An Improved Lunar Gravity Field Model from SELENE and Historical Tracking Data

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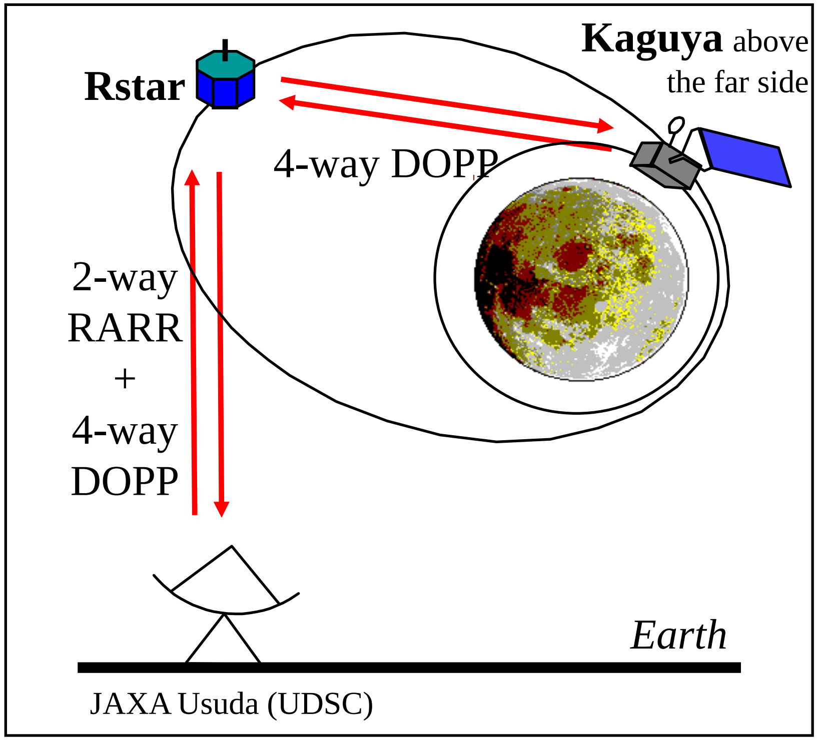
[2] Shanghai Astronomical Observatory
[3] Japan Aerospace Exploration Agency
[4] Chiba Institute of Technology
[5] NASA Goddard Space Flight Center
[6] University of Tasmania
[7] Geodetic Observatory Wettzell
[8] Urumqi Astronomical Observatory

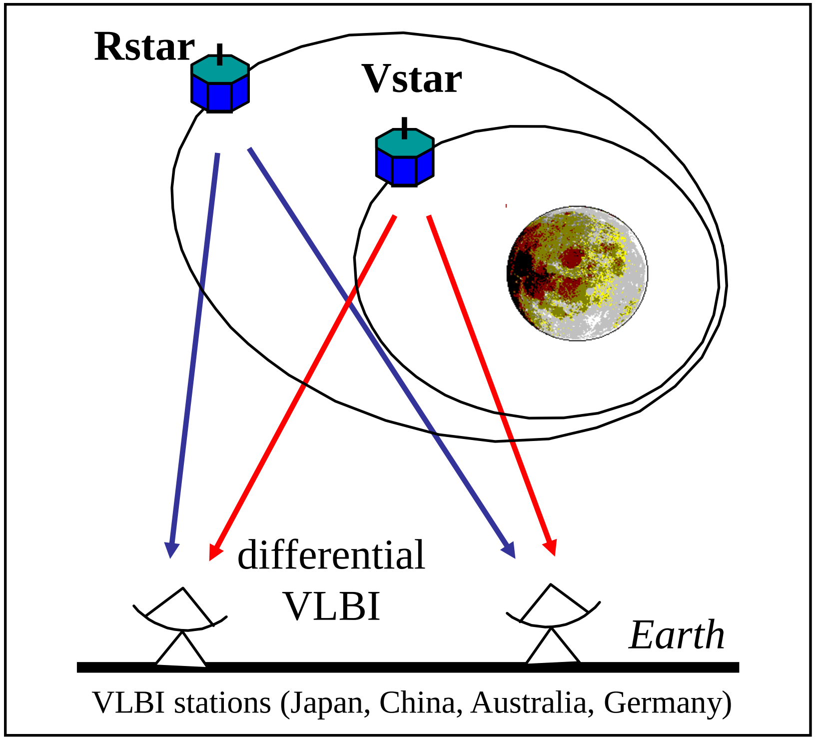
SELENE gravimetry

RSAT Mission
4-way Doppler for farside coverage



First half of this talk

VRAD Mission
Differential VLBI
Doubly differenced 1-way range



Second half

Status of the SELENE satellites

- 2007.09.14 Launched from Tanegashima Space Center
- 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
  → put into 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
  because of its natural orbital evolution
- 2009.06.10 Controlled crash of the Main satellite
- 2009.06.29 The last tracking of Vstar (VLBI sub-satellite)

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

Tracking data

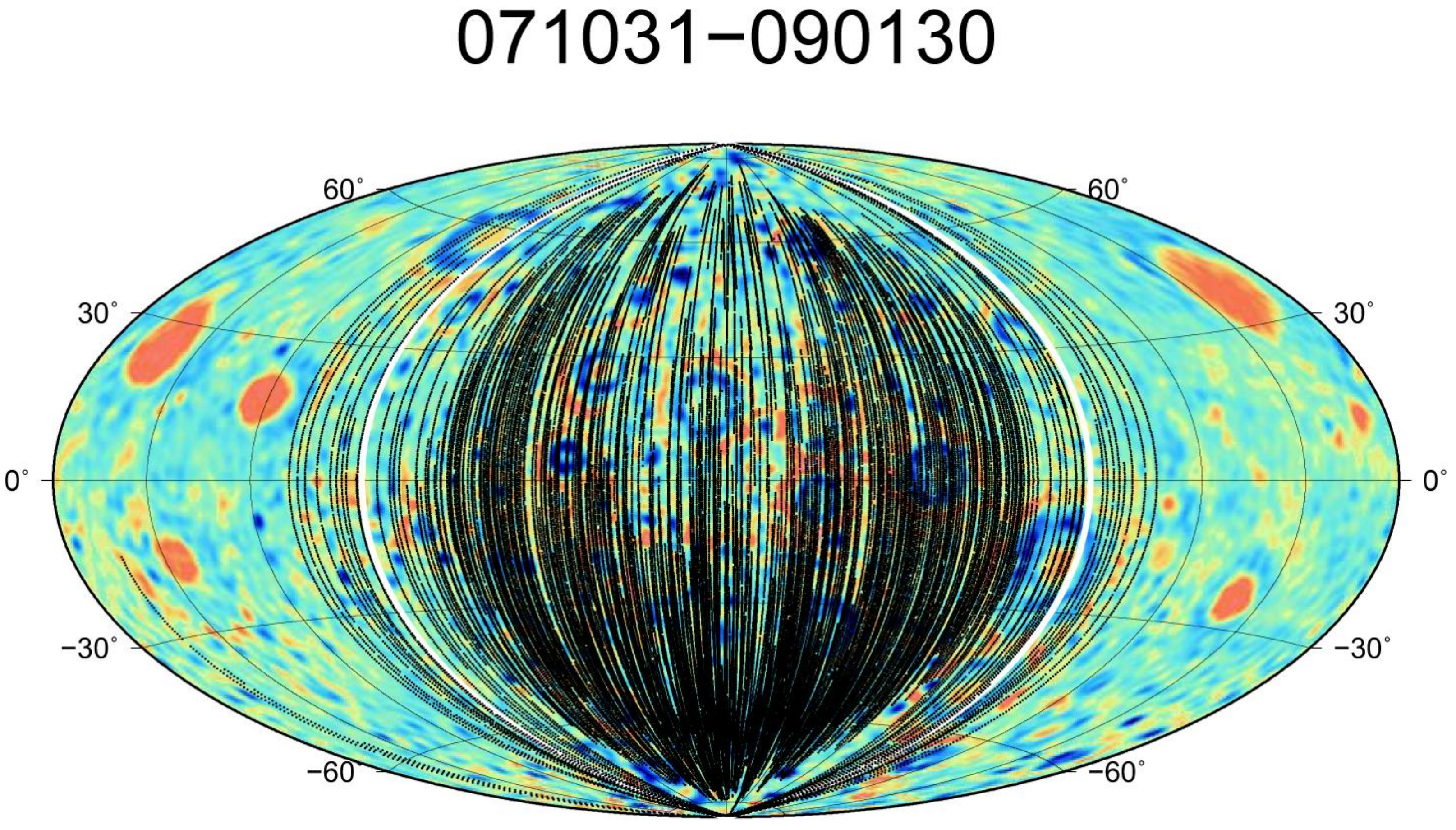
- SELENE：2007.10.20～2008.12.26 & 2009.01.30
  Doppler + range (no VLBI data)
- Historical: LO I-V, A15/16ss, Clementine,
  LP nominal mission, SMART-1

Setting

- NASA GSFC 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

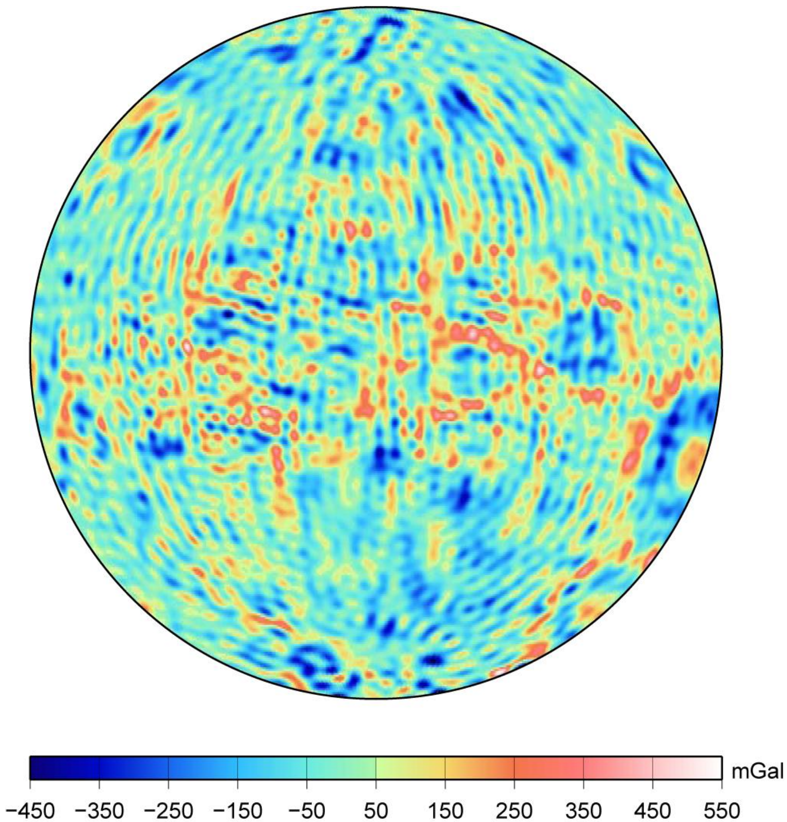
For more detail, see Matsumoto et al., JGR Planets, in press.
This model is available online at SELENE Level 2 Database.

