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PenWP User Manual and Reference Guide

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KNMI, De Bilt, the Netherlands

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PenWP User Manual and Reference Guide

KNMI, De Bilt, the Netherlands

This documentation was developed within the context of the EUMETSAT Ocean and Sea Ice Satellite Application Facility (OSI SAF).

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2.0	Oct 2015	Anton Verhoef	Version for first public PenWP release, split original UM into UM, PS and TLD docs
2.0.02	Nov 2015	Anton Verhoef	Modified according to DRI comments
2.1	Feb 2017	Jur Vogelzang	Added version 2.1 options
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1 Introduction

This document is the User Manual (UM) of the Pencil beam Wind Processor (PenWP) software package. The current introductory section gives general information about PenWP. Section 2 provides information on how to install, compile, and link the PenWP software. The use of PenWP is discussed in section 3.

More information about PenWP can be found in several other documents. The Product Specification (PS) [1] contains more details about the design 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 Aims and scope

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, see table 1.1. Details of these instruments can be found in [3] and [4], respectively, and on several web sites, see e.g. information on the NASA and ISRO web sites. PenWP is intended to be a generic wind processor for Ku-band pencil beam scatterometer data. It will be adapted to handle data from future instruments like the ScatSat-1 successor Oceansat-3 (from ISRO) once they become available. Some background information on the development history of PenWP can be found in Appendix B.

Instrument	Satellite	Period of operations
SeaWinds	QuikSCAT	1999 – 2009
SeaWinds	ADEOS-II	2003
OSCAT	Oceansat-2	2009 – 2014
OSCAT	ScatSat-1	2016 – 2021
HSCAT	HY-2A	2011 – 2020
RapidScat	ISS	2014 – 2016
HSCAT	HY-2B	2018 -
HSCAT	HY-2C	2020 -
HSCAT	HY-2D	2021 -

Table 1.1 Satellite instruments that can be processed with PenWP.

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All Ku-band pencil beam scatterometers measure the ocean radar backscatter in very similar configurations and wavelengths and thus provide essentially the same geophysical measurements. After correction of the instrument gain calibration by ocean calibration and the performance of verification tests, indeed standard processing of this category of instruments can be performed without loss of quality for any of the instruments. On the other side, the PenWP standard allows:

- A clearer separation of instrument and ocean response.
- Simplification of the processing of pencil-beam scatterometer data and further generic processing improvements.
- Ease of application.

PenWP generates surface winds based on pencil beam radar backscatter data. It has the ability to perform the ambiguity removal with the Two-dimensional Variational Ambiguity Removal (2DVAR) method and it supports the Multiple Solution Scheme (MSS). The output of PenWP consists of wind vectors which represent surface winds within the ground swath of the scatterometer. The input of PenWP is Normalized Radar Cross Section (NRCS), σ^0 , data in BUFR format. These data may be near real-time. Conversion programs are included in the package to convert Hierarchical Data Format (HDF5) data from various instruments to BUFR. Output is written using the NOAA SeaWinds BUFR template by default or in the KNMI BUFR template with generic wind section. The NOAA BUFR template allows writing of up to 4 wind solutions whereas the KNMI BUFR template allows to write all 144 MSS wind solutions, see [1] for a description of these formats.

Apart from the scatterometer input data, PenWP needs Numerical Weather Prediction (NWP) model winds as a first guess for the Ambiguity Removal step. These data need to be provided in GRIB edition 1 or 2.

PenWP is developed as code which can be run in an operational setting as is done by, e.g., the Ocean and Sea Ice Satellite Application Facility (OSI SAF). The coding is mainly in Fortran 90 with some parts in C and has followed the procedures specified for the NWP SAF [6]. Special attention has been paid to robustness and readability. PenWP may be run on every Unix or Linux machine. PenWP can also be run on a Windows machine if a Linux environment like the Windows Installer for Ubuntu (Wubi) is installed or on a MacOS machine (Darwin).

1.2 Testing PenWP

Modules are tested by test programs. Many test programs are part of the modules themselves. Test programs can be compiled separately. For PenWP, the description of the test programs and the results of the testing are reported in [5].

1.3 Why use PenWP?

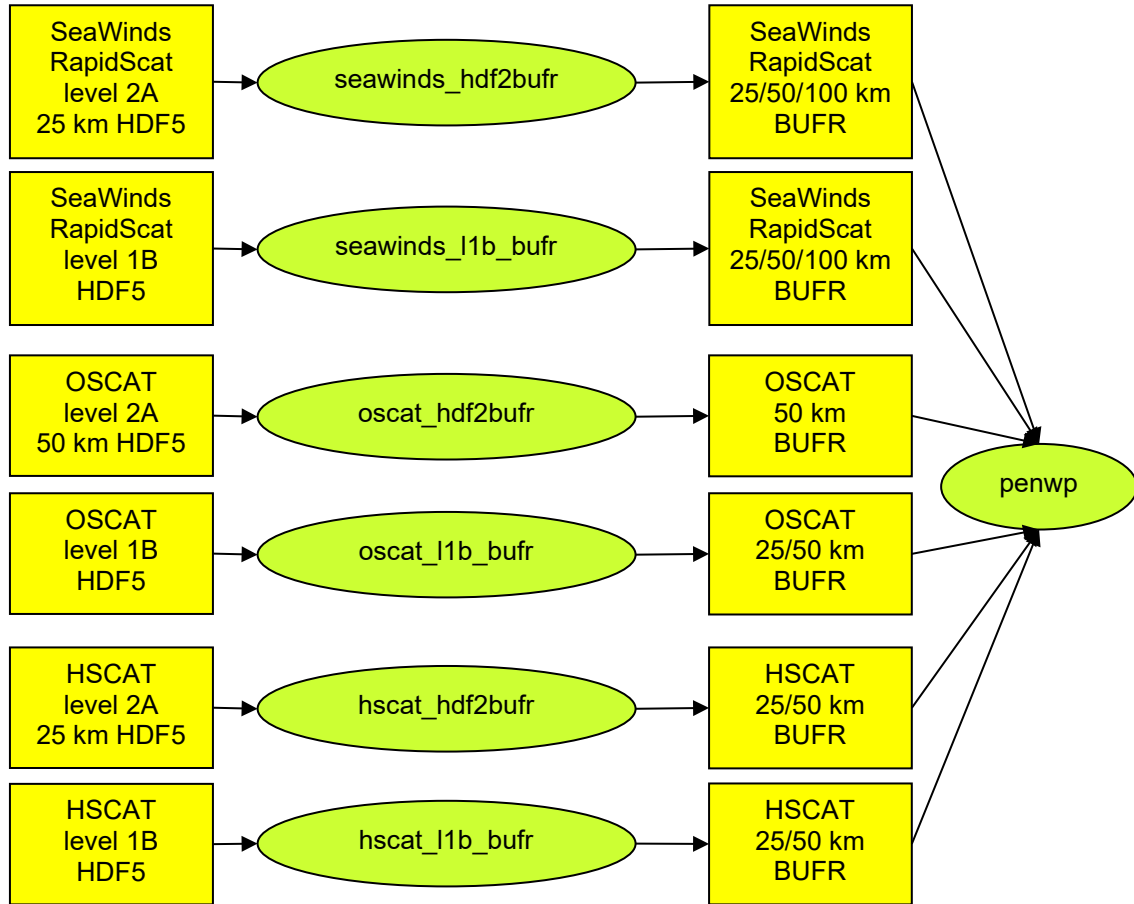


Figure 1.1 PenWP pre-processing scheme.

