Cross–calibration and Long–term Monitoring of the Microwave Radiometers of ERS, TOPEX, GFO, Jason and Envisat

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Summary

The wet tropospheric delay as deduced from microwave radiometers occupies an important place in the error budget of sea-level change estimates from satellite altimetry. Just as the altimeter range can drift, so can the measured brightness temperatures and hence the wet tropospheric delay that maps fully into the sea level trend.

Earlier investigations by *Ruf et al.* showed that 1.0 mm/year should be added to sea level trends until the end of 1999 to compensate for a drift in the 18 GHz channel of the T/P radiometer. Our investigations show that, in fact, the drift continues until today as a quadratic function of time and has recently reversed direction. The new analyses suggest that an additional 0.1 mm/year are to be added to the sea level rise estimates.

This presentation shows how the drift can be compensated. Additionally, we propose a simple algorithm to better detect radiometer data affected by sea ice.

The 23.8 GHz channel of the ERS-2 radiometer is known to be biased and drifting since a hardware event leading to gain loss in 1996. Previous corrections suggested by *Eymard et al.* are reviewed using additional techniques and are extended to present day. A modified model for the drift of the ERS-2 radiometer is proposed.

The studies are complemented by analyses of the microwave radiometer data of ERS-1, GFO, Jason-1 and Envisat, as well as model grids. The various analyses throughout all missions attempt to provide a consistent look at all radiometer-derived wet tropospheric delays and their effect on sea level change studies.

Clearly, radiometer drift is an important part of the sea level change budget!

Satellite radiometers

TMR: TOPEX/Poseidon microwave radiometer brightness temperatures (18, 21, 37 GHz) and wet tropospheric delay from AVISO MGDRs, corrected for drift and yaw as per GCP version C.

JMR: Jason-1 microwave radiometer brightness temperatures (18.7, 23.8, 34.0 GHz) and wet tropospheric delay from PO.DAAC GDRs.

ERS-1 MWR: Brightness temperatures (23.8, 36.5 GHz) from OPR v6; wet tropospheric delay from *Eymard and Boukabara* algorithm.

ERS-2 MWR: Brightness temperatures (23.8, 36.5 GHz) from OPR v6, corrected for gain loss and drift according to *Eymard et al.*; wet tropospheric delay from *Eymard and Boukabara* algorithm.

Envisat MWR: Brightness temperatures (23.8, 36.5 GHz) and wet tropospheric delay from (I)GDRs.

GFO MWR: Brightness temperatures (22, 37 GHz) and wet tropospheric delay from NOAA GDRs.

Atmospheric models

ECMWF: Operational ECMWF model analysis

- Resolution: 6 hours, 2.5°×2.5°.
- From GDR and OPR data (tri-linear interpolation).
- Regular improvements lead to discontinuities (*example:* 22 Jan 2002).
- Subject to scaling bug by FMO prior to 1 Dec 1997 (ERS-1, ERS-2, **and T/P**).

ERA40: ECMWF 40-year re-analysis

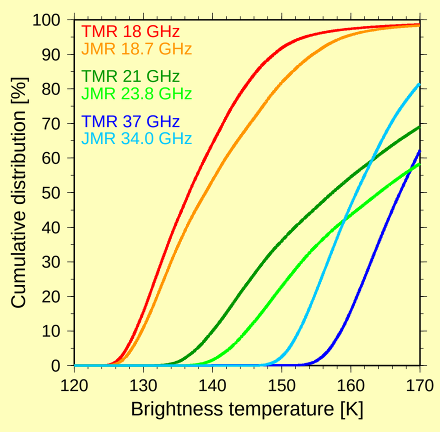
- Same resolution. Cubic-spline interpolation in space, linear in time.
- No discontinuities, but known to have drawbacks compared to analysis.

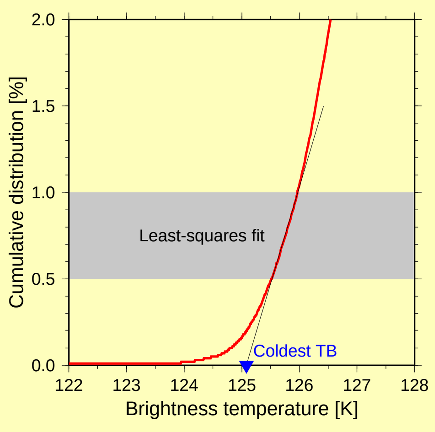
NCEP: NCEP/NCAR model re-analysis

- Older than ECMWF models.
- Same resolution. Cubic-spline interpolation in space, linear in time.
- No discontinuities.

