ASCAT Soil Moisture Report Series No. 8

WARP^{NRT} 1.0
Reference Manual

Vienna University of Technology
Institute of Photogrammetry and Remote Sensing

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Summary

This document represents the software documentation of WARP^{NRT} 1.0, a software for near real-time surface soil moisture retrieval from ERS-1/2 scatterometer data. Written in C programming language, the software applies algorithms developed by the Institute of Photogrammetry and Remote Sensing (I.P.F.) to derive surface soil moisture products in orbit geometry, including several quality parameters for 50 km ERS products.

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List of Acronyms

ASCAT	Advanced Scatterometer
DGG	Discrete Global Grid
DSR	Data Set Record
ECMWF	European Centre for Medium-Range Weather Forecasts
ERS	European Remote Sensing Satellite
ESD	Estimated Standard Deviation
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
GLWD	Global lakes and wetlands database
GTOPO30	Global Topography - 30 arc-seconds
IDL	Interactive Data Language
MPH	Main Product Header
NRT	Near-Real Time
NWP	Numerical Weather Prediction
PPF	Product Processing Facility
SPH	Secondary Product Header
TU WIEN	Vienna University of Technology
UWI	Wind Scatterometer Fast Delivery Product
WARP	WAter Retrieval Package
WARP^{NRT}	WAter Retrieval Package for Near-Real Time

Contents

1 Introduction

This Reference Manual summarizes the scientific background, the implementation and product definitions of WARP^{NRT} 1.0. WARP^{NRT} 1.0 is a software package for producing surface soil moisture products from ERS-1/2 scatterometer data in satellite geometry based on Fast Delivery (UWI) products. To enable the soil moisture retrieval, WARP^{NRT} 1.0 requires a global parameter database, describing scattering characteristics for each point of the Earth land surface. To assemble the parameter database, the software WARP 4.0 (soil WAter Retrieval Package) is used. This software allows the retrieval of backscatter characteristics of the land surfaces based on the analysis of multi-annual backscatter time series. WARP 4.0 is written entirely in the software language IDL (Interactive Data Language).

The scientific basis and algorithms have been fully published in a series of conference and journal papers, most important of which are (Wagner et al. 1999abc), (Wagner and Scipal 2000), (Wagner et al. 2003) and (Ceballos et al. 2005).

Further information

See the G*lobal Soil Moisture Archive 1992-2000 from ERS Scatterometer Data* (http://www.ipf.tuwien.ac.at/radar/ers-scat/home.htm).

1.1 What is WARP^{NRT} 1.0?

WARP^{NRT} 1.0 is a software for near real-time (NRT) processing of surface soil moisture products from 50 km ERS-1/2 scatterometer fast delivery products (UWI format). The software is written in C programming language for a UNIX environment and foreseen for implementation at EUMETSAT's central product processing facility (PPF). One input of the software is a global parameter database extracted from multi-annual time-series of ERS-1/2 scatterometer data (08/1991-01/2000).

The following processing steps are implemented:

- Reading the ERS-1/2 backscatter data.

- Resampling of the global parameter data base to the scatterometer swath grid.
- Application of the algorithms to retrieve the surface soil moisture product. Additional products such as the normalised backscattering coefficient at 40° incidence angle $\sigma^0(40)$, estimated error in surface soil moisture, estimated error of $\sigma^0(40)$ and soil moisture sensitivity are calculated.
- Setting of complementary correction, processing, and advisory flags (internal quality checks and specific processing details).
- Storing the products.

Fulfilling the NRT-precondition, the processing of one complete scatterometer orbit is done in a matter of seconds.

1.2 System Requirements

WARP^{NRT} 1.0 is developed in C for UNIX environments. The software has been tested on an IBM machine with standard system libraries (IBM RS6000/43P, AIX version 4.3.3, Compiler version 5), as well as a small subset of general C libraries developed at the I.P.F. For the processing of data, WARP^{NRT} 1.0 requires a parameter database, which is provided along with sample UWI data.

1.3 Software Installation

Unzip the file *WARP_NRT_v10.zip*. Depending on the platform used, the executable file for running the WARP^{NRT} 1.0 processing is named as following:

- *WARP_NRT_v10_WIN32.exe* (for Windows)
- *WARP_NRT_v10_AIX* (for IBM AIX).

Additionally to the code, a file with sample data called *WARP_NRT_Sample_Data.zip* is provided. This file contains the required input parameter databases and index array, as well as one test input UWI file from the Maspalomas station of 2005 Nov 27.

1.4 Software Usage

Calling sequence of the executable (Windows):

```
WARP_NRT_v10_WIN32 -s <IN_PATH_1> [-e] -p <IN_PATH_2> -i <FILENAME> [-x] -n <IN_PATH_3> [-t] -o <OUT_PATH>
```

For UNIX systems, `WARP_NRT_v10_AIX` should be used rather than `WARP_NRT_v10_WIN32`.

The following attributes can be set:

- -s <IN_PATH_1>
  The full path and file name of the input UWI binary files.
- `-e`
  Set this attribute for swapping the endian of the input UWI file. Intel, etc systems use little endian. Sun SPARC, IBM, etc systems use big endian.
- -p <IN_PATH_2>
  The full path and file name of the scatterometer parameter binary file.
- `-i <FILENAME>`
  The file name of the index array binary file (its path assumed the same as the one of the scatterometer parameter file).
- `-x`
  Set this attribute for swapping the endian of the scatterometer parameter and index array files.
- -n <IN_PATH_3>
  Common path of non-scatterometer parameter files (*frozen, topo, wetland, snow*) as well as *ms_ mean*. The season-dependent *frozen*, *snow* and *ms_ mean* files have to lie in their own */frozen*, */snow* and */ms_ mean* directories. The files have to be named *mmdd.bin*. The *wetland* file lies directly under this directory and has to be named *wetland.bin*. The *topo* file lies directly under this directory and has to be named *topo.bin*.
- `-t`
  Use this to display some data from the original UWI file in command prompt. For testing purposes only.
- -o <OUT_PATH>
  The path to where the output binary UWI_MS file will be placed. The output file will have the same name as the input file with an additional *'_ ms'* suffix and the extension *'.bin'*.

For code editing/recompiling purposes, the C distribution also contains the full source code, with the UNIX make-file and the Visual Basic project-files (for Windows).

1.5 Calling Sequence Example (Windows)

- Path to sample data:
  D:\temp\WARP_NRT_Sample_Data

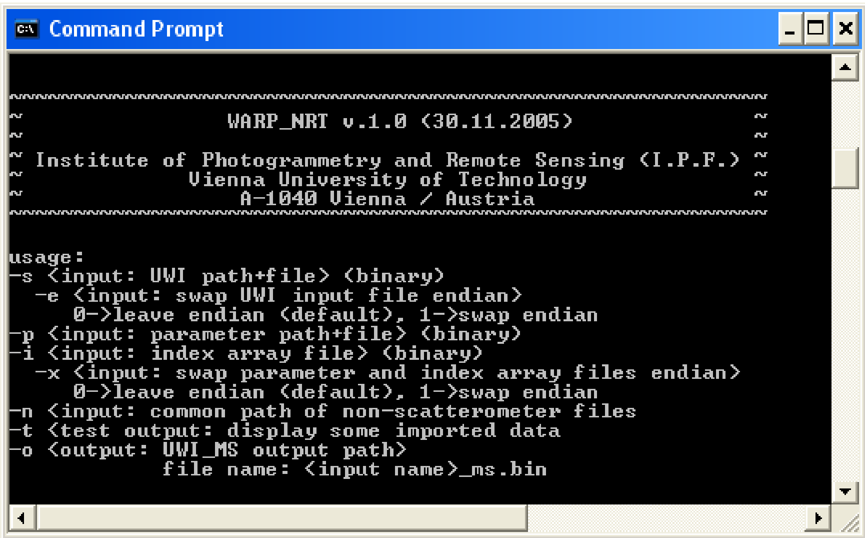

Figure 1–1

Screenshot of the WARP[NRT] *1.0 command prompt.*

At the command prompt of the software (Figure 1–1), type the following calling sequence:

```
WARP_NRT_v10_WIN32 -s "D:\temp\WARP_NRT_Sample_Data\
scat_input\UWI__051127MSMO6196.E2" -p "D:\temp\
WARP_NRT_Sample_Data\param_input\warp4_parameter_
db_09.bin" -i "warp4_indexarr_xtend_04.bin" -n
"D:\temp\WARP_NRT_Sample_Data\param_input\par_ns" -o
"D:\temp\WARP_NRT_Sample_Data\scat_output"
```

This call will create an output file called *UWI__051127MSMO6196_ms.bin* in the output folder named *D:\temp\WARP_NRT_Sample_Data\scat_output*.

