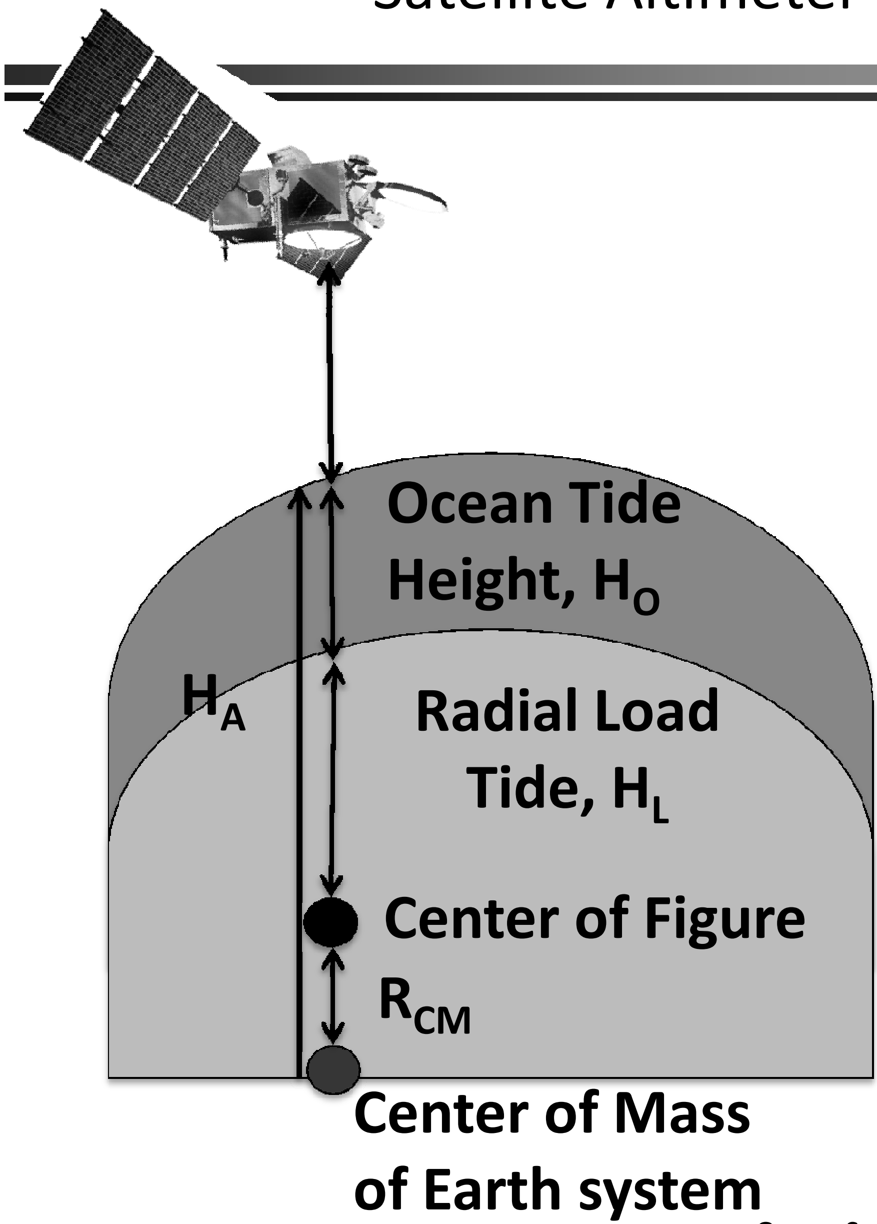
Introduction

- Tidal geocenter motion previously ignored when developing ocean tide models from satellite altimetry.
  - Since first Geosat model, e.g., Cartwright and Ray (1991).
- Especially important when comparing ocean tide heights observed by satellite altimetry with in-situ measurements.
- Tide gauges and ocean bottom pressure recorders observe displacement of sea surface with respect to ocean bottom.
- Satellite altimeters observe sea surface height with respect to frame origin of orbital position of the satellite.
  - Natural satellite orbital motion is about the center of mass of the total Earth system.
  - **Center of mass of the total Earth system, including ocean tides, is frame origin of altimetric sea surface heights…at least for tides.**

