



「かぐや」による
月地形重力の成果

佐々木晶

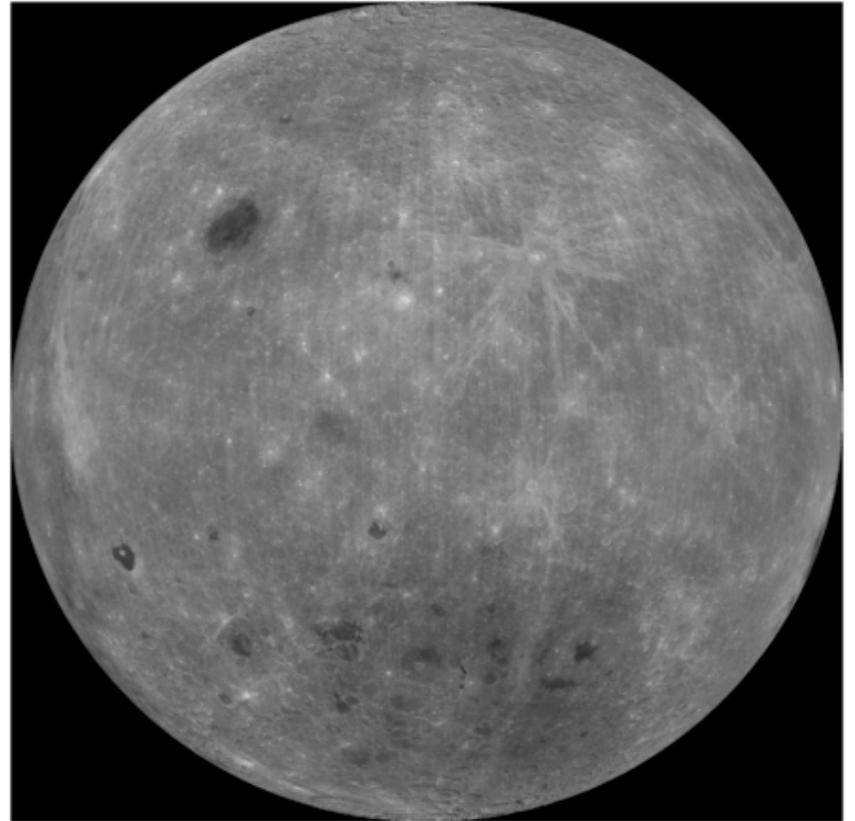
国立天文台

RISE月探査プロジェクト

VERAユーザーズmeeting 090902

- VERAの皆様、とくに各地上局（水沢、入来、小笠原、石垣）の担当の方々、国際協力局の皆様、においては、長い期間「かぐや」の観測に協力をしていただき（保守期間の調整も）、ときには観測時間の無理を聞いていただき、どうもありがとうございました。