Scatterometers provide valuable observational data over the world's oceans. Hence, successful assimilation of scatterometer data in numerical weather prediction systems generally improves weather forecasts. PenWP has been developed to fully exploit scatterometer data. It is meant to form the key component of the observation operator for surface winds in data assimilation systems.

The input of the PenWP main program is BUFR data which has been converted from HDF5 using one of the conversion programs (for SeaWinds/RapidScat, OSCAT or HSCAT) included in the package. The PenWP BUFR output wind product can also be read again and reprocessed. Figure 1.1 gives an overview of the different ways to obtain input BUFR data from scatterometer input data. Depending on the grid spacing of the input BUFR product, PenWP will process the data on 25 km, 50 km or 100 km grid spacing. The SeaWinds/RapidScat HDF5 to BUFR converters can create BUFR data on 25, 50 or 100 km grid spacing by averaging the backscatter data in the level 1b or level 2a input file to the requested gridding. The OSCAT HDF5 to BUFR converter `oscat_hdf2bufr` will create BUFR data with the same grid spacing as the level 2a input file. This is 50 km when using the level 2a input data from the Indian Space Research Organisation (ISRO). When using level 1b input data from ISRO in combination with `oscat_l1b_bufr`, 25 or 50 km BUFR data can be created. HSCAT level 1b and level 2a input data can be written on 25 km or 50 km grid spacing.

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The general scheme of PenWP (and any other wind scatterometer data processor) is given in figure 1.2. Besides scatterometer data, NWP model GRIB input containing land-sea mask, sea surface temperature and first guess winds over the globe is necessary. 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 section 3.1 for more information on this.

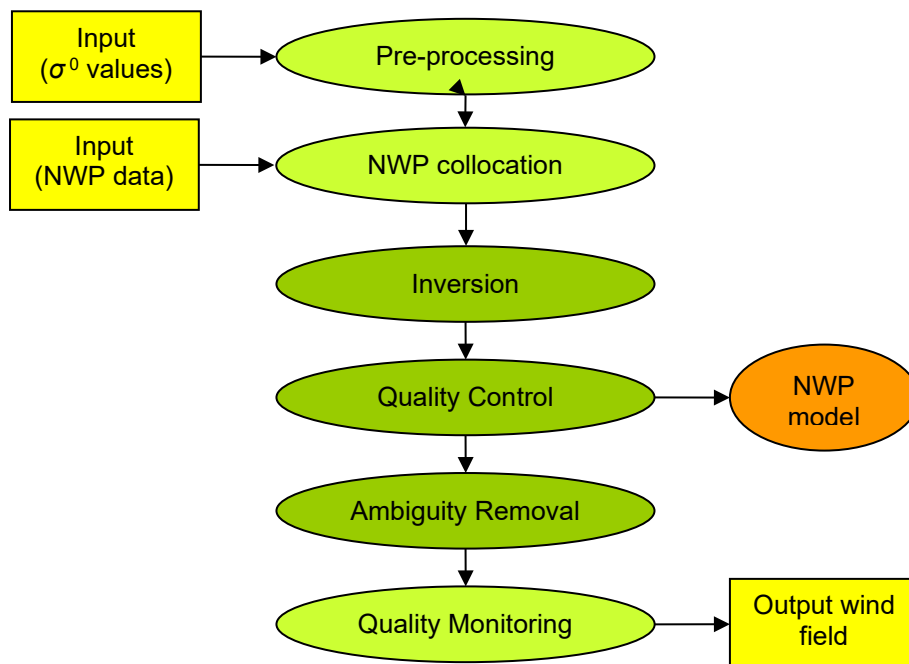


Figure 1.2 PenWP processing scheme. The wind vectors and their probabilities after Quality Control may be fed directly in the Data Assimilation step of a Numerical Weather Prediction model.

The PenWP processing chain contains several steps (see figure 1.2):

1. Pre-processing. The input file is decoded and the radar backscatter (σ^0) values are written in the data structures of PenWP. The individual backscatter measurements are averaged to a backscatter value on Wind Vector Cell level. Some quality control on the input data is done.
2. Collocation with NWP data. The GRIB edition 1 or 2 files containing NWP data are read and the values for land fraction, sea surface temperature and first guess winds are interpolated and stored with the information of each WVC.
3. Inversion. The σ^0 values are compared to the Geophysical Model Function (GMF) by means of a Maximum Likelihood Estimator (MLE). The wind vectors that give the best description of the σ^0 values (the solutions) are retained. The MLE is also used to assign a probability to each wind vector. The normal scheme allows 4 solutions at most, but in the Multiple Solution Scheme (MSS) the maximum number of solutions is 144.
4. Quality Control. Solutions that lie far away from the GMF are likely to be contaminated by, e.g., sea ice or confused sea state. During Quality Control these solutions are identified and flagged.
5. Ambiguity Removal. This procedure identifies the most probable solution using some form of external information. PenWP uses a two-dimensional variational scheme (2DVAR) as default.

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A cost function is minimized that consists of a background wind field and all solutions with their probability, using meteorological balance, mass conservation and continuity as constraints.

6. Quality Monitoring. The last step is to output quality indicators to an ASCII monitoring file and to write the results in a BUFR format output file.

Steps 2 and 6 of the processing chain are rather trivial; the real work is done in steps 1, 3, 4, and 5.

As further detailed in [1], PenWP profits from developments in

- Inversion and output of the full probability density function of the vector wind (Multiple Solution Scheme, MSS) [7], [8].
- Quality Control (QC) [9], [10], [11].
- Meteorologically balanced Ambiguity Removal (2DVAR) [12], with optional empirical background error correlations [13].
- Quality monitoring.
- Capability to process scatterometer data on 100 km, 50 km and 25 km cell spacing.

A complete specification of PenWP can be found in the Product Specification in [1]. The software is based on generic genscat routines. Genscat lies at the base of all scatterometer wind processors developed within OSI SAF. Genscat is a library of generic code suitable for all scatterometer instruments. It contains routines for e.g. wind inversion, ambiguity removal, reading and writing of files in BUFR, GRIB, and other formats. It also contains more low-level routines for e.g. date/time handling and numerical conversions. These routines are discussed in more detail in [2].

The genscat code base is quite stable and most development work is done in the instrument-specific code that is built on top of genscat. For each new wind processor release, a dedicated genscat version is delivered which is tested by running the new configuration in parallel to the operational one and carefully comparing the outputs.