1.6 Related Documents

Table 1–1 lists already existing documents of the ASCAT Soil Moisture Report Series that acted as input to this document.

Report Series No.	Report Title
1	Kidd, R. (2005). *NWP User Community Requirements Summary.*
2	Kidd, R. (2005). *METOP ASCAT Data Streams and Data Formats.*
3	Bartalis, Z. (2005). *Azimuthal Anisotropy of Scatterometer Measurements over Land.*
4	Kidd, R. (2005). *Discrete Global Grid Systems.*
5	Wagner, W. (2005). *Implementation Plan for a Soil Moisture Product for NWP*
6	Bartalis, Z. (2005). *Selection of Resampling Procedure.*
7	Scipal, K. et al. (2005). *Definition of Quality Flags.*

Table 1–1

ASCAT Soil Moisture Report Series.

2 The Soil Moisture Retrieval Method

To allow a better understanding of the implementation of WARP^{NRT} 1.0 and its attached databases we will present a brief summary of the TU Wien model and its implementation in WARP 4.0 in the following section.

The TU Wien method for retrieving soil moisture from ERS scatterometer data is, from its conception, a change detection method (Wagner et al. 1999b). Instantaneous backscatter measurements are extrapolated to a reference incidence angle (taken at 40°) and are compared to dry and wet backscatter references ($\sigma^0{}_{dry}$ and $\sigma^0{}_{wet}$ respectively). The influence of vegetation is determined by exploiting the multi-incidence angle viewing capabilities of the ERS scatterometer sensors. The theoretical background of the TU Wien model is described in detail in (Wagner et al. 1999a; Wagner et al. 1999b; Wagner et al. 1999c; Wagner and Scipal 2000). As a result, time series of the topsoil moisture content m_s (< 5 cm) are obtained in relative units ranging between 0 (dry) and 1 (saturated). All parameters required for the processing of raw backscatter measurements are derived from analysis of multi-annual backscatter time series of the period 08/1991 to 01/2001.

2.1 Methodology

Soil moisture retrieval as established under WARP 4.0 is implemented as an interactive program package that allows a stepwise processing of raw data. In a pre-processing step, the scatterometer data are rearranged from the orbit geometry to a time series format without altering the data. In this way, multi-year time series of scatterometer measurements are built up over a predefined global grid. The further processing steps use as input all available scatterometer data (08/1991 to 01/2001). The processing steps are (Table 2–1):

Step 1: Estimated Standard Deviation of σ^0

Estimate the standard deviation of σ^0 due to instrument noise, speckle and azimuthal effects based on the measurements of the fore- and backwards looking antennas.

Step 2: Incidence Angle Dependency

Determine the mean annual cycle of the incidence angle behaviour of σ^0 by making use of the fact that the scatterometer provides instantaneous measurements at two different incidence angles. The incidence angle dependency is described by a second order polynomial determined by the slope σ' and the curvature σ''. The slope and the curvature show a distinct annual cycle, determined by vegetation growth and decay. The slope and its annual cycle is described by the annual minimum slope value C', the annual dynamic range D' and an empirical periodic function $\Psi'(t)$ describing the annual variation of σ'. The curvature is determined correspondingly by the annual minimum slope value C'', the annual dynamic range D'' and $\Psi''(t)$. The parameters C', D', C'', D'' and the periodic functions $\Psi'(t)$ and $\Psi''(t)$ are determined by regression analysis independently for each point of the global grid.

Step 3: Normalisation $\sigma^0(40)$

Extrapolate all σ^0 taken over the entire incidence angle range from 18 to 59° to a reference angle of 40° and calculate the average $\sigma^0(40)$ based on the backscatter triplet.

Step 4: Estimated Error of $\sigma^0(40)$

Based on the rules of error propagation the estimated standard deviation of $\sigma^0(40)$ is calculated.

Step 5: $\sigma^0(40)$ under dry and wet conditions

After σ^0 has been normalised with respect to the incidence angle, vegetation phenology effects and the exact positions of the dry and wet soil backscatter reference curves, $\sigma^0_{dry}(t)$ and $\sigma^0_{wet}(t)$, are determined by fitting the curves to the $\sigma^0(40)$ time series.

The dry and wet references are determined by the crossover angles θ_{dry} and θ_{wet}, (incidence angles at which an increase in volume scattering due to vegetation growth and decrease in surface scattering compensate), which are set empirically to $\theta_{dry} = 25°$, $\theta_{wet} = 40°$ and the parameters C^0_{dry}, C^0_{wet} (the annual minimum and maximum backscatter values), which are determined by a fitting process and $D'\Psi'(t)$ and $D''\Psi''(t)$ (parameters from the incidence angle model).

Step 6: Wet reference correction

In dry climates the wet reference estimation can be biased given that there may never be enough rainfall to thoroughly wet the soil surface layer (Wagner and Scipal 2000). To correct biased $\sigma^0_{wet}(t)$ in dry climates, an empirical correction approach is used which is based on the close relation of C' and the sensitivity $C^0_{wet} - C^0_{dry}$ (Scipal 2002). In WARP 4.0 two parameterisations of this model are used where model 1 results in a stronger correction and model 2 in a weaker correction. Models have been selected empirically and are only applied in dry climates.

Step 7: Surface Soil Moisture

Calculate the surface soil moisture series m_s by comparing $\sigma^0(40)$ to the dry and wet reference curves.

Step 8: Estimated Standard deviation of the Surface Soil Moisture

Calculate the estimated standard deviation of the surface soil moisture by rules of error propagation.

Table 2–1

The core mathematical model of the applied soil moisture retrieval method as implemented in WARP 4.0.

Processing Step	Mathematical Formulation
Step 1 *Estimated Standard Deviation of* σ^0	$ESD(\sigma^0) = \dfrac{SD(\sigma^0_{fore} - \sigma^0_{aft})}{\sqrt{2}}$
Step 2 *Incidence Angle Dependency*	$\sigma'(40,t) = C' + D' \cdot \Psi'(t)$ $\sigma''(40,t) = C'' + D'' \cdot \Psi''(t)$
Step 3 *Normalisation*	$\sigma^0(40,t) = \frac{1}{3}\sum_{i=1}^{3} \sigma_i^0(\theta,t) - \sigma'(40,t)(\theta-40) - \frac{1}{2}\sigma''(40,t)(\theta-40)^2$
Step 4 *Estimated Standard Deviation of* $\sigma^0(40)$	$ESD(\sigma^0(40)) = \sqrt{100 \cdot ESD(\sigma')^2 - \frac{5}{3} ESD(\sigma^0)^2}$
Step 5 *Dry and Wet backscatter references and normalisation of vegetation effects*	$\sigma^0_{DRY}(40,t) = C^0_{DRY} - D'\Psi'(t)(\theta_{DRY}-40) - \frac{1}{2}D''\Psi''(t)(\theta_{DRY}-40)^2$ $\sigma^0_{WET}(40,t) = C^0_{WET} - D'\Psi'(t)(\theta_{WET}-40) - \frac{1}{2}D''\Psi''(t)(\theta_{WET}-40)^2$
Step 6 *Wet backscatter reference correction*	$C^0_{WET} = C^0_{DRY} + (19 + 30 \cdot C')$ $C^0_{WET} = C^0_{DRY} + (17 + 30 \cdot C')$
Step 7 *Surface soil moisture*	$m_s(t) = \dfrac{\sigma^0(40,t) - \sigma^0_{dry}(40,t)}{\sigma^0_{wet}(40) - \sigma^0_{dry}(40,t)}$
Step 8 *Estimated standard deviation of surface soil moisture*	$ESD(m_s) = \dfrac{ESD(\sigma^0_{40})}{\sigma^0_{wet}(40,t) - \sigma^0_{dry}(40,t)}$

2.2 Underlying Assumptions

The TU Wien model is based on certain assumptions:

- At the resolution of the scatterometer, roughness and land cover are temporal invariant. The measurement process, due to the low resolution of the sensor, suppresses local fluctuations.