Satellite Altimeter Observations of Ocean Tides



- Altimeter observations, H_A:

  $$\mathbf{H_A = H_O + H_L + R_{cm}}$$

- **H_O** = Ocean tide height relative to crust.
  - E.g., tide gauge observation.
  - Reflects mass of displaced water only.
- **H_L** = Radial load tide.
  - Ocean tide mass load causes displacements in Earth's crust.
- **R_{CM} = Geocenter motion (radial).**
  - **Ignored for > 20 years.**
  - Ocean tide mass causes relative motion between center of mass of total Earth system and crust-fixed frame.
- Body tide.
  - Typically modeled: model accuracy ≤ 1 mm.
  - Error smaller than geocenter motion.
  - Ignored here.

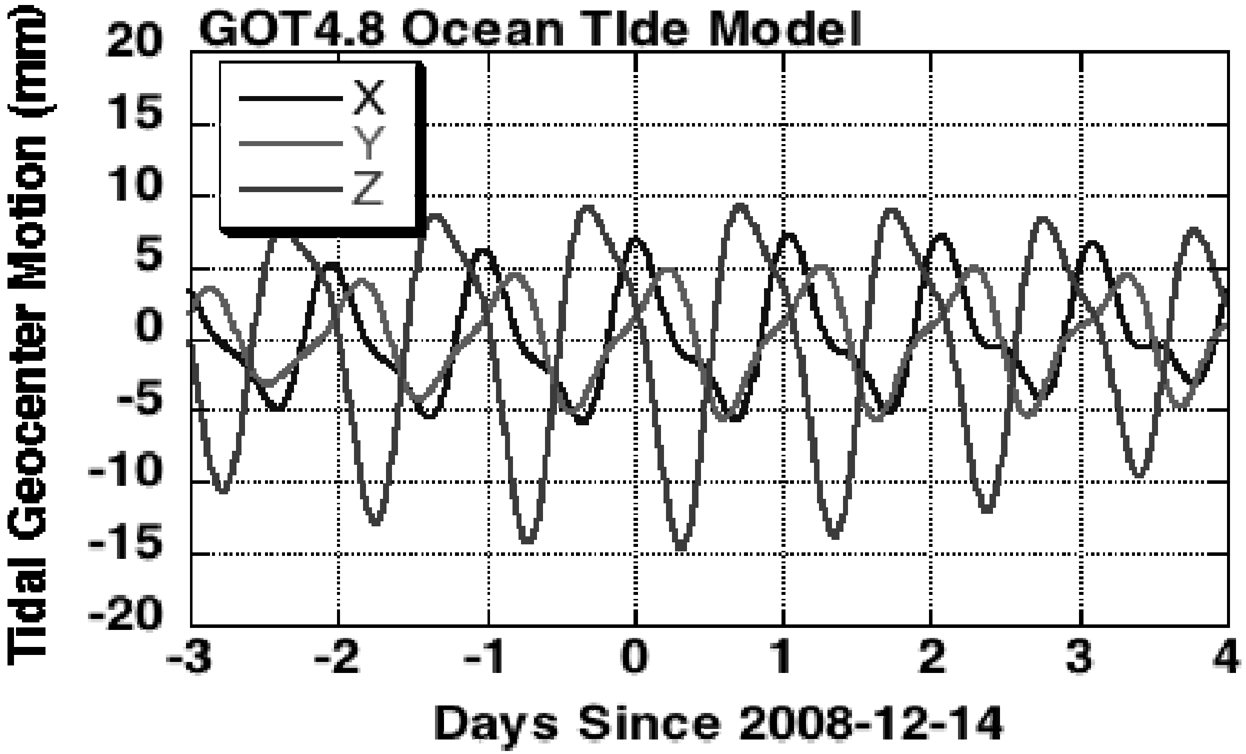
Who is Affected?

- **No impact from ignoring tidal geocenter motion for most altimeter users.**
  - **IF** applying an altimeter-based model to the altimeter sea surface heights.
  - These users need consistent model of ocean tide height relative to frame origin of orbital position, H_A.
- Users requiring accounting of tidal geocenter motion for correct extraction of ocean tide height relative to Earth's crust, H_O:
  - **Geodesists**: need model of mass redistribution from only oceans.
    - Apply to models of tidal potential, Earth orientation parameters, load tide displacements, geocenter motion.
    - Geocenter error primarily affects degree 1 spherical harmonic component.
      - Impact on tidal potential (e.g., GRACE) and Earth orientation models is small.
  - **Ocean tide modelers**: need consistency between altimeter and in-situ measurements.
    - In-situ measurements are relative to Earth's crust.

