

「かぐや」重力場モデルの 構築について

国立天文台 RISE月探査プロジェクト 松本晃治

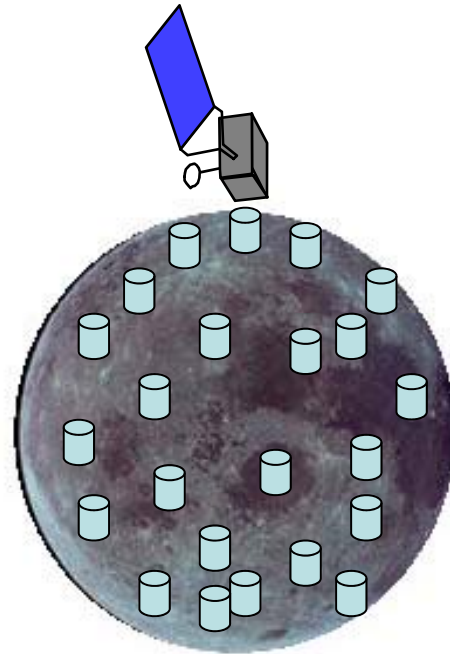


月の重力場の測り方

- 電波を用いた人工衛星追跡
- 裏側を測るにはひと工夫必要

月・惑星の重力場 どうやってはかる？


重力計

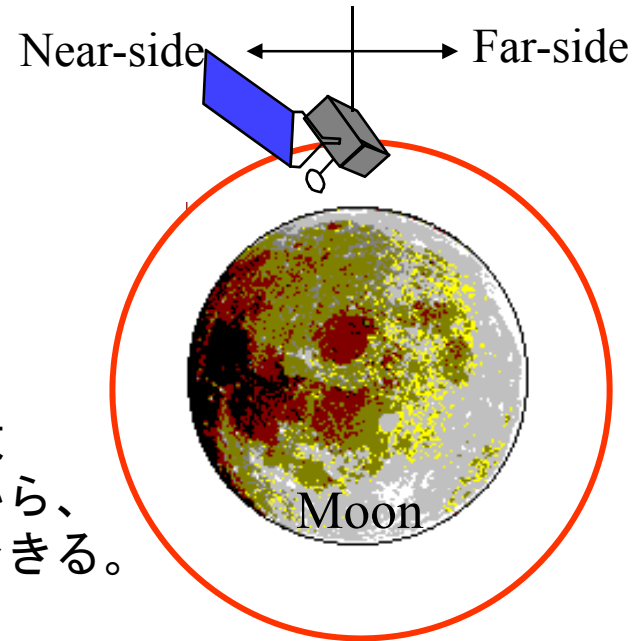


Earth

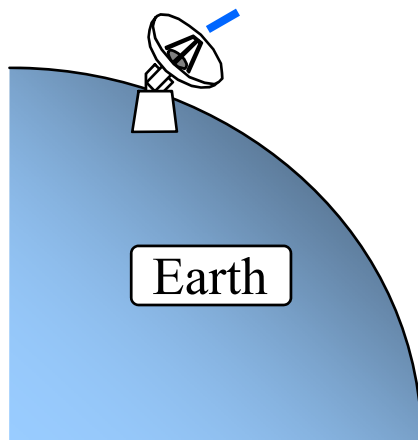


電波などを利用して人工衛星の飛び方を調べる

ドップラー観測



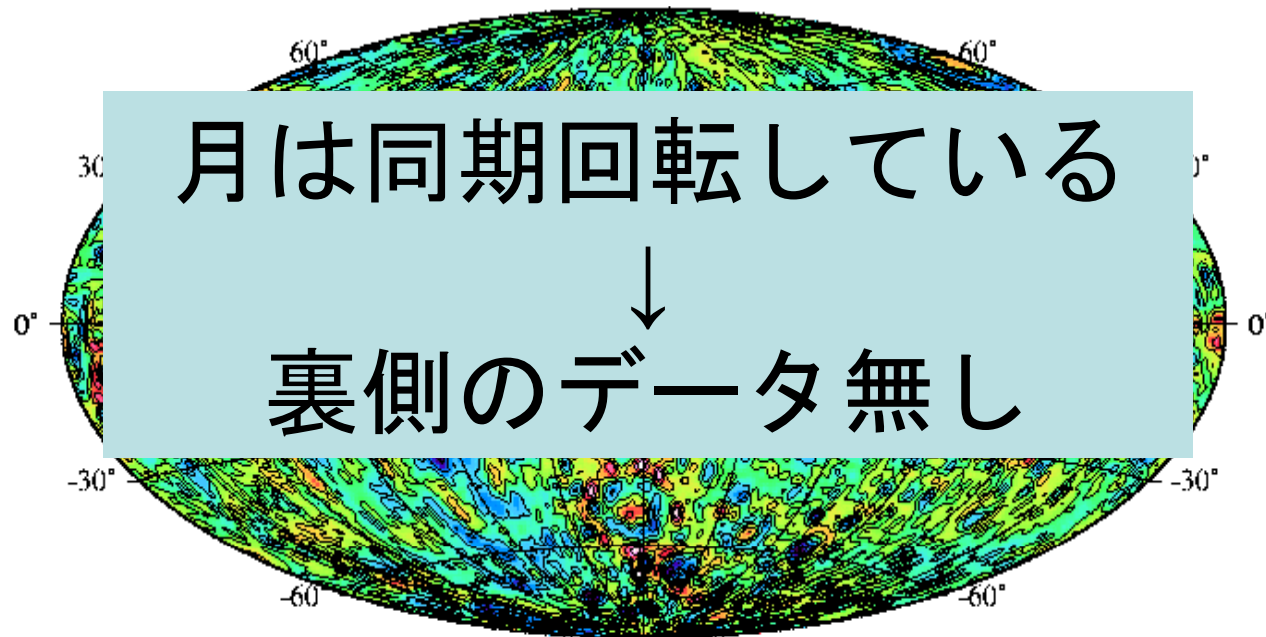
ドップラー効果によって送信周波数と受信周波数が異なる。この違いから、人工衛星の視線方向の速度が観測できる。



ルナプロスペクターがはかった月重力場



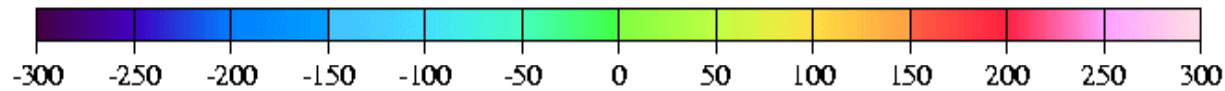
LP100J degree and order upto 100



月は同期回転している



裏側のデータ無し



(mgals)

Far-side



Near-side

拘束条件がないと . . .

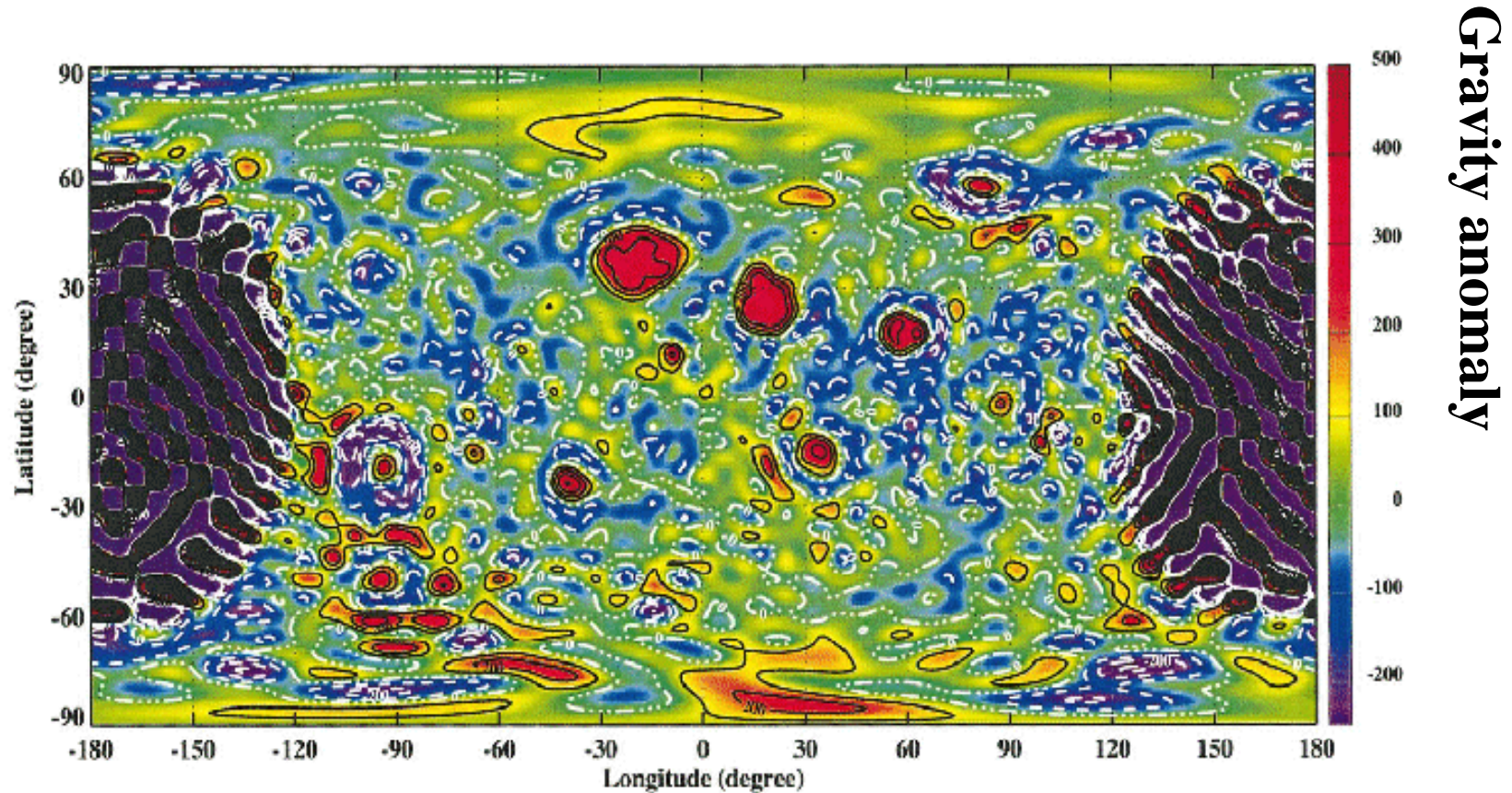
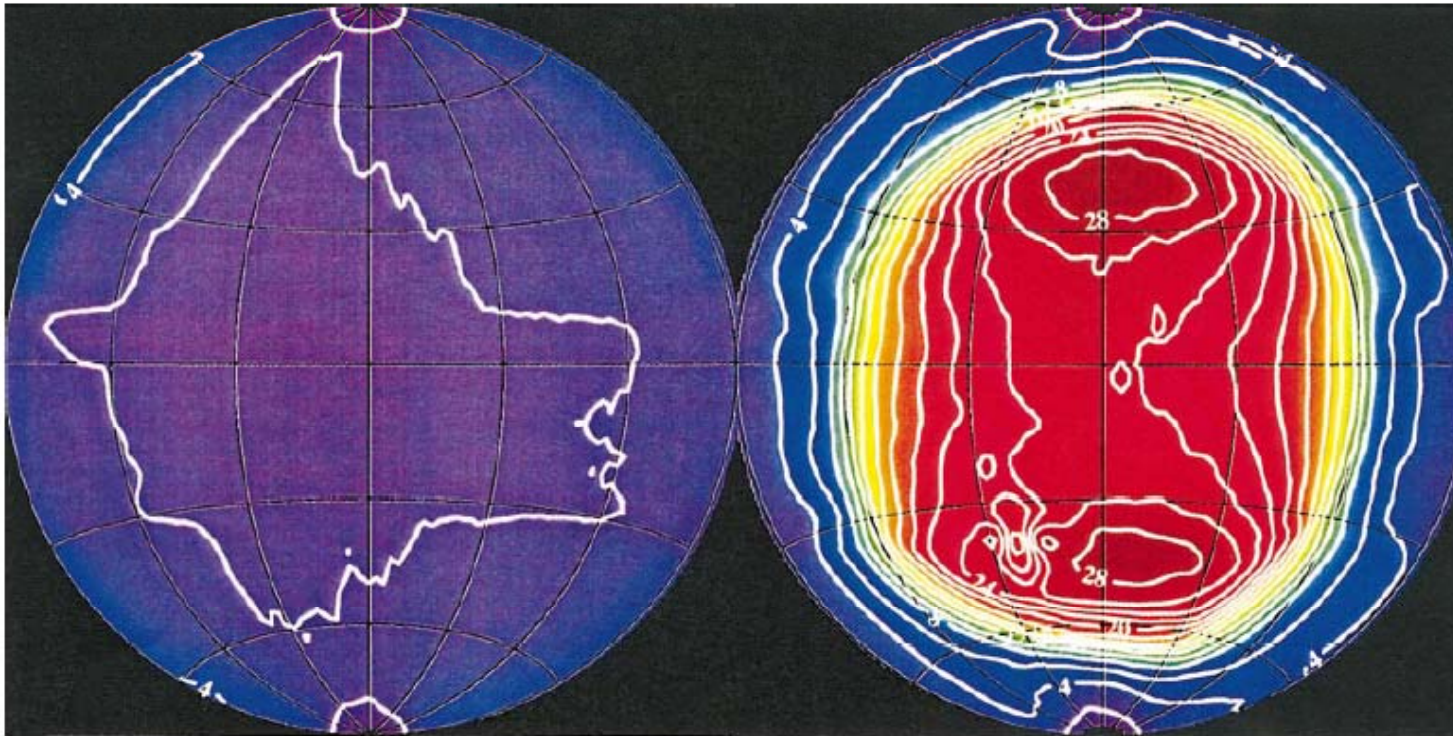


FIG. 4. Unconstrained 50th degree and order lunar gravity field (LP50PNOAP for no a priori) accelerations at the lunar surface. Large oscillations on the lunar farside indicate where there is no direct observation of the gravity field.

Konopliv et al., 2001

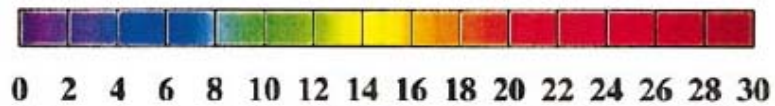


拘束条件をつけても . . .



