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# Near real-time water vapour monitoring with shipborne GNSS for numerical weather prediction

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## Context & Objectives

MAP-IO (Marion Dufresne Atmospheric Program Indian Ocean) is a research project that aims to collect long-term atmospheric, biological and oceanic observations to document the under-instrumented areas of the Indian and Southern Oceans. To this end, the French research vessel (R/V) Marion-Dufresne, based on the island of Réunion in the Indian Ocean, has been equipped with about twenty autonomous instruments to take measurements along its route. [Tul+24].

Among the instruments deployed on this R/V, a GNSS antenna is in operation since autumn 2020, providing unique and continuous measurements of atmospheric water vapor in this part of the world.

The R/V Marion Dufresne © N. Gravier (left) and the GNSS antenna (right)

## Routine processing strategies

The data were initially transmitted daily to shore for **Ultra** (day +1) and **Rapid** (day +3) routine analysis in PPP-AR using Gipsy-Oasis 6.4 [Zum+97].

| Strategy | Latency | Orbits & Clocks | Sampling | Troposphere | GNSS |
|---|---|---|---|---|---|
| **Ultra** | Day + 1 | JPL ultra | 300 s | GPT / GMF | G |
| **Rapid** | Day + 3 | JPL rapid | 30 s | GPT / GMF | G |

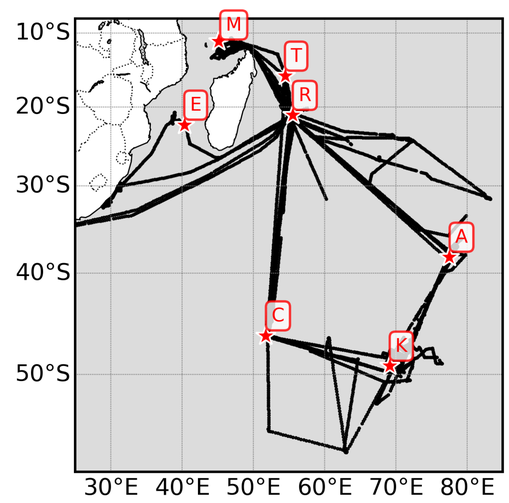
The troposphere effect on GNSS signal propagation is modeled by time-varying Zenith Hydrostatic Delays (ZHD), Zenith Wet Delays (ZWD) and horizontal gradients. The ZHD is corrected a priori using the GPT model. The ZWD is estimated during the processing as a stochastic parameter modeled by a random walk of 5 mm $h^{-1/2}$.

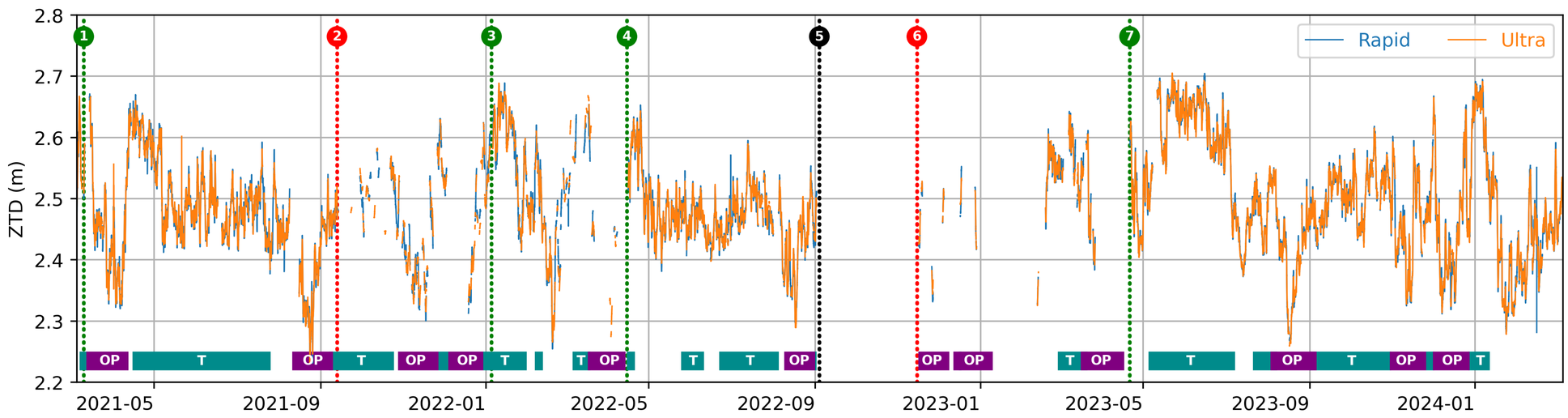
The GNSS Zenith Troposphere Delays (ZTD) is finally obtained by summing ZHD and ZWD. The Integrated Water Vapor (IWV) content is also derived from ZTD estimates using ship-borne temperature and pressure measurements using standard methods [Bev+92; Bos+07].

The quality of the retrieved IWV was assessed in a multi-technique intercomparison study [Bos+22].

The data are continuously made available to the scientific community via the AERIS atmosphere Data and Services Centre.

## ZTD measurements over the period 2021 - 2024




The R/V operates 4 annual rotations (**OP**) fom Reunion Island (**R**) among the French Austral Islands: Crozet Archipelago (**C**), Kerguelen Islands (**K**), Saint-Paul and Amsterdam Islands (**A**). The rest of its mission consists of conducting oceanographic and geophysical campaigns in the open sea or near French islands as Mayotte (**M**), Îles Éparses (**E**) and Tromelin (**T**).

The time series of ZTD produced by the 2 routine analyses cover almost 70% of the period. Periods of interruption are associated with ship maintenance (❺) and instrument issues (antenna, ❷ and cable, ❻). Changing the antenna location on the ship (❶ and ❸) and the equipment (❹ and ❼) solved these problems.

