Exploitation of the ENA Ground-Based Water Vapour Radiometers in Satellite Altimetry

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1. Introduction and Objectives

- This study aims to investigate ground-based radiometer (**MWR_{GB}**) as a reliable source of tropospheric water vapour measurements for deducing the wet tropospheric correction (WTC) of altimetric observations.
- The use of these WTC measurements (**WTC_{GB}**) can contribute as a new source for altimeter observations over coastal zones and for calibration and validation purposes.
- WTC_{GB} is assessed by comparison with four independent WTC sources:
  - (1) Microwave radiometers on board (**MWR_{OB}**) altimetry missions: Sentinel-3A and -3B, SARAL/AltiKa and Jason-3;
  - (2) Global Navigation Satellite Systems (**GNSS**);
  - (3) Radiosondes (**RS**);
  - (4) ECMWF (European Centre for Medium-Range Weather Forecasts) **ERA5** atmospheric model.
- Among these comparisons, the only one that is not independent is the comparison with RS, since the information provided by this source is also introduced in the WTC_{GB} retrieval algorithms.
- Additionally, two neural network algorithms were tuned to estimate the WTC directly from MWR_{GB} brightness temperatures (TB) observations. Both were assessed with GNSS data.

2. Data and Methodology

The following methodology was adopted:

- MWR_{GB} from the ENA (Eastern North Atlantic) observatory (Fig 2.1) of the Atmospheric Radiation Measurement (ARM) user facility have been used. Retrievals from two ARM algorithms were used to evaluate which one best suits the needs of Satellite Altimetry – **NN** or **MWRRETV2**;
- All WTC from external sources were reduced at MWR_{GB} ENA height;
- Two neural network algorithms were created, using 2 or 3 TB as input and the WTC from ERA5 as output:
  - **WTCGB_2TB** - TB from both the 23.8 and 30 GHz bands;
  - **WTCGB_3TB** - TB from both the 23.8, 30 and 89 GHz bands.

Table 2.1 shows the geographical details of each WTC source, for which the following datasets have been analysed:

- **TB** and **WTC_{GB}** derived from ENA ground-based radiometer (MWR_{GB});
- On-board MWR valid measurements (**WTC_{OB}**) from various altimeter missions;
- **WTC_{GNSS}** derived from ENAO GNSS station (IGS network);
- **WTC_{RS}** derived from LAJES Radiosonde station - Integrated Global Radiosonde Archive (IGRA);
- **WTC_{ERA5}** derived from ERA5 model at 0.25º x 0.25º spatial resolution and 3 h temporal resolution.

Table 2.1 – Geographical details of each WTC source. Latitude and longitude are in decimal degrees and Height is above mean sea level.

WTC sources	Latitude (º)	Longitude (º)	Height (m)	Distance from ENA MWR_{GB} (km)
MWR_{GB} (ENA)	39.092	-28.026	30.48	---------
MWR_{OB} (Sentinel-3 A and B; SARAL/AltiKa; Jason-3)	---------	---------	---------	0 - 100
GNSS (ENAO)	39.091	-28.026	73.0	0.051
Radiosonde (Lajes)	38.780	-27.086	306.0	89.1
ERA5	Fully spatial collocated posed by interpolation			

