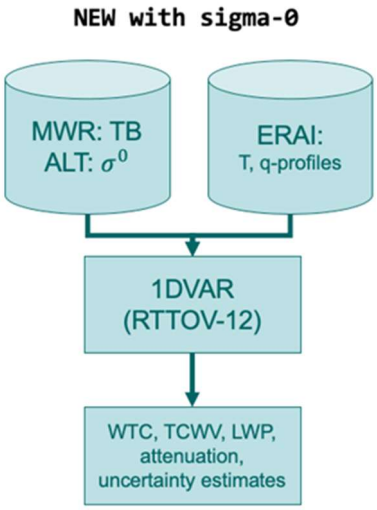

Scheme of the new EMiR V2.0 retrieval, integrating the latest RTTOV and 1D-Var versions and using the Altimeter sigma-0 to consider sea surface roughness.

ESA contract

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

Technical Note

Inclusion of sigma-0 in 1D-VAR retrieval

Deliverable
DLV-CCN2-SIGMA0

Berlin, 13. May 2019

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1 Introduction

1.1 Overview on EMiR

The project "ERS/Envisat MWR Recalibration and Water Vapour Thematic Data Record Generation" (EMiR) is being funded by the European Space Agency (ESA) as part of its Long-Term Data Preservation (LTDP) activities (https://earth.esa.int/web/gscb/ltdp).

LTDP EMiR has the following objectives:

- To generate a fundamental data record (FDR) of top-of-atmosphere (TOA) brightness temperatures from the Microwave Radiometer (MWR) series of instruments flown onboard the platforms 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 from MWR observations.
- To compare the newly derived TDR on TCWV with other long-term TCWV data records through the GEWEX water vapour assessment (GVAP, see http://gewex-vap.org/).
- To assess the impact of improved TCWV information obtained from MWR on the accuracy of concomitant ocean altimetry observations from ERS-1, ERS-2, and Envisat.
- To provide guidance for the next generation of MWR instruments flown onboard the Sentinel-3 series of satellites.

Further information about the EMiR project can be found under http://esa-mwr.org.

1.2 Purpose and structure of this document

The retrieval underlying the EMiR V1.0 and EMiR V1.1 dataset uses surface wind speed from ERA- Interim to parameterize surface roughness for surface emissivity calculations. The EMiR project has shown that 1D-VAR retrievals based on the two MWR-observed brightness temperatures already provide results almost equal to or better than the current operational statistical retrievals, despite the latter making use of additional information on the sea surface roughness derived from the concomitant altimeter observations [EMIR-VALREP, 2017]. This provides a strong indication that, if the altimeter backscatter is suitably included into the 1D-VAR retrieval scheme, results are likely to overall improve. Consequently, it was recommended that:

- 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 in the 1D-VAR retrieval scheme for TCWV will 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 part of EMiR CCN-2, these suggested improvements were to be implemented and tested. Because of the limited duration of the CCN-2, it was not foreseen to again reprocess the entire EMiR dataset. Rather, an initial implementation was to be developed and initial consistency checks were to be performed.

During the early phases of EMiR CCN-2, it further became clear that the heritage retrieval used for EMiR V1.0 and V1.1 could no longer be used in the context of EMiR. This heritage algorithm was based on RTTOV 7 and an outdated and in the meantime depreciated version of 1D-VAR[1]. It was therefore decided to also upgrade the underlying 1D-VAR/RTTOV retrieval to its latest version.

The purpose of the present document is therefore:

(1) To document changes made to the 1D-VAR/RTTOV retrieval algorithm as part of EMiR CCN-2.

(2) To document initial inter-comparisons between old and new retrievals.

1.3 Acronyms and abbreviations

Acronym	Description
CLS	Collecte Localisation Satellites
EMiR	ERS/Envisat MWR Recalibration and Water Vapour TDR Generation
Envisat	Environmental Satellite
ERS	European Remote Sensing satellite
ESA	European Space Agency
FDR	Fundamental data record
GDR	Geophysical data record
GEWEX	Global Energy and Water Exchanges project
GVAP	GEWEX water vapour assessment
L1	Level-1 processing
L2	Level-2 processing
L3	Level-3 processing
LTDP	Long-term data preservation
LWP	Liquid water path
MWR	Microwave Radiometer
NetCDF/CF	Network Common Data Form / Climate and Forecast
RA	Radar Altimeter
RA-2	Radar Altimeter 2
TB	Brightness temperature
TCWV	Total column water vapour
TDP	Thematic data product
TDR	Thematic data record
TOA	Top-of-Atmosphere
WTC	Wet tropospheric correction

[1] See: https://www.nwpsaf.eu/site/software/1d-var/

2 Retrieval versions

Figure 1 shows the evolution of the EMiR retrieval scheme during CCN-2. The various retrieval evolution stages are described in more detail in sections 2.1 to 2.3 below.

