Towards 500-m Resolution Lunar Surface Gravitational Maps LGM2026 based on 3D Crustal Density Information [G33B-3381]

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Abstract

LGM2026 is an initiative to develop a suite of **lunar surface gravitational maps** at 500-m resolution based on 3D density. Long-wavelengths (~50 km) will be taken from a GRAIL model, while short-scale signals (~500 m) will be derived from the LOLA topography and a 3D crustal density model. Depicted will be the surface gravitational potential and the full surface gravitational vector. To avoid divergence of spherical harmonics on the lunar surface, a new spherical-harmonic-based technique has been developed that can also handle 3D density contrasts (SGFM-3D). The release of LGM2026 is scheduled to mid-2026.

Challenges

Global spectral gravity-forward modelling techniques cannot be applied on the lunar surface due to their divergence. A new spherical-harmonic-based technique has been therefore developed that avoids divergence even on the lunar surface. It allows to forward-model only masses beyond some sufficiently large distance from evaluation points. The remaining near-zone masses are then modelled separately by slow but divergence-free spatial-domain methods.

Design

SGFM-3D will deliver high-frequency **far-zone gravitational effects** of residual topographic masses as defined by the LOLA topography and a 3D density model. **Near-zone effects** will be obtained by a divergence-free spatial-domain technique. The sum of the two components added to long-wavelength signals from a **GRAIL-based model** will yield the final LGM2026 maps.