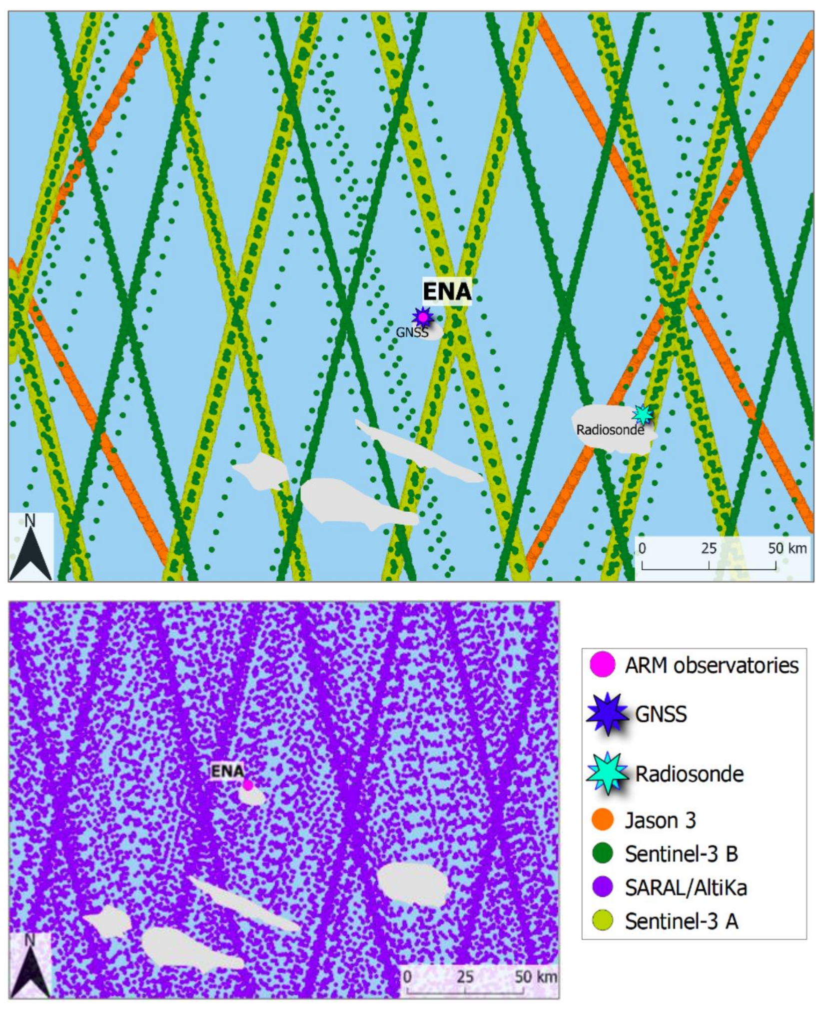

Fig. 2.1 – Spatial distribution of the WTC sources around the ENA observatory – Azores, Portugal. Top figure: MWR_{GB} (ENA), GNSS, radiosonde, Jason-3, Sentinel-3 A and B. Bottom figure: MWRGB (ENA) and SARAL/AltiKa.

3. Comparison with Radiosondes

The non-collocated (89 km away) and non-independent comparison between MWR_{GB} and RS is shown.

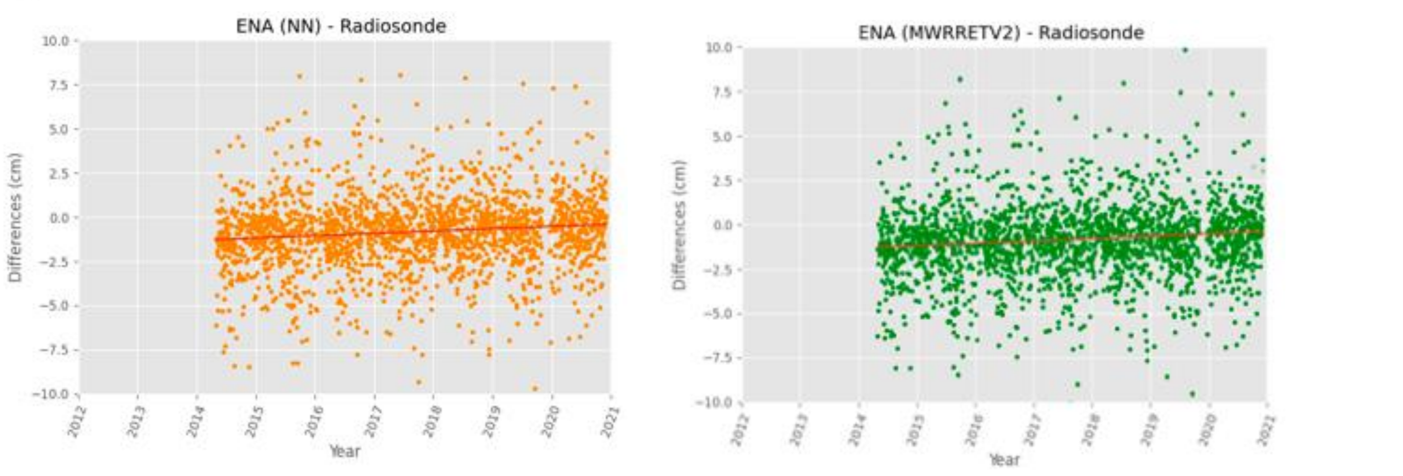

Fig. 3.1 – WTC differences between the products of the radiosonde and ARM algorithms - NN (left) and MWRRETV2 (right).