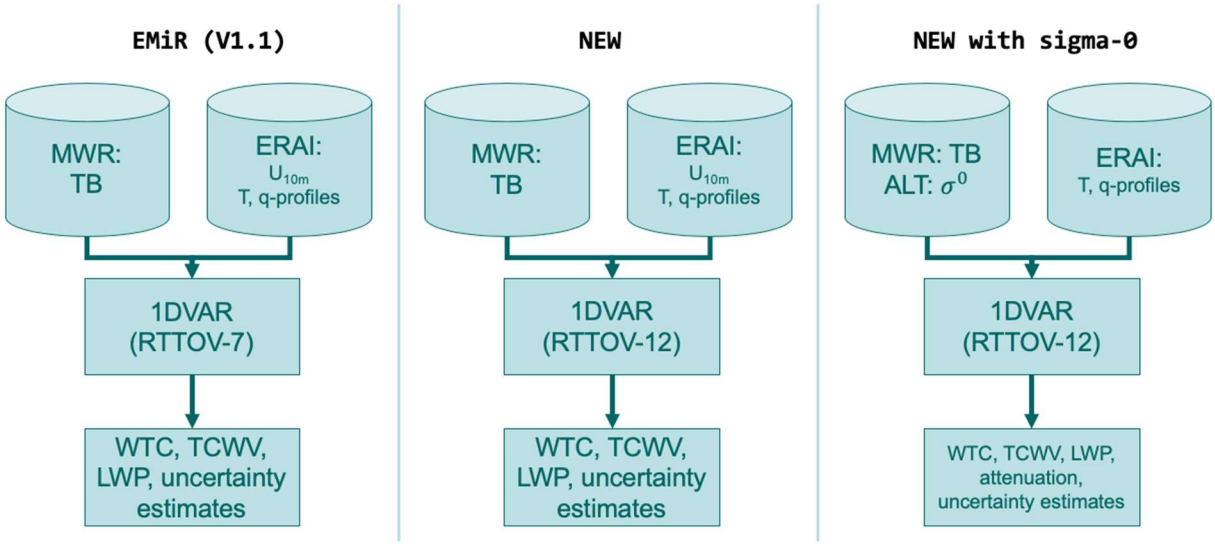

Figure 1: Schematic overview of the evolution of the EMiR retrieval during EMiR CCN-2. The left-hand version (*'EMIR V1.1'*) is the retrieval used for the production of the EMiR V1.1 dataset. The middle retrieval (*'NEW'*) replaces the outdated RTTOV-7 (with the new RTTOV 12.2. The final retrieval (*'NEW with sigma-0'*) additionally replaces ERAI wind speed by the altimeter sigma-0 to characterize surface roughness.

2.1 EMiR (V1.1) retrieval

The EMiR TCWV V1.1 retrieval is fully described in the corresponding ATBD [EMIR-V11-ATBD, 2019]. The EMiR TCWV V1.1 (as well as the older V1.0) retrieval is based on a 1D-VAR scheme initially developed at ECMWF by Phalippou [1996] with a focus on microwave observations from SSMIS and AMSU. It was extended by Deblonde and English [2001] towards a stand-alone scheme applicable to SSM/I, SSMIS, and AMSU. In the context of the ESA DUE GlobVapour project, the TCWV retrieval scheme has been optimized for SSM/I, including the usage of the CMSAF SSM/I Fundamental Data Record (FDR), and later on adopted to MWR observations.

Within the EMiR project, this scheme has been further improved to derive TCWV from brightness temperatures specifically from the MWR sensor family on-board ERS-1/2 and Envisat over the ice-free ocean. The best estimate of the atmospheric state, characterised through atmospheric temperature and moisture profiles as well as surface temperature and wind speed, is determined by an iterative procedure to match simulated satellite radiances with the corresponding measurements within their respective uncertainties. The scheme follows optimal estimation theory considering the uncertainties in the required meteorological background information, forward modelling (radiative transfer simulations), and satellite observations. This methodology enables the provision of retrieval

uncertainties that are mathematically consistent with the uncertainties of the input brightness temperatures and background fields and consistent among the retrieved variables.

