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PenWP Product Specification

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KNMI, De Bilt, the Netherlands

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KNMI, De Bilt, the Netherlands

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1 Introduction

The Pencil Beam Wind Processor (PenWP) is a software package written mainly in Fortran 90. The parts and libraries for handling HDF5, NetCDF, and BUFR format data have been partly written in C. The processor can handle data from the SeaWinds (on QuikSCAT or ADEOS-II), OSCAT (on Oceansat-2 and ScatSat-1), HSCAT (on HY-2A/B/C/D) and RapidScat (on the International Space Station) scatterometer instruments. This document is the Product Specification (PS) of the PenWP software package. Section 2 provides information on the purpose, outputs, inputs and system requirements of the PenWP software. More information about the functionality of the processing steps in PenWP is available in section 3.

More information about PenWP can be found in several other documents. The User Manual and Reference Guide (UM) [1] contains more details about the installation and use of PenWP. Reading the UM and the PS should provide sufficient information to the user who wants to apply PenWP as a black box.

The Top Level Design (TLD) of the code and the Module Design (MD) of the PenWP code can be found in [2]. This document is of interest to developers and users who need more specific information on how the processing is done.

PenWP can be obtained through the NWP SAF website at <https://nwp-saf.eumetsat.int/>. Please note that any questions or problems regarding the installation or use of PenWP can be addressed at the OSI SAF helpdesk at <https://osi-saf.eumetsat.int/>.

1.1 Conventions

Names of physical quantities (e.g., wind speed components u and v), modules (e.g. *Buf_rMod*), subroutines and identifiers are printed italic.

Names of directories and subdirectories (e.g. `penwp/src`), files (e.g. `penwp.F90`), and commands (e.g. `penwp -f input`) are printed in Courier. Software systems in general are addressed using the normal font (e.g. PenWP, genscat).

Hyperlinks are printed in blue and underlined (e.g. <https://scatterometer.knmi.nl/>).

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2 PenWP product specification

2.1 Purpose of PenWP

The Pencil Beam Wind Processor (PenWP) has been developed to fully exploit σ^0 data from pencil beam Ku-band scatterometer instruments, to generate surface winds. PenWP may be used for real-time data processing. The main application of PenWP is to form the core of an Observation Operator for scatterometer data within an operational Numerical Weather Prediction System.

PenWP is also a level 2 data processor. It reads (using conversion tools) data from level 2a HDF5 products or from the scatterometer BUFR products generated by PenWP itself. PenWP applies algorithms for inversion, quality control, and Ambiguity Removal. These methods are mainly developed and published by KNMI. The output of PenWP is a BUFR file in the NOAA BUFR format that was used for QuikSCAT data [3]. Additionally, a BUFR file containing a generic wind section (identical to the wind part of the ASCAT BUFR files) can be written. This BUFR format (also referred to as KNMI BUFR format) is not approved by WMO but can be handled by generic decoders. The BUFR formats are described in Appendix A.

2.2 Output specification

The wind vectors generated by PenWP represent the instantaneous mean surface wind at 10 m height in a 2D array of Wind Vector Cells (WVCs) with specified size ($100 \times 100 \text{ km}^2$, $50 \times 50 \text{ km}^2$ or $25 \times 25 \text{ km}^2$, depending on the cell spacing of the input product). These WVCs are part of the ground swath of the instrument.

In conventional mode, the wind output for every WVC consists of up to 4 ambiguities (wind vector alternatives, with varying probabilities). The wind solutions are ordered by decreasing probability and the selected wind vector (after ambiguity removal) is indicated by a selection index pointing to the chosen solution. For every WVC additional parameters are stored. These are e.g.: latitude, longitude, time information, orbit and node numbers, NWP background wind vector, WVC quality flag, and information on the scatterometer beams including σ^0 and K_p data.

The BUFR data descriptors of both available data formats are listed in Appendix A.

2.3 Input specification

PenWP is able to handle several types of input data:

- SeaWinds and RapidScat level 1b or level 2a data in HDF, see [4]. It is possible to reduce the WVC grid spacing to 25 km, 50 km or 100 km, see [1] for more details. Alternatively, the SeaWinds and RapidScat level 2b HDF wind data can be read, but in this case wind processing is not possible since the level 2b product does not contain σ^0 data. The data need to be converted to HDF5 first, and then converted to BUFR format using `seawinds_l1b_bufr` or `seawinds_hdf2bufr`.

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- OSCAT level 1b or level 2a HDF5 data from Oceansat-2 and ScatSat-1. These products are created by ISRO; see [5]. It is possible to reduce the WVC grid spacing to 25 km or 50 km, see [1] for more details. Alternatively, the OSCAT level 2b HDF5 Wind Data Product can be read, but in this case wind processing is not possible since the level 2b product does not contain σ^0 data. The data need to be converted to BUFR format before using them in PenWP using `oscat_11b_bufr` or `oscat_hdf2bufr`. See [1] for more details.
- HSCAT level 1b or level 2a HDF5 data from HY-2A, HY-2B, HY-2C, and HY-2D, as created by NSOAS. It is possible to reduce the WVC grid spacing to 25 km or 50 km, see [1] for more details. Alternatively, the HSCAT level 2b HDF5 wind data can be read, but in this case wind processing is not possible since the level 2b product does not contain σ^0 data. The data need to be converted to BUFR format before using them in PenWP using `hscat_11b_bufr` or `hscat_hdf2bufr`. See [1] for more details.