Lunar Surfaces



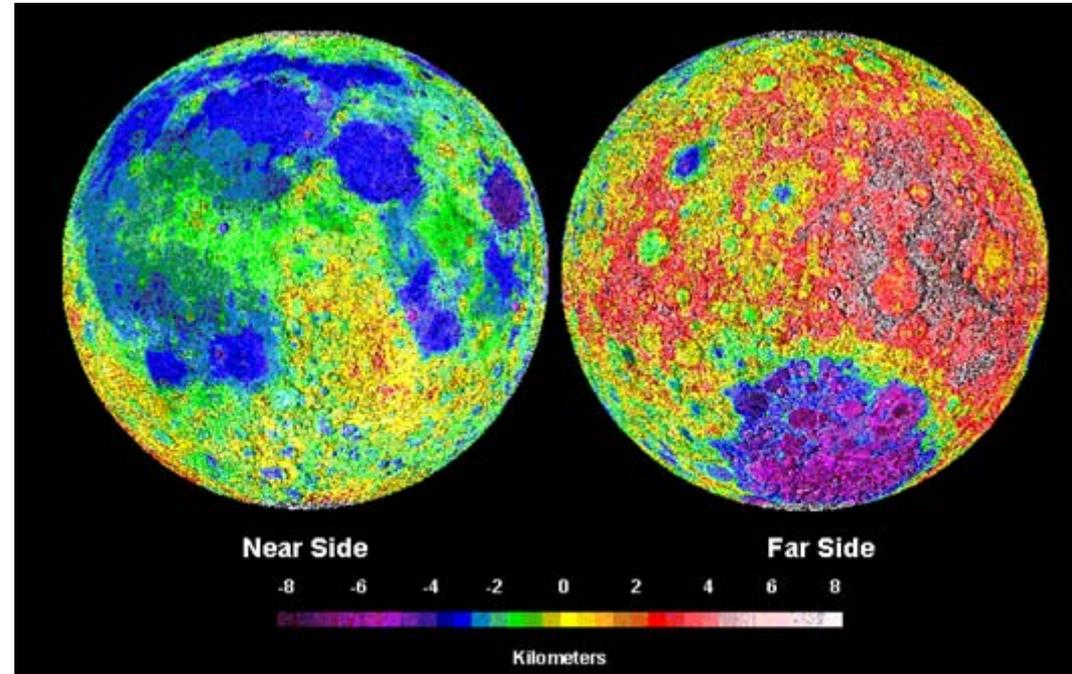
二分性

- 大きい海とそれ以外
- 衝突盆地とそれ以外
 - 表側の海、SPA
- Th分布の高い場所とそれ以外
 - Lunar Prospector
 - マグマオーシャンの最終固化層が地下にある場所

月の二分性

表(海)と裏(高地)

マグマオーシャン説
衝突説
火山活動説

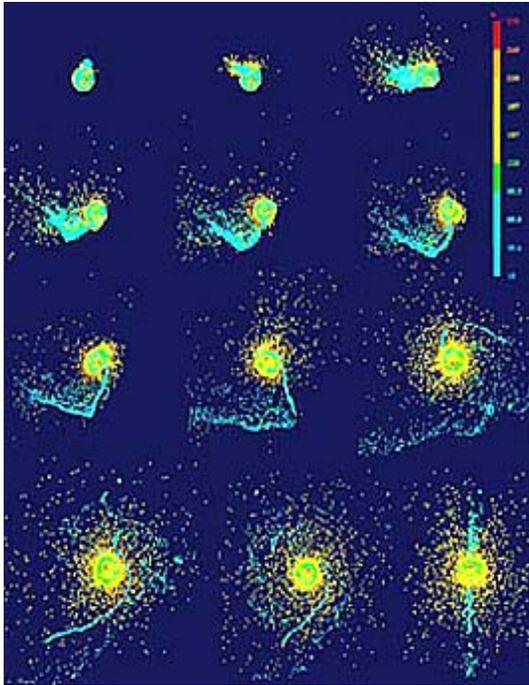


内部構造探査 → 二分性の『根の深さ』

二分性の起源 ⇔ 月の起源 (巨大衝突?)

