Tidal geopotential dependence on Earth ellipticity and seawater density and its detection with the GRACE Follow-On laser ranging interferometer

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Ocean tide, Earth gravity and satellite orbit

- Orbit of LEO satellites is significantly perturbed by geopotential change caused by ocean tide.

- Tidal geopotential variation is commonly:

➢ accounted for in precise orbit determination of satellites.

➢ removed from satellite gravity observations to study other geophysical mass changes.

From ocean tide to geopotential

- Conversion of ocean tide elevation to geopotential requires information about the Earth's geometry (shape) and seawater density.

- The common practice is to assume (1) a uniform seawater density, and (2) spherical approximation of the Earth.

Aim

- We examined these two assumptions of spherical Earth and uniform seawater density.
- We developed an accurate and efficient algorithm to rigorously account for these two effects when computing geopotential from an ocean-tide elevation grid.
- We demonstrate the systematic errors introduced by these two assumptions using the novel laser inter-satellite data (LRI) from GRACE Follow-On.

Formulation of tidal geopotential

- In satellite geodesy, ocean tide elevation and its induced geopotential are expressed in terms of spherical harmonic (SH) series.

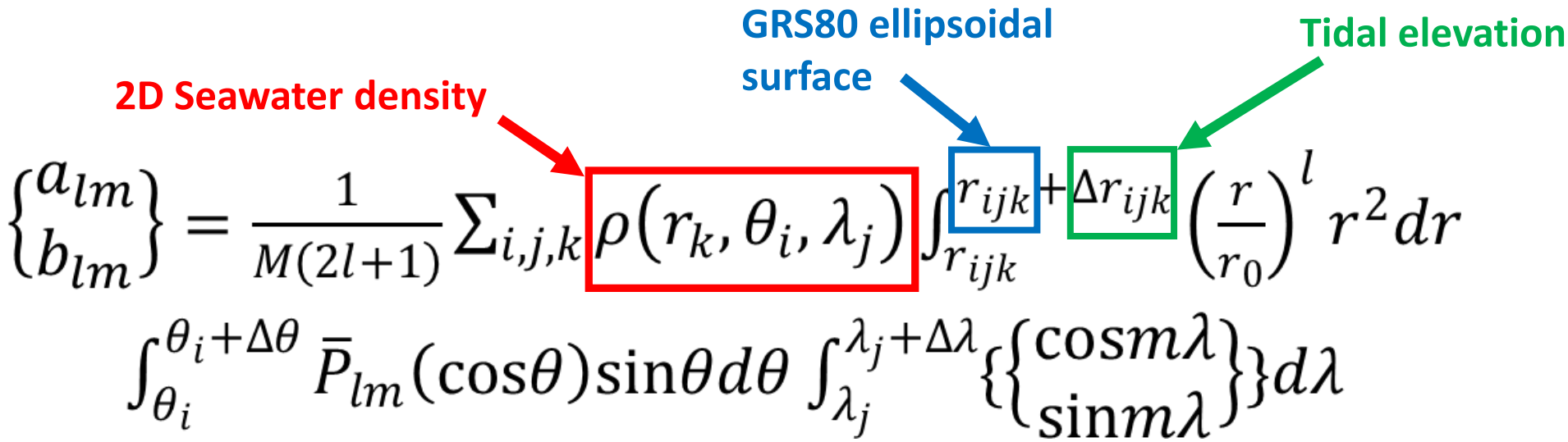
- Tidal geopotential for in-phase or quadrature component of a tidal constituent like M2:

$$V_i(\theta', \lambda') = \frac{GM}{r_0} \sum_{l=0}^{\infty} (1 + k_l') \sum_{m=0}^{l} a_{lm} \bar{P}_{lm}(\cos\theta') \cos m\lambda' + b_{lm} \bar{P}_{lm}(\cos\theta') \cos m\lambda'$$

➢ $\{a_{lm}, b_{lm}\}$: dimensionless geopotential coefficients

Methodology: 3D integration

Tidal geopotential coefficients $\{a_{lm}, b_{lm}\}$ are computed by 3D integration of tidal elevation with 2D variable density:

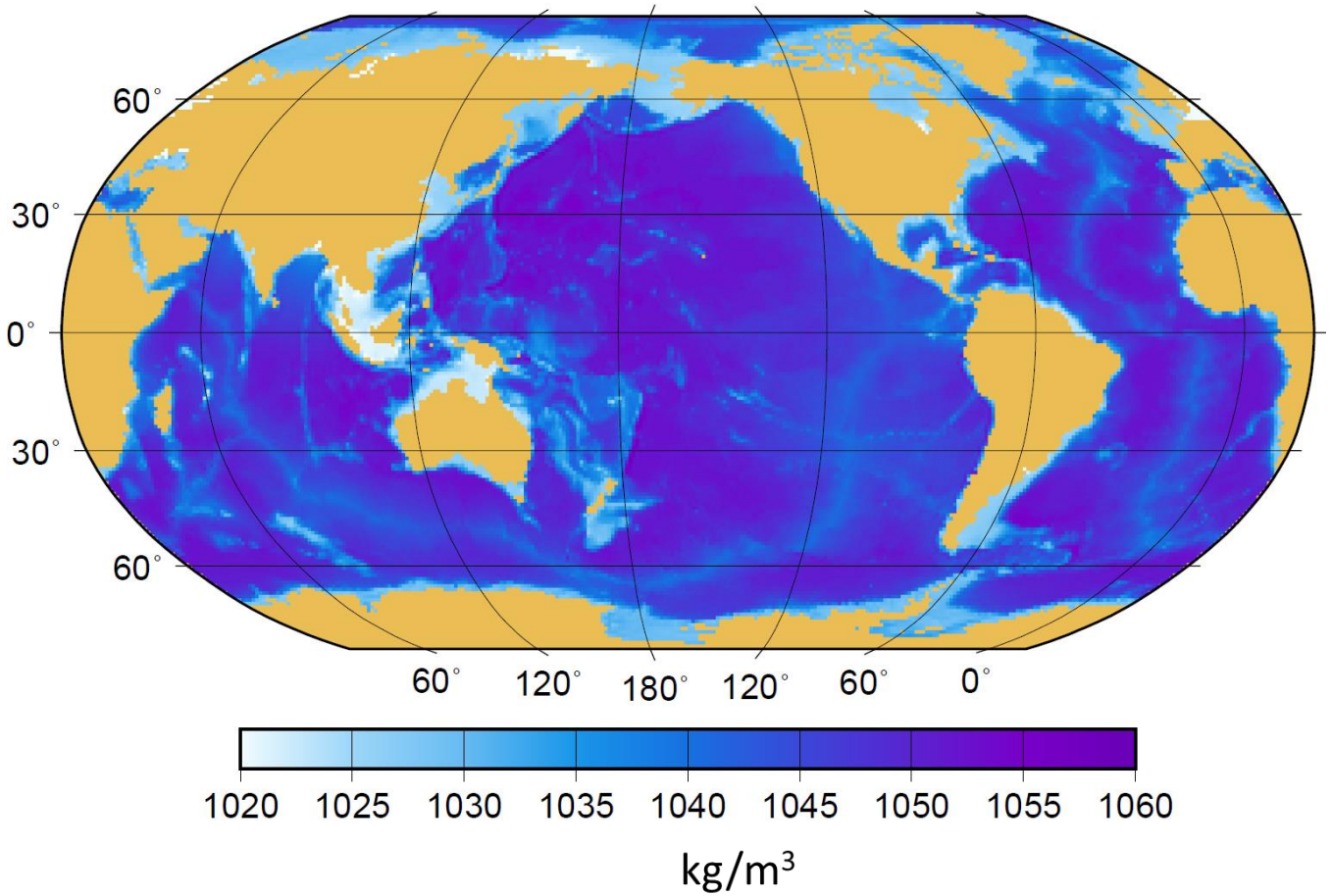


- ❖ All three integrals are solved analytically.
- ❖ FFT is used along each parallel, resulting in an efficient and fast algorithm.