1.4 Modes of using PenWP

There are several modes to assimilate the scatterometer data in NWP models using PenWP. Anyway, the first thing to assure oneself of is the absence of biases by making scatter plots between scatterometer and NWP model first guess for at least wind speed, but wind direction and wind components would also be of interest to guarantee consistency; for more detailed guidance on bias correction see [15].

The scatterometer wind product, available as a deliverable from the EUMETSAT OSI SAF project, could be the starting point for NWP data assimilation:

1. The unique solution at every WVC may be assimilated as if it were buoy data. This is the fastest way and one exploits the data to a large extent. For a small advantage, PenWP could be installed to provide 2DVAR solutions based on the local first guess.
2. The PenWP software may be used to modify the 3DVAR or 4DVAR data assimilation system to work with the ambiguous wind solutions and their probabilities at every WVC in order to provide the full information content to the data assimilation system. This represents some investment, but the approach is generic and applicable to all scatterometer data. With respect to option 1, this option only occasionally leads to an improved ambiguity removal, but often in

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dynamical atmospheric cases (storms or cyclones) that are really relevant.

Both options can be based on PenWP in standard or MSS mode [8]. MSS is somewhat more dependent on the balance constraints in 2DVAR or the user's own data assimilation system than the standard PenWP, but much less noisy. A substantial advantage is thus obtained by using option 2 and MSS, where potentially the full benefit of the scatterometer data is achieved. The mode of using PenWP thus depends on the opportunities, experience, and time the user has to experiment with scatterometer data in the NWP system under consideration; for more detailed guidance on scatterometer data assimilation see [16].

PenWP can, of course, also be used to create a stand-alone wind product, e.g., for nowcasting purposes. Such stand-alone wind products are deliverables of the OSI SAF project. More information on this project can be found on <https://osi-saf.eumetsat.int/>.

1.5 Conventions

Names of physical quantities (e.g., wind speed components *u* and *v*), modules (e.g. *bufrio_module*), 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 Installing PenWP

The PenWP software package can be ordered from the NWP SAF website <https://nwp-saf.eumetsat.int/site/software/scatterometer/download/>. PenWP is written in Fortran 90 (with a few low level modules in C) and is designed to run on a computer system under Linux or Unix. PenWP needs a Fortran 90 compiler and a C compiler for installation. Also, CMake version 3.6 or higher (<https://cmake.org/>) is required in order to compile the ecCodes library. PenWP comes along with a complete make system for compilation. In some cases, the Makefiles call installation scripts which are written in Bourne shell to enhance portability. 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 1 GB of disk space is needed. The output needs about 12 MB disk space to store one orbit of BUFR output data and 5 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 is recommended.

The package is intended to be installed in a user directory (e.g. the home directory) and sufficient disk space and write permissions should be available. If the executable is to be installed into a system directory like `/usr/bin`, generally root permissions are necessary.

PenWP has been successfully implemented on many different computer platforms and with many different compilers and compiler versions. Hence we can not specify exact requirements to compiler versions. For example, PenWP has been tested recently with the following compiler versions:

- GCC version 11.2.1 of 20210728
- GNU Fortran (gfortran) version 11.2.1 of 20210728
- Portland Fortran compiler version 11.10-0

To install PenWP, the following steps must be taken:

1. Copy the PenWP package (file `PenWP<version>.tar.gz`) to the directory from which PenWP will be applied, and unzip and untar it. This will create subdirectories `penwp` and `genscat` that contain all code needed (see section 2.1), and a script called `compile_penwp` for easy compilation.
2. Unlike in older PenWP versions, it is not necessary anymore to download the ecCodes library separately from the ECMWF website, it now falls under the Apache License, Version 2.0 and can be redistributed in combination with PenWP. You may obtain a copy of the License at <http://www.apache.org/licenses/LICENSE-2.0>.
3. Go to the top directory where the PenWP package (tar file) was copied to and run the `./compile_penwp` script. The script will ask for the compiler used and it will invoke the make system for compilation and linking of the software (see also section 2.5).

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Suppose that PenWP is to be installed in directory /data/penwp_install and that the PenWP tar file is already in this directory, then the compilation looks like this:

```

user@machine /data/penwp_install> tar -xzf PenWP4_0_00.tar.gz
user@machine /data/penwp_install> ls -l
total 66924
-rwxr-xr-x 1 user group      3583 Mar  1 16:01 compile_penwp
drwxr-xr-x 7 user group      4096 Mar  1 15:01 genscat
drwxr-xr-x 10 user group      4096 Mar  1 15:01 penwp
-rw-r--r-- 1 user group 68513838 Jun 20 13:51 PenWP4_0_00.tar.gz
user@machine /data/penwp_install> ./compile_penwp
=====
PenWP compilation script
=====

ECCODES library file ./genscat/support/eccodes/ecmwf/eccodes-2.24.2-Source.tar.gz found

PenWP can be compiled with the following Fortran compilers:
 1 : GNU g95
 2 : GNU Compiler Collection gfortran
 3 : Portland f90
 4 : Intel Fortran Compiler
 5 : Default Fortran and C compilers (f90, cc) for this platform
 6 : Other choice
For an other compiler: manual installation is needed
Abort this script and consult the PenWP User Manual and Reference Guide in penwp/doc

Enter the number of your compiler [1-5]:
2
GNU Compiler Collection gfortran selected
./Set_Makeoptions
Set_Makeoptions started
  Operating system seems to be: LINUX
  using gfortran as linker
  using gfortran as linker for creating shared object files
  using gcc as linker for c-programs
  using gfortran as f90 compiler
  using gfortran as f77 compiler
  using gcc as c compiler
  using: F90FLAGS = -O -fPIC -g -Wall -fbounds-check -Wextra
  using: F77FLAGS = -O -fPIC
  using: CFLAGS   = -O -fPIC -DINTEGER_IS_INT
Set_Makeoptions completed
*****
*** Make in support
*****
make[1]: Entering directory '/nobackup/users/user/penwp_install/genscat/support'
*****

< compilation continues >

gfortran ../../genscat/support/convert/convert.o ../../genscat/support/Compiler_Features/Compiler_Features.o ../../genscat/support/eccodes/bufrio_module.o ../../genscat/support/eccodes/gribio_module.o ../../genscat/support/ErrorHandler/ErrorHandler.o ../../genscat/support/file/LunManager.o ../../genscat/support/hdf5/HD F5Mod.o ../../genscat/support/hdf5/hdf5io.o ../../genscat/support/num/numerics.o ../../genscat/support/sort/SortMod.o ../../genscat/support/datetime/DateTimeMod.o ../../src/penwp_prepost.o ../../src/penwp_bufr.o ../../src/penwp_data.o -L../../genscat/support/hdf5 -lhdf5 -lz -ldl ../../genscat/support/eccodes/libeccodes_f90.a ../../genscat/support/eccodes/libeccodes.a seawinds_11b_bufr.o -o seawinds_11b_bufr
make[1]: Leaving directory '/data/penwp_install/penwp/seawinds'
make[1]: Entering directory '/data/penwp_install/penwp/execs'
make[1]: Leaving directory '/data/penwp_install/penwp/execs'
make[1]: Entering directory '/data/penwp_install/penwp/data'
make[1]: Leaving directory '/data/penwp_install/penwp/data'
user@machine /data/penwp_install>

```

PenWP is now ready for use, provided that the environment variables discussed in section 2.6 have the proper settings. See also sections 2.6 and 3.1 for directions on how to run PenWP. The three

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steps in this section are sufficient to perform a standard compilation. Sections 2.2 to 2.5 provide more detailed information, especially for users interested to use advanced compiler options.