Near-side

Far-side



Selenoid height error (m)

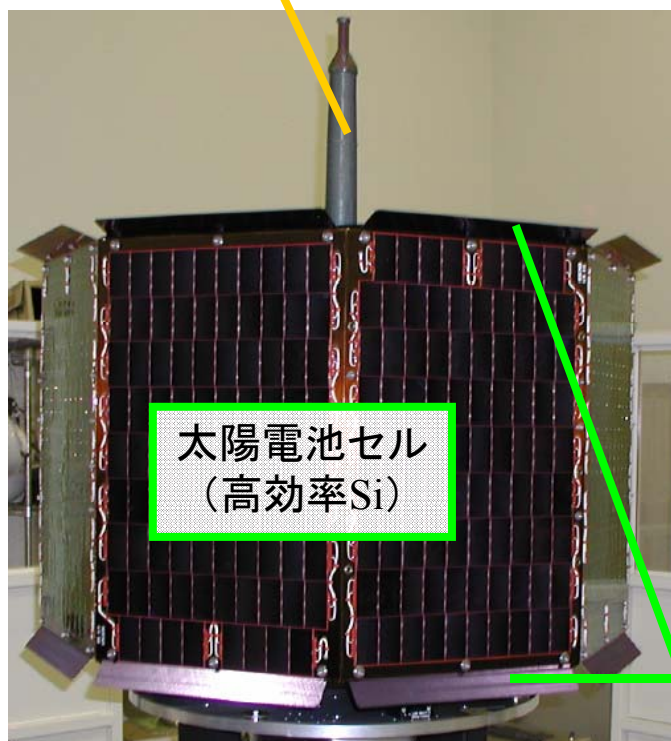
Konopliv et al., 2001

リレー衛星



サイズ: 1m × 1m × 0.65m
質量: 45kg
電力: 70W

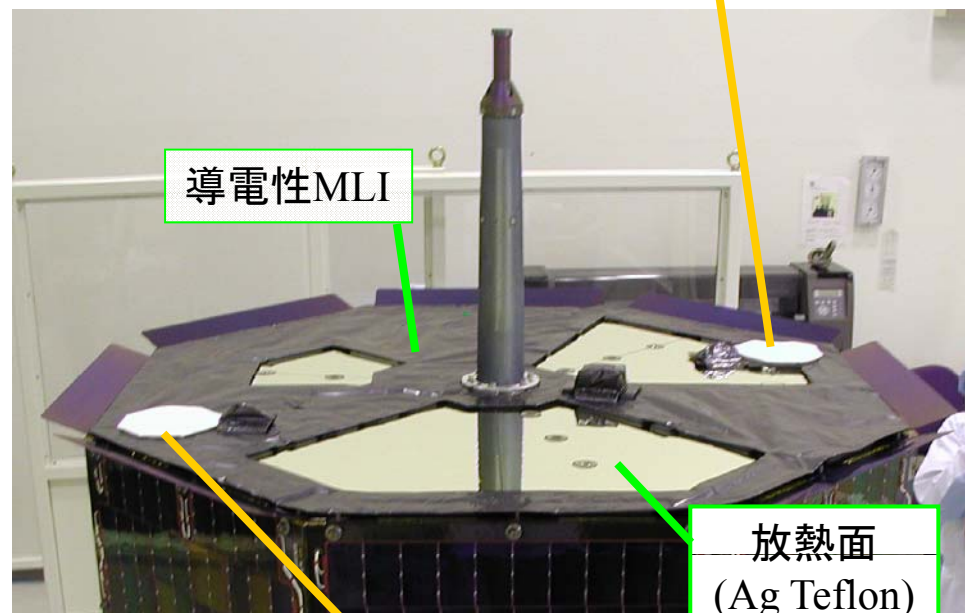
S/X帯垂直ダイポールアンテナ
[地球向けビーム]



太陽電池セル
(高効率Si)

太陽風キャンセル板
(Geコーティング)

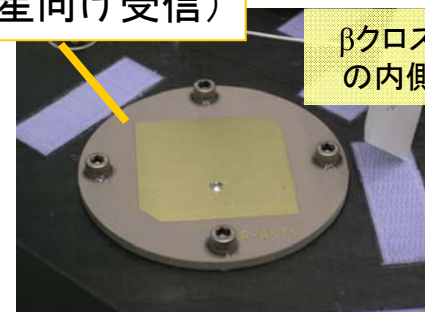
S帯平面アンテナ(上下に配置)
(主衛星向け送信)



導電性MLI

放熱面
(Ag Teflon)

S帯平面アンテナ
(主衛星向け受信)



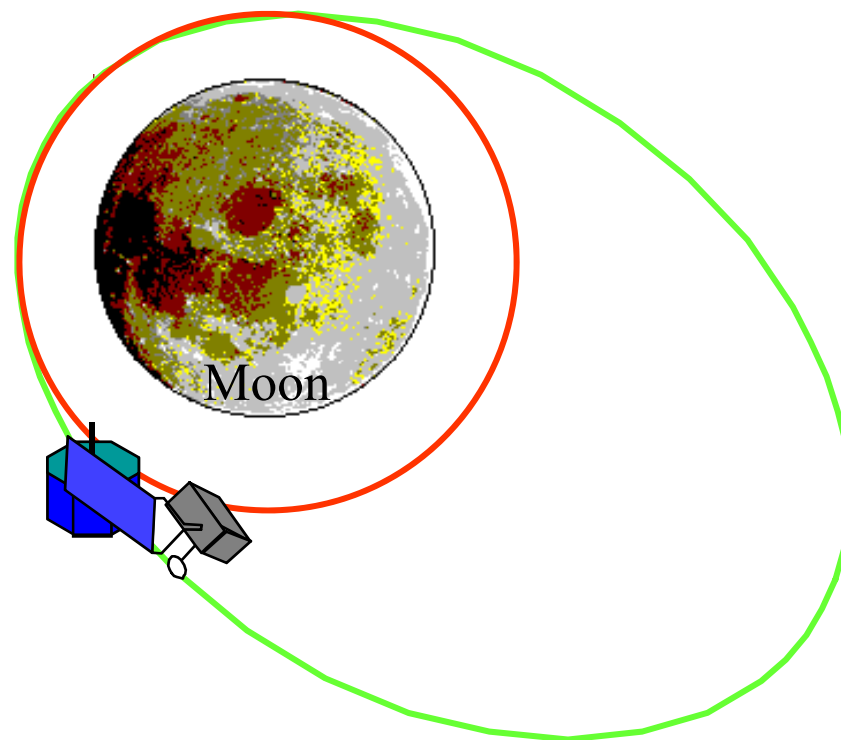
βクロス
の内側

4-way Doppler measurement

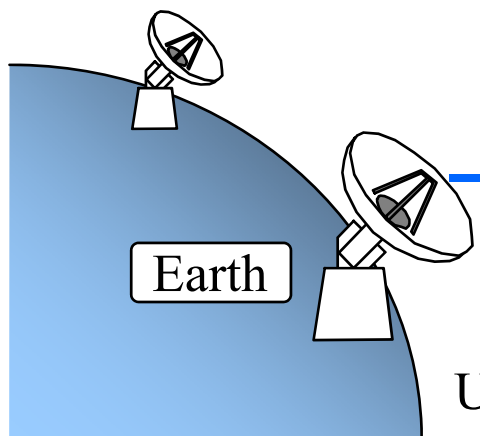


世界初！月裏側重力場の直接観測！

Near-side ← → Far-side



JAXA GN



JAXA
UDSC-64m

4-way RR (Doppler) for main satellite by way of Rstar
1 mm/s accuracy

臼田64mアンテナ



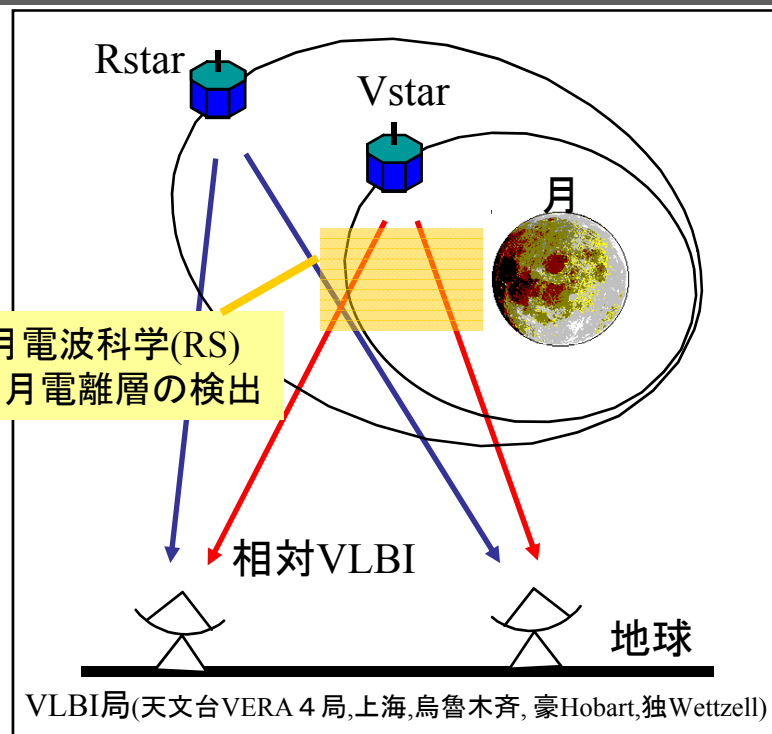
VRAD: 衛星電波源の多周波相対VLBI観測



相対VLBI観測量

$$\begin{aligned} &[(S1-T1) - (S1-T2)] - \\ &[(S2-T1) - (S2-T2)] \end{aligned}$$

S: Satellite
T: Tracking Station



RstarとVstarから発信される電波を多周波相対VLBI観測する。



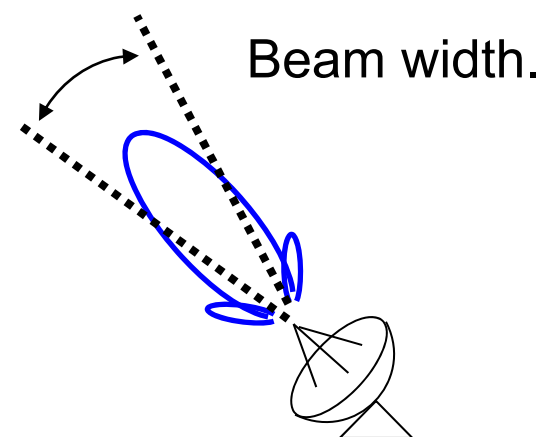
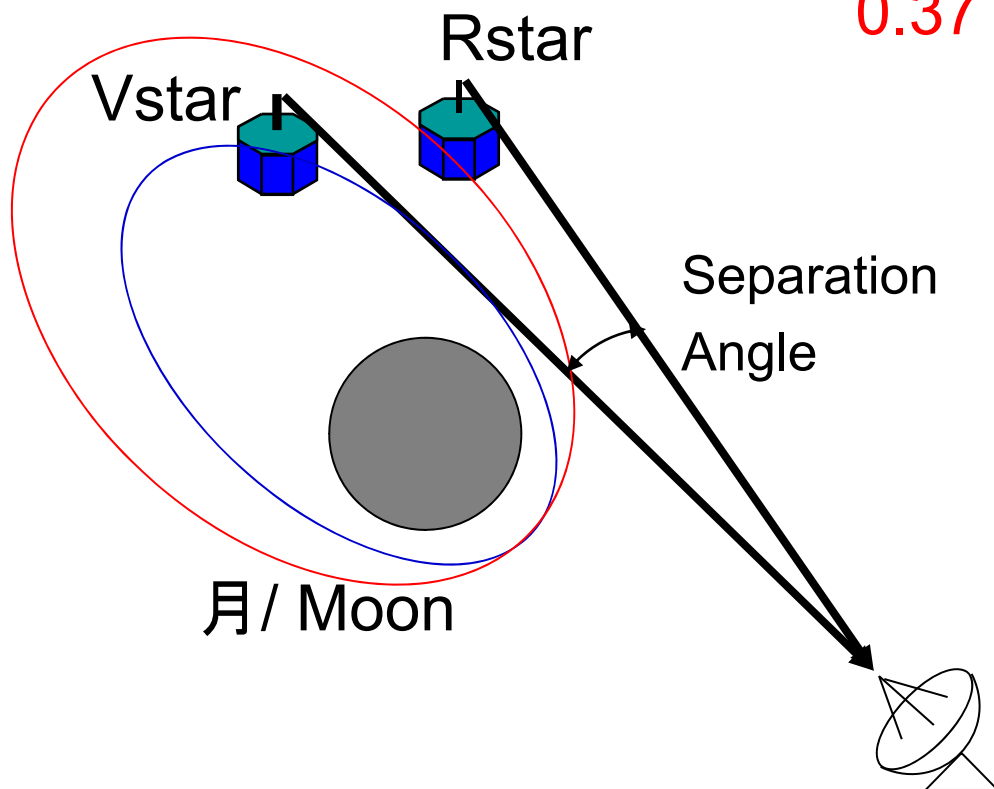
RARRより高精度の位置決定、視線垂直面方向の改善を行い、重力場の低次項を改善する。

Switching and Same beam VLBI Observation

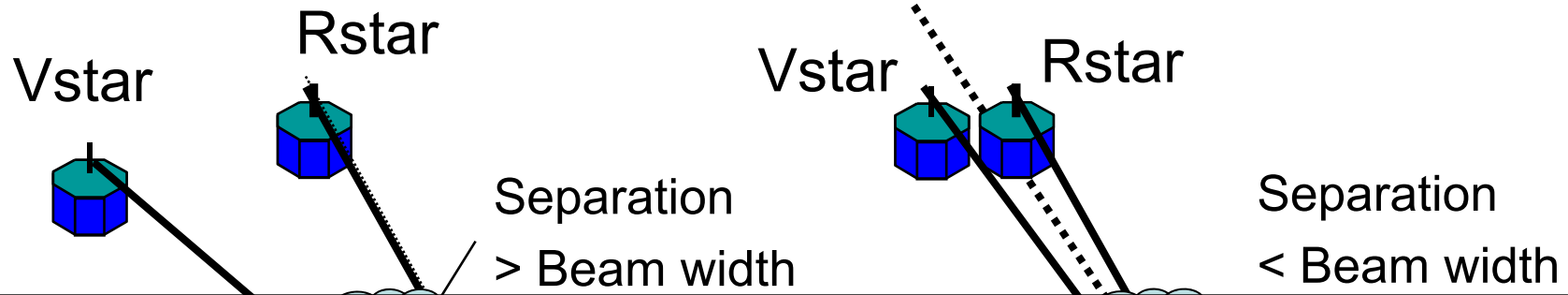


Separation angle between Rstar and Vstar changes between **0 to 0.9 degrees**.

Beam width of ground antenna (20m diameter) is **0.1 degrees** for X-band signal
0.37 degrees for S-band signal



Switching and Same beam VLBI Observation



Most of atmospheric 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.