For details of the algorithm, refer to: ***Šprlák, M., Han, S. C., & Featherstone, W. E. (2018). Forward modelling of global gravity fields with 3D density structures and an application to the high-resolution (~ 2 km) gravity fields of the Moon. Journal of Geodesy, 92(8), 847-862.***

Seawater density

- IERS 2010 Conventions adopts a constant seawater density of 1025 kg/m^3.
- The global average of seawater density is ~1035 kg/m^3, but it varies widely over the ocean, primarily according to water depth.
- We used climatological data from the World Ocean Atlas 2013 (WOA13) to determine seawater density.



Synthetic numerical experiments to quantify ellipticity and 2D density effects

- We computed 3 case of tidal geopotential coefficients from FES2014b and GOT4.7 models:

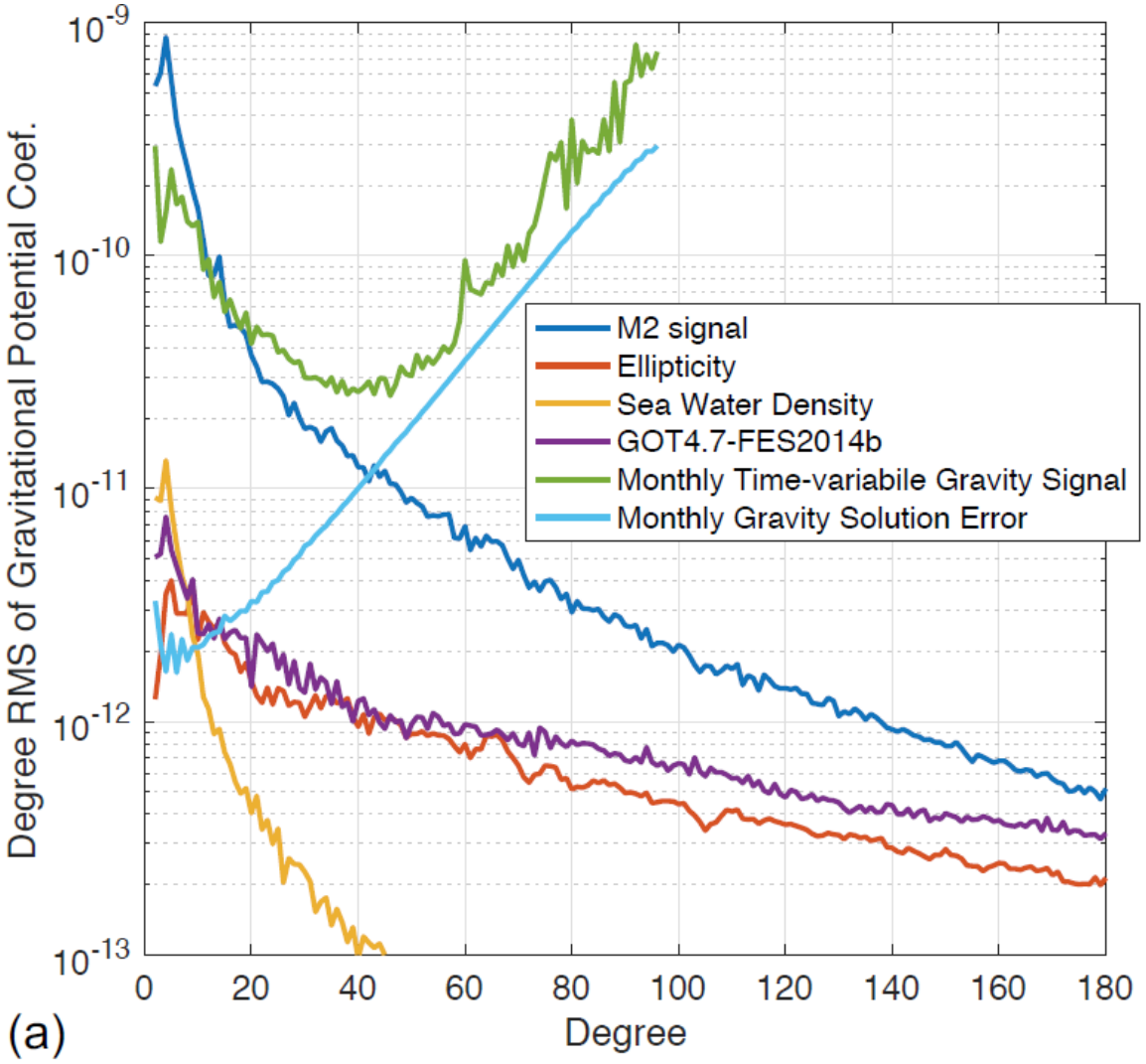
❖#1: Spherical geometry (radius 6378136.3 m) and uniform density (1035 kg/m^3).

❖#2: Ellipsoidal geometry (GRS ellipsoid) and uniform density (1035 kg/m^3).

❖#3: Ellipsoidal geometry (GRS ellipsoid) and laterally variable density (WOA13).