2.1 Directories and files

All code for PenWP is stored in a file named `PenWP<version>.tar.gz` that is made available through the NWP SAF website. This file should be placed in the directory from which PenWP is to be run. After unzipping (with `gunzip PenWP<version>.tar.gz`) and untarring (with `tar -xf PenWP<version>.tar`), the PenWP package is extracted in subdirectories `penwp` and `genscat`, which are located in the directory where the tar file was located. Subdirectories `penwp` and `genscat` each contain a number of files and subdirectories. A copy of the release notes can also be found in the directory `penwp/docs`.

Name	Contents
<code>data</code>	Look-up tables necessary in several processing steps
<code>doc</code>	Documentation, including this document
<code>execs</code>	Link to <code>penwp</code> executable, shell script for running PenWP
<code>hscat</code>	Tool to convert HSCAT HDF5 data to BUFR
<code>oscat</code>	Tool to convert OSCAT HDF5 data to BUFR
<code>seawinds</code>	Tool to convert SeaWinds and RapidScat HDF5 data to BUFR
<code>src</code>	Source code for PenWP program and supporting routines
<code>tests</code>	Example BUFR and GRIB input files for testing purposes.

Table 2.1 Contents of directory `penwp`.

Name	Contents
<code>ambrem</code>	Ambiguity removal routines
<code>ambrem/twodvar</code>	KNMI 2DVAR ambiguity removal routines
<code>icemodel</code>	Ice screening routines
<code>inversion</code>	Inversion and quality control routines
<code>support</code>	General purpose routines sorted in subdirectories
<code>support/BFGS</code>	Minimization routines needed in 2DVAR
<code>support/Compiler_Features</code>	Compiler specific routines, mainly command line handling
<code>support/convert</code>	Conversion between wind speed/direction and u and v
<code>support/datetime</code>	Date and time conversion routines
<code>support/ErrorHandler</code>	Error handling routines
<code>support/file</code>	File handling routines
<code>support/eccodes</code>	BUFR and GRIB file handling routines
<code>support/hdf5</code>	HDF5 handling routines
<code>Support/netcdf</code>	NetCDF handling routines
<code>support/num</code>	Numerical definitions and number handling routines
<code>support/singletonfft</code>	FFT routines needed in minimization
<code>support/sort</code>	Sorting routines

Table 2.2 Contents of directory `genscat`.

Tables 2.1 and 2.2 list the contents of directories `penwp` and `genscat`, respectively, together with the main contents of the various parts. Depending on the distribution, more directories may be present, but these are of less importance to the user.

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Directories `penwp` and `genscat` and their subdirectories contain various file types:

- Fortran 90 source code, recognizable by the `.F90` extension;
- C source code, recognizable by the `.c` extension;
- Files and scripts that are part of the make system for compilation like `Makefile_thisdir`, `Makefile`, `Objects.txt`, `use_`, and `Set_Makeoptions` (see 2.3.4 for more details);
- Scripts for the execution of PenWP in directory `penwp/execs`;
- Look-up tables needed by PenWP;
- Files with information like `Readme.txt`.

After compilation, the subdirectories with the source code will also contain the object codes of the various modules and routines.

2.2 Installing the ecCodes library

PenWP needs the ECMWF ecCodes library for its input operations. The library tar file was downloaded from ECMWF and it is included in the PenWP software package. The package contains scripts for compilation and installation.

Directory `genscat/support/eccodes` contains a Makefile that unzips, untars, and compiles the ecCodes library file. This Makefile is part of the `genscat` make system and it is automatically invoked when compiling `genscat`. Note that CMake version 3.6 or higher (<https://cmake.org/>) is required in order to compile the ecCodes library.

By default, the library for handling GRIB messages that are compressed using the JPEG algorithm, (as is done e.g. by NCEP) is not linked in the compilation process. This option can be activated by adding the link option `-lopenjpeg` to the `Makeoptions` file in directory `genscat`:

```
LINKFLAGS = $(LIB) -lopenjpeg
```

After this change, the software in directories `genscat/support/eccodes` and `penwp/src` needs to be recompiled using the commands `make clean` and `make`.

2.3 Installing the HDF5 library

The HDF5 software library from the HDF Group (<https://www.hdfgroup.org/>) is used by PenWP for reading and decoding HDF5 input files. See Appendix C for the copyright statement and the terms of use of this software. The library tar file was downloaded from the HDF Group and it is included in the PenWP software package. The package contains scripts for compilation and installation.

Directory `genscat/support/hdf5` contains a Makefile that unzips, untars, and compiles the HDF5 library file. This Makefile is part of the `genscat` make system and it is automatically invoked when compiling `genscat`.

2.4 Installing the NetCDF library

The NetCDF software library from Unidata (<https://www.unidata.ucar.edu>) is used by PenWP for reading and writing NetCDF input files. See Appendix D for the copyright statement and the terms

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of use of this software. The library tar file was downloaded from Unidata and it is included in the PenWP software package. The package contains scripts for compilation and installation.

Directory `genscat/support/netcdf` contains a Makefile that unzips, untars, and compiles the NetCDF library file. This Makefile is part of the `genscat` make system and it is automatically invoked when compiling `genscat`.

2.5 Manual compilation and linking

PenWP can be manually compiled (without using the `compile_penwp` script) when the user is interested to use more advanced compiler options. This is done in three steps:

1. Set the compiler environment variables according to the choice entered on request. This can be done by running the appropriate `use_*` scripts in directory `genscat`.
2. Go to directory `genscat` and type `make`.
3. Go to directory `penwp` and type `make` to produce the executable `penwp` in directory `penwp/src`.

Before activating the make system, some environment variables identifying the compiler should be set. These variables are listed in table 2.4. The environment variables in table 2.4 can be set by using one of the `use_*` scripts located in directory `genscat`. Table 2.5 shows the properties of these scripts. The scripts are available in Bourne shell (extension `.bsh`) and in C shell (extension `.csh`). Note that if one of the environment variables is not set, the default `f90` and `cc` commands on the Unix platform will be invoked. Note that in the top directory a script called `compile_penwp` is provided that asks the user which compiler he wants to use and invokes the appropriate `use_*` script (step 1 above), after which the compilation in the `genscat` and `penwp` directories is performed (steps 2 and 3 above).

