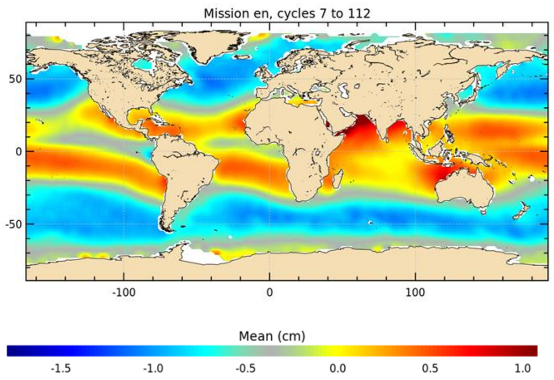

Average temporal differences between the EMiR and the operational wet tropospheric correction (WTC) for ERS-2. Source: EMiR document DLV-INT-12, *"EMiR WTC performance analysis"*.

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ERS/Envisat MWR Recalibration and Water Vapour FDR Generation (EMiR)

Guidance for Sentinel-3

(DLV-EXT-08)

Version 1.02

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1 Introduction

1.1 Purpose of document

This document provides a high-level assessment of the outcome of ESA's Long Term Data Preservation (LTDP) project *"ERS/Envisat MWR Recalibration and Water Vapour FDR Generation"* (EMiR), and, based on the lessons learnt, offers guidance for the exploitation of the SRAL/MWR Surface Topography Mission (STM) on board the Sentinel-3 series of satellites.

Particular emphasis is put on the generation and maintenance of long-term data records that adhere to standards and requirements formulated by the World Meteorological Organisation (WMO) in the framework of the Global Climate Observing System (GCOS).

More information on the EMiR project can be obtained from the EMiR Website under http://www.esa-mwr.org. The EMiR dataset itself is publicly available under DOI 10.5676/DWD_EMIR/V001.

1.2 Acronyms and abbreviations

Acronym	Description
AltiKa	Ka-band Altimeter
AMR	Advanced Microwave Radiometer
CNES	Centre National d'Études Spatiales
ECMWF	European Centre for Medium-Range Weather Forecasting
ECV	Essential Climate Variable
Envisat	Environmental Satellite
EMiR	ERS/Envisat MWR Recalibration and Water Vapour Thematic Data Record Generation
ERA	ECMWF Re-Analysis
ERS	European Remote Sensing (Satellite)
ESA	European Space Agency
EUMETSAT	European Organization for the Exploitation of Meteorological Satellites
FDR	Fundamental Data Record
GCOS	Global Climate Observing System
GNSS	Global Navigation Satellite System
ISRO	Indian Space Research Organisation
JASON	Joint Altimetry Satellite Oceanography Network
JMR	Jason-1 Microwave Radiometer
LWP	Liquid Water Path
LTDP	Long-Term Data Preservation
MWR	Microwave Radiometer
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
Poseidon	Positioning, Ocean, Solid Earth, Ice Dynamics, Orbital Navigator
RA	Radar Altimeter
SARAL	Satellite with ARGOS and AltiKa

Acronym	Description
SRAL	Sentinel-3 Radar Altimeter
SSH	Sea Surface Height
S3-A/B/C/D	Sentinel 3A/3B/3C/3D
TCWV	Total Column Water Vapour
TDR	Thematic Data Record
TOA	Top-of-Atmosphere
TOPEX	Topography Experiment
TMR	TOPEX Microwave Radiometer
WMO	World Meteorological Organization
WTC	Wet Tropospheric Correction
1D-VAR	One-Dimensional Variational Analysis

2 Scientific background

2.1 GCOS requirements on sea surface height and total column water vapour

Long-term observations of trends in sea surface height (SSH) as well as total column water vapour (TCWV) are critical for understanding impacts and risks of climate change. In particular, changes in SSH are of critical societal importance globally as well as regionally. The Global Climate Observing System (GCOS) has thus identified both SSH and TCWV as essential climate variables (ECVs), with the accuracy and stability requirements listed in Table 1.

Table 1: Key GCOS requirements *[GCOS-154, 2011]* on SSH and TCWV. If not indicated otherwise, stability targets refer to time intervals of typically one decade.