2.2 Updated 1D-VAR/RTTOV retrieval

During the early phases of EMiR CCN-2, it became clear that the heritage version of the EMiR retrieval used for the V1.0 and V1.1 would have to be discontinued. In particular, NWP SAF in June 2018 directed users to move to the new 1D-VAR Version 1.1.1 / RTTOV-12 after a bug was identified in the previous versions[2]. This new software released by NWP SAF had been completely redesigned and rewritten and, critically, had differing software interfaces implemented. The former 1D-VAR used for EMIR V1.1 was deprecated. This significant upgrade in the underlying radiative transfer model and 1D-VAR required the EMiR consortium to re-write all interfaces and test the updated version against the old version used for the operational production of EMiR V1.1 to ensure the retrievals were still consistent.

These upgrades needed to be tested against the existing old EMiR V1.1 with the same input data. To do so, as shown in Figure 1 we have added an intermediate version of the 'NEW' retrieval that uses exactly the same input as the old V1.1. In particular, it does not use sigma-0 to characterize the ocean surface but uses 10-m wind speed from ERA-Interim in the same manner the old V1.1 did. This intermediate version is not planned to be continued in the future. It was only devised to ensure compatibility and traceability of retrievals between the old version and the new version of the 1D-VAR retrieval itself.

After testing of the new retrieval, it was found that the results were consistent with the results of EMiR V1.1 (shown in section 3). We note here that EMiR V1.1 has been extensively validated against GNSS and other satellite-based datasets for TCWV and via mesoscale cross-over analysis for WTC. It has also been assessed in the framework of G-VAP and shown to provide stable and reliable climatological estimates of TCWV [EMIR-VALREP, 2017]. We therefore conclude that the transition to the new 1D-VAR retrieval scheme was successful.

2.3 Inclusion of sigma-0 into upgraded retrieval

The new/updated retrieval was then extended to include the altimeter sigma-0 to replace surface wind speed for the lower boundary condition. In particular, we implemented the method by Abdalla [2012] to estimate surface wind speed from sigma-0. The corresponding wind speed is then passed to 1D-VAR instead of the ERA-Interim wind speed. There are three perceived advantages of doing so:

- Abdalla [*ibid.*] points out that ERA-Interim wind speed is biased slightly low compared to his sigma-0 based wind speed retrievals (globally by approximately 0.3 m/s).

[2] https://www.nwpsaf.eu/site/software/1d-var/

- Reanalysis data are never collocated perfectly in time with the satellite observations. For ERA-Interim, reported at 6-hourly intervals, the time difference can be as big as 3 hours. For more recent reanalysis frameworks (e.g. ERA5), it can still be in the order of one hour. With surface wind being highly variable, these differences might deteriorate results.
- ERA-Interim as well as other forecast models fail to account for small-scale variability in wind speed that might affect the state of the sea surface locally but are captured in concomitantly acquired altimeter observations.

The inclusion of sigma-0 will therefore likely lead to improvements in instantaneous retrievals because the state of the sea surface is evaluated virtually at the same time and at a similar spatial scale as the MWR observations.

3 Initial consistency check

Initial consistency checks between the different retrievals outlined in Figure 1 were performed for selected data from one month (January 1994) of ERS-1 observations. These data were selected because they exhibit large biases between observations and forward simulations [Bennartz *et al.*, 2017], so that improvements in bias-correction would be more visible. In the following section these bias-corrections are addressed. Subsequently, we then compare TCWV obtained from the three different retrievals.

3.1 Bias correction

Bias-corrections were re-evaluated for the three retrievals ("V1.1", "NEW", "NEW with sigma-0") and the results are summarized in Figure 2. Following the method outlined in Bennartz *et al.* [2017], offsets were varied systematically for both the 23 and the 36 GHz channel. The correct bias correction was then identified as the one that has zero bias against ERA-Interim in TCWV and zero bias in LWP for cloud-free LWP retrievals. The resulting bias-corrections can be identified as the green dots in the two rightmost panels in Figure 2.

The following conclusions can be drawn from this exercise:

- The bias-corrections for EMiR "V1.1" and "NEW" (without sigma-0) retrievals were nearly identical (to within 0.05 K). This highlights that the old and new 1D-VAR system function nearly identically.
- The inclusion of sigma-0 reduces the magnitude of the bias between observations and simulations both at 23 GHz (from -7.5 K to -7.0 K) and at 36 GHz (from -4.5 K to -3.8 K) compared to the retrieval without sigma-0.

