最新の「かぐや」月重力場モデルについて

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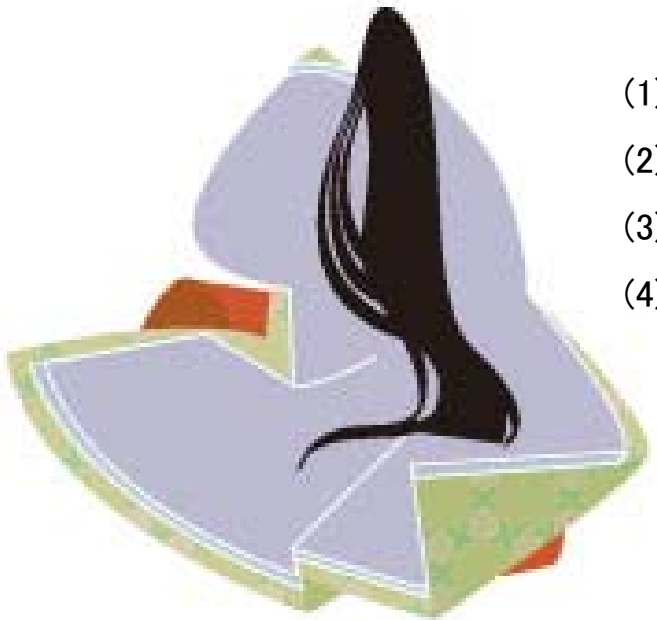
岩田隆浩 (2) 、並木 則行 (3) 、野田寛大 (1) 、花田英夫 (1) 、
RSAT/VRADミッションチーム



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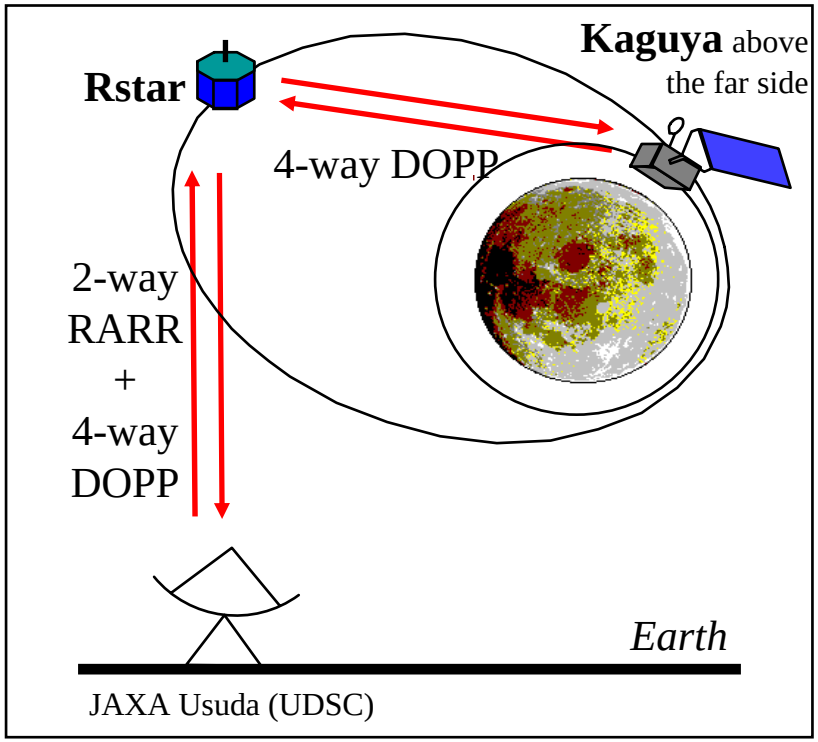
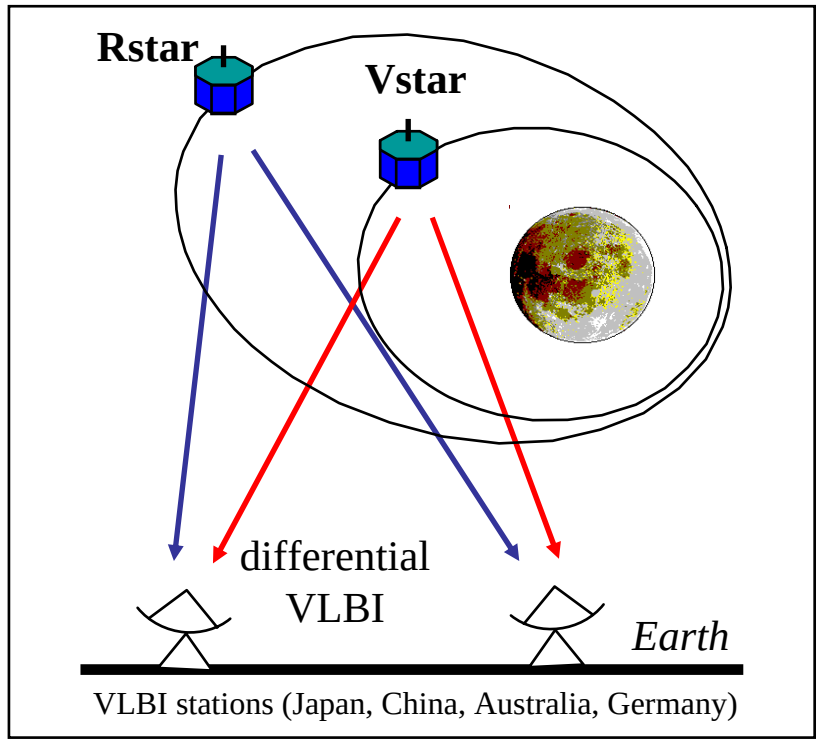
SELENE gravimetry

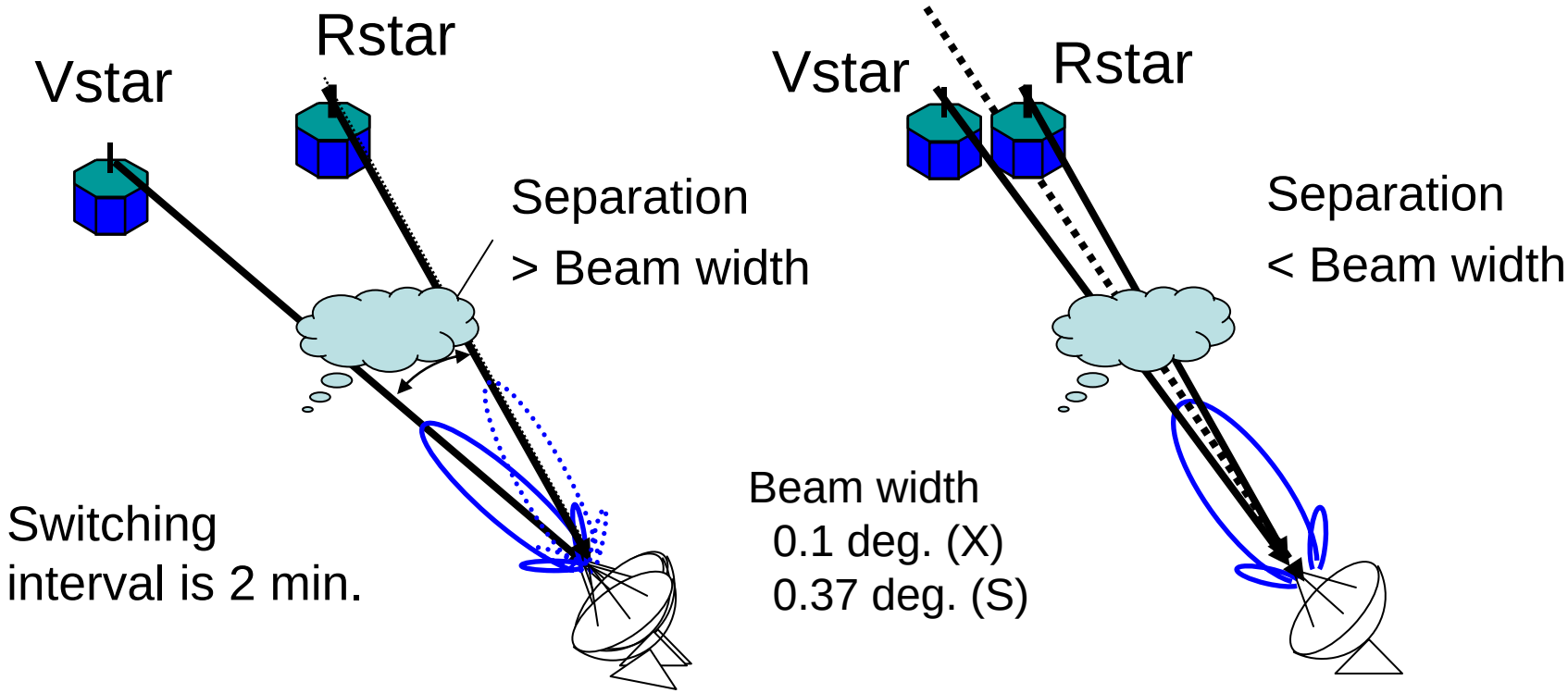
RSAT Mission
4-way Doppler for far-side coverage



VRAD Mission
Differential VLBI



Switching and Same beam VLBI Observation



Most of atomospheric and ionospheric fluctuation, clock offset, and instrumental delay can be canceled out.

