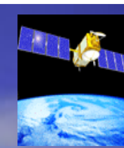
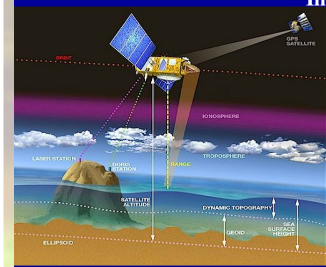
Assessment of Revised TOPEX/Jason Global and Regional Mean Sea Level Estimates Referenced to ITRF2014



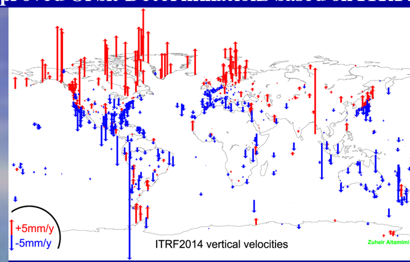
B. D. Beckley, N. P. Zelensky, Xu Yang, M. Ricko - SGT, Inc.
F. G. Lemoine, R.D. Ray, B.D. Loomis - NASA/GSFC
R. S. Nerem – Univ. of Colorado
G. T. Mitchum - Univ. of S. Florida

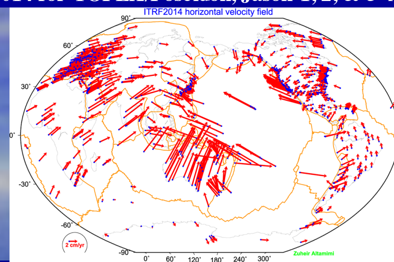
Abstract: The terrestrial reference frame is the foundation for analysis and interpretation of Earth science observations, especially for data from ocean radar altimeter satellites. The accuracy of the coordinates as well as the consistency of the technique solutions within an ITRF affect the accuracy with which orbits are computed, and map into the accuracy of the estimates for global mean sea level (GMSL). The recent launch of Jason-3 offers the possibility of continuing GMSL monitoring well into the next decade. In an effort to provide a consistent TOPEX/Jason altimeter sea surface height (SSH) time series and seamless transition to Jason-3, we have generated orbits for the entire time span based on the revised ITRF2014 terrestrial reference frame. We report the efficacy of the revised terrestrial reference frame towards improving precise orbit determinations leading to the development of the NASA MEaSUREs (Making Earth System Data Records for Use in Research Environments) V4.0 revised sea surface height Climate Data Record. We provide an assessment of recent improvements to the accuracy of the 25-year SSH time series, describe continuing calibration/validation activities, and evaluate the subsequent impact on current global and regional mean sea level estimates.

Improved Orbit Determinations based on ITRF2014 for TOPEX/Poseidon, Jason-1, 2, & 3 Altimetry

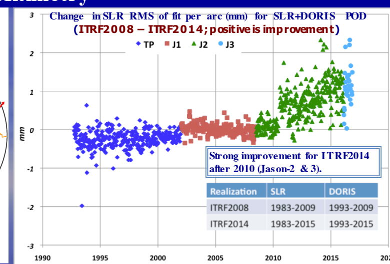


A precise geodetic reference frame and precise orbit determination (POD) are a fundamental science requirement for monitoring sea level change from satellite altimetry.





Revised GSFC replacement orbits (std1504_dpod2014) have been generated for the entire TOPEX/Jason altimetric time series based on a new release of the International Terrestrial Reference Frame ITRF2014. Improvements over the prior ITRF2008 is realized by the "extended observation history of the four space geodetic techniques (very long baseline interferometry (VLBI), satellite laser ranging (SLR), Global Navigation Satellite Systems (GNSS), and Doppler orbitography and radiopositioning integrated by satellite (DORIS), as well as an enhanced modeling of nonlinear station motions, including seasonal (annual and semiannual) signals of station positions and postseismic deformation for sites that were subject to major earthquakes" (*Altamimi et al., 2016*). Images above (from *Altamimi et al., 2016*) show the tracking stations vertical and horizontal velocities with formal error less than 0.2 mm/y.