ECV	Spatial resolution	Temporal resolution	Accuracy	Stability	Comments
Global mean sea level (SSH)	50 km	10 days	2-4 mm	< 0.3 mm per year	Accuracy and stability strongly depending on the accurate estimation of the wet tropospheric delay.
Regional sea level (SSH)	25 km	weekly	1 cm	< 1.0 mm per year	Accuracy and stability strongly depending on the accurate estimation of the wet tropospheric delay.
Total column water vapor (TCWV)	25 km	4 hours	2 %	0.3 %	TCWV is required for the estimation of the wet tropospheric delay.

The rationale of the GCOS requirements on SSH is to assess the regional variability and global trends of the sea level on decadal time scales for the detection of climate change impacts and model improvements. To reach the required product accuracy, individual sea-surface-height measurements are expected to be accurate to 1-2 cm.

The GCOS resolution and accuracy requirements for TCWV are driven by the need to reliably link humidity changes to changes in precipitation and evaporation. Stability targets for TCWV are based on constant relative humidity and 0.2 K per decade temperature trend.

2.2 Importance of Sentinel 3 SRAL/MWR time series

The sun-synchronous, high inclination observations taken between 1991 and 2012 by the radar altimeters and microwave radiometers on-board the ERS-1, ERS-2, and Envisat satellites are at the core of any global altimetry CDR, complementing the observations from the mid-inclination, drifting TOPEX/Jason satellite series (see Table 2).

Since February 2016, the former observations are being continued by the SRAL/MWR pair of instruments flown on board the Sentinel-3A (S3-A) satellite, which shall be complemented in the near future by the identically equipped Sentinel-3B (S3-B), as well as, from 2021, Sentinel-3C and Sentinel-3D satellites. S3-A to S3-D will thus provide critical continuing radar altimeter and MWR coverage at a 10:00 sun-synchronous high inclination orbit for the next ca. twenty years to come.

Table 2: List of radar altimeter missions with MWR-like instruments. Sun-synchronous high inclination orbits are marked light orange. Drifting mid-inclination orbits are marked light green.

Mission	Instruments	Start	End	Orbit	Repeat cycle [d]	Operator
ERS-1	RA MWR	07-1991(*)	06-1996(*)	10:30 sun-sync, desc	35 (3, 168)	ESA
ERS-2	RA MWR	04-1995(*)	07-2011(*)	10:30 sun-sync, desc	35	ESA
ENVISAT	RA-2 MWR	03-2002(*)	04-2012(*)	10:00 sun-sync, desc	35, 30 from 10/2010	ESA
SARAL/ AltiKa	AltiKa Radiometer	06-2013	operational	6:00 sun-sync, asc	35	CNES/ISRO
Sentinel-3A	SRAL MWR	02-2016	operational	10:00 sun-sync, desc	27	EUMETSAT/ESA
Sentinel-3B	SRAL MWR	Scheduled for 2017	Not launched	10:00 sun-sync, desc	27	EUMETSAT/ESA
Sentinel-3C	SRAL MWR	From 2021	future	10:00 sun-sync, desc	27	EUMETSAT/ESA
Sentinel-3D	SRAL MWR	From 2021	future	10:00 sun-sync, desc	27	EUMETSAT/ESA
TOPEX/ Poseidon	Poseidon-1 TMR	08-1992	09-2005	66 deg. drifting	9.9	NASA/CNES
Jason-1	Poseidon-2 JMR	12-2001	06-2013	66 deg incl. drifting	9.9	NASA/CNES/ EUMETSAT/NOAA
Jason-2	Poseidon-3 AMR	07-2008	operational	66 deg incl. drifting	9.9	NASA/CNES/ EUMETSAT/NOAA
Jason-3	Poseidon-3B AMR	02-2016	operational	66 deg incl. drifting	9.9	NASA/CNES/ EUMETSAT/NOAA
Jason CS 1	Poseidon-4 AMR-C	2020	future	66 deg incl. drifting	9.9	NASA/CNES/ EUMETSAT/NOAA
Jason CS 2	Poseidon-4 AMR-C	2026	future	66 deg incl. drifting	9.9	NASA/CNES/ EUMETSAT/NOAA

(*): Refers to actual MWR instrument lifetime.

2.3 Importance of MWR observations

MWR is of crucial importance to the ECVs SSH and TCWV as it provides direct observations of TCWV over the ocean, which, in turn, allow for an accurate correction of the delay of the radar signals in the atmosphere due to the variable content in water vapour without which the required SSH accuracies could not be achieved.