Ellipticity and 2D density effect: *Spectral domain*

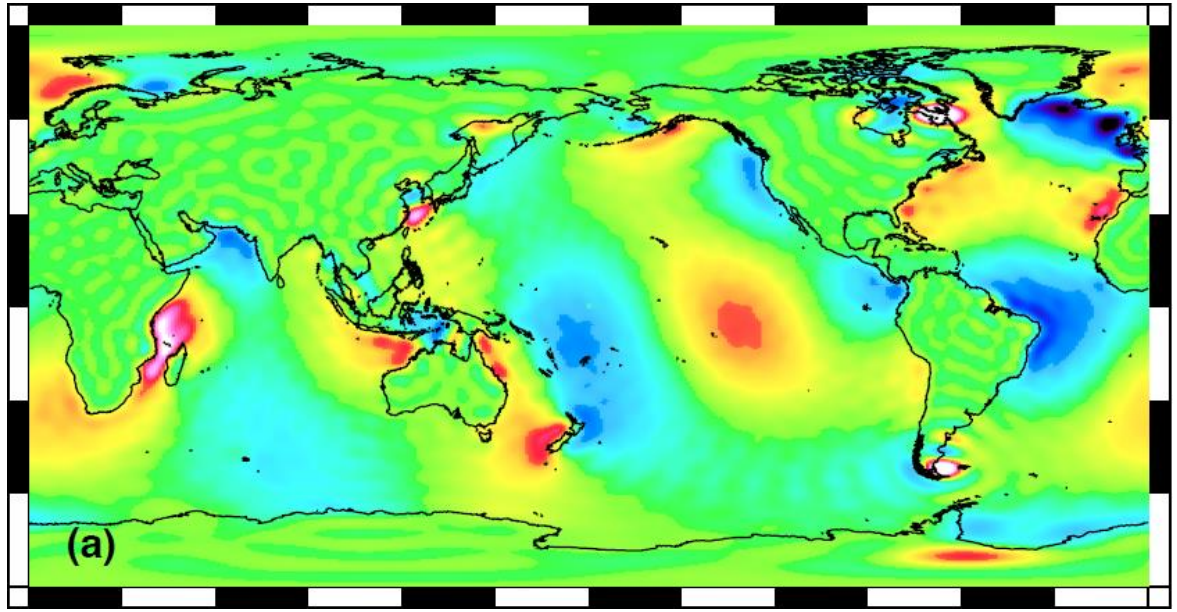
- ✓ **Effects of ellipticity and lateral density change are most significant over degrees lower than 10.**
- ✓ **The ellipticity effect weighs up to 20% of the signal at degree 90 and 40% at 180!!!**
- ✓ ***The ellipticity effect is comparable to tidal elevation model error (estimated by the difference between GOT4.7 and FES2014b)!!!***

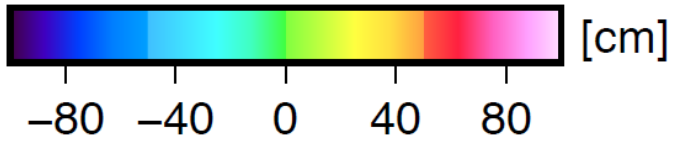


Ellipticity and 2D density effect: *spatial domain*

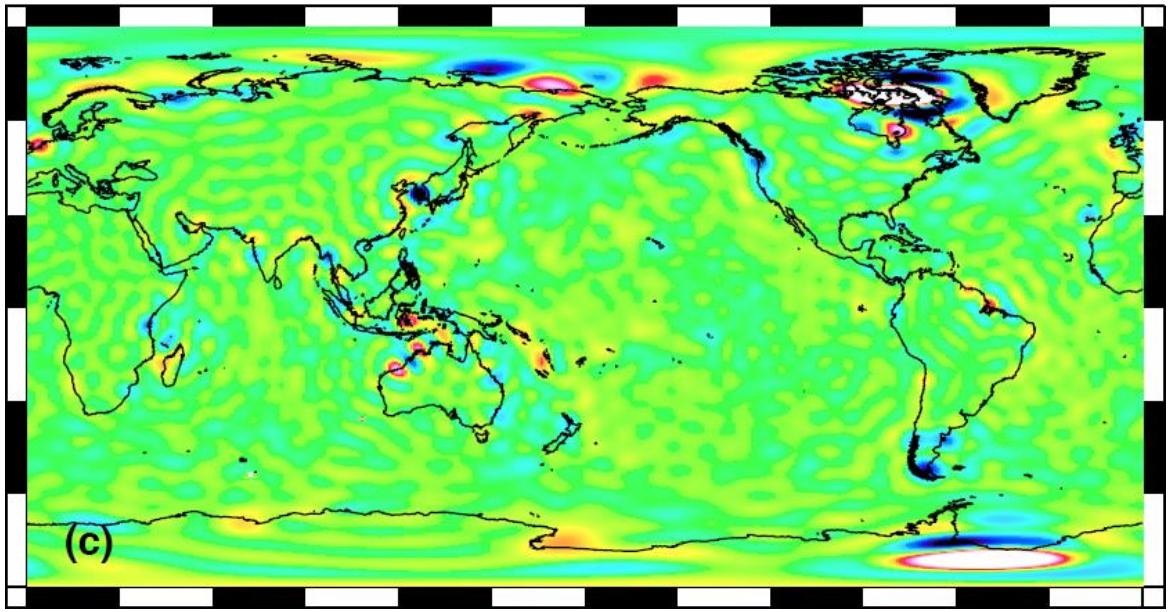
We compute EWH on the ellipsoid using the approach by Ghobadi-far et al. (2019) using the 3 cases of tidal geopotential coefficients.

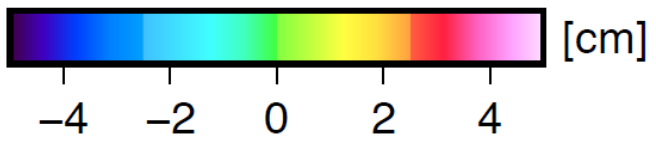
In-phase M2 tidal elevation





M2 tidal elevation error (GOT4.7 – FES2014b)



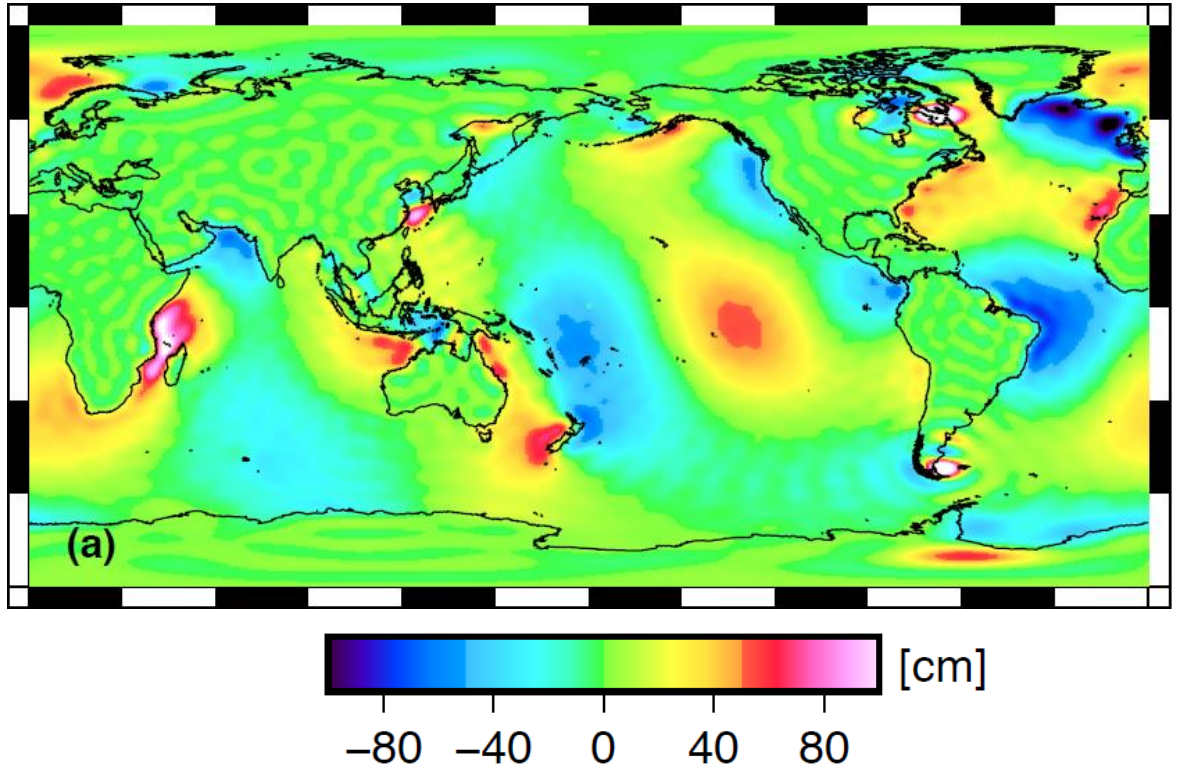


Ghobadi-Far, K., Šprlák, M., & Han, S. C. (2019). Determination of ellipsoidal surface mass change from GRACE time-variable gravity data. Geophysical Journal International, 219(1), 248-259.