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

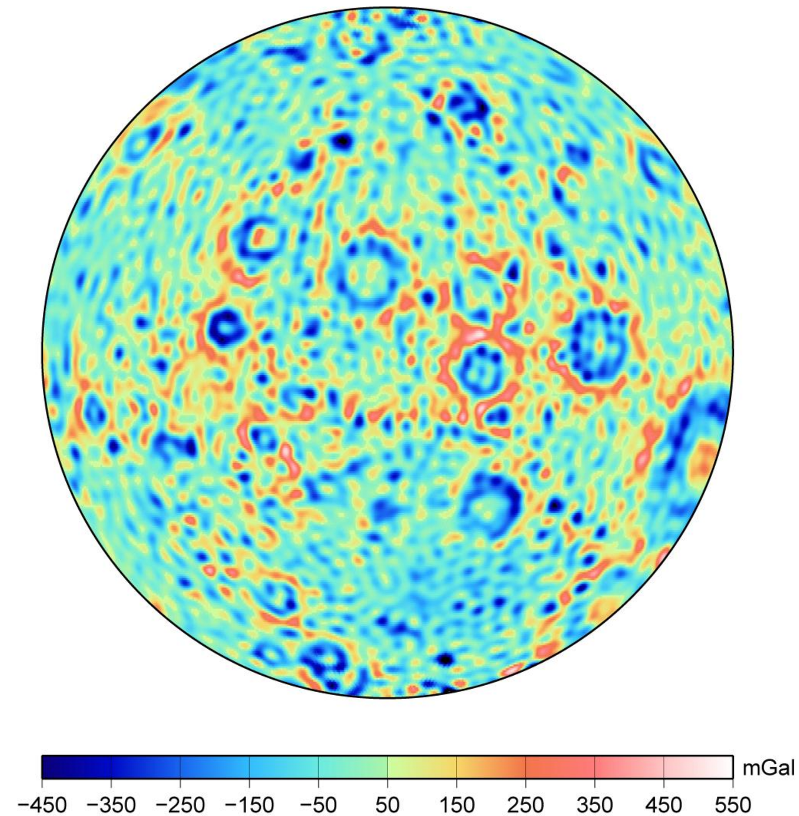


White solid line indicates the boundary between the near-side and the far-side

Old and new views of farside gravity field

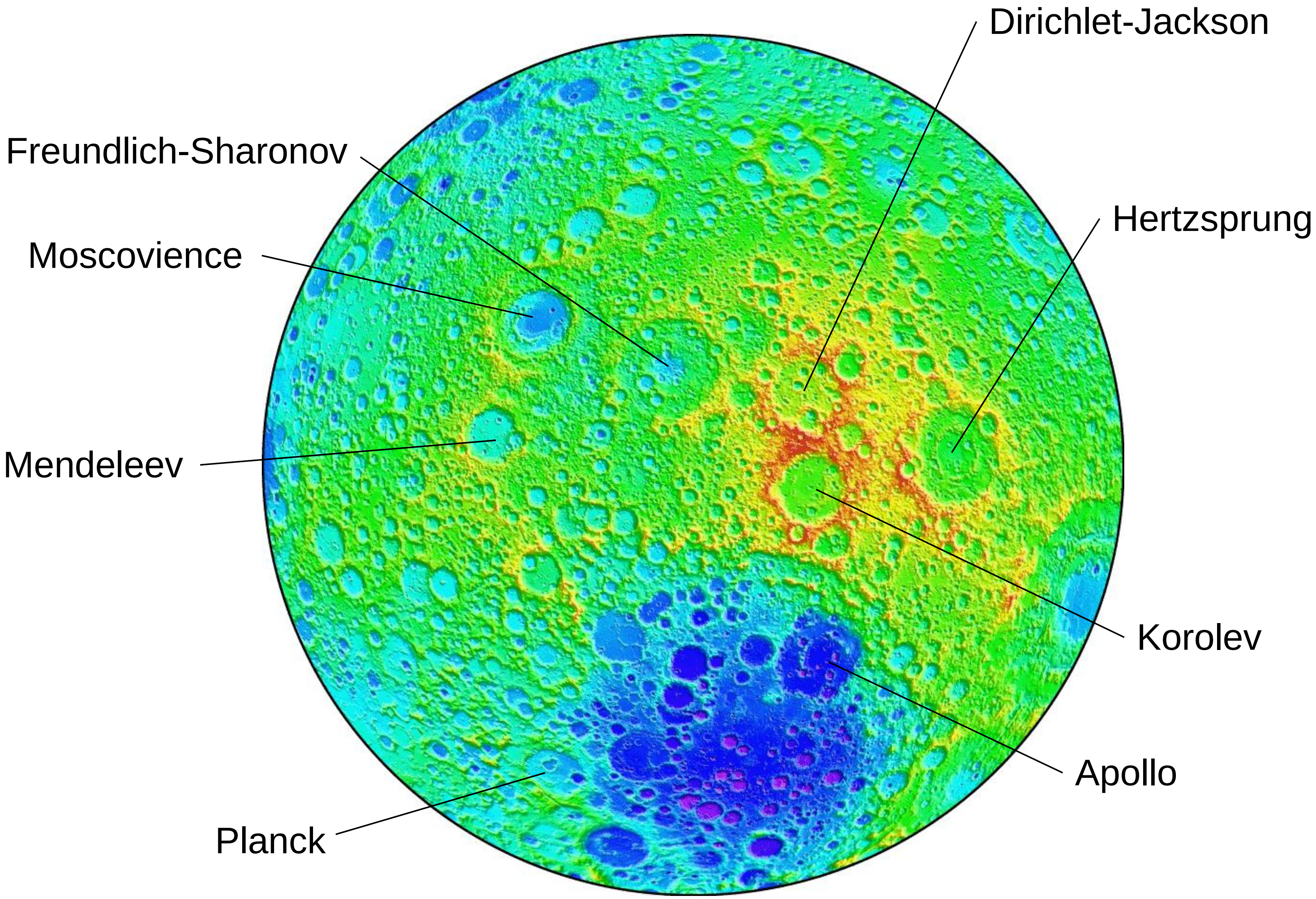


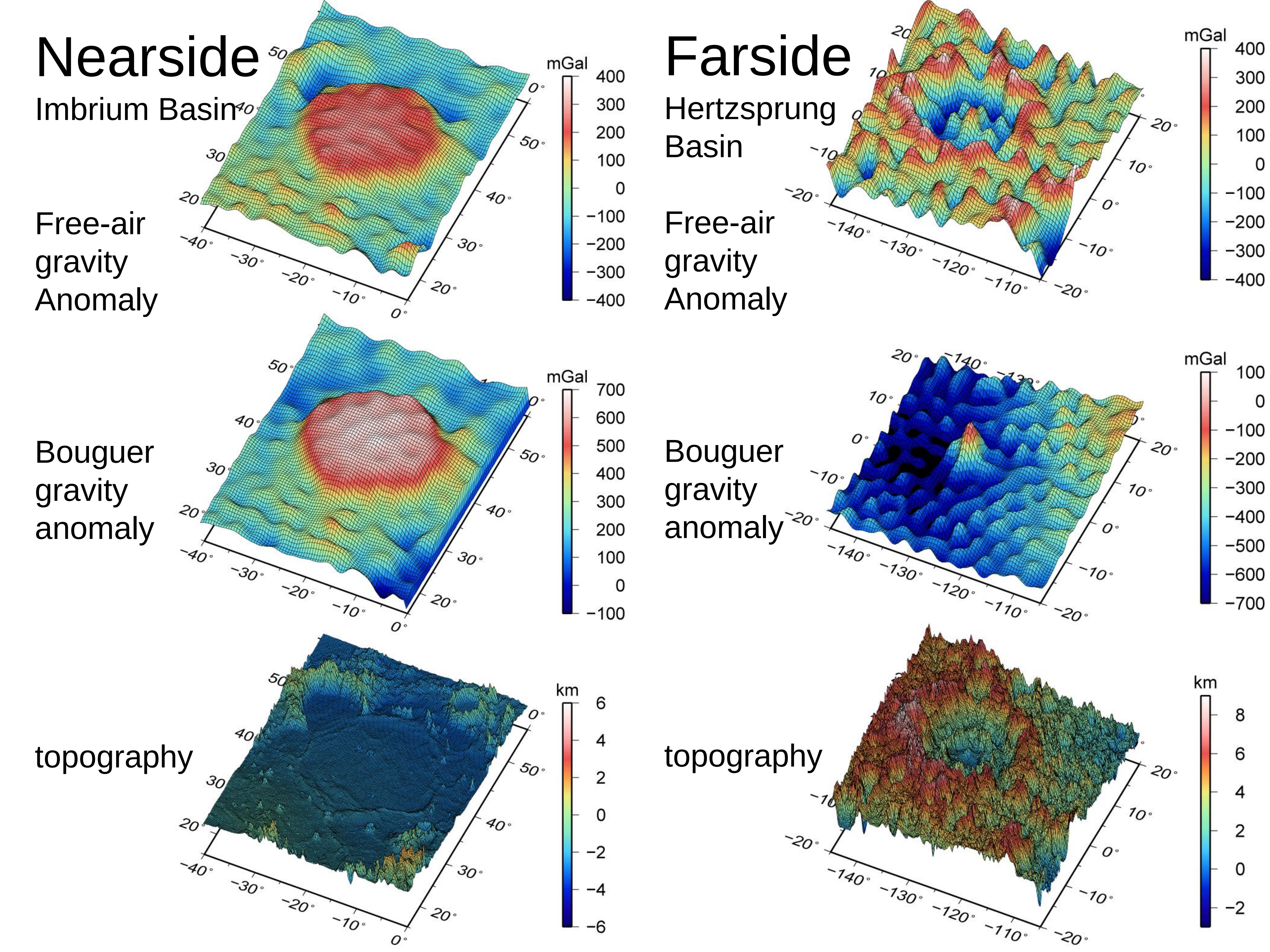
LP100K



SGM100h

Topography-gravity correspondence

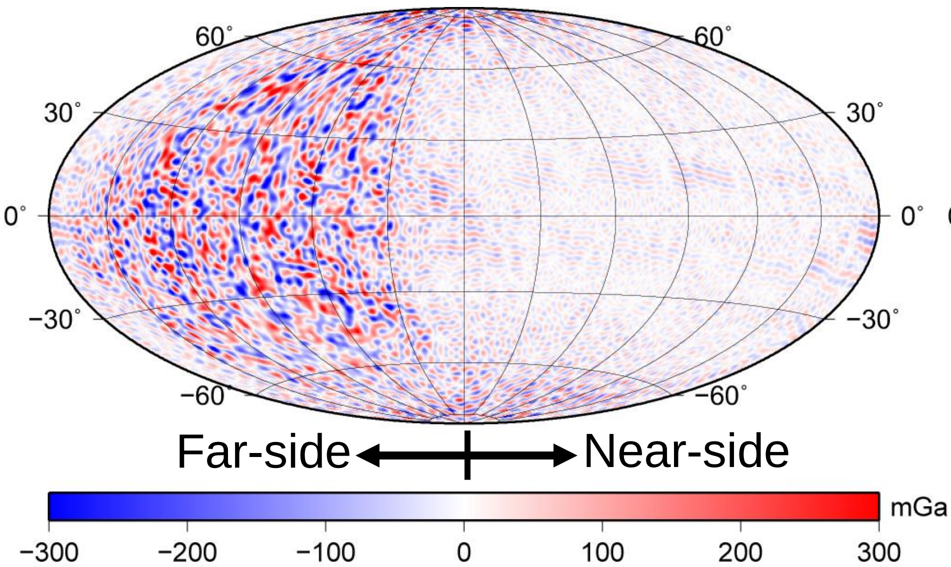




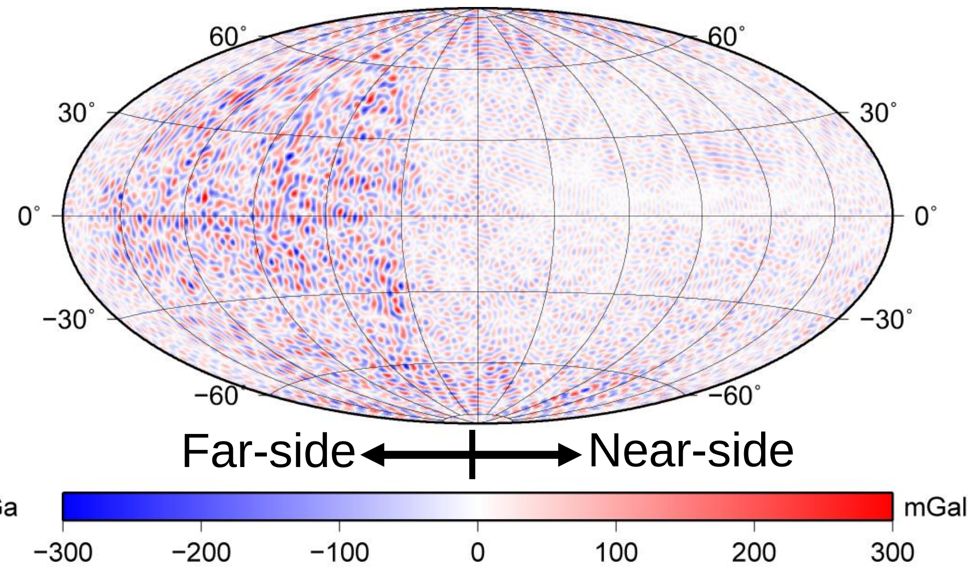
Nearside
Imbrium Basin
Free-air gravity Anomaly
Bouguer gravity anomaly
topography
Farside
Hertzsprung Basin
Free-air gravity Anomaly
Bouguer gravity anomaly
topography
mGal
400
300
200
100
0
−100
−200
−300
−400
mGal
700
600
500
400
300
200
100
0
−100
km
6
4
2
0
−2
−4
−6
mGal
100
0
−100
−200
−300
−400
−500
−600
−700
km
8
6
4
2
0
−2

Free air gravity anomaly differences

SGM100h-LP100K



SGM100h-SGM90d



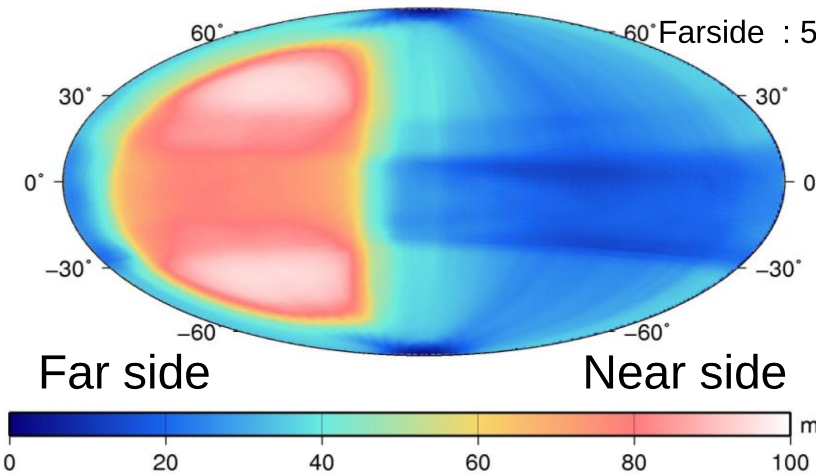
Min: -495mGal
Max: 544mGal
RMS:
near-side 46mGal
far-side 96mGal
global 76mGal

Min: -313mGal
Max: 355mGal
RMS:
near-side 43mGal
far-side 67mGal
global 57mGal

Gravity anomaly errors from the full covariance matrix

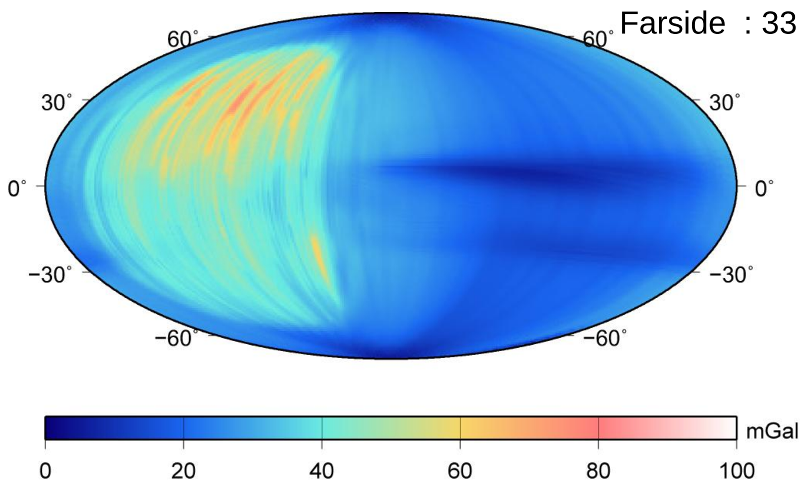
LP100K

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

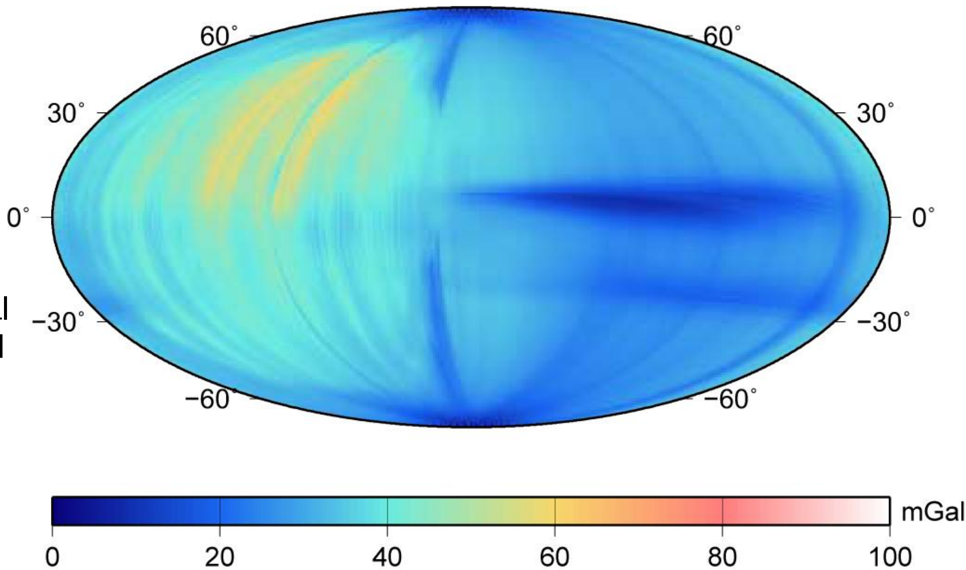


SGM90d

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

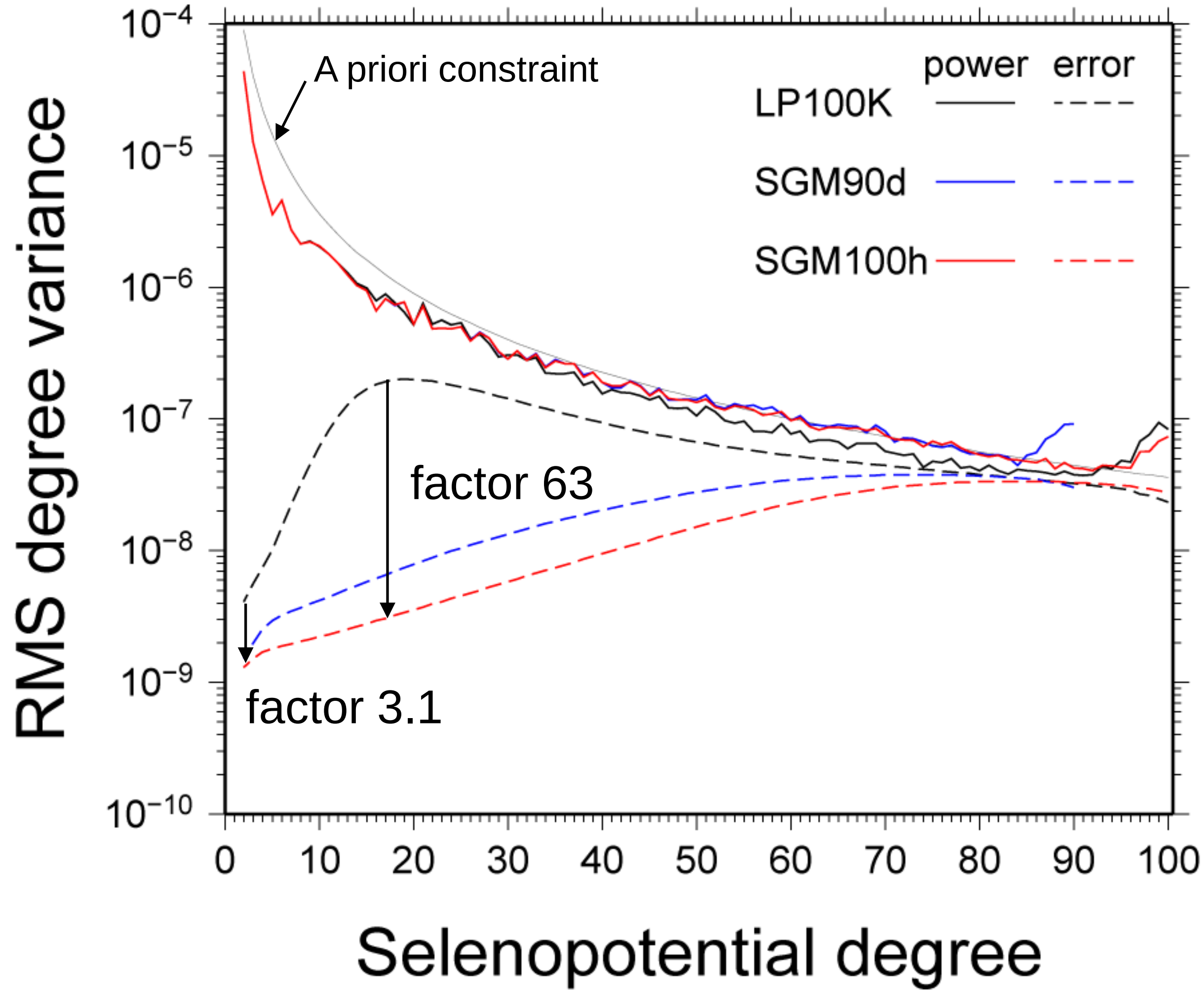


SGM100h



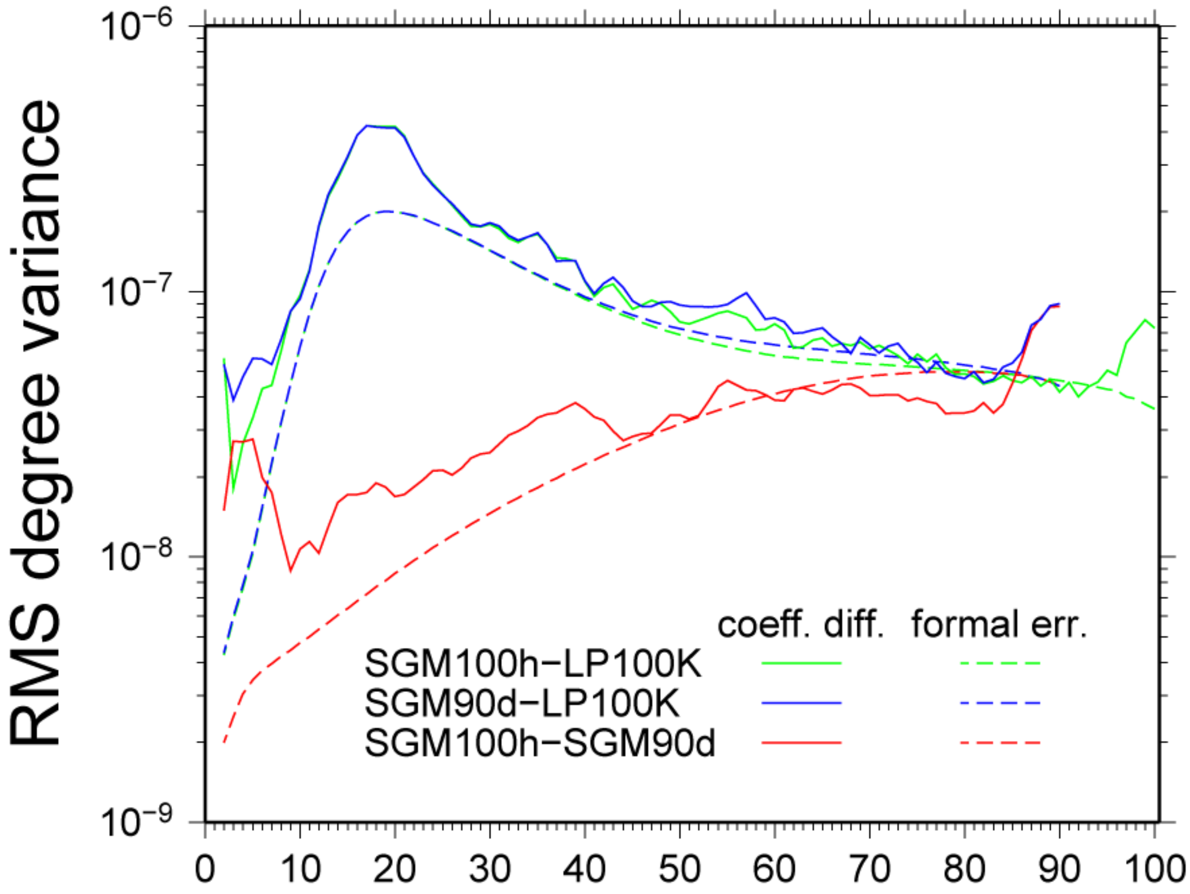
Max : 62 mGal
Nearside: 26 mGal
Farside : 35 mGal