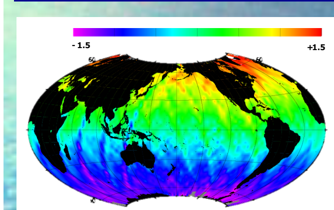
Realization	SLR	DORIS
ITRF2008	1983-2009	1993-2009
ITRF2014	1983-2015	1993-2015

For altimetric satellite POD outside the "station solution interval" (1979 to 2008 for ITRF2008), the tracking station coordinates must be extrapolated. It is in this "extrapolation period" that we can see increasing degradation in tracking data fits and the resultant orbits based on ITRF2008, which can include potential drift error. We have evaluated ITRF2014 and compared its performance to ITRF2008 (*Zelensky et al., 2017*). We see an improvement in the Satellite Laser Ranging Data RMS of fits per 10-day arc of 1-2 mm for ITRF2014 after 2010.

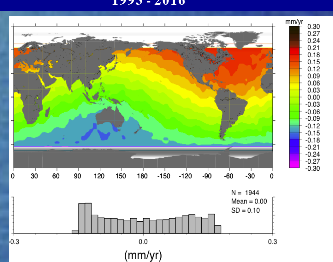
Global and Regional Mean Sea Level Estimates Referenced to ITRF2014

Regional Sea Level Trend Differences

ITRF2008 minus CSR-95 based orbits 1993 – 2002

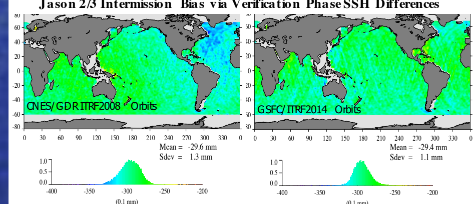


ITRF2014 minus ITRF2008 based orbits 1993 - 2016

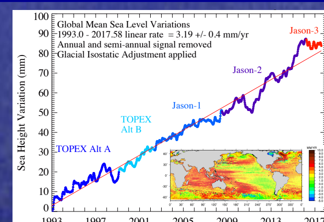


The images above show the impact of outdated and/or inconsistent terrestrial reference frames on regional sea level estimates. The left image (*update of Beckley et al., 2007*) shows zonal sea level trend differences exceeding 1.5 mm/y when T/P orbits based on CSR95 reference frame are employed as compared to orbits based on ITRF2008. The right image (note ± 0.3 mm/y color scale) shows expected regional sea level trend differences over the 1993-2016 period when orbits are based on ITRF2014 versus ITRF2008. A standard deviation of 0.1 mm/y provides a stability metric for the most recent ITRF (*Zelensky et al., 2017*).

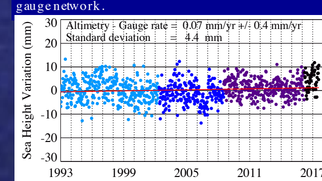
Jason 2/3 Intermission Bias via Verification Phase SSH Differences



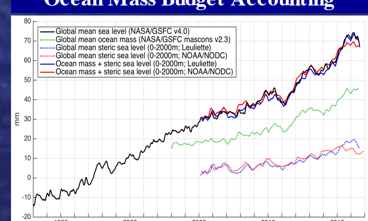
Accurate measures of GMSL derived from multi-mission altimetry requires accurate estimates of global inter-mission biases. As seen in the Jason-3 Jason-2 SSH residuals during the Jason-3 verification phase, the revised GSFC orbits based on ITRF2014 further reduce geographically correlated errors, when compared to the CNES GDR ITRF2008-based orbits.



