IGS 2026 WORKSHOP
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Earth's Gravitational Coefficient GM and Geocenter Motion Determination using LEO GPS Data

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ORGANIZING INSTITUTIONS

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Background and Motivations

- A precise determination of GM and Geocenter motion is very important for **realizing ITRF**.
- The accuracy of GM has an impact on the reference **frame scale**, and Geocenter motion parameters affect the **reference frame origin.**
- The current conventional GM value was determined using multi-year SLR data in 1992 (Ries).
- GM and Geocenter motion parameters are currently derived mainly from multi-year SLR data. And the GM solutions from SLR are **not stable**. They change with year by year.
- The GM and Geocenter motion parameters could be also determined using **LEO GPS data**.

❑ **How well** can GM and Geocenter motion parameters be determined using LEO GPS data?

❑ What are the **main impacts** on GM and Geocenter motion parameters determination?

Objectives

- To investigate the **method** of LEO-GPS-based GM and Geocenter motion determination

- To study the **Impacts (such POD radial bias, reference frame, antenna offset …)** on the GM and Geocenetr motion determination

- To assess the solutions through **internal and external** comparisons

Methods to determine GM and Geocenter motion

Dynamic method for GM (Degree 0) determination:

- Satellite is treated as a moving object, whose motion can be described by dynamic models.
- One of them is the gravity field model, which includes GM parameter.
- Usually, GM is a given parameter during dynamic orbit determination. When GM is treated as an unknown parameter, then GM is determined.

Kinematic method for Geocenter (Degree 1) motion determination:

- The fixed ground station coordinates determine the location of the CN.
- Satellite motion provides the location of the CM.
- The three geocenter offset coordinates between CN and CM are directly estimated.

Used Data and Estimated Parameters

Data used	Description
Observation: GPS DD (Double-differenced) from GRACE/GRACE-FO and 57 IGS stations	IF **DD carrier phase;** arc-length: 24 hours; 30 second sampling,
JPL IGS GPS orbits, clocks and quaternions	Final orbits and 30 second clocks as well as quaternion
Estimated parameters	
LEO (GRACE/GRACE-FO) initial state	3D epoch position and velocity
GPS DD carrier phase ambiguity	One per combination per pass
Empirical 1-cpr T and N accelerations	**1-cpr per revolution (10^{-8} m/s^2 a priori)**
Drag coefficient	One per orbital revolution
Onboard antenna correction	One per arc in radial direction
Geocenter motion parameters	Three offset (X-, Y- , Z-component) per month
GM parameter	One per month

Effects of GM on Orbits and Scale

Based on **Kepler's third law**, there is the following relationship:

$$GM = \frac{4\pi^2 r^3}{T^2} \quad (1)$$

From the equation (1), the following equation can be derived (effect of GM on orbit radius):

$$\Delta r = \frac{r}{3GM} \Delta GM \quad (2)$$

From the equation (2), we can obtain the scale effect (ΔS) of GM on satellite orbits:

$$\Delta S = \frac{\Delta r}{r} = \frac{\Delta GM}{3GM} \quad (3)$$

Note: those relationships will be proved in results section.

Test Data and Test Cases

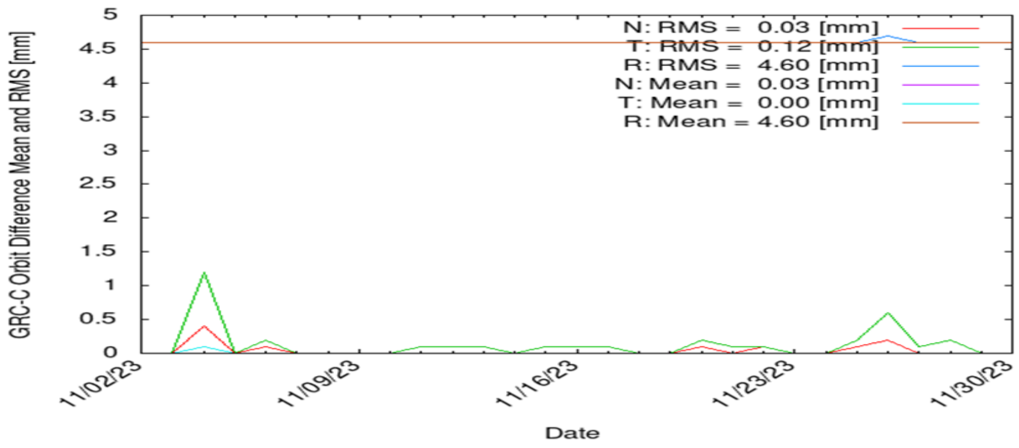
- GM and Geocenter: GRACE/GRACE-FO GPS Observations **(2004-2025)**
- POD: GRACE-FO1 (2020 and Nov. 2023); Sentinel-6A (Nov. 2023) ; Lageos-1 (Nov. 2023)

