radar Cross Section	dB
082	(21106)	Kp Variance Coefficient (Alpha)	Numeric
083	(21107)	Kp Variance Coefficient (Beta)	Numeric
084	(21114)	Kp Variance Coefficient (Gamma)	dB
085	(21115)	Seawinds Sigma-0 Quality Flag	Flag Table
086	(21116)	Seawinds Sigma-0 Mode Flag	Flag Table
087	(08018)	Seawinds Land/Ice Surface Flag	Flag Table
088	(21117)	Sigma-0 Variance Quality Control	Numeric
089	(21112)	Number of Inner-Beam Sigma0 (aft of sat.)	Numeric
090	(05002)	Latitude (Coarse Accuracy)	Degree
091	(06002)	Longitude (Coarse Accuracy)	Degree
092	(21118)	Attenuation Correction On Sigma-0	dB
093	(02112)	Radar Look (Azimuth) Angle	Degree
094	(02111)	Radar Incidence Angle	Degree
095	(02104)	Antenna Polarisation	Code Table
096	(21105)	Normalized Radar Cross Section	dB
097	(21106)	Kp Variance Coefficient (Alpha)	Numeric
098	(21107)	Kp Variance Coefficient (Beta)	Numeric
099	(21114)	Kp Variance Coefficient (Gamma)	dB

Number	Descriptor	Parameter	Unit
100	(21115)	Seawinds Sigma-0 Quality Flag	Flag Table
101	(21116)	Seawinds Sigma-0 Mode Flag	Flag Table
102	(08018)	Seawinds Land/Ice Surface Flag	Flag Table
103	(21117)	Sigma-0 Variance Quality Control	Numeric
104	(21113)	Number of Outer-Beam Sigma0 (aft of sat.)	Numeric
105	(05002)	Latitude (Coarse Accuracy)	Degree
106	(06002)	Longitude (Coarse Accuracy)	Degree
107	(21118)	Attenuation Correction On Sigma-0	dB
108	(02112)	Radar Look (Azimuth) Angle	Degree
109	(02111)	Radar Incidence Angle	Degree
110	(02104)	Antenna Polarisation	Code Table
111	(21105)	Normalized Radar Cross Section	dB
112	(21106)	Kp Variance Coefficient (Alpha)	Numeric
113	(21107)	Kp Variance Coefficient (Beta)	Numeric
114	(21114)	Kp Variance Coefficient (Gamma)	dB
115	(21115)	Seawinds Sigma-0 Quality Flag	Flag Table
116	(21116)	Seawinds Sigma-0 Mode Flag	Flag Table
117	(08018)	Seawinds Land/Ice Surface Flag	Flag Table
118	(21117)	Sigma-0 Variance Quality Control	Numeric

8. Appendix B: NetCDF data format

The wind products are also available in the NetCDF format, with the following characteristics:

- The data format meets the NetCDF Climate and Forecast Metadata Convention version 1.6 (https://cfconventions.org/).
- The data contain, contrary to the BUFR data, only level 2 wind and sea ice information, no sigma0 information. The aim was to create a compact and easy to handle product for oceanographic and climatological users.
- The data contain only the selected wind solutions, no ambiguity information.
- The wind directions are in oceanographic rather than meteorological convention (see section 2.1)
- The format is identical for all scatterometer wind data provided in the OSI SAF.
- The data has file sizes smaller than those of the corresponding BUFR data. With NetCDF-4 internal compression, the size of one file in NetCDF reduces to 1/10th of the BUFR data size.