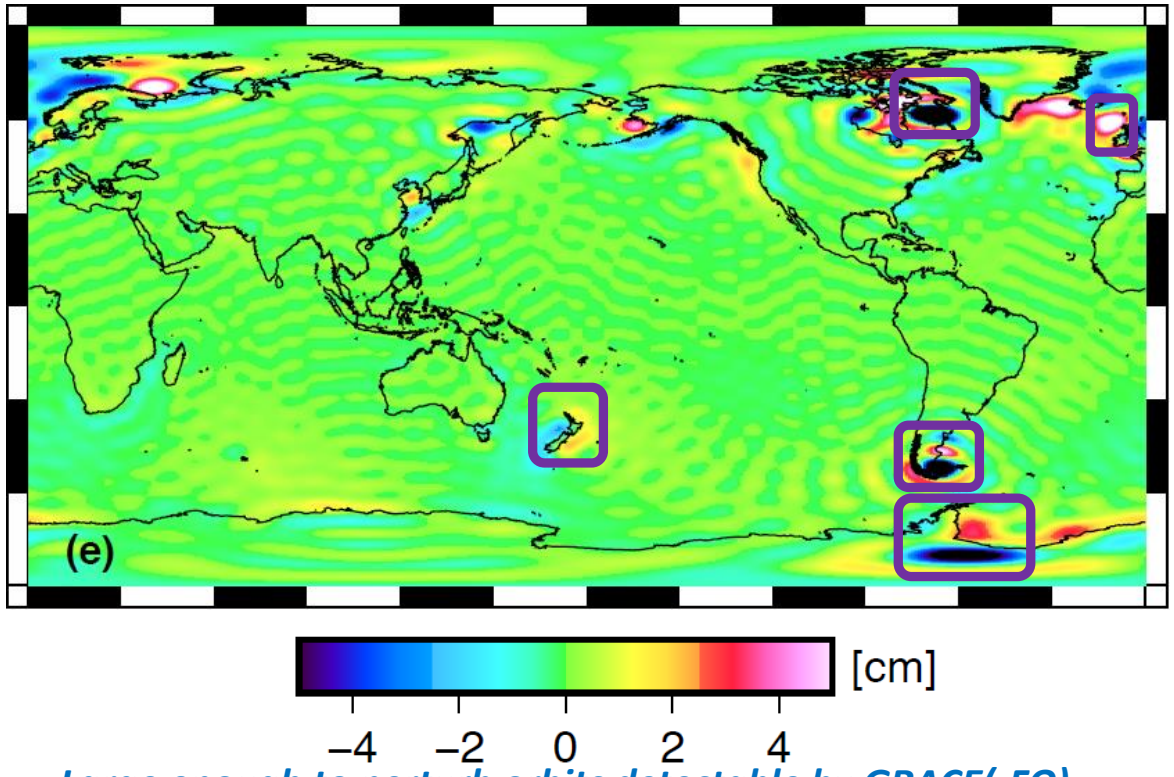
Ellipticity and 2D density effect: *spatial domain*

The error caused by neglecting the ellipticity depend on (1) signal size and (2) location.

In-phase M2 tidal elevation



Ellipticity effect
(spherical approximation error!)

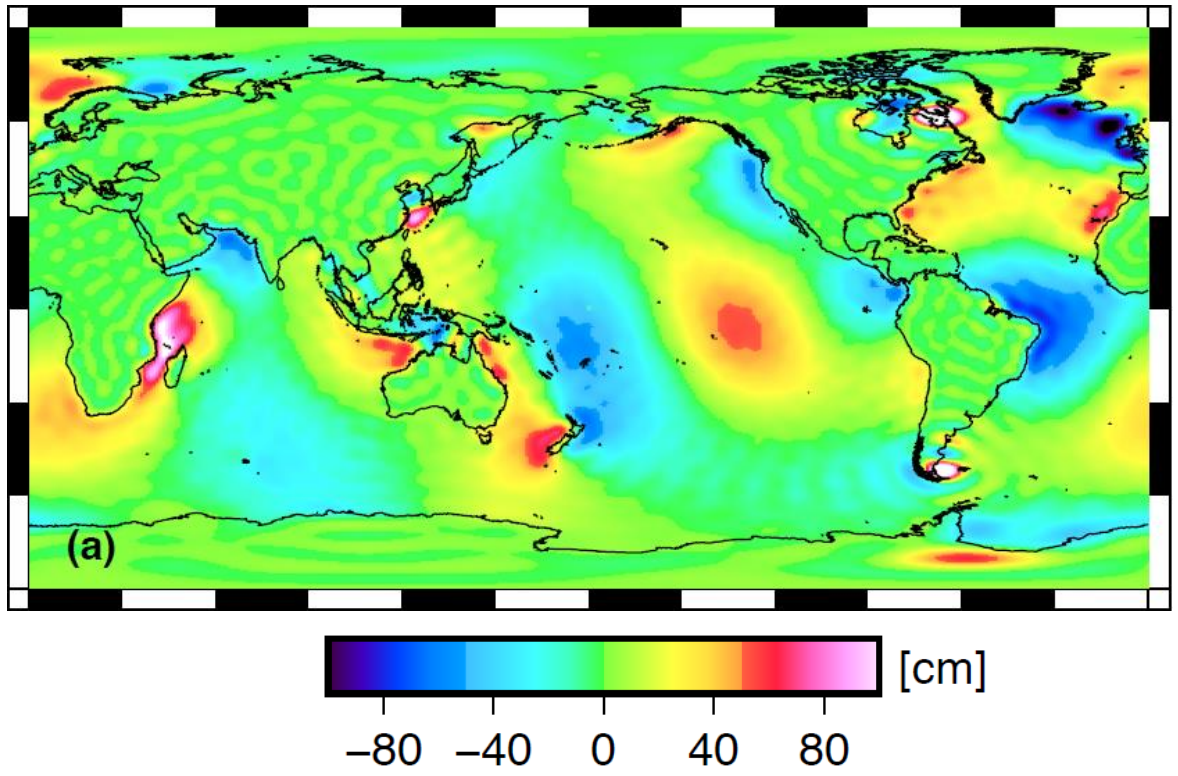


Large enough to perturb orbits detectable by GRACE(-FO) inter-satellite ranging!!!

