Document NWPSAF-KN-DS-002
Version 2.2
May 2018

# PenWP Product Specification

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This documentation was developed within the context of the EUMETSAT Satellite Application Facility on Numerical Weather Prediction (NWP SAF), under the Cooperation Agreement dated 29 June, 2011, between EUMETSAT and the Met Office, UK, by one or more partners within the NWP SAF. The partners in the NWP SAF are the Met Office, ECMWF, KNMI and Météo France.



| **Change record** | | | |
|---|---|---|---|
| **Version** | **Date** | **Author / changed by** | **Remarks** |
| 1.9 | May 2015 | Anton Verhoef | First version for PenWP beta release |
| 2.0 | Oct 2015 | Anton Verhoef | Version for first public PenWP release, split original UM into UM, PS and TLD docs |
| 2.0.01 | Nov 2015 | Anton Verhoef | Modified according to DRI comments |
| 2.1 | Feb 2017 | Jur Vogelzang | Added NBEC’s |
| 2.2 | May 2018 | Anton Verhoef | Version for release 2.2 |

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# 1 Introduction

The Pencil Beam Wind Processor (PenWP) is a software package written mainly in Fortran 90 with some parts in C for handling data from the SeaWinds (on QuikSCAT or ADEOS-II), OSCAT (on Oceansat-2 and ScatSat-1), HSCAT (on HY-2A) 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.

Please note that any questions or problems regarding the installation or use of PenWP can be addressed at the NWP SAF helpdesk at http://nwpsaf.eu/.

## 1.1 Conventions

Names of physical quantities (e.g., wind speed components *u* and *v*), modules (e.g. *BufrMod*), 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. http://www.knmi.nl/scatterometer/).

# 2 PenWP product specification

## 2.1 Purpose of PenWP

The Pencil Beam Wind Processor (PenWP) has been developed to fully exploit $\sigma^0$ 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 anemometer height in a 2D array of Wind Vector Cells (WVCs) with specified size ($100 \times 100$ km$^2$, $50 \times 50$ km$^2$ or $25 \times 25$ 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 $\sigma^0$ 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 2a data in HDF, see [4]. It is possible to reduce the WVC grid spacing from 25 km to 50 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 $\sigma^0$ data. The data need to be converted to HDF5 first, and then converted to BUFR format using `seawinds_hdf2bufr`.

- OSCAT level 2a (L2A) HDF5 data. These products are created by ISRO; see [5]. The first operational ISRO L2A product is denoted version 1.3. PenWP has the ability to process earlier experimental and pre-operational versions as well. 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 $\sigma^0$ data. The data need to be converted to BUFR format before using them in PenWP using `oscat_hdf2bufr`. See [1] for more details.
- OSCAT level 1b (L1B) HDF5 data. These products are created by ISRO; see [5]. A conversion program called `oscat_l1b_l2a` is available to convert these data to level 2a data at 25 or 50 km WVC spacing in HDF5. These data can subsequently be converted to BUFR and processed by PenWP. See [1] for more details.
- HSCAT level 2a HDF5 data, as created by NSOAS. 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 $\sigma^0$ data. The data need to be converted to BUFR format before using them in PenWP using `hscat_hdf2bufr`. See [1] for more details. Note that PenWP has been tested only with a limited amount of HSCAT data.

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 ERA-Interim archive (http://www.ecmwf.int/en/research/climate-reanalysis/era-interim) 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

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. The equivalent of a personal computer will suffice to provide a timely NRT wind product. PenWP requires about 150-200 MB disk space when installed and compiled.

| Platform | Fortran compiler | C compiler |
| --- | --- | --- |
| Fedora Linux workstation | Portland pgf90<br>GNU g95<br>GNU gfortran | GNU gcc |
| Redhat Linux cluster | Portland pgf90 | GNU gcc |
| Apple MacBook | GNU gfortran | GNU gcc |

**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, and that the BUFR and GRIB libraries are properly installed. For Windows a Linux environment like Wubi is needed. PenWP can also run on a MacOS machine (Darwin).