Additionally, fluctuations whose periods are shorter than switching interval can be canceled out in same beam VLBI.

Status of the SELENE satellites

- 2007.10.31 Start acquiring 4-way Doppler data
- 2008.07.23 One of four reaction wheels of Main satellite failed (AMD interval 12h→6h)
- 2008.10.31 End of nominal mission
- 2008.12.26 Another wheel went out of order
  → thruster control mode
- 2009.01.30 The last 4-way Doppler data acquisition with 3 reaction wheels turned on
- 2009.02.12 Rstar (relay sub-satellite) crashed into the Moon
- 2009.06.10 Controlled crash of the Main satellite
- 2009.06.29 The last tracking of Vstar (VLBI sub-satellite)

VRADデータ解析進捗状況

観測期間2007年11月～2009年6月（全20ヵ月）一月当たり約100時間

◎Rstar&Vstar **same beam VLBI観測データ** (2009年2月まで、全16ヵ月間)

相関処理（1次処理）：完了

遅延推定（2次処理）：完了　→　7ヵ月分を【SGM100h_VLBI】に使用

◎Rstar&Vstar **switching VLBI観測データ** (2009年2月まで、全16ヵ月間)

相関処理（1次処理）：完了

遅延推定（2次処理）：25%（4ヵ月分）完了

◎Rstar&QSO or Vstar&QSO 相対VLBI観測データ (Vstarは2009年6月まで)

相関処理（1次処理）：完了

Data and analysis setting for SELENE Gravity Model version h (SGM100h)

Tracking data

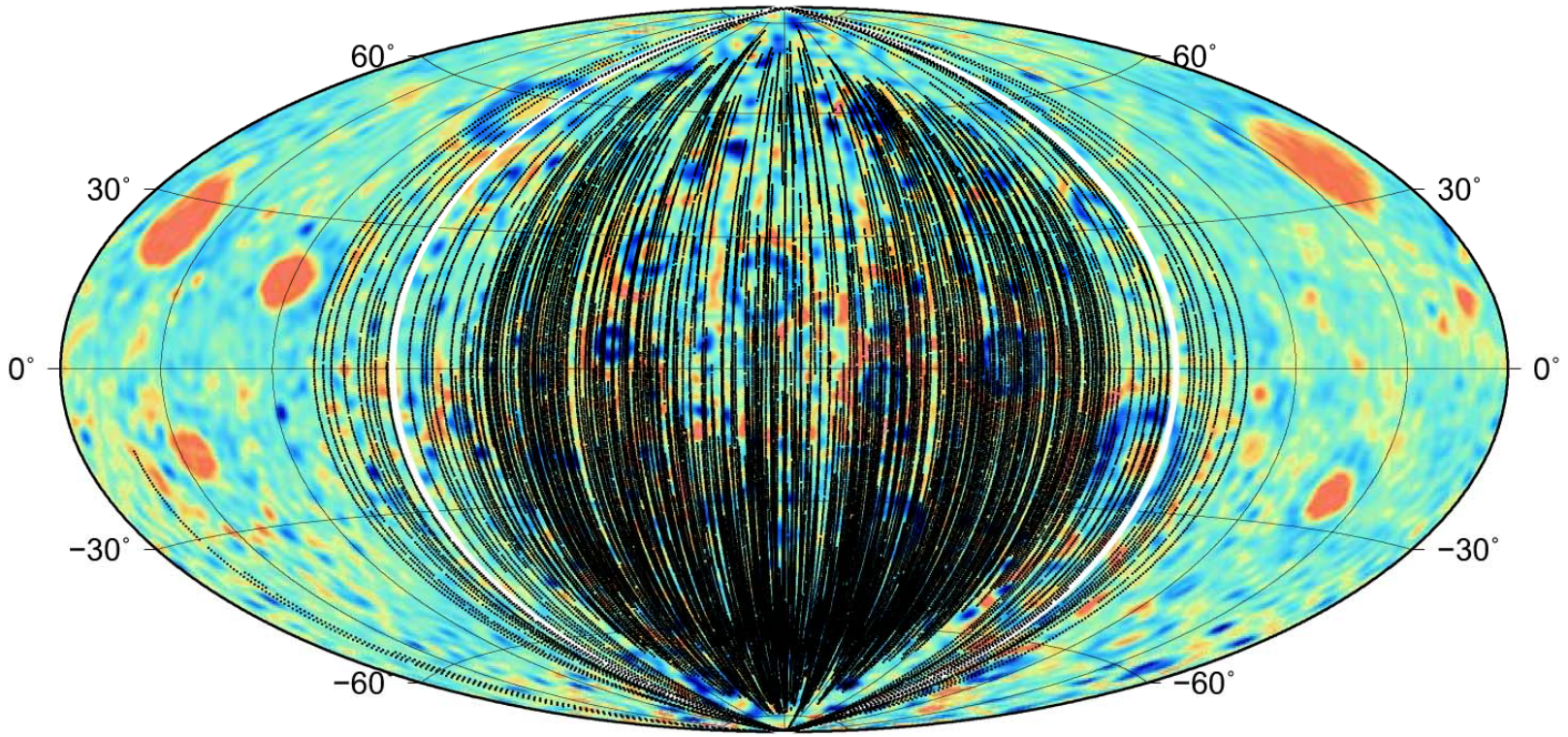
- SELENE : 2007.10.20～2008.12.26 & 2009.01.30
  Doppler + range (no VLBI data)
- Historical: LO I-V, A15/16ss, Clementine,
  LP nominal mission, SMART-1

Setting

- GEODYN II, SOLVE system
- Expanded up to degree and order 100
- Ephemeris: DE421
- A Kaula-type constraint of $3.6 \times 10^{-4}/n^2$
- Solar radiation pressure model
  SELENE Main: box + wing
  SELENE R/Vstar and other satellites : cannonball
- Mean arc length of Rstar = 2.6 days
- VLBI data not included

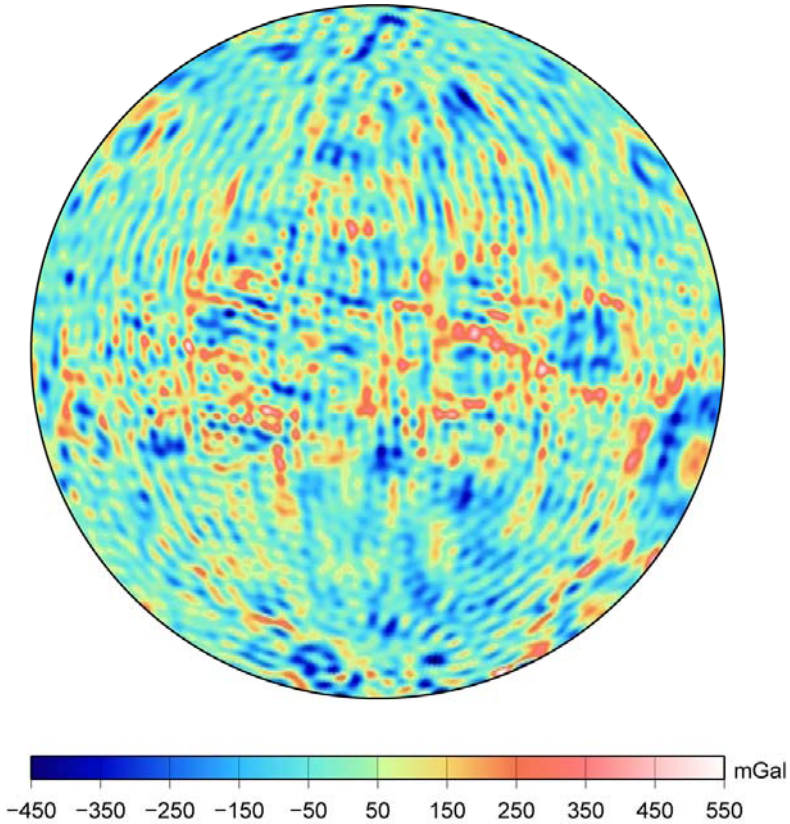
4-way Doppler data coverage achieved during the lifetime of Rstar

