Self-Consistent Treatment of Tidal Variations in the Geocenter for Satellite Geodesy

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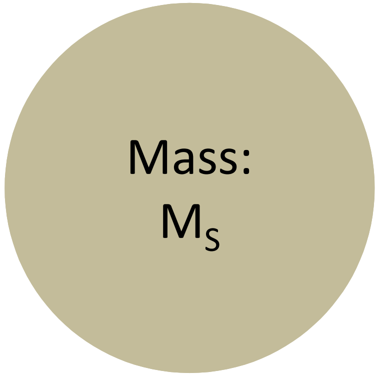
Introduction

- Best available global models of the ocean tides use satellite altimeter measurements of sea surface height.
  - Used to predict ocean tide contribution to various geodetic parameters.
    - E.g., geocenter motion, surface loading displacements, Earth orientation parameters, geopotential
- Tidal geocenter motion previously (25 years) ignored in altimetric ocean tide solutions.
  - Geosat, e.g., Cartwright and Ray (1990)
  - Topex/Poseidon, Jason-1, Jason-2, e.g., Shum et al. (1997), Stammer et al. (2014).
- Geocenter motion contributes to ocean tide height observed by satellite altimeters.
  - Precise orbit determination solutions of satellites.

Geocenter Motion

Solid Earth
(no surface load)

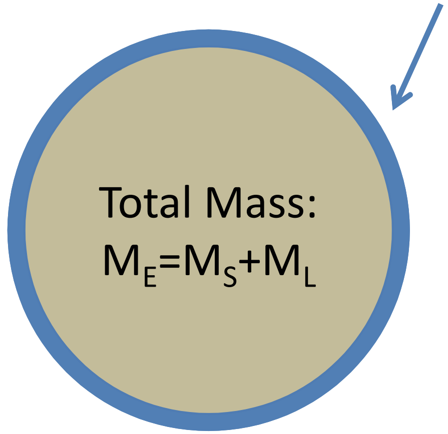


$$M_E\mathbf{r}_{\mathbf{CM}} = M_S\mathbf{r}_{\mathbf{CE}} + M_L\mathbf{r}_{\mathbf{L}}$$

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

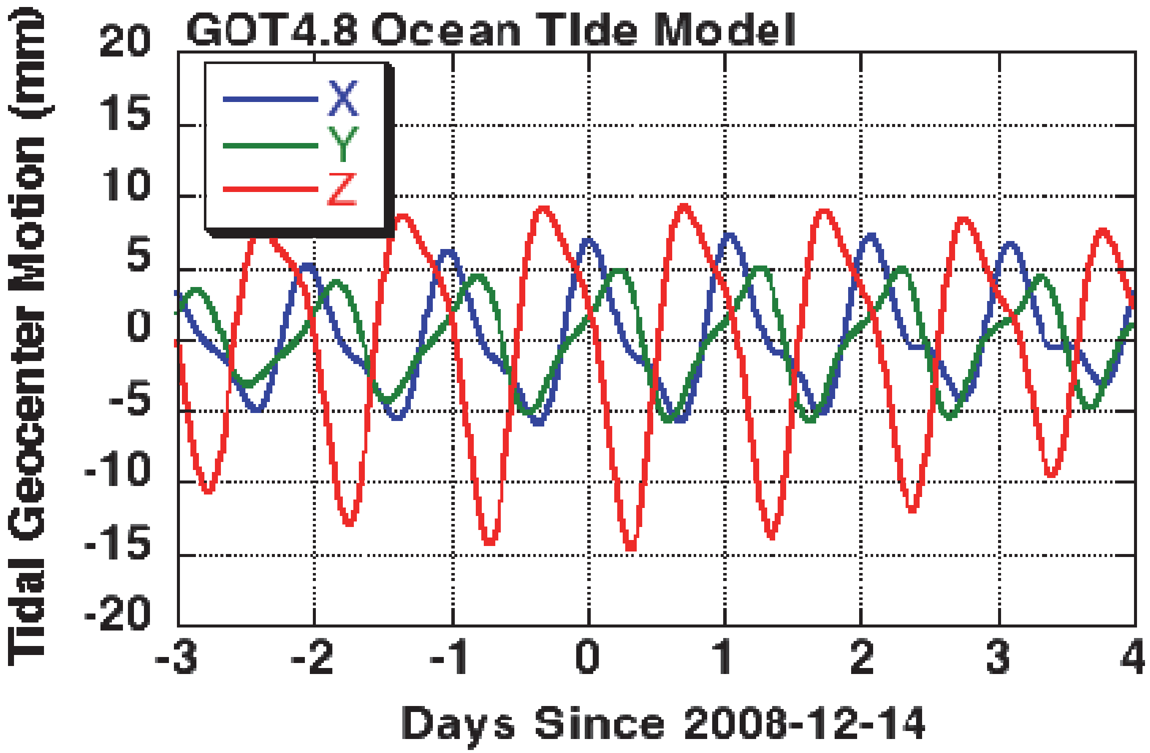
$$\mathbf{r}_{\mathbf{CE}}=0 \text{ (Origin of frame)}$$

Total Earth System
(including surface loading mass, M_L)

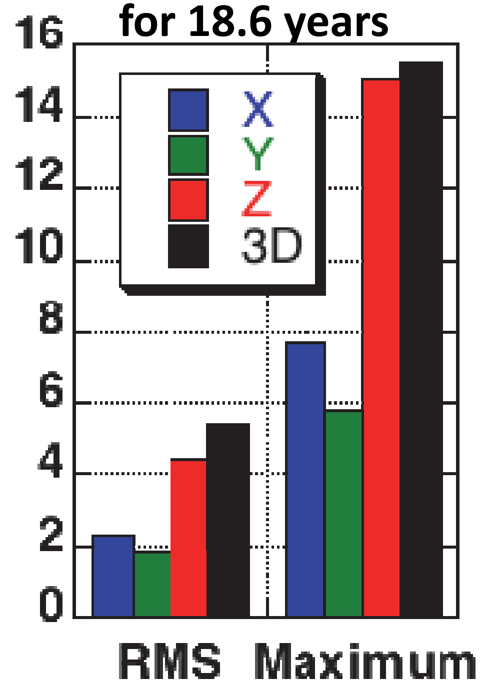


- Geocenter motion: Relative motion between center of mass of total Earth system ($\mathbf{r}_{\mathbf{CM}}$) and solid Earth ($\mathbf{r}_{\mathbf{CE}}$) (or center of figure).
  - Center of figure (CF) is measurable from station positions.
  - CM-CF motion is 2% larger than CM-CE motion.
- Geocenter 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.