- The global statistics parameters (Table 3.1) showed that both algorithms achieved very similar performances.
- The results of the differences (Fig. 3.1) showed a slightly positive slope (all below 0.02 mm/yr) in the presented time series.

Table 3.1 – Global statistics of the WTC difference between the products of the ARM algorithms and the radiosonde.

	Samples	Mean (cm)	StD (cm)	RMS (cm)	Min (cm)	Max (cm)
NN	1,976	-0.84	2.22	2.37	-11.94	12.30
MWRRETV2		-0.90	2.19	2.36	-11.97	12.18

- The RMS statistics showed values close to 2.37 cm for both algorithms. Since the measurements in this comparison are non-collocated at approximately 89 km, the accuracy found is in agreement with the results in the further comparison (WTC_{GB}, WTC_{OB}), where the farthest classes for the Sentinel-3 A/B and SARAL/AltiKa missions showed RMS in the same order of magnitude.
- The conclusions at these distances must be carefully analysed, as they are at the limit of the WTC spatial correlation scale.

4. Comparison with ERA5

Table 4.1 – Global statistics of the WTC differences between the products of the ARM algorithms and the ERA5 model.

	Samples	Mean (cm)	StD (cm)	RMS (cm)	Min (cm)	Max (cm)
NN	761,451	-0.48	1.09	1.19	-10.75	9.73
MWRRETV2	677,017	-0.35	1.04	1.09	-8.31	9.35

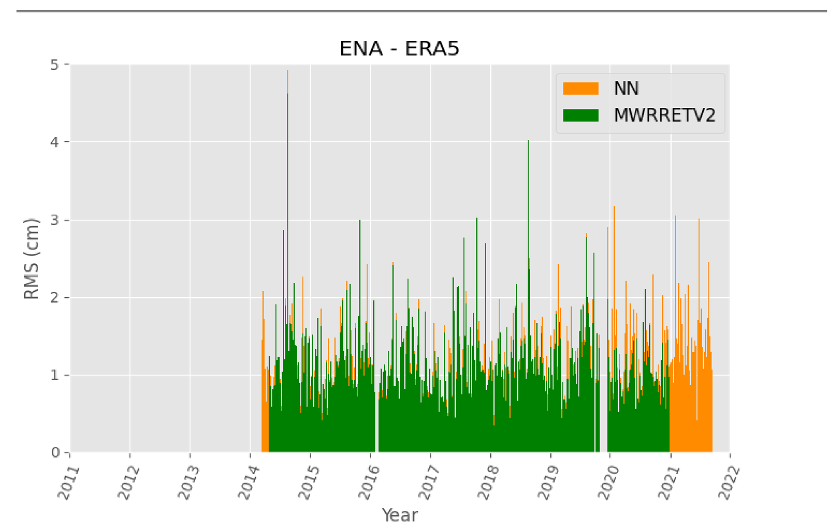

Fig. 4.1 – RMS of the daily WTC differences between the products of the ARM algorithms and the ERA5 model.

This is a spatial and temporal fully collocated comparison posed by interpolation.

- Table 4.1 shows that the global statistics of the differences for the MWRRETV2 algorithm obtained better agreement with ERA5
- Since ERA5 reproduce a smoothed version of the chaotic atmosphere, the better agreement between MWRRETV2 and the ERA5 model could actually indicate that this algorithm is producing smoother retrievals than the NN.
- A weak seasonal signal is observed for the ENA observatory (Fig. 4.1), which is reinforced by the well-known categorization of WTC variability: while the ENA region has a high annual **WTC mean of 14.6 cm**, the WTC annual variability is smaller, represented by a **StD of 5.3 cm**.

5. Comparison with GNSS

The collocated (51 m away) and independent comparison between MWR_{GB} and GNSS is presented.