071031−090130

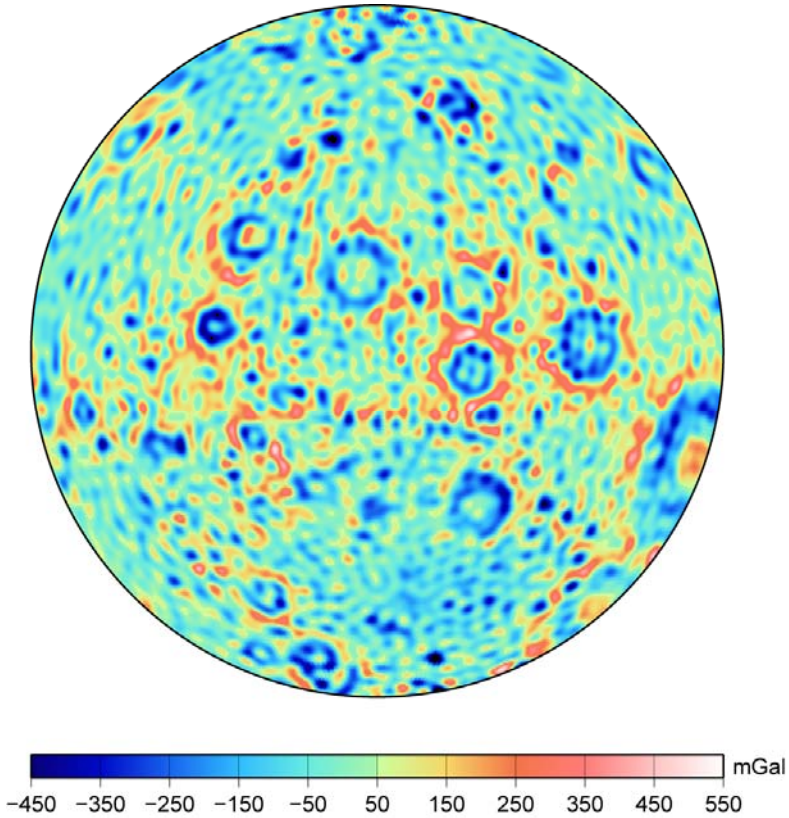


White solid line indicates the boundary between the near-side and the far-side

Old and new views of far-side gravity field

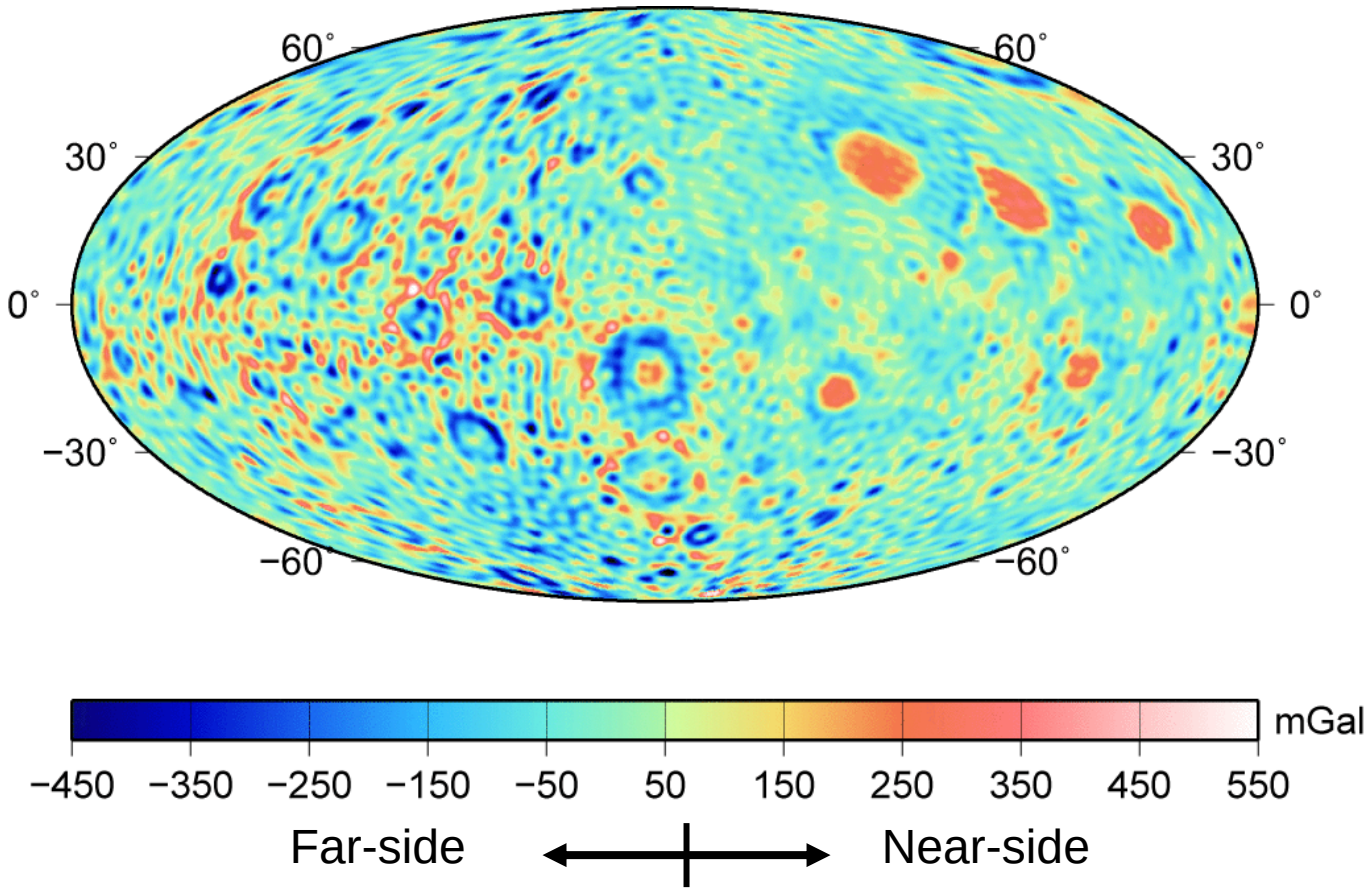


LP100K



SGM100h

SGM90d and SGM100h



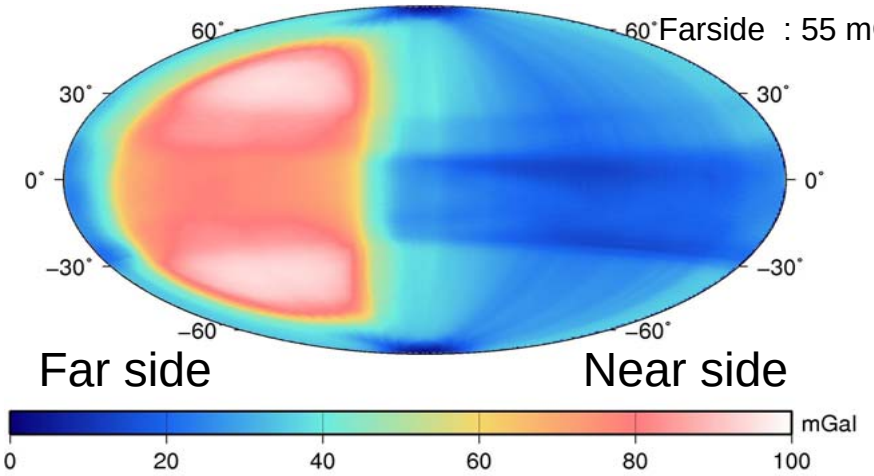
SGM90d
Namiki et al. (2009)
based on 5-month of SELENE data
plus historical data

SGM100h
Matsumoto et al. (submitted to JGR)
based on 14-month of SELENE data
plus historical data