These results confirm the stability of the new retrieval with respect to bias correction and also provide some initial evidence that the inclusion of sigma-0 will positively impact the retrieval process as a whole (as indicated by the better agreement between simulated and observed brightness temperatures).

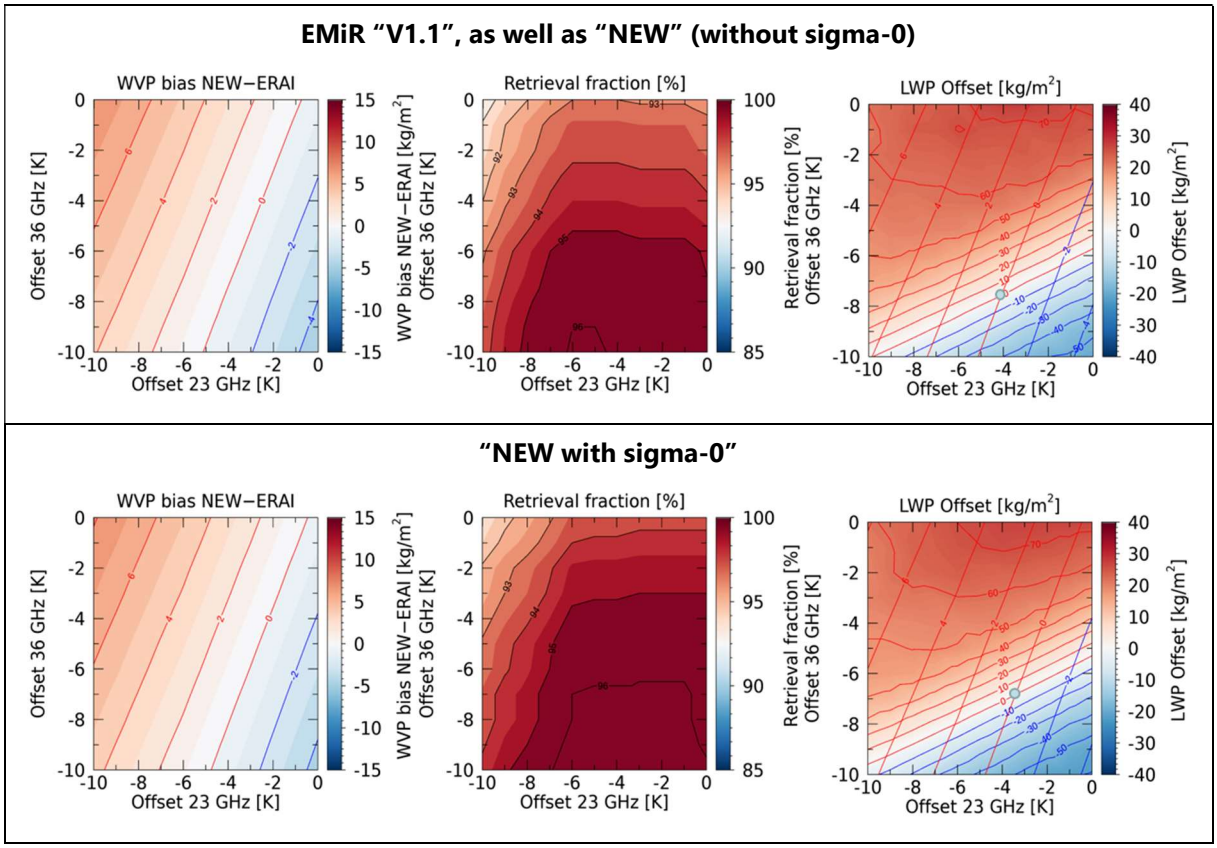

Figure 2: Bias-correction examples for EMiR V1.1 and NEW with sigma-0. For details see ATBD [EMIR-V11-ATBD, 2019] and Bennartz *et al.* [2017]. Note that the bias corrections for EMiR "V1.1" and "NEW" (without sigma-0) are nearly identical.

3.2 Retrievals

In a second step, after biases were established, we have performed actual retrievals on the bias-corrected brightness temperatures following again the methodology outlined in Bennartz *et al.* [2017]. Comparisons between the three retrievals characterised in Figure 1 are shown in Figure 3 and Table 1.

The key result of this analysis is that all three retrievals perform nearly identically well. There are only very modest apparent differences between the three retrievals. Since the comparison dataset is limited, we caution against interpreting the numbers shown in Table 1 beyond a clear agreement. Any of the minute differences seen in the statistics could easily be caused just by the selection of the dataset and might change for a different dataset.