Global mean sea level variations from 1993 to early 2017 are estimated from NASA MEaSUREs v4.0 altimetry based on ITRF2014 using SLR & DORIS-based orbits. The red line is the linear fit to the SSH variations after removal of annual and semi-annual signal and application of GIA. Note, the TOPEX cal-1 mode range correction is not applied. The inset image shows the regional sea level trends over the same period. The image below shows a comparison of altimeter SSH variations compared to a 64-site tide gauge network.

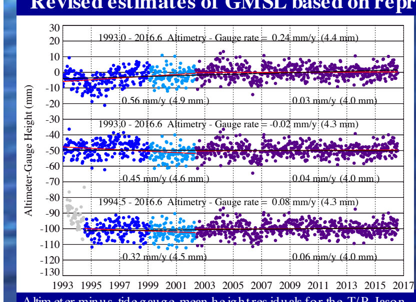


Ocean Mass Budget Accounting



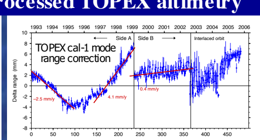
NASA MEaSUREs v4.0 GMSL (https://climate.nasa.gov) variations are compared to sum total of ocean mass+steric variations in an accounting towards mass budget closure (top image). The above image shows the total ocean mass variations derived from GRACE GSFC Mascons v2.3 (*Luthcke et al., 2015*) and the steric component derived from two separate ARGO processing sources.

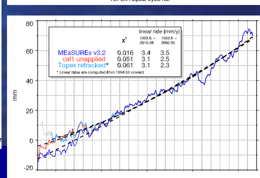
Revised estimates of GMSL based on reprocessed TOPEX altimetry

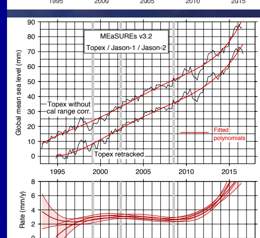


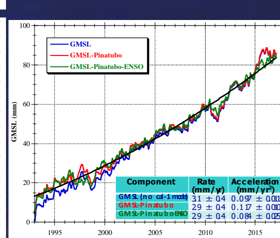
Altimeter minus tide gauge mean height residuals for the T/P, Jason-1, and Jason-2 sea-surface height time series (above image), following methodology of *Mitchum (2000)*. Linear rates and standard deviation of residuals (in brackets) are reported for TOPEX Side-A (dark blue) and Side-B (light blue), and for Jason-1 and -2 combined (purple). (Top): MEaSUREs v3.2, which has TOPEX cal-mode range correction (see top right image) applied to both TOPEX Sides A and B. (Middle): MEaSUREs v3.2 with TOPEX Side A and B cal-mode correction unapplied. (Bottom): TOPEX heights based on retracked waveform data. Early cycles (gray dots) are excluded from all comparison statistics.

GMSL estimates for each of the three solutions are shown in middle image at right. Black dashed lines are quadratic fits to the three SSH curves. Revised GMSL estimates (*Beckley et al., 2017*) agree with recent works by *Watson et al. (2015)* and *Dieng et al. (2017)* noting that current estimates are believed to be closer to 3.0 than 3.5 mm/y.









Component	Rate (mm/yr)	Acceleration (mm/yr²)
GMSL (no cal-1 mode)	3.1 ± 0.4	0.097 ± 0.011
GMSL-Pinatubo	2.9 ± 0.4	0.117 ± 0.010
GMSL-Pinatubo-ENSO	2.9 ± 0.4	0.084 ± 0.025

Bottom right image: Global mean sea level from TOPEX, Jason-1, and Jason-2 altimetry, for the two time series with revised TOPEX data, seasonal cycle removed. The two curves are offset by 15 mm for plotting purposes. The red curves are polynomials fitted to the sea-level curves. The order of the polynomials is selected according to the Akaike Information Criterion (AIC) [*von Storch and Zwiers, 1999*]. Grey vertical bars mark transitions between altimeters: TOPEX A-B, TOPEX B-Jason1, Jason1-Jason2. (Bottom panel) Derivatives, analytically evaluated, for the fitted polynomials of top panel. Background shading represents 1-σ. Implied rates of sea-level rise hovered around 3 mm/y for most of the two-decade time series, but the rates have markedly increased over the past few years. Recent work by *Nerem et al. (2017)* have attempted to isolate the climate-driven acceleration of GMSL change by accounting for the impacts of the Mount Pinatubo volcanic eruption and ENSO events.