1) **GF1-POD, SEN-POD and LAG-POD: proving formulas (equation 2 and 3) on radial bias, scale change and GM offset for nearly circular orbits**
2) **GRC-AC-GM: Monthly GRACE-A/GRACE-FO1 GM estimates**
3) **GRC-BD-GM: Monthly GRACE-B/GRACE-FO2 GM estimates**
4) **GRC-FO1/2-GM: Monthly GRC-FO1 and –FO2 GM estimates without estimating antenna offset**
5) **GRC-FO1: orbit comparison in 6-hour overlaps for evaluating orbit accuracy**
6) **GRC-AC-GCM: Monthly Geocenter time series for X-, Y-, and Z-components derived from GRACE-A/GRACE-FO1 GPS data**
7) **GRC-BD-GCM: Monthly Geocenter time series for X-, Y-, and Z-components derived from GRACE-B/GRACE-FO2 GPS data**

Effects of GM offset ($\mathbf{0.0008 \times 10^9}\mathrm{m^3s^{-2}}$) on Satellite Orbits and Scale

Orbit radial biases [mm] due to GM offset (Equation 2)

Satellite Radius [km]	6857 (GRC-FO1)	7710 (Sentinel-6A)	12265 (Lageos-1)
Computed bias [mm]	4.6	5.1	8.2
Determined bias [mm]	4.6	5.2	8.2