Predicted Tidal Geocenter Motion

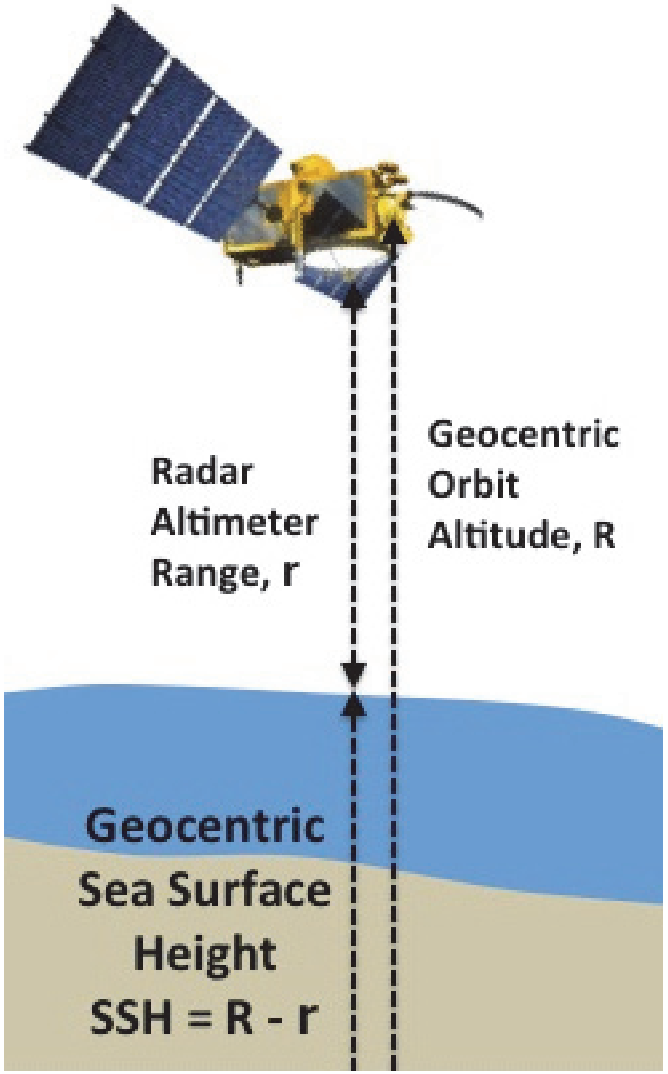


15-min samples for 18.6 years



- 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 (once per sidereal day) and O1.

Satellite Altimeter Sea Surface Observations



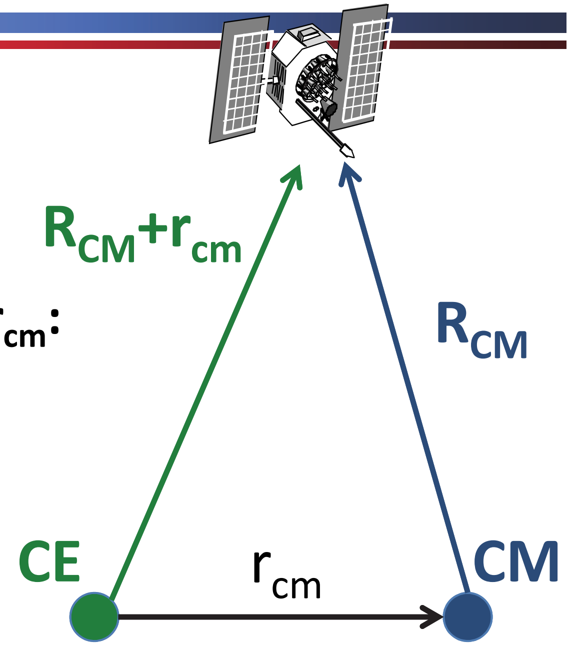
- Frame of altimeter sea surface height measurements is provided by precise orbit determination (POD) solutions.
- Governing equations of satellite orbital motion implicitly tied to center of mass of total Earth system (CM).
  - By necessity in inertial frame.
  - Degree 1 terms of geopotential do not exist in CM frame, and typically ignored in orbit propagation/POD.
- Consistency with tracking stations especially important for tidal effects.
  - Potential for aliasing of diurnal/semi-diurnal tidal geocenter motion.

GPS-Based POD for Jason-2

- Jason-2 POD: < 1 cm radial RMS orbit accuracy.
  - High accuracies reveal subtle effects from geocenter motion.
- Perform GPS-based Jason-2 POD.
  - 4.5 years spanning July 2008 to December 2012.
  - Aim for consistency with equations of motion (CM).
    - E.g., Degree 1 terms of tidal geopotential are zero (as usual).
- Use JPL's IGS08-based orbit/clock products for GPS constellation.
  - Aim for consistency with equations of motion (CM).
    - Degree 1 terms of tidal geopotential are zero (as usual).
    - Load tide displacement at stations referenced to CM.