RMS degree variances



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

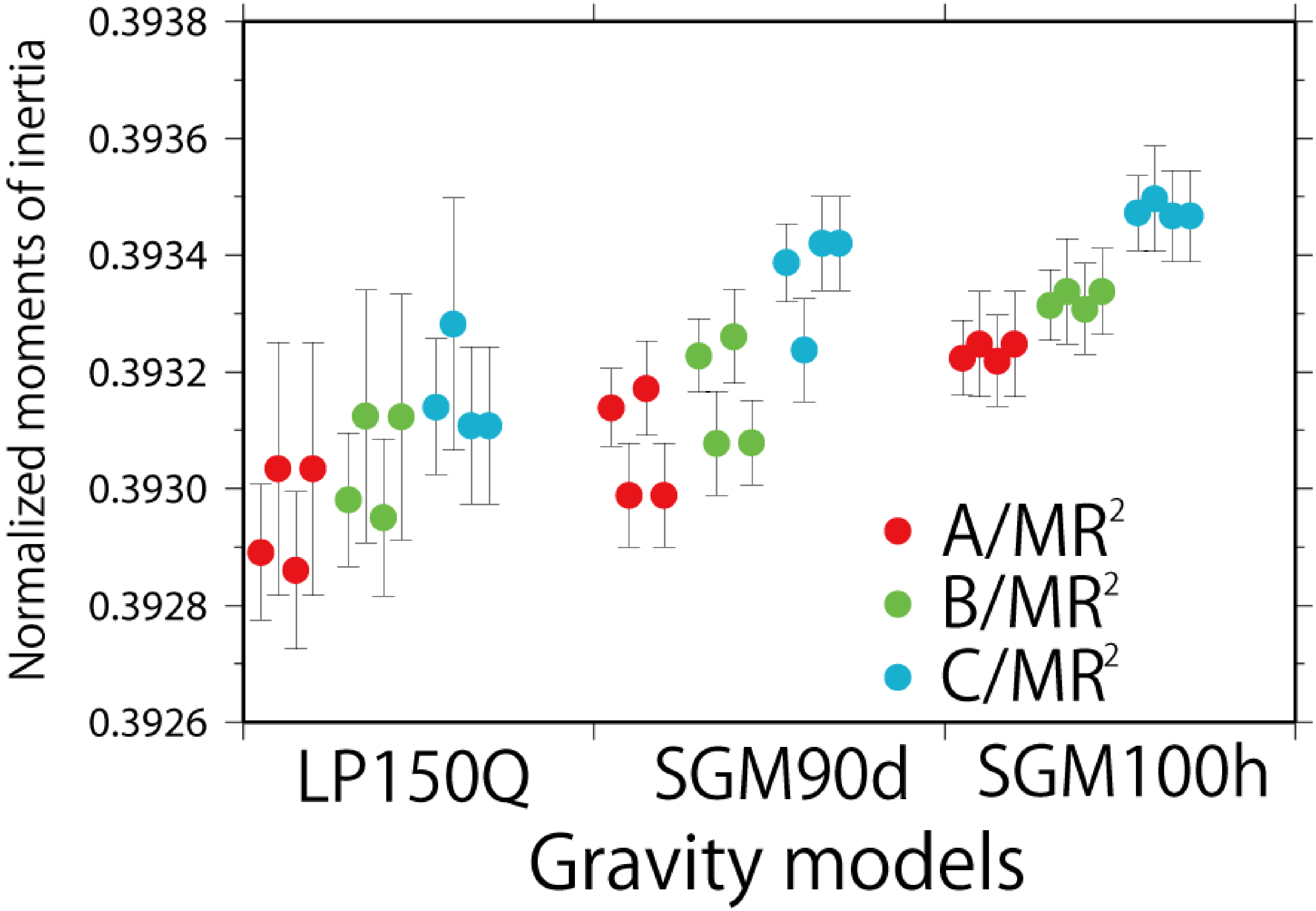
Coefficient differences



The coefficient differences agree with the formal errors within a range of 3 sigmas for $n > 8$, but there are larger deviations for the lower-degree terms. In particular, discrepancies exceeding 10 sigmas occur at degrees 2 and 3.

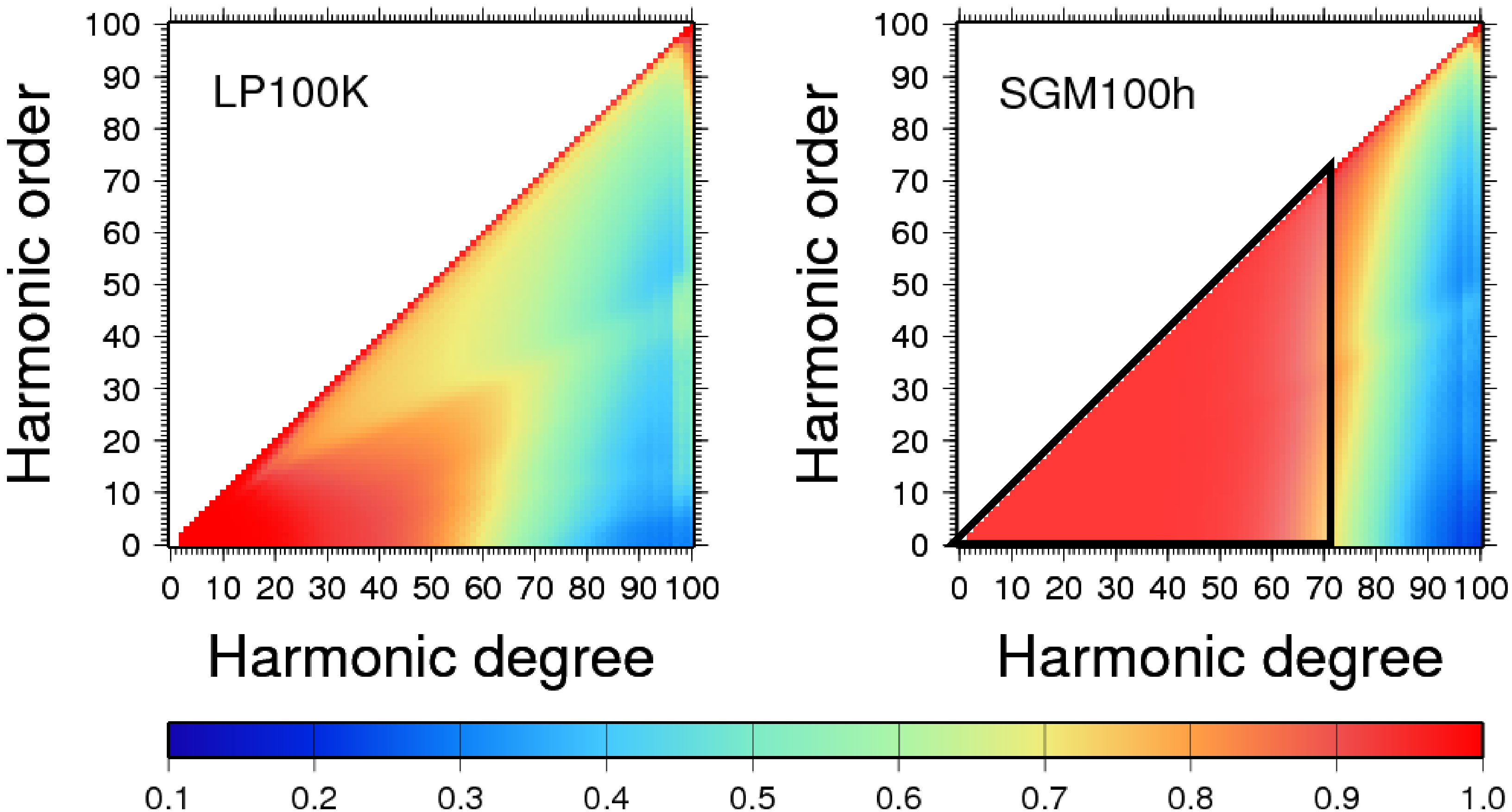
Low-degree coefficients

- Which model is better?
- Moments of inertia can be used as an index of coefficient accuracy of J_2 and C_{22}.
- Principal moments of inertia A, B, C ($A < B < C$) can be calculated using gravity coefficients J_2 and C_{22}, and libration parameters beta and gamma which come from Lunar Laser Ranging analysis.
- This constitutes an over-determined system, with four constraints on three parameters.
- Provided that the libration parameters are accurate enough, better J_2 and C_{22} should result in better self-consistency.

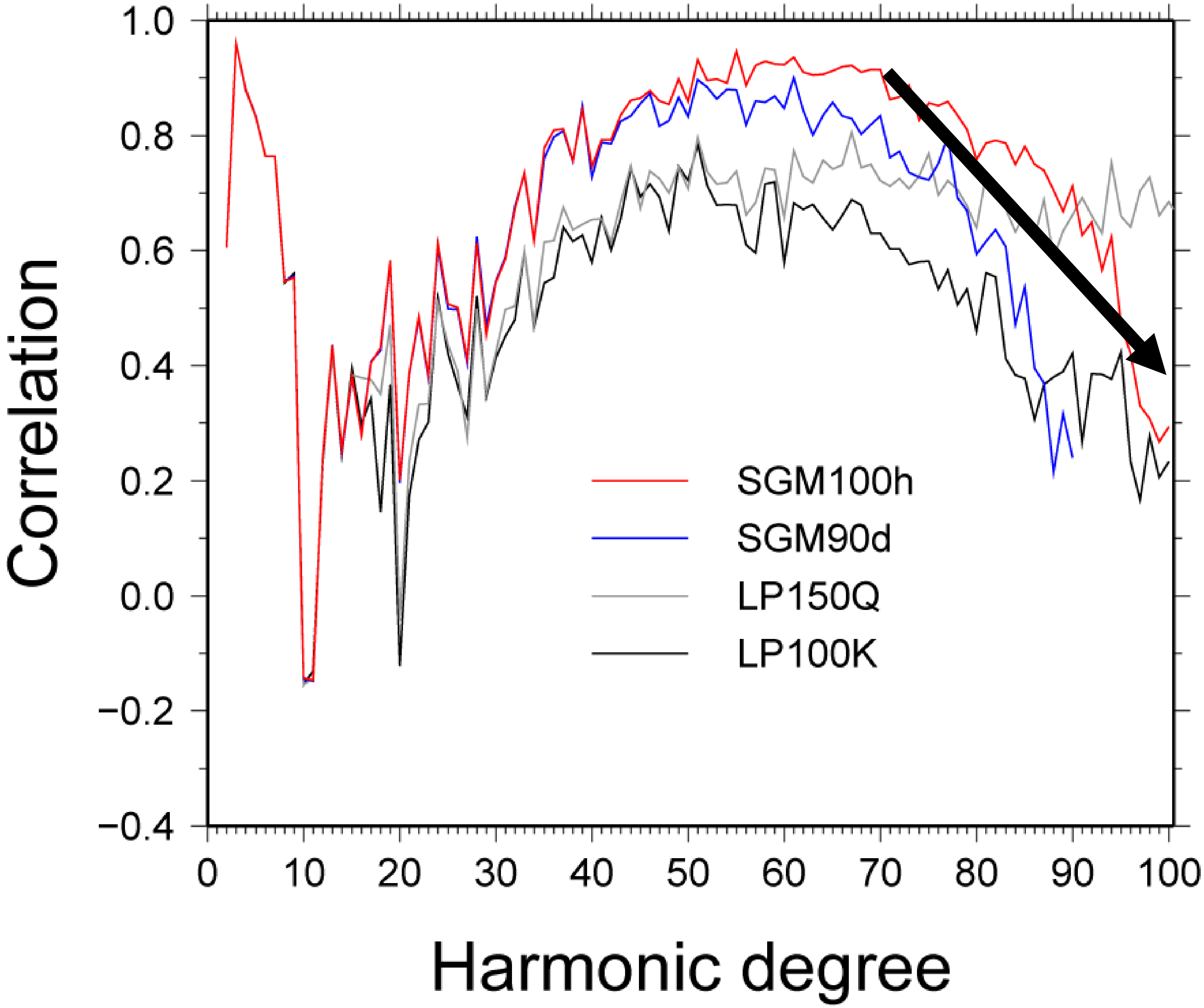


Four different solutions for the three principal moments of inertia. Error bars are based on five times formal error.

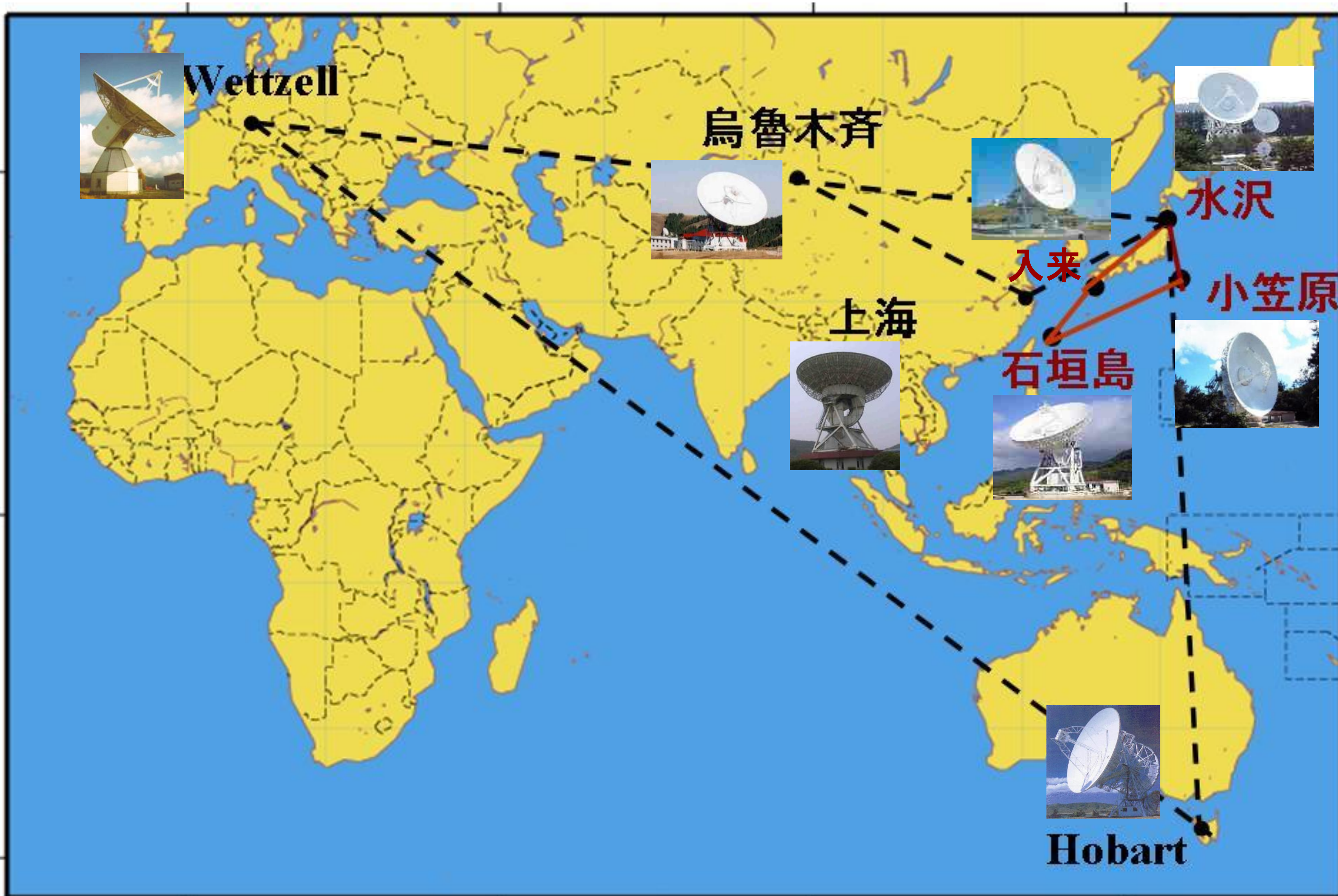
Contribution measures



Correlation between gravity and topography



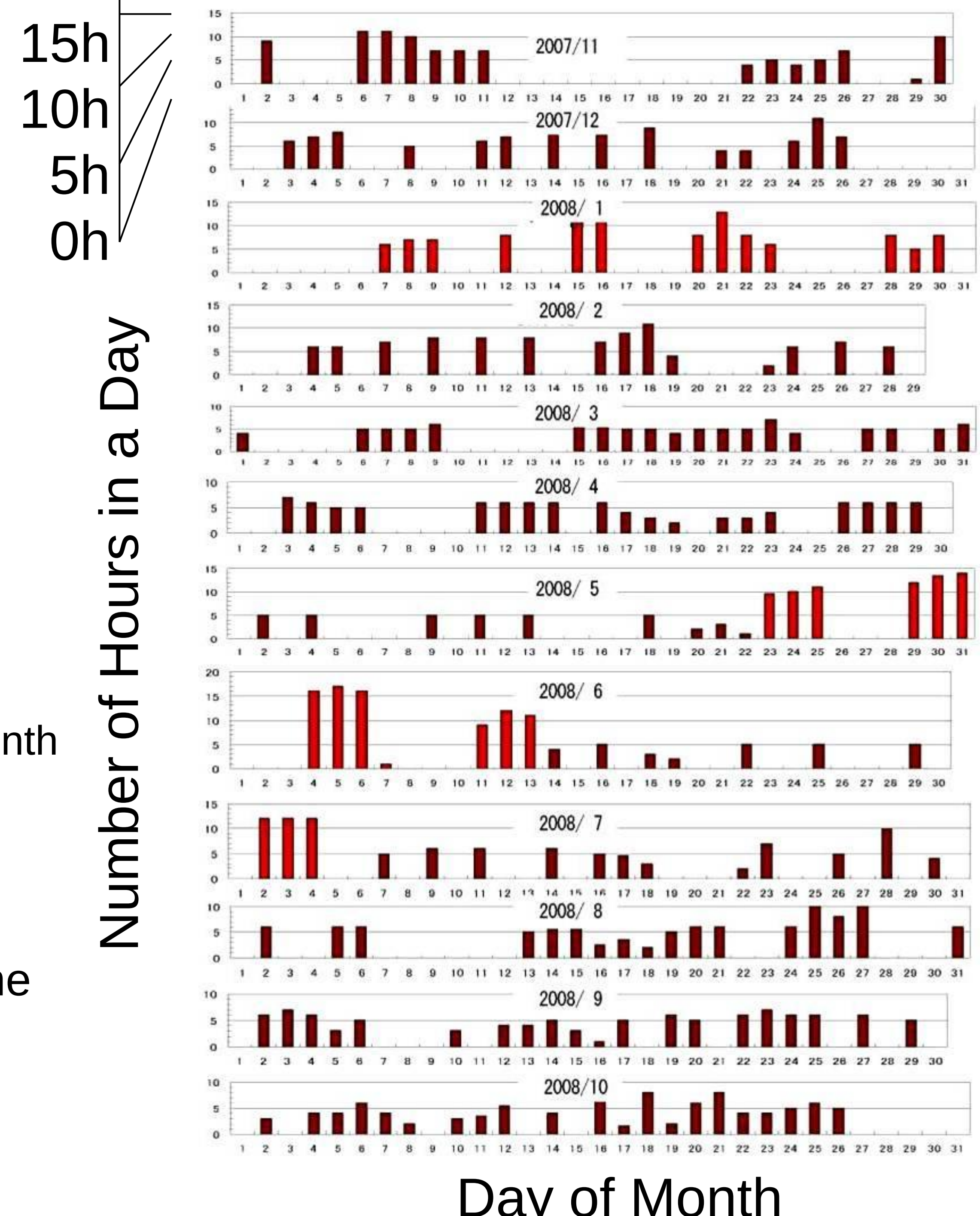
Distribution of VLBI stations for SELENE