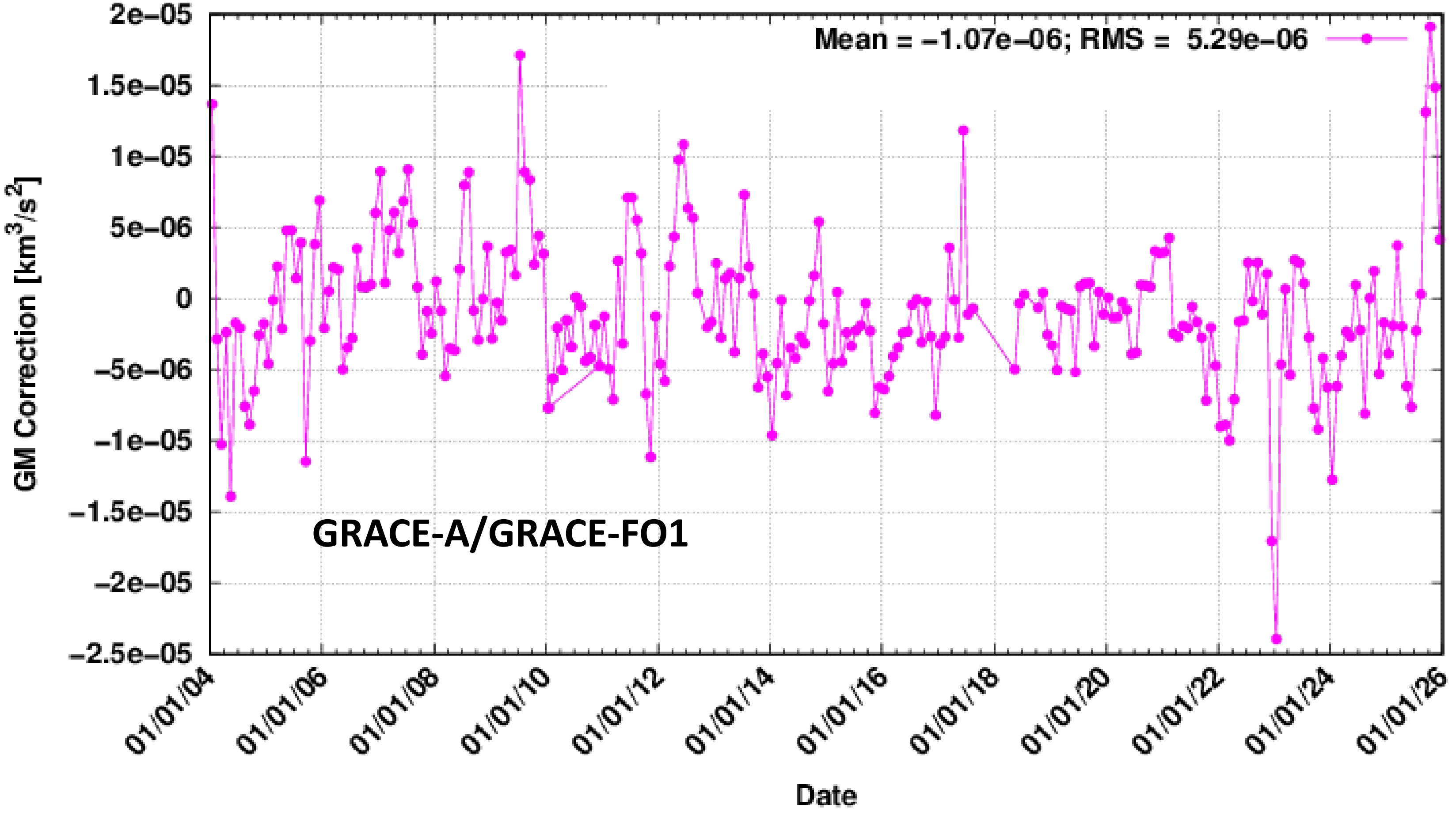


GRC-FO1 orbit comparison for with/without GM offset

Helmert transformation parameters determined by orbit comparison with/without GM offset (computed based on equation 3: **0.6690 E-09**)

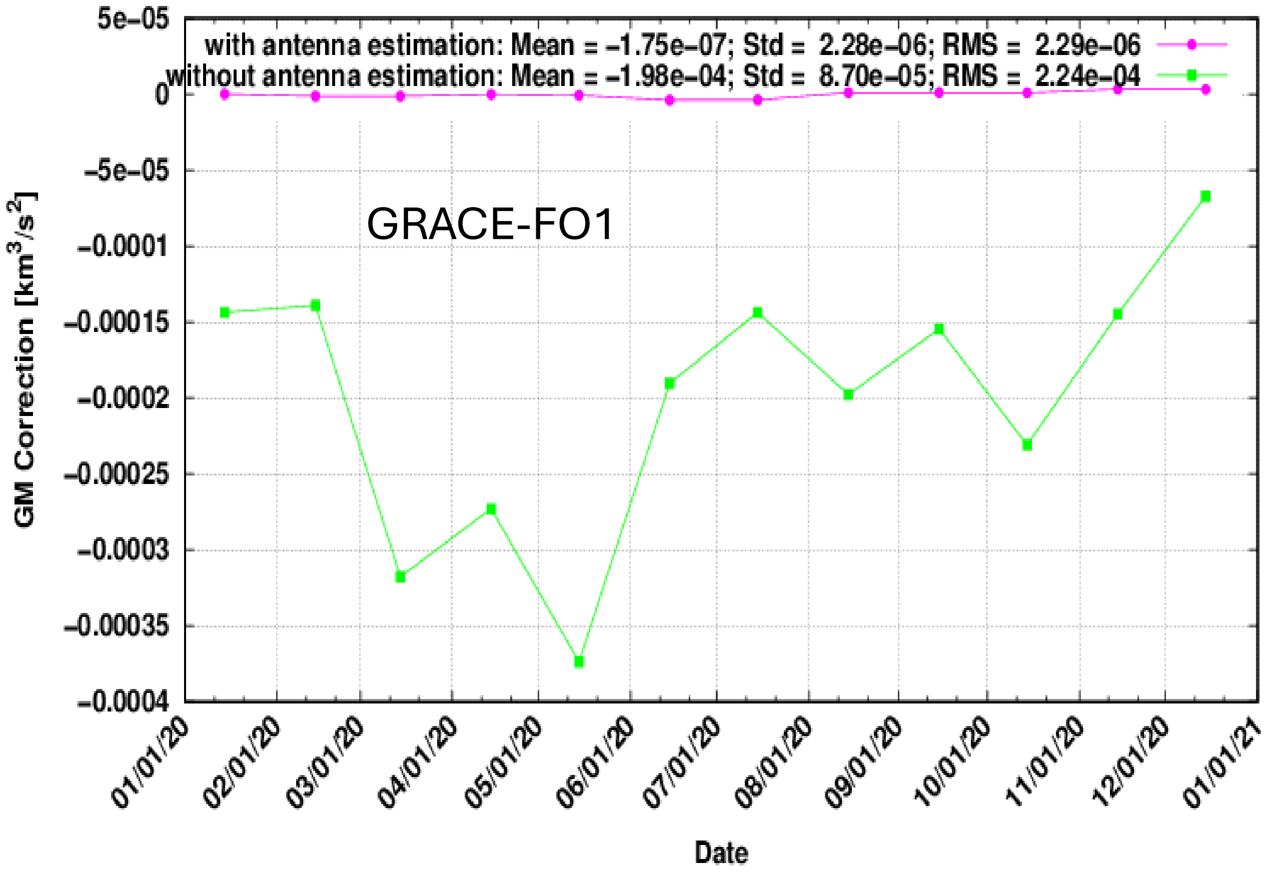
	Tx [mm]	Ty [mm]	Tz [mm]	Scale 1E-09	Rx [rad] 1E-09	Ry [rad] 1E-09	Rz [rad] 1E-09
GRACE-FO1	-0.0006	-0.0003	-0.0112	**0.6697**	0.00058	0.00087	-0.00007
Sentinel-6A	-0.0136	-0.0021	0.00117	**0.6684**	-0.00452	0.00216	0.00215
Lageos-1	-0.1144	0.0483	0.2911	**0.6692**	-0.05018	0.05246	-0.00288