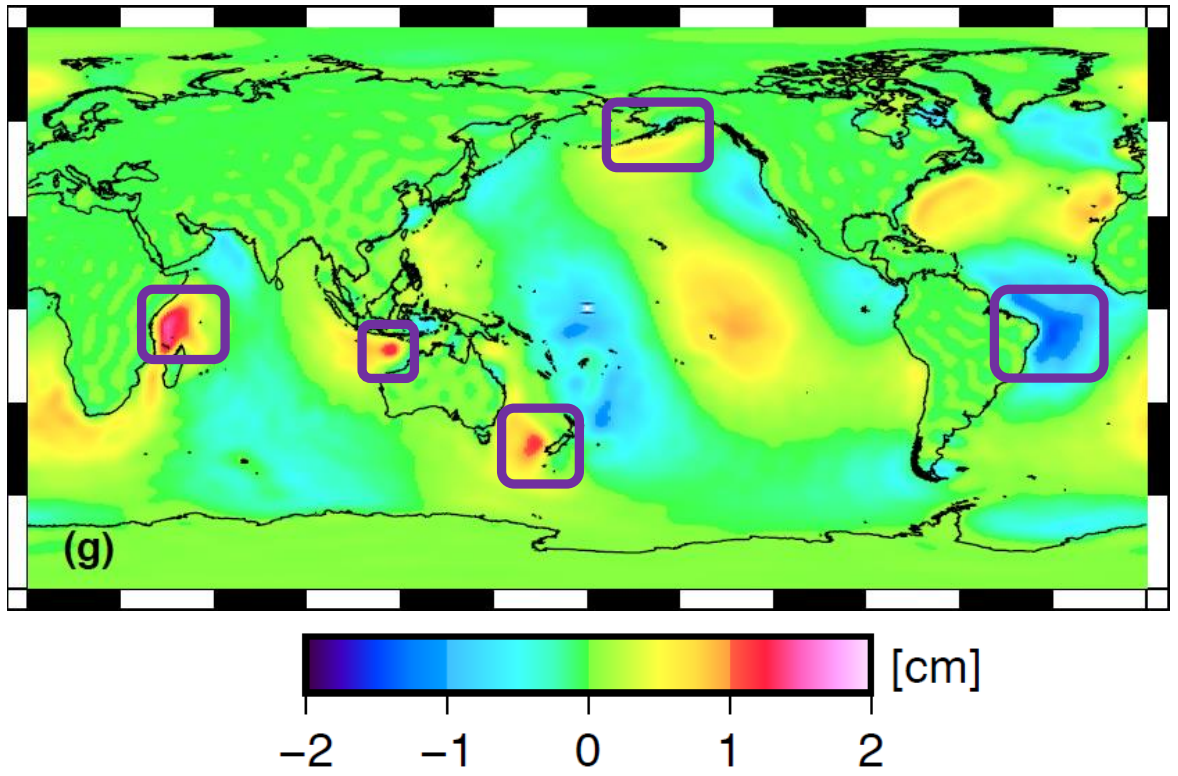
Ellipticity and 2D density effect: *spatial domain*

- Large spatial-scale errors are found in mid and low latitude oceans due to uniform density assumption.
- The error amounts to 1-2 cm and is correlated with the spatial pattern of the tidal signal.

In-phase M2 tidal elevation



Lateral density variation effect



“GRACE-FO LRI detects the ellipticity and variable seawater density effects”

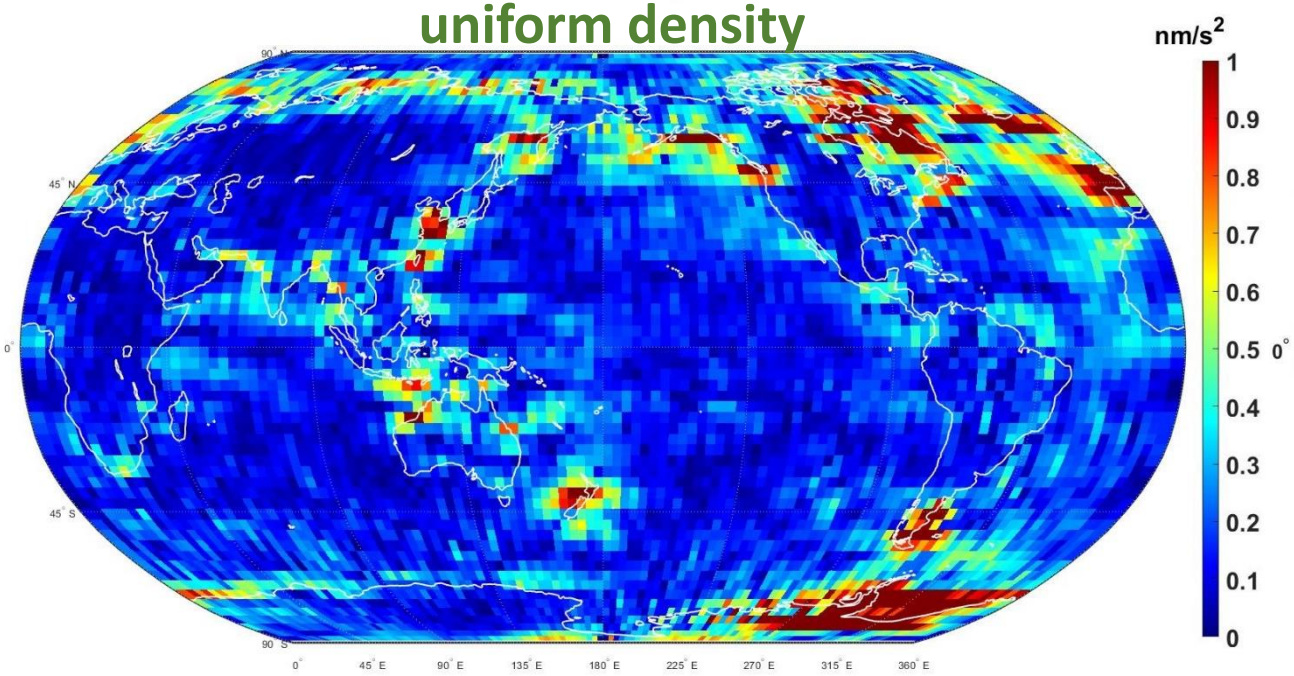
- We use GRACE-FO inter-satellite LRI residual data in 2019.
- The background ocean tide model is FES2014b. Tidal geopotential is computed with uniform seawater density of 1025 kg/m^3 and spherical approximation (6378136.3 [m] radius).
- We compute line-of-sight gravity difference (LGD) observations from LRI range-acceleration residuals using Ghobadi-Far et al. (2018).
- Amplitude of tidal constituents is estimated from LRI LGD observations globally on 3×3 degree grid cells.

Ghobadi-Far, K., Han, S. C., et al. (2018). A Transfer Function Between Line-of-Sight Gravity Difference and GRACE Inter-Satellite Ranging Data and an Application to Hydrological Surface Mass Variation. Journal of Geophysical Research: Solid Earth, 123(10), 9186-9201.