- Vegetation phenology influences σ^0 on a monthly scale. The measurement process, due to the low resolution of the sensor, suppresses local short-term fluctuations.
- There exist distinct incidence angles θ_{dry} and θ_{wet}, where the backscattering coefficient σ^0 is relatively stable despite seasonal changes in above ground vegetation biomass for dry and wet conditions.
- The relationship between soil moisture and σ^0, expressed in dB, is linear.

2.3 The Product Quality

The quality control of the product has been investigated following several strategies, ranging from comparison with precipitation data to comparison with modelled data or in-situ soil moisture data.

The correlation between soil moisture of the 0-50 cm layer and rainfall anomalies as well as with a global vegetation and water balance model shows that soil moisture data agree reasonably well over tropical and temperate climates (Wagner et al. 2003). The performance of derived soil moisture data in a semi-arid Mediterranean environment shows significant correlation with soil moisture measured by a network of soil moisture stations (Ceballos et al. 2005).

3 The NRT Software Implementation

3.1 Processing Steps Overview

Near real time processing as implemented in WARP^{NRT} 1.0 is in principle identical to the processing architecture of WARP 4.0, briefly described in the previous chapter. The processing is however limited to the generation of products and does not require the intermediate parameter retrieval steps. Following processing steps are therefore implemented in WARP^{NRT} 1.0:

- **Step 1**: Restoring the WARP 4.0 parameter database and the index array (the parameters of the previously described methodological steps 1-6 are realised in WARP 4.0 and stored in the parameter database).
- **Step 2**: Reading UWI satellite product.
- **Step 3**: Checking for data quality, setting of respective processing flags.
- **Step 4**: Generating a neighbourhood for subsequent resampling of the parameter database grid at each satellite product node.
- **Step 5**: Calculation of time-dependent scattering parameters.
- **Step 6**: Resampling (Hamming window) of parameters.
- **Step 7**: Calculation of extrapolated backscatter at 40° incidence angle, its estimated error, and setting of respective processing flags.
- **Step 8**: Calculation of final surface soil moisture products, its estimated error, and setting of respective processing and correction flags.
- **Step 9**: Restoring additional climatological database, and setting of advisory flags.

The abovementioned processing steps are shown schematically in Figure 3–1.

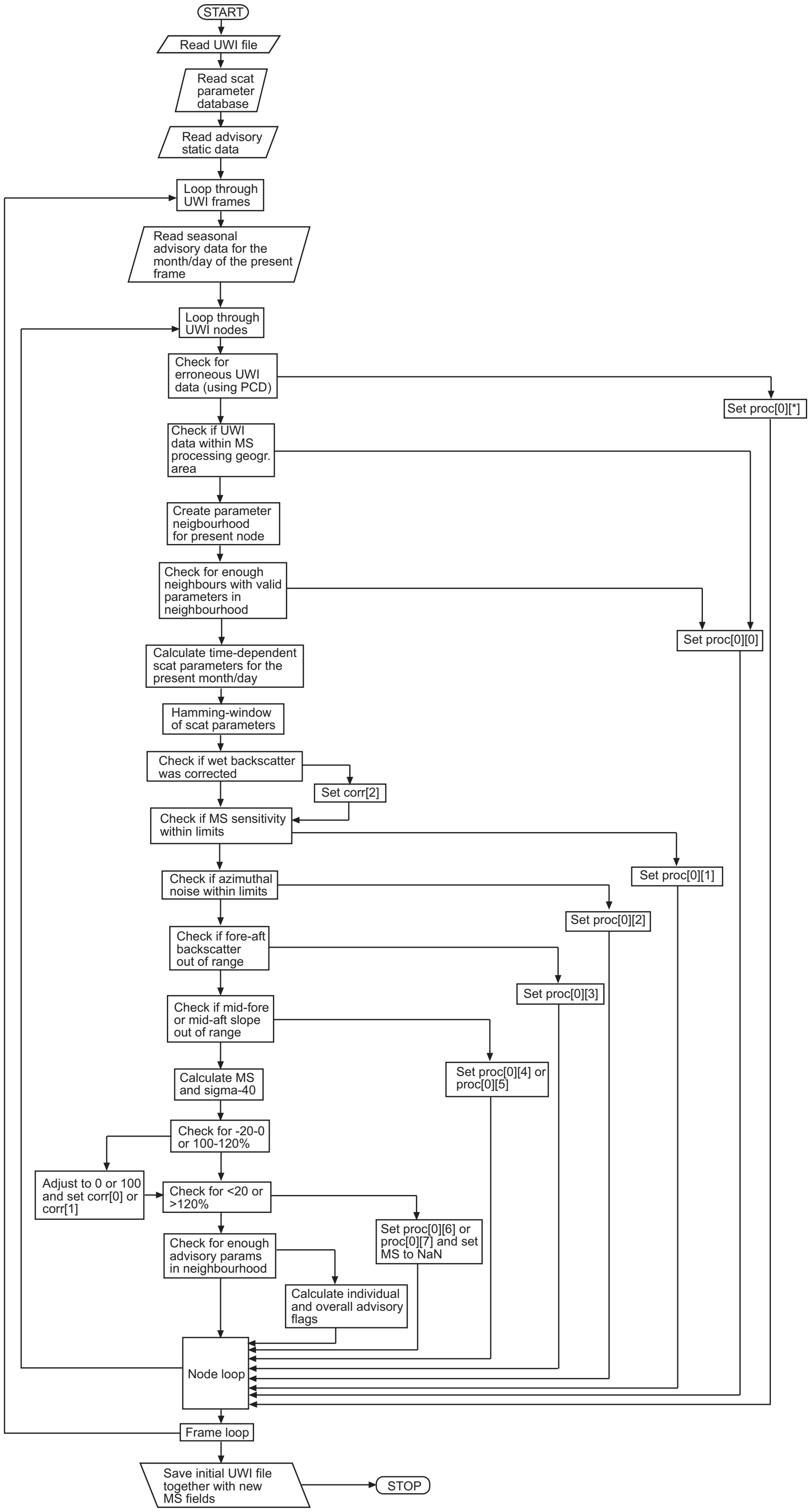

Figure 3–1

Flowchart of processing steps.

3.2 Input Data

3.2.1 Scatterometer Data

As input data the TU Wien model uses the ERS Scatterometer data. The ERS Scatterometer is a multi-incidence angle radar operating at 5.3 GHz (C-band), VV polarization and has been flown on the European Remote Sensing Satellites ERS-1 and ERS-2 operated by the European Space Agency. The current implementation of the TU Wien model is based on ERS-1/2 Wind Scatterometer Fast Delivery Product (ERS.WSC.UWI).

The Wind Scatterometer uses three antennae to generate radar beams looking 45 degrees forward, sideways, and 45 degrees backwards with respect to the satellites' flight direction. These beams illuminate a 500 km-wide swath as the satellite moves along its orbit, and each provides measurements of radar backscatter on a 25 km grid. The result is three independent backscatter measurements for each grid point, obtained using the three different viewing directions and separated by a short time delay.

ESA Scatterometer Fast Delivery Products formatted in UWI format are generated in the ESA ERS Ground Stations and are disseminated over an electronic telecommunication link from the stations. The products can be accessed via subscription from a rolling FTP archive and are available within 3 hours of observation.

Figure 3–2 shows the current active station network for receiving ERS-2 scatterometer data. For a detailed format specification of the UWI format see Table 3–1 and the Appendix.

Table 3–1

UWI Product Characteristics.

Product Characteristics	
Frame area	500 x 500 km
Frame size	19 x 19 grid points
Frame volume	17 Kbytes
Product volume per month/cycle	~ 700 Mbytes
Spatial Coverage	
Southernmost Latitude	-82.0
Northernmost Latitude	82.0
Westernmost Longitude	180.0
Easternmost Longitude	180.0
Temporal Coverage	
ERS-1	1991-07-30 – 2000-03-10
ERS-2	1995-04-21 – ongoing

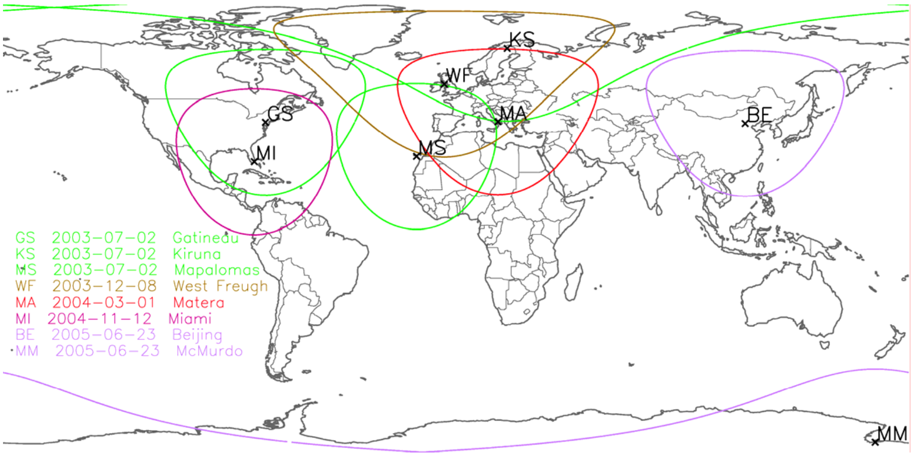

Figure 3–2

Visibility zones of ERS ground stations relevant for UWI product as of Nov 30, 2005.