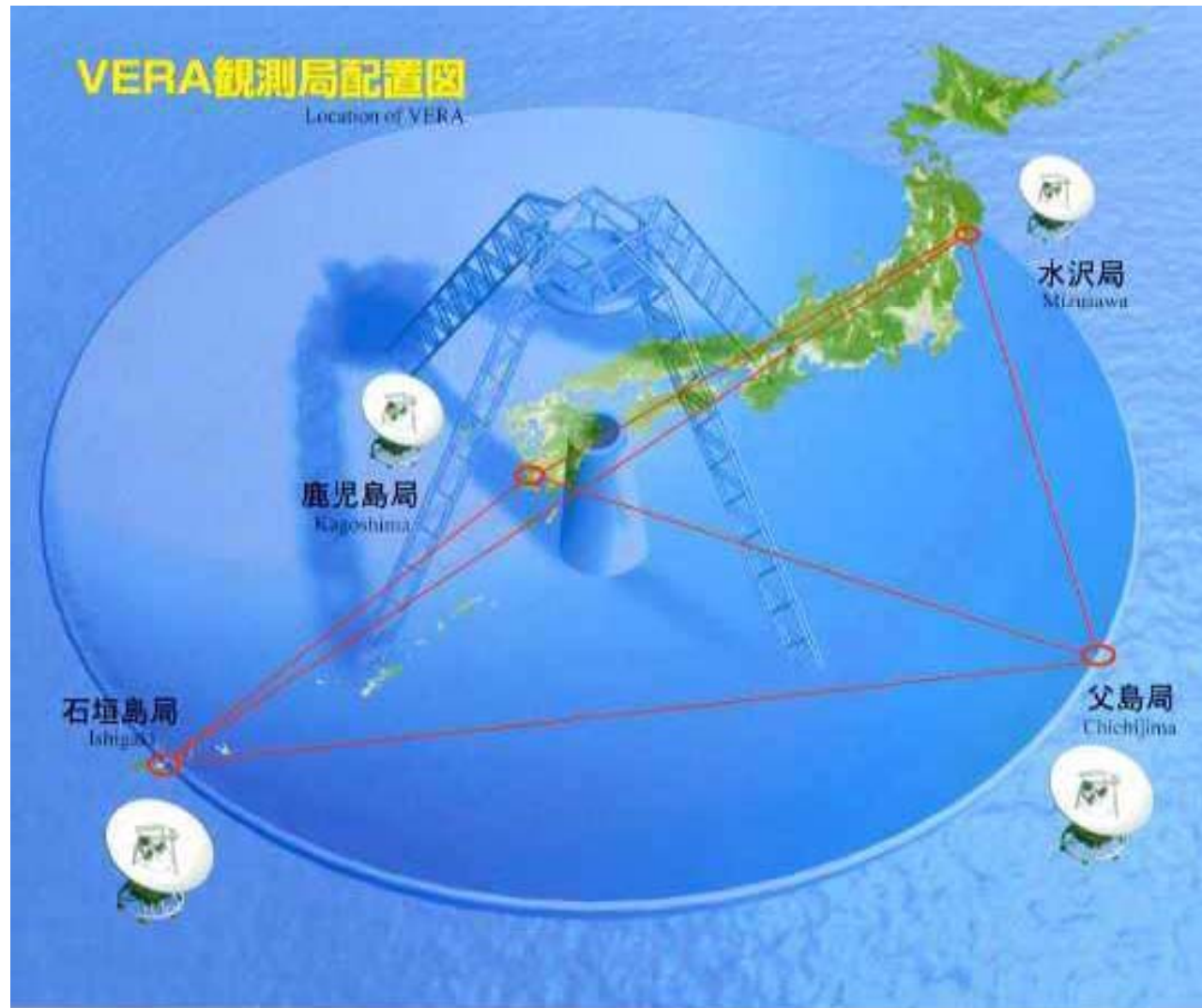
Switching VLBI

Ex) Radio astronomy
Nozomi, Geotail, etc

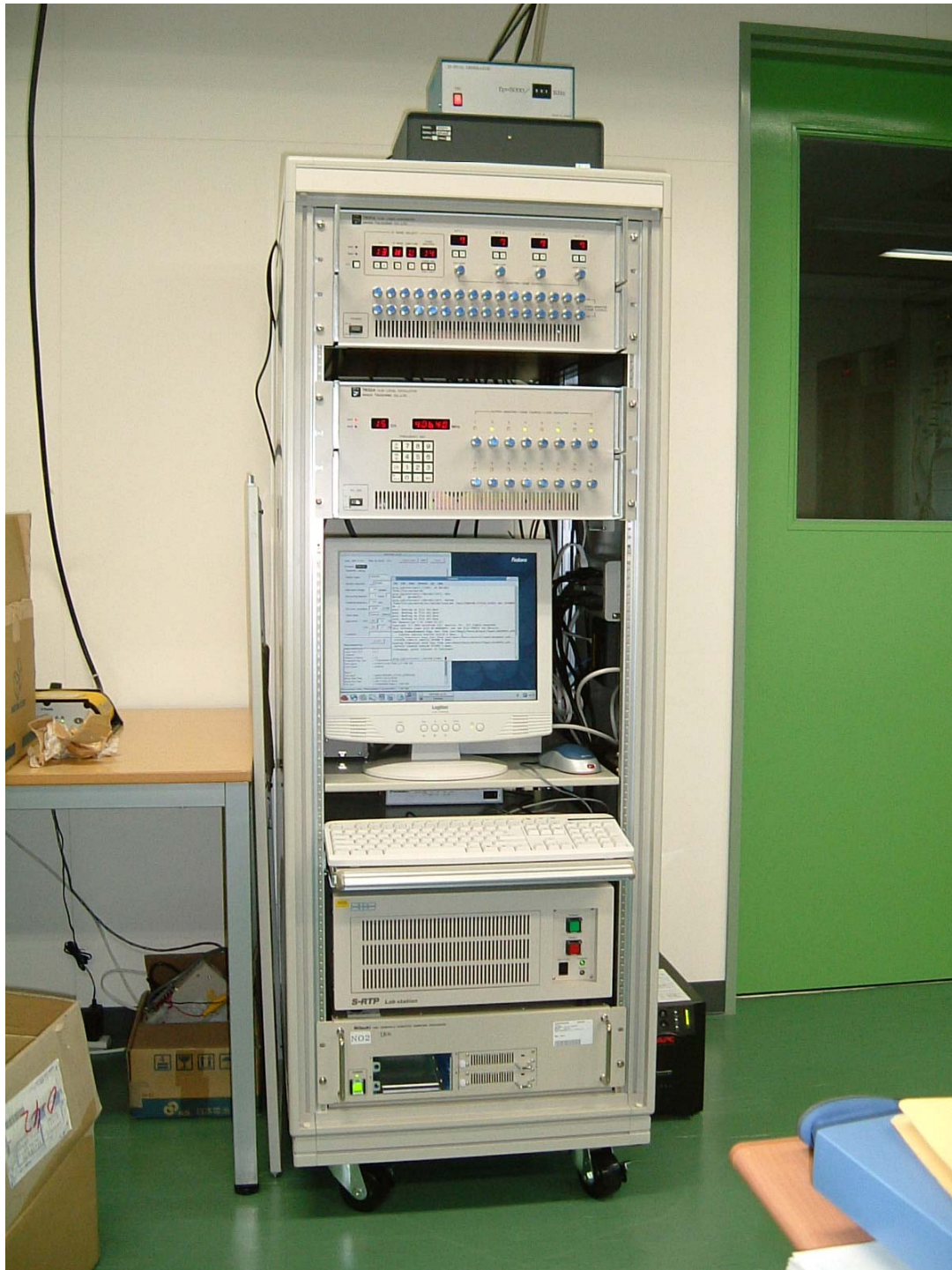
Same beam VLBI

Ex) Magellan and Pioneer Venus

VLBI局 (VERA)

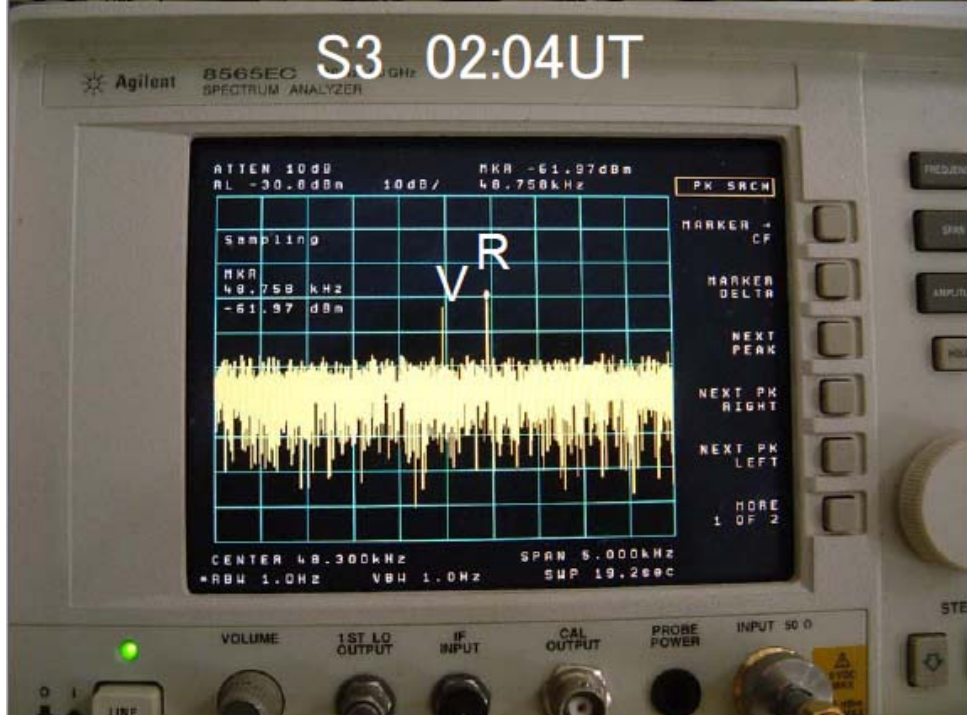
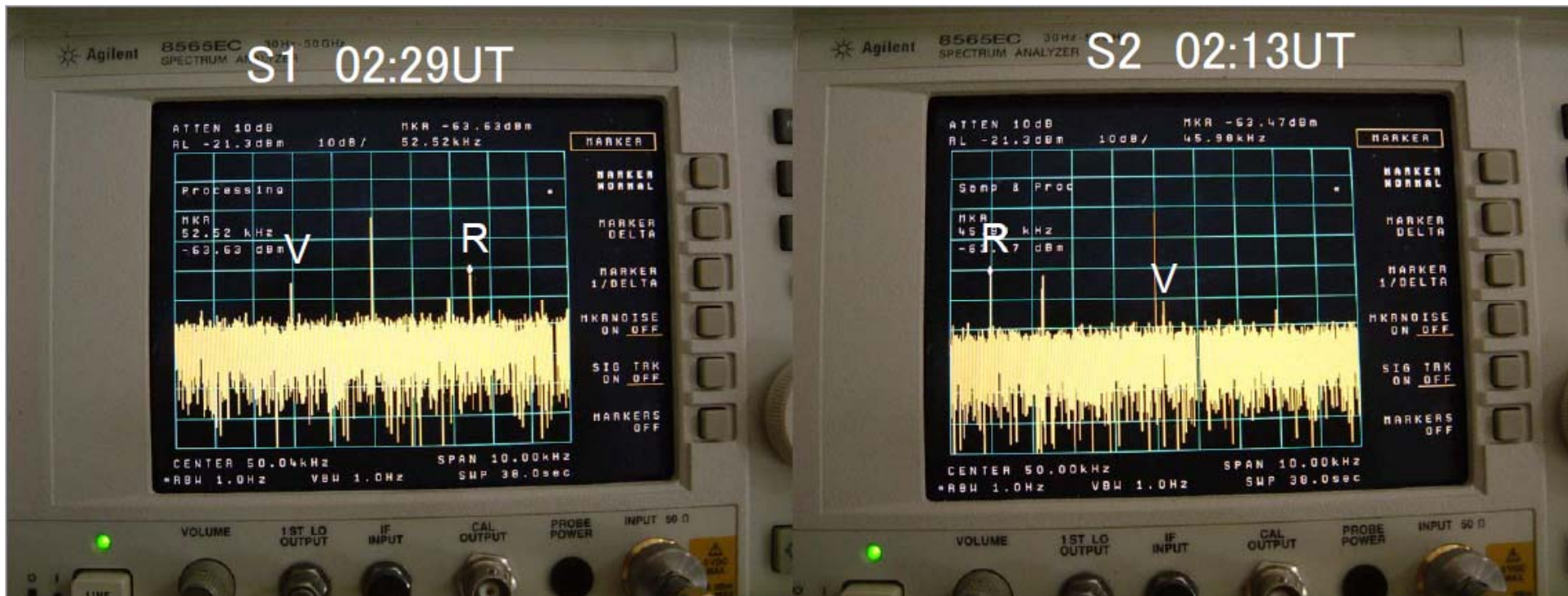


加えて、ホバート(オーストラリア), 上海, ウルムチ(中国), ウェッツェル(ドイツ)の海外4局



VLBIデータ記録システム

データはRAID1構成のHDDへ記録



S-band Samebeam signal @ Ishigaki
2007.11.07

国立天文台・三鷹

JAXA・相模原キャンパス内 SOAC解析室

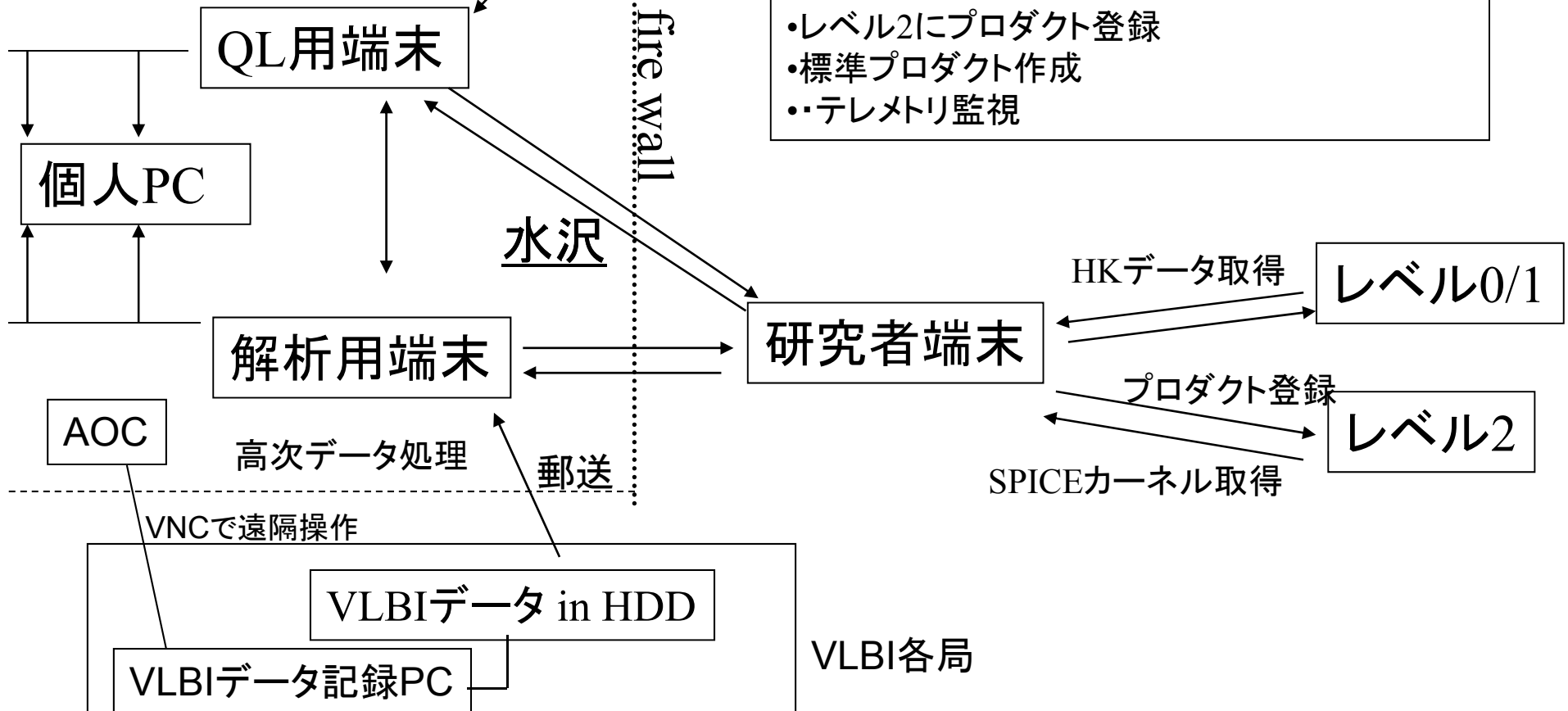
QL用端末での作業

- 準リアルタイムテレメトリデータ監視 (クイックルック機能)
- 運用要求用の情報ファイル取得
- 運用要求

準リアルタイム
テレメトリ監視用
データサーバに
接続

研究者端末でのユーザ作業

- レベル0/1からHKデータ取得
- レベル2にプロダクト登録
- 標準プロダクト作成
- テレメトリ監視



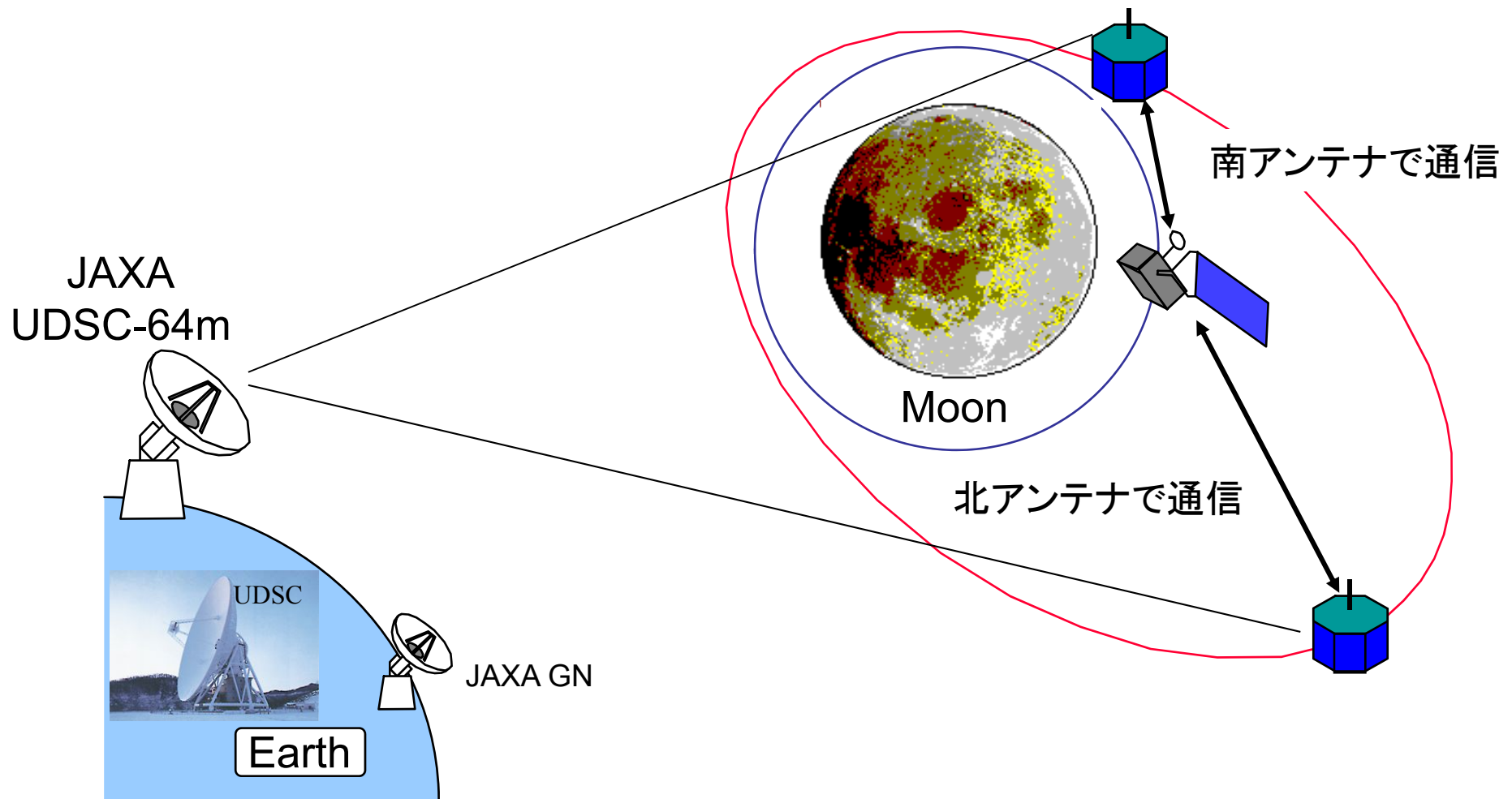
子衛星R/Vstar観測計画立案

R/Vstar観測計画立案

- Rstarには4つのモードがある。
 - (1) FWD : 4-way Doppler
 - (2) VRAD: 相対VLBI
 - (3) RSRD: 2-way Range & Doppler
 - (4) STBY : スタンバイ
- どのモードを使うかは、衛星の位置関係・地上局からの可視条件によって時間変化する。
- その度に地上局からコマンド送信。
- 前もって切り替え時刻を知らなければならない。