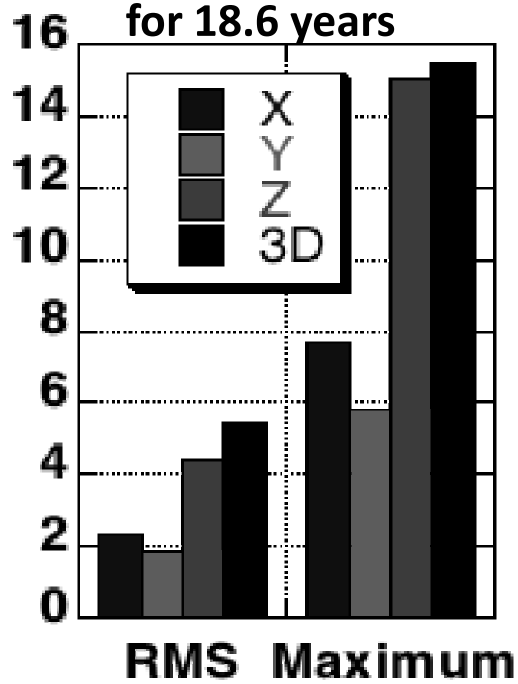
Separating Ocean, Load, and Geocenter

- Model ocean tide as spherical harmonic expansion.
  - $H_O = \Sigma_n H_n$
- Altimeter observations can then be expressed:
  - $$\left.\begin{aligned} H_A &= H_O + H_L \quad \mathbf{+\, r_{cm}} \\ &= \Sigma_n H_n + \Sigma_n(h'_n K_n)H_n \quad \mathbf{-\, K_1 H_1} \\ &= \Sigma_n(1+h'_n K_n)H_n \quad \mathbf{-\, K_1 H_1} \\ &= \Sigma_{n>1}(1+h'_n K_n)H_n + (1 + (h'_1 \mathbf{-\, 1})K_1)H_1 \end{aligned}\right\} \quad \textbf{Geocenter Contribution}$$
  - h'_n = Load Love numbers typically published in crust-fixed frame.
  - K_n = Known scaling factor (function of Earth constants).
- Iterative approaches used to extract ocean tide height relative to crust (H_O) from altimeter measurements (H_A).
- **Geocenter motion easily accounted using effective degree 1 load Love number: (h'_1 – 1).**