3.2.2 The Parameter Database

To enable retrieval of soil moisture information knowledge about the specific scattering characteristics of the land surface is required. These parameters are derived from the analysis of multi-annual time series and are stored for each point of a predefined discrete global grid (DGG) in a parameter database. The database contains 340349 grid points. An example of one of the layers is shown in Figure 3–3, its structure is specified in Tables 3–2 and 3–3.

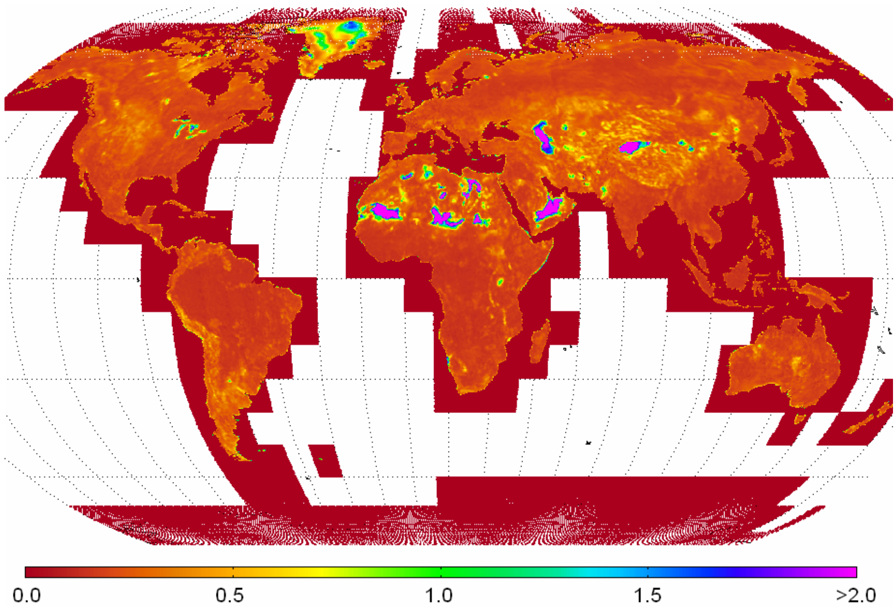

Figure 3–3

Example of one layer of the parameter database. Shown is the spatial distribution of the estimated standard deviation of normalised backscatter coefficient, given in dB. The parameter database consists of 340349 points.

Variable Name	Details	Type	Unit	Range
LON	The longitude of the grid point	F	deg	[-180,180]
LAT	The latitude of the grid point	F	deg	[-90,90]
ESD	Estimated standard deviation of backscatter coefficient	F	dB	[0,5]
SLO	Structure containing: *NAME:* the name of the slope periodic function	A	–	–
	C: the first coefficient of the slope periodic function	F	dB/deg	[-1,0]
	D: the second coefficient of the slope periodic function	F	dB/deg	[0,0.5]
	PHASE: the third coefficient of the slope periodic function	F	month	[-6,6]
CURV	Structure containing: *NAME:* the name of the curvature periodic function	A	–	–
	C: the first coefficient of the curvature periodic function	F	dB/deg^2	[-0.1,0.1]
	D: the second coefficient of the curvature periodic function	F	dB/deg^2	[0,0.1]
	PHASE: the third coefficient of the curvature periodic function	F	month	[-6,6]
NOISE_SIG40	Estimated standard deviation of normalised backscatter coefficient	F	dB	[0,5]
NOISE_SLOPE	Noise of incidence angle model	F	dB/deg	[0,0.5]
DRY	Dry backscatter reference	F	dB	[0,15]
WET	Wet backscatter reference	F	dB	[0,15]
WET_COR	Correction of wet backscatter reference. Set to 1 means correction applied.	B	–	0/1

Table 3–2

The characteristics of the parameter database.

Data type	Meaning
F	4-byte float
A	7-character ASCII
B	1 byte
No Data Value:	Float: -999999999. Long Int: -999999999 Byte: 255 ASCII: “Missing”

Table 3–3

Data types of the parameter database.

3.2.3 The Index Array

The parameter database is stored in a one-dimensional vector of structures. An index array (look-up table) is used, to accelerate the interpolation of parameters stored in the discrete global grid (DGG) geometry to the geometry of the orbit grid. This allows efficient storage avoiding a lot of void parameters, as well as efficient referencing of positions of the nearest DGG point given any location of the earth surface in longitude and latitude coordinates.

Further information Report Series No. 6 *Selection of Resampling Procedure*

3.3 Output Parameters

WARP^{NRT} 1.0 generates a number of products and associated parameters, which will briefly be discussed here. Format details are reviewed in the Chapter 4.

3.3.1 Surface Soil Moisture and Its Noise

The surface soil moisture measure represents the degree of saturation of the topmost soil layer ($<$ 5 cm) and is given in percent, ranging from 0 (dry) to 1 (wet). The surface soil moisture is complemented by the root mean square error of the measure, which is derived by error propagation of the measurement noise (covering instrument noise, speckle and azimuthal effects).

3.3.2 Normalised Backscatter Coefficient and Its Estimated Standard Deviation

The ERS scatterometers measure backscatter under various incidence angles. The normalised backscatter coefficient is equivalent to backscatter at a reference incidence angle of 40°. The normalised backscatter is complemented by the root mean square error of the measure, which is derived by error propagation of the measurement noise (covering instrument noise, speckle and azimuthal effects).

3.3.3 Seasonal Variation of Slope and Its Noise

The incidence angle dependency of the backscatter is largely determined by the amount of above ground biomass and by surface roughness. Mathematically it can be described by a second order polynomial determined by a slope and a curvature term. The slope term is especially sensitive to vegetation growth and senescence. The slope is complemented by the root mean square error of the measure, which is derived by error propagation of the measurement noise (covering instrument noise, speckle and azimuthal effects).

3.3.4 Sensitivity, Dry Backscatter Reference, Wet Backscatter Reference

The sensitivity of the TU Wien model to measure soil moisture is defined by the difference of the dry and wet backscatter reference values $\sigma^0{}_{dry}(40)$ and $\sigma^0{}_{wet}(40)$. For a given point in time generally, the sensitivity depends on the amount of aboveground biomass. High amounts of biomass result in a low sensitivities to soil moisture.

3.3.5 Mean Surface Soil Moisture

The TU Wien model is very sensitive in tracking soil moisture changes, but less sensitive in determining the absolute soil moisture level. The soil moisture mean is therefore a subsidiary measure to assist in the interpretation of the surface soil moisture product. The mean is derived from surface soil moisture data of the period 08/1991-01/2001. Considering the short observation period and the relative low temporal sampling (once/twice per week), the mean soil moisture has been derived for monthly intervals to obtain a reliable measure (i.e. all measurements of the month January have been averaged). Daily data has been derived by interpolation of the monthly means.

3.3.6 Rainfall Detection

Surface soil moisture is very sensitive to rainfall events. In principal simple change detection should allow to track rainfall events in the surface soil moisture product. Currently a suitable method has not been implemented but given the importance of rainfall information in various applications, this flag has been reserved for future use.

3.4 Advisory Flags

Soil Moisture can not be estimated if the fraction of dense vegetation, open water surfaces or snow/frozen soils dominate the scatterometer footprint. To support data users in judging the quality of the soil moisture products, advisory flags are stored as complementary information.

3.4.1 Soil Moisture Quality

This is an aggregated quality control indicator that serves as an overall quality flag depending on the advisory flags of snow cover fraction, frozen land surface fraction, inundation and wetland fraction, and topographic complexity.