R/Vstar観測計画立案

- 4-way観測が出来る条件
 - (1) 主衛星が臼田から非可視(例外:全可視オプション運用)
 - (2) Rstarが臼田から可視
 - (3) 主衛星-Rstarが可視(間に月が入らない & HGA機械的リミット内)
- 適宜Rstarの対主衛星アンテナを上下(南北)で切り替え



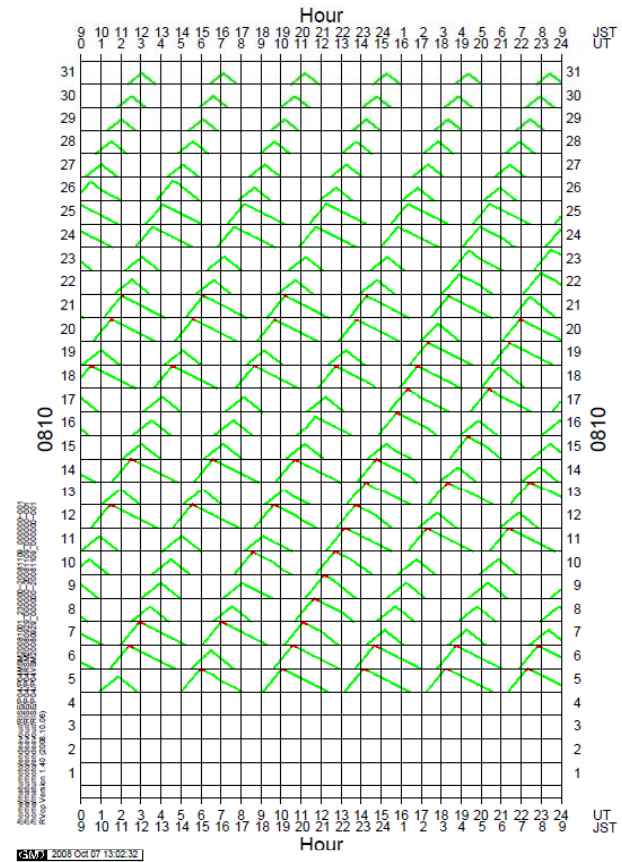
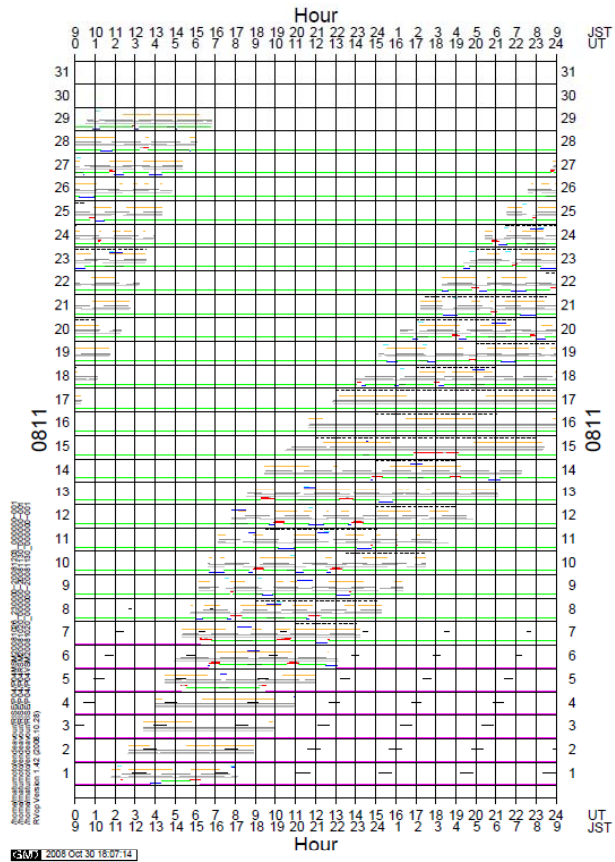
R/Vstar観測計画立案

- R/Vstarは小型衛星でバッテリーも小さい
- 食軌道中はDOD(放電深度)を予測し、20%を超えないように調整する。
- 主衛星掩蔽中、Rstar・Vstarどちらを追跡？
4-way優先。
RS観測機会はできるだけ生かす。
- 毎週月・木に軌道力学から軌道予報値が出る度に立案作業→火・金に運用指示書発行。

VLBI観測計画立案

- VERA局(水沢・小笠原・入来・石垣)と調整し、約100時間/月のアンテナ時間を確保
- 2ヶ月～1ヶ月半前に、Same-beam VLBIのチャンスがある時間帯を出来るだけ狙って観測提案
- (FWD or RSRD) と VRADモードを共存させていないので、Same-beamチャンスを十分に生かしきれない場合もある
 - 後期運用では共存(11/22から実施)

立案結果の例



立案結果の例

時刻(UT)	M可視情報	R可視情報	V可視情報	M-R可視情報	R日陰情報	V日陰情報	R運用モード	RS観測機会	実施局
10/05 00:56					R日陰開始				
10/05 00:59						V日陰開始			
10/05 01:33				M-R可視開始(北)					
10/05 01:52						V日陰終了			
10/05 01:53					R日陰終了				
10/05 02:47				M-R可視終了(北)					
10/05 03:33						V日陰開始			
10/05 03:57		R可視開始							
10/05 03:59							STBY→VRAD		UDSC
10/05 04:00	M可視開始								
10/05 04:00			V可視開始						UDSC運用開始
10/05 04:00									
10/05 04:26						V日陰終了			
10/05 04:36	M可視終了						VRAD→RSRD		UDSC
10/05 05:00							RSRD→VRAD		UDSC
10/05 05:01	M可視開始								
10/05 05:02					R日陰開始				
10/05 05:08			V可視終了						
10/05 05:26				M-R可視開始(北)					
10/05 05:29			V可視開始						
10/05 05:59					R日陰終了				
10/05 06:08						V日陰開始			
10/05 06:35	M可視終了						VRAD→FWD		UDSC
10/05 06:40				M-R可視終了(北)					
10/05 06:40							FWD→RSRD		UDSC
10/05 06:58							RSRD→VRAD		UDSC
10/05 06:59	M可視開始								
10/05 07:00						V日陰終了			
10/05 07:43			V可視終了						
10/05 08:03			V可視開始						
10/05 08:33	M可視終了								
10/05 08:42						V日陰開始			
10/05 08:56	M可視開始								
10/05 09:07					R日陰開始				
10/05 09:18				M-R可視開始(北)					
10/05 09:34						V日陰終了			
10/05 10:04					R日陰終了				UDSC運用終了
10/05 10:05									
10/05 10:06			V可視終了						
10/05 10:07	M可視終了								
10/05 10:08		R可視終了							
10/05 10:33				M-R可視終了(北)					
10/05 11:16						V日陰開始			
10/05 12:09						V日陰終了			
10/05 13:08				M-R可視開始(南)					
10/05 13:12				M-R可視終了(南)					
10/05 13:12				M-R可視開始(北)					
10/05 13:12					R日陰開始				
10/05 13:50						V日陰開始			
10/05 13:53				M-R可視終了(北)					
10/05 13:53				M-R可視開始(南)					
10/05 14:09					R日陰終了				
10/05 14:11				M-R可視終了(南)					
10/05 14:11				M-R可視開始(北)					
10/05 14:26				M-R可視終了(北)					
10/05 14:43						V日陰終了			
10/05 16:25						V日陰開始			
10/05 16:53				M-R可視開始(南)					
10/05 17:16				M-R可視終了(南)					
10/05 17:16				M-R可視開始(北)					
10/05 17:17					R日陰開始				
10/05 17:17						V日陰終了			
10/05 17:31				M-R可視終了(北)					
10/05 17:31				M-R可視開始(南)					

指示書の例

衛星	GN	UDSC USC	軌力	SELENE 運用指示書 (リレー衛星/VRAD衛星)				版	承認	点検	作成
				2008年11月20日木曜日				2008年11月13日作成			並木
予定時刻	可視情報			食情報	観測・運用モード		実施局	手順書			
(UT)	主衛星 (地上局から)	R/VStar (地上局から)	RStar (空機局から)	R/VStar 日照	観測モード	R/VStar 運用モード	運用局	運用内容	ファイル名	備考	
20日											
16:53	非可視	可視	非可視	日照	R-SAFE	S+VRAD	UDSC	<<Rstar運用: RSAT 2-WAY観測>> 白田局: アップリンク・2-WAY捕捉, SOAC: ヘルステチェック	main2-rsst04	管制: 野田, モニタ係: 杉田	
17:04	↓	↓	↓	↓	R-2-WAY	RSRD		白田局: RNG計測開始	dscm-c8-vd-rs04		
17:06	↓	↓	↓	↓	R-SAFE	S+VRAD		白田局: RNG計測停止, SOAC: モード切替	dscm-c5-rs-vd04		
					RV-VLBI	VRAD		終了			
17:09	非可視	非可視	N/A	日照	RS	VRAD	UDSC	<<Vstar運用: RS観測, TTC>> RS (電波科学) 観測開始	main2-vrad04	(*) 短い切替時間に注意	
17:11	↓	↓	↓	↓	V-SAFE	S+VRAD		白田局: アップリンク・2-WAY捕捉, SOAC: ヘルステチェック			
17:29	↓	↓	↓	↓	V-2-WAY	TTC+VRAD		白田局: RNG計測開始			
17:31	↓	↓	↓	↓	V-SAFE	S+VRAD		白田局: RNG計測停止, SOAC: モード切替			
					RV-VLBI	VRAD		終了			
18:42	可視	可視	可視(北)	日照	R-SAFE	S+VRAD	UDSC	<<Rstar運用: RSAT 4-WAY観測>> 白田局: アップリンク・2-WAY捕捉, SOAC: ヘルステチェック	main2-rsst04	18:43-19:29 RSAT-2 ON	
18:47	↓	↓	↓	↓	4-WAY	FWD		白田局: 4-WAYドップラ・RNG計測開始	dscm-c7-vd-fw04	19:00-19:06 HGA'95°	
19:07	↓	↓	非可視	↓	R-2-WAY	↓		4-WAYリンク終了			
19:27	↓	↓	↓	↓	R-SAFE	S+VRAD		白田局: RNG計測停止, SOAC: モード切替	dscm-c2-fw-vd04		
19:29	↓	↓	↓	↓	RV-VLBI	VRAD		終了			
20:48	非可視	可視	N/A	日照	V-SAFE	S+VRAD	UDSC	<<Vstar運用: TTC>> 白田局: アップリンク・2-WAY捕捉, SOAC: ヘルステチェック	main2-vrad04		
21:24	↓	↓	↓	↓	V-2-WAY	TTC+VRAD		白田局: RNG計測開始			
21:26	↓	↓	↓	↓	V-SAFE	S+VRAD		白田局: RNG計測停止, SOAC: モード切替			
					RV-VLBI	VRAD		終了			
22:37	可視	可視	可視(北)	日照	R-SAFE	S+VRAD	UDSC	<<Rstar運用: RSAT 4-WAY観測>> 白田局: アップリンク・2-WAY捕捉, SOAC: ヘルステチェック	main2-rsst04	22:38-23:24 RSAT-2 ON	
22:42	↓	↓	↓	↓	4-WAY	FWD		白田局: 4-WAYドップラ・RNG計測開始	dscm-c7-vd-fw04	22:52-22:58 HGA'95°	
22:59	↓	↓	非可視	↓	R-2-WAY	↓		4-WAYリンク終了			
23:22	↓	↓	↓	↓	R-SAFE	S+VRAD		白田局: RNG計測停止, SOAC: モード切替	dscm-c2-fw-vd04		
23:24	↓	↓	↓	↓	HOLD	VRAD		終了			

特記事項

・各イベント時刻は、予報値精度の影響ですれる場合があります。
・4way捕引: DEC, 10 kHz, 1 kHz/s, 捕引終了後にX帯再捕捉する。(別途指示する場合があります。)

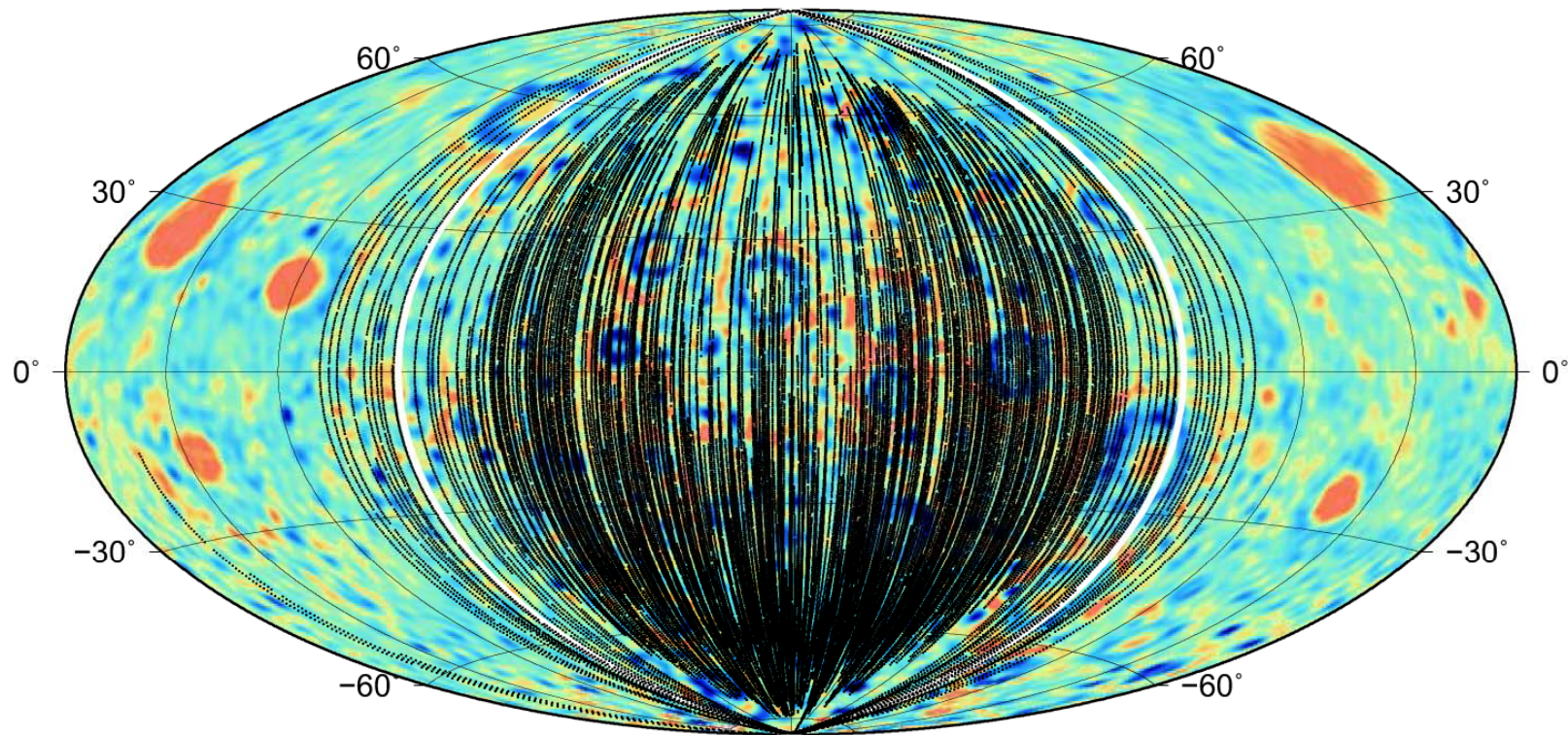
「かぐや」重力場モデル

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 on the Moon
- 2009.06.10 Main satellite will hit the Moon
- 2009.06.29 The last tracking of Vstar (VLBI sub-satellite)

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

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
- Historical: LO I-V, A15/16ss, Clementine,
LP nominal mission, SMART-1