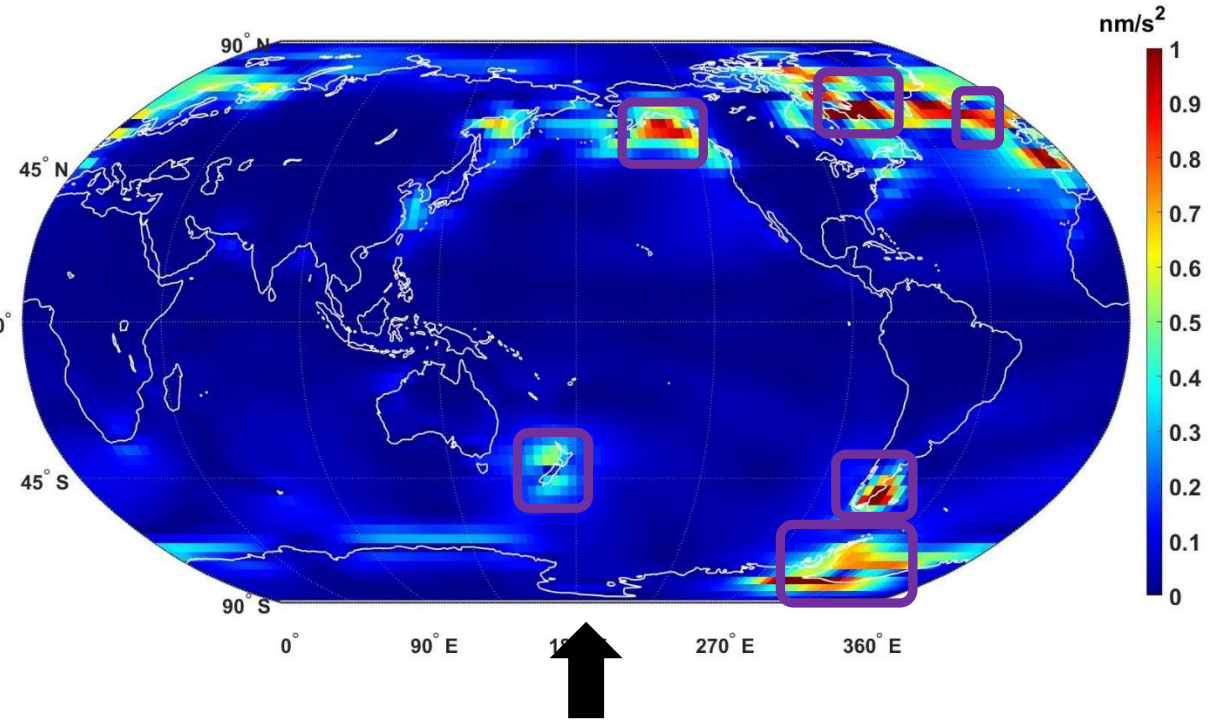
“GRACE-FO LRI detects the ellipticity and variable seawater density effects”