Vicarious Cold Temperatures

Ruf et al. pointed out that the coldest brightness temperature measured over the ocean should be stable. Any drift in the radiometer will show up as a drift in these vicarious cold temperatures. Like *Ruf et al.* we find the coldest temperatures by extrapolation of the cumulative distribution of the brightness temperatures to 0%. To find this point a straight line is fitted through the cumulative distribution between 0.5% and 1.0%.
The vicarious cold temperatures are determined per cycle for T/P and Jason-1, per half cycle for GFO, and per third cycle for ERS-1, ERS-2 and Envisat.



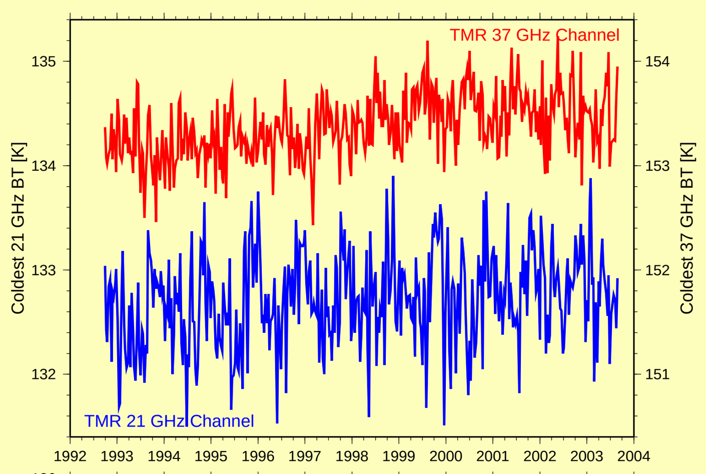


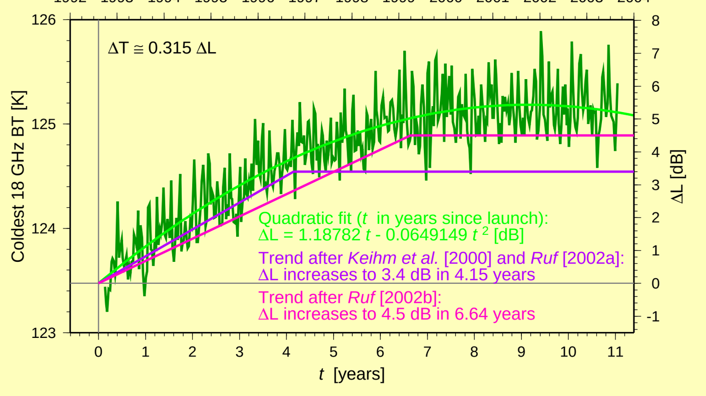
TOPEX Microwave Radiometer (TMR)