Setting

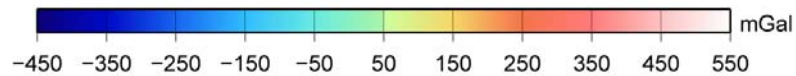
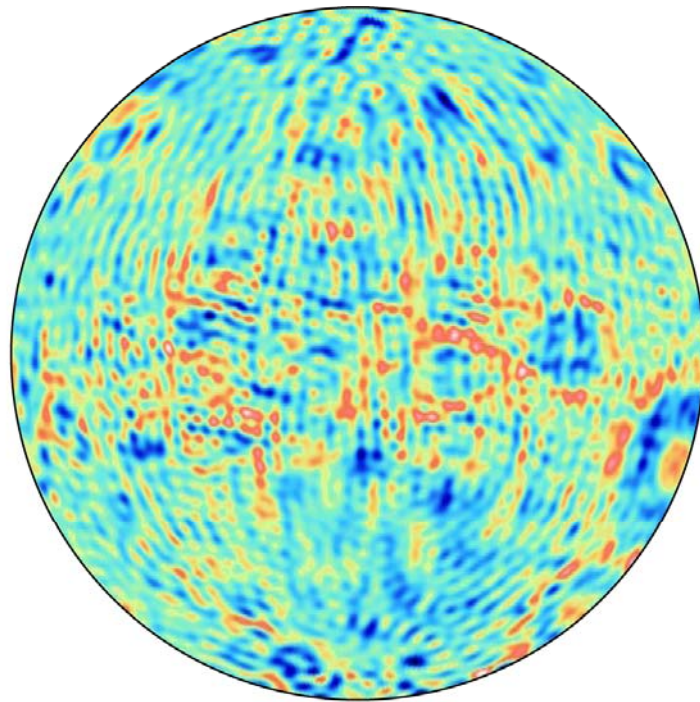
- GEODYN II, SOLVE system
- Expanded up to degree and order 100
- Ephemeris: DE421
- A Kaula-type constraint of $3.6 \times 10^{-4}/n^2$
- Solar radiation pressure model
SELENE Main: box + wing
SELENE R/Vstar and other satellites : cannonball
- Mean arc length of Rstar = 2.6 days
- VLBI data not included

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

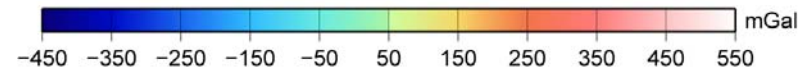
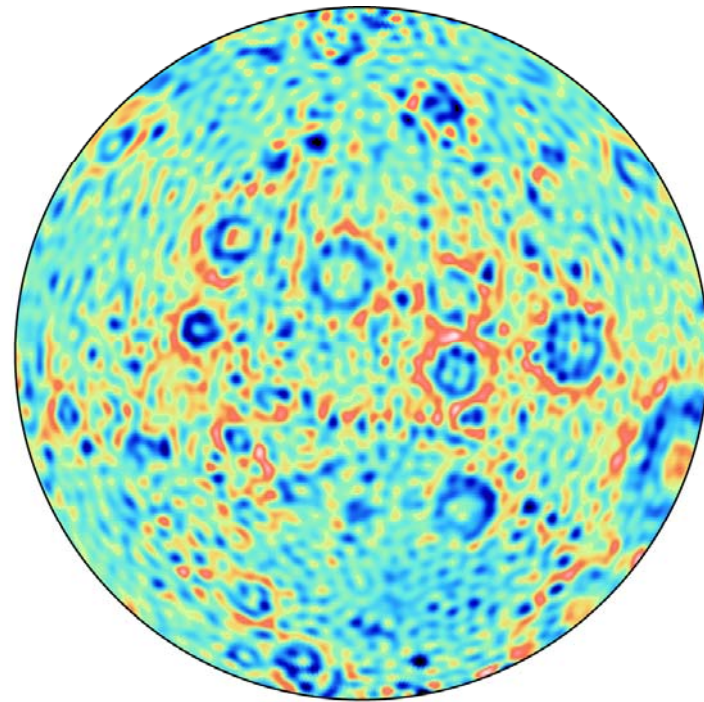
	Satellite	Data type	Amount	Arc length	Data weight	
Far side	SELENE 4-way	Doppler	78,004	2.6 days	1 mm/s	
	SELENE Main	Doppler UDSC	1,786,747	12 hours *	1 mm/s	
		Doppler GN			2 mm/s	
		Range			5 m	
	SELENE Rstar	Doppler	159,225	2.6 days	1 mm/s	
		Range	150,470		5 m	
	SELENE Vstar	Doppler	42,502	2.4 days	1 mm/s	
		Range	35,567		5 m	
	Near side	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 (Pommonkey 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

Old and new views of far-side gravity field

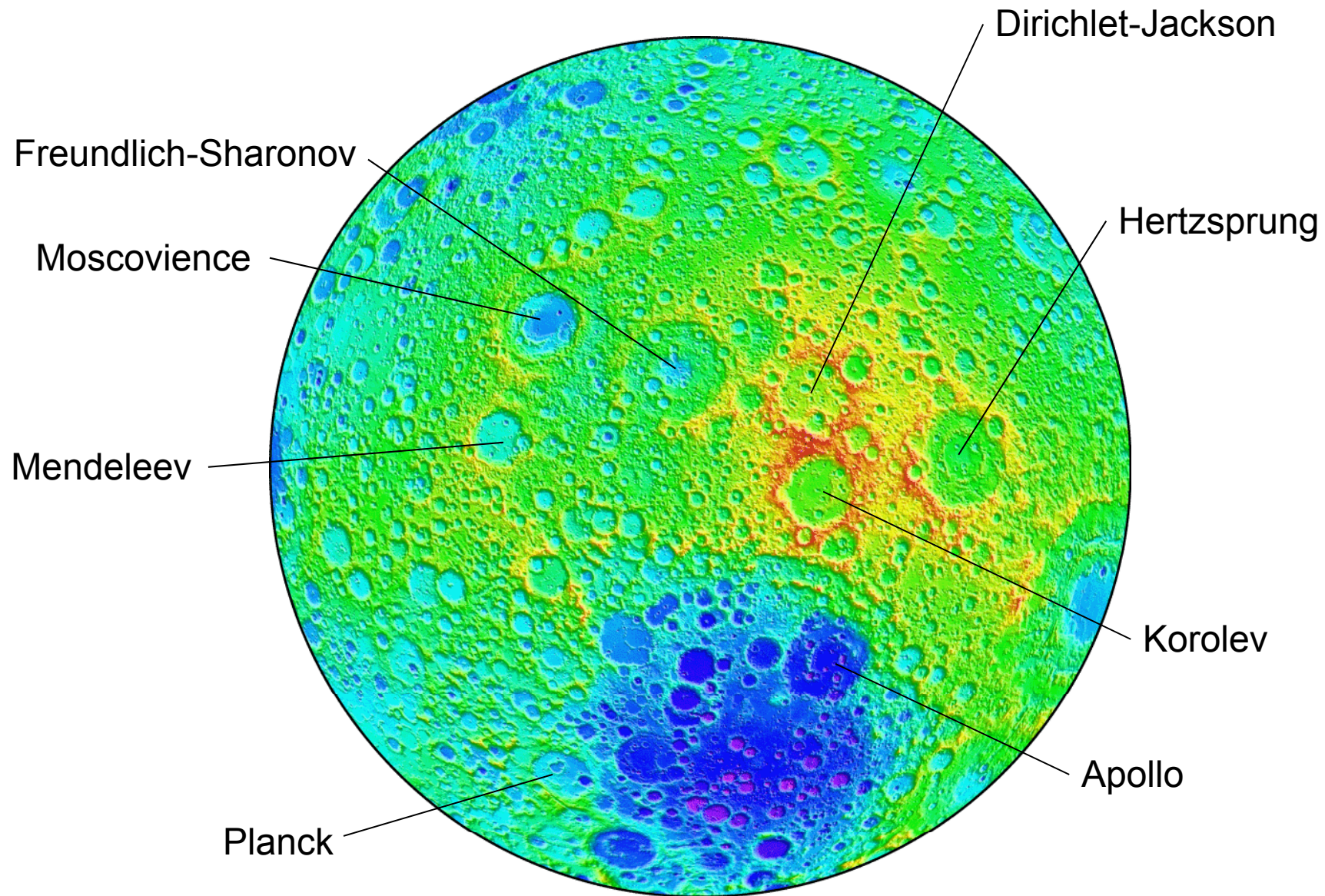


LP100K

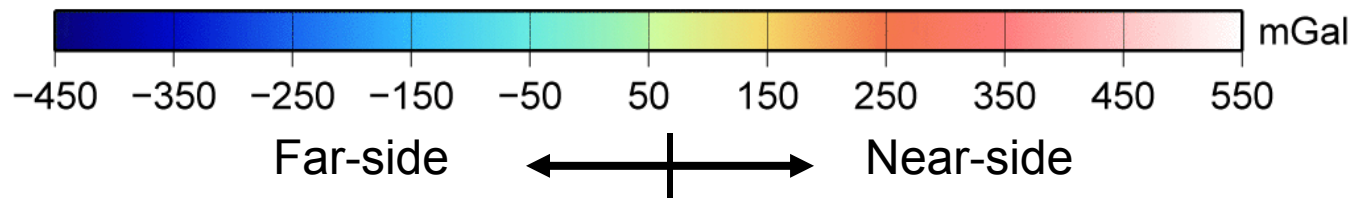
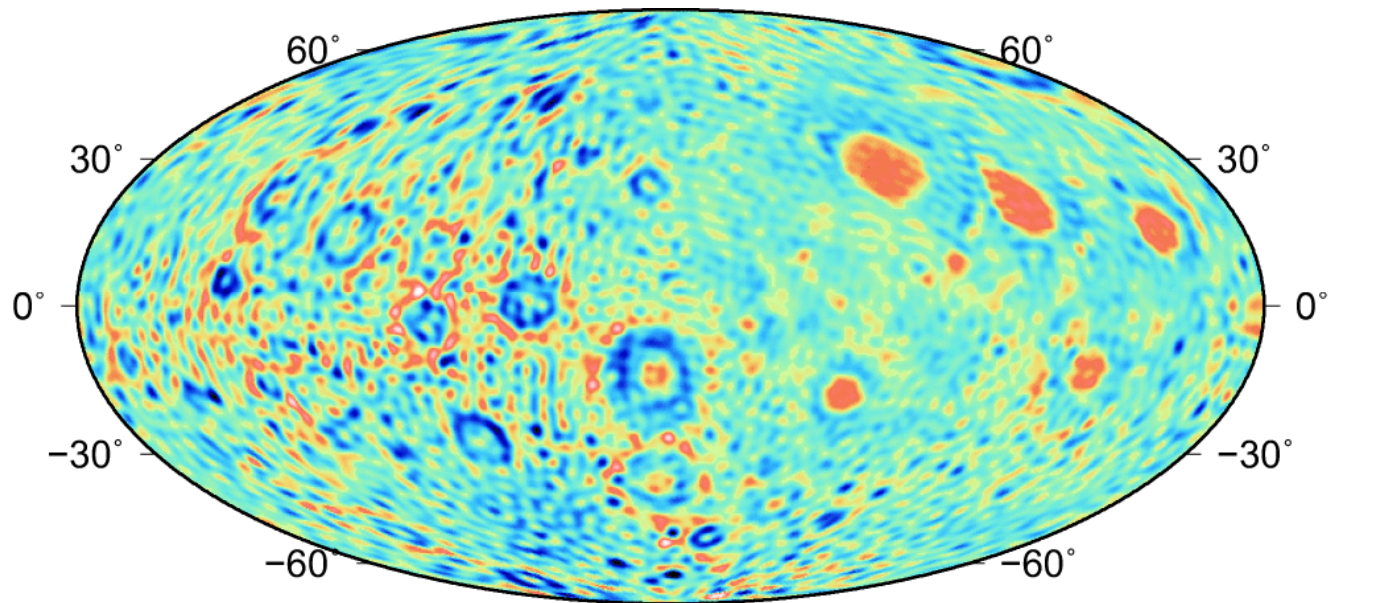