Predicted Tidal Geocenter Motion



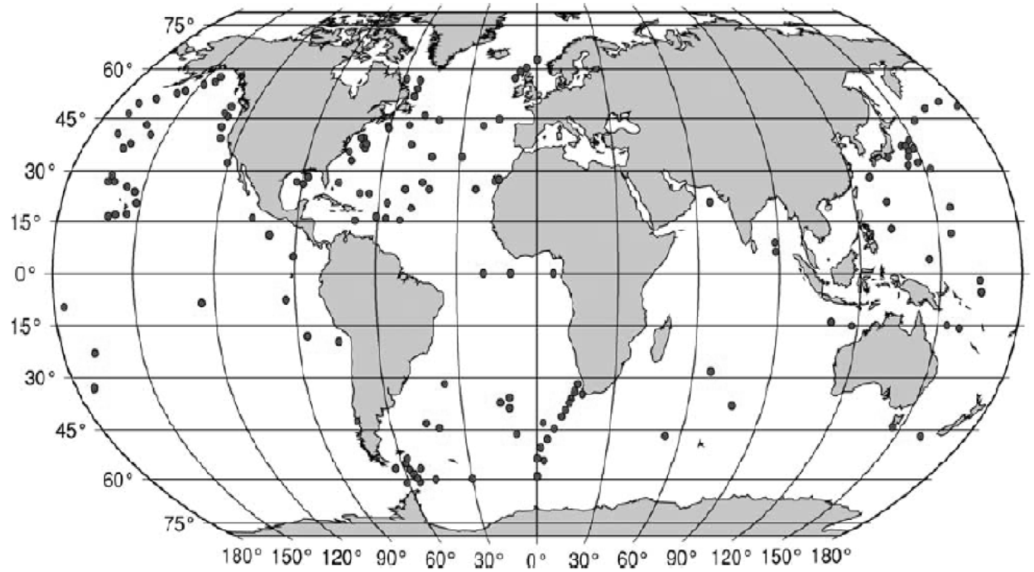
15-min samples for 18.6 years

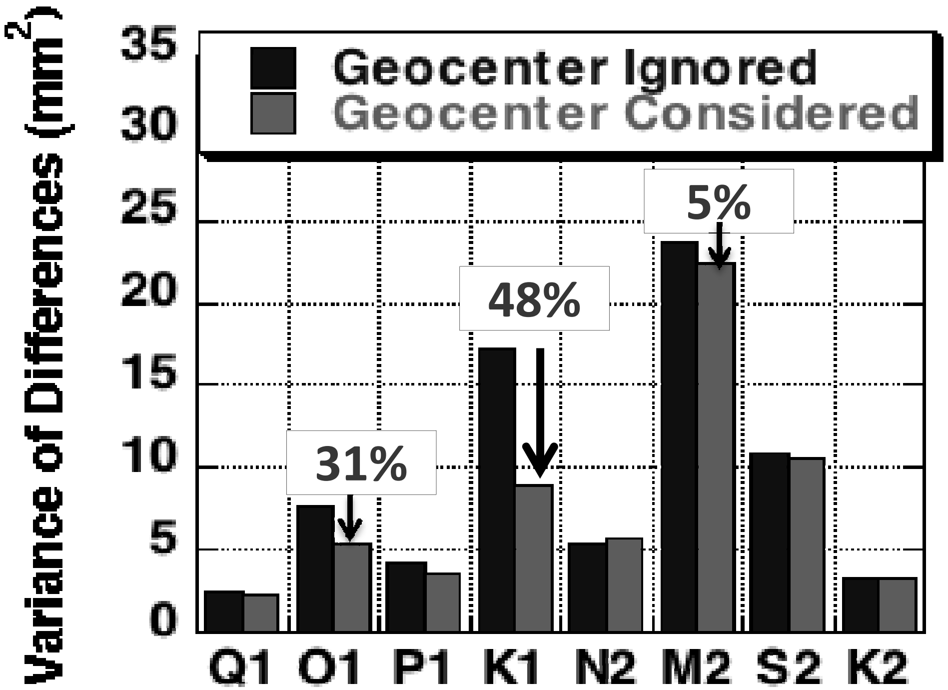


- 3-D tidal geocenter motion as large as 16 mm, RMS < 6 mm.
  – Largest effect is along along Earth's spin axis (Z).
  – Largest contribution from diurnal tides, especially K1 and O1.