Gravity anomaly errors from the full covariance matrix

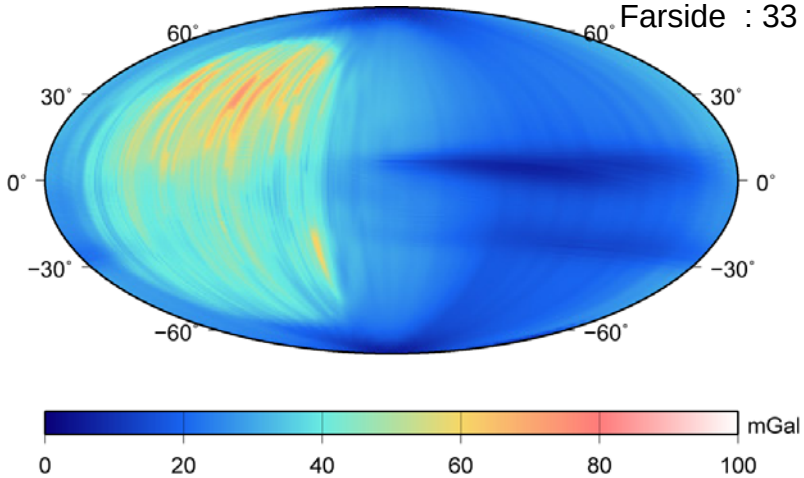
LP100K

Max : 95 mGal
Nearside: 25 mGal
Farside : 55 mGal

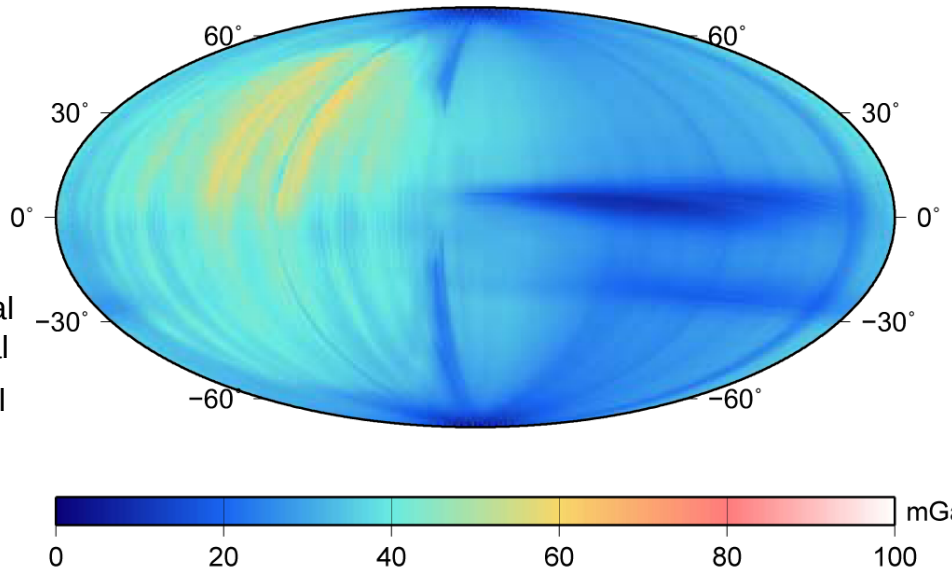


SGM90d

Max : 75 mGal
Nearside: 20 mGal
Farside : 33 mGal

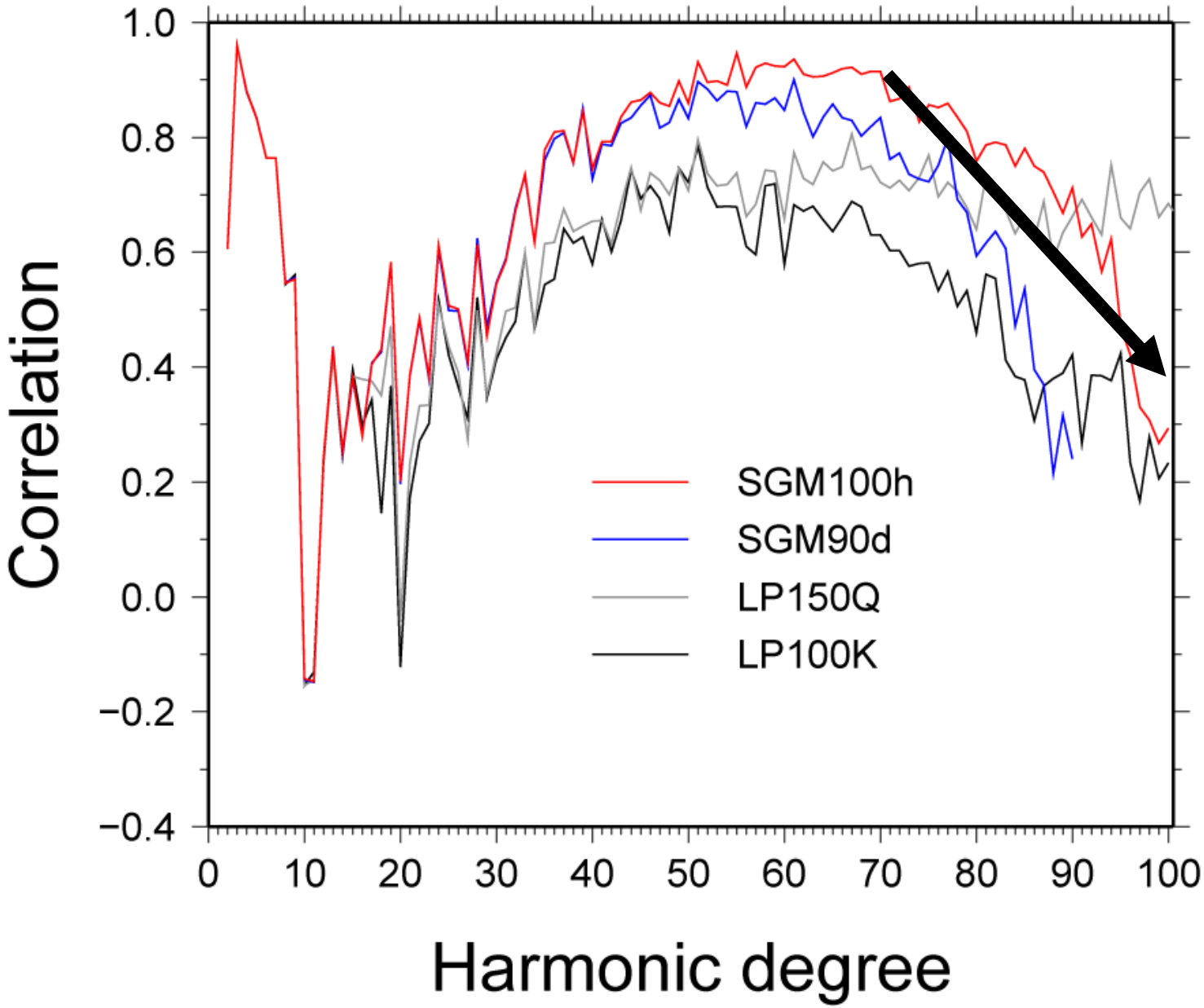


SGM100h

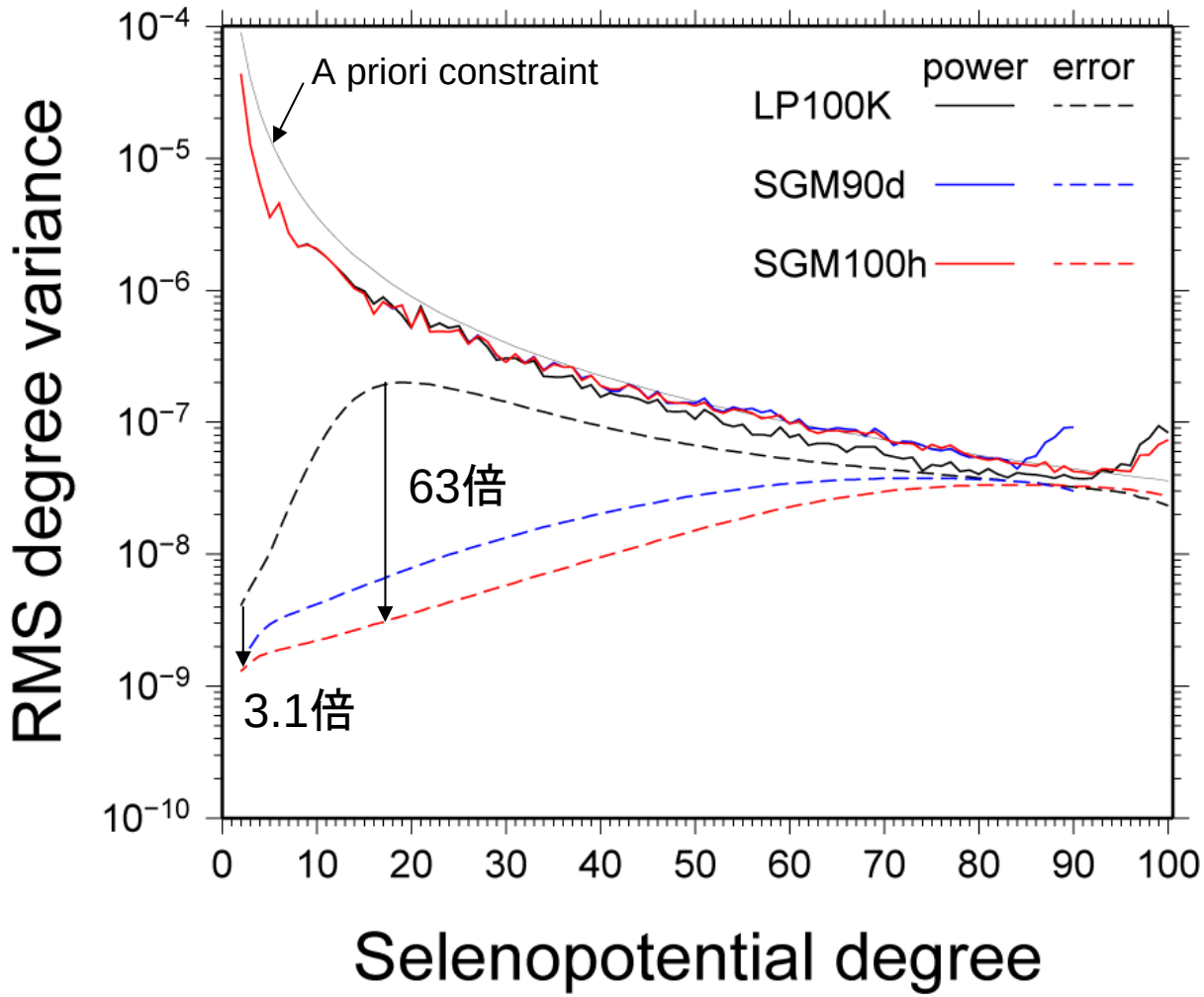


Max : 62 mGal
Nearside: 26 mGal
Farside : 35 mGal

Correlation between gravity and topography



RMS degree variances

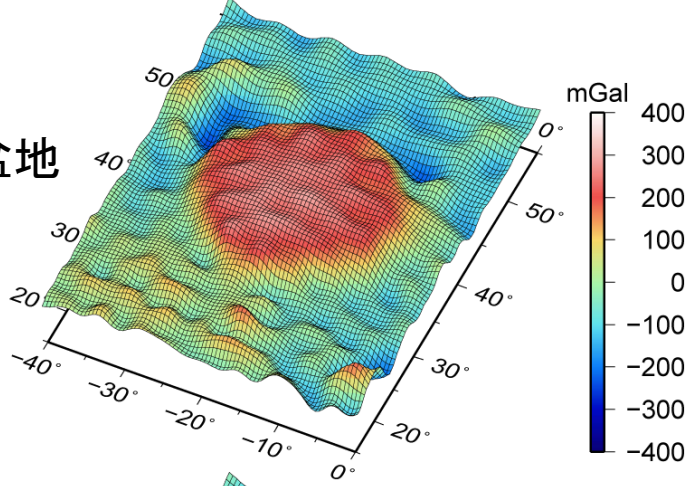


SGM100h gives more than one order of magnitude smaller formal errors with respect to LP100K for degrees 7-39.