It is also possible to reprocess level 2 data from SeaWinds/RapidScat, OSCAT and HSCAT in NOAA BUFR format or KNMI BUFR format containing generic wind section, and treat them as if they are input data.

Apart from the scatterometer data, GRIB files containing NWP output with global coverage are necessary for the wind processing. At least three wind forecasts with constant forecast time intervals of e.g. 1 or 3 hours are necessary to perform interpolation with respect to time and location. The forecast times need to be before and after the data acquisition time, e.g. when an observation at 7:00 UTC is considered, there should be forecast wind fields available at 6:00, 7:00 and 8:00 UTC or at 3:00, 6:00 and 9:00 UTC. More details on the time interpolation are in the `gribio_module` description in [2]. Apart from this, GRIB fields of Sea Surface Temperature and Land Sea Mask are necessary for land and ice masking. These fields are not time interpolated, it is sufficient to provide only one field.

NWP model data are publicly available for example from the ECMWF ERA5 archive (<https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5>) and from the NOAA NCEP Global Forecasting System (<http://www.nco.ncep.noaa.gov/pmb/products/gfs/>).

NWP data is not needed when PenWP is used on level 2 BUFR data which already contains model winds and ice flagging, or when ambiguity removal is omitted. See the description of the command line options in [1] for more information on this.

2.4 System requirements

PenWP is designed for Unix (Linux) based computer platforms with a Fortran compiler and a C compiler (Table 2.1). CMake version 3.6 or higher (<https://cmake.org/>) is required in order to compile the ECMWF ecCodes library. Also, some of the scripts in the PenWP package are written in ksh (Korn shell scripting) and bash (Bash shell scripting), hence ksh and bash need to be installed as well.

To install the PenWP package, approximately 1G of disk space is needed. The output needs about 11 MB disk space to store one orbit of 25 km BUFR output data and 2 MB disk space to store one orbit of NetCDF output data. For near-real time processing, keeping a rolling archive of a couple of days, typically 20 GB of disk space is needed. A minimum of 16 GB RAM and a minimum CPU speed of 3.5 GHz are recommended. PenWP is not designed for multi-threaded use. Given the

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relatively short computing times and the fact that parallel computing is not easily implemented for the ambiguity removal step where mutual dependencies between Wind Vector Cells exist, it was not considered necessary to invest in this.

Most scatterometer wind processors for ASCAT, OSCAT, and HSCAT instruments are used in the OSI SAF near real time wind processing at KNMI where one orbit input file should be processed and dissemination within typically 10 minutes. To allow some margin we request the complete PenWP processing (L1B to L2B BUFR) to be done within 5 minutes. This time needs to be feasible on a system having the minimal hardware requirements for CPU speed and RAM.

Table 2.1 shows the platform and compiler combinations for which PenWP has been tested. However, the software is designed to run on any Unix (Linux) based computer platform with a Fortran compiler and a C compiler.

Platform	Fortran compiler	C compiler
Fedora Linux workstation	Portland pgf90 v11.10-0 GNU gfortran v11.2.1-1	GNU gcc v11.2.1-1
Redhat Linux cluster	GNU gfortran v4.8.5-44	GNU gcc v4.8.5-44
Apple MacBook	GNU gfortran v4.8.5-44	GNU gcc v4.8.5-44

Table 2.1 Platform and compiler combinations for which PenWP has been tested.

PenWP may also run in other environments, provided that the environment variables discussed in section 2.2 are set to the proper values. For Windows a Linux environment like Wubi is needed. PenWP can also run on a MacOS machine (Darwin).

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3 Details of functionality

3.1 BUFR IO and coding

Data sets of near-real time meteorological observations are generally coded in the Binary Universal Form for Representation (BUFR). BUFR is a machine independent data representation system (but it contains binary data, so care must be taken in reading and writing these data under different operating systems). A BUFR message (record) contains observational data of any sort in a self-descriptive manner. The description includes the parameter identification and its unit, decimal, and scaling specifications. The actual data are in binary code. The meta data are stored in BUFR tables. These tables are therefore essential to decode and encode the data.

BUFR tables are issued by the various meteorological centres. The largest part of the data descriptors specified in the BUFR tables follows the official BUFR descriptor standards maintained by the World Meteorological Organization (WMO, <http://www.wmo.int/>). However, for their different observational products meteorological centres do locally introduce additional descriptors in their BUFR tables.

Appendix A contains a listing of the data descriptors of the BUFR data output of PenWP in the NOAA QuikSCAT BUFR product format and the KNMI BUFR format with generic wind section. For more details on BUFR, the reader is referred to [6].

ECMWF maintains a library of routines for reading (writing) and decoding (encoding) the binary BUFR messages. This library forms the basis of the genscat BUFR module and hence the PenWP BUFR interface, see [2].