Comparison of Altimeter Model to In-Situ Bottom Pressure Recorder Observations

Ray (2013): 151 deep-ocean bottom-pressure stations

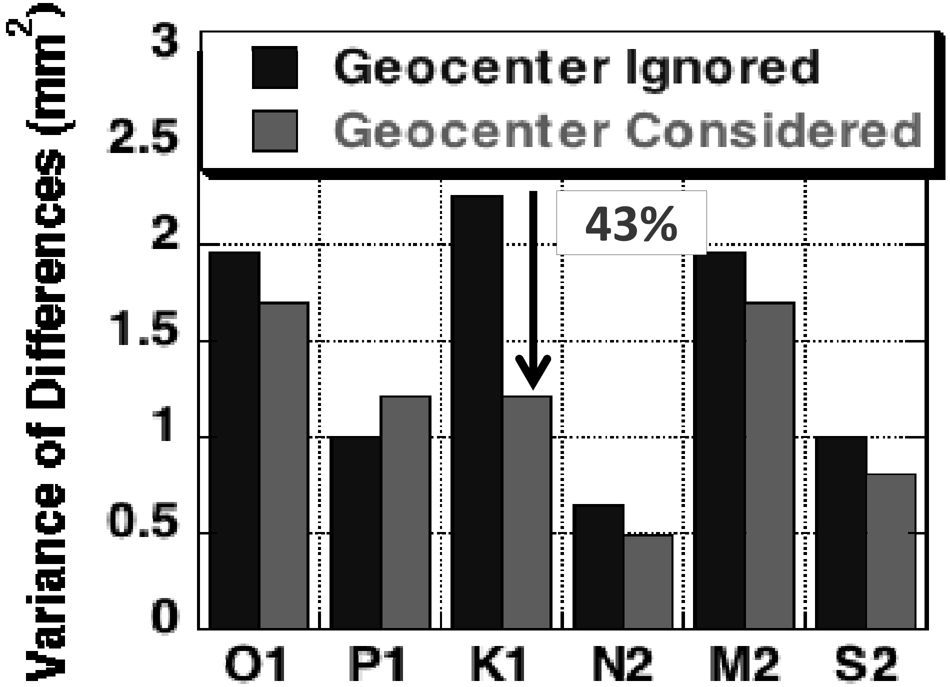




- Consider **GOT4.10 ocean tide model** with and without consideration of geocenter contribution.
  - Mostly empirical model based upon altimetry.
- **Significantly improves comparisons between altimeter and in-situ observations.**
  - Most significant improvement for O1 and K1 components.

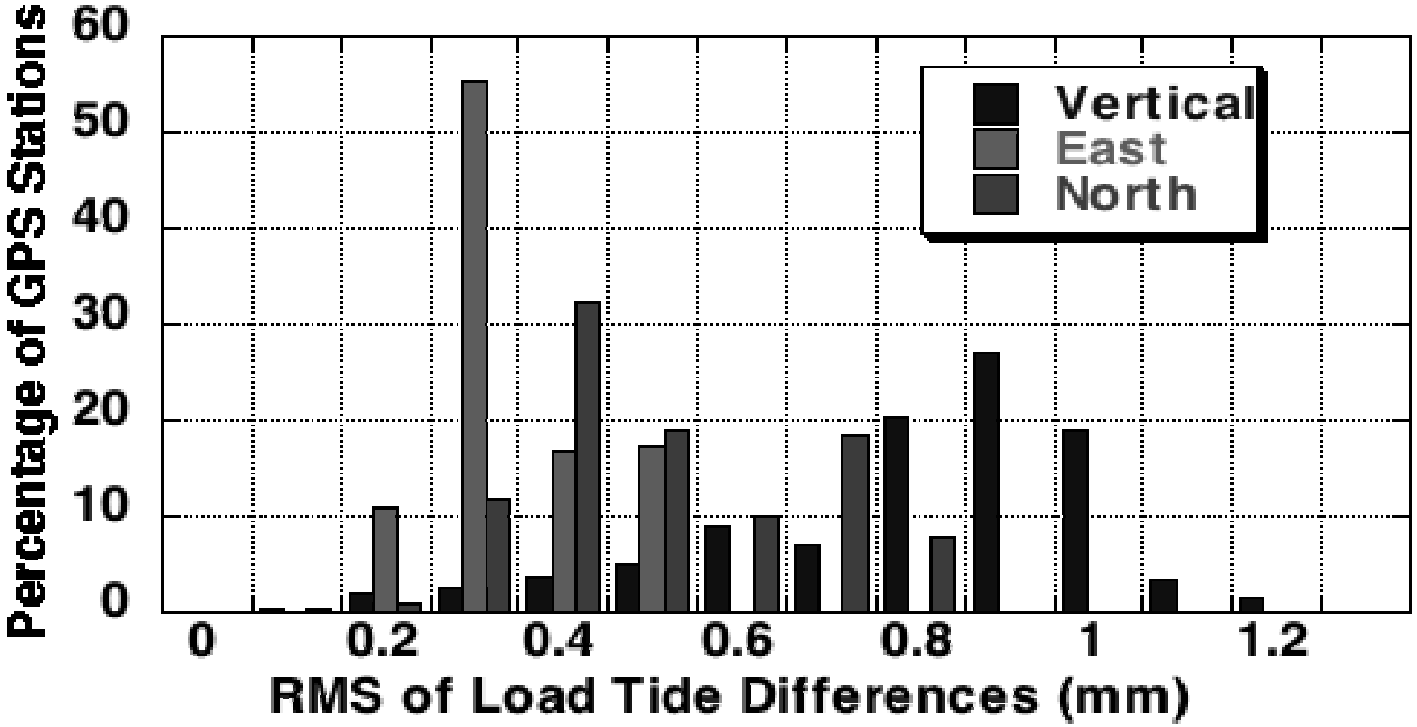
Tidal Geocenter Variations: GOT4.8 Model Prediction Versus SLR Observations