火星の二分性との比較

月のマグマオーシャン



溶融状態から月進化は始まる

コア形成

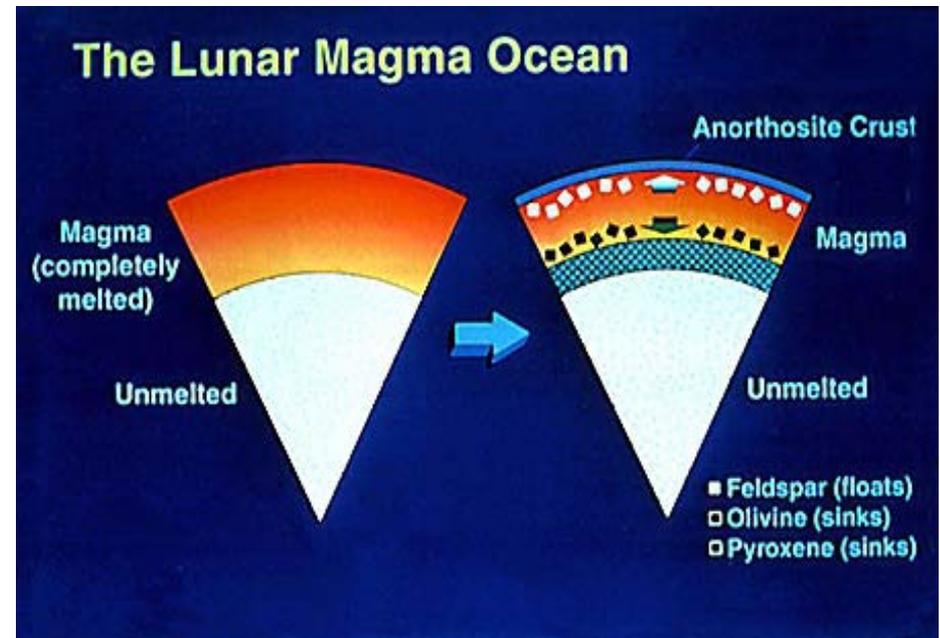
マグマオーシャン固化

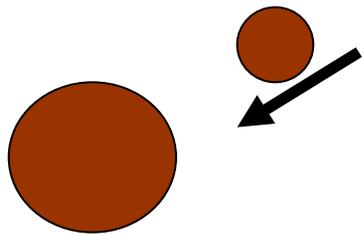
=> 成層構造形成



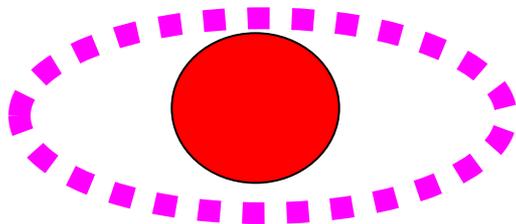
地球に火星サイズの天体が衝突した巨大衝突で形成された、地球周囲のディスクから月が形成

のディスクから月が形成

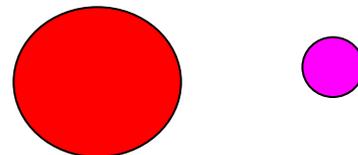




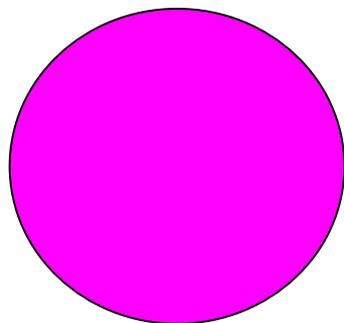
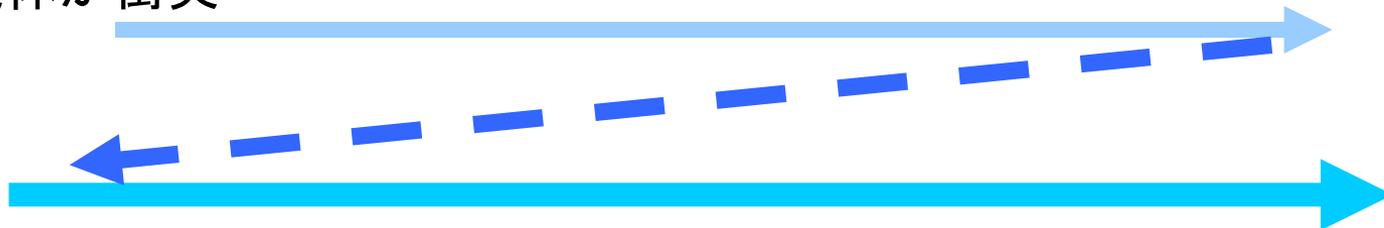
原始地球に火星サイズの天体が衝突