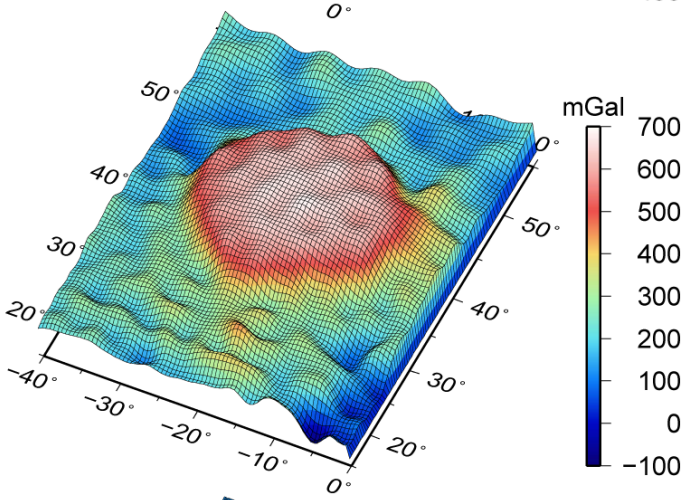
表側

Imbrium盆地

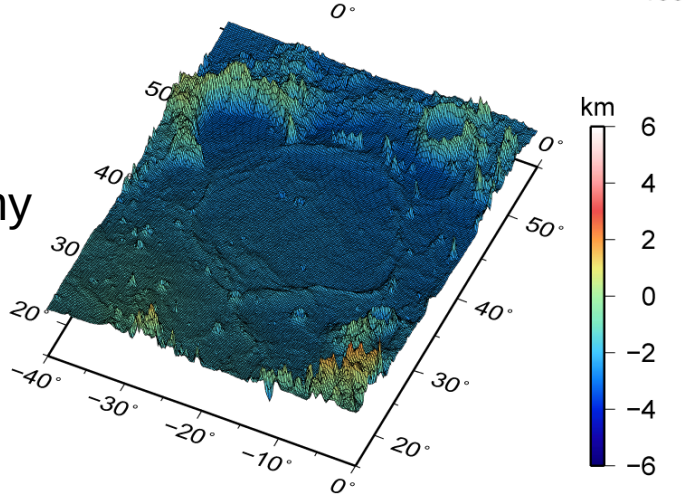
Free-air gravity Anomaly



Bouguer gravity anomaly



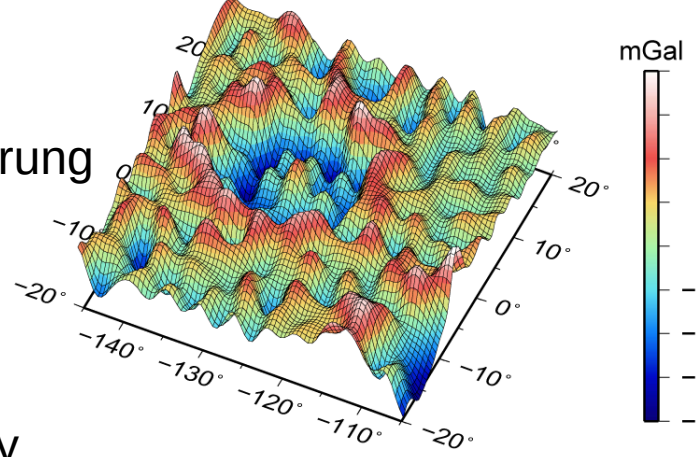
topography



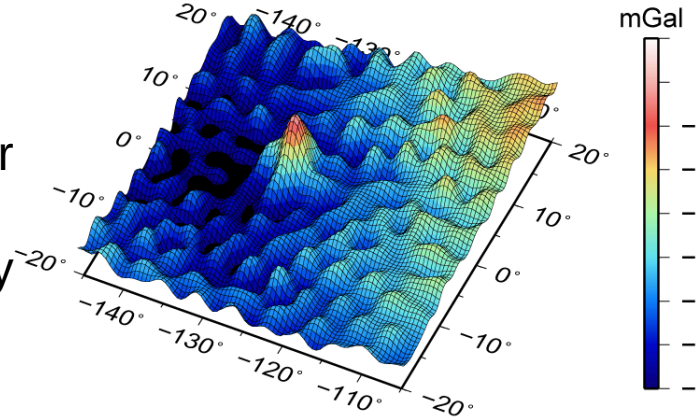
裏側

Hertzsprung 盆地

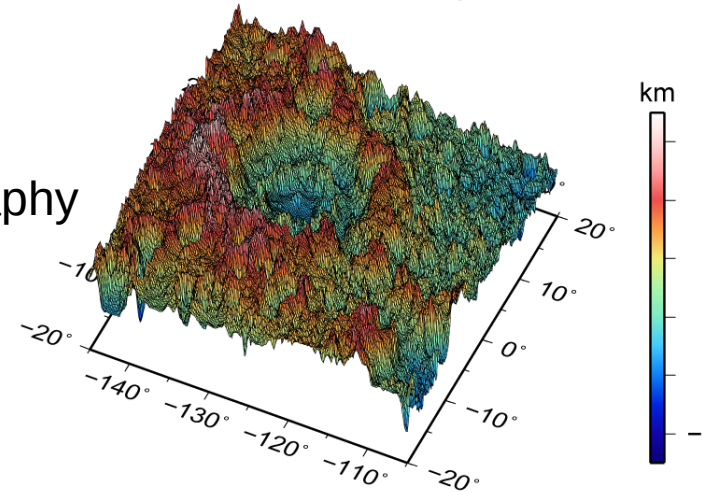
Free-air gravity Anomaly



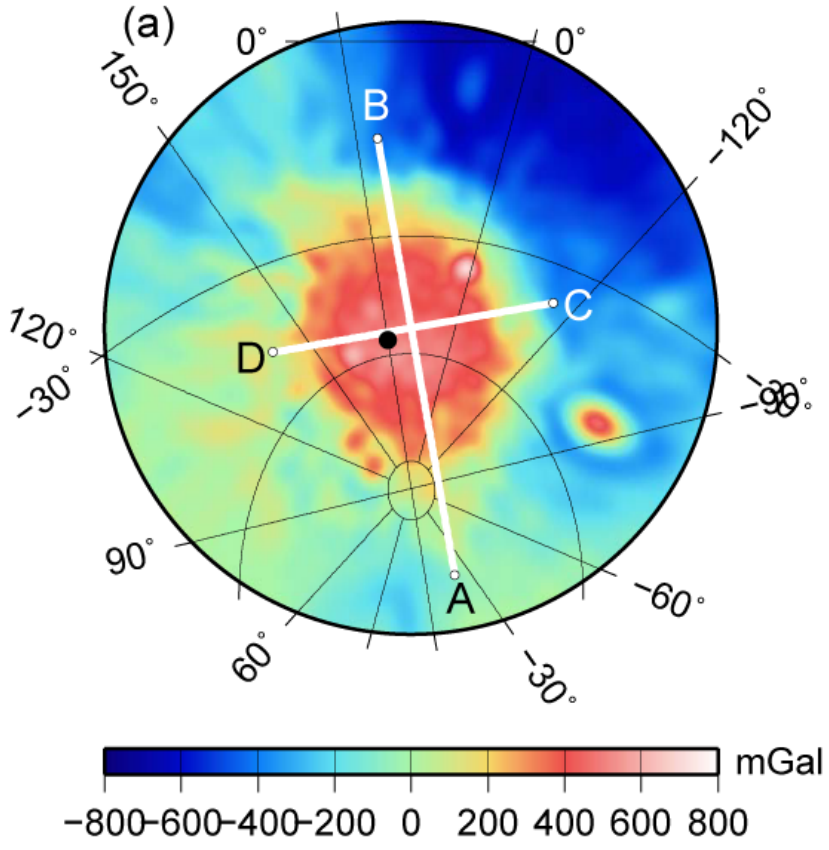
Bouguer gravity anomaly

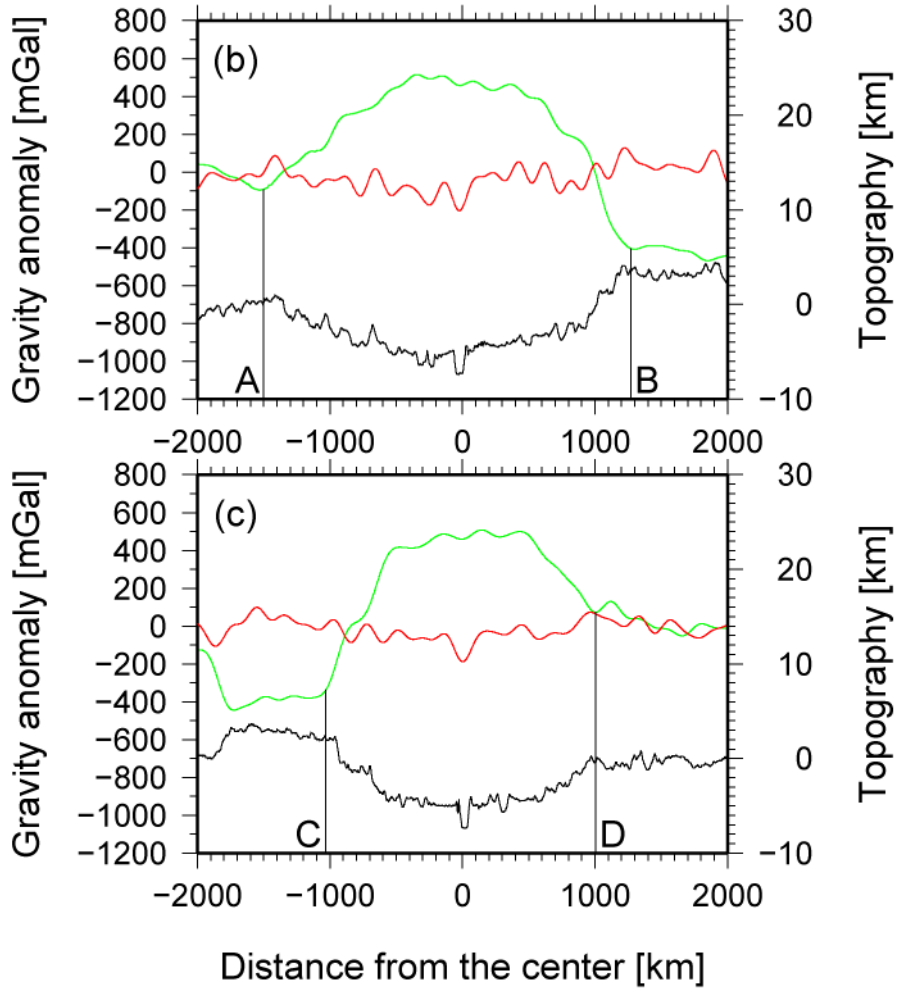


topography