References

Altamimi, Z., P. Rebischung, L. Métivier, and X. Collilieux (2016). ITRF2014: A new release of the International Terrestrial Reference Frame modeling nonlinear station motions, J. Geophys. Res. Solid Earth, 121, 6109–6131. doi:10.1002/2016JB013098.

Beckley, B.D., P.S. Callahan, D.W. Hancock, G.T. Mitchum, and R.D. Ray (2017). On the "cal mode" correction to TOPEX satellite altimetry and its effect on the global mean sea-level time series, J. Geophys. Res-Oceans, 122. doi:10.1002/2017JC013090

Beckley, B. D., N. P. Zelensky, S. A. Holmes, F. G. Lemoine, R. D. Ray, G. T. Mitchum, S. Desai, S. T. Brown (2010), Assessment of the Jason-2 extension to the TOPEX/Poseidon, Jason-1 sea-surface height time series for global mean sea level monitoring, *Marine Geod., 33(S1)*, 447–471, doi: 10.1080/01490419.2010.491029.

Beckley, B. D., F. G. Lemoine, S. B. Luthcke, R. D. Ray, and N. P. Zelensky (2007), A reassessment of global and regional mean sea level trends from TOPEX and Jason-1 altimetry based on revised reference frame and orbits, *Geophys. Res. Lett.*, 34, L14608.

Boening, C., J. K. Willis, F. W. Landerer, R. S. Nerem, and J. Fasullo (2012), The 2011 La Niña: So strong, the oceans fell, *Geophys. Res. Lett.*, 39, L19602, doi:10.1029/2012GL053055.

Dieng, H. B., A. Cazenave, B. Meyssignac, and M. Ablain (2017). New estimate of the current rate of sea level rise from a sea level budget approach, Geophys. Res. Lett., 44, doi:10.1002/2017GL073308.

Luthcke, S.B., D.D. Rowlands, T.J. Sabaka, B.D. Loomis, M. Horwath, and A.A. Arendt (2015), Chapter 10: "Gravimetry measurements from space," **Remote Sensing of the Cryosphere**, Ed. M. Tedesco, Oxford, Wiley Blackwell, ISBN 9781118368855, pp. 231-247.

Mitchum, G. T. (2000), An improved calibration of satellite altimetric heights using tide gauge sea levels with adjustment for land motion, *Marine Geodesy*, 23, 145–166.

Nerem, R.S., B. D. Beckley, J. Fasullo, B. D. Hamlington, D. Masters, and G.T. Mitchum (2017), Climate Change Driven Accelerated Sea Level Rise Detected In The Altimeter Era, Proceedings of the National Academy of Sciences (in review).

Von Storch, H., and F. W. Zwiers (1999), Statistical Analysis in Climate Research, Cambridge Univ. Press, Cambridge.

Watson, C.S., N.J. White, J.A. Church, M.A. King, R.J. Burgette, and B. Legresy (2015). Unabated global mean sea-level rise over the satellite altimeter era, Nature Clim. Change, 5, 565–568, doi:10.1038/nclimate2635.

Zelensky, N.P., et al. Impact of ITRS 2014 realizations on altimeter satellite precise orbit determination. Adv. Space Res. (2017), doi:10.1016/j.asr.2017.07.044.

This work is performed thanks to support by NASA through the Sea Level Science Team, Ocean Surface Topography Science Team (OSTST), and MEaSUREs funding.

2017 Ocean Surface Topography Science Team Meeting, October 23-27, 2017, Miami, Florida, USA