3.2 Backscatter slice or egg averaging

The HDF5 level 2a backscatter data from pencil beam scatterometers are organised in ‘slices’ or ‘eggs’, containing individual radar data acquisitions. The slices or eggs need to be beam-wise accumulated to a Wind Vector Cell (WVC) level before wind inversion can be done. The individual contributions are averaged using:

$$\sigma^0 = \frac{\sum_s \alpha_s^{-1} \sigma_s^0}{\sum_s \alpha_s^{-1}} \quad (3.1)$$

where σ^0 is the WVC backscatter, σ_s^0 is the slice/egg backscatter and α_s is the slice/egg K_p -alpha. The weights α_s^{-1} were found to be proportional to the estimated transmitted power contained in a slice and thus the above weighting relates to a summation over backscattered power.

The WVC K_p values α , β and γ are computed from the slice/egg K_p ’s as

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$$\alpha = \left(\sum_s \alpha_s^{-1} \right)^{-1}, \quad \beta = \left(\sum_s \beta_s^{-1} \right)^{-1}, \quad \gamma = \left(\sum_s \gamma_s^{-1} \right)^{-1}, \quad (3.2)$$

the WVC received power P is computed from the slice received power as

$$P = \sum_s P_s, \quad P_s = 2 \cdot SNR_s / \beta_s \quad (3.3)$$

and the WVC SNR (Signal to Noise Ratio) is calculated as

$$SNR = \beta \cdot P / 2. \quad (3.4)$$

Now $K_p^2 = \alpha + \beta/SNR + \gamma/SNR^2$ is obtained for each WVC view.

This averaging is implemented in the tools that convert level 1b and level 2 data into BUFR (see section 2.3). Quality flags present in the HDF5 data is evaluated and egg or slice data with one of the following flags set are skipped for SeaWinds, see [4]:

- Sigma0 Measurement Usable Flag
- Low SNR Flag
- Sigma0 Out of Range Flag
- Pulse Quality Flag
- Cell Location Flag
- Frequency Shift Flag
- Temperature Range Flag
- Attitude Data Flag
- Ephemeris Data Flag

The following quality flags in the OSCAT level 2a data are evaluated and slice data with one of these flags set are skipped for OSCAT, see [5]:

- σ^0 is poor
- K_p is poor
- Invalid footprint
- Footprint contains saturated slice

For HSCAT, no level 1b or level 2a quality flags are evaluated since there is no information available about these flags. However, backscatter data with unrealistic values (-99 dB or smaller) are skipped.

Note that in the outer swath no HH-polarised beam data is available, so normally the WVC beams 1 and 3 will not contain backscatter data. The conversion tools will re-distribute the VV slice information over four (more or less independent) backscatter views. The VV fore slice or egg data will be split into two sets and the VV aft slice or egg data as well. Observations are accumulated and

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averaged based on their azimuth angles. First, the average azimuth angle of all VV fore slices belonging to a WVC is computed. Then, all slices/eggs with a smaller azimuth angle than this average are taken and their average backscatter, incidence angle and azimuth angle are computed using the formulas above. This is considered as one WVC fore view. Then, all slices/eggs with a larger azimuth angle than the average are taken and the same is done to obtain the second WVC fore view. The same is done for the VV aft slices and in this way, four WVC views are obtained.

3.3 Atmospheric attenuation

The Ku band radiation from spaceborne scatterometers is attenuated by the atmosphere. Climatological values of this attenuation were determined as a function of location and time of the year [7]. The attenuation is based on a climatology of water vapour. The attenuation includes atmospheric oxygen, water vapour, and nominal cloud. A mean global cloud liquid water cover of 0.1 mm is assumed.

A table containing the monthly climatological attenuations was kindly provided by NOAA and it is delivered with PenWP in `data/atm_attn_360_180_12.dat`. The attenuations are the same that were used for QuikSCAT. The one-way nadir looking values A_{map} (dB) in the table are transformed into an attenuation correction A using the following formula:

$$A = 2A_{\text{map}} / \cos(\theta), \quad (3.5)$$

where θ is the beam incidence angle, and the attenuation correction is added to the beam σ^0 value (in dB). The two-way nadir looking values (i.e., without the incidence angle correction) are stored in the BUFR output data.

3.4 Quality control

The quality of every WVC is controlled. Before processing the beam data, checks are done on the completeness and usability of the σ^0 data. After the wind inversion step, the distance of the wind solutions to the GMF (also known as Maximum Likelihood Estimator, MLE) is considered. If this value is too large, the wind solutions are flagged. The MLE threshold depends on WVC number and wind speed. The optimum threshold values are determined using the same method as was used for QuikSCAT in the past [8], [9]. Recently, a new quality control mechanism was implemented which takes advance of the so-called J_{oss} parameter which is computed in the ambiguity removal step. The MLE-based KNMI QC flag was replaced by a new one with better skill, and a new, less strict, QC flag for nowcasting purposes was added [10].