3.4.2 Snow Cover Fraction

Backscatter measurements are very sensitive to snow properties. The exact scattering behaviour of snow depends on the dielectric properties of the ice particles and on their distribution and density. Therefore soil moisture cannot be retrieved under snow conditions. The implementation of the snow flag uses a historic analysis of SSM/I snow cover data and gives the probability for the occurrence of snow for any day of the year. Examples of snow cover probabilities are given in Figures 3–4 and 3–5.

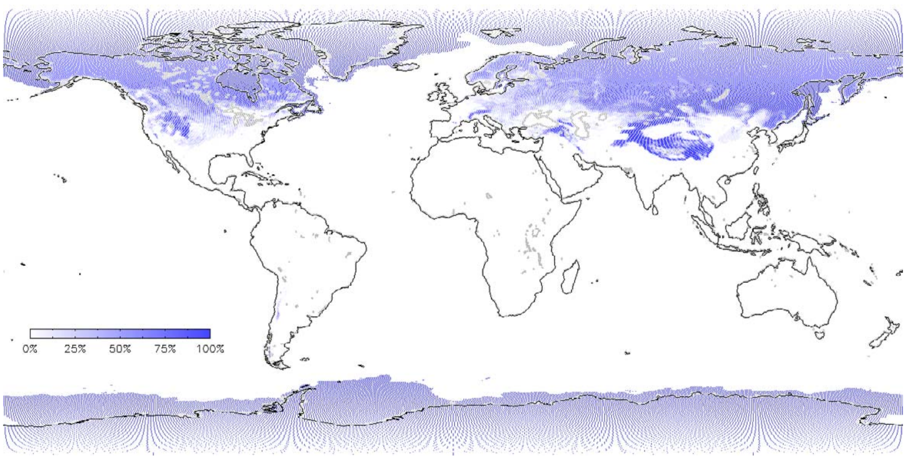

Figure 3–4
Snow Cover (SSM/I) 1st of January.

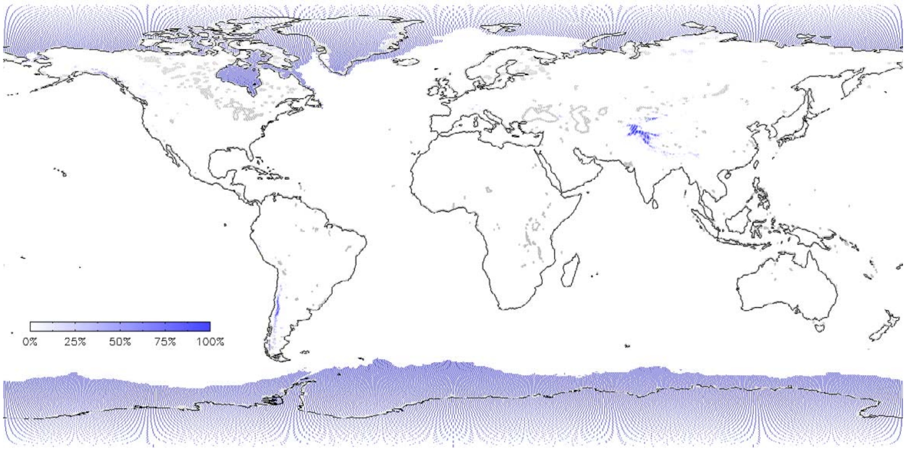

Figure 3–5

Snow Cover (SSM/I) 1st of July.

3.4.3 Frozen Land Surface Fraction

Taking into consideration the processes mentioned for snow, freezing can result in low backscatter, but also in high backscatter e.g. over frozen lakes. To avoid any negative implication in the use of backscatter representing frozen conditions these measurements have to be masked. The flag is based on a historic analysis of modelled climate data (ERA-40) and gives the probability for the frozen soil/canopy conditions for each day of the year (Figures 3–6 and 3–7).

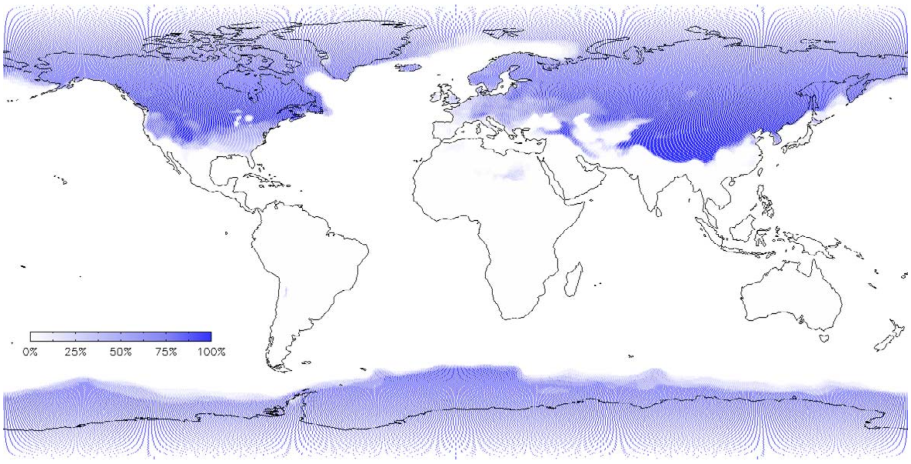

Figure 3–6

Frozen soil probability (ERA-40 modelled product) 1st of January.

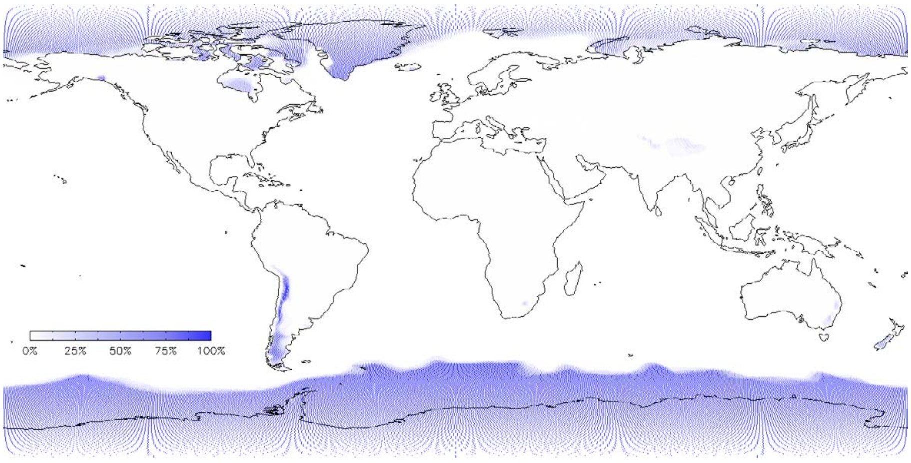

Figure 3–7

Frozen soil probability (ERA-40 modelled product) 1st of July.

3.4.4 Inundation and Wetland Fraction

The penetration depth of C-band microwaves into water is less than about 2 mm and therefore, as is the case for bare soil and wet snow, σ^0 of water is dependent on the roughness of the surface. When the water surface is calm, then specular reflection occurs and σ^0 at off-nadir angles is very low. Wind generates water waves that increase scattering into the backward direction. The radar return is highest when the radar looks into the upwind or downwind direction and is smallest when it looks normal to the wind vector. The main contributions do not come from large waves, even if they are many meters in height. Rather, scattering is dominated by short waves that ride on the top of the larger waves (Ulaby et al. 1982). Generally, open water should not effect the retrieval, if the percent area covered by the open water surface is small. Nevertheless, there exist regions were the area percentage of open water surfaces can reach a significant magnitude which result in dominating backscatter effects.

To account for this, the open water flag is defined as fraction coverage of inundated and wetland areas. These areas are derived from the *Global Lakes and Wetlands Database (GLWD)* level 3 product which includes several wetland and inundation types (Lehner and Döll 2004). An example of the inundation and wetland fraction is given in Figure 3–8.