Three Jason-2 POD Solutions

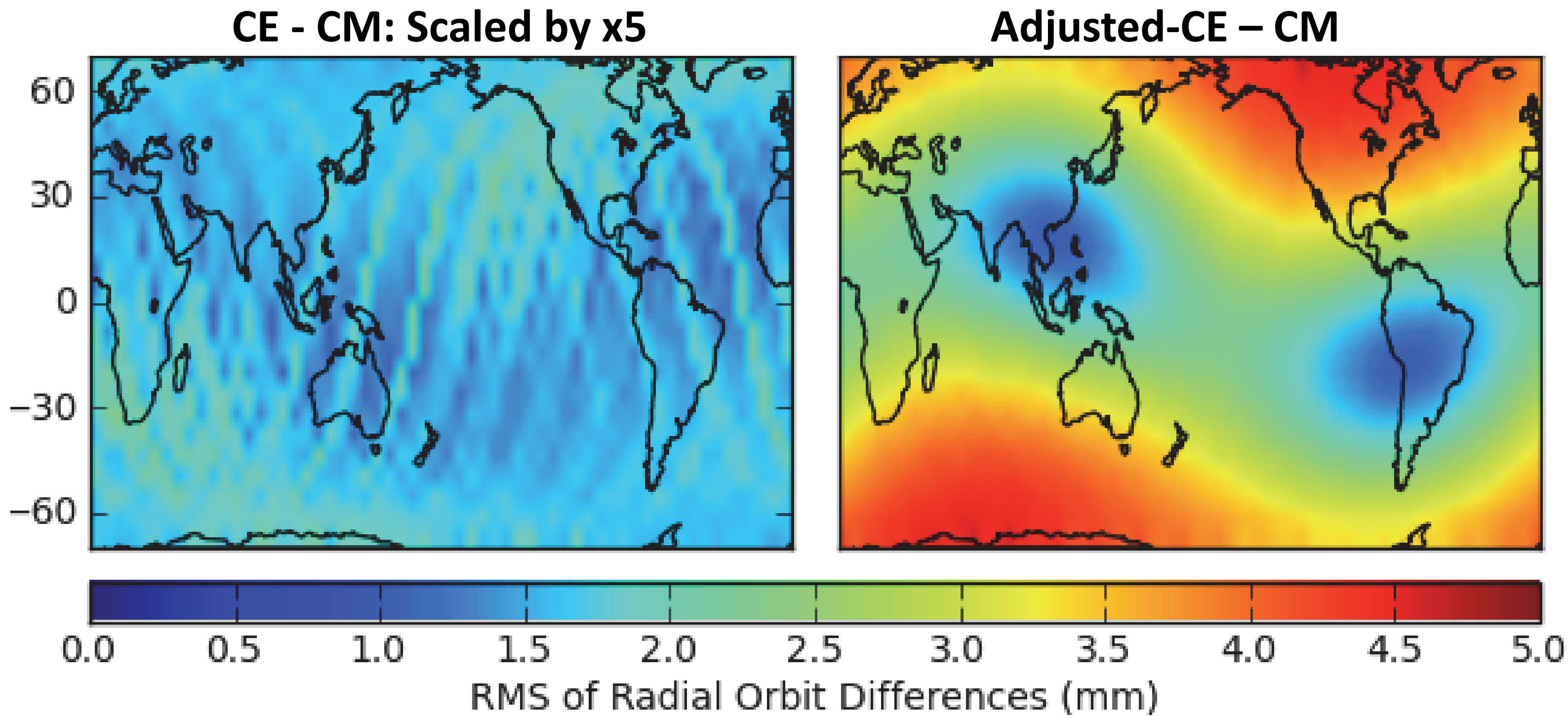
- **Use two GPS orbit/clock products:**
  1. **Exactly as computed (relative to CM): R_{CM}**
     - As provided to JPL's GIPSY users.
  2. **Apply geometric "center of mass correction", $R_{CM}+r_{cm}$:**
     - As delivered to IGS according to IERS/IGS conventions.



- Consider three different Jason-2 orbit ephemerides.

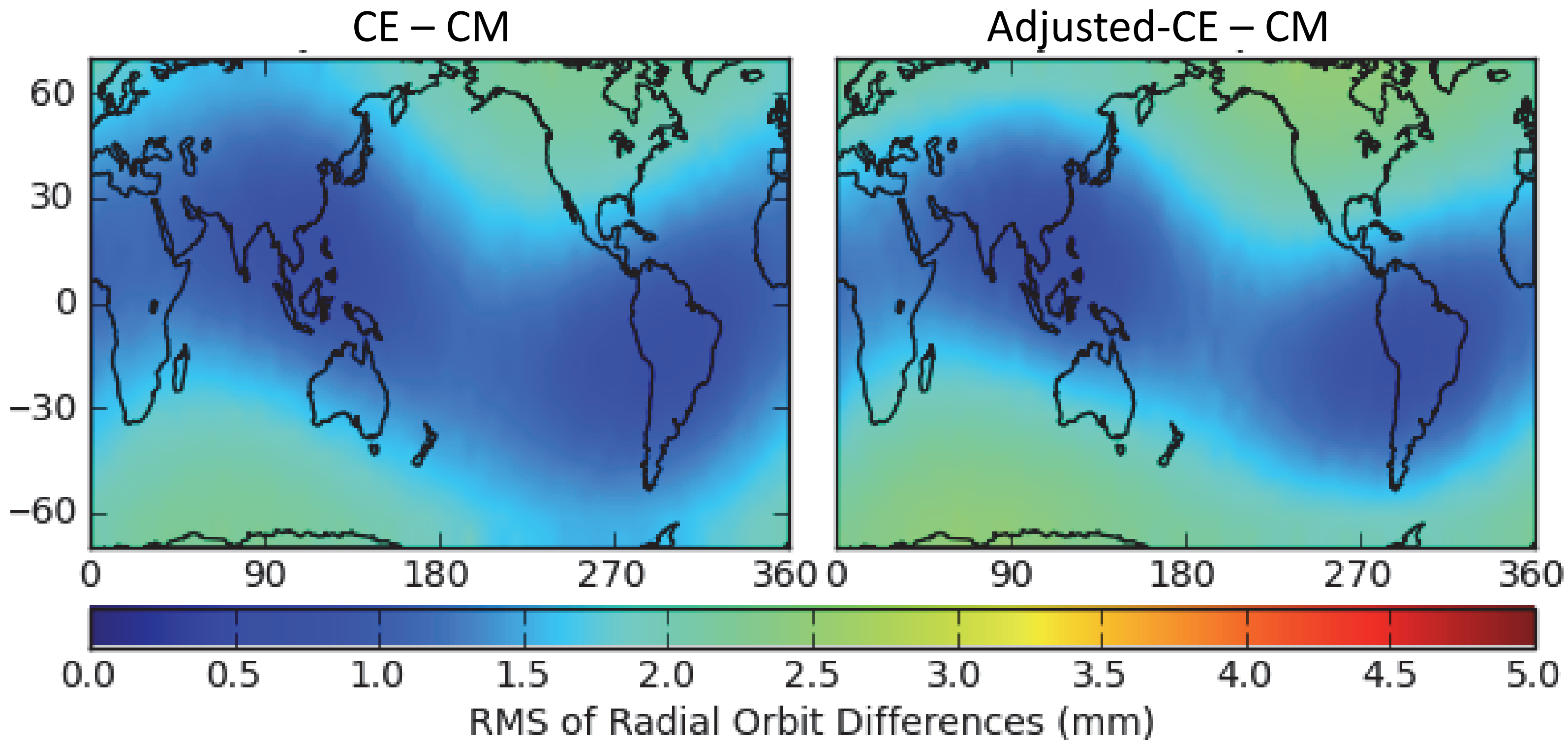
Name of Jason-2 Ephemeris	GPS Orbit Positions and Clocks	Jason-2 Orbit Positions
CM	R_{CM}	**POD solution as computed.**
CE	$R_{CM} + r_{cm}$	POD solution as computed.
Adjusted-CE	$R_{CM} + r_{cm}$	Geometrically adjust CE POD solution by "center of mass correction": e.g., CE POD solution – r_{cm}