3.5 Inversion

In the inversion step of wind retrieval, the radar backscatter observations in terms of the Normalized Radar Cross Sections (σ^0 's) are converted into a set of ambiguous wind vector solutions. In fact, a Geophysical Model Function (GMF) is used to map a wind vector (specified in terms of wind speed and wind direction) to a σ^0 value. The GMF depends not only on wind speed and wind direction but also on the measurement geometry (relative azimuth and incidence angle) and beam parameters (frequency and polarization). The NSCAT-4DS GMF is delivered with PenWP; it is based on the NSCAT-2 GMF that proved to be successful in the SDP processing software for QuikSCAT. As

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compared to NSCAT-2, NSCAT-4DS yields lower wind speeds in the wind speed regime above 15 m/s and smaller systematic wind direction biases for all wind speeds. The NSCAT-4DS winds better fit ECMWF model winds, buoy winds, and ASCAT winds [11].

PenWP also includes the Multiple Solution Scheme (MSS). In MSS mode, a large number of wind vector solutions is produced, typically 144. The wind vector solutions are ranked according to their probability based on the MLE and constitute the full wind vector probability density function. Subsequently, the 2DVAR Ambiguity Removal method, see section 3.7, is applied with a much larger set of wind vector solutions. The output BUFR format with generic wind section can accommodate any number of wind solutions due to the use of the so-called delayed descriptor replication. Details on the KNMI inversion approach can be found in [2]. For SeaWinds, MSS compares better to an independent NWP model reference and buoys than conventional two or four-solution schemes [12], [13], and for other Ku-band scatterometers the same is true.

Technical information on the KNMI inversion approach can be found in [2].

3.6 Ice screening

A Bayesian sea ice detection algorithm was developed for SeaWinds [14] and this algorithm is implemented in PenWP. It is based on the probabilistic distances to ocean and sea ice geophysical model functions. When a combination of backscatter measurements is close to the wind GMF, the probability that the WVC is covered with water is high. On the other hand, when the measurement is close to the sea ice GMF, the probability that the WVC contains ice is high. Each satellite overpass over the poles will yield new measurements which contribute to an ice map containing the ice probabilities.

3.7 Ambiguity Removal

The Ambiguity Removal (AR) step of the wind retrieval is the selection of the most probable surface wind vector among the available wind vector solutions, the so-called ambiguities. Various methods have been developed for AR. More information on Ambiguity Removal is given in [2]. The default method implemented in PenWP is the KNMI 2DVAR AR scheme. A description of its implementation can be found in [2]. The Multiple Solution Scheme (MSS) offers the possibility to postpone AR to the NWP data assimilation step in order to use the full information content of the scatterometer measurements. Further details on the algorithms and their validation can be found in [15], [16] and [17].

The performance of 2DVAR with meteorological balance constraints was tested and optimized for ERS data. It was found to be superior to other schemes, also when used for data other than ERS. Further testing for SeaWinds is described in [13].

From PenWP version 2.1 onwards it is also possible to use Numerical Background Error Correlations (NBEC's) in 2DVAR. These are derived from ASCAT-coastal data and are much broader than the default Gaussian background error correlations [18], [19]. With NBEC's the observations get larger weight in 2DVAR, resulting in better agreement with buoy winds at the cost of a 40% increase in processing time.

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3.8 Setting and unsetting of WVC quality flag bits

The attributes of the WVC quality flag (see [2]) are read from the BUFR input file and they are changed only when necessary and when the relevant processing step is invoked. This means that

- The ice flag will be set or unset depending on the Sea Surface Temperature from the GRIB model input when this is available, or depending of the result of the Bayesian ice screening when this is activated through the command line. It will not be changed when no NWP SST is used and the ice screening is not used.
- The land flag will be set or unset based on the land-sea mask from the GRIB model input when this is available. It will not be changed when no GRIB land-sea mask is used.
- The KNMI QC flag, QC flag for visualisation and nowcasting, rain detected flag and GMF distance too large flag are unset whenever the wind inversion is invoked, and set after wind inversion depending on the result. They will not be changed when the wind inversion is skipped.
- The variational QC flag is unset whenever the wind inversion or ambiguity removal are invoked, it is set after ambiguity removal depending on the result. It will not be set when the ambiguity removal is not used.

3.9 Monitoring

For the automatic ingestion of observations into their NWP systems, meteorological centres require quality checks on the NRT products. Hence a monitoring flag is defined, which was originally developed for the SeaWinds Wind Product. This flag indicates that several measures on the level of corruption of the output BUFR files are above a specified threshold. Data with the monitoring flag set should be rejected for ingestion in the NWP data assimilation system. Details on the monitoring flag can be found in the NWP SAF document [16].

3.10 Details of performance

Table 3.1 gives the approximate times needed for processing one HY-2B HSCAT BUFR 50 km or 25 km orbit file under various options on a workstation with a 3.60 GHz Intel Xeon 8 Core CPU processor under Linux using the Portland Fortran compiler.

Cell spacing (m)	MSS?	Inversion (seconds)	AR (seconds)	BUFR IO (seconds)	GRIB IO (seconds)	Total (seconds)
50000	No	3.3	0.6	1.2	0.5	5.7
50000	Yes	4.0	3.1	1.2	0.5	9.0
25000	No	13	4	2.6	1.0	21
25000	Yes	16	16	2.6	1.0	36

Table 3.1 Approximate times needed by PenWP to process one HSCAT orbit file using various options.

