Progress in the Wet Tropospheric Correction for Altimetry: Jason-3 to Sentinel-6 and Beyond

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Topex  Jason-1
Topex  Jason-2/3
Jason-CS

1992  2018
• Measurement of global mean sea level rise not possible without extremely well calibrated measurement system

• Radiometer wet path delay correction generally considered largest source of uncertainty in long term GMSL trend estimate
  - Requires careful monitoring and application of periodic post-launch corrections
  - Corrections of up to 30x GMSL trend have been applied to radiometer wet PD record

Table 2. MSL trend uncertainties from 1993 to 2008 for each correction or model impacting the MSL calculation.

<table>
<thead>
<tr>
<th>Source of error for the MSL calculation</th>
<th>MSL trend uncertainties from 1993 to 2008</th>
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<tbody>
<tr>
<td></td>
<td>Minima</td>
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<tr>
<td>Orbit: Cnes POE (GDR B) for Jason-1 and GSFC (ITRF2000) for T/P.</td>
<td>0.10 mm/yr</td>
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<tr>
<td>Radiometer Wet troposphere correction: JMR and TMR (with drift correction).</td>
<td>0.20 mm/yr</td>
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<tr>
<td>Dynamical atmospheric and dry troposphere corrections using ECMWF pressure fields.</td>
<td>0.05 mm/yr</td>
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<tr>
<td>Sigma0 drift impacting altimeter wind speed and sea state bias correction</td>
<td>0.05 mm/yr</td>
</tr>
<tr>
<td>Bias uncertainty to link TOPEX A and TOPEX B, and TOPEX and Jason-1.</td>
<td>0.10 mm/yr</td>
</tr>
<tr>
<td>Total error budget</td>
<td>absolute sum</td>
</tr>
<tr>
<td></td>
<td>quadratic sum</td>
</tr>
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<td></td>
<td>inverse formalism</td>
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</table>

Ablain et al., 2009
When the first derivative is no longer enough.....

Nerem et al., PNAS, 2018

Satellite observations show sea levels rising, and climate change is accelerating it

New NASA study finds dramatic acceleration in sea level rise
Topex and Jason-1

- TMR drifted at a rate of about 1 mm/year over the first 6 years of the mission

- JMR exhibited two jumps of about 5 mm then an additional 8 mm
  - 6mm/year when treated as drift

Observed instability significant compared to sea level rise signal
Jason-2 and Jason-3

• Jason-2 AMR PD – ECMWF without ARCS Processing

Jason-2 AMR PD – ECMWF without ARCS Processing

• Jason-2 AMR had jumps of totaling ~2cm over 3 years

• Jason-3 AMR exhibits monotonic drift of 20 mm/yr

Jason-3 AMR drifting at a rate of 20 mm/yr
Ancillary Methods for Monitoring Long Term Stability

• Brightness temperature models
  – Vicarious Cold Reference \((\text{Ruf, 2000, TGARS})\)
  – Amazon pseudo-blackbody regions \((\text{Brown and Ruf, 2005, JTECH})\)
  – On-orbit references sensitive to climate variability; require corrections; risk of aliasing geophysical signals

• Inter-sensor TB comparisons
  – AMSR-E, SSMI, TMI, JMR
  – Requires model to transfer one sensor’s measurement to another
  – Requires stability of other systems

• Compare geophysical retrievals to in-situ measurements, models and other sensors
  – ECMWF, NCEP, SSMI, TMI, AMSR-E, GPS, RaOb
  – Dependent on long term stability of other sensors/models
Cold Sky Calibration

- Cold sky calibration performed by rotating the spacecraft which provides a calibration reference through the same path as the Earth scene.

- Presents stable 1-point calibration to the radiometer.