Differences of Dynamic Jason-2 Orbit Solutions over 4.5 years



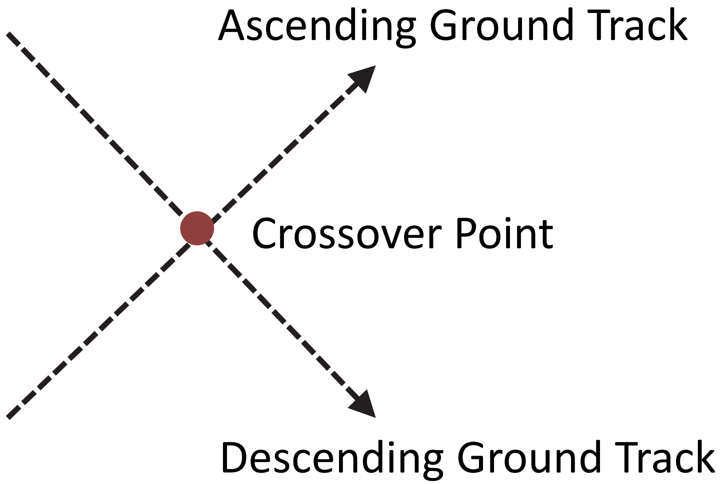
- Dynamic POD solutions favor motion about CM – as expected.
  - “center of mass” correction to GPS satellite orbits reflected in higher post-fit residuals.
- Adjusted-CE vs. CM orbit differences reflect geometric “center of mass” correction.

Differences of Reduced-Dynamic Orbit Solutions over 4.5 years

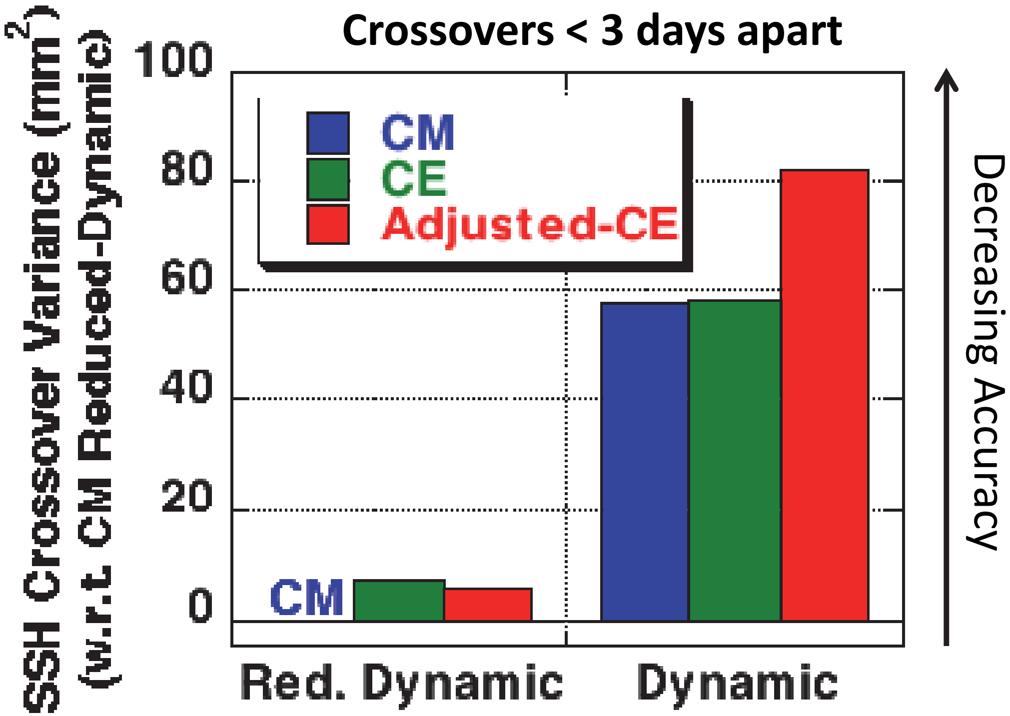


- Reduced-dynamic POD contaminated by inconsistent treatment of tidal geocenter motion.
  - Data (ie. Geometric range) has stronger influence on solution via stochastic accelerations.
  - Fraction of "center of mass" correction contaminates both CE and Adjusted-CE Jason-2 orbit solutions.