Elliptical signature of the South Pole-Aitken Basin





Bouguer gravity anomaly around SPA

SGM100h_VLBI 【VLBI data included】

Data

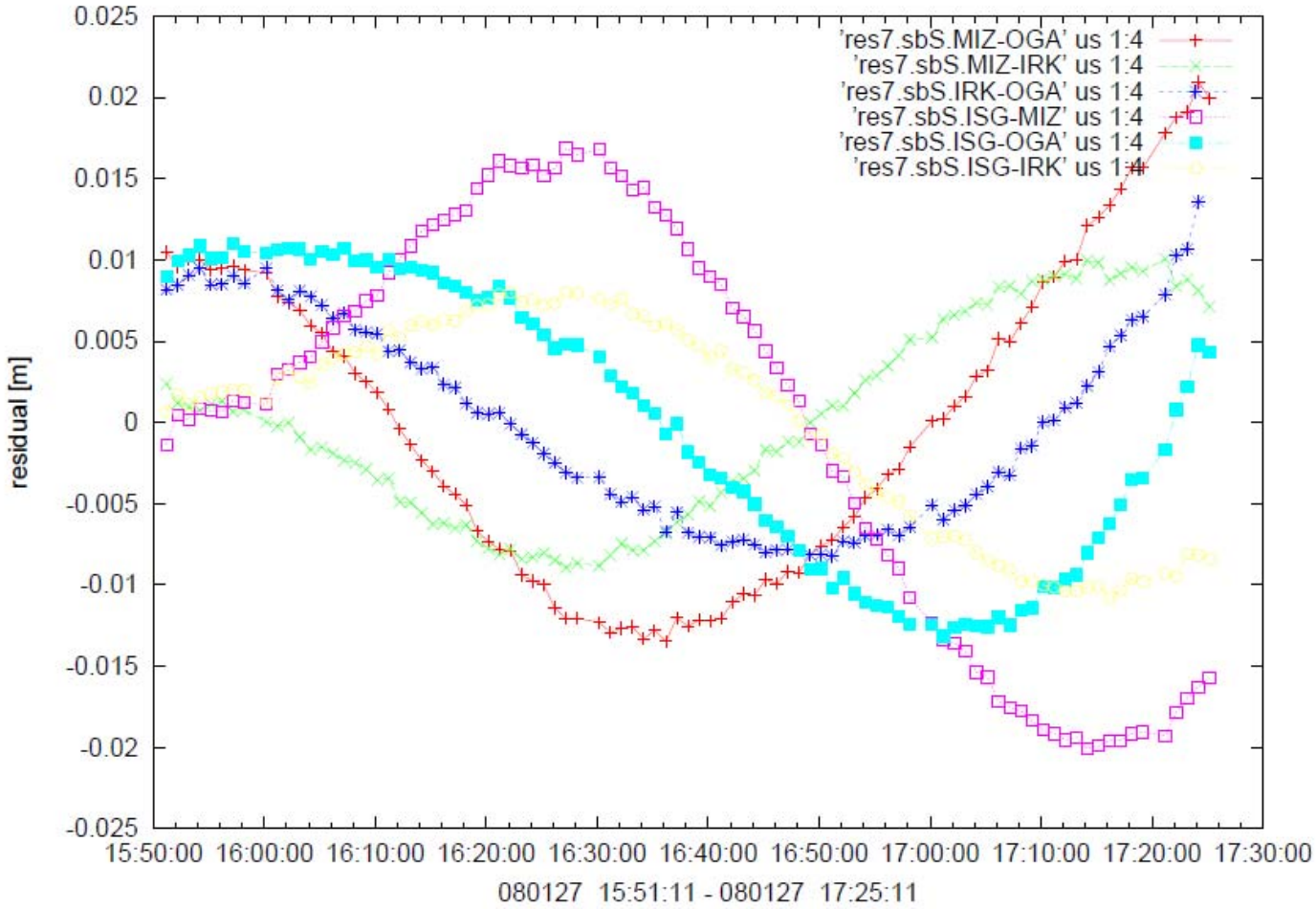
- S-band same-beam VLBI data.
- Differential phase delays are determined for January, March, April, May, June, July, and August 2008 (7 months).
- Doubly differenced 1-way range (DDOR).
- Expected accuracy of differential phase delay = 3.44 ps (Kikuchi et al., Radio Science, 2009) → 1 mm.