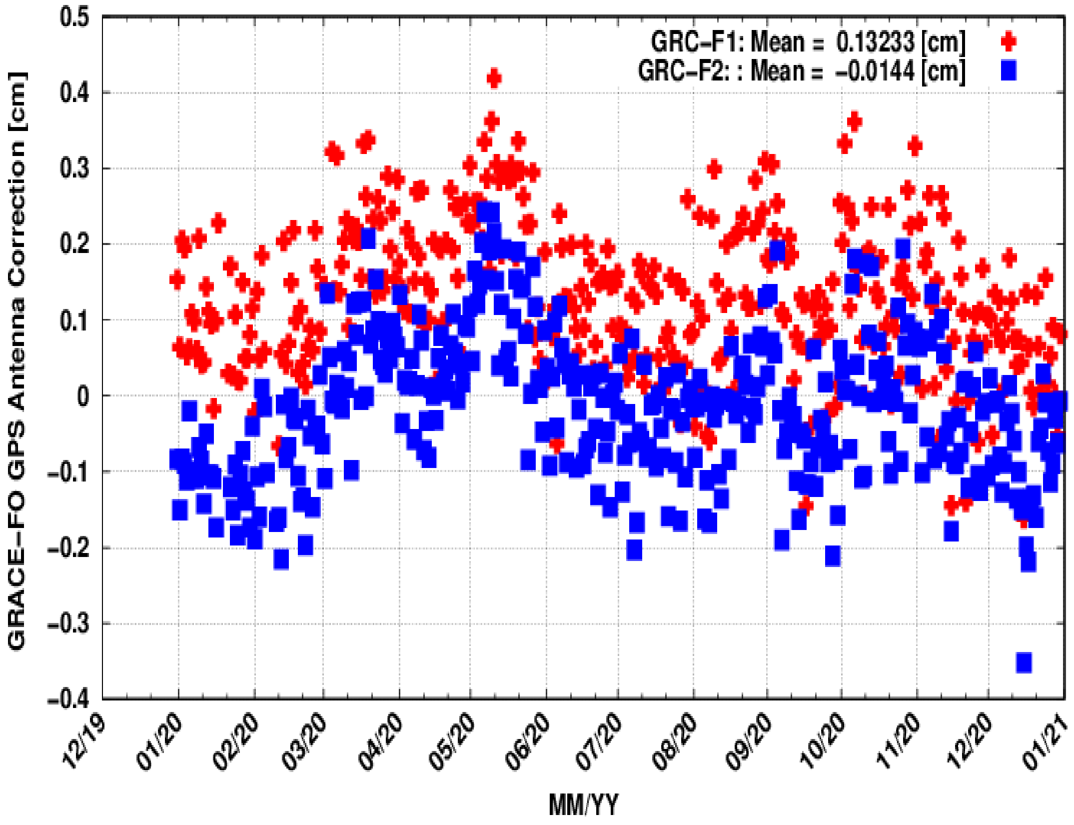
Monthly GM Estimates from GRACE/GRACE-FO GPS Data