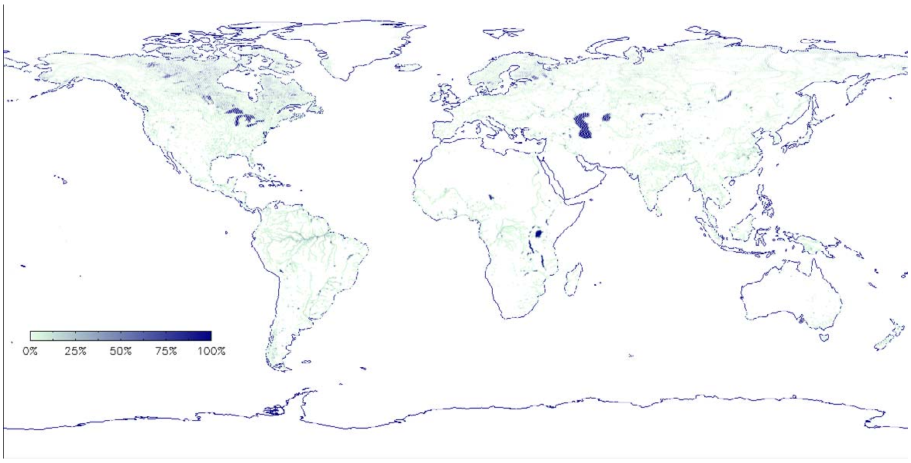

Figure 3–8

Inundation and wetland fraction derived from GLWD.

3.4.5 Topographic Complexity

Backscatter of mountainous regions can be subject of several distortions. Main error sources are calibration errors due to the deviation of the surface from the assumed ellipsoid and the rough terrain, the influence of permanent snow and ice cover, a reduced sensitivity due to forest and rock cover and highly variable surface conditions.

The topographic complexity flag is derived from GTOPO30 data. For each cell of the Discrete Global Grid, standard deviation of elevation is calculated and the result is normalized to values between 0 and 100 %, as can be seen in Figure 3–9.

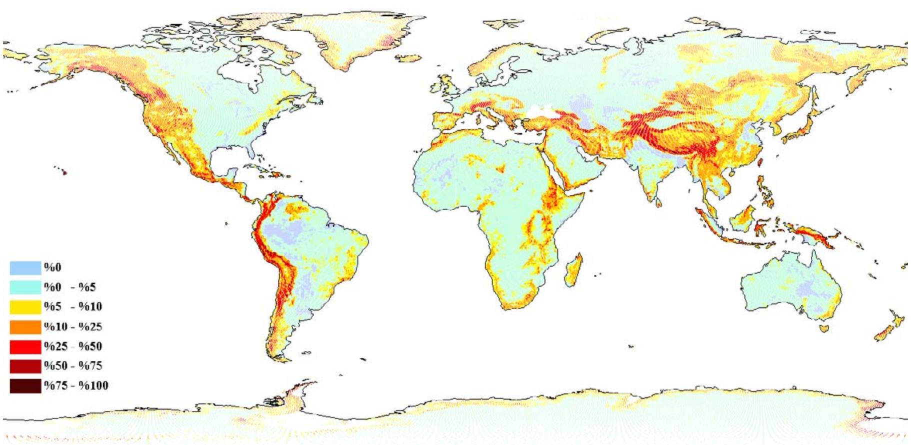

Figure 3–9

Topographic Complexity (Normalized standard deviation of topography), derived from GTOPO30.

Further information Report Series No. 7 *Definition of Quality Flags*

4 Product Description

4.1 Product Format

The product format is principally determined by the input data, which is the Wind Scatterometer Fast Delivery Product ERS.WSC.UWI (see Chapter 3.2.1 Scatterometer Data). The output data format of the soil moisture product is appended to the original UWI data. The soil moisture product, derived in WARP^{NRT} 1.0, is appended to the original UWI data. A product example is given in Figure 4–1. Each product has the same structure:

- Main Product Header (MPH),
- Specific Product Header (SPH),
- Data Set Record (DSR) containing the appended soil moisture data.

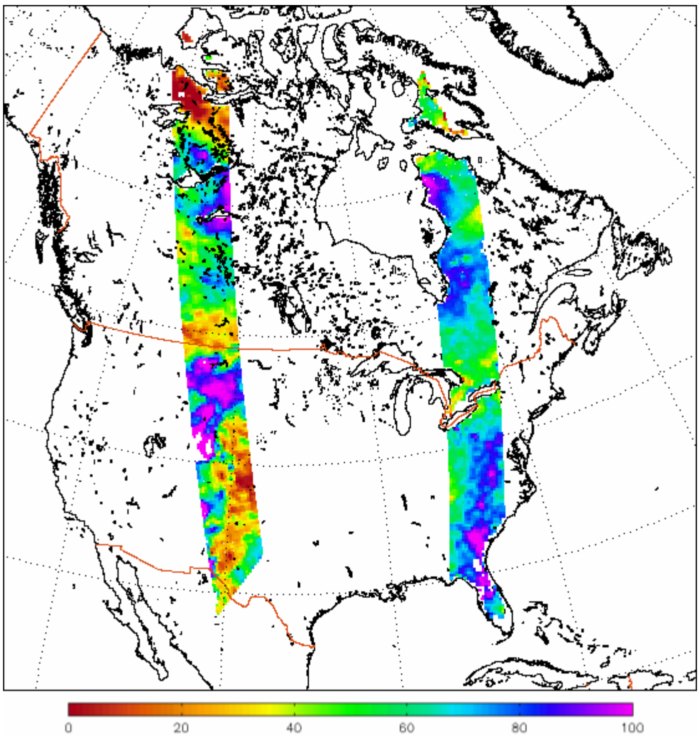

Figure 4–1

Product example of surface soil moisture (in %) over Northern America. The image shows two satellite swaths. (2005 Oct 09, Sensor: ERS-2, 50 km resolution, left: ascending swath, 05:13 UTC, right: descending swath, 15:16 UTC).

4.2 Soil Moisture Product Description Sheet

The following Tables 4–1 and 4–2 give a description of the currently available soil moisture product.

Symbol / Variable Name	Details	Type	Unit	Range
Software Identification *SOFT*	Version of software WARP^{NRT}	F	–	–
Database Identification *PARAM_DB*	Parameter database needed for retrieval	F	–	–
m_s *MS*	Surface soil moisture	F	%	[0,100]
$ESD(m_s)$ *NOISE_MS*	Estimated error in surface soil moisture	F	%	[0,100]
$\sigma^0(40)$ *SIGMA40*	Extrapolated backscatter at 40 degree incidence angle	F	dB	[-35,0]
$ESD(\sigma^0(40))$ *NOISE_SIG40*	Estimated error in extrapolated backscatter at 40 degree incidence angle	F	dB	[0,5]
$\sigma'(40,t)$ *SLO40*	Slope at 40 degree incidence angle	F	dB/deg	[-0.8,0.1]
$\varepsilon_{\sigma'}$ *NOISE_SLOPE*	Estimated error in slope at 40 degree incidence angle	F	dB/deg	[0,0.5]
S *SENS*	Soil moisture sensitivity	F	dB	[0,25]
$\sigma^0{}_{dry}$ *DRY*	Dry backscatter	F	dB	[-30,-5]
$\sigma^0{}_{wet}$ *WET*	Wet backscatter	F	dB	[-25,0]
$\overline{m}_s$ *MS_MEAN*	Mean surface soil moisture	F	%	[0,100]
Rainfall Detection *RAIN*	Rainfall detection (currently not implemented) *	B	%	[0,200]
Correction Flag *CORR*	*Bit1:* m_s between -20% and 0% *Bit2:* m_s between 100% and 120% *Bit3:* Correction of wet backscatter reference applied ($WET\_COR = 1$) *Bit4:* Correction of dry backscatter reference applied (currently not implemented) *Bit5*: Correction of volume scattering in sand applied (currently not implemented) *Bit6-Bit8*: Reserved All 8 bits set to 1 means flag is missing.	B	–	–

Table 4–1

Overview of soil moisture products and complement quality flags.

* Stored values have to be multiplied by a factor of 0.5 to obtain actual values.