As can be seen from table 3.1, the use of MSS results in slightly larger processing times needed for inversion, in much larger processing times needed for AR and an overall increase in processing time of about 60 to 70%. The choice of platform, compiler and compiler settings will result in a large variation in the processing times.

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References

- [1] Verhoef, A., Vogelzang, J., Verspeek, J. and Stoffelen, A., 2022, *PenWP User Manual and Reference Guide*, Report NWPSAF-KN-UD-009, EUMETSAT.
- [2] Verhoef, A., Vogelzang, J., Verspeek, J. and Stoffelen, A., 2022, *PenWP Top Level Design*, Report NWPSAF-KN-DS-001, EUMETSAT.
- [3] Leidner, M., Hoffman, R., and Augenbaum, J., 2000 *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>).
- [4] Jet Propulsion Laboratory, 2006, *QuikSCAT Science Data Product User's Manual*, version 3.0, JPL D-18053.
- [5] SCATSAT-1 Data Products & Retrieval Team, 2016, *Algorithm and Theoretical Basis Document for SCATSAT-1 Data Products*, December 2016, ISRO.
- [6] Dragosavac, M., 2008, *BUFR User's Guide*, ECMWF. (Available on <https://www.ecmwf.int/>)
- [7] Wentz, F.J., 1996, *Climatology of 14-GHz Atmospheric Attenuation* (final delivery), Remote Sensing Systems, May 20, 1996.
- [8] Portabella, M., 2002, *Wind field retrieval from satellite radar systems*, PhD thesis, University of Barcelona. (Available on <https://scatterometer.knmi.nl/publications/>).
- [9] Verhoef, A. and A. Stoffelen, 2012, *Quality Control of Ku-band scatterometer winds*, OSI SAF Report SAF/OSI/CDOP2/KNMI/TEC/RP/194. (Available on <https://scatterometer.knmi.nl/publications/>).
- [10] Verhoef, A. and A. Stoffelen, 2021, *Advances in Ku-band scatterometer Quality Control*, OSI SAF Report SAF/OSI/CDOP3/KNMI/SCI/TN/404. (Available on <https://scatterometer.knmi.nl/publications/>).
- [11] See https://scatterometer.knmi.nl/nscat_gmf/ and references thereon.
- [12] Portabella, M. and Stoffelen, A., 2004, *A probabilistic approach for SeaWinds Data Assimilation*, Quart. J. Royal Meteor. Soc., **130**, pp. 127-152.

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- [13] Vogelzang, J., Stoffelen, A., Verhoef, A., de Vries, J. and Bonekamp, H., 2009, *Validation of two-dimensional variational ambiguity removal on SeaWinds scatterometer data*, J. Atm. Oceanic Technol., 7, 2009, 26, 1229-1245, doi:10.1175/2008JTECHA1232.1.
- [14] Belmonte Rivas, M. and Stoffelen, A., 2011 *New Bayesian algorithm for sea ice detection with QuikSCAT*, IEEE Transactions on Geoscience and Remote Sensing, I, **49**, 6, 1894-1901, doi:10.1109/TGRS.2010.2101608.
- [15] de Vries, J. and Stoffelen, A., 2000, *2D Variational Ambiguity Removal*. KNMI, Feb 2000. (Available on <https://scatterometer.knmi.nl/publications/>).
- [16] de Vries, J., Stoffelen, A., and Beysens, J., 2005, *Ambiguity Removal and Product Monitoring for SeaWinds*. KNMI. (Available on <https://scatterometer.knmi.nl/publications/>).
- [17] Vogelzang, J., 2016, *Two-dimensional variational ambiguity removal (2DVAR)*. NWP SAF Technical Report KN-TR-004. (Available on <https://scatterometer.knmi.nl/publications/>).
- [18] Vogelzang, J. and Stoffelen, A., 2012, *NWP model error structure functions obtained from scatterometer winds*, IEEE Transactions on Geoscience and Remote Sensing, **50**, 7, 2525-2533, doi: 10.1109/TGRS.2011.2168407.
- [19] Vogelzang, J., 2014, *Estimation of background error correlations*, NWP SAF Technical Report KN-TR-023 (Available on <https://scatterometer.knmi.nl/publications/>).

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Appendix A: BUFR data descriptors

This appendix contains lists of descriptors for the NOAA and KNMI BUFR formats in tables A.1 and A.2, respectively.