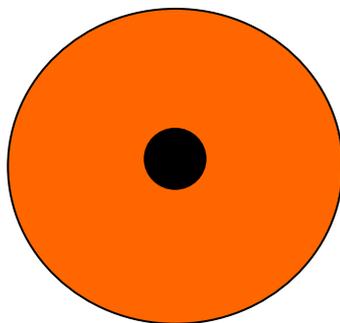
地球周囲に高温のディスク



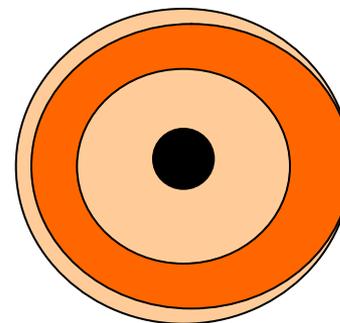
ディスクから月形成



高温の原始月



コア形成とマグマ
オーシャン



マグマオーシャン
の冷却

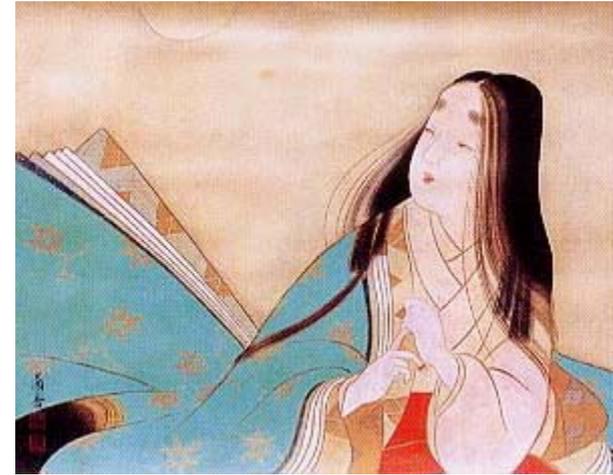
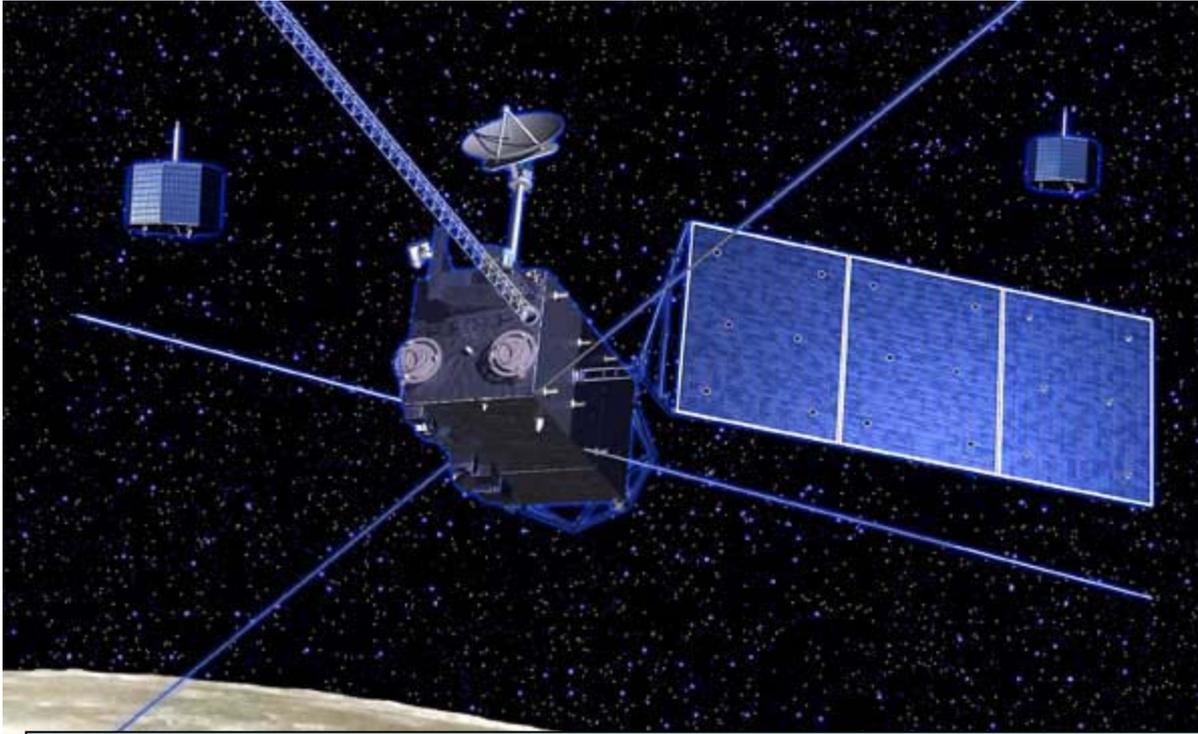
厚さの不均質の原因