Antenna time allocated for SELENE VLBI observations in nominal mission period (- Oct. 2008)

Regular International

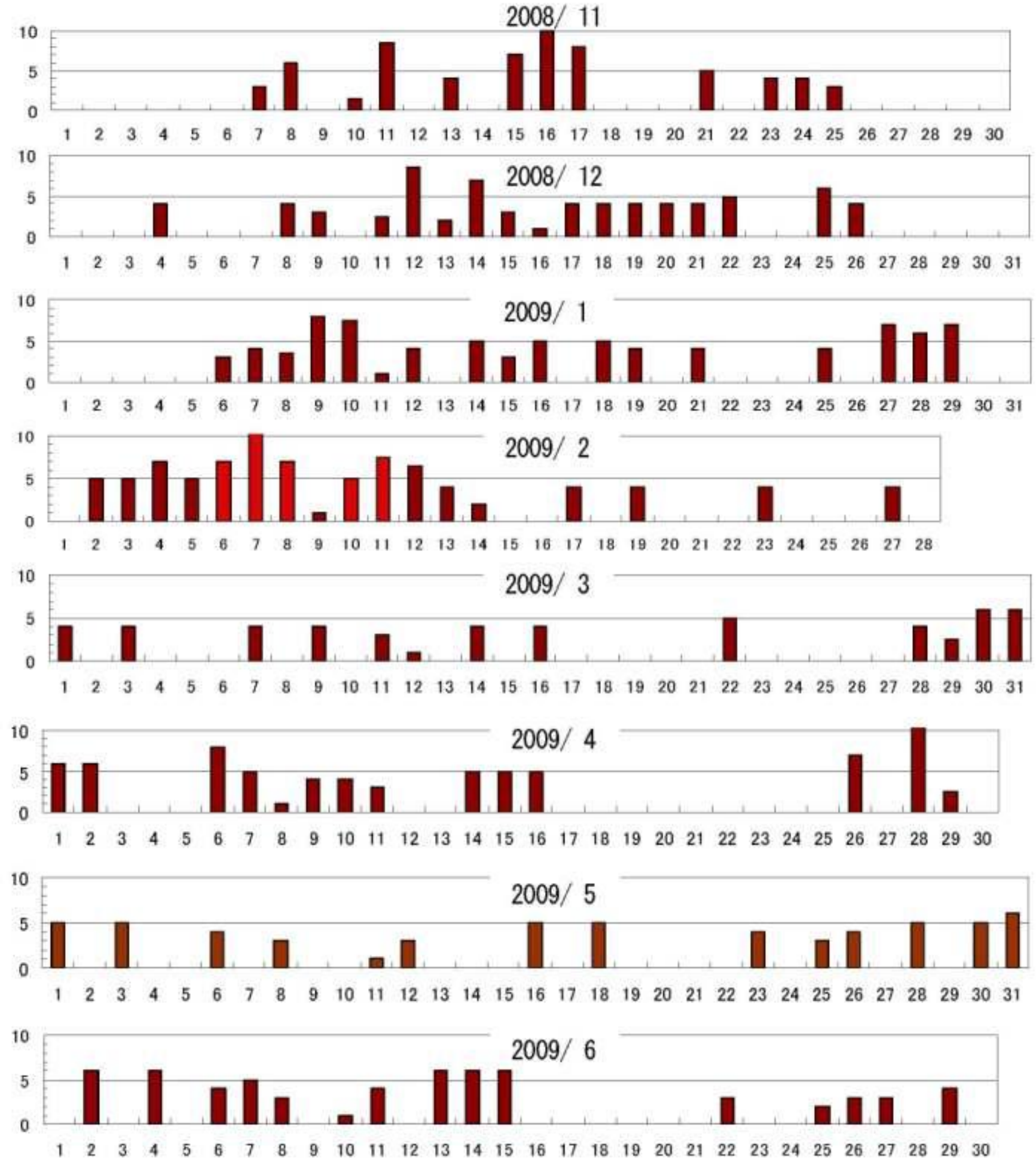
antenna time of ～100hours/month



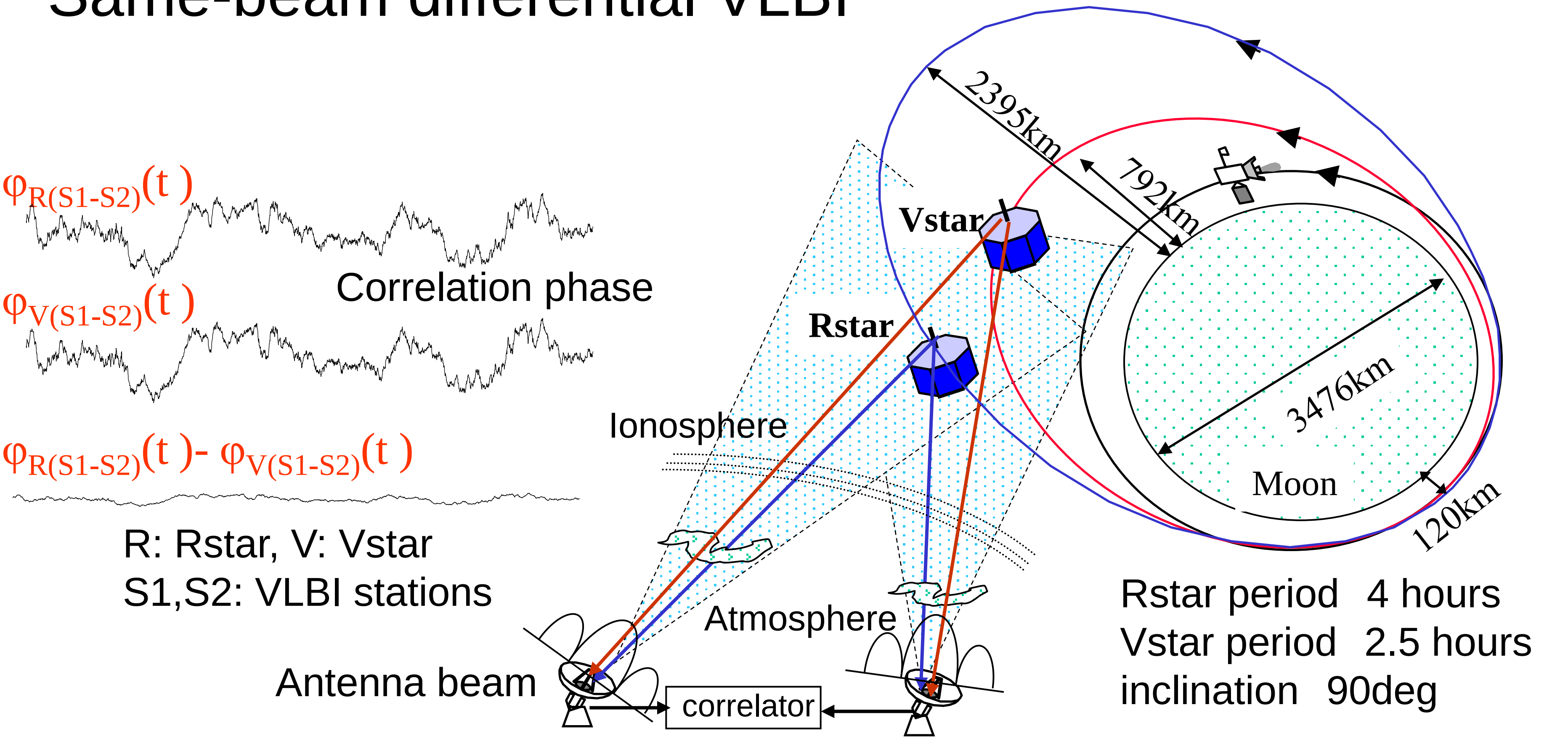
There were two spans of international VLBI tracking campaigns (Jan. 08, May-June 08). The span of each international campaign was 1 month.

Antenna time allocated for SELENE VLBI observations in extended mission period (Nov. 2008 - June 2009)

Hobart and Urumqi stations participated in the last international observation in Feb. 2009, just before the end of Rstar’s lifetime.



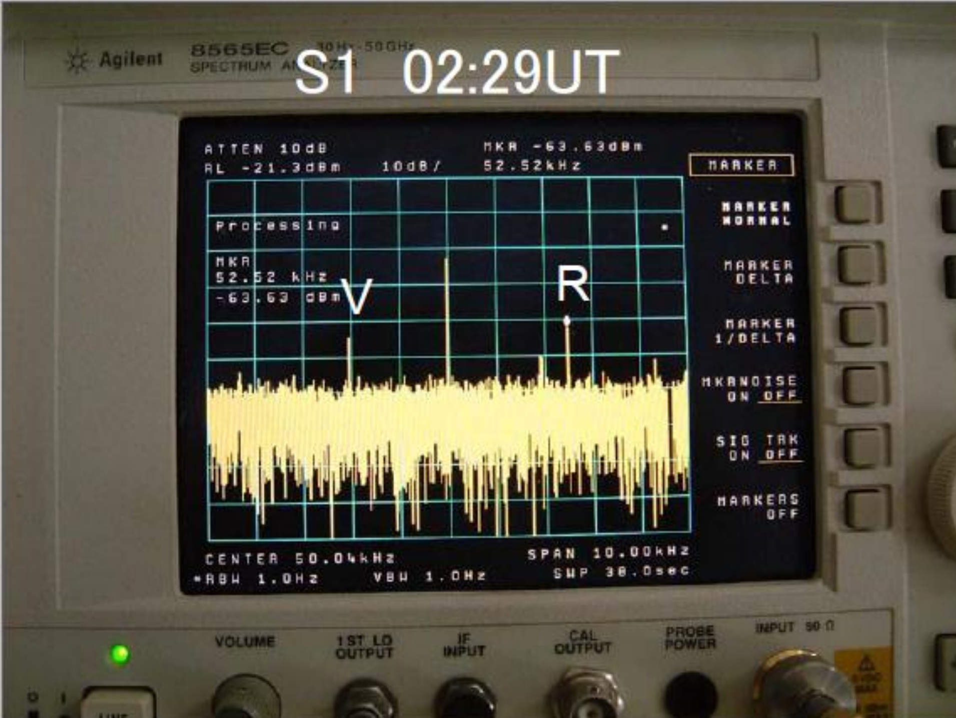
Same-beam differential VLBI

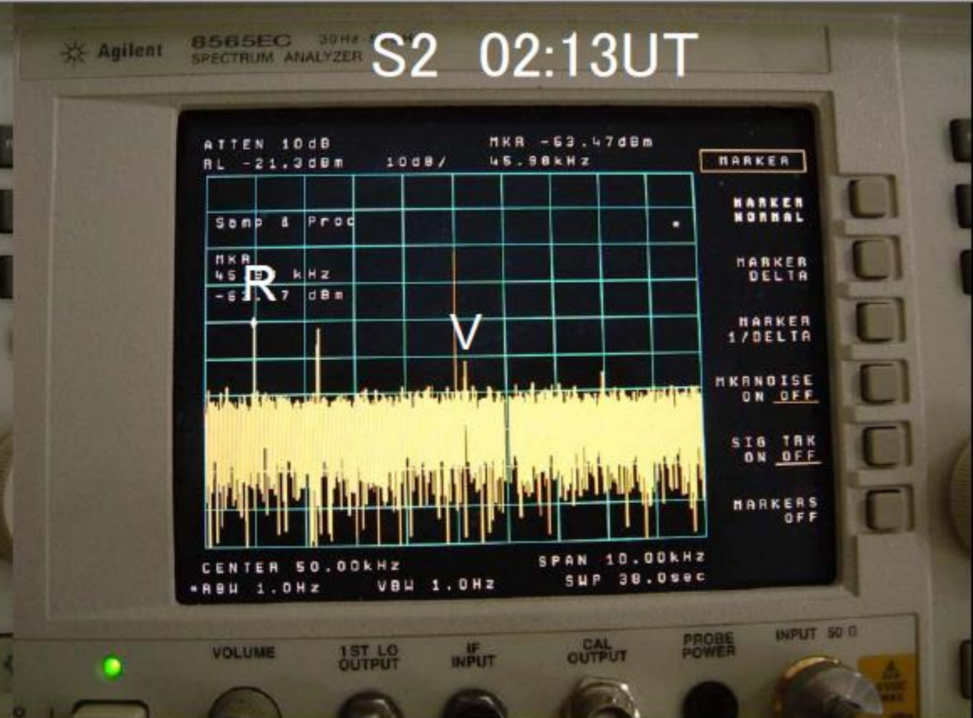


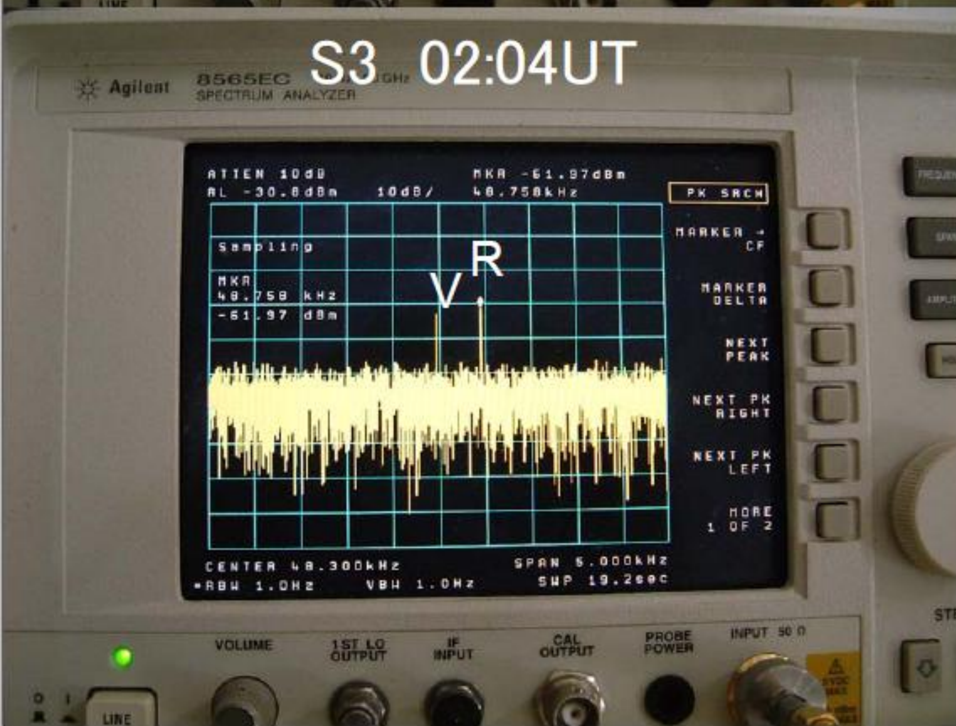
In the same-beam VLBI Rstar and Vstar are simultaneously observed when the separation angle is smaller than the beam width

Influences of the receiver, atmosphere and ionosphere are nearly canceled.