Relative Accuracy of POD Solutions

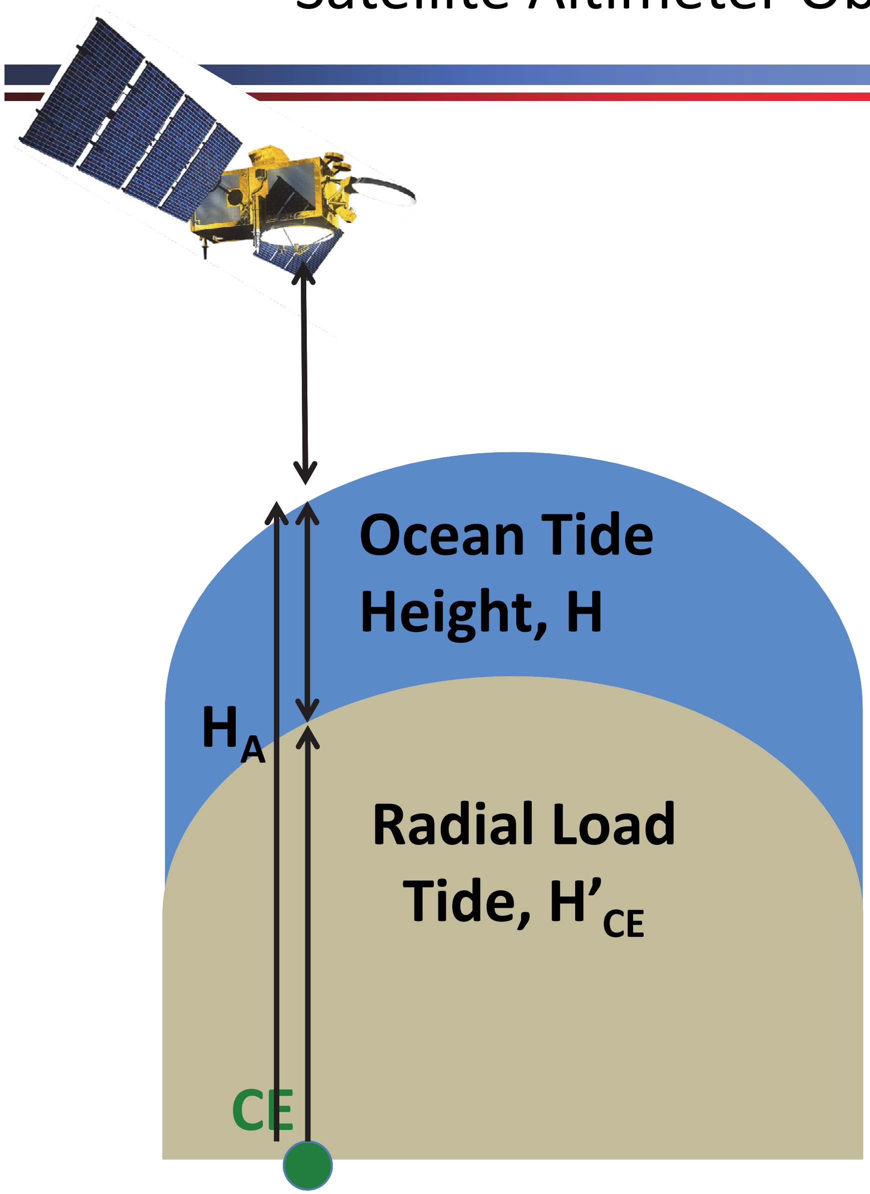


SSH Crossover Difference =
SSH (Ascending Track)
– SSH (Descending Track)



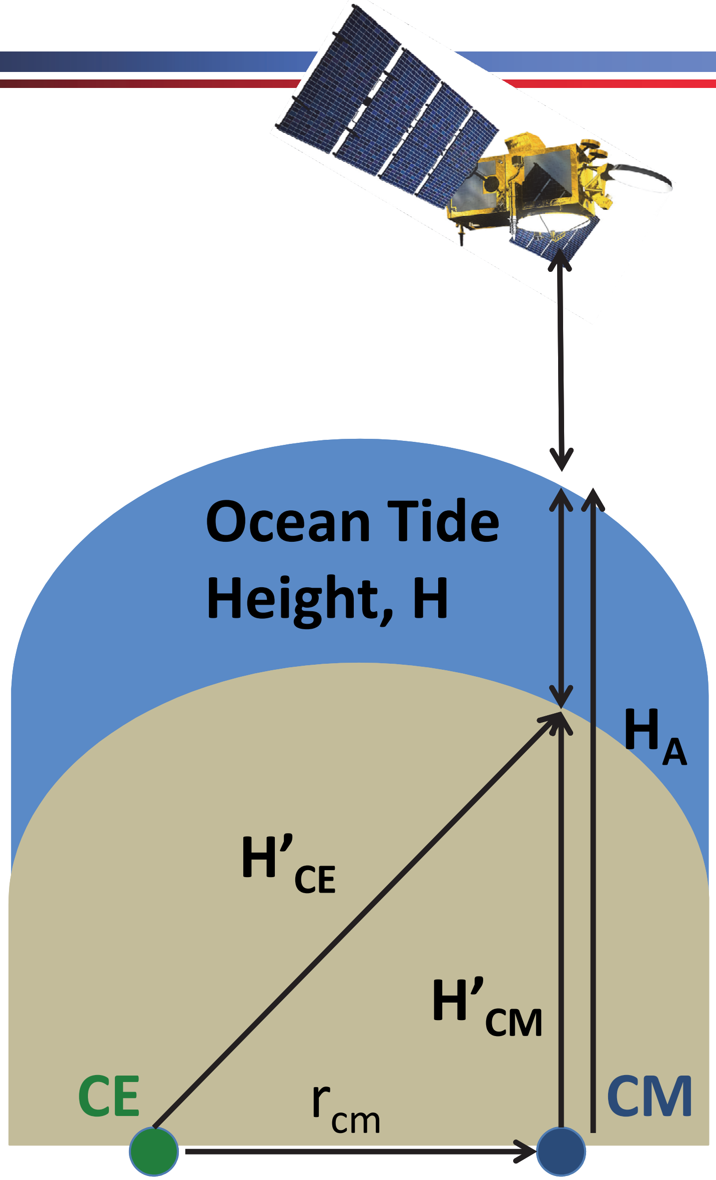
- Sea surface height (SSH) crossover variance provides powerful unbiased measure of relative accuracy of orbit solutions/models.
- **Best POD solutions achieved when pseudo-tracking stations (GPS satellites) and equations of motion consistently referenced to CM.**
- **Dynamic POD solutions mitigate inconsistent treatment of tidal geocenter variations.**