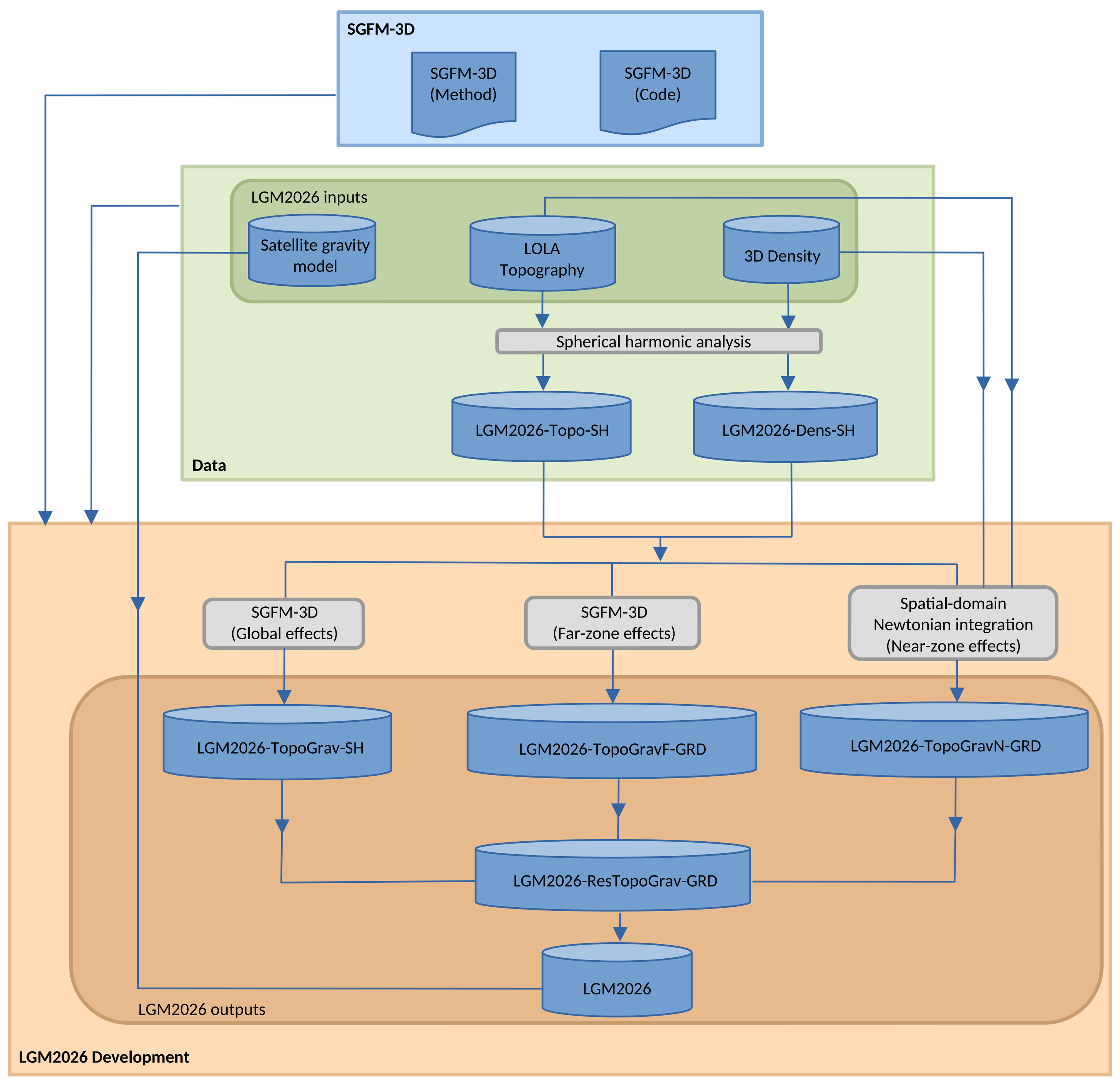

Figure 1. LGM2026 development flowchart

SGFM-3D

The gravitational potential of topographic masses is given by the Newton integral

$$V(r,\Omega) = G \iint\limits_{\Omega'} \int\limits_{r'=R}^{R+H(\Omega')} \frac{\rho(r',\Omega')}{\ell(r,\psi,r')} \, (r')^2 \, \mathrm{d}r' \, \mathrm{d}\Omega', \tag{1}$$

where ρ is assumed to be a smooth 3D density function that it can be expressed as

$$\rho(r',\Omega') = \sum_{i=0}^{I} \rho_i(\Omega') \, (r')^i, \qquad \text{where} \qquad \rho_i(\Omega') = \sum_{n=0}^{N_{\rho_i}} \sum_{m=-n}^{n} \bar{\rho}_{nm}^{(i)} \, \bar{Y}_{nm}(\Omega'). \tag{2}$$

After restricting the integration domain in Eq. (1) to masses within (j = 'In') or outside (j = 'Out') an integration radius ψ_0, we obtain the spectral relation for **near- and far-zone gravitational effects**,

$$V^j(r,\Omega,\psi_0) = \frac{GM}{R} \sum_{n=0}^{N} \sum_{m=-n}^{n} \bar{V}_{nm}^{0,0,j}(r,\psi_0,R) \, \bar{Y}_{nm}(\Omega), \tag{3}$$

where

$$\bar{V}_{nm}^{0,0,j}(r,\psi_0,R) = \frac{2\pi \, R^3}{M} \sum_{p=1}^{P} \sum_{i=0}^{I} Q_{npi}^{0,0,j}(r,\psi_0,R) \, \overline{\mathrm{H}\rho}_{nm}^{(pi)}, \tag{4}$$

$$\overline{\mathrm{H}\rho}_{nm}^{(pi)} = \frac{1}{4\pi} \iint\limits_{\Omega'} \left[\left(\frac{H(\Omega')}{R} \right)^p \rho_i(\Omega') \, R^i \right] \bar{Y}_{nm}(\Omega') \, \mathrm{d}\Omega'. \tag{5}$$

In Eq. (4), $Q_{npi}^{0,0,j}(r,\psi_0)$ are Molodensky's truncation coefficients, which restrict the integration domain to near- or far-zone masses, depending on j. With $\psi_0 = 180°$ and j = 'In' (or equivalently $\psi_0 = 0°$ and j = 'Out'), **global gravitational effects** $V(r,\Omega)$ as defined by Eq. (1) are obtained as a special case. The method was developed for the gravitational potential, the gravitational vector and the gravitational tensor.

Numerical implementation is available through CHarm, a C/Python library for high-degree spherical harmonic transforms (`https://www.charmlib.org`).

SGFM-3D vs. GRAIL

Input data to **SGFM-3D**:

- Topography: MoonTopo2600p [1] to degree 2160
- Constant density: $2550 \ \mathrm{kg \ m^{-3}}$
- 3D density: surface density and density gradient grids ($I = 1$) due to [2] transformed to $\bar{\rho}_{nm}^{(0)}$ and $\bar{\rho}_{nm}^{(1)}$ up to degree $N_{\rho_0} = N_{\rho_1} = 2160$
- The bottom bounding sphere of the gravitating masses: $R = 1{,}728{,}000$ m
- Other parameters: $N = 1200$, $P = 25$

Fig. 2 plots the admittance between two forward-modelled gravitational fields and the reference model GL1500E [3]. Until degree 32, both curves stay below ~0.8 which is expected, as the topography does not explain the lowest lunar gravitational harmonics sufficiently. After reaching its maxima between degrees, say, 35 and 55, the orange curve gradually decreases until degree ~700. This implies that the quality of the gravitational information that can be recovered under the constant-density assumption decreases with increasing harmonic degree.

On the other hand, between degrees ~100 and 700, the 3D-density-based model experiences an almost horizontal admittance curve, staying always near the value of 1. Thus, the lunar gravitational field harmonics observed by GRAIL are better explained by 3D density information than by a constant density value.