SGM100h

Topography-gravity correspondence



SGM90d and SGM100h

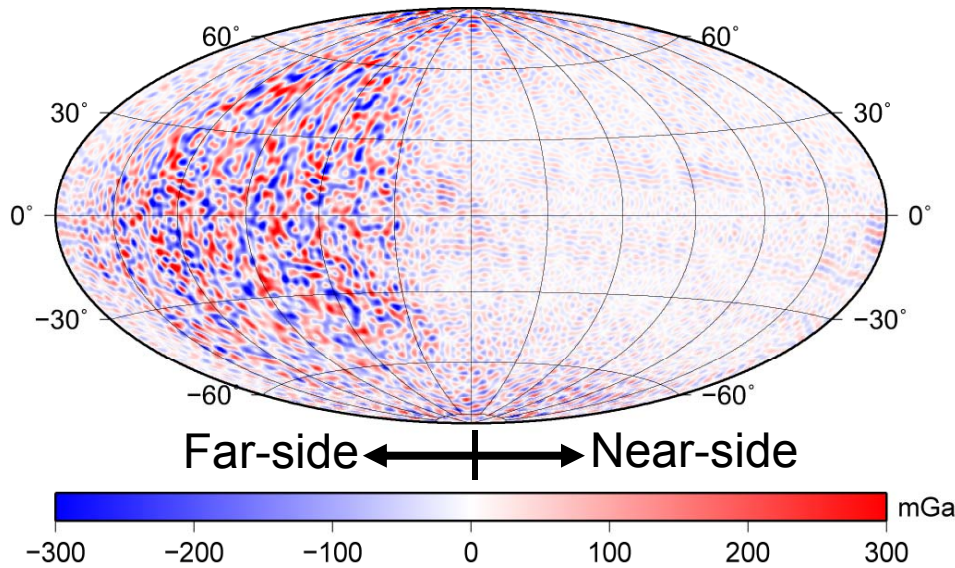


SGM90d
Namiki et al. (2009)
based on 5-month of SELENE data
plus historical data

SGM100h
This study
based on 14-month of SELENE data
plus historical data

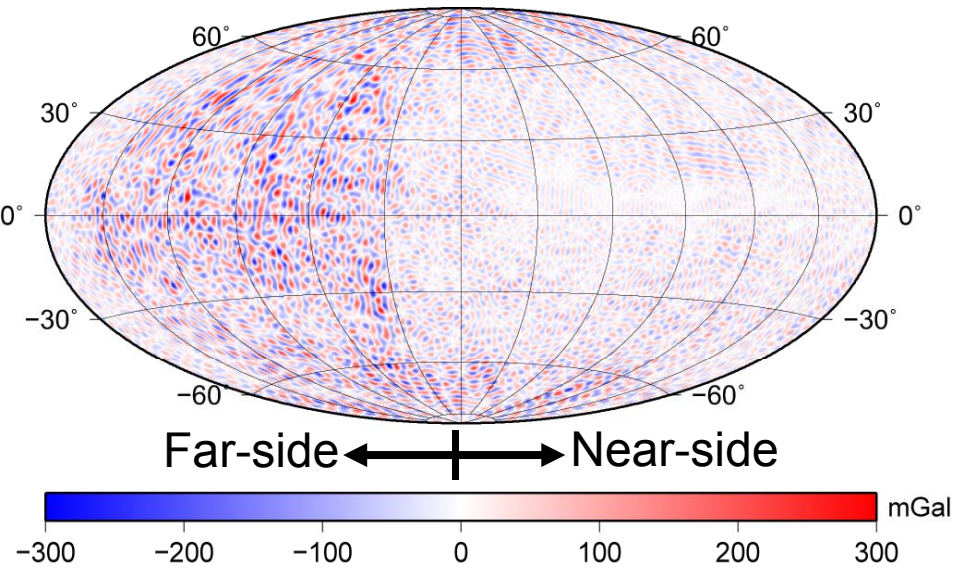
Free air gravity anomaly differences

SGM100h-LP100K



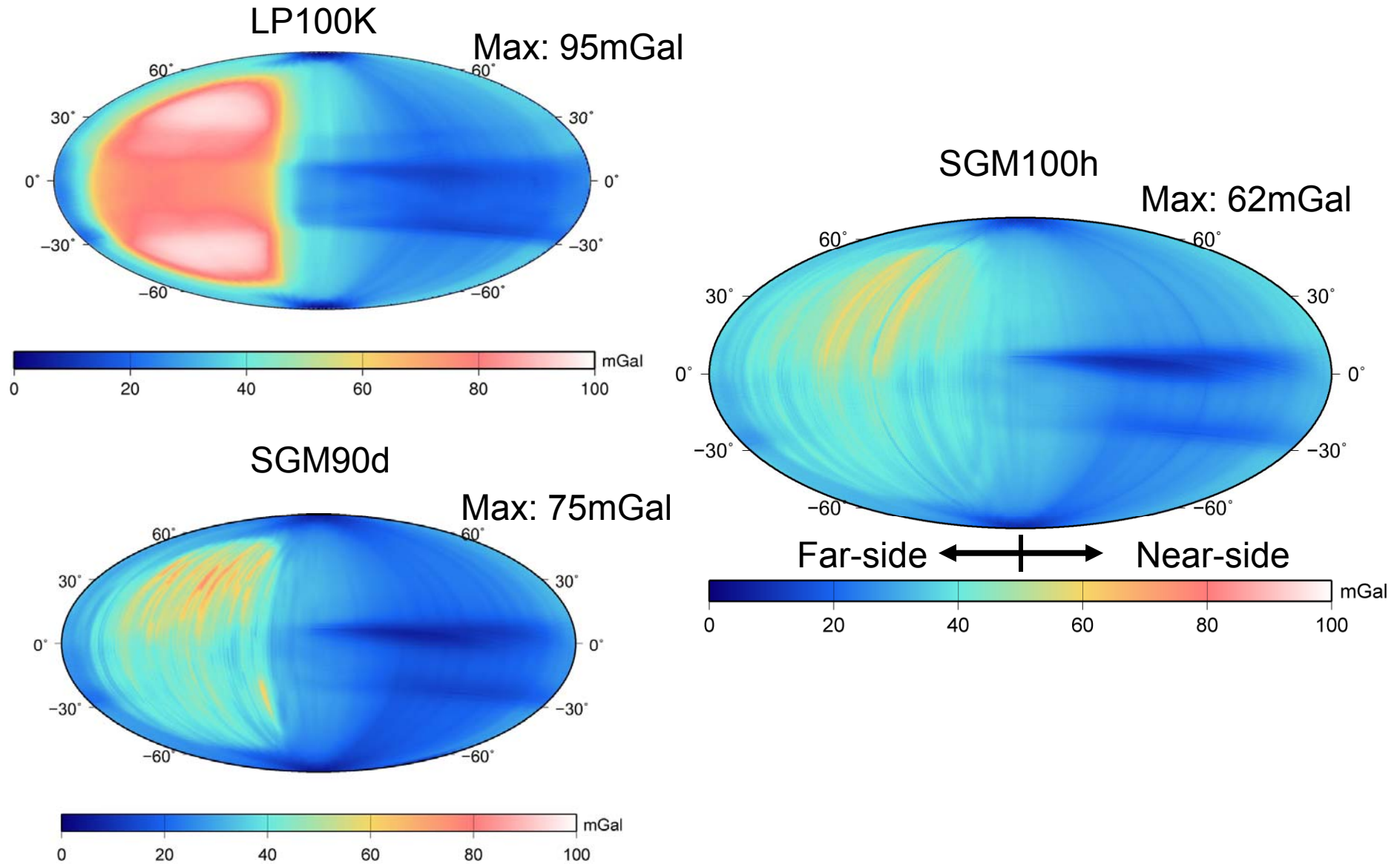
Min: -495mGal
Max: 544mGal
RMS:
near-side 46mGal
far-side 96mGal
global 76mGal

SGM100h-SGM90d

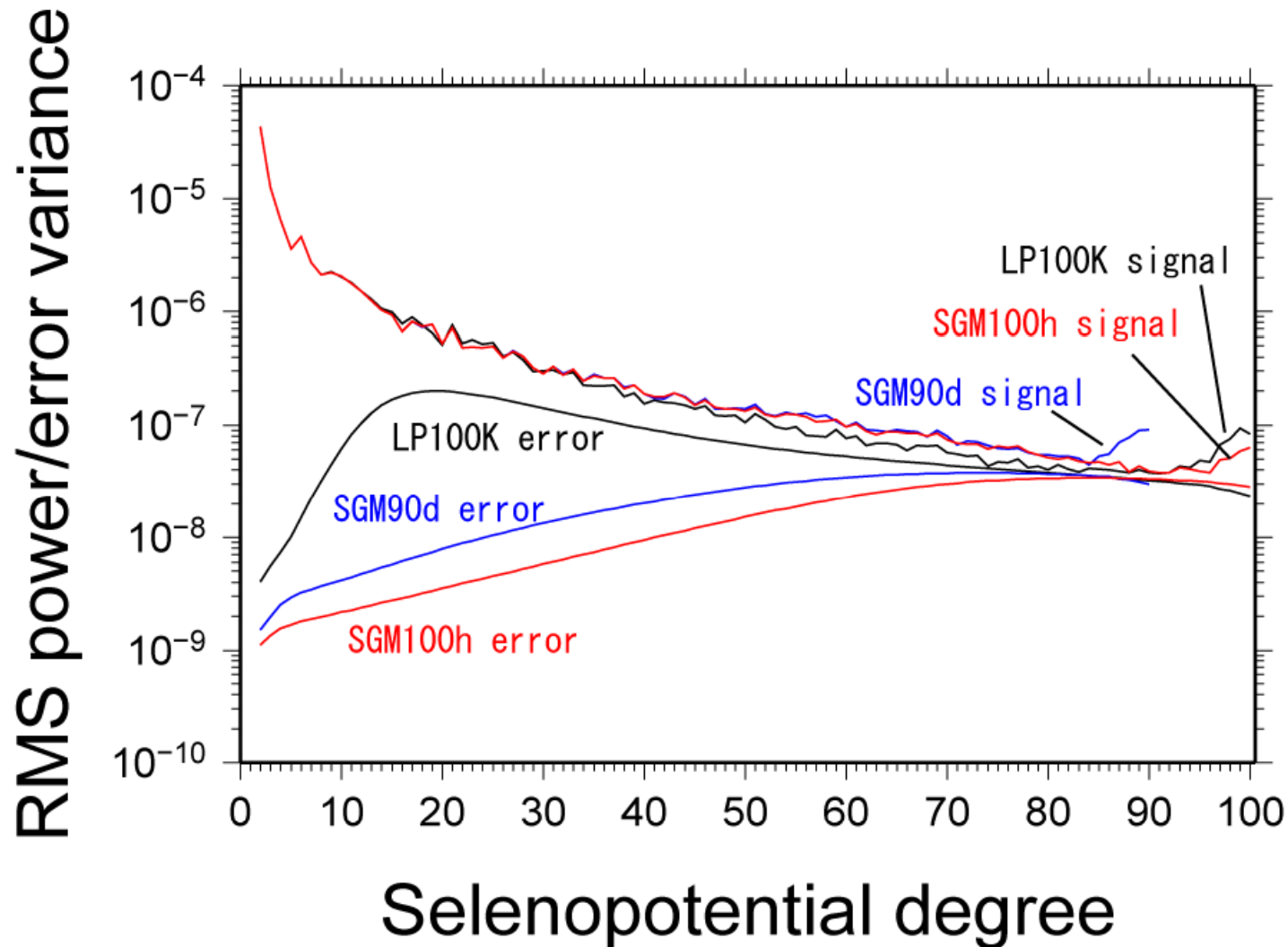


Min: -313mGal
Max: 355mGal
RMS:
near-side 43mGal
far-side 67mGal
global 57mGal

Gravity anomaly errors from the full covariance matrix

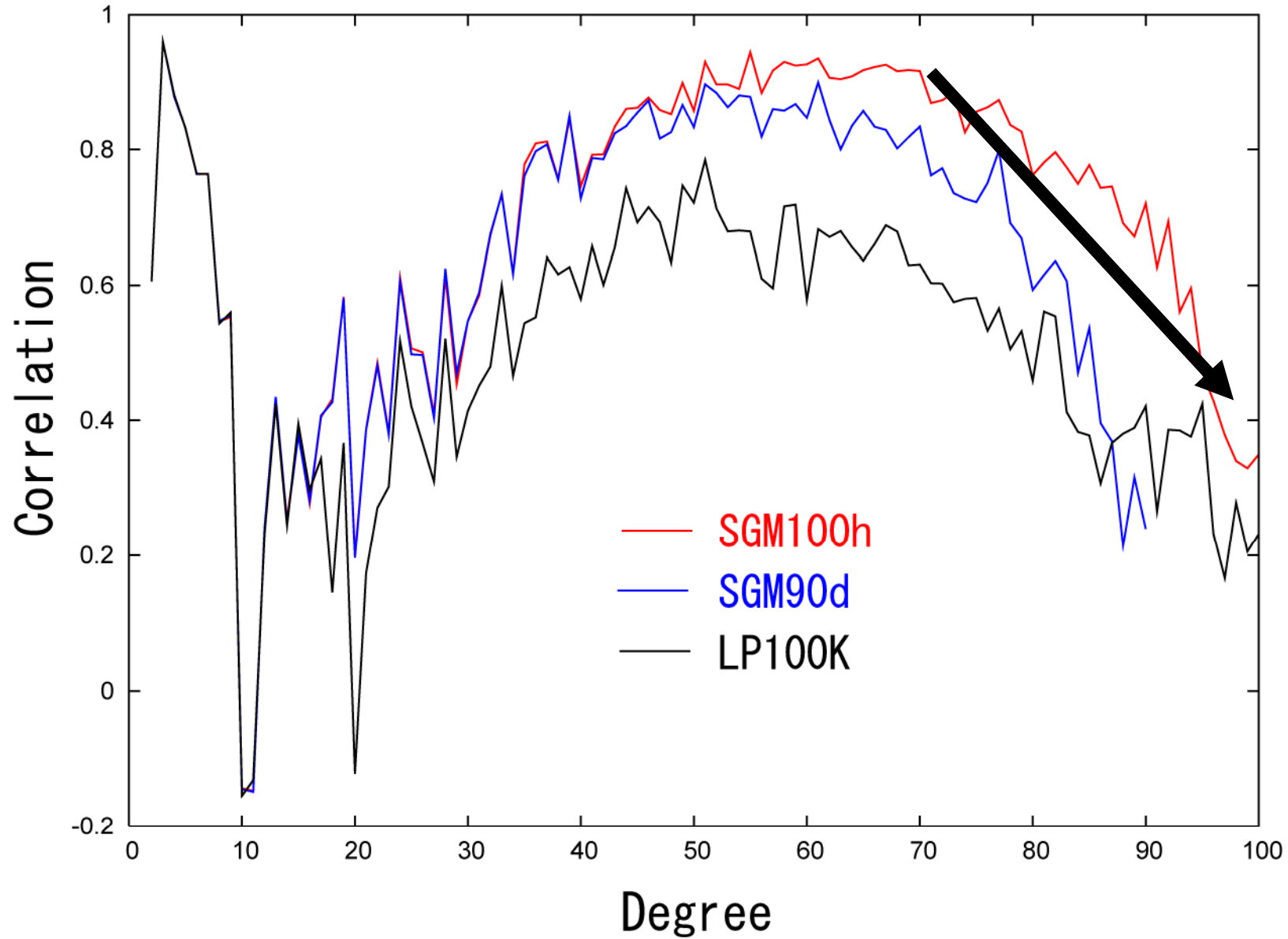


Degree variances

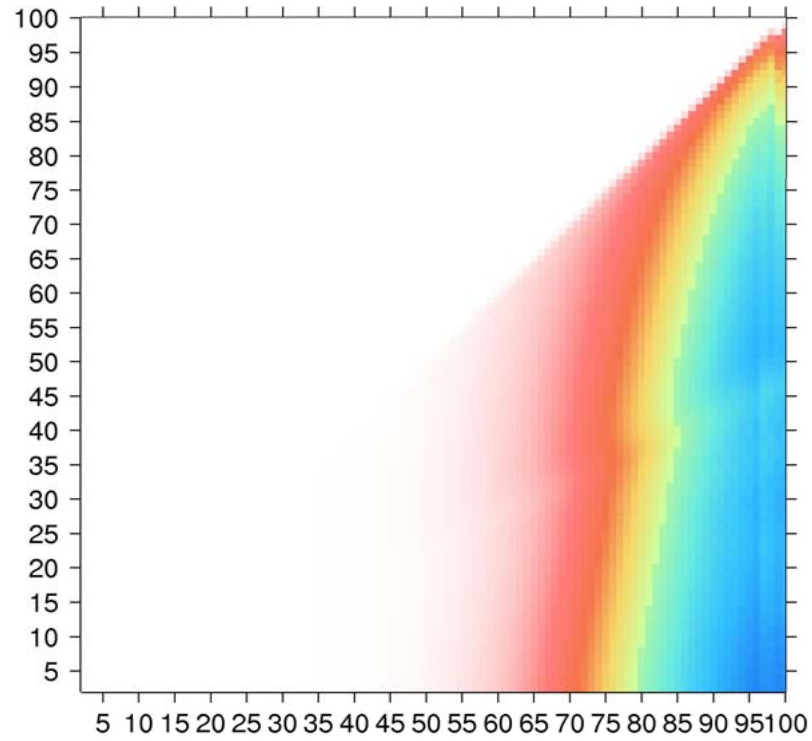


SGM100h gives more than one order of magnitude smaller formal errors with respect to LP100K for degrees 7-39.

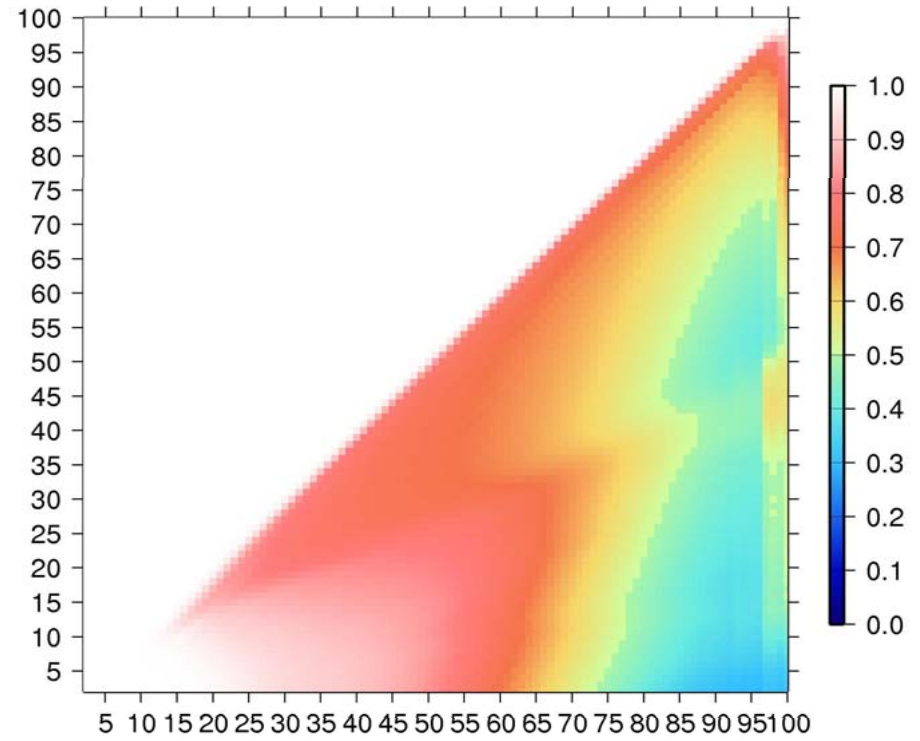
Gravity-topography correlation



Contribution measure



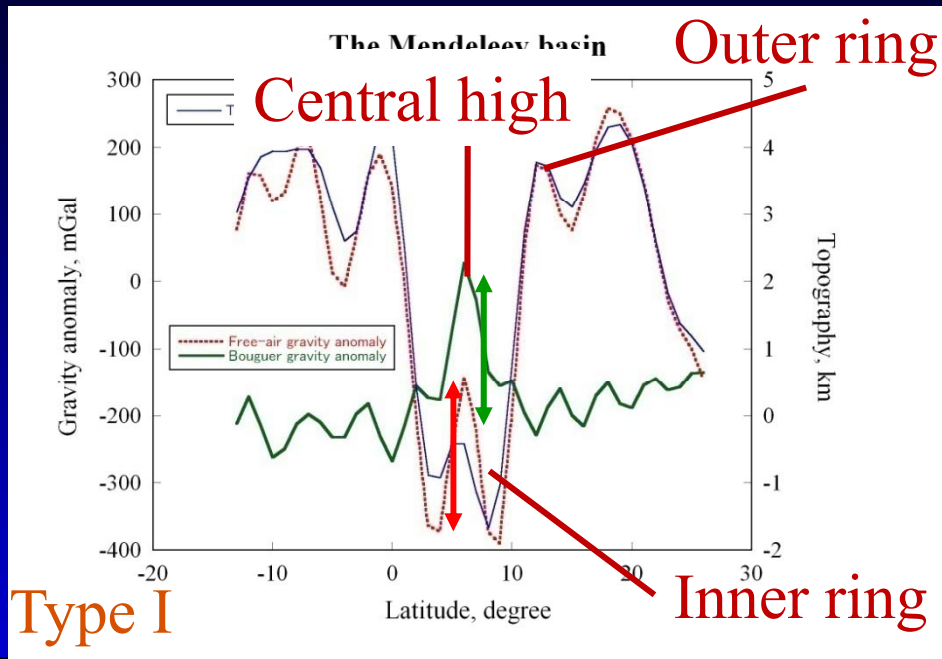
SGM100g



LP100K

Farside basins: A new classification

Blue line =
topography
Red line = Free-air
anomalies
Green line =
Bouguer
anomalies