Satellite Altimeter Observations of Ocean Tides



- Body tide known to ≤ 1 mm.
- Ocean tide as spherical harmonic expansion.
  - $H = \Sigma_n H_n$
- Last 25 years of altimetry:
  - Effectively assumed observations relative to CE:
  - $H_A = H + H'_{CE}$
    $= \Sigma_n(1 + h'_n K_n) H_n$
  - h'_n = load Love number.
    - Typically defined relative to CE.
  - Iterative approaches used to separate loading mass (H) from crust's response to load (H'_{CE}).

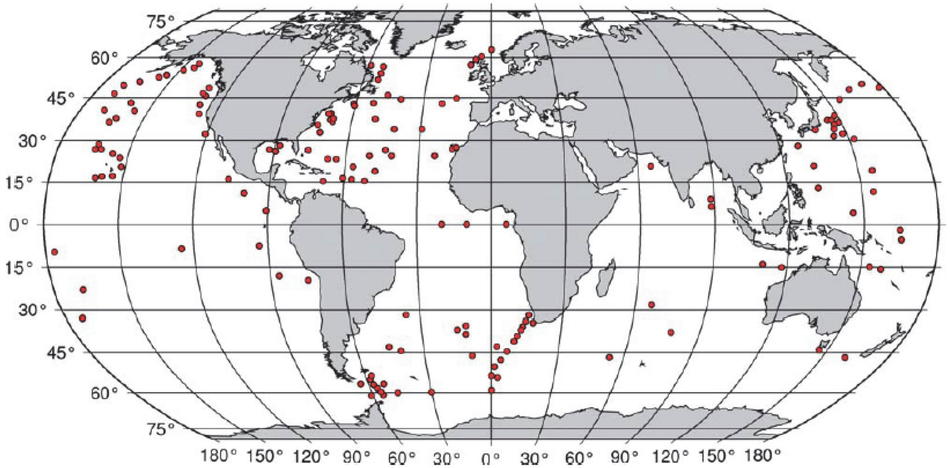
Satellite Altimeter Observations of Ocean Tides

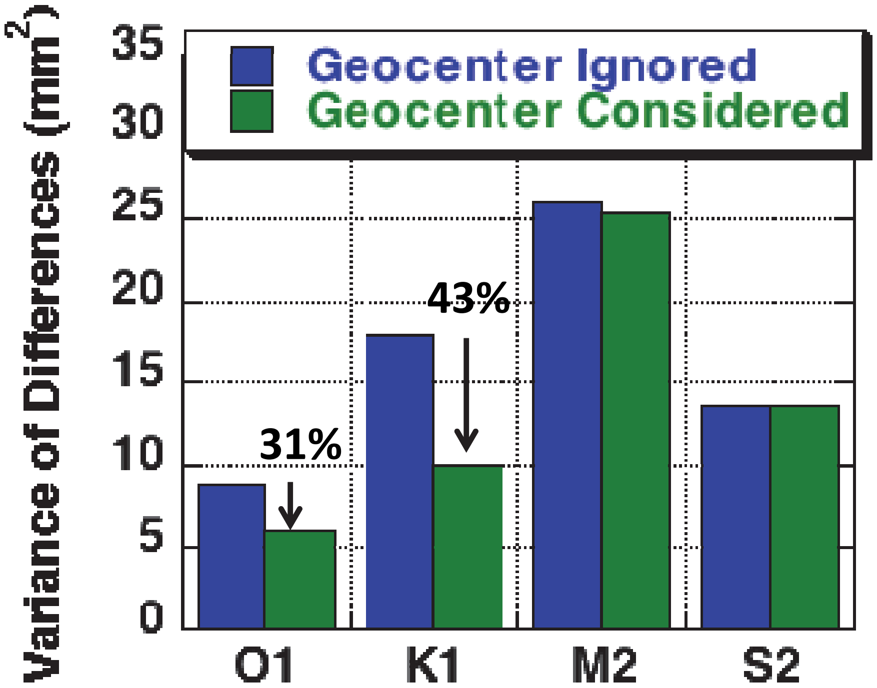


- True mass of load is of interest to geodesy.
- Ocean tide as spherical harmonic expansion.
  - $H = \Sigma_n H_n$
- **Recognize altimeter observations relative to CM:**
  - $H_A = H + H'_{CM}$
    $= H + H'_{CE} - \mathbf{r_{cm}}$
    $= \Sigma_n(1 + h'_n K_n)\, H_n - \mathbf{h'_1 K_1 H_1}$
  - h'_n = load Love number.
  - **Effective degree 1 load Love number of ($h'_1 - 1$) can be used to separate loading mass from crust's response to load.**

Ocean Tide Heights from GOT4.8 Altimetric Model w.r.t. In-Situ Bottom Pressure Recorder Observations