After degree ~700, a substantial drop is seen in both models, likely being caused by the Kaula regularization applied in GL1500E and by the GRAIL data noise.

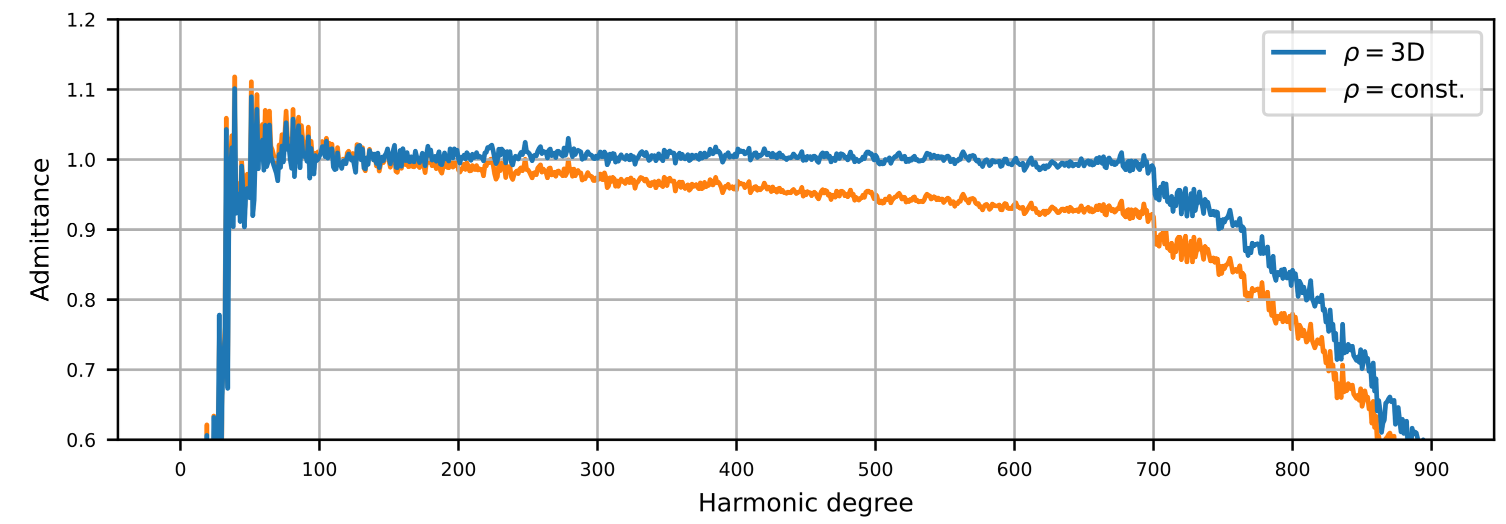

Figure 2. Admittance between forward-modelled gravitational fields and GRAIL-based reference model GL1500E [3]. The coefficients of GL1500E were rescaled to our GM value and to a Brillouin sphere of the radius $1{,}750{,}000$ m, which passes outside of all gravitating masses.

The results depend on the internal sphere, which represents the bottom boundary of gravitating masses. Our radius $1{,}728{,}000$ m ensures that the minimum topographic height is close to zero, thereby improving convergence of a certain binomial series. The sphere is thus close to the maximum Bjerhammar sphere and does not represent the base of the lunar crust.

Summary

- Initiated development of 500-m lunar surface gravitational maps
- New spectral method to forward-model 3D densities developed and implemented in CHarm, a C/Python library for high-degree spherical harmonic transforms (`https://www.charmlib.org`)
- Successful validation with respect to synthetic data and a GRAIL-based model
- Expected release of LGM2026 in mid-2026

References

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[2] S. Goossens, T. J. Sabaka, M. A. Wieczorek, G. A. Neumann, E. Mazarico, F. G. Lemoine, J. B. Nicholas, D. E. Smith, and M. T. Zuber, "High-resolution gravity field models from GRAIL data and implications for models of the density structure of the Moon's crust," *Journal of Geophysical Research: Planets*, vol. 125, p. e2019JE006086, 2020.

[3] A. S. Konopliv, R. S. Park, D. N. Yuan, S. W. Asmar, M. M. Watkins, J. G. Williams, E. Fahnestock, G. Kruizinga, M. Paik, D. Strekalov, N. Harvey, D. E. Smith, and M. T. Zuber, "High-resolution lunar gravity fields from the GRAIL Primary and Extended Missions," *Geophysical Research Letters*, vol. 41, no. 5, pp. 1452–1458, 2014.

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