NOAA BUFR format			
Number	Descriptor	Parameter	Unit
1	001007	Satellite Identifier	Code Table
2	001012	Direction Of Motion Of Moving Observing Platform	Degree True
3	002048	Satellite Sensor indicator	Code Table
4	021119	Wind Scatterometer Geophysical Model Function	Code Table
5	025060	Software Identification	Numeric
6	002026	Cross Track Resolution	m
7	002027	Along Track Resolution	m
8	005040	Orbit Number	Numeric
9	004001	Year	Year
10	004002	Month	Month
11	004003	Day	Day
12	004004	Hour	Hour
13	004005	Minute	Minute
14	004006	Second	Second
15	005002	Latitude (Coarse Accuracy)	Degree
16	006002	Longitude (Coarse Accuracy)	Degree
17	008025	Time Difference Qualifier	Code Table
18	004006	Time to Edge	Second
19	005034	Along Track Row Number	Numeric
20	006034	Cross Track Cell Number	Numeric
21	021109	SeaWinds Wind Vector Cell Quality	Flag Table
22	011081	Model Wind Direction At 10 m	Degree True
23	011082	Model Wind Speed At 10 m	m/s
24	021101	Number Of Vector Ambiguities	Numeric
25	021102	Index Of Selected Wind Vector	Numeric
26	021103	Total Number of Sigma-0 Measurements	Numeric
27	021120	Probability of Rain	Numeric
28	021121	SeaWinds NOF* Rain Index	Numeric
29	013055	Intensity of Precipitation	kg/m ² s
30	021122	Attenuation Correction of Sigma-0 (from Tb)	dB
31	011012	Wind Speed At 10 m	m/s
32	011052	Formal Uncertainty in Wind Speed	m/s
33	011011	Wind Direction At 10 m	Degree True
34	011053	Formal Uncertainty in Wind Direction	Degree True
35	021104	Likelihood Computed For Solution	Numeric
36	011012	Wind Speed At 10 m	m/s
37	011052	Formal Uncertainty in Wind Speed	m/s
38	011011	Wind Direction At 10 m	Degree True
39	011053	Formal Uncertainty in Wind Direction	Degree True
40	021104	Likelihood Computed For Solution	Numeric

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NOAA BUFR format			
Number	Descriptor	Parameter	Unit
41	011012	Wind Speed At 10 m	m/s
42	011052	Formal Uncertainty in Wind Speed	m/s
43	011011	Wind Direction At 10 m	Degree True
44	011053	Formal Uncertainty in Wind Direction	Degree True
45	021104	Likelihood Computed For Solution	Numeric
46	011012	Wind Speed At 10 m	m/s
47	011052	Formal Uncertainty in Wind Speed	m/s
48	011011	Wind Direction At 10 m	Degree True
49	011053	Formal Uncertainty in Wind Direction	Degree True
50	021104	Likelihood Computed For Solution	Numeric
51	002104	Antenna Polarisation	Code Table
52	008022	Total Number (w.r.t. Accumulation or Average)	Numeric
53	012063	Brightness Temperature	K
54	012065	Standard Deviation Brightness Temperature	K
55	002104	Antenna Polarisation	Code Table
56	008022	Total Number (w.r.t. Accumulation or Average)	Numeric
57	012063	Brightness Temperature	K
58	012065	Standard Deviation Brightness Temperature	K
59	021110	Number of Inner-beam Sigma-0 (Forward of Satellite)	Numeric
60	005002	Latitude (Coarse Accuracy)	Degree
61	006002	Longitude (Coarse Accuracy)	Degree
62	021118	Attenuation Correction on Sigma-0	dB
63	002112	Radar Look Angle	Degree
64	002111	Radar Incidence Angle	Degree
65	002104	Antenna Polarisation	Code Table
66	021123	SeaWinds Normalised Radar Cross Section	dB
67	021106	Kp Variance Coefficient (Alpha)	Numeric
68	021107	Kp Variance Coefficient (Beta)	Numeric
69	021114	Kp Variance Coefficient (Gamma)	dB
70	021115	SeaWinds Sigma-0 Quality	Flag Table
71	021116	SeaWinds Sigma-0 Mode	Flag Table
72	008018	SeaWinds Land/Ice Surface Type	Flag Table
73	021117	Sigma-0 Variance Quality Control	Numeric
74	021111	Number of Outer-beam Sigma-0 (Forward of Satellite)	Numeric
75	005002	Latitude (Coarse Accuracy)	Degree
76	006002	Longitude (Coarse Accuracy)	Degree
77	021118	Attenuation Correction on Sigma-0	dB
78	002112	Radar Look Angle	Degree
79	002111	Radar Incidence Angle	Degree
80	002104	Antenna Polarisation	Code Table
81	021123	SeaWinds Normalised Radar Cross Section	dB
82	021106	Kp Variance Coefficient (Alpha)	Numeric
83	021107	Kp Variance Coefficient (Beta)	Numeric
84	021114	Kp Variance Coefficient (Gamma)	dB
85	021115	SeaWinds Sigma-0 Quality	Flag Table
86	021116	SeaWinds Sigma-0 Mode	Flag Table
87	008018	SeaWinds Land/Ice Surface Type	Flag Table
88	021117	Sigma-0 Variance Quality Control	Numeric
89	021112	Number of Inner-beam Sigma-0 (Aft of Satellite)	Numeric
90	005002	Latitude (Coarse Accuracy)	Degree
91	006002	Longitude (Coarse Accuracy)	Degree
92	021118	Attenuation Correction on Sigma-0	dB
93	002112	Radar Look Angle	Degree
94	002111	Radar Incidence Angle	Degree