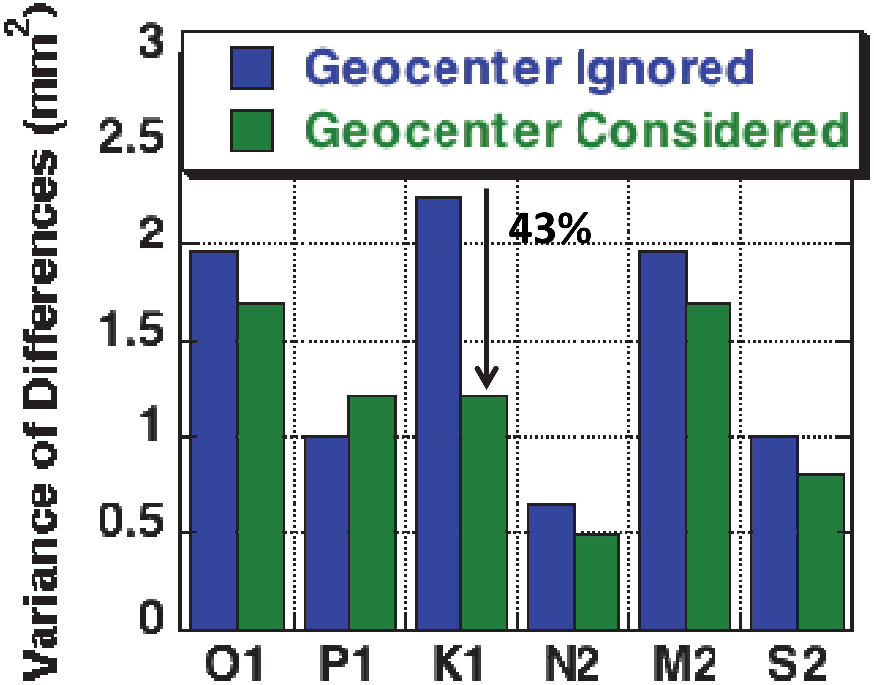
Ray (2013): 151 deep-ocean bottom-pressure stations





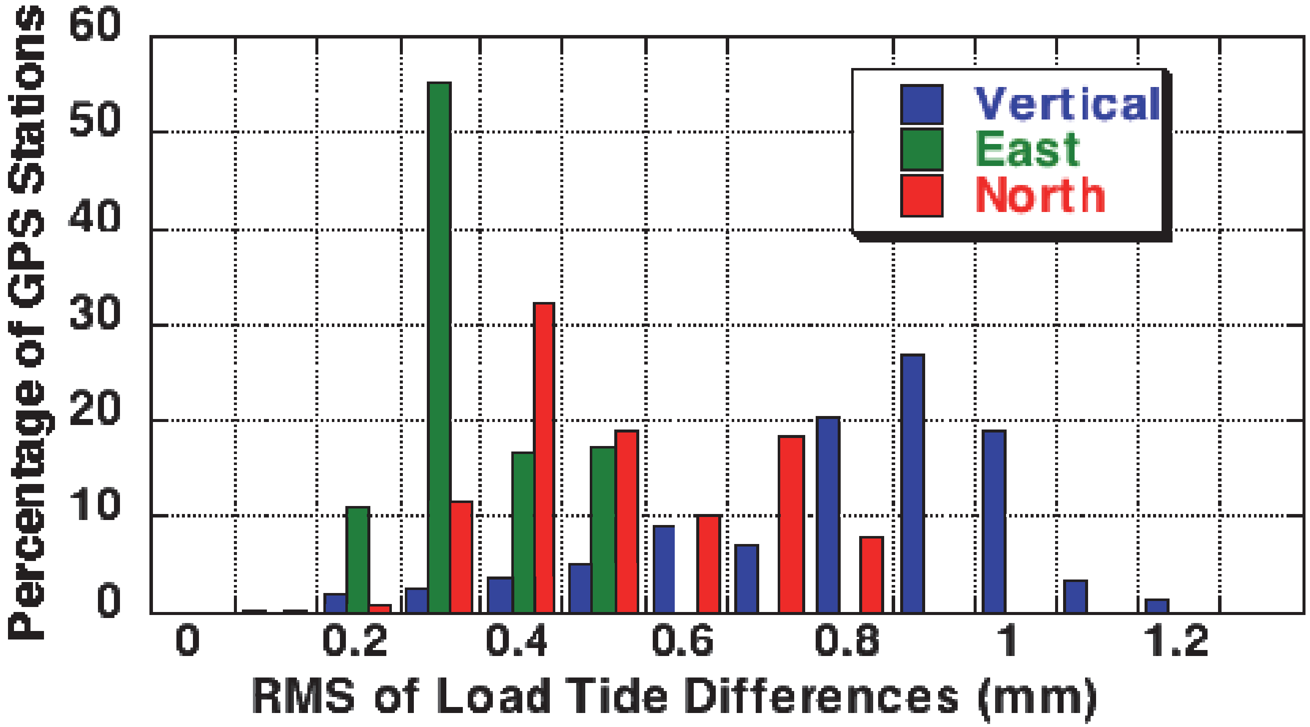
- **GOT4.8 ocean tide model** with/without consideration of geocenter variations.
  - Mostly empirical model based upon altimetry.
  - Sea surface heights derived from dynamic POD solution.
    - Very likely have frame origin of CM.
- **Improves comparisons between altimeter and in-situ observations.**

Tidal Geocenter Variations: Predicted from GOT4.8 Altimeter Model w.r.t. SLR Observations



- Comparison to SLR observations (Watkins and Eanes (1997)) improves for 5 of 6 primary tidal components.
- 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.
  - Degree-1 terms of loading mass linearly correlated with predicted contribution to geocenter motion.

Impact on Ocean Tide Load Tide Displacement



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

Conclusion

- Self-consistent treatment of tidal geocenter variations provides detectable improvements to:
  - Comparison of ocean tide height models with bottom pressure recorder observations.
  - Predicted tidal geocenter motion.
  - Precise orbit determination of Earth orbiters.
- Improvements primarily in:
  - Diurnal tidal components.
    - Especially K1 and O1.
  - Degree 1 spherical harmonic components of ocean tide models amplified by 15-22%.
    - Similar amplification of predicted geocenter motion
    - Impacts predicted surface loading displacements of stations on crust. (< 1.5 mm)
- No impact on ocean circulation users of altimetry.
- Impact on gravity recovery from space (e.g., GRACE) and EOP predictions likely negligible.
  - Very small impact on other spherical harmonic components of ocean tide model.