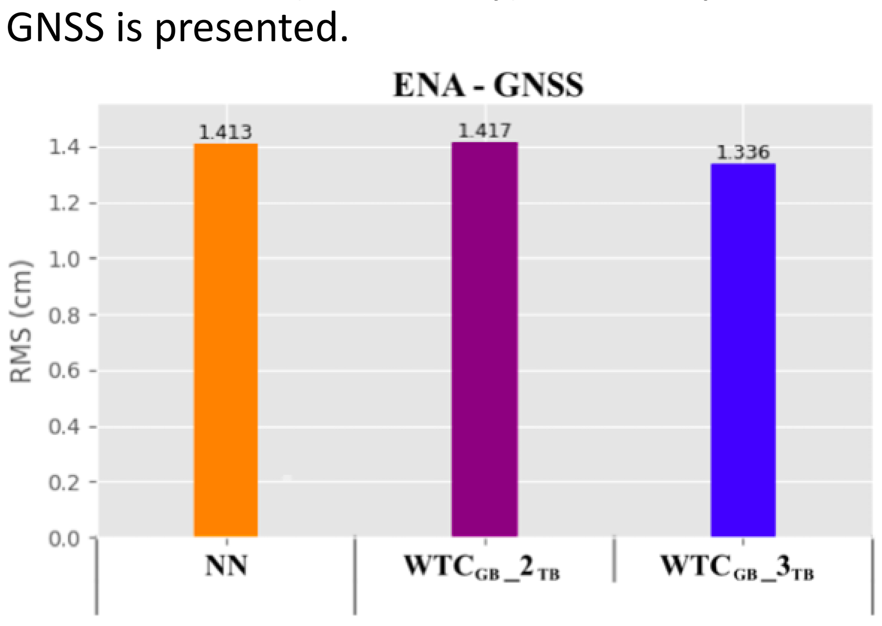

Fig. 5.1 – RMS of the WTC differences of NN, WTCGB_2TB and WTCGB_3TB algorithms relative to the GNSS data. The data period collected is approximately 15 consecutive months

Table 5.1 – Global statistics of the WTC differences of NN, WTCGB_2TB and WTCGB_3TB algorithms relative to the GNSS data.

	Samples	Mean (cm)	StD (cm)	Min (cm)	Max (cm)
NN	42,052	-0.261	1.389	-9.818	6.099
WTC_{GB}_2_{TB}		0.277	1.389	-8.119	16.280
WTC_{GB}_3_{TB}		0.322	1.296	-8.179	16.110

- This comparison (WTC_{GB}, WTC_{GNSS}) was carried out only with the NN algorithm, since only for this algorithm were data available for a period of more than one year (approximately 15 months).
- The NN algorithm showed a RMS of 1.41 cm (Fig. 5.1) which is in agreement with other previous comparisons for the ENA observatory, such as the comparison with MWR_{OB} - classes up to 40 km for all mission (1.02 - 1.30 cm) and the comparison with NWM (1.09 - 1.19 cm).
- The WTCGB_3TB showed a better accuracy when compared with the WTCGB_2TB, in spite of the RMS differences between both versions being in sub-millimetre scale. Therefore, information from the 89 GHz band of the MWR_{GB} - which is intended to detect lower amounts of precipitable water vapor (TCWV < 5 mm), proved to be an information with a positive contribution to the algorithm's retrieval.

6. Comparison with on-board Microwave Radiometers

Non-collocated comparisons between the MWR_{GB} and MWR_{OB} instruments are performed and analysed as a function of distance.

- Figures below represent the RMS of these differences (left axes), for both algorithms and for each class of distance to coast (20 km), for the various missions. Grey bars (right axes) represent the number of measurements used to compute the statistics.