References
Liu et al., IEICE, 2006
Liu et al., Adv. Space Res, 2007
Kikuchi et al., Radio Sci., 2008

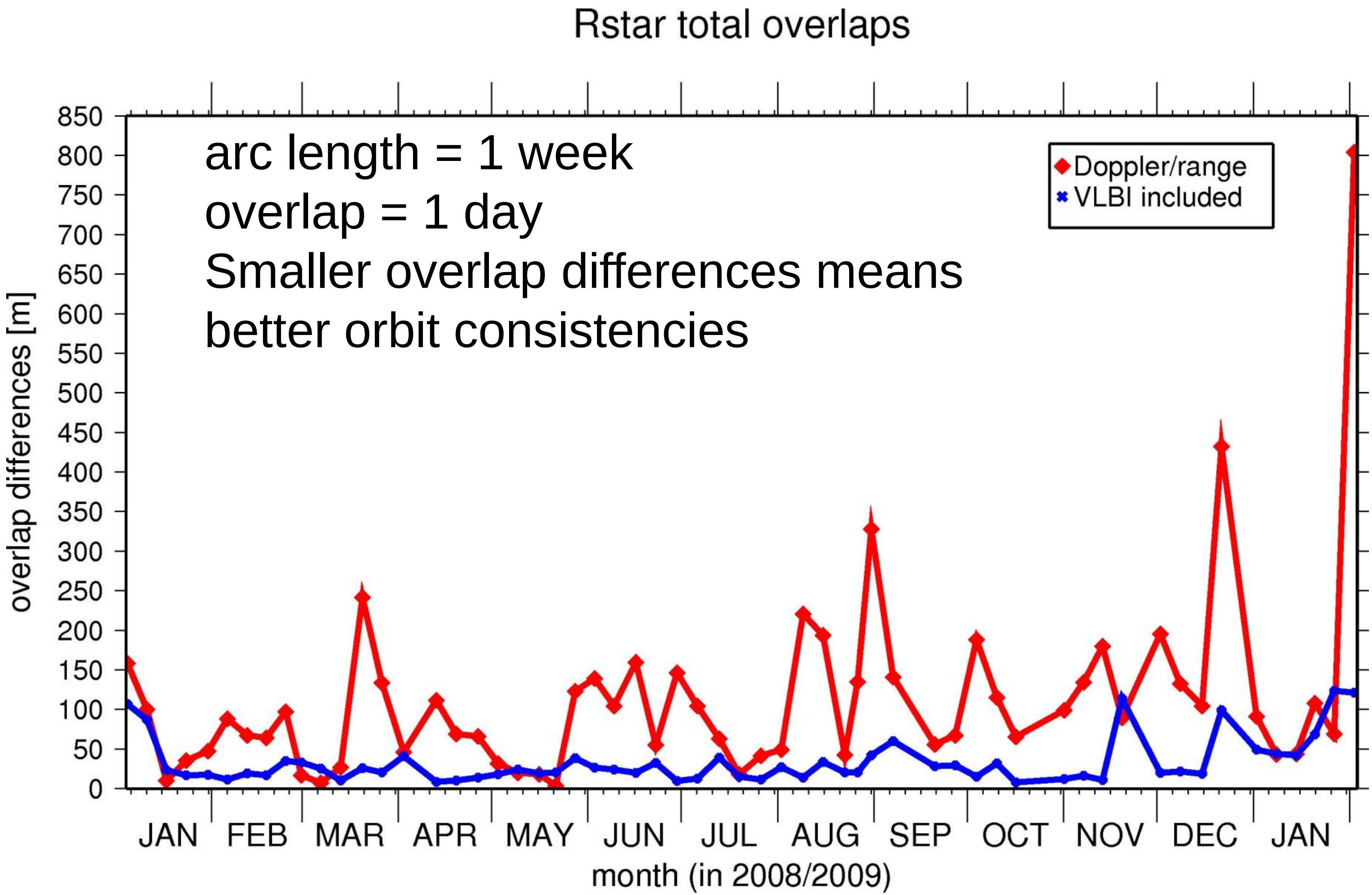


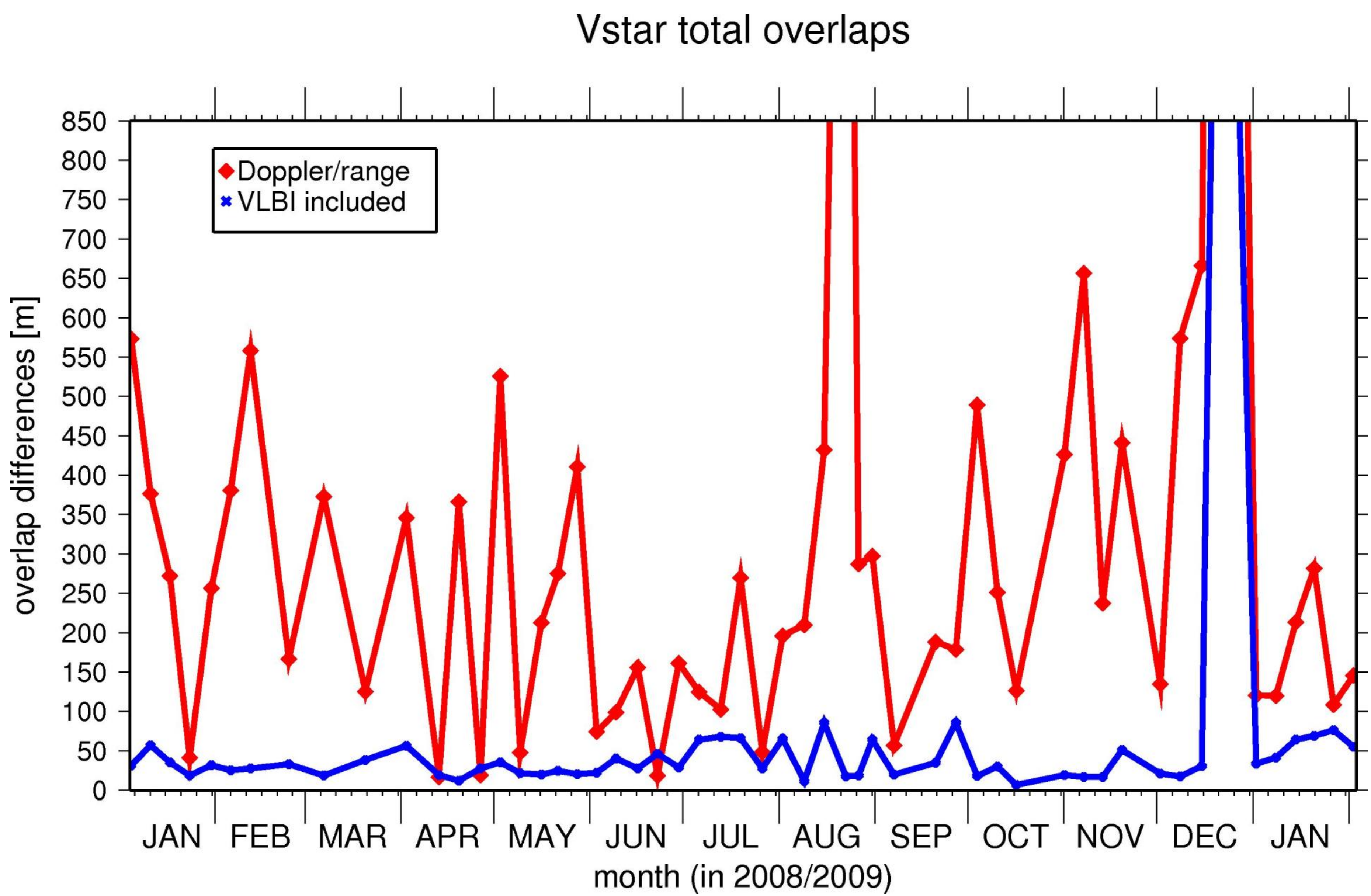




S-band Samebeam signal @ Ishigaki
2007.11.07

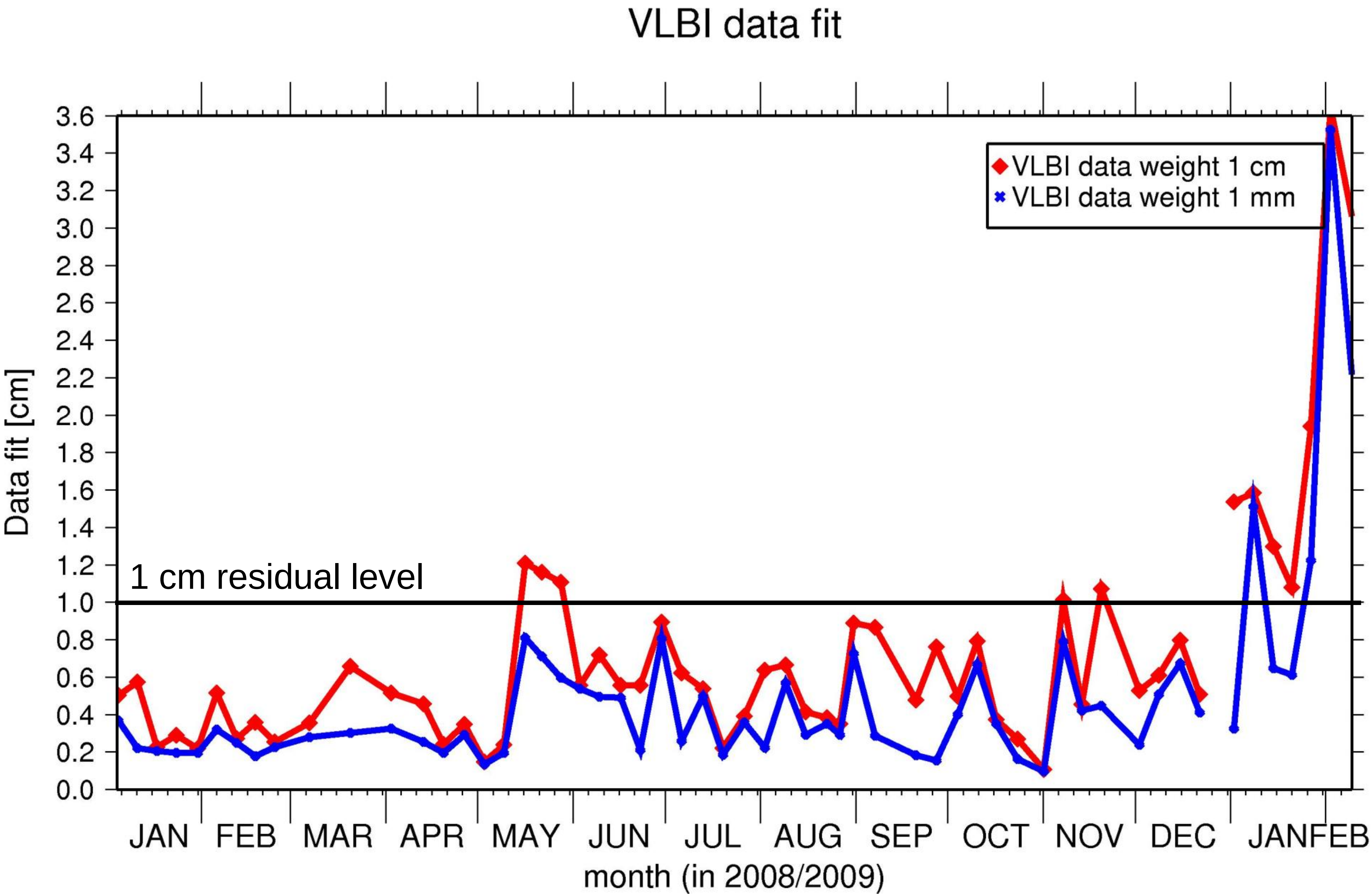
2-way Doppler and range have line-of-sight sensitivity. VLBI data add plane-of-sky sensitivity and can help to improve orbit determination for Rstar and Vstar.

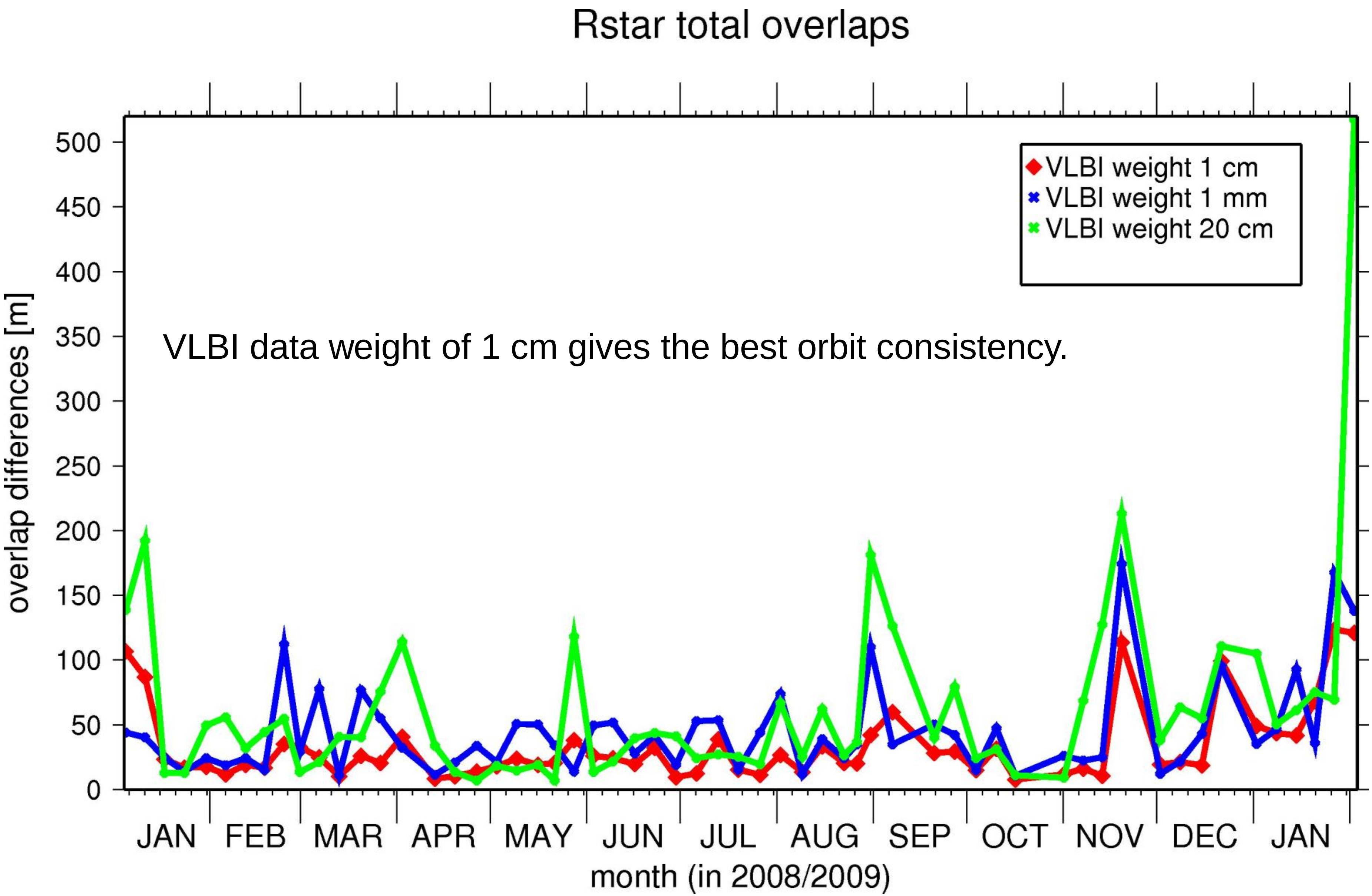




Vstar total overlaps
Doppler/range
VLBI included
overlap differences [m]
850
800
750
700
650
600
550
500
450
400
350
300
250
200
150
100
50
0
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
JAN
month (in 2008/2009)

VLBI residual levels with different data weight

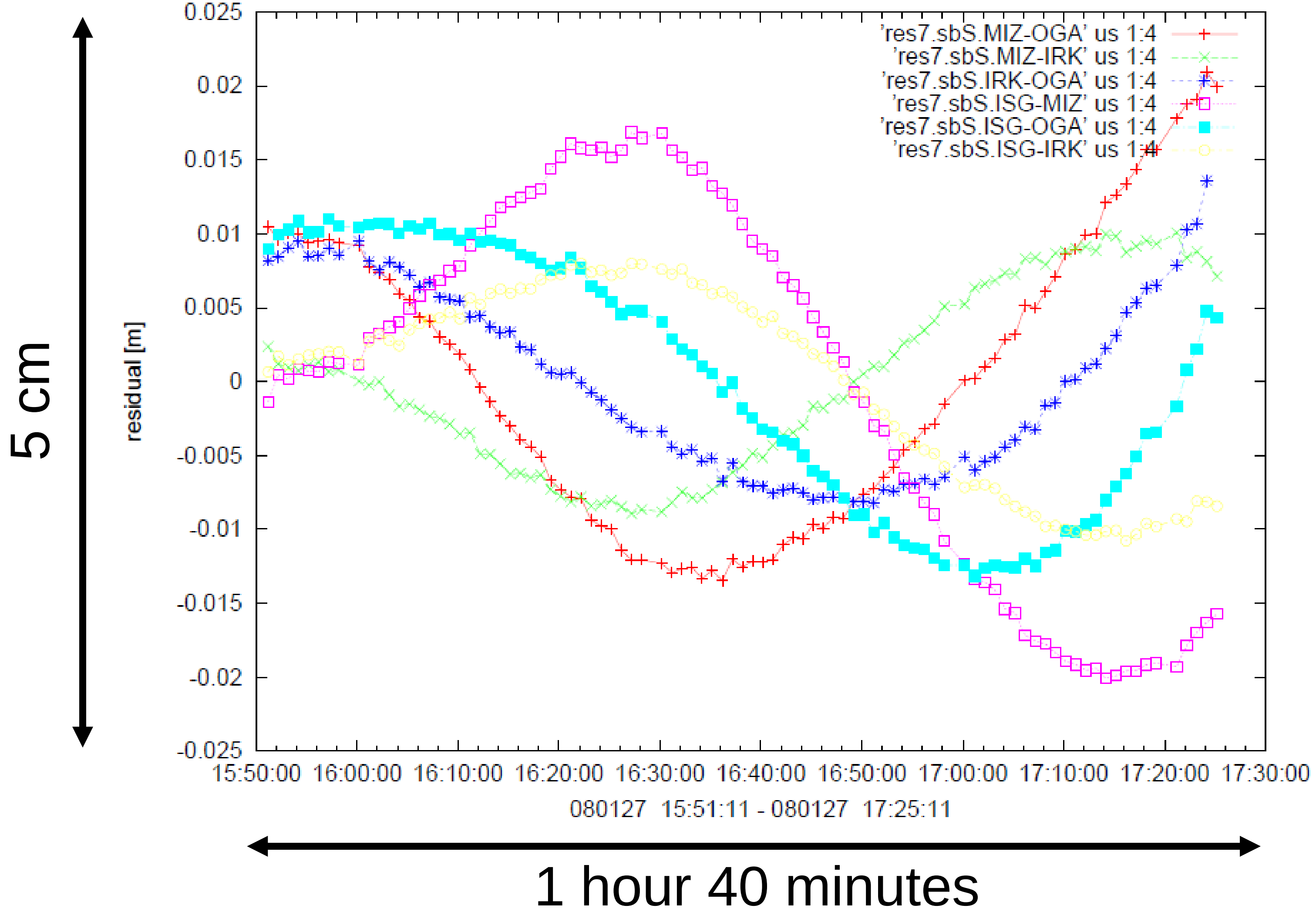




VLBI data weight of 1 cm gives the best orbit consistency.