Variable	Function
<code>\$GENSCAT_F77</code>	Reference to Fortran 77 compiler
<code>\$GENSCAT_F90</code>	Reference to Fortran 90 compiler
<code>\$GENSCAT_CC</code>	Reference to C compiler
<code>\$GENSCAT_LINK</code>	Reference to linker for Fortran objects
<code>\$GENSCAT_CLINK</code>	Reference to linker for C objects
<code>\$GENSCAT_SHLINK</code>	Reference to linker for shared objects

Table 2.4 Environment variables for compilation and linking.

Script	Fortran compiler	C compiler	Remarks
<code>use_g95</code>	<code>g95</code>	<code>gcc</code>	GNU compilers by Andy Vaught
<code>use_gfortran</code>	<code>gfortran</code>	<code>gcc</code>	GNU-GCC compiler collection
<code>use_ifort</code>	<code>ifort</code>	<code>icc</code>	Intel Fortran and C compilers
<code>use_pgf90</code>	<code>pgf90</code>	<code>gcc</code>	Portland Fortran compiler

Table 2.5 Properties of the `use_*` scripts.

Example: To select the GNU Gfortran compiler under Bourne, Bash or Korn shell type

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“`./use_gfortran.bsh`”, the first dot and space being absolutely necessary in order to apply the compiler selection to the current shell. Under C shell the equivalent command reads “`source use_gfortran.csh`”.

If the user wants to use a Fortran or C compiler not included in table 2.6, he can make his own version of the `use_*` script, or set the environment variables for compilation and linking manually.

PenWP is delivered with a complete make system for compilation and linking under Unix or Linux. The make system is designed as portable as possible, and system dependent features are avoided. As a consequence, some tasks must be transferred to shell scripts. The make system consists of two parts: one for PenWP and one for genscat. The genscat part should be run first. For compilation and linking of the genscat part, the user should move to the `genscat` directory and simply enter `make`.

The `Makefile` refers to each subdirectory of `genscat`, invoking execution of the local `Makefile` and, in cases where a subdirectory contains code as well as a subdirectory containing code, `Makefile_thisdir`. The settings for the compilers are located in file `Makeoptions` in directory `genscat`. This file is generated by the Bourne shell script `Set_Makeoptions` which is called automatically by the `genscat` make system.

Compilation and linking of the PenWP part is done in a similar manner: go to the `penwp` directory and enter `make`. As with `genscat`, the make system will execute `Makefiles` in every subdirectory of `penwp`. The result is the executable `penwp` in directory `penwp/src` and a symbolic link to this executable in `penwp/execs`. PenWP is now ready for use. The make system of PenWP doesn't need any further files except the `genscat` file `Makeoptions`. This is the reason why `genscat` should be compiled first.

When recompiling (part of) PenWP or `genscat` with the make system, one should be sure to enter `make clean` first. To recompile part of the software invoke the make system where needed. The compiler settings from file `Makeoptions` in directory `genscat` will be used again. If a change in these settings is necessary, type `make clean` in the `genscat` directory and `Makeoptions` will be removed. Don't forget to rerun the `use_*` commands to select the right compiler.

2.6 Environment variables

PenWP needs a number of environment variables to be set. These are listed in table 2.3 together with their possible values.

Name	Value
<code>\$GRIB_DEFINITION_PATH</code>	<code>genscat/support/eccodes/definitions</code>
<code>\$LUT_FILENAME_KU_HH</code>	<code>penwp/data/<platform>/nscat4ds_250_73_51_hh.dat</code>
<code>\$LUT_FILENAME_KU_VV</code>	<code>penwp/data/<platform>/nscat4ds_250_73_51_vv.dat</code>
<code>\$LUTSDIR</code>	<code>penwp/data</code>
<code>\$NBEC_FILE</code>	<code>genscat/ambrem/nbec_ascat-a-coa_cos-auto-4000_tccal_obserrcorr.dat</code>

Table 2.3 Environment variables for PenWP.

The `$GRIB_DEFINITION_PATH` variable is necessary for a proper functioning of the GRIB decoding software.

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The variables `$LUT_FILENAME_KU_HH` and `$LUT_FILENAME_KU_VV` point PenWP to the correct binary Ku band GMF lookup tables (LUT) at HH and VV polarisation, respectively. They should contain a file name including a valid path. NSCAT lookup tables are delivered with PenWP in big endian and little endian binary formats, the `<platform>` part in the paths should be set to `big_endian` or `little_endian` depending on the computer platform type. PenWP uses the NSCAT-4DS Geophysical Model Function [14] by default.

The variable `$LUTSDIR` points PenWP to a directory containing some look up tables that are used to normalise the inversion residuals and to compute atmospheric attenuations for the Ku band radar data. The necessary tables are delivered with PenWP.

The variable `$NBEC_FILE` points PenWP to the file from which it can read the Numerical Background Error Correlations, to be used optionally in 2DVAR.

It may happen that running PenWP results in an error message like ‘error while loading shared libraries: libzzz’. In such cases it may help to locate the specified shared object file on the system and to set the `$LD_LIBRARY_PATH` variable to this directory.

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3 Processing details

3.1 Command line options

The PenWP main program is started from directory `penwp/execs` with the command

penwp [options/modes] -f <input file> [-nwpfl <file>]

with `<>` indicating obligatory input, and `[]` indicating non-obligatory input. For normal PenWP operation we recommend to use the `penwp/execs/penwp_run_4ds` script which will call PenWP and pass its command line options to the PenWP executable. The following command line options are available.

- f <input file>** Process a BUFR input file with name `input file`.
PenWP can only handle data in BUFR format. Conversion tools are available to convert HDF level 1b, level 2a or level 2b data from SeaWinds, RapidScat, OSCAT or HSCAT to BUFR, see below in this section.
Example: `penwp -f QS_D08001_S0152_E0323_B4444445` will process this file. The results will be written to a new BUFR file, see below in this section for the output file naming convention. It is possible to concatenate multiple BUFR input files into one using the Unix `cat` command.
- nwpfl <file>** Read a list of GRIB file names in the file named `file`.
The files in the list are read and the GRIB edition 1 or 2 data are used in the wind processing. The most convenient way to construct a file list is to use the Unix command `ls -l GRIB file pattern > file`. Note that the `'-l'` contains the number `'1'` and not the character `'l'`. If no GRIB data are used, only the land masking which is present in the level 2a/b files will be used. No ice screening will be performed (unless the `-icemodel` option is used). Ambiguity removal will be performed only if model winds are already present in the input BUFR file (i.e., in case of reprocessing of a level 2 file) or if the `-armeth 1strank` option is used (i.e., selection of the 1st rank wind solution). If level 2 data are reprocessed and no NWP data are read, the `qual_sigma0` flag which was set in the initial processing is evaluated and it will be used to determine if a WVC contains suitable backscatter data for wind inversion.

Several options for the processing can be invoked.