The GCOS stability requirements on both SSH and TCWV can only be met if:

- The MWR brightness temperature time series from ERS-1, -2, and Envisat is sufficiently inter-calibrated and a stable FDR is obtained.
- Wet tropospheric correction (WTC) and TCWV derived from MWR brightness temperatures are sufficiently stable and homogeneous.

The GCOS requirements on the temporal resolution of TCWV (4 h) cannot be met by MWR observations. This is not critical, since the main objective of the MWR instruments is to provide TCWV information concomitantly to radar altimetry observations to allow for an accurate WTC of the latter. In addition, MWR-derived TCWV time series can play a fundamental role in climate studies or reanalyses.

3 EMiR objectives and achievements

The EMiR project was funded by ESA as part of its Long-Term Data Preservation (LTDP) activities. LTDP EMiR has started in November 2013 and lasted until October 2016. It had the following objectives:

- To generate a fundamental data record (FDR) of top-of-atmosphere (TOA) brightness temperatures from the MWR instruments flown on board ERS-1, ERS-2, and Envisat.
- To generate a thematic data record (TDR) of the total column water vapour (TCWV) above the world's ice free oceans, independent of other satellite-based TCWV data records, covering the period from 1991 to 2011.
- To compare the newly derived TDR on TCWV with other long term data sets on TCWV through the GEWEX water vapour assessment (G-VAP), see http://www.gewex-vap.org.
- To assess the impact of the improved TCWV information on the accuracy of the SSH obtained from concomitantly acquired altimeter observations.

EMIR's main achievements are summarised in Panel 1. Details can be obtained from the EMiR website and the documents offered

3.1 EMiR key results

- *The inter-calibration of the MWRs on-board ERS-1, ERS-2, and Envisat is of crucial importance for the generation of FDRs and TDRs. Calibration discontinuities between the three MWR instruments on the order of 2 K were identified and corrected for. Without such corrections, a homogeneous FDR or TDR cannot be obtained [EMIR_DLV_EXT_07_ATBD, 2016].*
- *For the first time, the retrieval of TCWV has been performed using an optimal estimation (1D-VAR) approach consistently for all three MWR instruments. This approach is superior to*

statistical retrievals as it allows for an objective assessment of a posteriori uncertainties as well as for a clear assessment of the impact of the observations versus a-priori knowledge.

- *A comparison of the MWR retrieved TCWV with GNSS-derived TCWV reference observations has shown that the GCOS requirements on stability appear to be met by the EMiR dataset [EMIR_DLV_EXT_08_VAL, 2016].*
- *An analysis of the short-term variability of SSH observations using the EMiR-derived WTC has not only shown significant improvements over purely model-based WTCs, but also an improved performance over the current operational radiometer WTC for selected time periods and latitude bands, particularly for ERS-1 and ERS-2 [EMIR_DLV_EXT_08_VAL, 2016].*

Panel 1: EMiR key results.

4 Guidance for Sentinel-3

4.1 Inter-calibration and consistency between altimeter missions

Even the best calibration of individual instruments does not guarantee a sufficiently accurate inter-calibration between different instruments. The inter-calibration between past (ERS-1/2, Envisat), current (Sentinel 3A), and future (Sentinel 3B-D) MWR instruments is of crucial importance for the successful derivation of long-term FDRs and the TDRs derived from these.

The observation gap between the end of the Envisat time series (04/2012) and the beginning of Sentinel 3A time series (02/2016) precludes direct inter-calibration efforts, although overlap with AltiKa as well as the Jason fleet could help mitigate this issue to some extent.

Vicarious inter-calibration using earth targets provide another possibility. The approach taken in LTDP-EMiR for example uses cloud free ocean targets to inter-calibrate MWR observations from ERS-1, ERS-2, and Envisat. Other approaches use land targets with known emissivity to inter-calibrate the different instruments.

- *Based on the EMiR findings, a combination of the above inter-calibration approaches described above is recommended for ERS-1, ERS-2, Envisat, and Sentinel-3.*
- *In the context of FDR generation, Sentinel-3 needs to be evaluated together with the precursor instruments.*
- *Feedbacks between improved calibration efforts for individual instruments and subsequent inter-calibration needs to be accounted.*

Panel 2: Recommendations to achieve consistency of MWR-based fundamental data records.