An example of the same-beam VLBI residuals

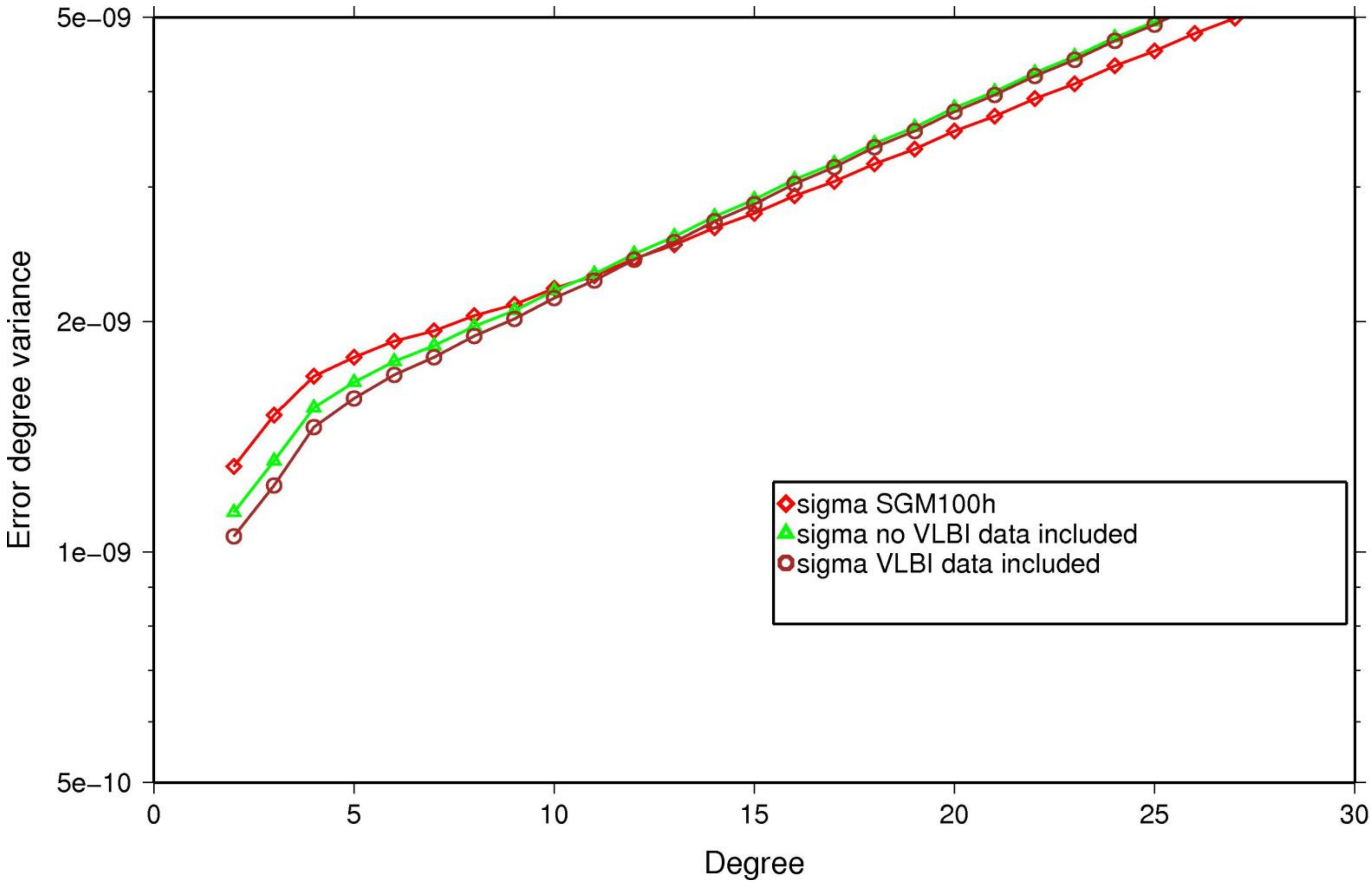
VLBI data weight = 1 cm, 4 VERA stations, 6 baselines



Not a white noise. VLBI senses something.

Errors in non-conservative forces?

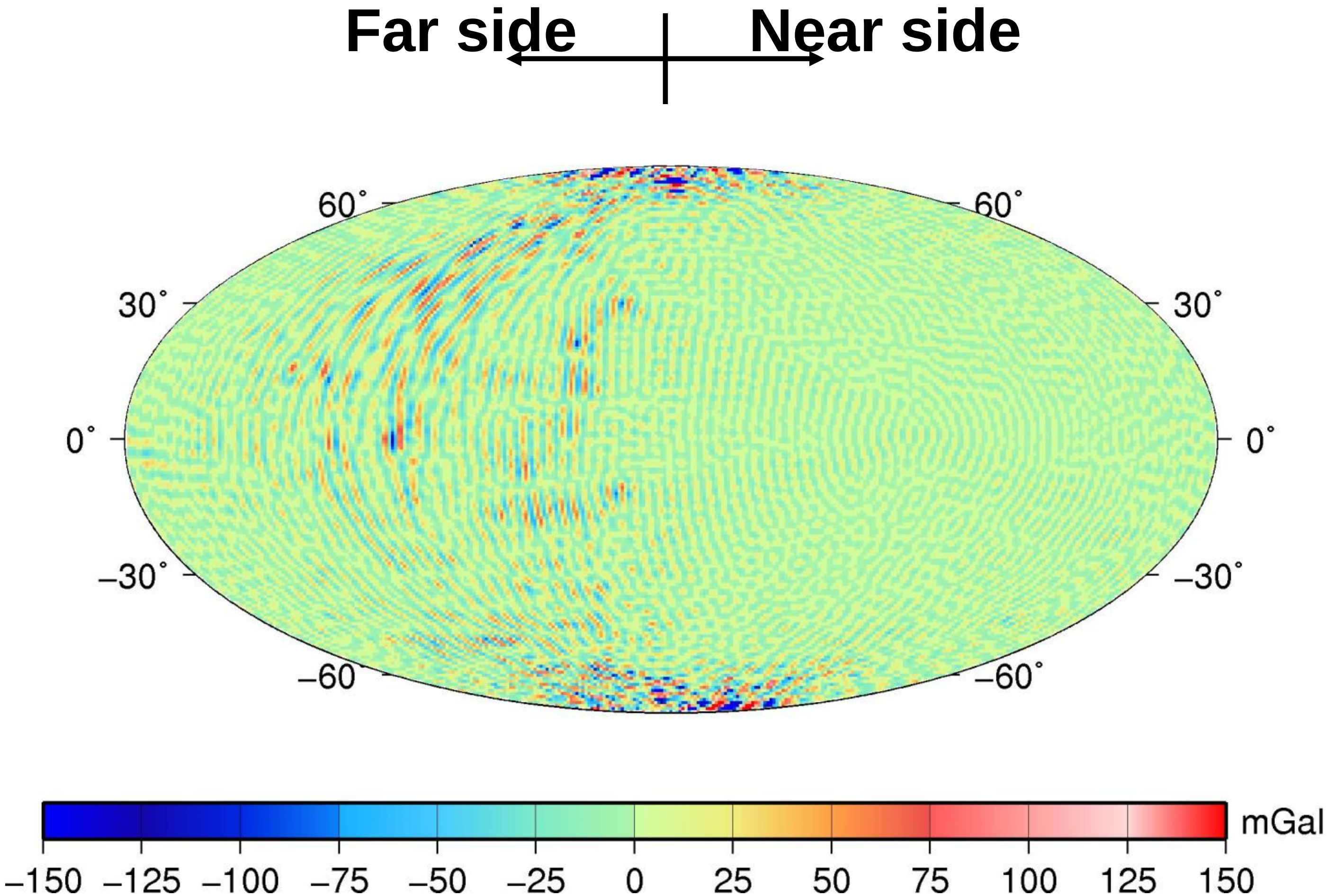
Error spectrum of the new gravity model which includes the S-band same-beam VLBI data



VLBI data weight = 1 cm

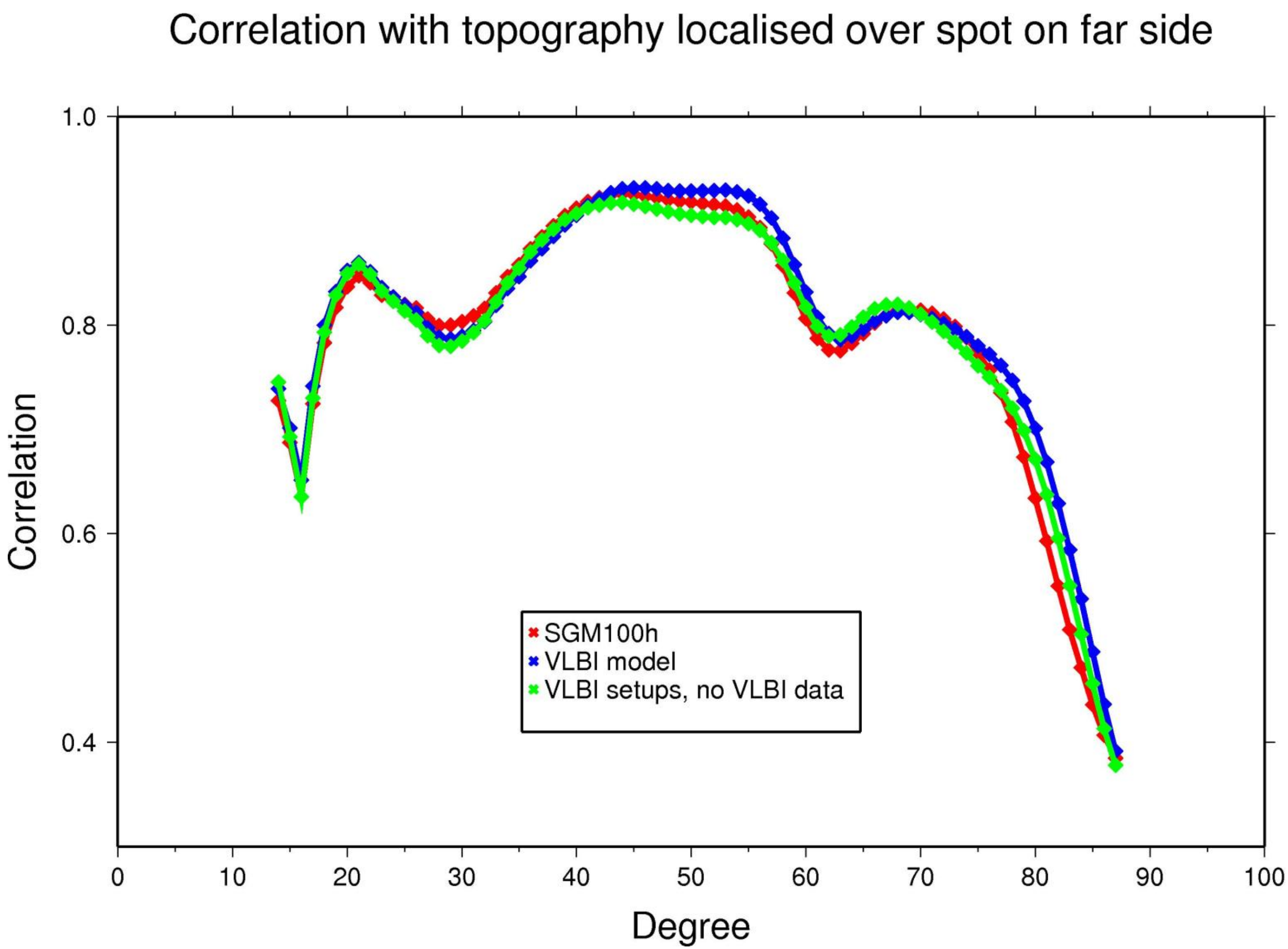
R/Vstar arc length = 1 week

Differences between SGM100h and the VLBI-included model

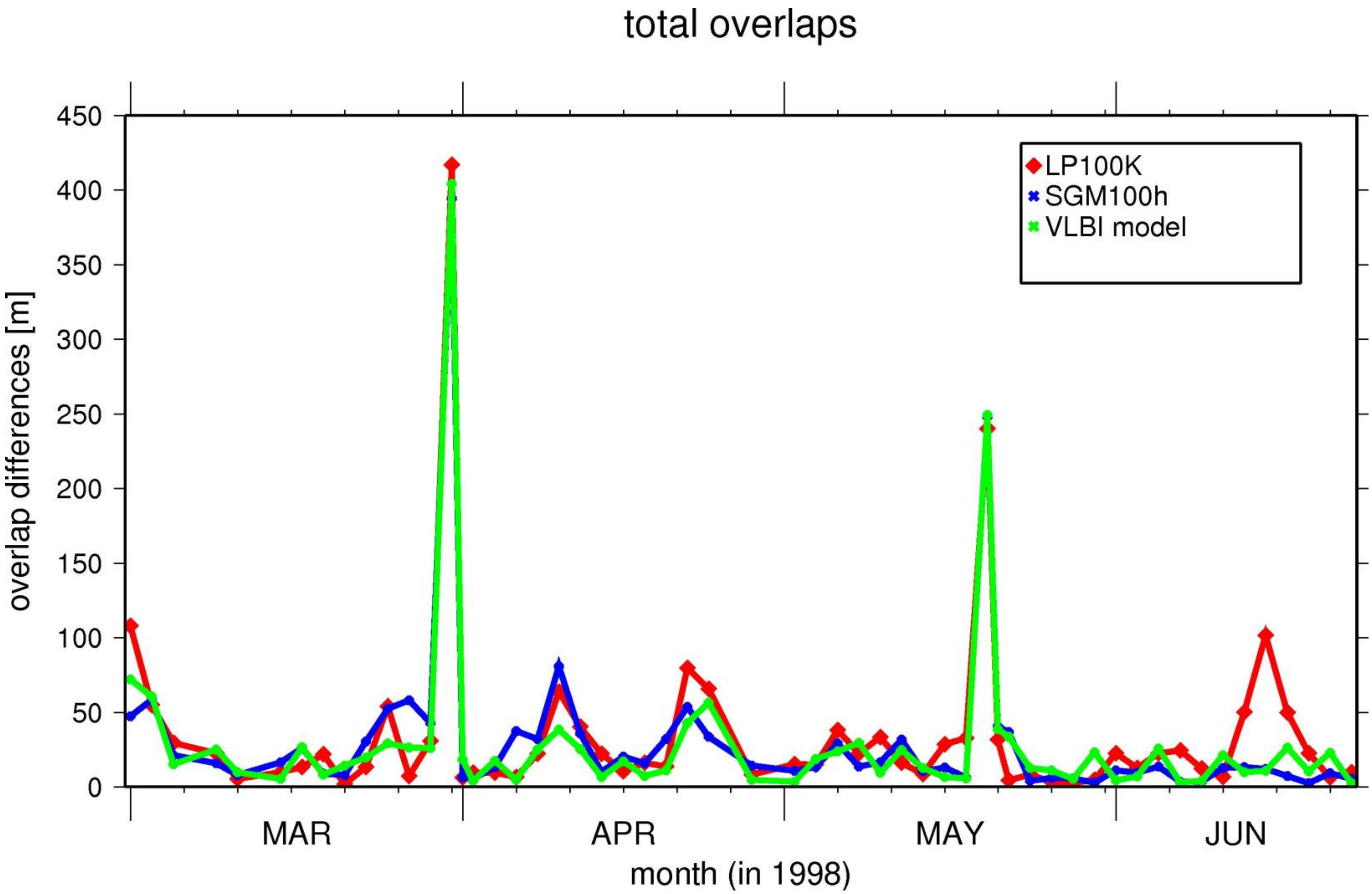


Farside gravity filed is affected through 4-way Doppler measurements
for which Rstar orbit serves as a reference.

Does VLBI model improve the correlation with topography?



Orbit overlaps for LP 1998 data



Summary 1/2

- Historical tracking data + SELENE range & Doppler data
  → SGM100h model which is available at SELENE Level 2 database.

- Farside gravity errors are drastically reduced.

- SGM100h produces a correlation with SELENE-derived topography as high as about 0.9, through degree 70.

- The gravity coefficients below degree and order 70 are now determined by real observations with contribution factors larger than 80 percent.

Summary 2/2

- VLBI data improve orbits of R/Vstar, and thus improve the gravity field, especially over the far side.

- Orbit consistency for low lunar orbits also improves with this model.

- Improvements in lower degree coefficients are modest at this moment.

Acknowledgements

We would like to express our sincere appreciation to all the collaborators, and also to IVS, for helping us coordinate and realize the SELENE international VLBI observations.

Thank you!!

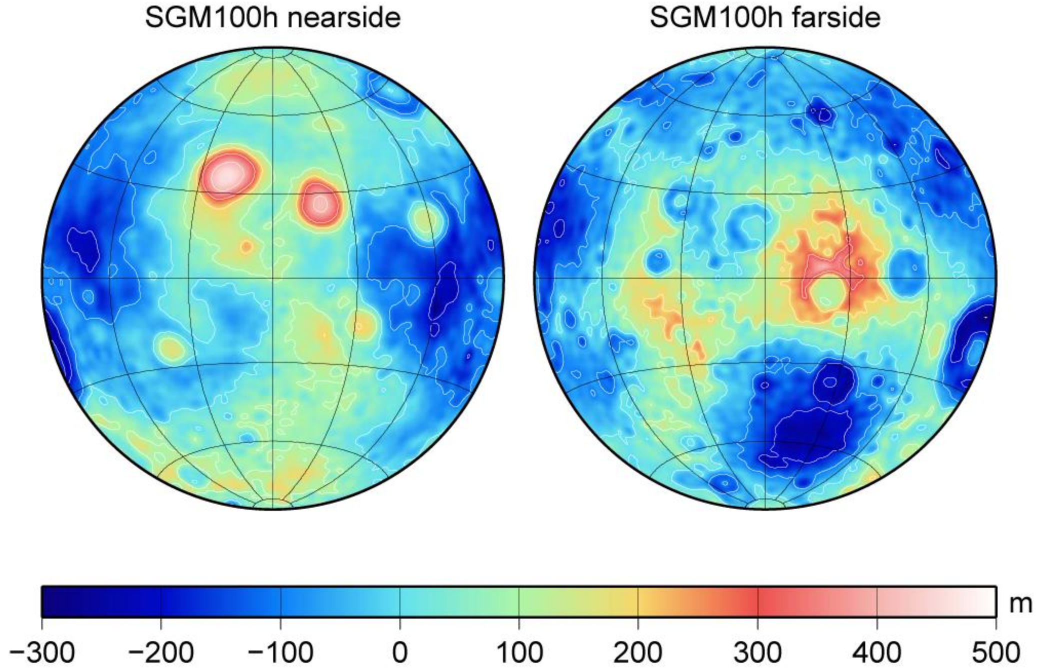
Acknowledgements

The authors appreciate the contribution of all the engineers of NEC/Toshiba Space Systems Ltd. (NTS), Nippon Antenna Co. Ltd., and Nippi Corporation who diligently developed the onboard instruments and sub-satellites. We also express thanks to the entire staff of the SELENE mission.