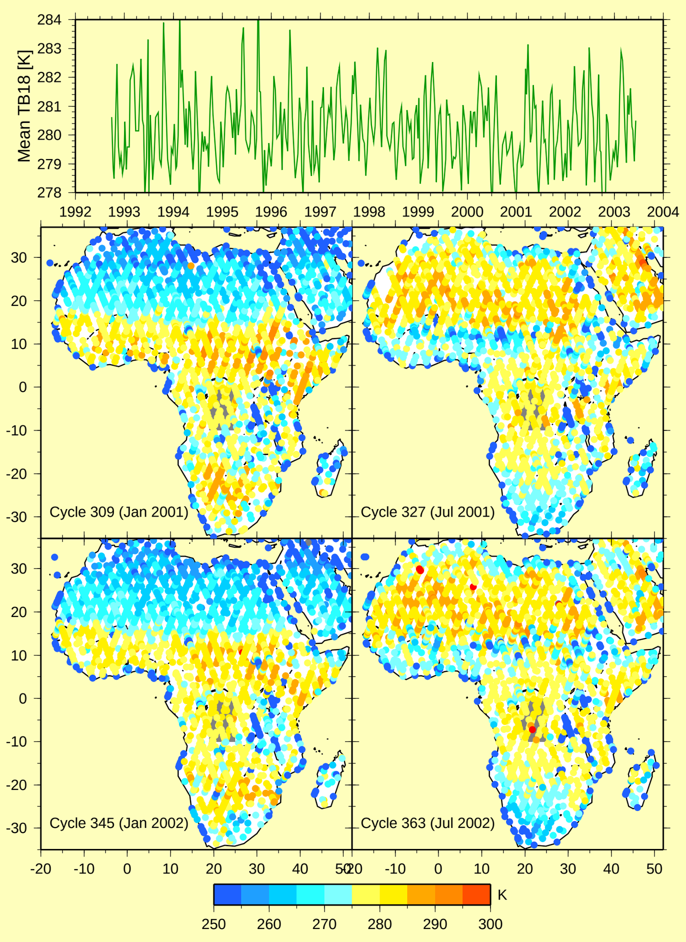
- The 21 GHz Channel shows the largest variation, but no significant drift over time.
- The 37 GHz Channel exhibits less variation and a slight, but likely insignificant increase by 0.4 K during 1997-1999.
- The 18 GHz Channel drifts significantly over time. The drift is better characterized by a parabola than by the ramp function suggested by *Keihm et al.* and *Ruf*. The increasing coldest brightness temperature correlates with a leakage of power from the hot load to the antenna of up to 5.5 dB, one dB more than suggested by *Ruf*. The total increase of brightness temperature is 1.7 K.
- Differentiation of the log-linear approximation of the wet tropospheric delay leads to:

$$\Delta PD = -5.0\,\Delta TB18 + 7.2\,\Delta TB21 - 0.9\,\Delta TB37$$

  where ΔPD is the excess path delay in mm for any excess brightness temperature ($TB18, TB21, TB37$) in K.
- To correct the drift in TB18, the path delay should be increased over time to about 8.6 mm, increasing sea level rise by about 1.0 mm/year.

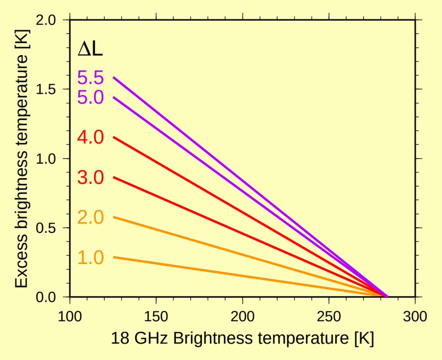






Is the 18 GHz channel drifting homogeneously (same at all temperatures)?

- To assess this question we look at the hottest instead of the coldest temperatures.
- It is often suggested to monitor the brightness temperatures over the Sahara, however, as shown on the left, the Sahara brightness temperatures exhibit a very large seasonal cycle.
- Tropical forests, like the Congo (grey box on the map) or the northern Amazon are more stable.
- The hottest 18 GHz temperatures show no significant drift.
- We assume that the drift of the coldest temperatures drops to 0 at 284 K (see graph below).

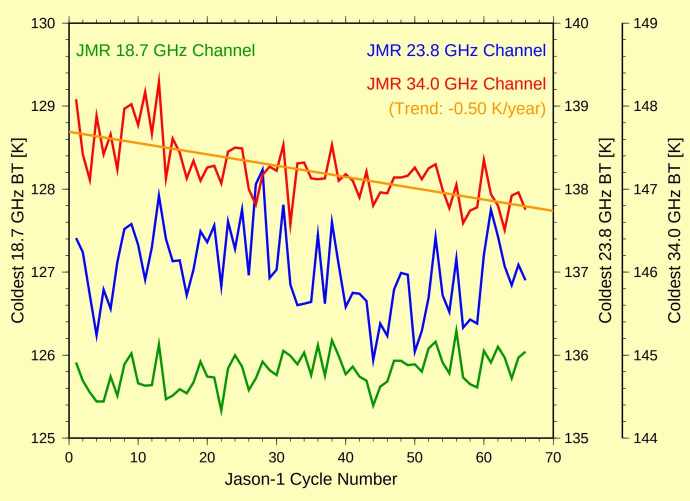


Jason–1 Microwave Radiometer (JMR)