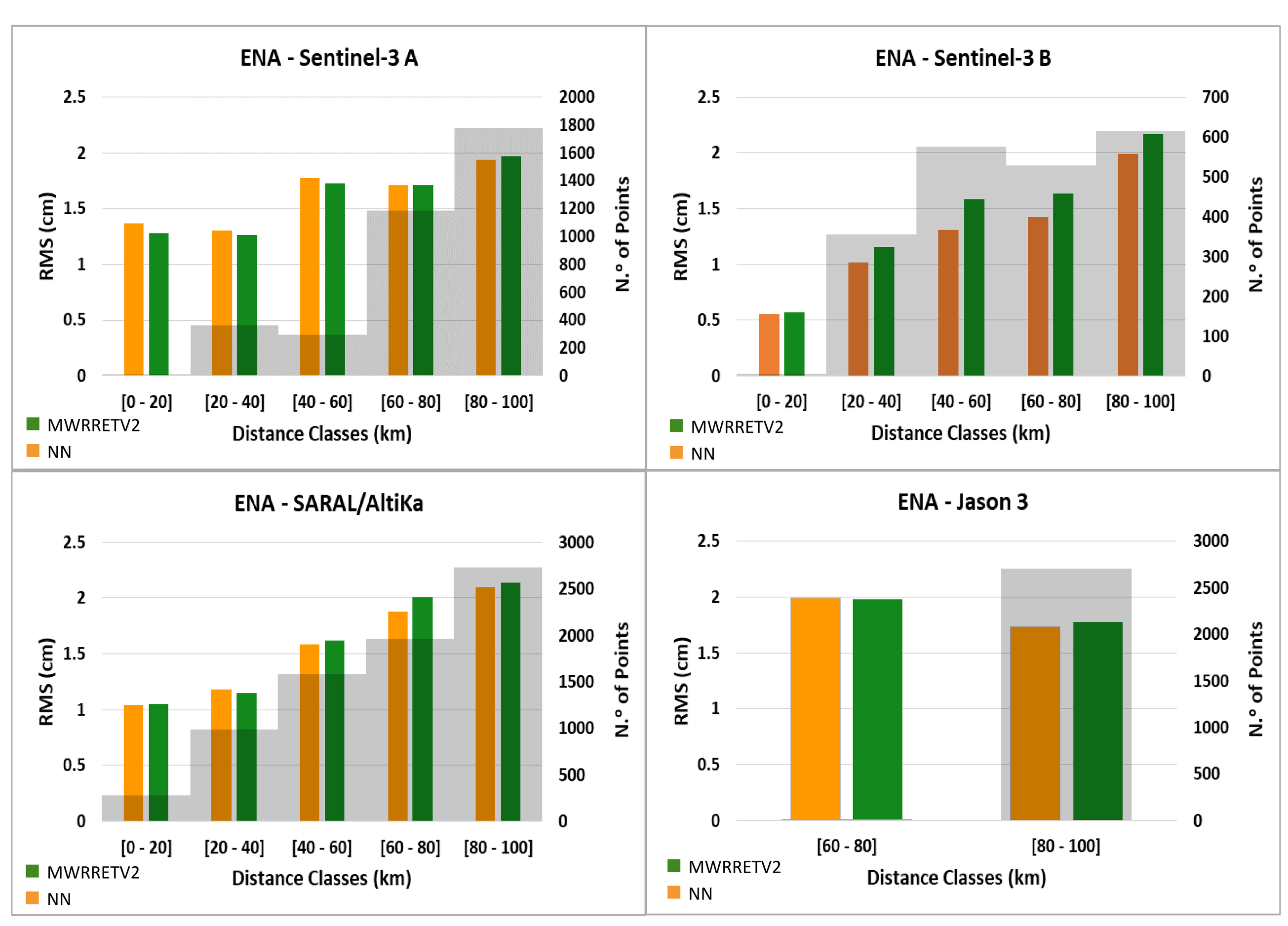

Fig. 6.1 – RMS of the WTC differences between the products of the ARM algorithms and Sentinel 3A and 3B, SARAL/AltiKa, and Jason 3. The differences were performed for 5 classes of distance to the ENA Observatory.

- Samples number are larger as the distance classes increase. This is because increasing distance ranges lead to larger WTC_{OB} data collection areas, as well as the contamination of WTC_{OB} measurements is lower due to the increased distance from the Coastal Zone.
- Fig. 6.1 showed that, in general, the WTC differences between the MWR_{GB} and MWR_{OB} instruments increased as the distance from the observatories increased. Thus, the high variability of water vapour is demonstrated in accordance with the increasing non-collocation spatial effect between measurements.
- The comparisons with SARAL classes [0 - 20 km] and [20 - 40 km], and Sentinel-3 A/B class [20 - 40 km], show that the RMS of the WTC range **from 1.02 to 1.30 cm.**

7. Summary of results

- This study showed relevant conclusions regarding the MWR_{GB}-derived WTC. The accuracy among the collocated, or up to 40 km away, assessments showed close RMS values within a **range of 1.02 - 1.41 cm**. Therefore, these measurements proved to be very useful for **correcting altimeter observations at a distance of up to 40 km**. This equipment can also be used for independent assessments or even for the calibration and validation of other instruments.
- The intra-algorithm assessment showed that in general the NN and MWRRETV2 algorithms have great similarity in their results, with RMS values in the range of 0 – 2.8 mm. Therefore, for the needs of satellite altimetry, the **NN** algorithm proves to be a reliable source for deducing WTC_{GB}, due to the near **real-time latency** of its retrieved data.
- The assessment of WTCGB_2TB and WTCGB_3TB algorithms showed an RMS accuracy of 1.42 and 1.34 cm, respectively. Therefore, this small difference in accuracy is probably due to the introduction of information from the 89 GHz channel in the WTCGB_3TB.