- noinv** Switch off inversion (default is switched on).
This option is useful to save processing time when wind inversion is already done in the input file, i.e., when a PenWP BUFR output file is reprocessed. For example, the NWP background winds can be replaced and the

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ambiguity removal performed in one run without repeating the wind inversion.

- icemodel** Switch on ice screening (default is switched off).
When switched off, no ice screening is done, except when a GRIB file containing sea surface temperature is read. The command line option invokes the Bayesian ice model which keeps the history of each location and uses this history to determine the sea or ice state of a WVC. The ice screening can be combined with the ice screening which is done in the GRIB collocation. In this case, the SST of the GRIB file will be used to assign a WVC as ‘surely water’ when the SST is above +5.0 °C, to support the Bayesian ice screening.
- noamb** Switch off ambiguity removal (default is switched on).
This option is useful if the selection of the scatterometer wind solution is left to the data assimilation procedure of a Numerical Weather Prediction model. In other words: the NWP model is fed with a number of solutions and their probability, and finds the best value when comparing with other data sources.
- nowrite** Do not produce BUFR output (default is switched on).
- nowrites0** Do not write σ^0 in output file (set σ^0 to missing).
- noc** Perform σ^0 calibration (NWP Ocean Calibration, default is switched off).
A calibration of the σ^0 values is performed, i.e., the backscatter values are changed in order to obtain better calibrated winds.
- armeth <meth>** Choose ambiguity removal method.
Valid methods are: `1strank` - the wind solution with the lowest distance to the GMF (residual) is selected, `bgclosest` - the wind solution closest to the background model wind is selected, `2dvar` - 2DVAR, see [2]. The default is `2dvar`.
- mss** Use the Multiple Solution Scheme for Ambiguity Removal.
If the Multiple Solution Scheme (MSS) is switched on, PenWP internally works with 144 different solutions for the wind vector. If MSS is switched off, PenWP calculates four solutions at most. MSS is switched off as default. Note that in the NOAA BUFR format, only 4 out of these 144 wind solutions will be written. The KNMI BUFR format may contain up to 144 wind solutions, see the `-genericws` option.
- sstcor** Apply SST dependent backscatter adjustments prior to wind inversion.
This will reduce the consistent wind speed biases associated with sea surface temperature differences. The backscatter adjustments have been derived from comparisons between C-band (ASCAT) and Ku-band (ScatSat-1) wind retrievals [17]. The list of GRIB files (see `-nwpfl` option) needs to contain a file with SST data, otherwise an error will occur. Using this option is not very demanding on computer resources and will add only

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marginally to the processing time.

- mixqc** Use mixed Quality Control evaluating both MLE and J_{oss} values.
See [11] for more information on the improved QC and rain screening for Ku-band instruments.
- nbec** Use Numerical Background Error Correlations (NBECs) in 2DVAR instead of the default Gaussian error correlations. NBECs give more weight to the observations, resulting in better agreement with buoy winds and less frequent setting of the KNMI QC and VarQC flags at the cost of increased processing time.
- genericws <N>** This option generates a second BUFR output file in the KNMI generic wind section format.
The number of wind solutions <N> to be written into the KNMI BUFR format is flexible due to the use of the so-called delayed replication and can be chosen between 1 (providing only the selected wind solution) and 144 (providing all wind solutions in MSS processing). The KNMI BUFR format is not approved by the WMO but can be handled by generic decoders.
- binof <file>** Write selected data of each WVC to a binary output file.
Data are written to a binary file <file>. This option is intended for research activities. More information on the file format can be found in the Fortran code of PenWP.
- mon** Switch on the monitoring function.
The monitoring results are written in an ASCII file with the name <name of BUFR output file>.mon. By default, no monitoring file is produced.
- verbosity <L>** Set the verbosity level to L (default is 0).
If the verbosity level is -1 or smaller, no output is written to the standard output except error messages. If the verbosity level equals 0 only some top level processing information is written to output. If the verbosity level is 1 or greater, also additional information is given.
- research, -wo** Various options intended for research activities. More information can be found in the Fortran code of PenWP and genscat.

The normal mode of operation of PenWP is wind processing, i.e., a BUFR file is read and the various processing steps are performed.

Besides the wind processing, some other modes of operation are available. If one of the modes is invoked, PenWP internally sets some of the options in order to obtain the desired result. Note that these modes are always used in combination with the `-f <input file>` option.

- mononly** Write the monitoring file without any processing.
- properties** Write some properties of the last row of the input file.
The data acquisition date and time of the last row are written to a small ASCII output file `properties.txt`.

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-writeonly

Write all data to BUFR output without processing.

This mode is useful to copy an input file to BUFR output without processing.

Running the command `penwp` without any command line options will display a list of all available command line options with a short explanation on the console. Running the command `penwp` with an illegal option will produce the same output, but preceded by an error message.

The output will be written into a BUFR file with the name

`INSTR_YYYYMMDD_HHMMSS_SAT_ORBIT_srv_o_SMPL_ovw_l2.bufr`,

where

- INSTR is the instrument, `seawi`, `oscat`, `hscat` or `rapid`.
- YYYYMMDD_HHMMSS is the acquisition date and time (UTC) of the first data in the file.
- SAT is the satellite (6 characters), `qscat_`, `adeos2`, `ocsat2`, `scasal`, `hy_2a_`, `iss_`, `hy_2b_`, `hy_2c_`, or `hy_2d_`
- ORBIT is the orbit number (5 digits) of the first data in the file.
- SMPL is the WVC sampling (cell spacing), 1000 for 100 km, 500 for 50 km and 250 for 25 km.
- If the above convention results in identical input and output file names, the extension '~' is added to the output file name.
- If the option `-genericws` (see above) is used, a second BUFR file with the same name and extension '.genws' is written.

Example: the output file name can look like:

`oscat_20111107_135116_ocsat2_11243_o_500_ovw_l2.bufr`

(Oceansat-2 50 km) or

`seawi_20080107_114220_qscat__44536_o_1000_ovw_l2.bufr`

(QuikSCAT 100 km)

3.2 Scripts

Directory `penwp/execs` contains a Bourne shell script `penwp_run_4ds` for running `penwp` with the correct environment variables. The script can be invoked with all valid command line options for `penwp`.

3.3 HDF conversion tools

Several tools are available to convert HDF data from SeaWinds/RapidScat, OSCAT and HSCAT to BUFR.

Directory `penwp/seawinds` contains the executable `seawinds_hdf2bufr`. It can read SeaWinds or RapidScat level 2a and level 2b files in HDF and will write the data in BUFR format. For level 2a, only the backscatter information in the BUFR output will be filled; for level 2b, only the wind information in the BUFR output will be filled. In the latter case wind processing is not possible since the HDF level 2b product does not contain σ^0 data but only winds. The backscatter

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‘eggs’ or ‘slices’ in the level 2a data are accumulated to WVC level backscatter data, see [1].

seawinds_hdf2bufr [options] -f <HDF5 file> -o <BUFR file>

to create one output file containing all data, or:

seawinds_hdf2bufr [options] -f <HDF5 file> -wpo

to create one output file per orbit. The available options are:

- properties** Write some properties of the last row of the input file.
The acquisition date and time are written to a small ASCII output file `properties.txt`.
- stride 2|4** Accumulate 25 km level 2a data with a stride of 2 or 4 to a 50 km or 100 km BUFR product. The 100 km product is not available for RapidScat.