Symbol / Variable Name	Details	Type	Unit	Range
Processing Flag *PROC*	*Bit1:* Not soil; Set if a) nodes are outside latitude range [-54°, 83°], or b) less than 3 valid neighbours in the parameter neighbourhood for Hamming windowing exist or c) the number of invalid (NaN) neighbours is larger than the number of valid neighbours. *Bit2:* Sensitivity to soil moisture below limit $(DRY - WET) \le 2$ [dB] *Bit3:* Azimuthal noise above limit $ESD \ge 1$ [dB] *Bit4:* Backscatter Fore-Aft beam out of range $\left\| \sigma_{fore} - \sigma_{aft} \right\| \ge (6 * ESD)$ [dB] *Bit5:* Slope Mid-Fore beam out of range $(> 6 * NOISE\_SLOPE)$ [dB] *Bit6:* Slope Mid-Aft beam out of range $(> 6 * NOISE\_SLOPE)$ [dB] *Bit7:* m_S below -20% *Bit8:* m_S above 120% *Bit9-Bit16:* Reserved All 16 bits set to 1 means flag is missing, i.e. when Data Set Record (Product Confidence Data Bits 2-9) states erroneous data or data over water.	B2	–	–
Soil moisture quality *MS_QUAL*	Aggregated quality flag *. Equal to the maximum value of *SNOW*, *FROZEN*, *WETLAND* and *TOPO*.	B	%	[0,200]
Snow cover fraction *SNOW*	Probability and fraction of snow cover *	B	%	[0,200]
Frozen land surface fraction *FROZEN*	Probability of soil temperature below 0°C *	B	%	[0,200]
Inundation and wetland fraction *WETLAND*	Area of open water surfaces (lakes, rivers, wetlands) *	B	%	[0,200]
Topographic complexity *TOPO*	Normalised standard deviation of elevation *	B	%	[0,200]

* Stored values have to be multiplied by a factor of 0.5 to obtain actual values.

Table 4–1 (continued)

Overview of soil moisture products and complement quality flags.

Data type	Meaning
F	4-byte float
A	7-character ASCII
B	1 byte or 8 bits (flags)
B2	2 bytes or 16 bits (flags)

No Data Value: Float: -999999999.
Long Int: -999999999
Byte: 255

Table 4–2

Data types of the product.

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Appendix – UWI Format Specifications

The appendix gives the product format of ERS-1/2 Wind Scatterometer Fast Delivery Product (ERS.WSC.UWI). Shown is the following information (Lecomte 1998):

- data types (Table A-1),
- the Main Product Header (MPH) description (Table A-2),
- the Specific Product Header (SPH) description (Table A-3),
- and the Data Set Record (DSR) description (Table A-4).

Table A-1: Data types in the ERS ground station products

Data Type	Meaning
I1	1-byte unsigned integer
I2	2-byte integer in DEC format
I4	4-byte integer in DEC format
A	ASCII
B	1 byte or bits (flags)
S	Special format, as defined in description field

Table A-2: Main Product Header (MPH) detailed description

Field	Bytes	Type	Description
1	17	A/I	Product identifier (for ESA internal operational use only), i.e. a set of characters and integers which form a unique identifier. The set of 17 Bytes is defined as follows: Byte 1: Originator of logical schedule (for ESA internal use only) e.g.: I: MMCC/EECF, Immediate Command M: MMCC/EECF, Logical Schedule J: Local operator, Immediate Command K: Local operator, Logical Schedule Byte 2-5: Sequential Counter of Logical Schedule Byte 6-9: Unique Identification or Schedule Offset Byte 10-13: Not used, set to 0 Byte 14-17: Sequential Number of Currently Generated Product
2	1	I1	Type of Product, see Table 3
3	1	I1	Spacecraft 1: ERS-1 2: ERS-2
4	24	A	UTC time of subsatellite point at beginning of product. Format in ASCII: DD-MMM-YYYY hh:mm:ss.ttt For example: 30-JAN-1987 14:30:27.123
5	1	I1	Station ID, where data was processed 1: Kiruna Station (KS) 2: Fucino Station (FS) 3: Gatineau Station (GS) 4: Maspalomas Station (MS) 5: EECF Station (ES) 6: Prince Albert Station (PS)
6	2	B	Product Confidence Data bit 1 PCD Summary Flag 0: product correctly generated 1: at least one of the remaining 15 bits of the PCD in the MPH is set. In particular the specific header flags are not read when this bit is set. bit 2 - 3 spare bit 4 - 5 Downlink Performance and X-Band acquisition chain. This value summarizes the PCD snapshots rel. to the products. 0: performance better than MMCC/EECF-supplied minimum threshold 1: performance equal to or worse than threshold 2: performance unknown bit 6 - 7 HDDT Summary. This value summarizes the PCD snapshots rel. to the product. 1: performance equal to or worse than threshold 2: performance unknown bit 8 - 9 Frame Synchronizer. This value summarizes the PCD snapshots rel. to the product. 0: performance better than MMCC/EECF-supplied minimum threshold 1: performance equal to or worse than threshold 2: performance unknown bit 10 - 11 FS to Processor I/F The LRDPF and SARFDP reads the status of the FS interface. 0: no parity error detected 1: at least one parity error detected 2: performance unknown bit 12 - 13 Checksum Analysis on LR Frames. The percentage of source packets, featuring a checksum error, and used in the actual product is compared to a MMCC/EECF given threshold. 0: lower than threshold 1: greater than threshold 2: performance unknown bit 14 - 15 Quality of Downlinked Formats and Source Packets. The RA product is based on using 80 consecutive source packets. The percentage of erroneous ones is determined and compared to a MMCC/EECF given threshold. 1: greater than threshold 2: performance unknown bit 16 Existence of Auxiliary Data. 0: auxiliary data and/or chirp correctly extracted 1: not all auxiliary data extracted
7	24	A	UTC time when MPH was generated; Format as in field 4.
8	4	I4	Size of Specific Product Header: Record in Bytes
9	4	I4	Number of Product Data Set Records
10	4	I4	Size of each Product Data Set Record in Bytes
11	1	B	Subsystem that generated the product. 0: SARFDP 1 1: SARFDP 2 2: LRDPF 3: VMP 4: LRDTF
12	1	B	OBRC flag used for SAR products only bit 1 - 2 0: not used 1: OGRC data 2: OBRC data
13	24	A	UTC reference time. Time relation used to convert from satellite to ground, used together with the next two fields.

Field	Bytes	Type	Description
14	4	I4	Reference binary time of satellite clock (32-bit unsigned integer)
15	4	I4	Step length of satellite clock in nanoseconds
16	8	I2	Processor software version used to generate product. Format as defined by MMCC/EECF. 8 bytes = 4 words of integer x 2
17	2	I2	Threshold table version number.
18	2	B	Spare
19	24	A	UTC time of ascending node state vector
20-25	24	6I4	Ascending node state vector in earth-fixed reference system
20	4	I4	State vector; X in 10-2 m
21	4	I4	State vector; Y in 10-2 m
22	4	I4	State vector; Z in 10-2 m
23	4	I4	State vector; X velocity in 10-5 m/s
24	4	I4	State vector; Y velocity in 10-5 m/s
25	4	I4	State vector; Z velocity in 10-5 m/s

Table A-3: Specific Product Header (SPH) for UWI Wind Product (UWI)

Field	Bytes	Type	Description	Units
1	2	B	Product Confidence Data for Processing bit 1 & 2: Processing equipment status 0: equipment working 1: some problems with equipment 2: equipment failed during product generation bit 3: Spare bit 4: I/Q Imbalance Flag 0: all beams better than MMCC/EECF-defined threshold 1: any beam above or equal to MMCC/EECF-defined threshold bit 5: Internal Calibration level flag 0: all beams within MMCC/EECF-defined level window 1: any beam out of MMCC/EECF-defined level window bit 6: Blank Product Flag 0: data available 1 no data available bit 7: Doppler Compensation: Center of Gravity flag 0: all beams below MMCC/EECF defined threshold 1: any beam above or equal to MMCC/EECF-defined threshold bit 8: Doppler Compensation: Standard Deviation flag 0: all beams below MMCC/EECF defined interval 1: any beam outside MMCC/EECF-defined interval bit 9 - 16: Spare	N/A
2	4	I4	Geodetic latitude of Product Center; A negative value denotes South latitude, and a positive value denotes North latitude.	10^{-3} deg
3	4	I4	East longitude (i.e. 0-360°) from Greenwich to East)	10^{-3} deg
4	4	I4	Subsatellite Track Heading w.r. to North, turning clockwise 0at time of product center	10^{-3} deg
5	2	I2	Mean distance between two successive along track nodes at product center	meter
6	2	I2	Center of Gravity of averaged power spectrum (forebeam)	2.344 Hz
7	2	I2	"Standard Deviation" of averaged power spectrum (forebeam)	2.344 Hz
8	2	I2	Center of Gravity of averaged power spectrum (midbeam)	2.344 Hz
9	2	I2	"Standard Deviation" of averaged power spectrum (midbeam)	2.344 Hz
10	2	I2	Center of Gravity of averaged power spectrum (aftbeam)	2.344 Hz
11	2	I2	"Standard Deviation" of averaged power spectrum (aftbeam)	2.344 Hz
12	4	I4	I Mean Noise Power, forebeam	10^{-3} ADC units
13	4	I4	Q Mean Noise Power, forebeam	10^{-3} ADC units
14	4	I4	I Mean Noise Power, midbeam	10^{-3} ADC units
15	4	I4	Q Mean Noise Power, midbeam	10^{-3} ADC units
16	4	I4	I Mean Noise Power, aftbeam	10^{-3} ADC units
17	4	I4	Q Mean Noise Power, aftbeam	10^{-3} ADC units
18	4	I4	Internal Calibration level monitoring factor, forebeam	10^{-3} ADC units
19	4	I4	Internal Calibration level monitoring factor, midbeam	10^{-3} ADC units
20	4	I4	Internal Calibration level monitoring factor, aftbeam	10^{-3} ADC units
21	2	B	Mode of operation - set by the first midbeam source packet contributing to spatial filtering for the first node (near swath) in the center row of a product. bit 1 and 2: 0: windmode 1: wind/wave mode 2: no data found to identify mode bit 3 - 16: Spare	N/A
22-71	82	I2	Parameter Table ID. Details as follows:	N/A
22	2	I2	Global threshold Parameter Table ID	N/A
23	2	I2	Static parameter Parameter Table ID	N/A
24	2	I2	Dynamic parameter Parameter Table ID	N/A
25	2	I2	F $R_b(n)$ Parameter Table ID	N/A
26	2	I2	$T_{orbit,ref,D}$ Parameter Table ID	N/A
27	2	I2	$*_F$ Parameter Table ID	N/A
28	2	I2	$*_M$ Parameter Table ID	N/A
29	2	I2	$*_A$ Parameter Table ID	N/A
30	2	I2	F $T_b(n)$ Parameter Table ID	N/A