The file name convention for the NetCDF product is identical to the naming of the BUFR products (see section 2.2). The only difference is that the ‘.bufr’ extension is replaced by ‘.nc’.

```
dimensions:
        NUMROWS = 1624 ;
        NUMCELLS = 76 ;
variables:
        int time(NUMROWS, NUMCELLS) ;
                time:long_name = "time" ;
                time:units = "seconds since 1990-01-01 00:00:00" ;
        int lat(NUMROWS, NUMCELLS) ;
                lat:long_name = "latitude" ;
                lat:units = "degrees_north" ;
        int lon(NUMROWS, NUMCELLS) ;
                lon:long_name = "longitude" ;
                lon:units = "degrees_east" ;
        short wvc_index(NUMROWS, NUMCELLS) ;
                wvc_index:long_name = "cross track wind vector cell number" ;
                wvc_index:units = "1" ;
        short model_speed(NUMROWS, NUMCELLS) ;
                model_speed:long_name = "model wind speed at 10 m" ;
                model_speed:units = "m s-1" ;
        short model_dir(NUMROWS, NUMCELLS) ;
                model_dir:long_name = "model wind direction at 10 m" ;
                model_dir:units = "degree" ;
        short ice_prob(NUMROWS, NUMCELLS) ;
                ice_prob:long_name = "ice probability" ;
                ice_prob:units = "1" ;
        short ice_age(NUMROWS, NUMCELLS) ;
                ice_age:long_name = "ice age (a-parameter)" ;
                ice_age:units = "dB" ;
        int wvc_quality_flag(NUMROWS, NUMCELLS) ;
                wvc_quality_flag:long_name = "wind vector cell quality" ;
                wvc_quality_flag:flag_masks = 64, 128, 256, 512, 1024, 2048, 4096, 8192,
```

```
16384, 32768, 65536, 131072, 262144, 524288, 1048576, 2097152, 4194304 ;
                wvc_quality_flag:flag_meanings = "distance_to_gmf_too_large
data_are_redundant no_meteorological_background_used rain_detected
not_usable_for_visualisation small_wind_less_than_or_equal_to_3_m_s
large_wind_greater_than_30_m_s wind_inversion_not_successful
some_portion_of_wvc_is_over_ice some_portion_of_wvc_is_over_land
variational_quality_control_fails knmi_quality_control_fails
product_monitoring_event_flag product_monitoring_not_used
any_beam_noise_content_above_threshold poor_azimuth_diversity
not_enough_good_sigma0_for_wind_retrieval" ;
        short wind_speed(NUMROWS, NUMCELLS) ;
                wind_speed:long_name = "wind speed at 10 m" ;
                wind_speed:units = "m s-1" ;
        short wind_dir(NUMROWS, NUMCELLS) ;
                wind_dir:long_name = "wind direction at 10 m" ;
                wind_dir:units = "degree" ;
        short bs_distance(NUMROWS, NUMCELLS) ;
                bs_distance:long_name = "backscatter distance" ;
                bs_distance:units = "1" ;
// global attributes:
                :title = "Oceansat-2 OSCAT Level 2 25.0 km Ocean Surface Wind Vector
Product" ;
                :title_short_name = "OSCAT-L2-25km" ;
                :Conventions = "CF-1.6" ;
                :institution = "EUMETSAT/OSI SAF/KNMI" ;
                :source = "Oceansat-2 OSCAT" ;
                :software_identification_level_1 = 2208 ;
                :instrument_calibration_version = 0 ;
                :software_identification_wind = 2208 ;
                :pixel_size_on_horizontal = "25.0 km" ;
                :service_type = "N/A" ;
                :processing_type = "O" ;
                :contents = "ovw" ;
                :granule_name = "OR2OSW025_20110101_061417_06744_OCEANSAT2.nc" ;
                :processing_level = "L2" ;
                :orbit_number = 6744 ;
                :start_date = "2011-01-01" ;
                :start_time = "06:14:17" ;
                :stop_date = "2011-01-01" ;
                :stop_time = "07:53:33" ;
                :equator_crossing_longitude = " 284.939" ;
                :equator_crossing_date = "2011-01-01" ;
                :equator_crossing_time = "04:59:48" ;
                :rev_orbit_period = "5958.6" ;
                :orbit_inclination = "98.3" ;
                :history = "N/A" ;
                :references = "Oceansat-2 Wind Product User Manual, https://osi-
saf.eumetsat.int/, https://scatterometer.knmi.nl/" ;
                :comment = "Orbit period and inclination are constant values. All wind
directions in oceanographic convention (0 deg. flowing North)" ;
                :creation_date = "2022-01-13" ;
                :creation_time = "17:17:27" ;
```

The interpretation of the wvc_quality_flag integer value is as follows. The flag_masks correspond to certain flag bits that may or may not be set. This means that e.g. the 'flag_mask' 64 corresponds to 'distance_to_gmf_too_large' and so on. The flag masks are powers of 2. The way to handle this is to take the integer value of the wvc_quality_flag and find out how it is composed of powers of 2. Suppose that one wants to test if the 'knmi_quality_control_fails' flag bit is set. This is the 12th item in the flag list, corresponding to an integer value of 131072 (=2^17) in the flag_masks table. You can test if this value is set using the function:

(integer flag value / 2^17) modulo 2

which gives 1 if the ‘knmi_quality_control_fails’ is set and 0 if the ‘knmi_quality_control_fails’ is not set. The other flag bits can be tested in the same way. See the table below for the flag bits present in the wvc_quality_flag. The last column in the table shows the integer value if only the given bit is set. Note that the NetCDF format from the dump above is generic for level 2 wind products and it contains some flag bits which are not used in these specific data. Table 5 lists the flag bits that are actually in use, these flag bits are set identical to the corresponding flag bits used in the BUFR data Table 2.