- 2-stable points required for complete calibration, therefore cold sky maneuver supplemented by on-Earth references.

\[
\Delta T_B(T_B, t) = (T_B - T_{\text{REF}}) \frac{\Delta T_{ND}(t, L, \Gamma)}{T_{ND}} + \Delta T_{\text{Offset}}(L, \Gamma)
\]
J3 Noise Diode Drift

- Cold sky maneuvers (CSM) used to characterize and remove drift in J3 AMR noise diodes
- Coefficients updated and provided to CNES after each CSM
- Latency has improved due to added CSMs
• Vicarious cold ocean reference used as independent validation of cold sky calibration

• No statistically significant long-term drift evident after cold sky calibration
• Path delays stable to within ~±1mm over mission
• Wind speed stable to 0.2 m/s
Sentinel-6 AMR-C

- Sentinel-6 AMR-C includes two new design features based on OSTST recommendations
  - External calibration system for long term stability
  - High Resolution Microwave Radiometer for coastal PD – experimental

Cold sky reflector

Microwave blackbody

High Resolution Microwave Radiometer (HRMR)
Path delay stability determined by target uncertainty and frequency of calibrations

$$\Delta T_B (T_B, t) = (T_B - T_{REF}) \frac{\Delta T_{ND} (t, L, \Gamma)}{T_{ND}} + \Delta T_{Offset} (L, \Gamma)$$
Sentinel-6: The New Climate Reference

Drift Estimation Uncertainty for Various References

- Sentinel-6
- Jason-2
- Jason-3
- Jason-CS

Legend:
- Hot/Cold every 10 days
- Hot/Cold every 5 days
- Hot/Cold every 1 day
- Cold Sky+VCR
- VCR+HotRef
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SCS (Supplemental Calibration System)
Example: Off-shore Winds

- Certain areas can result in large systematic biases

- Example of Santa Ana winds off California coast
  - ~3-4 cm bias at the coast
High Resolution Microwave Radiometer

- 3-frequencies at 90, 130 and 166 GHz
- Co-located footprints with a spatial resolution of 2-5km
- Noise diode and switch to reference load for calibration
  - 0.2K TB uncertainty
• Channels between 90-160 GHz sensitive to water vapor continuum
• Also more sensitive to cloud liquid water and water vapor scale height
• Hybrid concept developed to use high-frequency channels near land with a dynamically trained retrieval algorithm – referenced to AMR low frequency channels

• Standard low-frequency channels (18-34 GHz) used for PD retrieval in open ocean (> 30 km from land)
• High-frequency window channels, 90, 130 and 166 GHz used to continue PD measurement to ~3km from land

\[
PD_{HF} = c_o + \sum_{i=1}^{N_t} c_i T_{Bi}
\]

where \( \hat{c} = \left( A^T A \right)^{-1} A^T PD_{LF} \)
Simulations show PD retrieval error < 7mm to within 3 km from coast in a global average sense.
West Coast Field Campaign November 2014

Observations at 150m spatial resolution
• First retrieved PD over the ocean using low-frequency 18-34 GHz channels

• Then, dynamically trained HF algorithm along track using 100km of along track data and evaluated performance over next 100km

• Evaluated performance by comparing to low-frequency “true” PD over next 100km
HF Retrieval Examples
• PD error as a function of extrapolation distance computed for both HF algorithm and for using last valid PD value

• Although dataset is limited, the HF algorithm performance is consistent with the simulated performance estimate

• Open ocean performance can be achieved in the coastal zone (<50km) with high frequency channels
• We have made significant progress over the past 25 years to align the radiometer capability to the expectations of the science users.

• Sentinel-6 AMR-C represents a significant advancement for both improving the GMSL trend measurement and for coastal altimetry.
• AMR-C merges two existing calibration approaches for satellite-borne microwave radiometers to produce a level of performance superior to either approach alone
  – External calibration approach excellent for maintaining long term stability
    • e.g. AMSU, AMSR-E, SSM/I, SSMIS, WindSat, MSU
    • 0.01 K long term TB stability estimated for MSU (Spencer et al., 1990): ~0.01 mm/yr
  – Internal calibration approach excellent for maintaining short term stability
    • e.g. Jason 1/2, Sentinel, GFO, Envisat, ERS, Topex
  – Combining both approaches gives stable calibration on all times scales from seconds to decades
    • AMR-C

• Highlights of AMR-C design and improvements from Jason-2 AMR
  – End-to-end calibration with traceable external calibration standards viewed through the feed for long term calibration (> 10 days)
  – High quality internal calibration sources for short time scale calibration (< 10 days)
  – Improved thermal stability