Setting

- Cannon ball model for solar radiation pressure (R/Vstar).
- R/Vstar mean arc length = 13.6 days (15 arcs).
- Fit the orbits of 3 satellites to 2-way range, 2-way Doppler, 4-way Doppler, and VLBI simultaneously.
- DDOR data weight = 1 cm.
- RMS VLBI residual: 1.4 cm with SGM100h as a priori

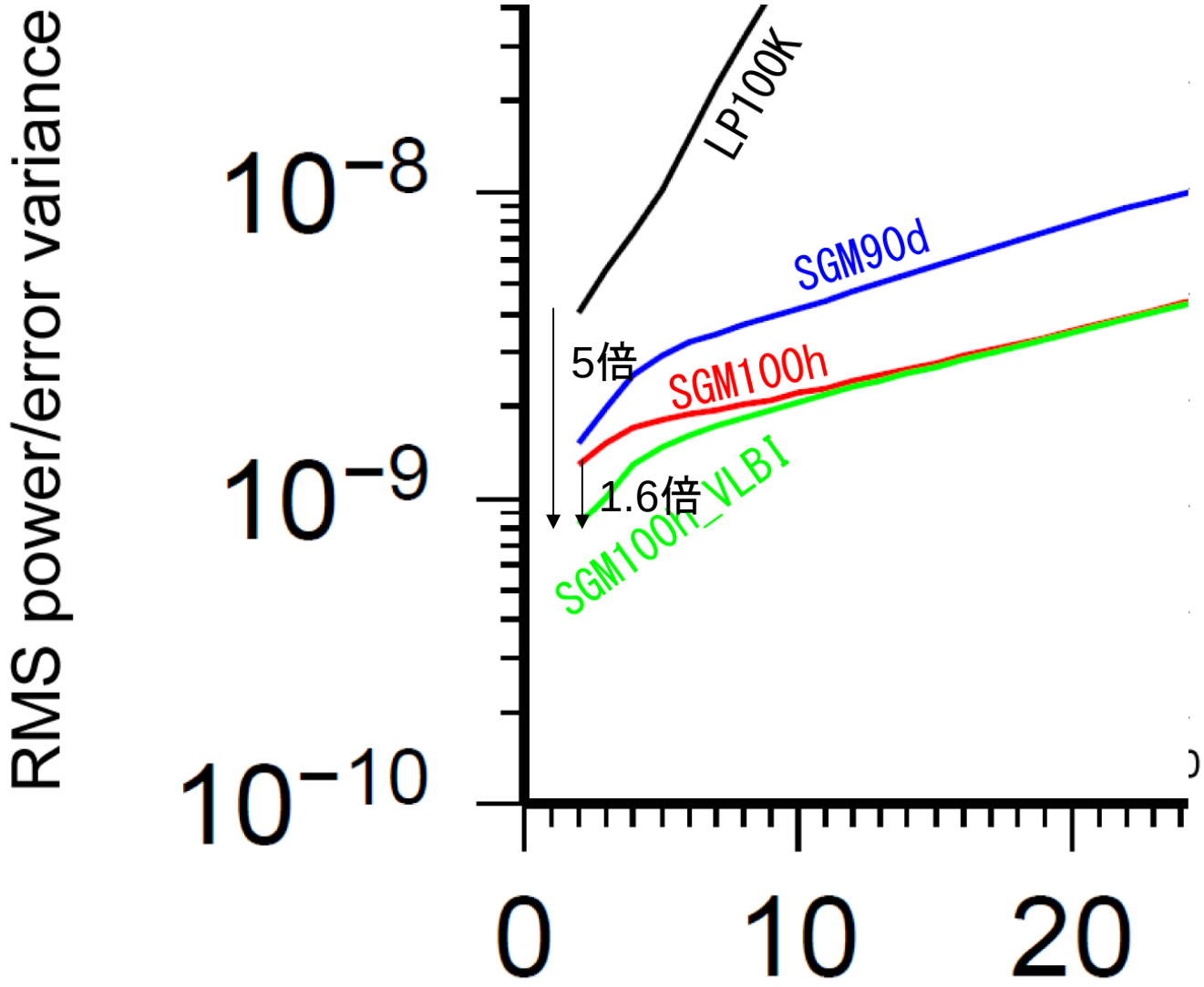
  → 0.9 cm (post-fit, i.e., with SGM100h_VLBI)