- The 23.8 GHz Channel shows the largest variation, but no significant drift.
- The 18.7 GHz Channel exhibits the least variation and no significant drift.
- The 34.0 GHz Channel drops significantly in temperature by about 0.5 K per year.
- Differentiation of the log-linear approximation of the wet tropospheric delay leads to:

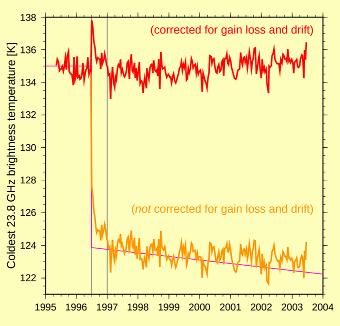
$$\Delta PD = -3.7\,\Delta TB18 + 6.7\,\Delta TB23 - 1.8\,\Delta TB34$$

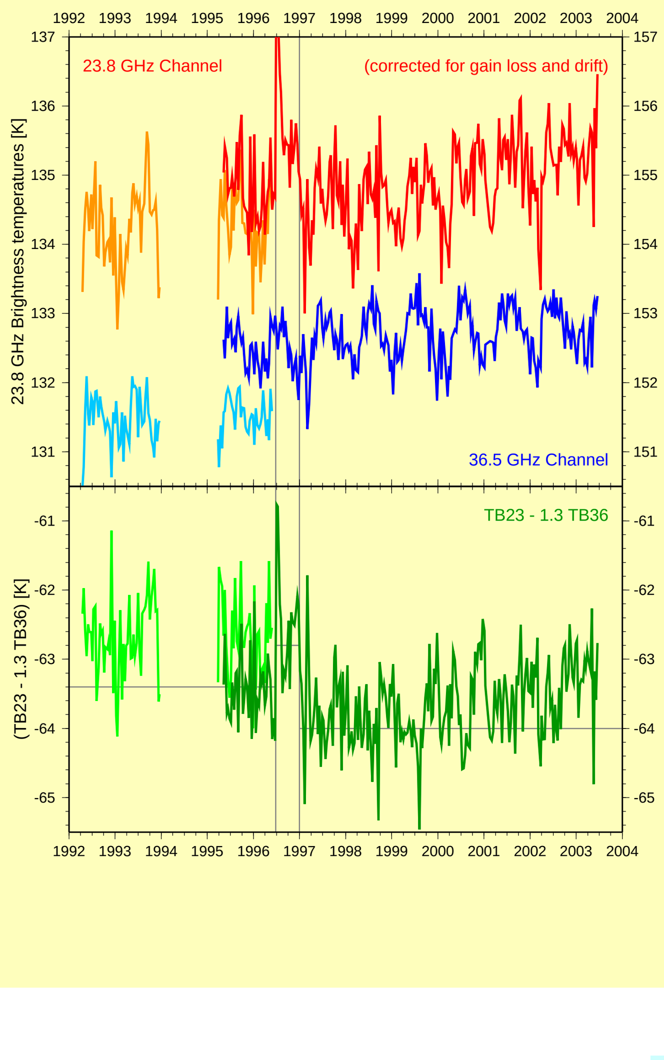
  where ΔPD is the excess path delay in mm for any excess brightness temperature ($TB18, TB23, TB34$) in K.
- To correct the drift in TB34, the path delay should be increased by 0.9 mm/year, increasing sea level rise by that amount.



ERS–1/2 Microwave Radiometer (MWR)