Outer ring: Topographic rim

Inner ring: Topographic depression

Central high: Density anomalies in the interior

Type I and II depending on magnitude of central high:

Type I basin

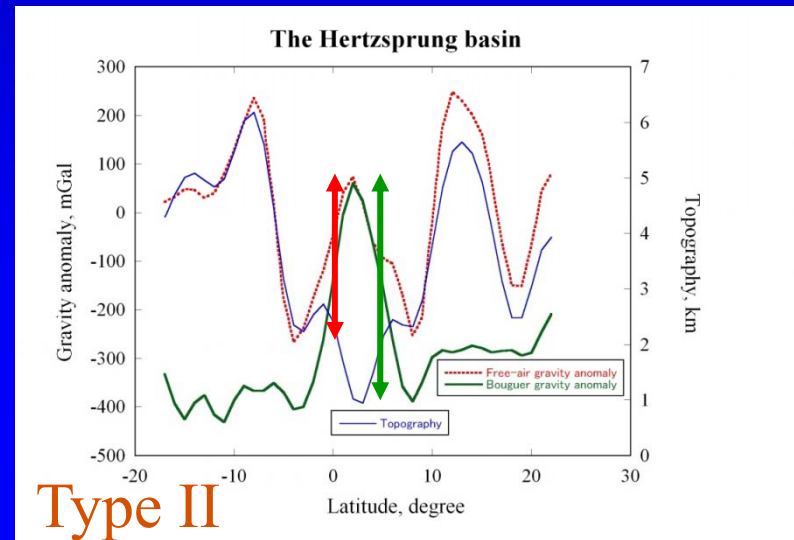
$$(\Delta g)_{FA} \sim (\Delta g)_B$$

Sharp central high
Central topography +
Mare volcanism rare

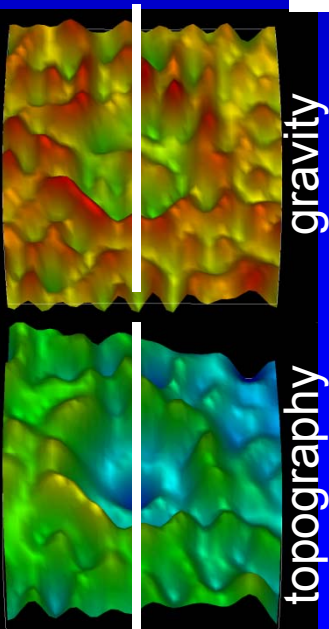
Type II basin

$$(\Delta g)_{FA} \sim (50-80\%) \times (\Delta g)_B$$

Broad central high
Central topography +/-
Associated with mare basalts



Type II

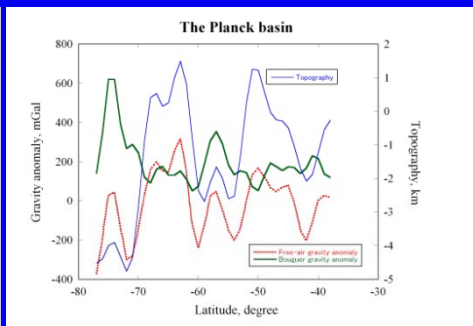
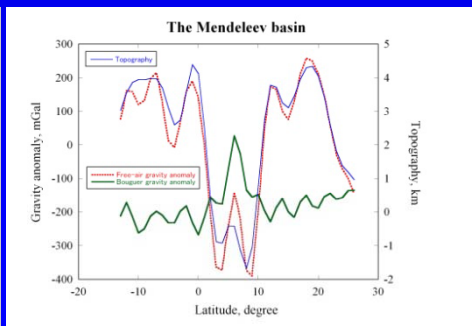
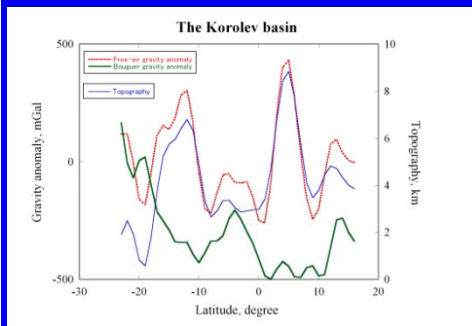
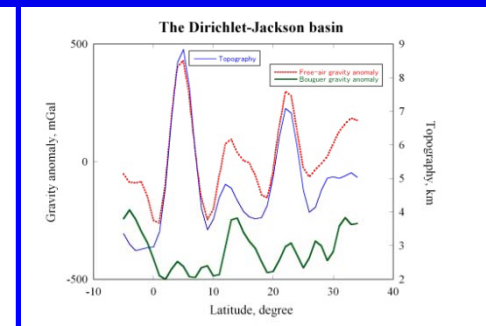
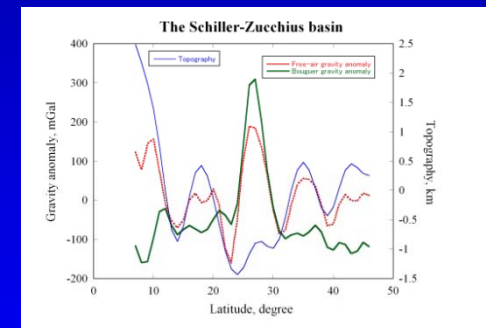
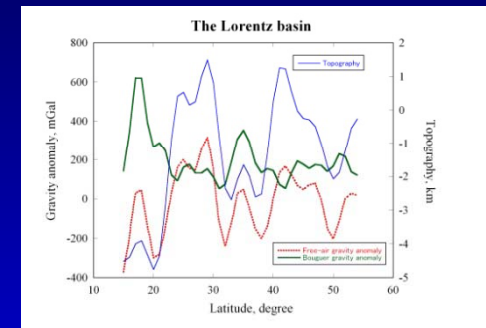


Inference of gravity signature: Type I basin

Outer and inner rings of $(\Delta g)_{FA}$ of Type I basins disappear in $(\Delta g)_B$ indicating **no isostatic compensation at the surface**. Depth of the basins is comparable to apparent depth of fresh impact craters [Pike, 1977].

Central gravity high irrelevant of topography is likely due to **overcompensated mantle**. Absence of magmatic activity from Type I basins exclude mare basalt as a source of gravity anomalies.

Neither isostatic compensation at the surface nor the crust-mantle boundary suggests **low T crust and mantle in the farside**.



Inference of gravity signature: Type II basin

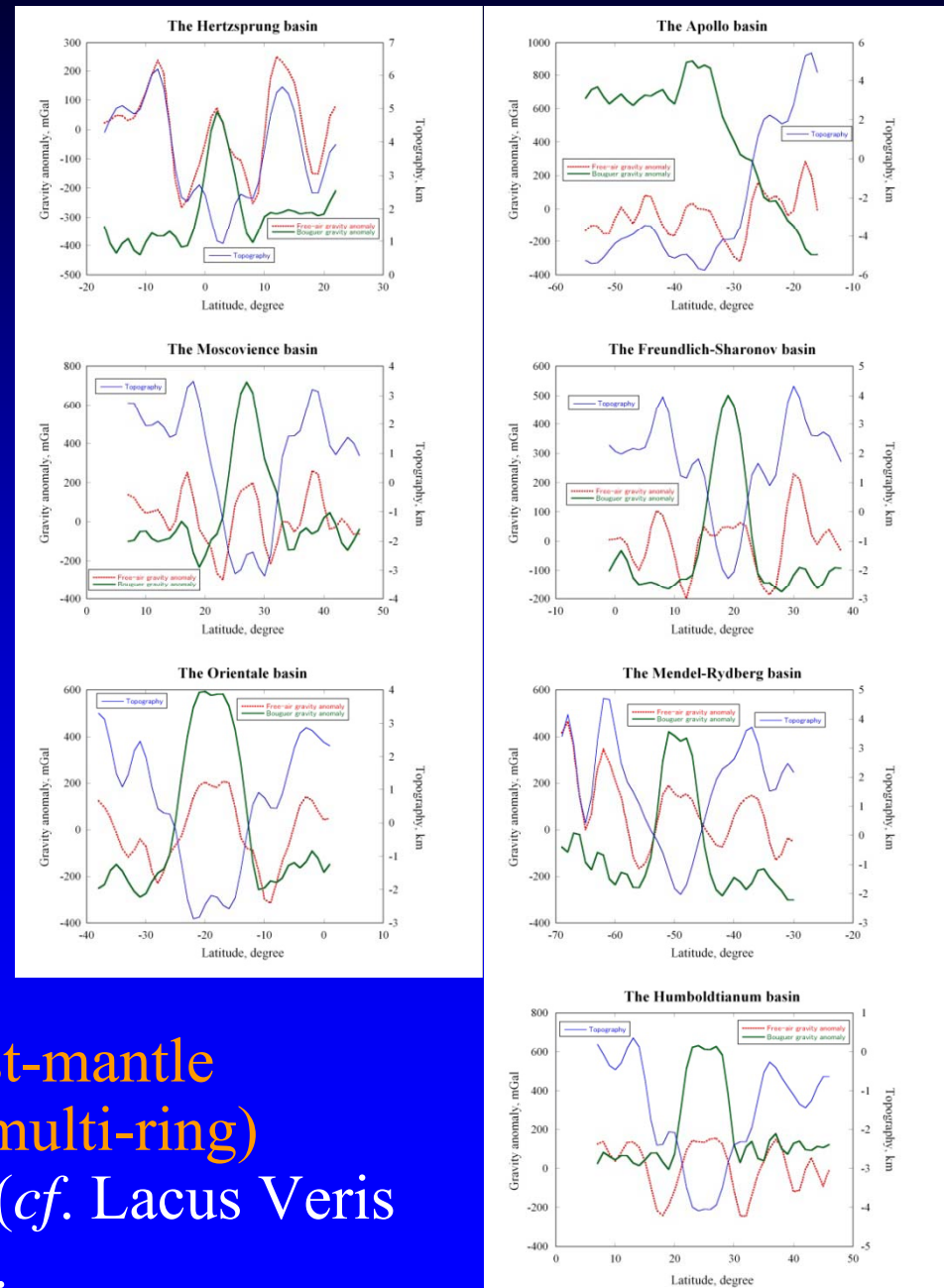
Outer and inner rings of $(\Delta g)_{FA}$ of Type II basins disappear in $(\Delta g)_B$ indicating **no isostatic compensation at the surface** (same as Type I).

Central gravity high could be due to either **overcompensated mantle** or **mare basalt**.

Magmatic activity at Apollo, Moscovience Mendel-Rydberg, and Humboldtianum basins [Whitford-Stark, 1982; Wilhelms *et al.*, 1987; Belton *et al.*, 1992].

Estimated thickness of mare basalt (< 1 km) indicates massive intrusion, while no surface manifestation.

Either **viscous relaxation at the crust-mantle boundary** or **formation of fault (multi-ring) system accompanied by magma** (*cf.* Lacus Veris and Lacus Autumni) is plausible.

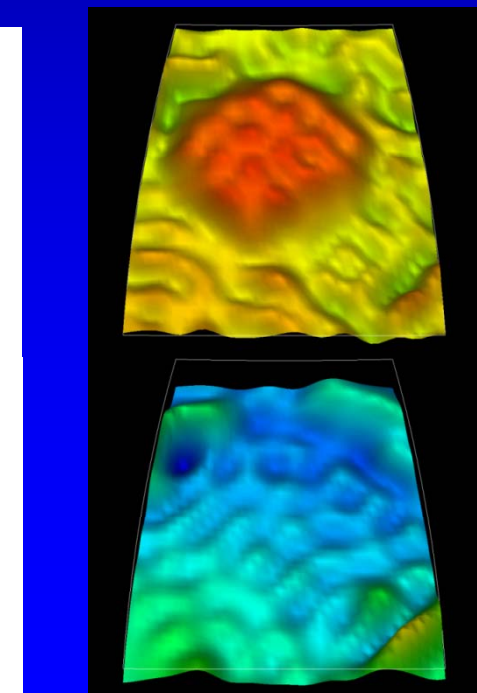
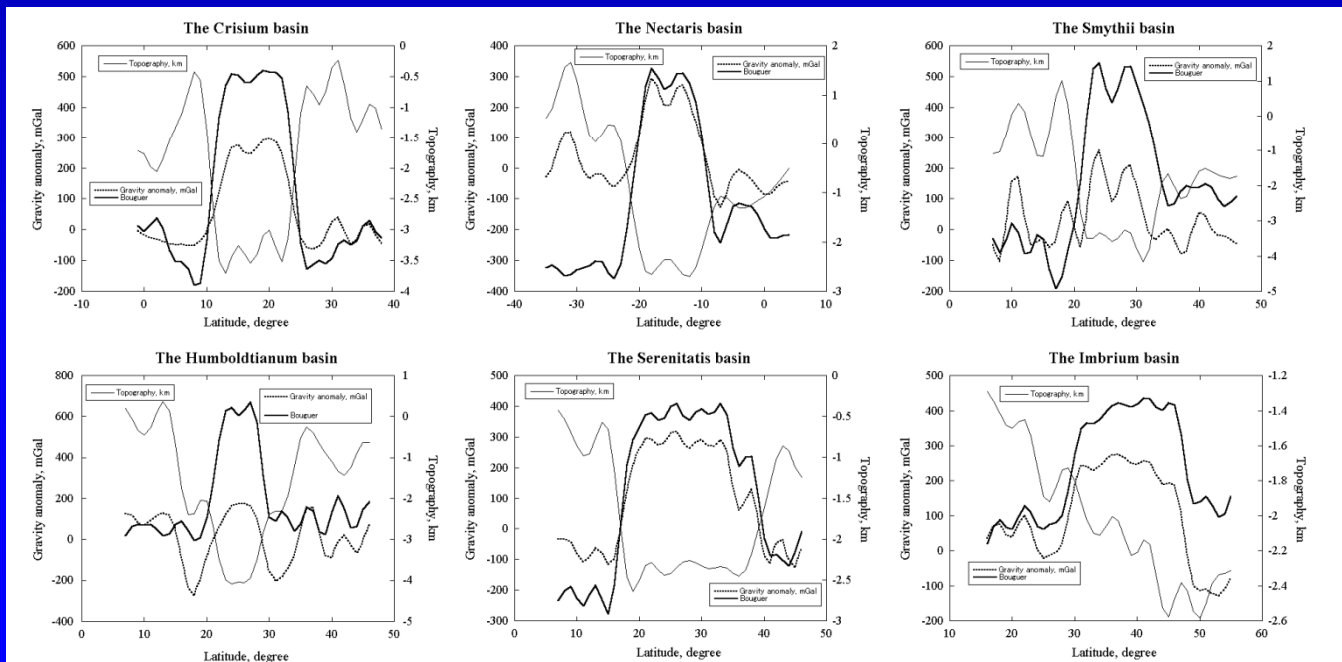


Inference of gravity signature: Primary mascon basin

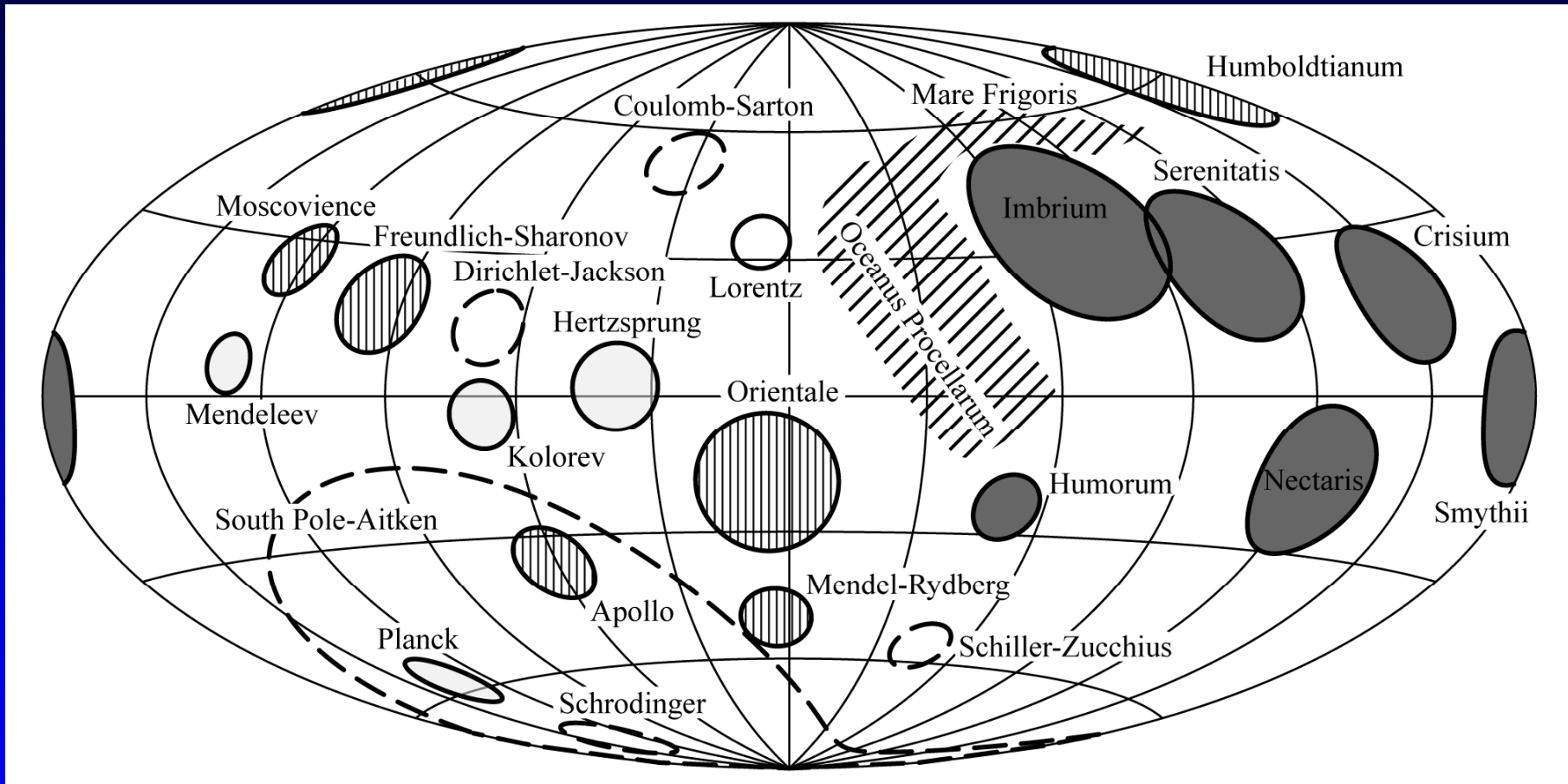
$(\Delta g)_{FA}$ of outer ring (rim) is nearly zero indicating **isostatic compensation of the surface rim**.