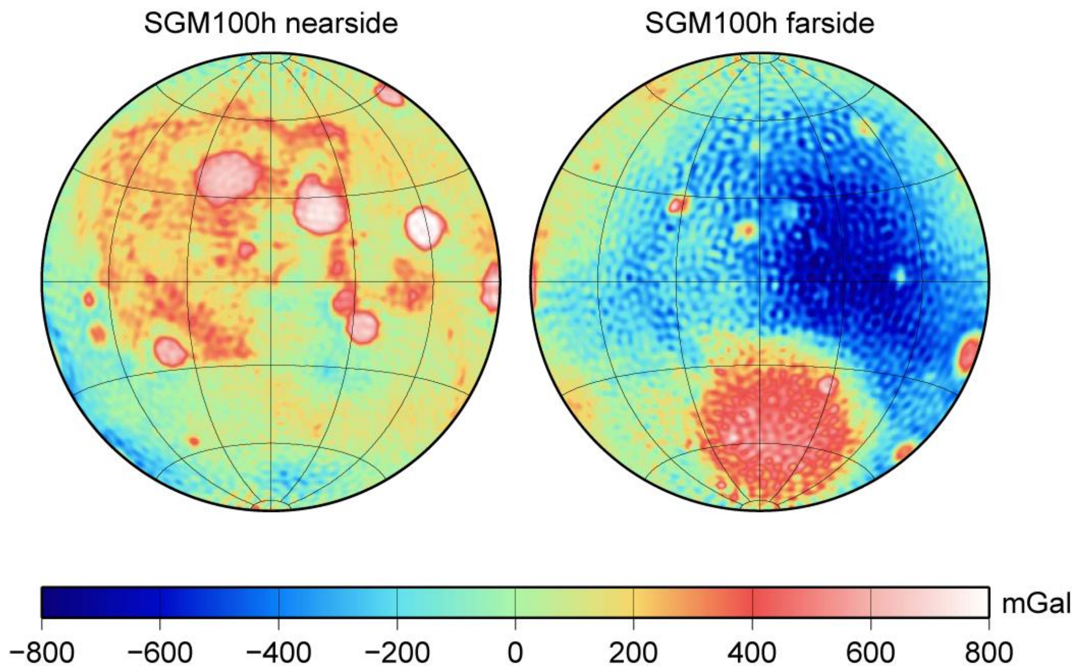
The gravity experiments conducted during the SELENE mission would never have been achieved without the prominent expertise and profound knowledge of Mr. Fumio Fuke, an NTS engineer who passed away two months after the mission was launched. We express sincere thanks to him for his contributions to science and mourn his passing and the loss it entails for Japanese space development.

Backup slides

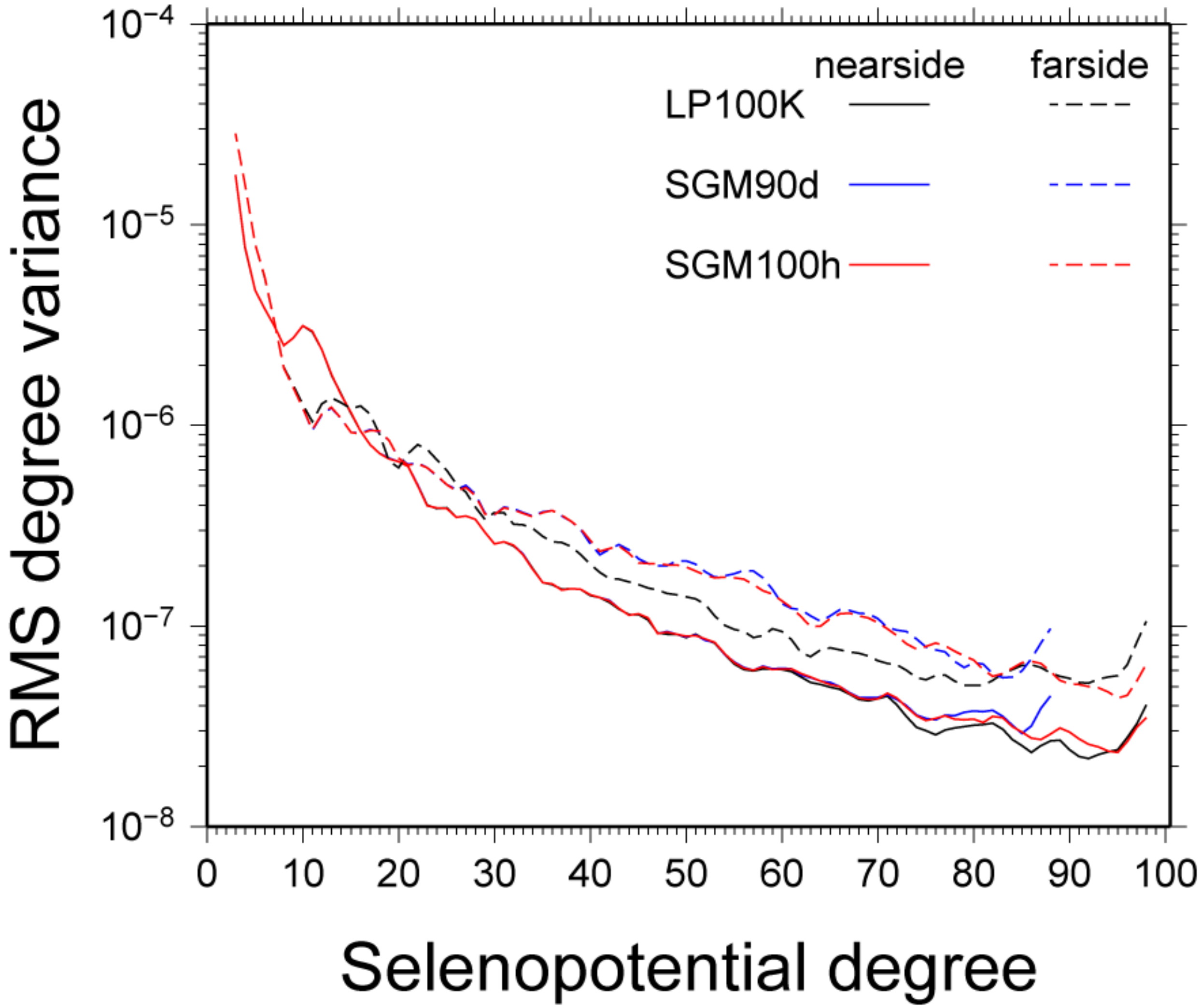
Selenoid



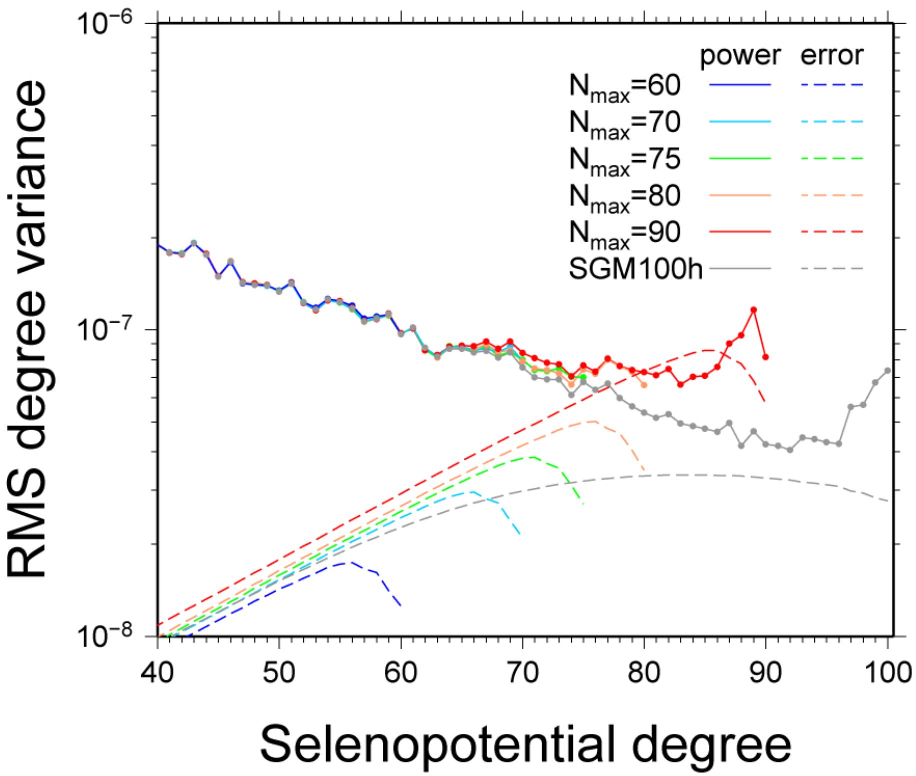
Bouguer

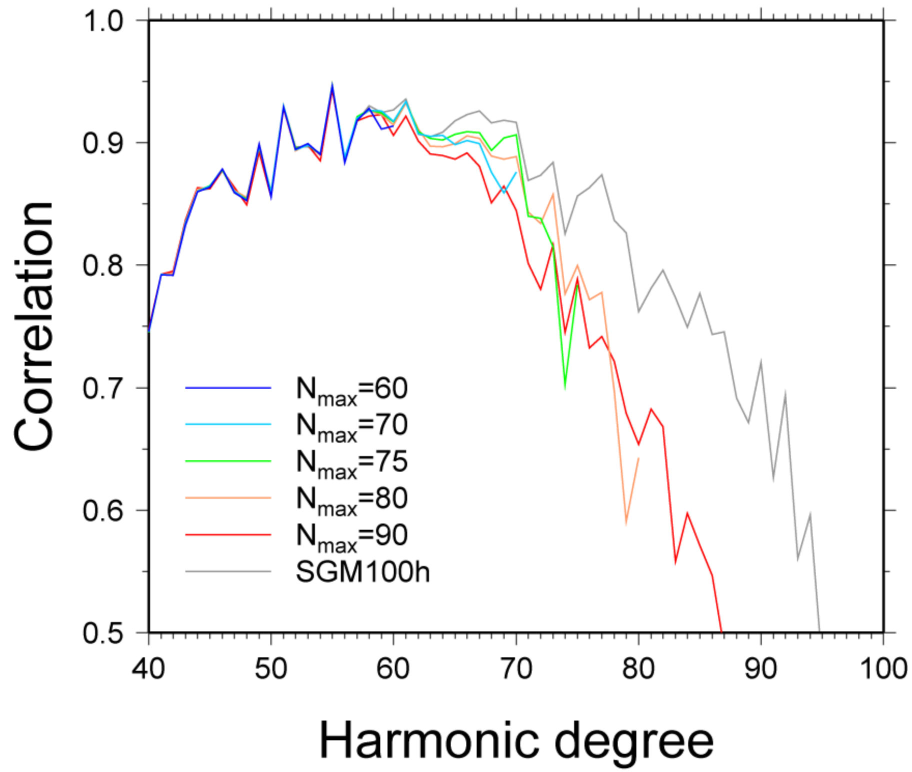


Localized RMS degree variances



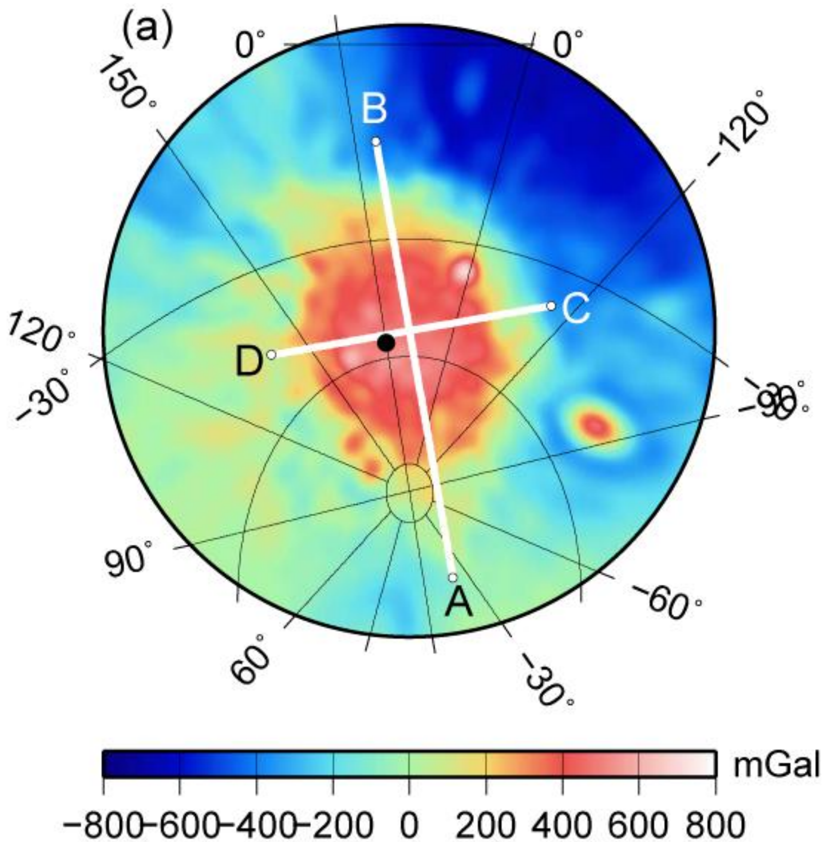
Solutions without a priori constraint

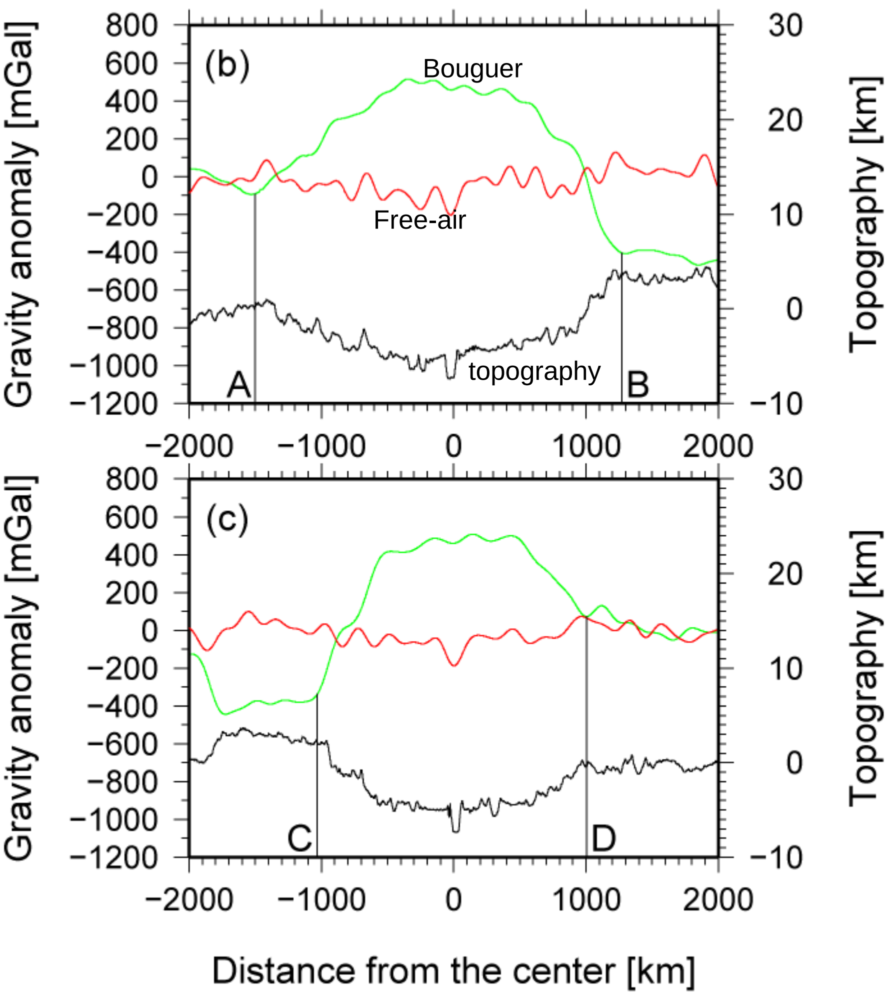




With the farside data coverage achieved, even with a small data gap still remaining in the northern hemi-sphere, it is possible to obtain a realistic gravity expansion up to degree and order 70 without any a priori constraint.