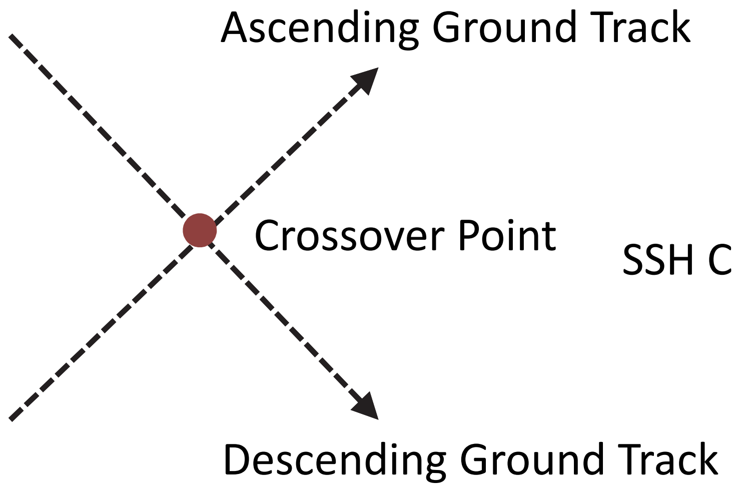
Center-of-mass correction for Space Geodesy?

- IERS2010 Conventions (adopted by IGS) state:
  The center-of-mass "correction should be applied, for instance, in the transformation of GPS orbits from the center-of-mass to the crust-fixed frame expected in the sp3 orbit format"

- Do space geodesy (especially POD) users endorse this recommendation?
  - No impact for station positioning as long as load tide model is consistent with frame of orbit solution there is no impact, (e.g., Fu et al., (2012), Desai et al., (2014)).

Back-Up Slides

Sea Surface Height Crossovers

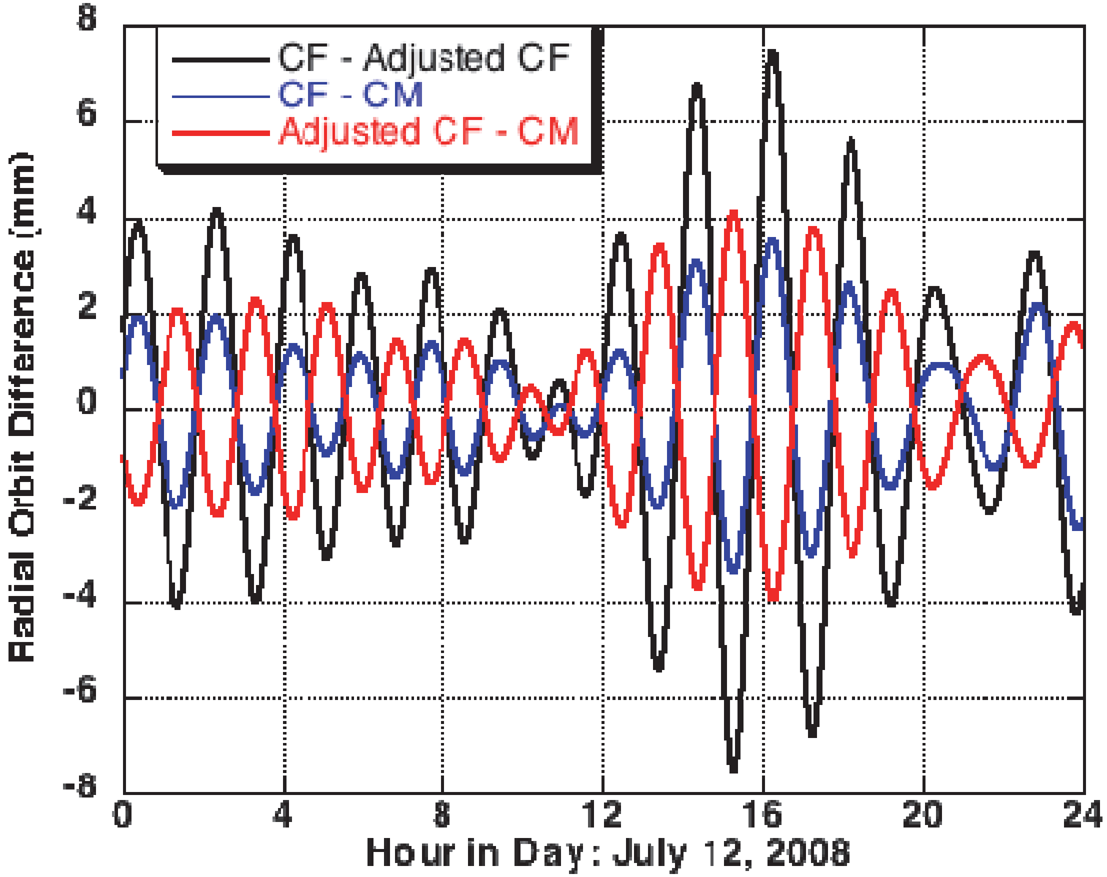


(SSH = Sea Surface Height)

SSH Crossover Difference = SSH (Ascending Track)
– SSH (Descending Track)

- Crossover points - Where ascending and descending ground tracks cross.
- Generate "corrected" sea surface height (SSH) by subtracting high frequency (<20 days) effects from observed SSH.
  - Use models, e.g., tides, inverse barometer, etc.
- Form differences of corrected sea surface height (SSH) at crossovers (< 3 days apart).
- Compute variance of sea surface height crossover differences.
- Provides powerful unbiased measure of relative accuracy of orbit solutions/models.
  - Assumes corrected SSH (.ie. Ocean circulation) has no appreciable change in 3 days.
  - Assumes the orbit solutions/models are independent of the crossover differences.

Sample Day of Radial Orbit Differences (Reduced-dynamic Orbit Solutions)



- CF-Adjusted CF = Geocenter motion.
- Fraction of inconsistency in CF POD solution contaminates reduced-dynamic orbit solution.