Consistent with suggested mare tectonics [*e. g.*, Solomon, 1982], but contrary to recent inference of LRS/SELENE [*Ono et al.*, 2009]

Plateau shape and steep shoulder of central gravity high indicating **viscous relaxation at the crust mantle boundary, formation of fault (multi-ring) system, or heat transferred to magma reservoir**.

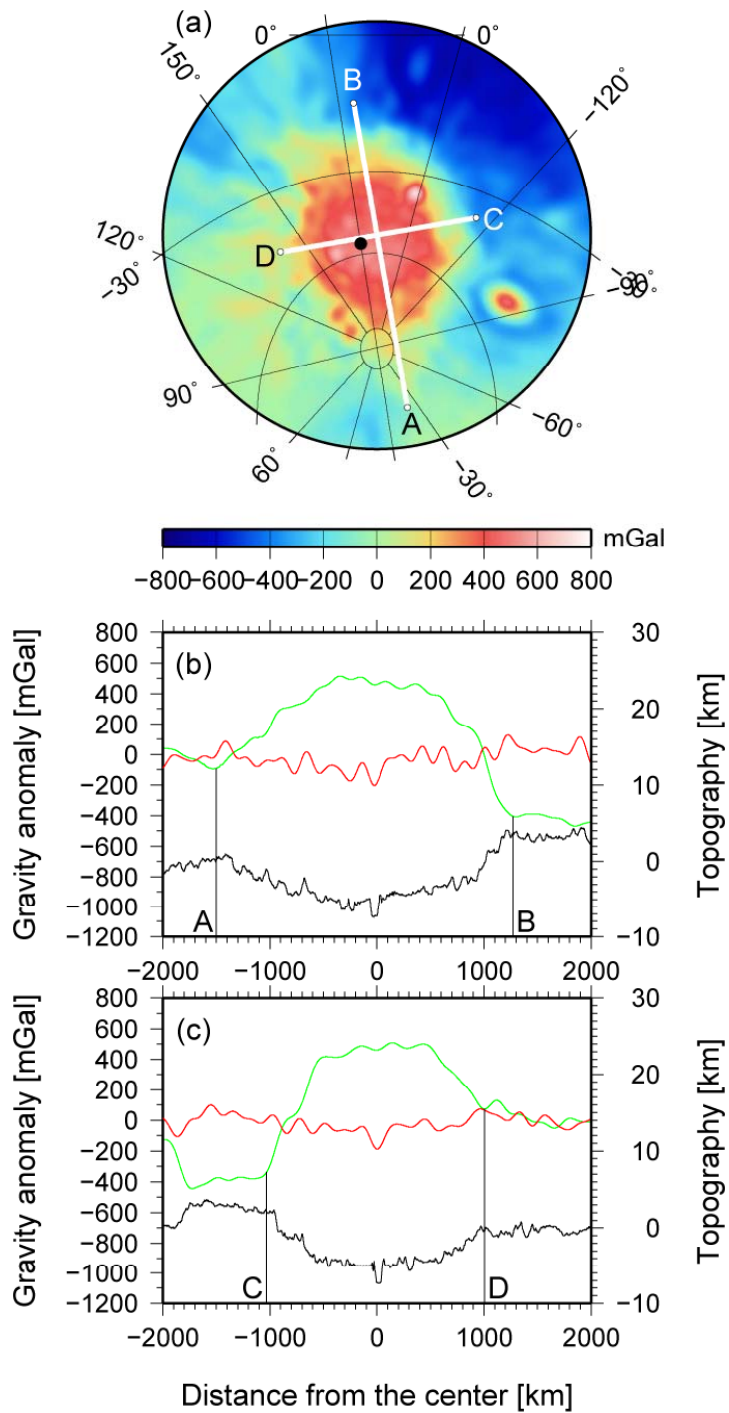


Distribution of major lunar basins



Shaded = primary mascon basins, Lightly shaded = Type I basins,
Hatched = Type II basins

No temporal order recognized.



南極エイトケン 盆地は楕円形 状を持つ

2800 x 2000 km
a/b = 1.4

Including VLBI data

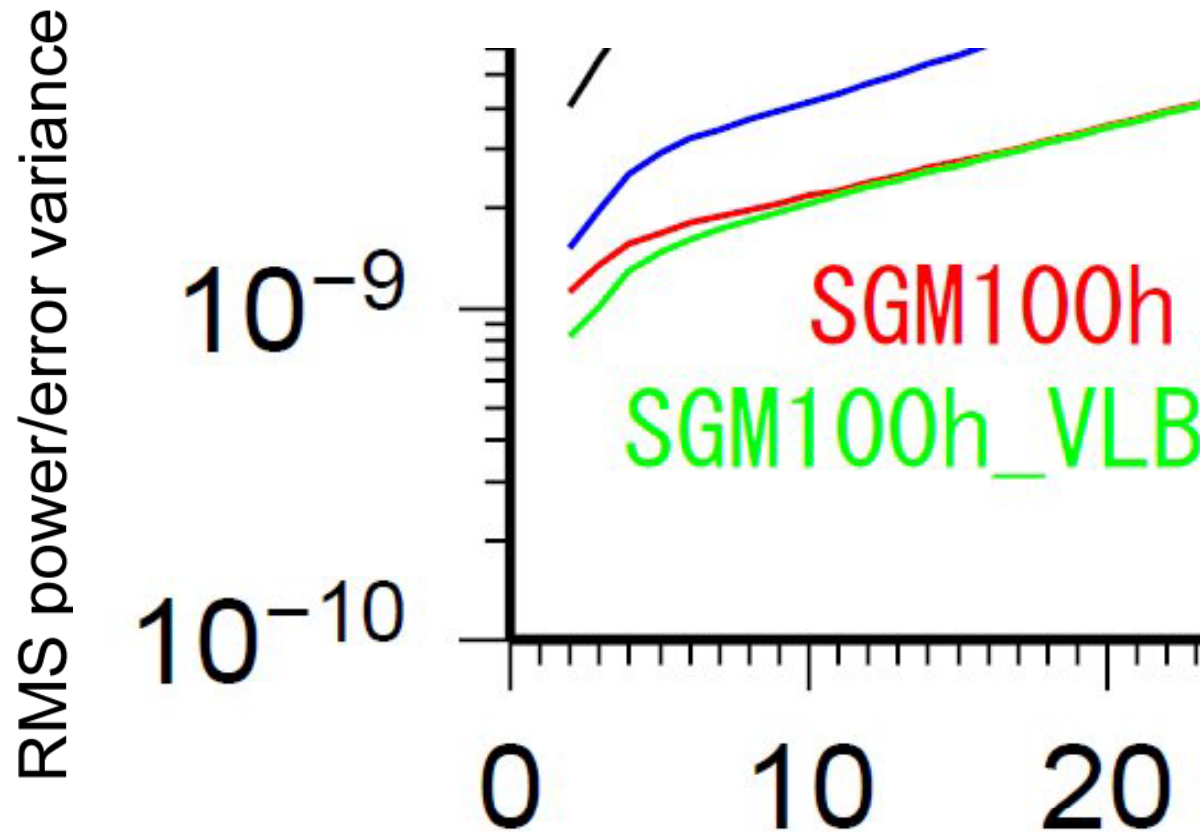
Data

- S-band same-beam VLBI data.
- Differential phase delays are determined for January, March, April, May, June, July, and August 2008.
- 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)

Contribution of VLBI data - error variance -

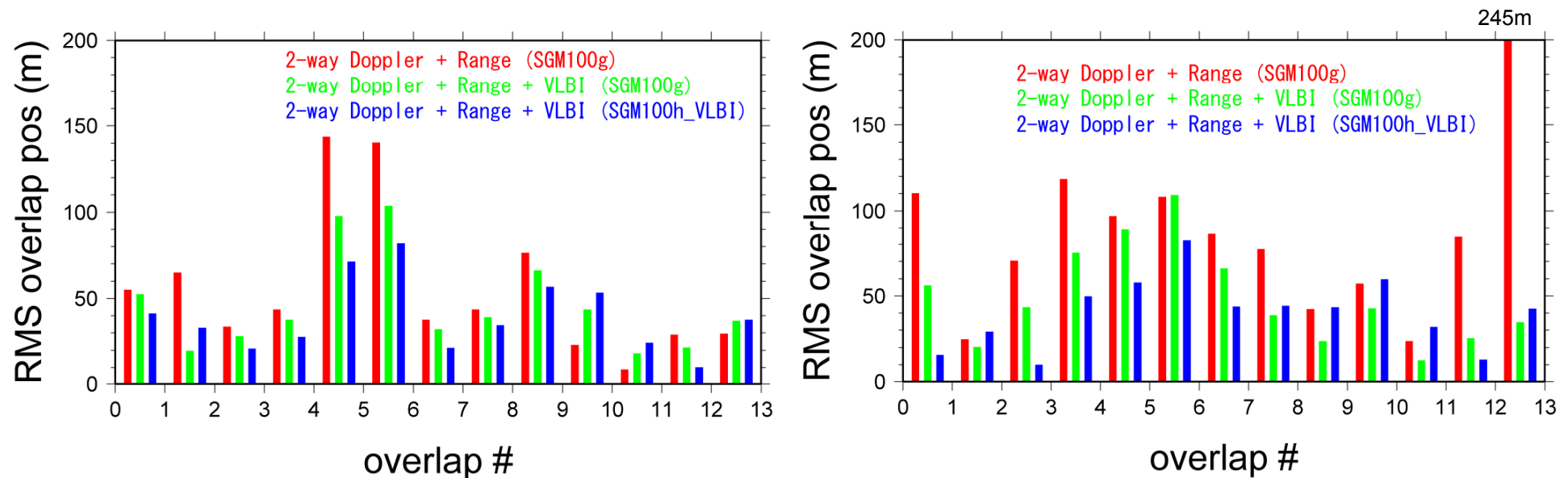


Ratio of degree 2 sigma variance
SGM100h / SGM100h_VLBI = 1.4
LP100K / SGM100h_VLBI = 5.0

Contribution of VLBI data - orbit overlap statistics -

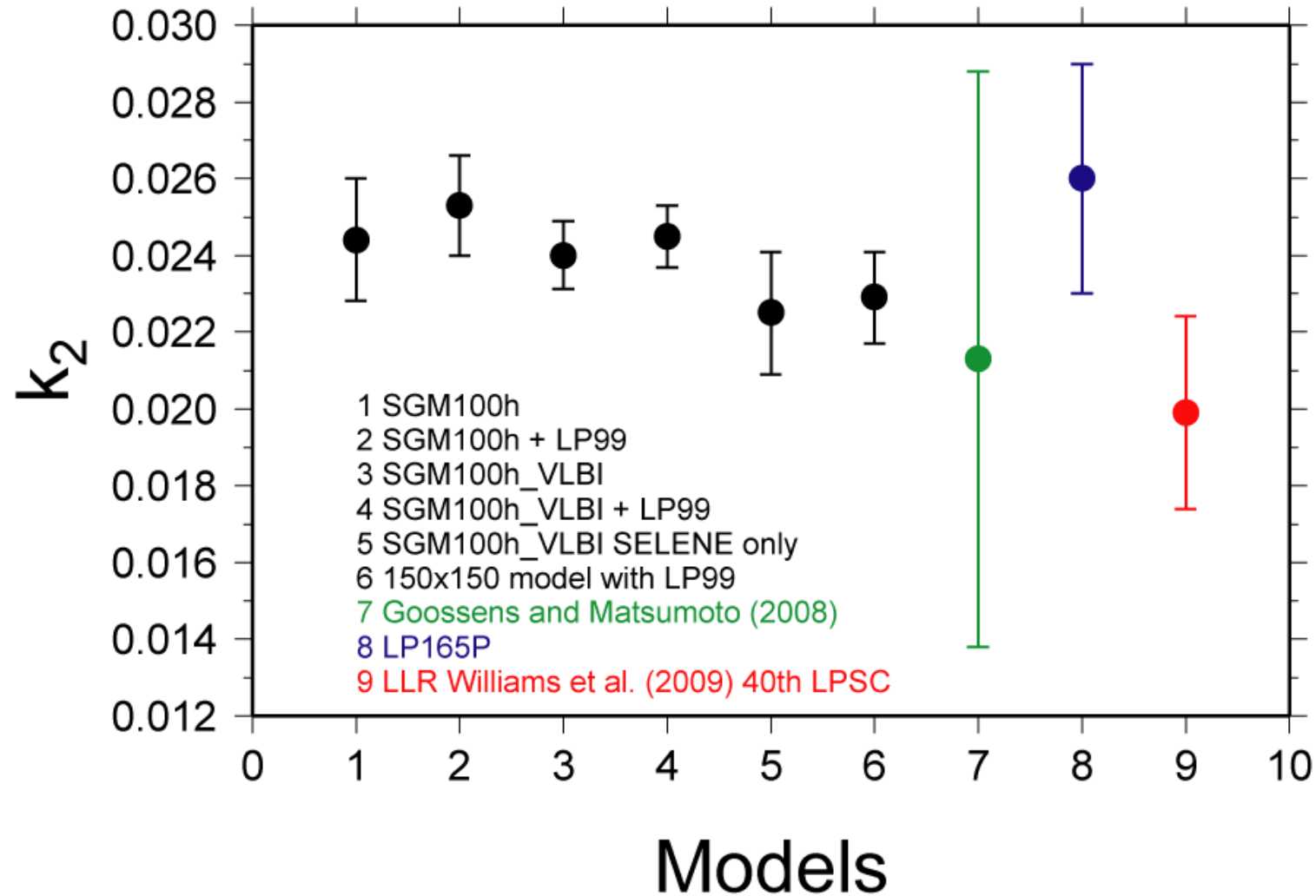
Rstar

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.

Summary

- Historical tracking data + SELENE range & Doppler data → SGM100h model
- Far side gravity errors are drastically reduced.
- Increased correlation between gravity and topography.
- Degree 70 expansion is possible without any a priori constraint.
- k_2 estimates still diverge to $\sim 11\%$ depending on data used.
- VLBI data improve the accuracy of the low degree coefficient and orbit consistency, but processing is still in progress.

Acknowledgements

We appreciate all engineers of NEC/Toshiba Space Systems Ltd., Nippon Antenna Co. Ltd., and Japan Aircraft MFG Co. Ltd. who diligently developed onboard instruments and sub-satellites. We are grateful to the entire staff of the SELENE mission as well.

The gravity experiments of SELENE would never be achieved without a prominent technique and a profound knowledge of Fumio Fuke who was an engineer of NTS and passed away 2 months after the launch. We express sincere thanks to his contribution and grieve over the loss for Japanese space development.