M2 constituent

M2 amplitude: spherical geometry & uniform density



Ellipticity correction

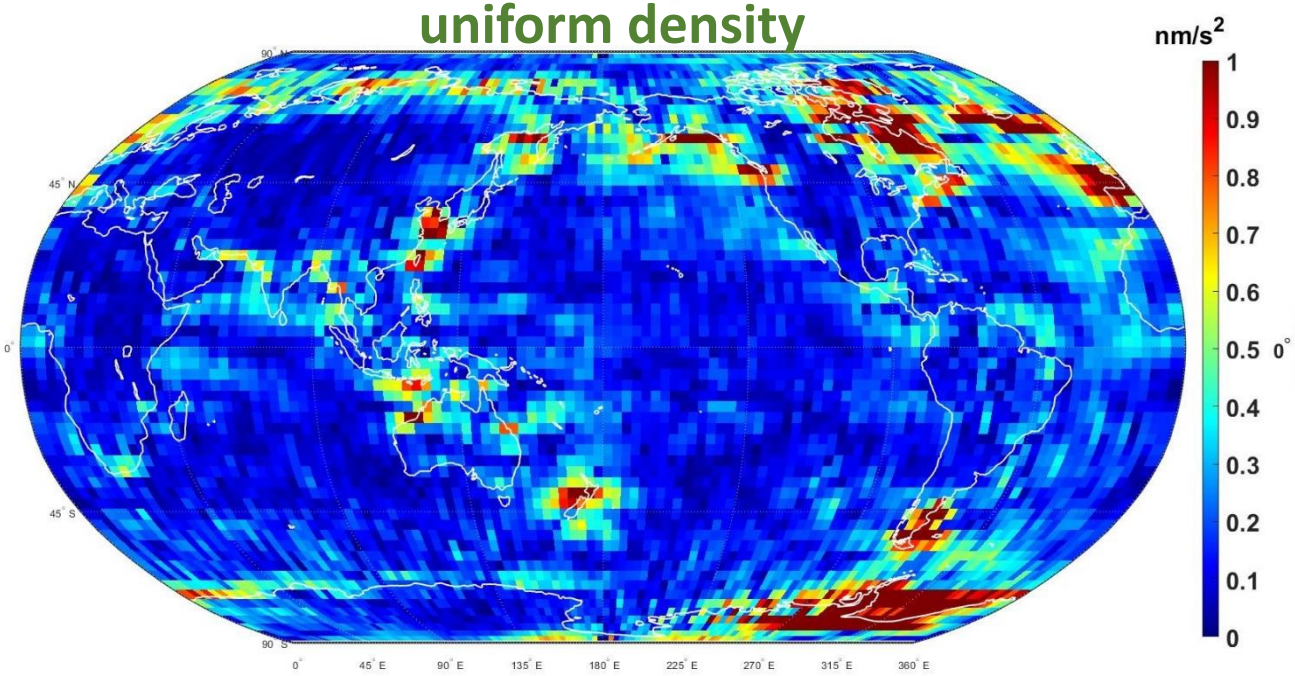


Error caused by the spherical approximation

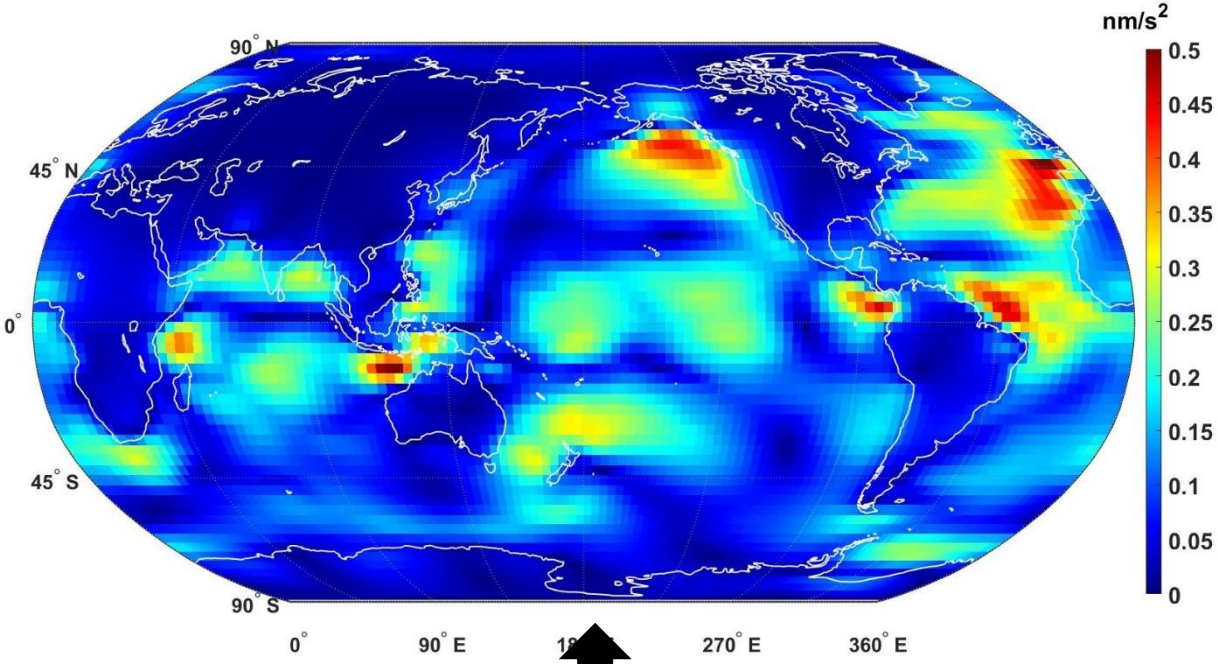
“GRACE-FO LRI detects the ellipticity and variable seawater density effects”

M2 constituent

M2 amplitude: spherical geometry & uniform density



2D density correction

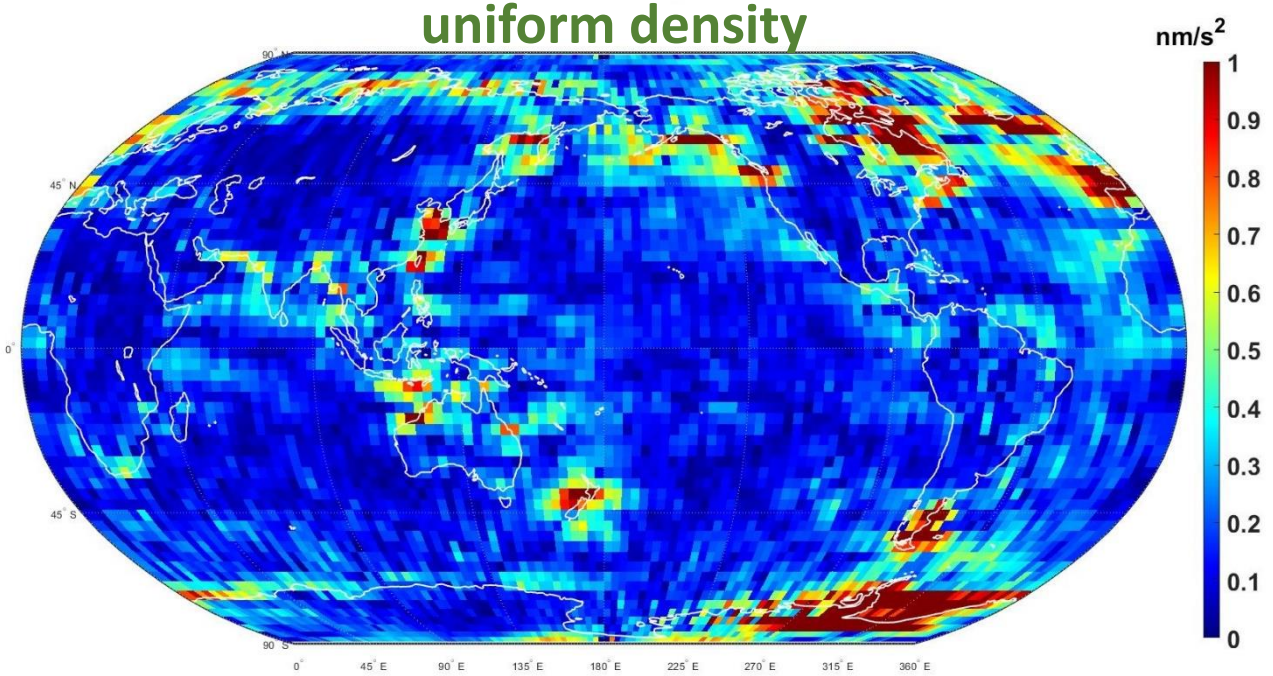


Error caused by the uniform density assumption

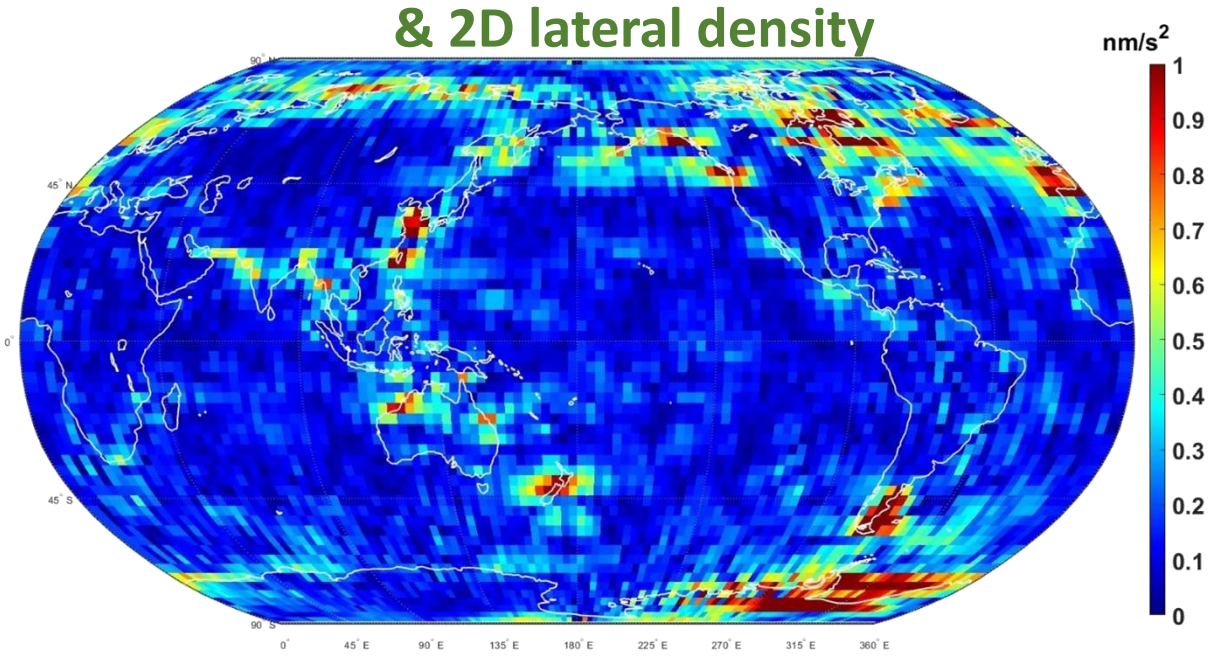
“GRACE-FO LRI detects the ellipticity and variable seawater density effects”