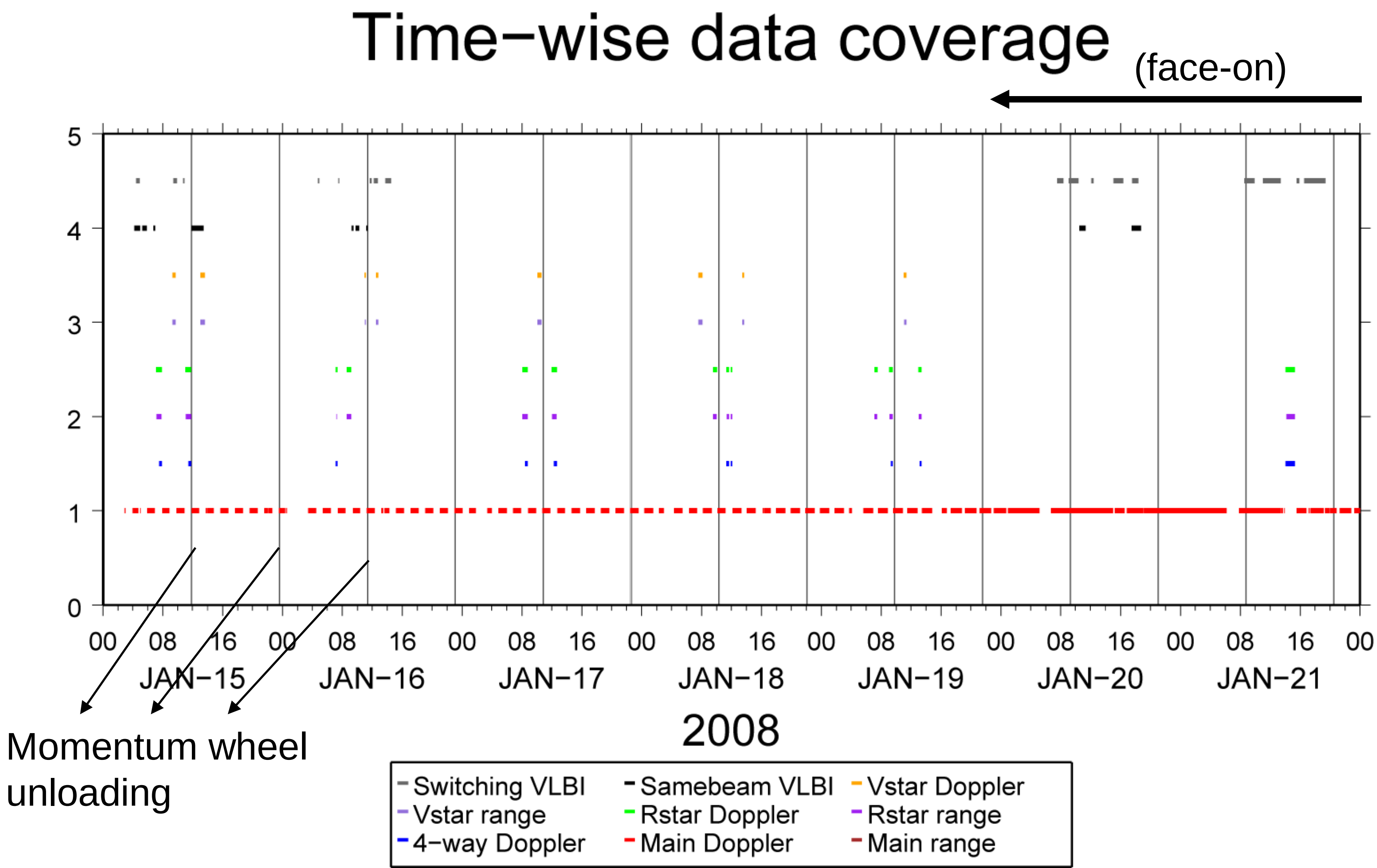
Elliptical signature of the South Pole-Aitken Basin



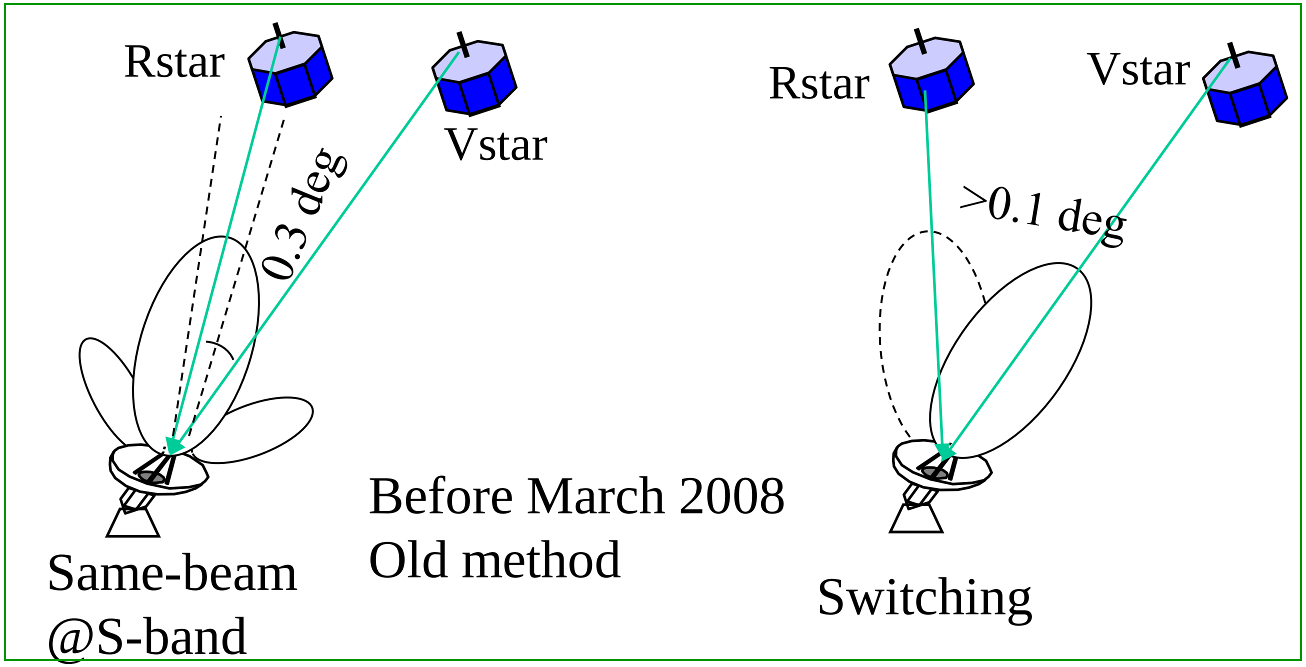


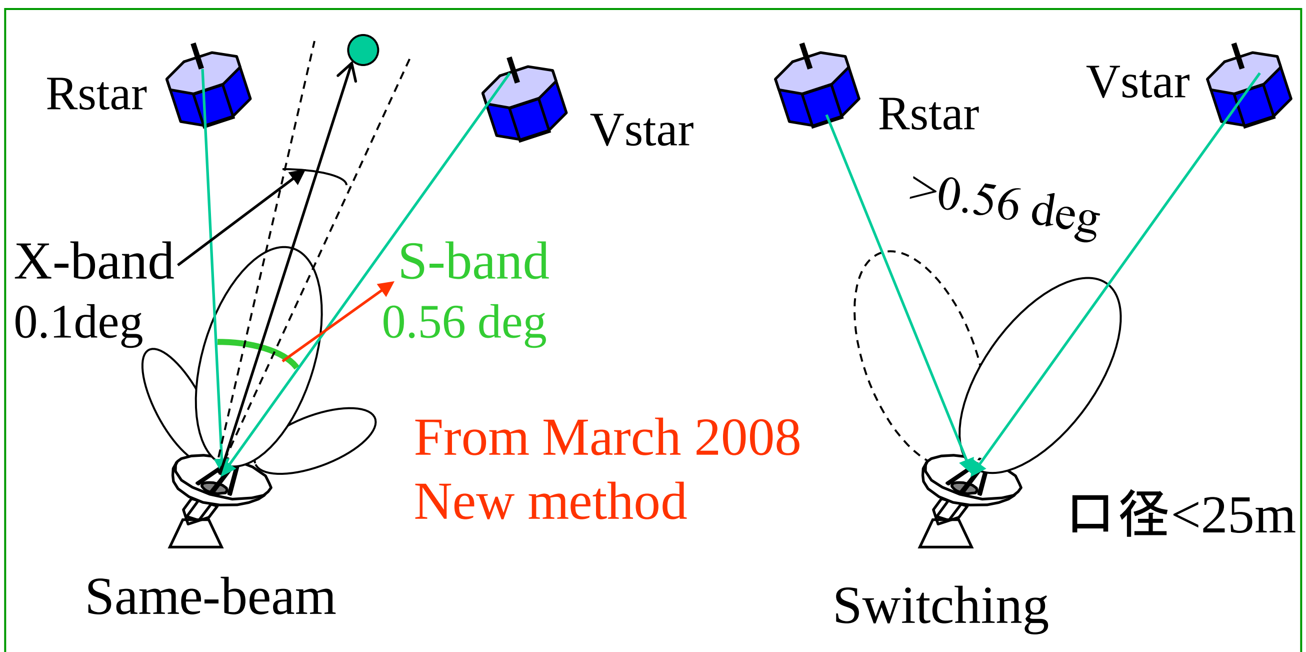
Bouguer gravity anomaly around SPA
degree and order up to 60

An example of time-wise data coverage of SELENE tracking data

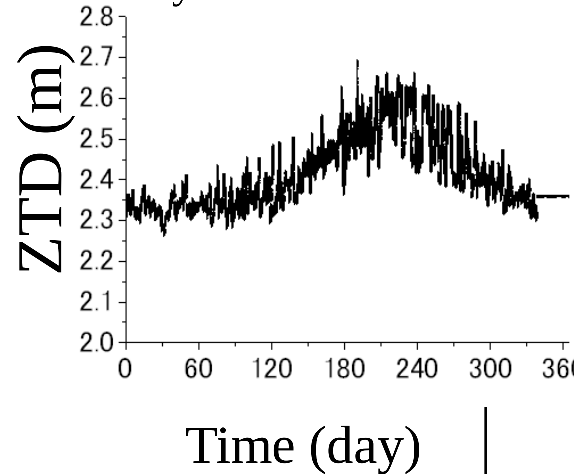


Observation mode





Zenith atmospheric delay
By GPS



Qinghui LIU et. al
Adv. Space Res, 2007

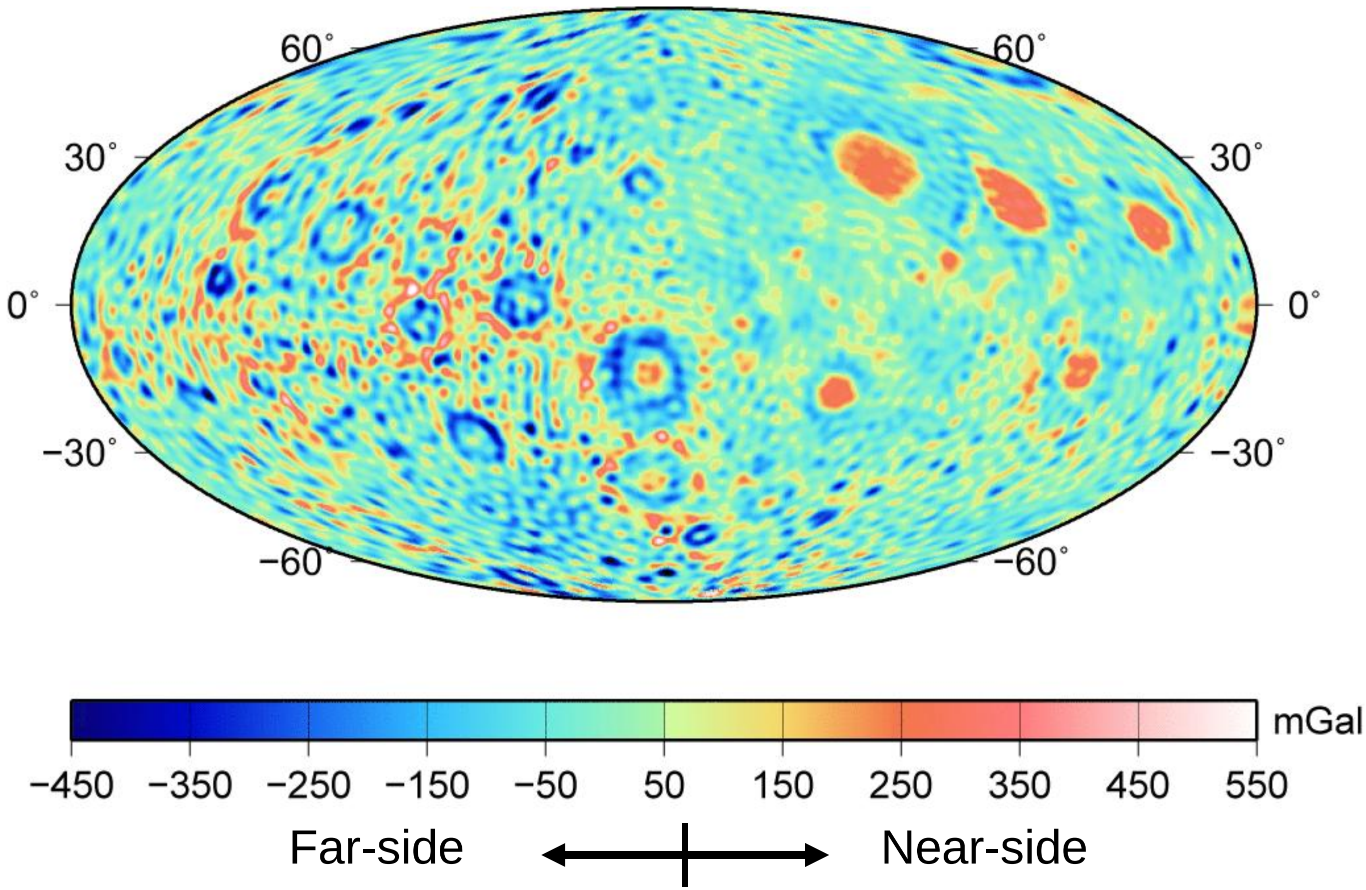
New method:
Period of same-beam
observations
becomes long

Summary of tracking data used for SGM100h (SELENE Gravity Model)

	Satellite	Data type	Amount	Arc length	Data weight
Far side	SELENE 4-way	Doppler	67,786	2.33 days	1 mm/s
Near side	SELENE Main	Doppler UDSC	1,786,771	12 hours *	1 mm/s
		Doppler GN			2 mm/s
		Range	62,438		5 m
	SELENE Rstar	Doppler	159,269	2.33 days	1 mm/s
		Range	150,470		5 m
	SELENE Vstar	Doppler	42,852	2.4 days	1 mm/s
		Range	35,386		5 m
	LO I-V	Doppler	6,301,236	12 hours	4.5 mm/s
	A15/16ss	Doppler		8 hours	4.5 mm/s
	Clementine	Doppler		2 days	3 mm/s (Pomonkey 10 mm/s)
		Range			4 m
	LP nominal mission	Doppler		2 days	2 mm/s
		Range			4 m
	SMART-1	Doppler		15 hours	10 mm/s

* 6 hours after 2009.07.23

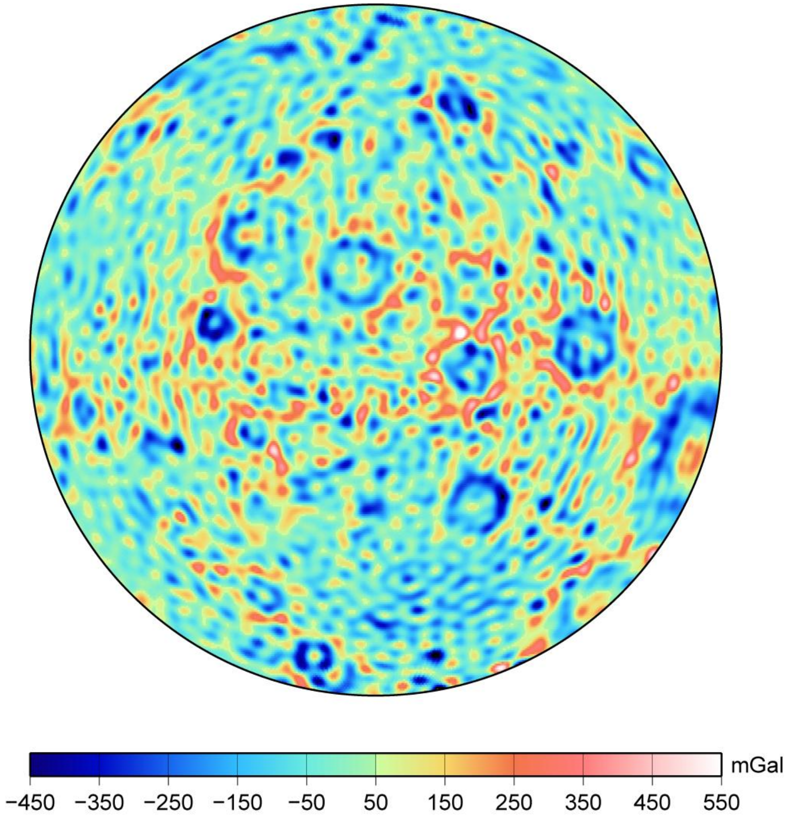
SGM90d and SGM100h



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

Far-side comparison between SGM90d and SGM100h



SGM90d
Namiki et al. (2009)
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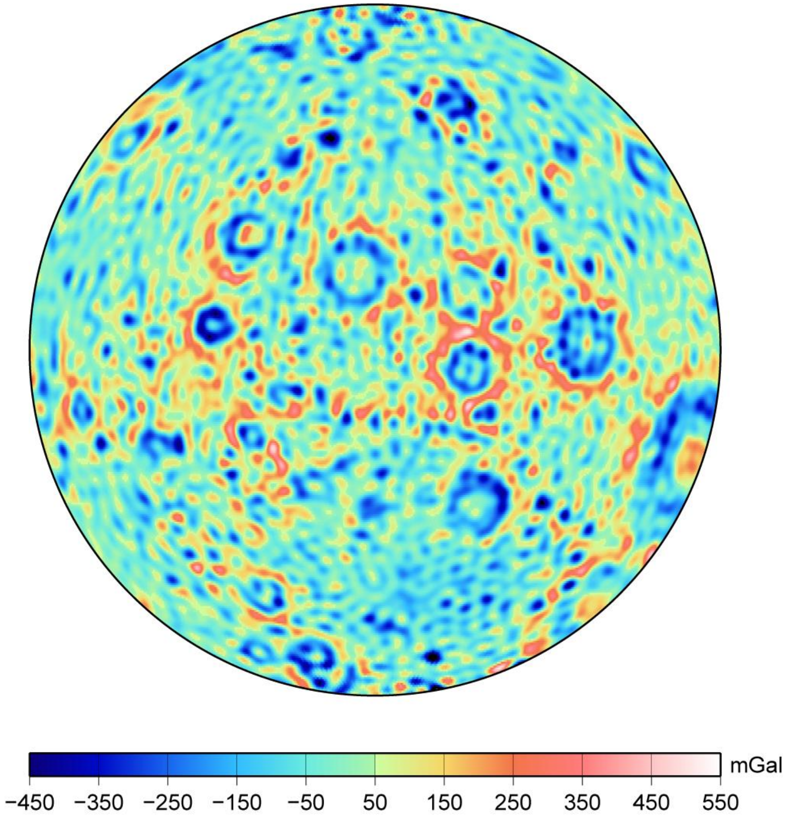
plus historical data



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