Description	Bit number	Integer value
Not used	0-8	
Rain flag algorithm detects rain	9	512
Quality Control data rejection for visualisation and nowcasting	10	1024
Reported wind speed is less than or equal to 3 m/s	11	2048
Reported wind speed is greater than 30 m/s	12	4096
Wind inversion not successful for wind vector cell	13	8192
Some portion of wind vector cell is over ice	14	16,384
Some portion of wind vector cell is over land	15	32,768
Variational quality control data rejection	16	65,536
KNMI Quality Control (including rain) data rejection	17	131,072
Product monitoring flag	18	262,144
Product monitoring not used	19	524,288
Not used	20	
Poor azimuth diversity among sigma-0 for wind retrieval	21	2,097,152
Not enough good sigma-0 available for wind retrieval	22	4,194,304

Table 5: Definition of flag bits in the Wind Vector Cell Quality Flag in NetCDF.

9. Appendix C: Data gaps

The QuikSCAT SeaWinds data record starts at orbit 430 on 19 July 1999 and ends at orbit 54296 on 21 November 2009. Some orbits are missing, sometimes isolated orbits and sometimes for longer periods. The tables below show the gaps with a length of at least one orbit in the data records and the number of files (orbits) per year, respectively.

Start date	End date	Last orbit before gap	First orbit after gap	Number of missing orbits
17-Nov-1999	19-Nov-1999	2144	2172	27
1-Jan-2000	2-Jan-2000	2792	2811	18
20-Jan-2000	21-Jan-2000	3067	3071	3
18-Jul-2000	19-Jul-2000	5626	5637	10
28-Aug-2000	29-Aug-2000	6216	6219	2
16-Nov-2000	18-Nov-2000	7355	7386	30
11-May-2001	14-May-2001	9858	9908	49
7-Jul-2001	9-Jul-2001	10666	10695	28
17-Nov-2001	19-Nov-2001	12571	12600	28
19-Mar-2002	21-Mar-2002	14305	14330	24
4-Jul-2002	4-Jul-2002	15830	15837	6
19-Aug-2002	20-Aug-2002	16491	16506	14
18-Nov-2002	20-Nov-2002	17787	17808	20
7-Feb-2003	7-Feb-2003	18938	18940	1
19-May-2003	20-May-2003	20384	20391	6
11-Sep-2003	12-Sep-2003	22027	22030	2
17-Dec-2003	18-Dec-2003	23410	23425	14
6-Aug-2004	6-Aug-2004	26721	26730	8
17-Jun-2006	17-Jun-2006	36417	36427	9
15-Jul-2006	17-Jul-2006	36820	36856	35
11-Nov-2006	12-Nov-2006	38523	38528	4
3-Mar-2007	3-Mar-2007	40112	40116	3
7-Apr-2007	8-Apr-2007	40618	40622	3
6-Dec-2007	7-Dec-2007	44085	44098	12
24-Jun-2008	25-Jun-2008	46942	46964	21
25-Nov-2008	28-Nov-2008	49148	49191	42
6-Dec-2008	6-Dec-2008	49295	49303	7
3-Sep-2009	5-Sep-2009	53167	53197	29

Year	Number of files
1999	2328
2000	5153
2001	5098
2002	5139
2003	5181
2004	5211
2005	5205
2006	5156
2007	5187
2008	5149
2009	4605
Total	53412

The Oceansat-2 OSCAT data record starts at orbit 1212 on 15 December 2009 and ends at orbit 23371 on 20 February 2014. Quite some orbits are missing, sometimes isolated orbits and sometimes for longer periods. The tables below show the gaps with a length of at least 10 orbits in the data records and the number of files (orbits) per year, respectively.