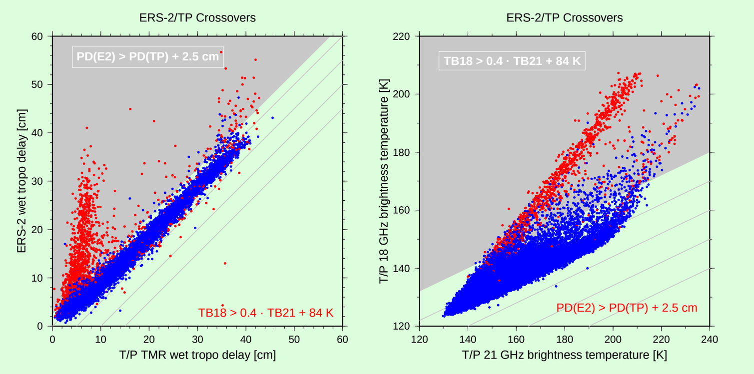
- ERS-1 values are shown in light colors (Phase C and G only). ERS-2 values are shown in dark colors.
- The 23.8 GHz Channel has dropped by about 11 K after gain loss in June 1996 and afterwards started to drift. *Eymard et al.* provide a temperature-dependent correction (plot below).
- The 36.5 GHz Channel has less variation and appears unaffected by the gain loss in the 23.8 GHz channel.
- There is a bias between ERS-1 and ERS-2 of about 1 K.
- It seems as if the annual variation in both channels increases after January 1997.
- The linear combination $TB23 - 1.3\,TB36$ reduces much of the annual variation and highlights that the corrected 23.8 GHz brightness temperature drops by 1.2 K after an initial rise of 0.6 K.
- The drift in the TB23 appears to be overcompensated since mid 1999. In fact, the drift seems to have been stopped since.

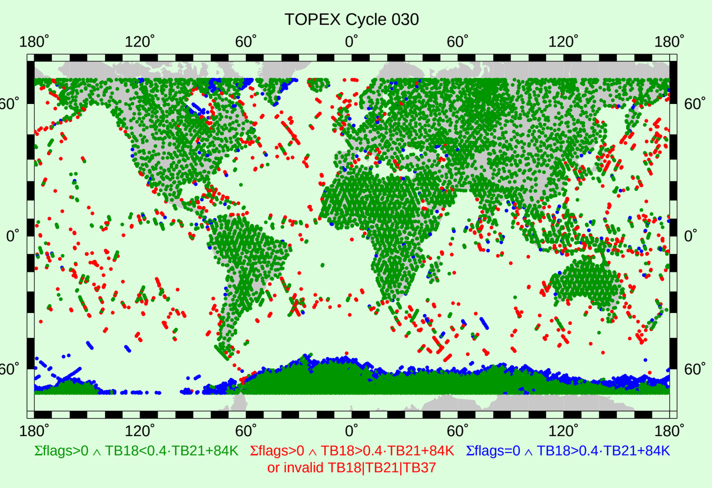




Ice Flagging of TMR Data

- The scatter plot of wet tropospheric delay for ERS-2 and TOPEX shows a large amount of points where the TMR suggests delays around 8 cm for a large range of MWR values. We designate all points with $PD(E2) > PD(TP) + 2.5$ cm (grey area in *top left* plot) as outliers.
- These outliers correspond largely to TMR brightness temperatures in the domain $TB18 > 0.4\,TB21 + 84$ K (grey area in *top right* plot).
- We tested which points correspond to the criterion $TB18 > 0.4\,TB21 + 84$ K *(bottom plot)*:
  - True: Red points are already designated in the MGDRs as affected by rain.
  - True: Blue points are not flagged in the MGDRs but are clearly related to ice (or rain).
  - False: Green points are mainly over land and do not trip the criterion.
- The criterion can be used, together with the MGDR flags to indicate TMR data affected by rain or ice.