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NOAA BUFR format			
Number	Descriptor	Parameter	Unit
95	002104	Antenna Polarisation	Code Table
96	021123	SeaWinds Normalised Radar Cross Section	dB
97	021106	Kp Variance Coefficient (Alpha)	Numeric
98	021107	Kp Variance Coefficient (Beta)	Numeric
99	021114	Kp Variance Coefficient (Gamma)	dB
100	021115	SeaWinds Sigma-0 Quality	Flag Table
101	021116	SeaWinds Sigma-0 Mode	Flag Table
102	008018	SeaWinds Land/Ice Surface Type	Flag Table
103	021117	Sigma-0 Variance Quality Control	Numeric
104	021113	Number of Outer-beam Sigma-0 (Aft of Satellite)	Numeric
105	005002	Latitude (Coarse Accuracy)	Degree
106	006002	Longitude (Coarse Accuracy)	Degree
107	021118	Attenuation Correction on Sigma-0	dB
108	002112	Radar Look Angle	Degree
109	002111	Radar Incidence Angle	Degree
110	002104	Antenna Polarisation	Code Table
111	021123	SeaWinds Normalised Radar Cross Section	dB
112	021106	Kp Variance Coefficient (Alpha)	Numeric
113	021107	Kp Variance Coefficient (Beta)	Numeric
114	021114	Kp Variance Coefficient (Gamma)	dB
115	021115	SeaWinds Sigma-0 Quality	Flag Table
116	021116	SeaWinds Sigma-0 Mode	Flag Table
117	008018	SeaWinds Land/Ice Surface Type	Flag Table
118	021117	Sigma-0 Variance Quality Control	Numeric

Table A.1 List of data descriptors for the NOAA BUFR format.

KNMI BUFR format			
Number	Descriptor	Parameter	Unit
1	001007	Satellite Identifier	Code Table
2	001012	Direction Of Motion Of Moving Observing Platform	Degree True
3	002048	Satellite Sensor indicator	Code Table
4	021119	Wind Scatterometer Geophysical Model Function	Code Table
5	025060	Software Identification	Numeric
6	002026	Cross Track Resolution	m
7	002027	Along Track Resolution	m
8	005040	Orbit Number	Numeric
9	004001	Year	Year
10	004002	Month	Month
11	004003	Day	Day
12	004004	Hour	Hour
13	004005	Minute	Minute
14	004006	Second	Second
15	005002	Latitude (Coarse Accuracy)	Degree
16	006002	Longitude (Coarse Accuracy)	Degree
17	008025	Time Difference Qualifier	Code Table
18	004006	Time to Edge	Second
19	005034	Along Track Row Number	Numeric
20	006034	Cross Track Cell Number	Numeric
21	021103	Total Number of Sigma-0 Measurements	Numeric
22	021120	Probability of Rain	Numeric
23	021121	SeaWinds NOF* Rain Index	Numeric

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KNMI BUFR format			
Number	Descriptor	Parameter	Unit
24	013055	Intensity of Precipitation	kg/m ² s
25	021122	Attenuation Correction of Sigma-0 (from Tb)	dB
26	002104	Antenna Polarisation	Code Table
27	008022	Total Number (w.r.t. Accumulation or Average)	Numeric
28	012063	Brightness Temperature	K
29	012065	Standard Deviation Brightness Temperature	K
30	002104	Antenna Polarisation	Code Table
31	008022	Total Number (w.r.t. Accumulation or Average)	Numeric
32	012063	Brightness Temperature	K
33	012065	Standard Deviation Brightness Temperature	K
34	021110	Number of Inner-beam Sigma-0 (Forward of Satellite)	Numeric
35	005002	Latitude (Coarse Accuracy)	Degree
36	006002	Longitude (Coarse Accuracy)	Degree
37	021118	Attenuation Correction on Sigma-0	dB
38	002112	Radar Look Angle	Degree
39	002111	Radar Incidence Angle	Degree
40	002104	Antenna Polarisation	Code Table
41	021123	SeaWinds Normalised Radar Cross Section	dB
42	021106	Kp Variance Coefficient (Alpha)	Numeric
43	021107	Kp Variance Coefficient (Beta)	Numeric
44	021114	Kp Variance Coefficient (Gamma)	dB
45	021115	SeaWinds Sigma-0 Quality	Flag Table
46	021116	SeaWinds Sigma-0 Mode	Flag Table
47	008018	SeaWinds Land/Ice Surface Type	Flag Table
48	021117	Sigma-0 Variance Quality Control	Numeric
49	021111	Number of Outer-beam Sigma-0 (Forward of Satellite)	Numeric
50	005002	Latitude (Coarse Accuracy)	Degree
51	006002	Longitude (Coarse Accuracy)	Degree
52	021118	Attenuation Correction on Sigma-0	dB
53	002112	Radar Look Angle	Degree
54	002111	Radar Incidence Angle	Degree
55	002104	Antenna Polarisation	Code Table
56	021123	SeaWinds Normalised Radar Cross Section	dB
57	021106	Kp Variance Coefficient (Alpha)	Numeric
58	021107	Kp Variance Coefficient (Beta)	Numeric
59	021114	Kp Variance Coefficient (Gamma)	dB
60	021115	SeaWinds Sigma-0 Quality	Flag Table
61	021116	SeaWinds Sigma-0 Mode	Flag Table
62	008018	SeaWinds Land/Ice Surface Type	Flag Table
63	021117	Sigma-0 Variance Quality Control	Numeric
64	021112	Number of Inner-beam Sigma-0 (Aft of Satellite)	Numeric
65	005002	Latitude (Coarse Accuracy)	Degree
66	006002	Longitude (Coarse Accuracy)	Degree
67	021118	Attenuation Correction on Sigma-0	dB
68	002112	Radar Look Angle	Degree
69	002111	Radar Incidence Angle	Degree
70	002104	Antenna Polarisation	Code Table
71	021123	SeaWinds Normalised Radar Cross Section	dB
72	021106	Kp Variance Coefficient (Alpha)	Numeric
73	021107	Kp Variance Coefficient (Beta)	Numeric
74	021114	Kp Variance Coefficient (Gamma)	dB
75	021115	SeaWinds Sigma-0 Quality	Flag Table
76	021116	SeaWinds Sigma-0 Mode	Flag Table
77	008018	SeaWinds Land/Ice Surface Type	Flag Table