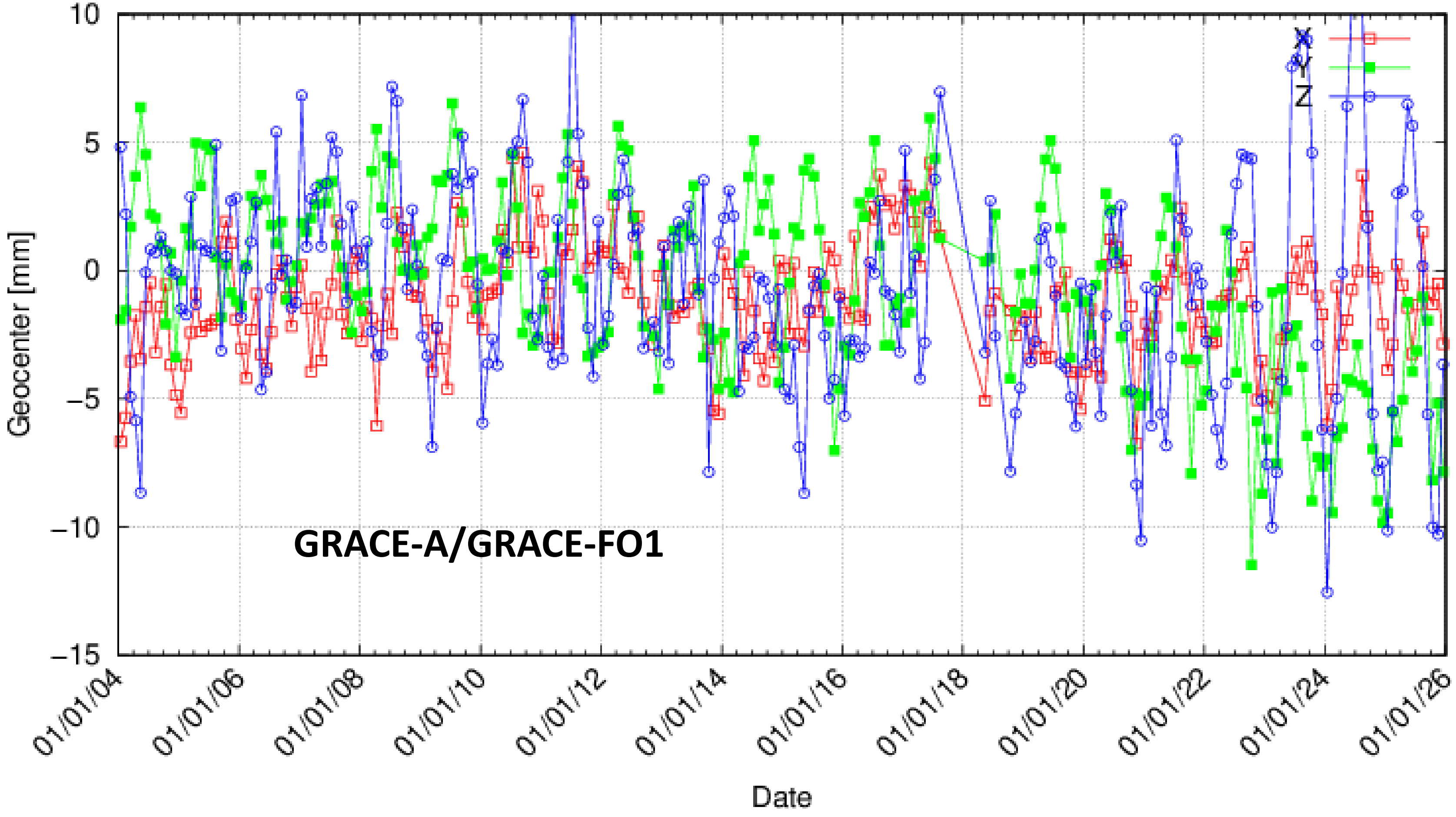
The GM monthly solutions from this study (LEO GPS) have a variation from -0.000025 to 0.000018 relative to official value; the GM yearly solutions from SLR have a variation from -0.0006 to 0.0035 (Couhert et al. 2019).