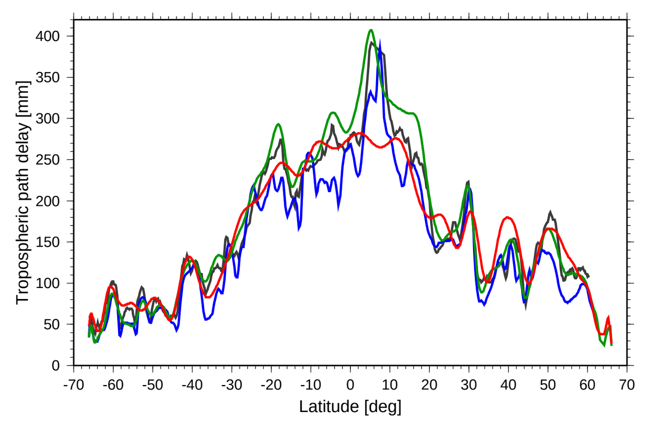




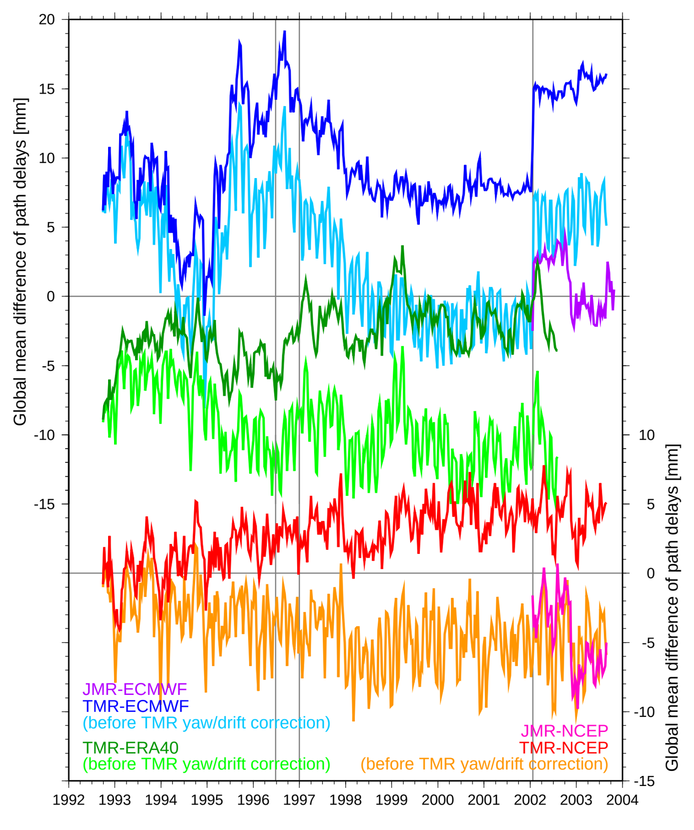
Cross–calibration of Wet Tropospheric Delay

Example of TOPEX pass across Atlantic Ocean.

- ECMWF has strange short-scale features that are not in TMR data or other models.
- NCEP does not follow peaks very well.
- ERA40 is more smooth than ECMWF and follows TMR data best.



TMR / JMR / Model Comparison



Blue, green, red: Difference between TMR and model wet tropospheric path delay, averaged per cycle.

- Light colored lines refer to data prior to drift and yaw corrections as per GCP version C.
- The yaw correction removes a lot of the short-periodic variations: compare ECMWF after and before.
- ECMWF analysis is currently very stable but was not so prior to 1998 and shows jump of 7 mm on 22 Jan 2002.
- NCEP/NCAR re-analysis shows larger annual variations and ERA40 re-analysis larger inter-annual variations.
- Comparison with NCEP and ECMWF suggests TMR getting wetter than models.
- Are models getting too dry, or TMR too wet?

Purple: Difference between JMR and model wet tropospheric path delay, averaged per cycle.

- Conspicuous jump of 4 mm at Cycle 30. Seen in both ECMWF and NCEP comparison. Phase change?
- JMR path delays are on average about 15 mm shorter than TMR path delay.

ERS / Envisat / GFO / Model Comparison

Blue, green, red: Difference between ERS-1 (light) and ERS-2 (dark) MWR and model wet tropospheric path delay, averaged per third of a cycle.

- Variation in ECMWF too large to detect trends.
- Annual variation in ERA40 much larger than NCEP.
- Small (1-2 mm) difference between ERS-1 and ERS-2.
- Annual variations appear smaller prior to gain loss (Jun 1996).