Over the whole period, the ZTD from the two analysis are highly consistent with differences of $0.1 \pm 7.1$ mm.

The space and time variations of the ZTD reflect the different climatic regions crossed by the R/V.

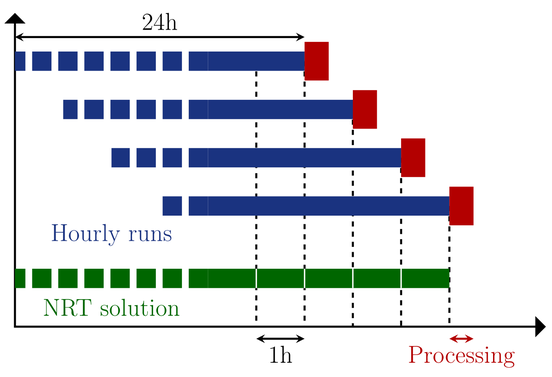
- More southerly passages during rotations (**OP**) are systematically accompanied by lower ZTD, mainly due to lower water vapor contents.
- On the other hand, during campaigns, mostly in tropical regions (**T**), ZTD reach higher values because the atmosphere may contain more water vapor due to higher temperatures.

## Near Real-Time processing strategy

With improved transmission facilities, raw GNSS measurements are now transmitted hourly since early 2023 and can be analyzed with a latency of less than 30 minutes. An initial assessment of the Near Real Time (**NRT**) processing was conducted based on GNSS raw data collected in August 2023 during a rotation of the R/V Marion-Dufresne in the French Austral Islands (**OP**).

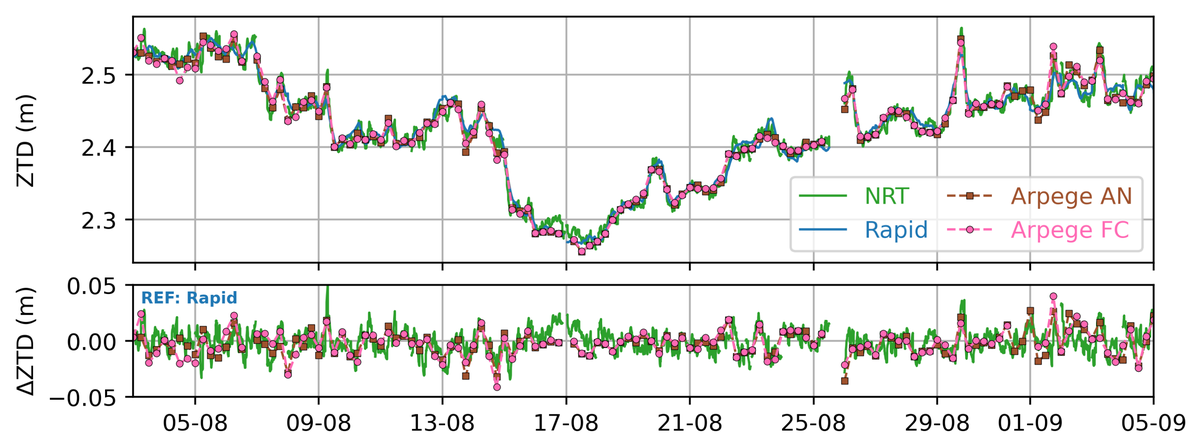
| Strategy | Latency | Orbits and Clocks | Sampling | Troposphere | GNSS |
|---|---|---|---|---|---|
| **NRT** | h + 20 min | JPL / GDGPS | 30 s | GPT / GMF | GRE |

The processing is done with GipsyX 2.0 in PPP mode [Ber+20]. The analysis is run every hour over a 24-hour window, using the raw hourly data transmitted by the R/V and the cumulative real-time ephemerides and clocks provided by JPL / GDGPS. Only the last hour of each analysis is then considered. The rest of the parameterization of this analysis is similar to the routine analyses.




The solutions of the **NRT** processing are compared with the ZTD computed from the mean sea level pressure and IWV fields of the Arpege Numerical Weather Prediction (NWP) model [Déq+94]. Two outputs from the model are used, the analysis (**Arpege AN**) and the 6h-forecast (**Arpege FC**).

## Near Real-Time processing assessment




There is good overall agreement between the different time series. The time series from the **NRT** calculation is slightly noisier, but accurately reproduces the overall evolution of the ZTD.

From a more quantitative point of view, the **NRT** calculation shows an RMS of differences of about 10 mm compared to the **Rapid** processing, with a low bias.

| (mm) | wrt **Rapid** | wrt **NRT** |
|---|---|---|
| **NRT** | $-0.7 \pm 10.2$ | – |
| **Arpege AN** | $-2.3 \pm 11.4$ | $-2.3 \pm 11.0$ |
| **Arpege FC** | $-1.8 \pm 11.7$ | $-1.9 \pm 11.5$ |

The Arpege **analysis** and **forecast** shows an RMS of differences about 11 mm with **NRT** and **Rapid** solutions, with a bias of about 2 mm (GNSS wetter than Arpege).

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## Conclusion & Perspectives

GNSS data collected aboard the R/V Marion Dufresne as part of the MAP-IO program are being used to monitor the spatio-temporal distribution of atmospheric water vapor in the Southern and Indian Oceans.

- The ZTD/IWV measurements routinely retrieved in this framework are intended to be used for long-term studies, as is common for ground-based antennas.
- The NRT calculation appears to be of sufficient quality for use in NWP (Cal/Val or assimilation).
- The next stage of this work will be to establish an operational procedure for the assimilation of these NRT GNSS troposphere solutions into NWP models. This also includes a possible adptation of the COST format to moving antennas.