M2 constituent

M2 amplitude: spherical geometry & uniform density



M2 amplitude: ellipsoidal geometry & 2D lateral density

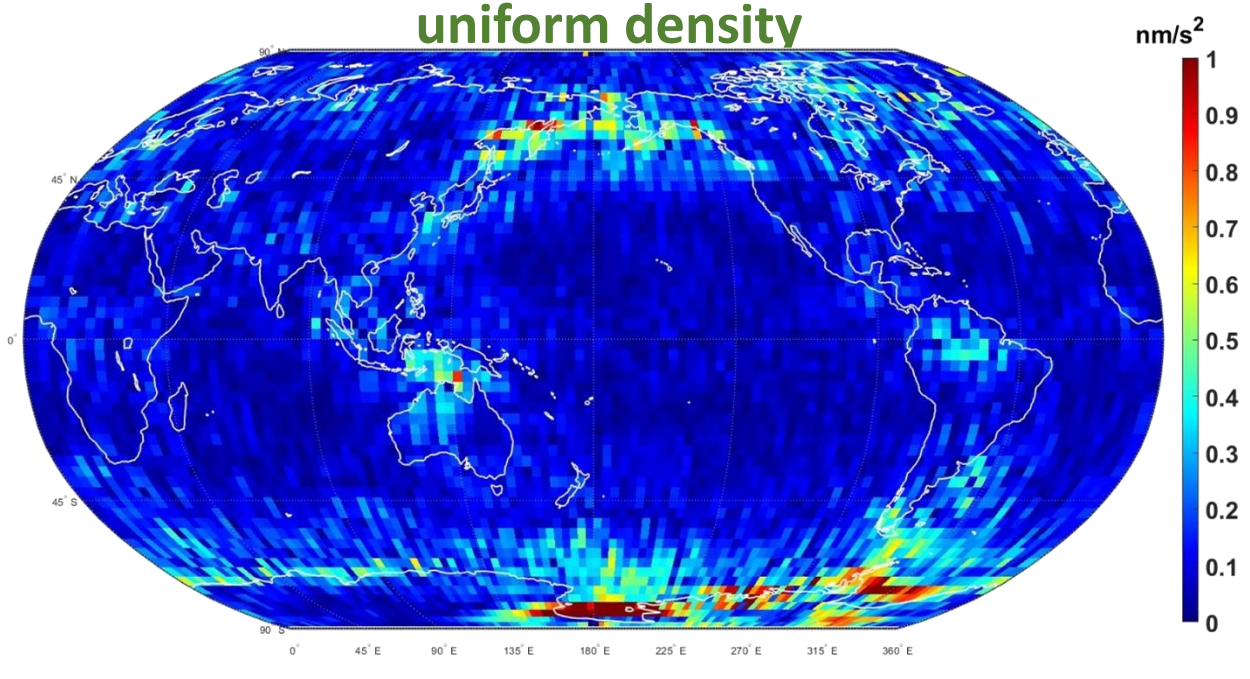


✓ ***The variance reduction in LRI residuals is as large much as ~40 % over areas with significant ellipticity effect and density variation.***

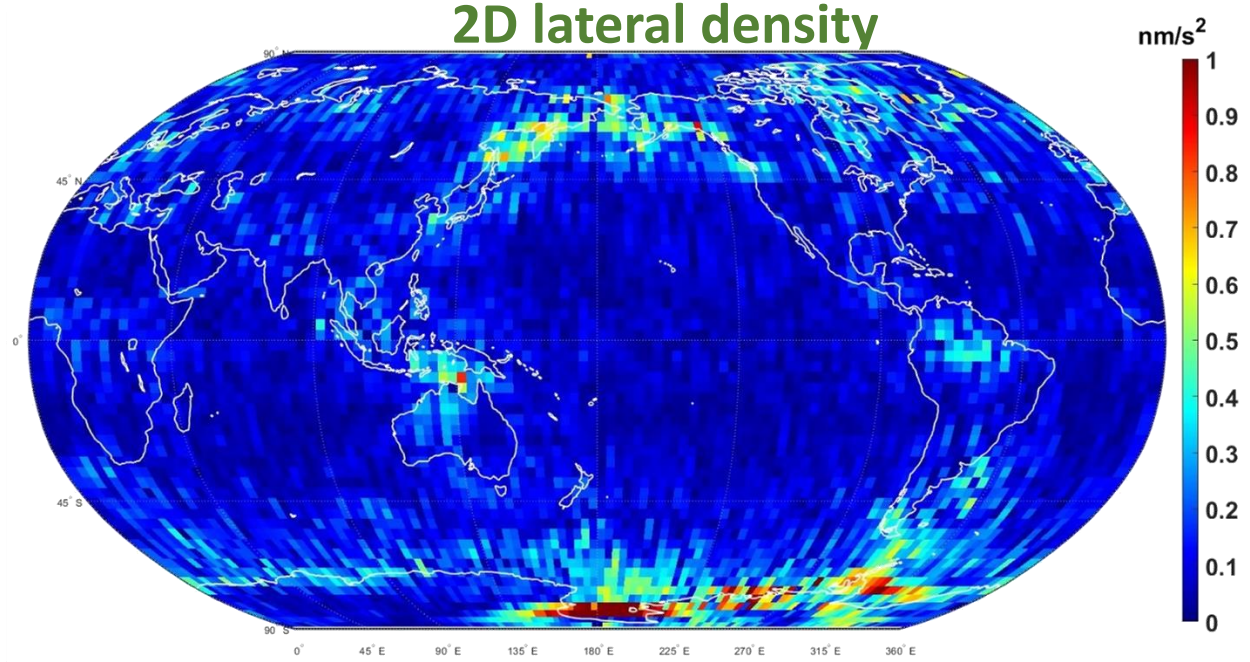
“GRACE-FO LRI detects the ellipticity and variable seawater density effects”

O1 constituent

O1 amplitude: spherical geometry & uniform density



O1 amplitude: ellipsoidal geometry & 2D lateral density



Paper and Software

❖ **Shin-Chan Han, Khosro Ghobadi-Far, Richard Ray, & Thomas Papanikolaou (2020).** ***Tidal geopotential dependence on Earth ellipticity and seawater density and its detection with the GRACE Follow-On laser ranging interferometer*****. Journal of Geophysical Research: Oceans.** ***Accepted*****.**

✓ ***Fortran codes to compute tidal geopotential considering the ellipticity and laterally variable seawater density are also released with the paper.***

Conclusions

- Systematic errors in inter-satellite ranging data caused by the spherical and uniform density assumptions have been interpreted as tidal elevation error in ocean tide studies with GRACE data.
- We showed that after applying the ellipticity and 2D density corrections, GRACE-FO LRI residuals (at tidal frequencies) are reduced by as much as 50 %. These assumptions are no longer tenable!
- Such systematic errors are aliased into monthly L2 solutions.
- We urge the GRACE and GRACE-FO processing centres to revise their computations of the ocean tide's gravitational potential.
- *Our computer codes can be readily used for that purpose*.

Thanks for your attention!

- Please contact Shin-Chan Han and/or Khosro Ghobadi-Far for inquiries about the methodology, GRACE-FO LRI data, software, etc.

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