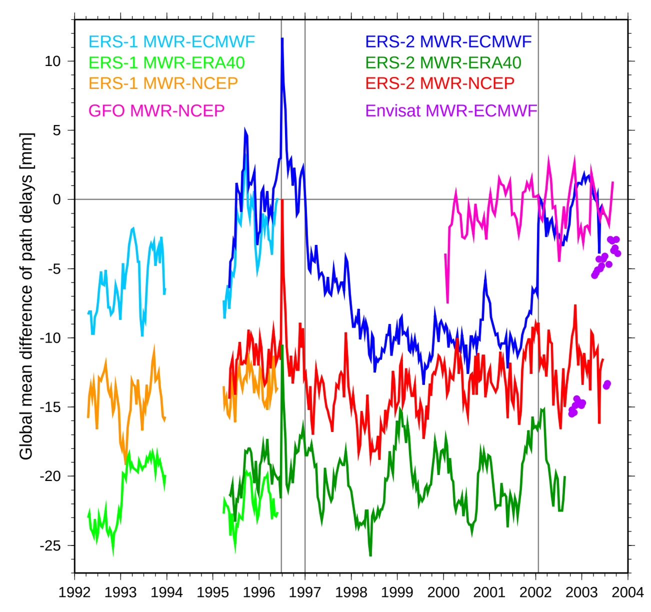
Purple dots: Difference between Envisat MWR and ECMWF wet tropospheric path delay, averaged per third of a cycle.

- Large jump between earlier (Cycle 10-12) and later cycles. Algorithm change?

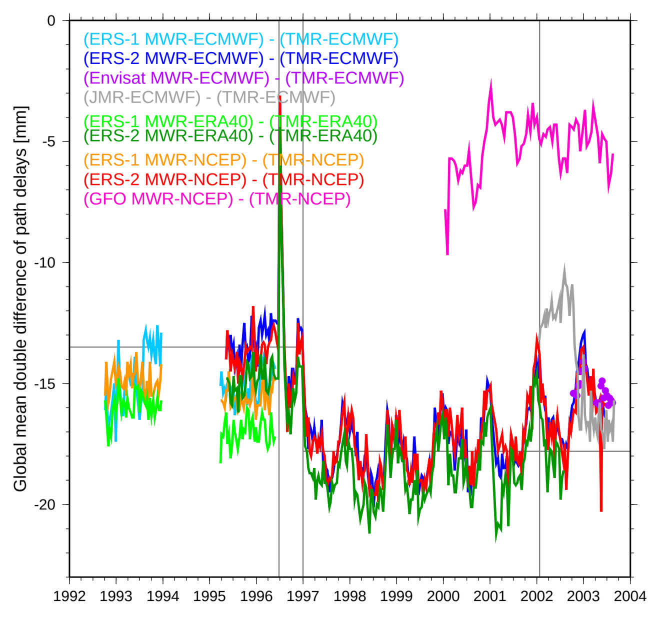
Pink: Difference between GFO MWR and NCEP wet tropospheric path delay, averaged per half cycle.

- Very stable except for first couple of cycles. No apparent drift.

Latitude constraint: All data are limited to latitude range 66°S-66°N to compare with TMR/JMR and reduce lingering effect of land and sea ice.



"Double–differences"



"Double-differences": Mean global difference between satellite A and model M, compared to mean global difference between satellite B and model M.

- Mimics difference between satellite A and B.
- More points, less noise, than crossovers with very short time difference.
- Model M works as intermediary only. Biases and erroneous variations in model are eliminated.

Blue, green, red: ERS-1 (light) and ERS-2 (dark) MWR compared to TMR.

- Different models now give very similar results.
- Path delays are on average 15-20 mm shorter than TMR path delays.
- Small annual variation remains in the differences.
- ERS-2 path delay drops by 5 mm in January 1997, 7 months after the gain loss. Why?
- ERS-2 path delays increase linearly since about 2000, by about 1 mm/year.

Purple dots: Envisat MWR compared to TMR.

Pink: GFO MWR compared to TMR.

- GFO MWR path delays are about 5 mm shorter than TMR path delays.
- GFO MWR does not show drift compared to TMR.
- First year to be investigated.

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Conclusions

Cold and hot brightness temperatures. Both the 18 GHz channel of TMR and the 34.0 GHz channel of JMR drift over time as seen in the cold temperatures.

- Rather than a ramp function, the TMR drift is more parabolic and exceeds previous estimates.
- The 23.8 GHz channel of ERS-2 suffered a gain loss and subsequent drift. The drift seems to have stopped since about 2000.

TMR ice algorithm. Together with the rain flag, the algorithm $TB18 > 0.4\,TB21 + 84$ K, can be used effectively to flag data affected by rain and/or sea ice.

Atmospheric model comparisons. Different models have different concerns: long- and short-term stability, biases.

- "Double-differences" can be used effectively to compare radiometer wet tropospheric corrections.