Same-beam VLBI residuals



数cmの振幅をもつ長周期変動が見られる。
太陽輻射圧モデル誤差に起因か？

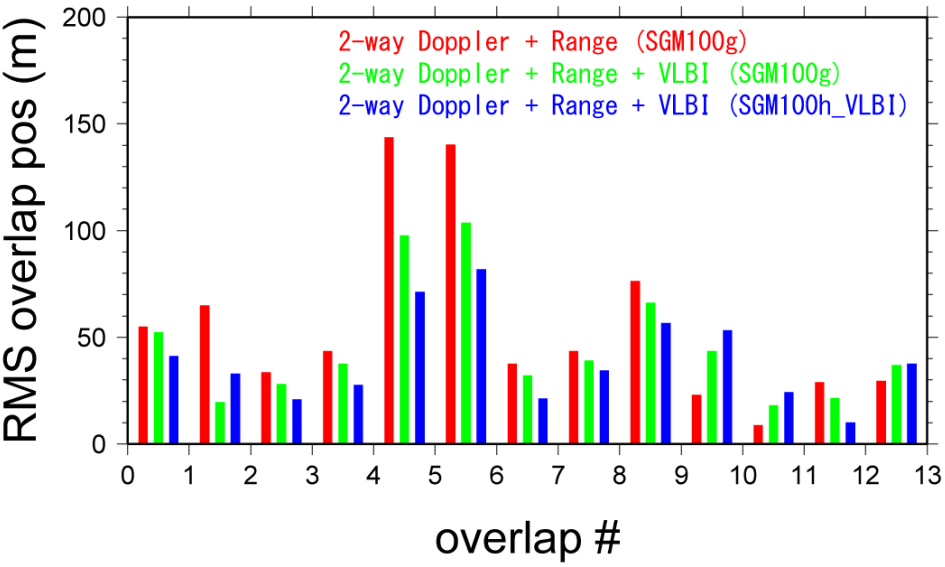
Contribution of VLBI data



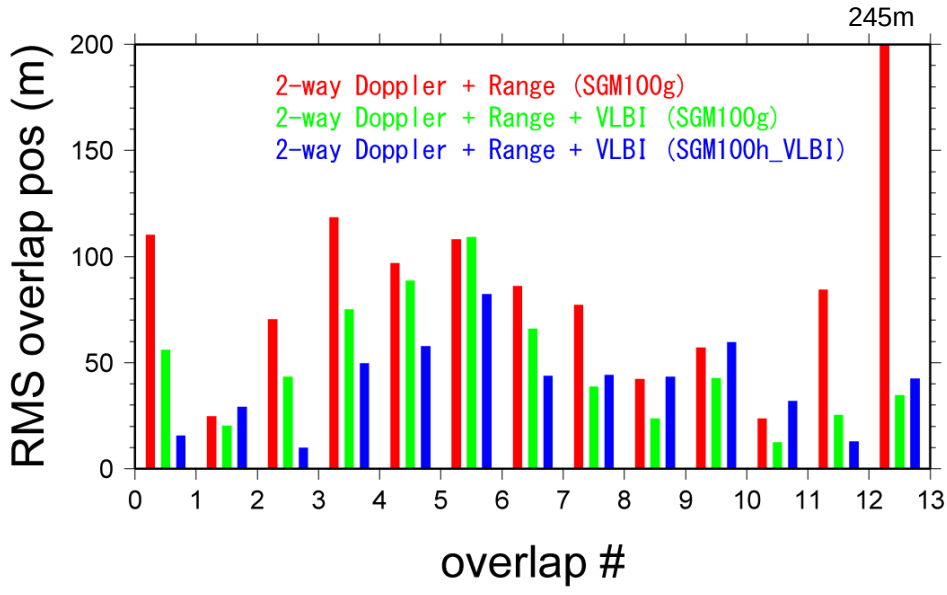
LP100K / SGM100h_VLBI = 5.0

Contribution of VLBI data - orbit overlap statistics -

Rstar

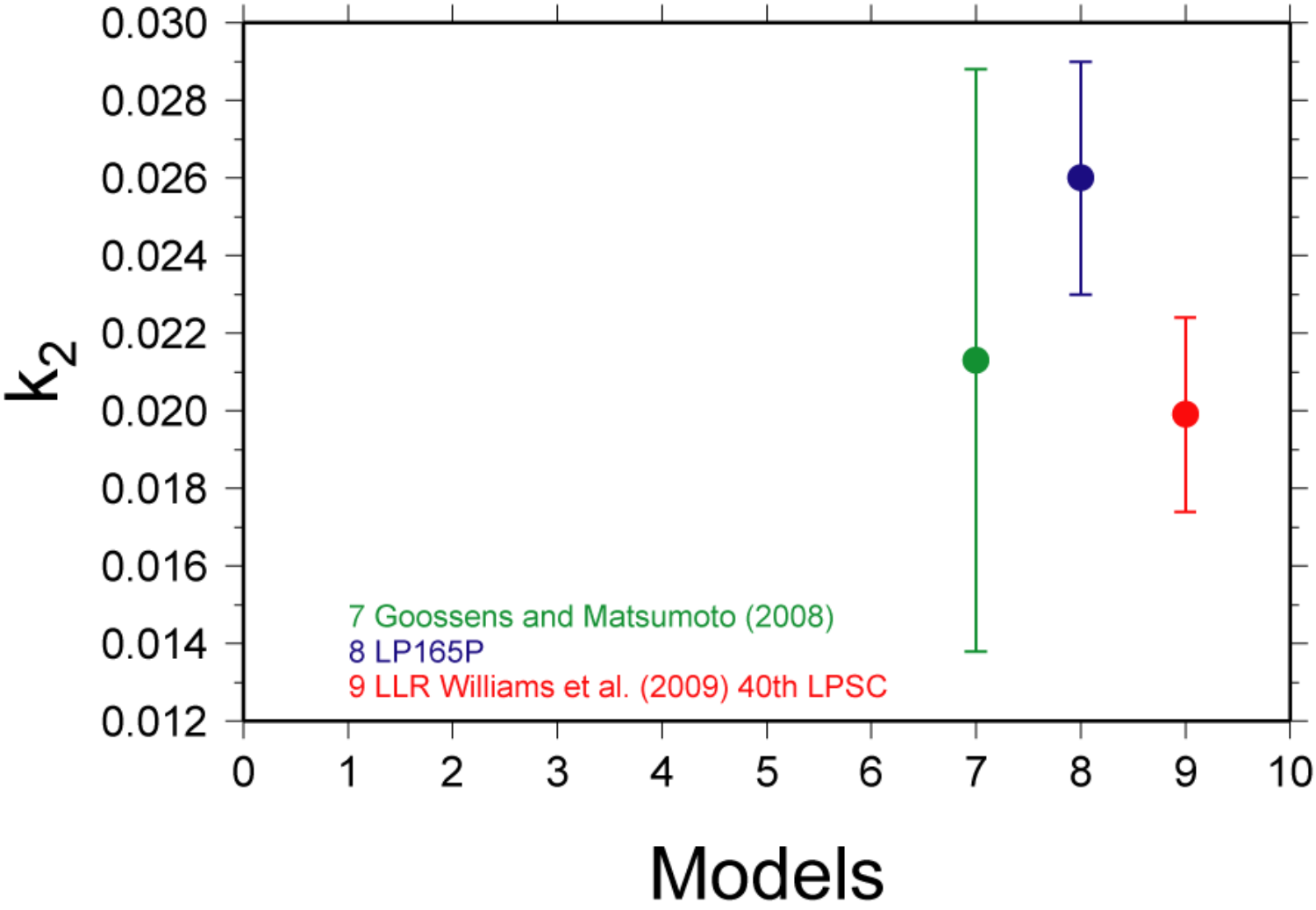


Vstar



- Mean arc length = 13.6 days , overlapping duration = 1 day.
- In general, overlap position differences decrease by adding VLBI data to conventional 2-way Doppler and range data.
- The orbit consistency is further improved, in more than half the cases, with the VLBI-included model SGM100h_VLBI.

k_2 estimates



Quoted sigma's for k_2 are ten times the formal error (except for LLR).
LP99: Tracking data of the low-altitude extended mission of Lunar Prospector.

MOI (Moment of inertia) estimates

【Setup】

[**SGM90d**, Namiki et al., 2009] k2 value: 0.023295
J2 coefficient (unnormalised): $203.514682 \times 10^{-6}$
C22 coefficient (unnormalised): 22.401900×10^{-6}

[**SGM100h**, Matsumoto et al., 2009(In preparation)] k2 value: 0.024046
J2 coefficient (unnormalised): $203.538961 \times 10^{-6}$
C22 coefficient (unnormalised): 22.416703×10^{-6}

[**SGM100h_VLBI**] k2 value: 0.024029
J2 coefficient (unnormalised): $203.433343 \times 10^{-6}$
C22 coefficient (unnormalised): 22.429570×10^{-6}

Libration parameters (Konopliv et al.,1998):
$\beta = 631.486 \times 10^{-6}$ +/- 0.09×10^{-6} , $\gamma = 227.871 \times 10^{-6}$ +/- 0.09×10^{-6}

【Result】

C/MR^2 = 0.3932 +/- 0.0002 [LP165P, Konopliv et al., 2001]
C/MR^2 = 0.393348714 +/- 0.000118 [SGM90d]
C/MR^2 = 0.393479418 +/- 0.000116 [SGM100h]
C/MR^2 = 0.393444435 +/- 0.000096 [SGM100h_VLBI]

Errors for *C/MR^2* are based on five times the formal errors of the gravity field.

Core density estimates

【Setup/Assumption】

Internal structure : 3 layer (crust, mantle, core)

(The following parameters are fixed.)

Density : Crust:**2850**, Mantle:**3360** [kg/m^3]

Radius of the Moon : **1737.15** [km]

Crustal thickness : **53** [km]

Core radius : **450** [km]

GM = 4902.8003 [km^3/s^2] [LP165P]
GM = 4902.8010 [km^3/s^2] [SGM90d]
GM = 4902.8021 [km^3/s^2] [SGM100h]
GM = 4902.8009 [km^3/s^2] [SGM100h_VLBI]

【Results in this presentation】

Core density = **3781 ～ 6650** [kg/m^3], err = ±**28%** [LP165P, Konopliv et al., 2001]

Core density = **5434 ～ 7131** [kg/m^3], err = ±**14%** [SGM90d]

Core density = **6387 ～ 8054** [kg/m^3], err = ±**12%** [SGM100h]

Core density = **6275 ～ 7662** [kg/m^3], err = ±**10%** [SGM100h_VLBI]

4700 [kg/m^3] : FeS
5300 [kg/m^3] : Eutectic Fe-FeS
7400 [kg/m^3] : Liquid Fe
7700 [kg/m^3] : solid Fe
8100 [kg/m^3] : γ-Fe [Kuskov, 1995] など

Summary

- Historical tracking data + SELENE range & Doppler data → SGM100h model
- Far side gravity errors are drastically reduced.
- k_2 estimates still diverge to ∼11% depending on data used(*).
- VLBI data improve the accuracy of the low degree coefficient and orbit consistency(*)
- MOI and core density of the Moon is estimated. The error is reduced from 30% to 10% compared with LP165P.

(*)The processing is still in progress.

長期にわたるサポートに感謝いたします。