The tool `seawinds_11b_bufr` in `penwp/seawinds` will convert level 1b files to BUFR format.

seawinds_11b_bufr [options] -f <HDF5 file> -o <BUFR file>

to create one output file containing all data, or:

seawinds_11b_bufr [options] -f <HDF5 file> -wpo

to create one output file per orbit. The available options are:

- properties** Write some properties of the last row of the input file.
The acquisition date and time are written to a small ASCII output file `properties.txt`.
- s 12|25|50** WVC grid size of the BUFR product in km.
- lsm <GRIB file>** Use GRIB file containing land-sea mask for land masking.
- egg** Read the footprint egg data rather than high resolution slice data.

Note that the SeaWinds and RapidScat data need to be converted from HDF4 to HDF5 before running `seawinds_hdf2bufr` or `seawinds_11b_bufr`. This can be done using a tool called `h4toh5` (https://support.hdfgroup.org/products/hdf5_tools/h4toh5/):

h4toh5 QS_S2A44444.20080021532 QS_S2A44444.20080021532.h5

Directory `penwp/oscat` contains the executable `oscat_hdf2bufr`. It can read OSCAT level 2a and level 2b data from ISRO and will write the data in BUFR format. For level 2a, only the backscatter information in the BUFR output will be filled; for level 2b, only the wind information in the BUFR output will be filled. In the latter case wind processing is not possible since the level 2b product does not contain σ^0 data. The conversion can be done with:

oscat_hdf2bufr [options] -f <HDF5 file> -o <BUFR file>

The available options are:

- properties** Write some properties of the last row of the input file.
The acquisition date and time are written to a small ASCII output file `properties.txt`.

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The tool `oscat_11b_buf` in `penwp/oscat` will convert level 1b files to BUFR format.

`oscat_11b_buf [options] -f <HDF5 file> -o <BUFR file>`

to create one output file containing all data, or:

`oscat_11b_buf [options] -f <HDF5 file> -wpo`

to create one output file per orbit. The available options are:

- properties** Write some properties of the last row of the input file.
The acquisition date and time are written to a small ASCII output file `properties.txt`.
- s 25|50** WVC grid size of the BUFR product in km.
- lsm <GRIB file>** Use GRIB file containing land-sea mask for land masking.
- egg** Read the footprint egg data rather than high resolution slice data.

Directory `penwp/hscat` contains the executable `hscat_hdf2buf`. It can read HSCAT level 2a and level 2b data from NSOAS and will write the data in BUFR format. For level 2a, only the backscatter information in the BUFR output will be filled; for level 2b, only the wind information in the BUFR output will be filled. In the latter case wind processing is not possible since the level 2b product does not contain σ^0 data. The conversion can be done with:

`hscat_hdf2buf [options] -f <HDF5 file> -o <BUFR file>`

The available options are:

- properties** Write some properties of the last row of the input file.
The acquisition date and time are written to a small ASCII output file `properties.txt`.
- stride 2** Accumulate 25 km level 2a data with a stride of 2 to a 50 km BUFR product.

The tool `hscat_11b_buf` in `penwp/hscat` will convert level 1b files to BUFR format.

`hscat_11b_buf [options] -f <HDF5 file> -o <BUFR file>`

to create one output file containing all data, or:

`hscat_11b_buf [options] -f <HDF5 file> -wpo`

to create one output file per orbit. The available options are:

- properties** Write some properties of the last row of the input file.
The acquisition date and time are written to a small ASCII output file `properties.txt`.
- s 25|50** WVC grid size of the BUFR product in km.
- lsm <GRIB file>** Use GRIB file containing land-sea mask for land masking.

3.4 Test data and test programs

Directory `penwp/tests` contains one HDF5 file for testing the PenWP executable. File `S1L2A2012006_12113_12114_2.h5.gz` contains (gzipped) Oceansat2 OSCAT level 2a

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data from 6 January 2012, 13:51 to 14:03 UTC with 50 km cell spacing, as obtained from ISRO. The files `ECMWF*.grib` contain the necessary NWP data (SST, land-sea mask and wind forecasts) to perform the NWP collocation step.

The user can test the proper functioning of PenWP using the files in the `penwp/tests` directory. To do this, first create a small file containing a list of NWP files:

```
ls -l ECMWF_* > nwpflist
```

Note that the '-l' contains the number 'l' and not the character 'I'. Then, gunzip the HDF5 file:

```
gunzip -c S1L2A2012006_12113_12114_2.h5.gz >
S1L2A2012006_12113_12114_2.h5

../execs/oscat_hdf2bufr -f S1L2A2012006_12113_12114_2.h5 -o
oscat.bufr
```

Then run PenWP:

```
../execs/penwp_run_4ds -f oscat.bufr -nwpfl nwpflist -mss -mon -noc
```

The result should be an OSCAT level 2 file in BUFR format, called `oscat_20120106_135109_ocsat2_12113_o_500_ovw_12.bufr`.

Figure 1.3 shows the global coverage of the test run. The colours indicate the magnitude of the wind speed as indicated by the legend.

Note that conversion software is delivered with PenWP to convert the BUFR output files into ASCII or NetCDF formats which are more convenient to visualise using publicly available software tools. These tools can be found in in directories `genscat/tools/bufr2asc` and `genscat/tools/bufr2nc` and are ready to use after compilation of PenWP. More information on the use of this software is available on https://scatterometer.knmi.nl/bufr_reader/.

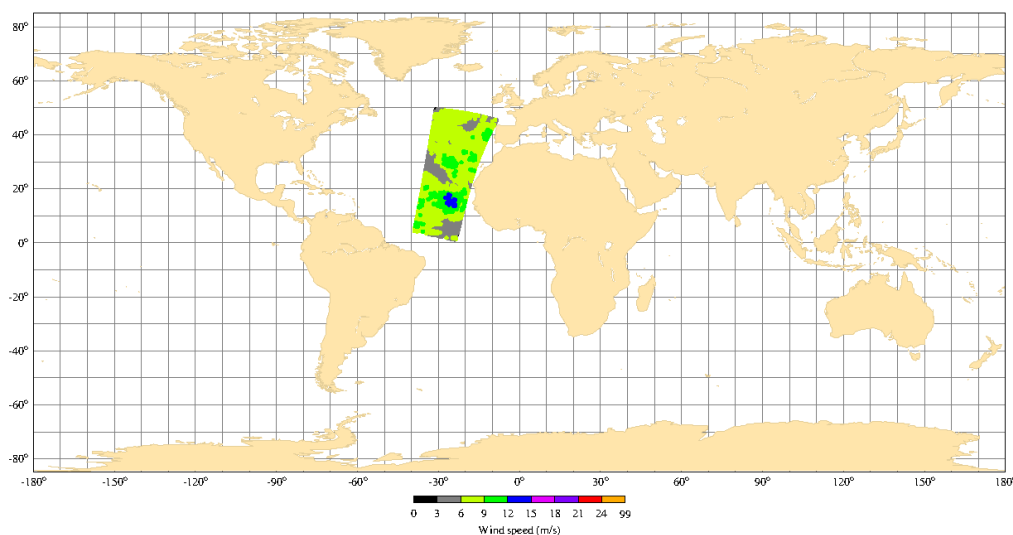


Figure 1.3 Global coverage of the test run. Wind speed results for the OSCAT 50 km product are shown.