Field	Bytes	Type	Description	Units
31	2	I2	$C_{ADC,b}(n)$ Parameter Table ID	N/A
32	2	I2	$T_{orbit,ref,N}$ Parameter Table ID	N/A
33	2	I2	$F_{N,F}$ Parameter Table ID	N/A
34	2	I2	$F_{N,M}$ Parameter Table ID	N/A
35	2	I2	$F_{N,F}$ Parameter Table ID	N/A
36	2	I2	$*_{N,b}(j,k)$ Parameter Table ID	N/A
37	2	I2	$*_{N,b}(j,k)$ Parameter Table ID	N/A
38	2	I2	$M_{eff,b}(j,k)$ Parameter Table ID	N/A
39	2	I2	N(j,k) Parameter Table ID	N/A
40	2	I2	Wind extraction software configuration Table ID	N/A
41	2	I2	$LA_b(i_r,i_c)$ Parameter Table ID	N/A
42	2	I2	$LZ_b(i_r,i_c)$ Parameter Table ID	N/A
43	2	I2	LN_b Parameter Table ID	N/A
44	2	I2	MA_b Parameter Table ID	N/A
45	2	I2	MS_b Parameter Table ID	N/A
46	2	I2	$NA_F(*,i_c)$ fore Parameter Table ID	N/A
47	2	I2	$NA_M(*,i_c)$ mid Parameter Table ID	N/A
48	2	I2	$NA_A(*,i_c)$ aft Parameter Table ID	N/A
49	2	I2	$NS_F(*,i_c)$ fore Parameter Table ID	N/A
50	2	I2	$NS_M(*,i_c)$ mid Parameter Table ID	N/A
51	2	I2	$NS_A(*,i_c)$ aft Parameter Table ID	N/A
52	2	I2	$NN_F(*,i_c)$ fore Parameter Table ID	N/A
53	2	I2	$NN_M(*,i_c)$ mid Parameter Table ID	N/A
54	2	I2	$NN_A(*,i_c)$ aft Parameter Table ID	N/A
55	2	I2	l_{ref} Parameter Table ID	N/A
56	2	I2	$a_F(*,i_c)$ fore Parameter Table ID	N/A
57	2	I2	$a_M(*,i_c)$ mid Parameter Table ID	N/A
58	2	I2	$a_A(*,i_c)$ aft Parameter Table ID	N/A
59	2	I2	$av_F(k,i_r,i_c)$ fore Param. Table ID	N/A
60	2	I2	$av_M(k,i_r,i_c)$ mid Parameter Table ID	N/A
61	2	I2	$av_A(k,i_r,i_c)$ aft Parameter Table ID	N/A
62	2	I2	i_b Parameter Table ID	N/A
63	2	I2	Spare	N/A
64	2	I2	Spare	N/A
65	2	I2	Meteo Table ID (table type 83, Forecast F18)	N/A
66	2	I2	Meteo Table ID (table type 84, Forecast F24)	N/A
67	2	I2	Meteo Table ID (table type 85, Forecast F30)	N/A
68	2	I2	Meteo Table ID (table type 86, Forecast F36)	N/A
69	2	I2	Spare	N/A
70	2	I2	Spare	N/A
71	2	I2	Spare	N/A

Table A-4: Data Set Record (DSR) for UWI Wind Product (UWI)

Field	Bytes	Type	Description	Units
1	4	I4	Data record number, starting with 1.	Count
2	4	I4	Geodetic latitude of Node. A negative value denotes South latitude, and a positive value denotes North latitude.	10^{-3} deg
3	4	I4	East longitude (i.e. 0-360* from Greenwich to east)	10^{-3} deg

Field	Bytes	Type	Description	Units
4	4	I4	σ° of forebeam	10^{-7} dB
5	2	I2	Incidence Angle for forebeam	0.1 deg
6	2	I2	Look Angle of forebeam clock- wise w.r.t. North at grid point	0.1 deg
7	1	I1	Kp Value of forebeam, set to 255 if the calculation is not possible.	%
8	1	I1	Counter of forebeam corrupted or missing source packets	Count
9	4	I4	σ° of midbeam	10^{-7} dB
10	2	I2	Incidence Angle of midbeam	0.1 deg
11	2	I2	Look Angle of midbeam clock- wise w.r.t. North at grid point .	0.1 deg
12	1	I1	Kp Value of midbeam, set to 255 if the calculation is not possible.	%
13	1	I1	Counter of midbeam corrupted or missing source packets	Count
14	4	I4	σ° of aftbeam	10^{-7} dB
15	2	I2	Incidence Angle of aftbeam	0.1 deg
16	2	I2	Look Angle of aftbeam clock- wise w.r.t. North at grid point.	0.1 deg
17	1	I1	Kp Value of aftbeam, set to 255 if the calculation is not possible.	%
18	1	I1	Counter of aftbeam corrupted or missing source packets	Count
19	1	I1	Wind speed (set to 255 if wind extraction is not possible)	0.2 m/s
20	1	I1	Wind direction with respect to North turning clockwise at grid point (set to 255 if wind extraction is not possible)	2 deg.
21	2	B	Product Confidence Data bit 1 Summary PCD factor 0: processing of cell according to full specification 1: result to be viewed with limitation, i.e. one of the PCD flags listed below is not 0 (except bits 11-13). bit 2 Forebeam Flag 0: beam OK 1: no forebeam calculation bit 3 Midbeam Flag 0: beam OK 1: no midbeam calculation bit 4 Aftbeam Flag 0: beam OK 1: no aftbeam calculation bit 5 Forebeam Arcing Flag 0: no arcing detected on forebeam 1: arcing detected on forebeam bit 6 Midbeam Arcing Flag 0: no arcing detected on midbeam 1: arcing detected on midbeam bit 7 Aftbeam Arcing Flag 0: no arcing detected on aftbeam 1: arcing detected on aftbeam bit 8 Limit of Kp value 0: all beams below MMCC/EECF-supplied threshold 1: any beam above or equal to MMCC/EECF-supplied threshold bit 9 Land-Sea Flag 0: Sea 1: Land bit 10 Rank one solution flag . 0: Ambiguity removed 1: No ambiguity removal performed or ambiguity removal not successful See Note 6. bit 11-12 Ambiguity Removal Method . 0: ambiguity removed autonomously 1: use of meteorological tables after failure of autonomous ambiguity removal 2: ambiguity removed using meteorological data only 3: no ambiguity removal attempted bit 13 Maximum likelihood distance flag . 0: Maximum Likelihood Distance M of the rank 1 solution is less than or equal to a threshold 1: Maximum Likelihood Distance M of the rank 1 solution (i.e. solution of minimum residual) is greater than a threshold (see note 9). bit 14 Frame Checksum Flag 0: Checksum correct 1: Checksum error detected, noise and calibration replaced with default bit 15 and 16 Spare	N/A