Start date	**End date**	**Last orbit before gap**	**First orbit after gap**	**Number of missing orbits**
2009-12-31	2010-01-16	1443	1665	221
2010-02-03	2010-02-06	1935	1977	41
2010-02-09	2010-02-12	2022	2067	44
2010-02-27	2010-02-28	2283	2298	14
2010-03-03	2010-03-06	2337	2381	43
2010-03-09	2010-03-12	2430	2471	40
2010-03-14	2010-03-16	2499	2529	29
2010-04-03	2010-04-06	2790	2828	37
2010-04-09	2010-04-12	2877	2922	44
2010-05-03	2010-05-06	3227	3271	43
2010-05-09	2010-05-12	3314	3358	43
2010-06-04	2010-06-06	3684	3719	34
2010-06-09	2010-06-12	3764	3807	42
2010-06-15	2010-06-16	3846	3857	10
2010-07-03	2010-07-06	4112	4154	41
2010-07-09	2010-07-12	4199	4241	41
2010-07-30	2010-08-01	4507	4532	24
2010-08-02	2010-08-06	4546	4604	57
2010-08-09	2010-08-12	4648	4691	42
2010-08-21	2010-08-23	4822	4849	26
2010-08-23	2010-08-24	4855	4869	13
2010-09-03	2010-09-06	5011	5053	41
2010-09-07	2010-09-08	5062	5075	12
2010-09-09	2010-09-12	5098	5140	41
2010-10-03	2010-10-06	5446	5489	42
2010-10-09	2010-10-12	5533	5576	42
2010-11-03	2010-11-06	5889	5939	49
2010-11-09	2010-11-12	5982	6026	43
2010-12-03	2010-12-06	6328	6373	44
2010-12-09	2010-12-12	6417	6460	42
2011-02-21	2011-02-22	7482	7505	22
2011-02-28	2011-03-02	7595	7610	13
2011-03-30	2011-03-31	8027	8040	12
2011-05-07	2011-05-09	8578	8606	27
2011-06-29	2011-07-01	9350	9365	14
2011-07-15	2011-07-16	9578	9593	14
2011-07-19	2011-07-20	9634	9650	15
2011-08-17	2011-08-18	10050	10065	14
2011-11-24	2011-11-25	11492	11507	14
2011-12-31	2012-01-02	12031	12053	21
2012-02-18	2012-02-20	12737	12768	30
2012-02-28	2012-03-01	12883	12903	19
2012-04-14	2012-04-15	13544	13556	11
2012-08-18	2012-08-19	15380	15396	15

Start date	End date	Last orbit before gap	First orbit after gap	Number of missing orbits
2012-10-01	2012-10-04	16013	16050	36
2013-03-02	2013-03-05	18212	18259	46
2013-08-28	2013-08-29	20819	20830	10
2013-10-01	2013-10-02	21302	21315	12
2013-11-28	2013-12-03	22152	22212	59
2013-12-31	2014-01-04	22631	22676	44
2014-01-31	2014-02-04	23068	23125	56

Year	Number of files
2009	218
2010	3739
2011	4839
2012	5099
2013	5109
2014	630
Total	19634

The ISS RapidScat data record starts at orbit 161 on 3 October 2014 and ends at orbit 10827 on 19 August 2016. Quite some orbits are missing, sometimes isolated orbits and sometimes for longer periods. The tables below show the gaps with a length of at least 10 orbits in the data records and the number of files (orbits) per year, respectively.

Start date	**End date**	**Last orbit before gap**	**First orbit after gap**	**Number of missing orbits**
20141006	20141007	203	226	22
20141015	20141015	338	349	10
20141020	20141020	415	427	11
20141023	20141027	469	534	64
20141028	20141029	551	562	10
20141109	20141110	734	750	15
20141123	20141124	947	970	22
20141127	20141127	1002	1014	11
20150111	20150112	1716	1728	11
20150114	20150115	1753	1764	10
20150210	20150211	2169	2186	16
20150213	20150214	2229	2241	11
20150311	20150312	2630	2645	14
20150327	20150328	2875	2895	19
20150416	20150417	3193	3207	13
20150424	20150425	3317	3331	13
20150427	20150428	3364	3377	12
20150520	20150521	3722	3734	11
20150526	20150527	3813	3832	18
20150610	20150611	4049	4062	12
20150615	20150616	4121	4140	18
20150704	20150705	4420	4435	14
20150722	20150727	4697	4780	82
20150813	20150814	5045	5058	12
20150815	20150819	5063	5127	63
20150819	20150820	5136	5152	15
20150823	20150825	5198	5220	21
20150827	20150828	5261	5277	15
20150903	20150905	5369	5396	26
20150928	20150928	5747	5760	12
20151001	20151003	5800	5839	38
20151208	20151209	6865	6880	14
20151210	20151211	6896	6911	14
20151215	20151215	6964	6975	10
20151218	20151219	7021	7036	14
20151222	20151228	7083	7174	90
20151229	20160105	7179	7296	116
20160218	20160219	7983	7999	15
20160301	20160302	8166	8185	18
20160318	20160319	8431	8450	18
20160325	20160326	8545	8559	13
20160329	20160330	8605	8623	17
20160402	20160403	8659	8686	26
20160409	20160410	8777	8795	17

Start date	End date	Last orbit before gap	First orbit after gap	Number of missing orbits
20160510	20160511	9260	9275	14
20160519	20160520	9396	9407	10
20160613	20160614	9790	9803	12
20160617	20160618	9850	9864	13
20160630	20160701	10043	10071	27
20160718	20160720	10327	10364	36
20160817	20160818	10792	10803	10

Year	Number of files
2014	1200
2015	4906
2016	3189
Total	9295