Directory `genscat/support/eccodes` contains a test program named `test_read_BUFR1`. It can be used to test the `genscat` `ecCodes` module for reading and writing BUFR data. The program

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uses as input the file `testreading.bufr` in directory `genscat/support/eccodes`. The output is written to a BUFR file named `testwrite.bufr`, and should be identical to the input.

Directory `genscat/support/eccodes` contains test programs named `test_read_GRIB1`, `test_read_GRIB2` and `test_read_GRIB3`. The programs can be run from the command line and read in the GRIB file `testfile.grib` in directory `genscat/support/eccodes`. Some properties of this file are written to ASCII output files. Note that the environment variable `$GRIB_DEFINITION_PATH` needs to be set to directory `(...)/genscat/support/eccodes/definitions`.

Subdirectories `Compiler_Features`, `convert`, `ErrorHandler`, `singletonfft`, `file`, `BFGS`, `num`, `hdf5`, `sort` and `datetime` of `genscat/support` contain test programs for the module in that subdirectory. The test programs write their result to the standard output. In some cases, a copy of the output is contained in the `.output` files for comparison. Table 3.1 gives an overview of the `genscat` test programs.

Subdirectory	Program name	Output file	Remarks
<code>eccodes</code>	<code>test_read_BUFR</code>	<code>testwrite.bufr</code>	BUFR handling
<code>eccodes</code>	<code>test_read_GRIB*</code>	several	GRIB handling
<code>Compiler_Features</code>	<code>TestCompiler_Features</code>	-	Command line handling
<code>convert</code>	<code>test_convert</code>	<code>test_convert.output</code>	Wind speed conversion
<code>ErrorHandler</code>	<code>TestErrorHandler</code>	-	Error handling
<code>singletonfft</code>	<code>TestSingleton</code>	-	Fast Fourier Transform
<code>file</code>	<code>TestLunManager</code>	<code>TestLunManager.output</code>	File management
<code>BFGS</code>	<code>Test_BFGS</code>	-	Minimization
<code>num</code>	<code>test_numerics</code>	<code>test_numerics.output</code>	Numerical issues
<code>hdf5</code>	<code>TestHDF5</code>	<code>testfile.h5</code>	Read/write HDF5 files
<code>sort</code>	<code>SortModTest</code>	<code>SortModTest.output</code>	Array sorting
<code>datetime</code>	<code>TestDateTimeMod</code>	<code>TestDateTimeMod.output</code>	Date and time conversion

Table 3.1 Test programs in `genscat/support`.

3.5 Documentation

Directory `penwp/doc` contains documentation on PenWP, including this document. Further information can be found in the `readme` text files, and in the comments in scripts, `Makefiles` and source code.

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Appendix A: Acronyms

Name	Description
ASCAT	Advanced SCATterometer on MetOp
AWDP	ASCAT Wind Data Processor
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
ISS	International Space Station
KNMI	Koninklijk Nederlands Meteorologisch Instituut (Royal Netherlands Meteorological Institute)
Ku-band	Radar wavelength at about 2 cm
L1b	Level 1b product
LUT	Look up table
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
NRCS	Normalized Radar Cross-Section (σ^0)
NWP	Numerical Weather Prediction
OSCAT	Scatterometer onboard of the Indian Oceansat and ScatSat satellites
OSI	Ocean and Sea Ice
OWDP	OSCAT Wind Data Processor
PenWP	Pencil Beam Wind Processor
QC	Quality Control
SAF	Satellite Application Facility
SDP	SeaWinds Data Processor
SST	Sea Surface Temperature
WVC	Wind Vector Cell, also called node or cell

Table A.1 List of acronyms.

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Appendix B: Development of PenWP

Software code for processing satellite data may become very complex. On the one hand, it consists of code related to the technical details of the satellite and instruments; on the other hand, the code drives complex algorithms to create the geophysical end products. Therefore, the EUMETSAT Satellite Application Facility (SAF) project for Numerical Weather Prediction (NWP) has included some explicit activities aiming at enhancing the modularity, readability and portability of the processing code.

For many years, the KNMI satellite observation research group has been developing processing code to supply Near Real Time (NRT) level 2 surface wind products based on the ERS, SeaWinds, ASCAT and OSCAT scatterometer level 1b Normalized Radar Cross Section data (σ^0). This work is coordinated and supervised by Ad Stoffelen. In the beginning only an adaptation of his ERS code existed. Later Marcos Portabella and Julia Figa added modifications and extensions to improve, e.g., the wind retrieval and quality control algorithms. In 2003 John de Vries finished the first official release of a processor within the NWP SAF. This processor was called the QuikSCAT Data Processor (QDP).

Meanwhile, Jos de Kloe has been updating the code for ERS scatterometer wind processing. For many parts of the process steps (e.g., the BUFR handling and part of the wind retrieval) a large overlap with SeaWinds Data processing coding exists. The KNMI Scatterometer Team is working towards generic NRT scatterometer processing. As a result, a new modular processing code for SeaWinds data was developed: the SeaWinds Data Processor (SDP) as successor of QDP. Based on the generic code already available for SeaWinds and ERS processing, a new ASCAT Wind Data Processor (AWDP) and later on an OSCAT Wind Data Processor (OWDP) were developed.

After SeaWinds on QuikSCAT and OSCAT on Oceansat-2 also HSCAT on HY-2A was launched, being the third Ku-band rotating pencil beam scatterometer in space. In 2014 RapidScat, built on the heritage of SeaWinds, was installed on the International Space Station. More instruments with similar configuration are planned for the (near) future. This has encouraged us to start the development of a generic wind processor being able to compute wind products for all these instruments: the Pencil beam Wind Processor (PenWP). The PenWP software is intended to replace both SDP and OWDP. It is already capable to process SeaWinds, OSCAT, HSCAT and RapidScat data and will be adapted when future instrument data become available.

Many persons contributed (directly or indirectly) to the development of the scatterometer software at KNMI: Hans Bonekamp, Jos de Kloe, Zhen Li, Marcos Portabella, Ad Stoffelen, Anton Verhoef, Jeroen Verspeek, Jur Vogelzang and John de Vries are (in alphabetical order) the most important contributors.

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