Effects of GRACE-FO GPS Onboard Antenna Offset Correction on GM Estimates





Geocenter Motion Time Series from GRACE/GRACE-FO GPS Data



The lager variations after 2022 are maybe due to the limitation of our methos, which is very dependent on selected reference frame (**IGS20**), namely the origin and kinematic station model. The frame is realized based on observations collected over the time span **1994.0–2021.0**. The unperfect frame origin and **station velocity model** made the estimated Geocenter motion parameters unusual after 2022.

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Estimated and Predicated Annual Component of Geocenter Motion

	X		Y		Z	
	Amplitude [mm]	Phase [deg]	Amplitude [mm]	Phase [deg]	Amplitude [mm]	Phase [deg]
INV GRACE (Swenson et al. 2008) *	1.9 ± 0.1	53 ± 3	2.5 ± 0.1	319 ± 2	1.9 ± 0.1	65 ± 4
GPS Global Inversion (Wu et al. 2010)	1.8 ± 0.1	49 ± 4	2.7 ± 0.1	329 ± 2	4.2 ± 0.2	31 ± 3
KALREF (Wu et al., 2015)	1.9 ± 0.1	52 ± 1	3.0 ± 0.1	337 ± 1	3.5 ± 0.1	19 ± 1
INV GRACE (Sun et al. 2015)	2.3 ± 0.1	52 ± 3	2.8 ± 0.1	327 ± 2	2.9 ± 0.2	69 ± 4
KALREF+GRACE (Wu et al. 2017)	1.3 ± 0.1	46 ± 4	3.0 ± 0.1	330 ± 2	3.3 ± 0.2	26 ± 3
GRACE-A/GRACE-FO1 2004-2022 GPS	**1.0 ± 0.1**	**37 ± 6**	**3.1 ± 0.1**	**315± 6**	**1.9 ± 0.1**	**27 ± 6**
GRACE-B/GRACE-FO2 2004-2022 GPS	**1.0 ± 0.1**	**31 ± 6**	**3.0 ± 0.1**	**316 ± 6**	**1.4 ± 0.1**	**10 ± 6**
GRACE-A/GRACE-FO1 2004-2025 GPS	**1.2 ± 0.1**	**35 ± 6**	**3.0 ± 0.1**	**319± 6**	**2.3 ± 0.1**	**11 ± 6**
GRACE-B/GRACE-FO2 2004-2025 GPS	**1.2 ± 0.1**	**28 ± 6**	**2.9 ± 0.1**	**319 ± 6**	**2.2 ± 0.1**	**2.7 ± 6**
SLR (LAG12) (Kang et al. 2019)	1.1 ± 0.1	65 ± 6	3.4 ± 0.1	325 ± 6	2.9 ± 0.1	22 ± 6
Inverse Model (Collilieux et al. 2009)	1.3 ± 0.3	6 ± 14	3.0 ± 0.3	338 ± 6	4.6 ± 0.2	23 ± 3
Forward Model (Collilieux et al. 2009)	2.1 ± 0.1	28 ± 2	2.1 ± 0.1	338 ± 2	2.7 ± 0.1	48 ± 2
ITRF2020 geocenter motion model	1.2 ± 0.2	57 ± 7	3.5 ± 0.2	333± 3	2.8 ± 0.3	40 ± 7

Summary

- **This study has demonstrated that GM and Geocenter motion parameters can be well determined using LEO GPS data.**
- **GM estimates are stable over the 20-year period using just one-month data.**
- **Estimated GM value is very dependent on the orbit accuracy in radial direction and GPS onboard receiver antenna offset.**
- **When the offset as a parameter must be estimated, the estimated GM can be used to verify GM used. If the offset can be precisely and absolutely provided, the GM can be precisely determined.**
- **Calibrated onboard GNSS receiver antenna for future satellite missions (such as Genesis) is suggested maybe in same way as the ground station GNSS receiver antenna calibration.**
- **The method used for Geocenter motion determination has a limitation due to fixed station coordinates. It is dependent on the kinematic model used for station coordinates.**