4.2 Retrieval algorithms for TCWV and WTC

TCWV retrievals are in itself ECVs, but are also key in determining WTC and thus govern the accuracy and stability of SSH. EMiR has shown that 1D-VAR retrievals based on the two MWR-observed brightness temperatures already partly provide results equal to or even better than the current operational statistical retrievals, despite the latter making use of additional information on the sea surface roughness derived from concomitant altimeter observations. This provides a strong indication that, in case the altimeter backscatter is suitably included into the 1D-VAR retrieval scheme, results are likely to overall improve.

- *Optimal estimation (1D-VAR) should be considered as operational retrieval mechanism for TCWV retrievals. Compared to statistical retrievals, the 1D-VAR approach allows for a better determination of uncertainties and for a more transparent treatment of systematic error sources.*
- *The inclusion of the altimeter backscatter coefficient σ_0 in the 1D-VAR retrieval scheme for TCWV will very likely have a positive impact on accuracy. This would require an extension of the current 1D-VAR scheme as well as some development work linking the altimeter backscatter to surface emissivity.*
- *As shown in EMiR, WTC can be based directly on the TCWV. The inclusion of a water-vapour weighted mean atmospheric temperature in the derivation of WTC further improves results [Bennartz et al., 2016]. This temperature will be readily available within the 1D-VAR framework, which requires a-priori temperature and water vapour profiles (e.g. from ERA-Interim).*

Panel 3: Recommendations for optimizing TCWV and WTC accuracies.

4.3 Re-processing considerations

A variety of reasons can lead to the necessity to re-process the entire MWR-based fundamental and thematic data records. For example:

- A new instrument shall be added to the MWR time series (e.g. Sentinel 3A),
- Processing errors affecting one or more instruments have been removed,
- Pre-processing (e.g. side-lobe correction) or retrieval (e.g. TCWV) algorithms have been improved.

To be able to timely provide data records representing the highest possible quality, an operational capacity for reprocessing the entire archive of MWR observations is required.

Due to the limited size of the MWR archive, the computational requirements for such re-processing are comparably low: Re-processing 20 years of MWR observations takes ca. 24 h on a standard workstation. Obviously, reprocessing the altimeter archive to apply e.g. an improved MWR-based wet tropospheric correction is a much larger endeavour.

- *The MWR dataset is relatively small. Efficient re-processing mechanisms for MWR-based FDRs (brightness temperatures) and TDRs (TCWV and WTC) can thus be set up to allow for the consistent incorporation of new and improved calibration and correction techniques.*

Panel 4: Recommendations towards establishing an operational re-processing capacity.

4.4 Exploiting synergies with other instruments

Synergies with other instruments should be exploited. Particularly on ENVISAT, useful cross-comparisons between TWCV derived from AATSR, MERIS and MWR have already been established *[EMIR_DLV_EXT_08_VAL]*. Similarly, Sentinel-3 synergies between MWR, OLCI and SLSTR can be exploited. Beyond direct comparisons of TCWV, such synergies may also help to e.g. identify and screen heavily precipitating areas that could not necessarily be identified by MWR alone.

- *Investigate and exploit Sentinel-3 synergies between MWR, OLCI, and SLSTR for TCWV retrievals and precipitation screening.*

Panel 5: Recommendations towards establishing synergy with other sensors.

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5 References

Bennartz, R., Höschen, H., Picard, B., Schröder, M., Stengel, M., Sus, O., Bojkov, B., Casadio, S., Diedrich, H., Eliasson, S., Fell, F., Fischer, J., Hollmann, R., Preusker, R., and Willén, U.: An intercalibrated dataset of Total Column Water Vapour and Wet Tropospheric Correction based on MWR on board ERS-1, ERS-2 and Envisat, Atmos. Meas. Tech. Discuss., doi:10.5194/amt-2016-304, in review, 2016.

EMIR_DLV_EXT_07_ATBD (2016), EMiR Level-2 and -3 product generation, Algorithm theoretical basis document (DLV-EXT-07), Version 2.1, 36 pp, June 2016.

EMIR_DLV_EXT_08_VAL (2016), EMiR product validation report, comparison of MWR and NCAR GNSS data (DLV-EXT-08), version 1.0, 40 pp, December 2016.

GCOS-154 (2011), Systematic Observation Requirements for Satellite-based Products for Climate. Supplemental details to the satellite-based component of the Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC (Update), Rep., 127 pp, World Meteorological Organization, Geneva, Switzerland.