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KNMI BUFR format			
Number	Descriptor	Parameter	Unit
78	021117	Sigma-0 Variance Quality Control	Numeric
79	021113	Number of Outer-beam Sigma-0 (Aft of Satellite)	Numeric
80	005002	Latitude (Coarse Accuracy)	Degree
81	006002	Longitude (Coarse Accuracy)	Degree
82	021118	Attenuation Correction on Sigma-0	dB
83	002112	Radar Look Angle	Degree
84	002111	Radar Incidence Angle	Degree
85	002104	Antenna Polarisation	Code Table
86	021123	SeaWinds Normalised Radar Cross Section	dB
87	021106	K _p Variance Coefficient (Alpha)	Numeric
88	021107	K _p Variance Coefficient (Beta)	Numeric
89	021114	K _p Variance Coefficient (Gamma)	dB
90	021115	SeaWinds Sigma-0 Quality	Flag Table
91	021116	SeaWinds Sigma-0 Mode	Flag Table
92	008018	SeaWinds Land/Ice Surface Type	Flag Table
93	021117	Sigma-0 Variance Quality Control	Numeric
94	025060	Software Identification	Numeric
95	001032	Generating Application	Code Table
96	011082	Model Wind Speed At 10 m	m/s
97	011081	Model Wind Direction At 10 m	Degree True
98	020095	Ice Probability	Numeric
99	020096	Ice Age (A-Parameter)	dB
100	021155	Wind Vector Cell Quality	Flag Table
101	021101	Number Of Vector Ambiguities	Numeric
102	021102	Index Of Selected Wind Vector	Numeric
103	031001	Delayed Descriptor Replication Factor	Numeric
104	011012	Wind Speed At 10 m	m/s
105	011011	Wind Direction At 10 m	Degree True
106	021156	Backscatter Distance	Numeric
107	021104	Likelihood Computed For Solution	Numeric
108	011012	Wind Speed At 10 m	m/s
109	011011	Wind Direction At 10 m	Degree True
110	021156	Backscatter Distance	Numeric
111	021104	Likelihood Computed For Solution	Numeric

Table A.2 List of data descriptors for the KNMI BUFR format with generic wind section. Note that descriptor numbers 104-107 can be repeated 1 to 144 times, depending on the value of the Delayed Descriptor Replication Factor (descriptor number 103)

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Appendix B: Acronyms

Name	Description
AR	Ambiguity Removal
ASCAT	Advanced SCATterometer on MetOp
BUFR	Binary Universal Form for the Representation of data
C-band	Radar wavelength at about 5 cm
ERS	European Remote Sensing satellites
ECMWF	European Centre for Medium-range Weather Forecasts
EUMETSAT	European Organization for the Exploitation of Meteorological Satellites
genscat	generic scatterometer software routines
GMF	Geophysical model function
HDF5	Hierarchical Data Format version 5
HSCAT	Scatterometer onboard of the Chinese Haiyang-2 series satellites
ISRO	Indian Space Research Organisation
KNMI	Koninklijk Nederlands Meteorologisch Instituut (Royal Netherlands Meteorological Institute)
Ku-band	Radar wavelength at about 2 cm
L1b	Level 1b product
Metop	Meteorological operational Satellite
MLE	Maximum Likelihood Estimator
MSS	Multiple Solution Scheme
NCEP	United States National Centers for Environmental Prediction
NOAA	United States National Oceanic and Atmospheric Administration
NWP	Numerical Weather Prediction
OSCAT	Scatterometer onboard of the Indian Oceansat and ScatSat satellites
OSI	Ocean and Sea Ice
PenWP	Pencil Beam Wind Processor
SAF	Satellite Application Facility
SDP	SeaWinds Data Processor
SNR	Signal to Noise Ratio
WVC	Wind Vector Cell, also called node or cell

Table B.1 List of acronyms.