# 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:

$$\sigma^0 = \frac{\sum_S \alpha_S{}^{-1} \sigma_S^0}{\sum_S \alpha_S{}^{-1}} \qquad (3.1)$$

where $\sigma^0$ is the WVC backscatter, $\sigma^0{}_S$ is the slice/egg backscatter and $\alpha_S$ is the slice/egg $K_p$-alpha. The weights $\alpha_S{}^{-1}$ 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 $\alpha$, $\beta$ and $\gamma$ are computed from the slice/egg $K_p$’s as

$$\alpha = \left( \sum_S \alpha_S^{-1} \right)^{-1}, \quad \beta = \left( \sum_S \beta_S^{-1} \right)^{-1}, \quad \gamma = \left( \sum_S \gamma_S^{-1} \right)^{-1}, \tag{3.2}$$

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

$$P = \sum_S P_S , \quad P_S = 2 \cdot SNR_S / \beta_S \tag{3.3}$$

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

$$SNR = \beta \cdot P / 2 . \tag{3.4}$$

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

This averaging is implemented in the conversion tools `seawinds_hdf2bufr`, `oscat_hdf2bufr` and `hscat_hdf2bufr`. Quality flags present in the HDF5 data is evaluated and egg data with one of the following flags set are skipped for SeaWinds in `seawinds_hdf2bufr`, 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 in oscat_hdf2bufr, see [5]:

- $\sigma^0$ is poor
- $K_p$ is poor
- Invalid footprint
- Footprint contains saturated slice

For HSCAT (`hscat_hdf2bufr`), no level 2a quality flags are evaluated since there is no information available about these flags. 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 for OSCAT and HSCAT offer the `–allswath` command line option which will re-distribute the VV slice information over four (more or less independent) backscatter data. For SeaWinds, this is always done and the `-allswath` command line option is not available. The

VV fore slice data will be split into two sets and the VV aft slice data as well. Slices are accumulated and 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 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 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 $A_{\text{map}}$ (dB) in the table are transformed into an attenuation correction $A$ using the following formula:

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

where $\theta$ is the beam incidence angle, and the attenuation correction is added to the beam $\sigma^0$ 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 $\sigma^0$ 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].

## 3.5 Inversion

In the inversion step of wind retrieval, the radar backscatter observations in terms of the Normalized Radar Cross Sections ($\sigma^0$'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 $\sigma^0$ 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-4 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 compared to NSCAT-2, NSCAT-4 yields lower wind speeds in the wind speed regime above 15 m/s. The NSCAT-4 winds better fit ECMWF model winds and buoy winds, [10].

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 3.6, 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 [11], [12], 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 [13] 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 [14], [15] and [16].

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 [12].

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 [17], [18]. 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 [19].

## 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, 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 [15].

## 3.10 Details of performance

Table 3.1 gives the approximate times needed for processing one ScatSat-1 OSCAT BUFR 50 km or 25 km orbit file under various options on a workstation with a 3.20 GHz Intel Xeon Quad 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 | 4.6 | 0.7 | 0.4 | 0.4 | 6.2 |
| 50000 | Yes | 5.3 | 4.2 | 0.4 | 0.4 | 10.4 |
| 25000 | No | 19 | 4 | 1.2 | 0.6 | 25 |
| 25000 | Yes | 22 | 23 | 1.2 | 0.6 | 48 |

**Table 3.1** Approximate times needed by PenWP to process one OSCAT 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 70 to 90%.

The choice of platform, compiler and compiler settings will result in a large variation in the processing times.

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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 | $kg/m^2s$ |
| 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 |

| 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 |

| 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 |

| KNMI BUFR format | | | |
|---|---|---|---|
| **Number** | **Descriptor** | **Parameter** | **Unit** |
| 24 | 013055 | Intensity of Precipitation | $kg/m^2s$ |
| 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 |

| **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 | Kp Variance Coefficient (Alpha) | Numeric |
| 88 | 021107 | Kp Variance Coefficient (Beta) | Numeric |
| 89 | 021114 | Kp 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)

# 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 |
| 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 |
| 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.