SLR observations from Watkins and Eanes (1997)



- Degree-1 terms of ocean tide linearly correlated with predicted contribution to geocenter motion.
  - Degree-1 components of GOT4.8 ocean tide height model amplified by 15-22% when accounting for geocenter motion in altimeter observations.
  - Phase changes by < 3 degrees.
- **Improved agreement for 5 of 6 primary tidal components.**

Impact on Ocean Load Tide Displacement



- Load tide model computed for ~3800 global GPS stations using GOT4.8 ocean tide model.
  - Differenced predicted effects from ocean tide height model with and without geocenter variations considered.
  - More than 20% have RMS of vertical differences > 1 mm.

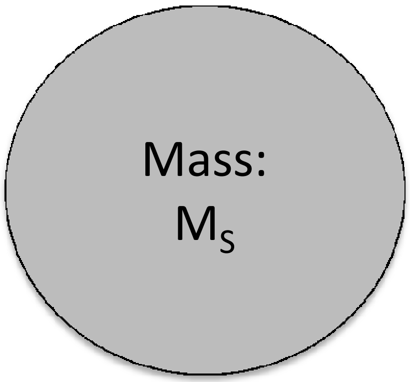
Conclusion

- Accounting for tidal geocenter motion in altimeter ocean tide models provides improved recovery of ocean tide height relative to crust of Earth.
- Evidenced through improved comparison between:
  - Altimeter and in-situ observations of ocean tides.
  - Predicted and observed tidal geocenter motion.
- Improvements primarily in:
  - Diurnal tidal components, especially K1 and O1.
  - Degree 1 spherical harmonic components of ocean tide models.
    - Amplified by 15-22%.
      - Explains improved prediction of tidal geocenter motion.
    - Impact on predicted load tide displacements of stations on crust < 1.5 mm.
- No impact on most users of altimetry sea surface heights.
  - These users need consistent model of ocean tide height relative to frame origin of orbital position (including radial load tide and geocenter motion, as observed).
- Negligible impact on gravity recovery from space (e.g., GRACE) and Earth orientation parameter predictions.
  - Small impact on degree 2 and higher spherical harmonic components of ocean tide model.

Back-Up Slides

Geocenter Motion

Solid Earth
(no surface load)

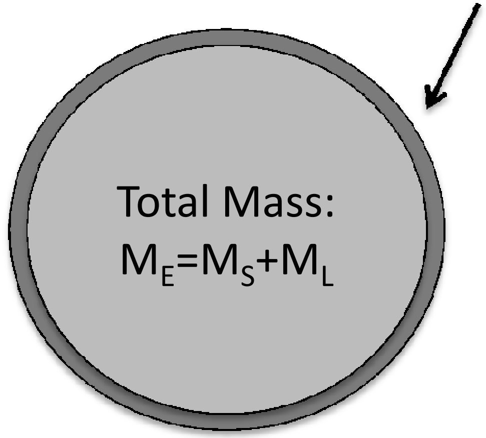


$$M_E\mathbf{r}_{\mathbf{CM}} = M_S\mathbf{r}_{\mathbf{CE}} + M_L\mathbf{r}_{\mathbf{L}}$$

$$\mathbf{r}_{\mathbf{CM}}=(M_L/M_E)\ \mathbf{r}_{\mathbf{L}}$$

$$\mathbf{r}_{\mathbf{CE}}=0 \text{ (Origin of frame)}$$

Total Earth System
(including surface loading mass, M_L)



- Geocenter motion: Relative motion between center of mass of total Earth system ($\mathbf{r}_{\mathbf{CM}}$) and solid Earth ($\mathbf{r}_{\mathbf{CE}}$) (or center of figure).
  - Center of figure (CF) is measurable from station positions.
  - CM-CF motion is 2% larger than CM-CE motion.
- Geocenter motion results from redistribution of surface loading mass (e.g., oceans, atmosphere, hydrology).
  - Center of mass of solid Earth compensates for surface mass redistribution to maintain center of mass of total Earth system in inertial space.