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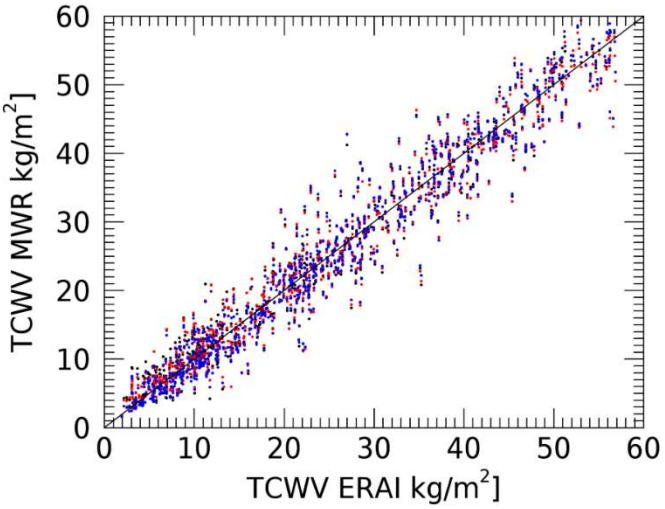

Figure 3: Scatterplot statistics of TCWV retrievals for the three retrievals characterised in Figure 1 against ERA-Interim. Black: EMiR "V1.1", red: "NEW" (without sigma-0), blue: "NEW with sigma-0".

We also want to point to the excellent long-term stability and accuracy of the EMiR V1.1 TCWV dataset [Schröder *et al.*, 2017, 2018], which will be very difficult to be further improved. Future studies, beyond the limited scope of CCN-2, will need to re-evaluate and carefully validate the retrieval applied to the entire dataset. In addition to the TCWV comparisons against GNSS, in particular the mesoscale variability analysis will provide an excellent benchmark to judge algorithm improvements. Such an analysis however requires intercalibration/homogenization of the entire dataset.

Table 1: Comparison statistics of TCWV retrievals for the three retrievals shown in Figure 1. Biases and RMS errors are given with respect to ERA-Interim.

EMiR Version	Bias [kg/m^2]	RMSE [kg/m^2]	Correlation
V1.1	0.16	3.38	0.974
NEW (without sigma-0)	-0.01	3.44	0.973
NEW with sigma-0	0.06	3.38	0.974

4 Recommendations for future studies

4.1 Updated retrieval

A key recommendation of EMiR CCN-2 is that the upgraded 1D-VAR retrieval shall be applied in any future reprocessing of the ERS-1, ERS-2, and Envisat time series. In particular, the combination of MWR observations with concomitantly acquired Altimeter sigma-0 information as described and tested in the current document should be further studied based on the entire long-term dataset where altimeter and concurrent MWR observations are available.

To this extent we also refer to the EMiR V1.1 Product Description [EMIR-V11-PROD], where detailed reprocessing recommendations for the ERS-1, ERS-2, and Envisat time series are developed. In

addition, the extension of the methodology proposed could be expanded to other Altimeter / Microwave Radiometer combinations, as for example outlined in more detail in [EMIR-S3-GUIDE] for the case of Sentinel-3.

4.2 Homogenization of long-term time series

Even the best calibration of individual instruments does not guarantee a sufficiently accurate inter-calibration/homogenization between different instruments in the context FDR generation. The inter-calibration between the MWRs on-board ERS-1, ERS-2, ENVISAT and other pertinent missions is of crucial importance for the successful derivation of long-term FDRs/TDPs.

Additionally, any the radiative transfer model underlying a given retrieval scheme must be un-biased with regard to the input brightness temperatures in order to avoid retrieval biases. These two issues (Homogenization and bias-correction) need therefore be addressed in the context of a given retrieval.

In the context of the 1D-VAR retrieval described here, the homogenization approach described in Bennartz *et al.*, (2017) therefore needs to be re-applied to the entire time series, once a new version of harmonized Level-1 brightness temperatures become available.

Vicarious inter-calibration using earth targets provide another possibility. The approach taken in LTDP-EMiR for example uses cloud-free ocean targets to inter-calibrated ERS-1, ERS-2, and Envisat. Other approaches use land targets with known emissivity to inter-calibrate the different instruments. These methods can provide important guidance on absolute calibration and stability, but do not per se guarantee the retrievals to be bias-free.

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