- 固化した地殻の水平移動(氷山モデル)
- 温度不均質による固化速度の違い
- 中心から徐々に付加的に成長
- 衝突

マグマオーションから固化

- Thの濃集 KREEP残液
- これが表側に移動した可能性は高い
- 熱源元素が表側に濃集したならば、冷え方が違ってもいいはず。その証拠は見つかるか？

かぐや (SELENE) 9月14日打上げ



1990年代半ばに、旧宇宙開発事業団(NASDA)と旧宇宙科学研究所(ISAS)の合同で開始されたミッション。当初は2002年打ち上げ予定だった。



月周回衛星かぐや (SELENE)

元素分布	XRS:蛍光X線分光計 GRS:ガンマ線分光計
鉱物分布	SP:スペクトルプロファイラ MI:マルチバンドイメージャ
表層構造	TC:地形カメラ LRS:月レーダサウンダ LALT:レーザ高度計
環境	LMAG:磁力計 UPI:プラズマイメージャ CPS:粒子線計測器 PACE:プラズマ観測器 RS:電波科学観測
重力分布 (RISE)	VRAD:相対VLBI用衛星電波源 RSAT:リレー衛星中継器 LALT:レーザ高度計

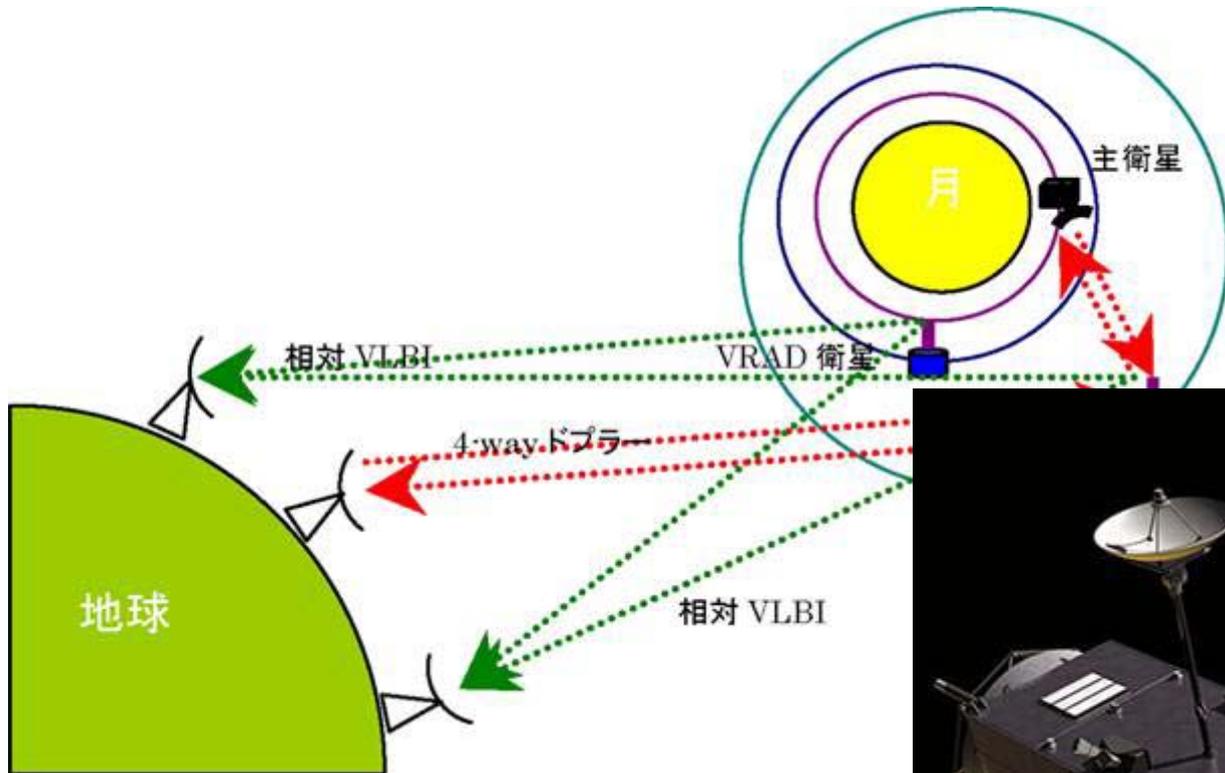
極軌道で
全球リモート
センシング

国立天文台
が担当

14ミッション機器＋
ハイビジョンカメラ

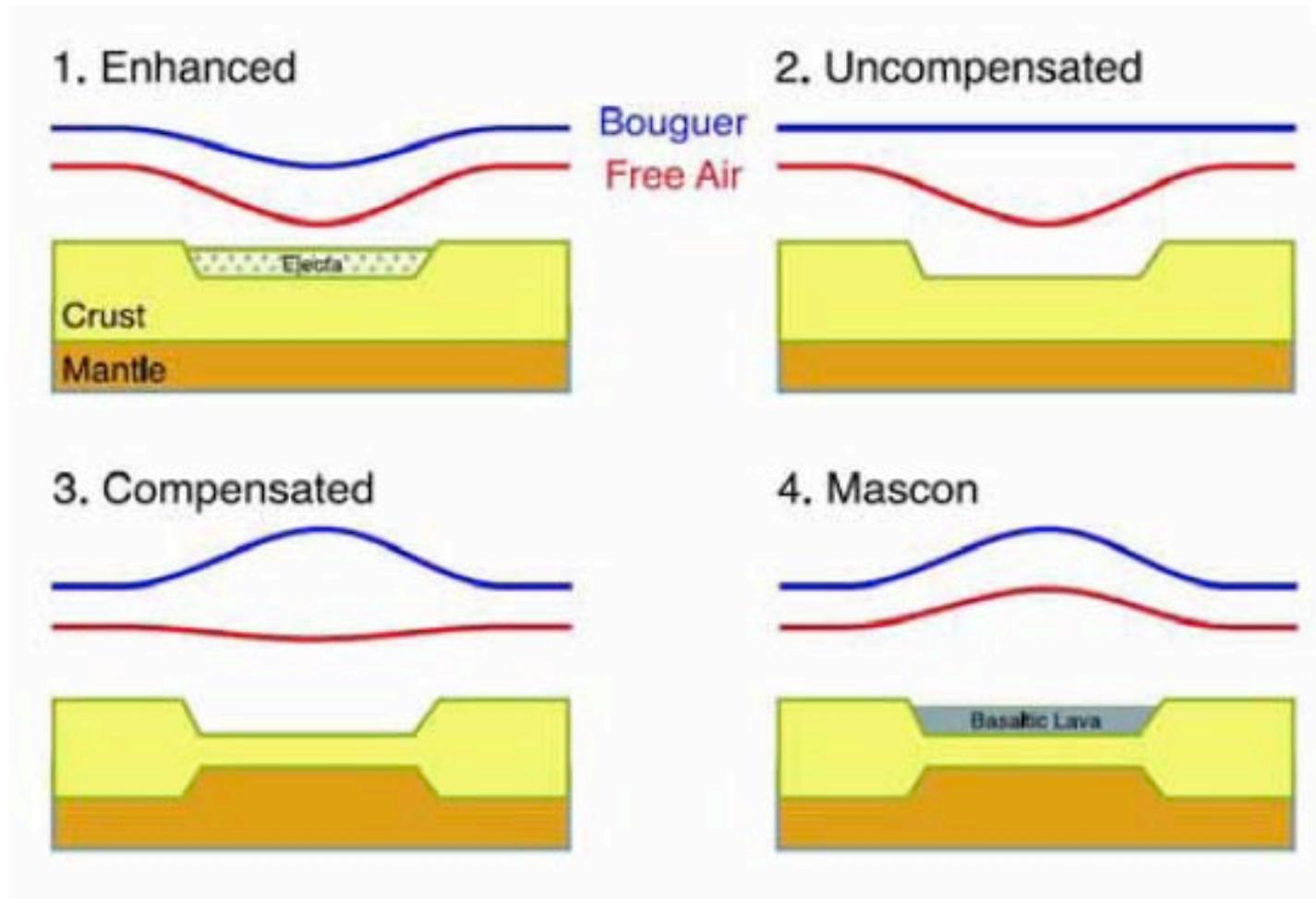
天文台

子衛星を使った重力測定と レーザ高度計



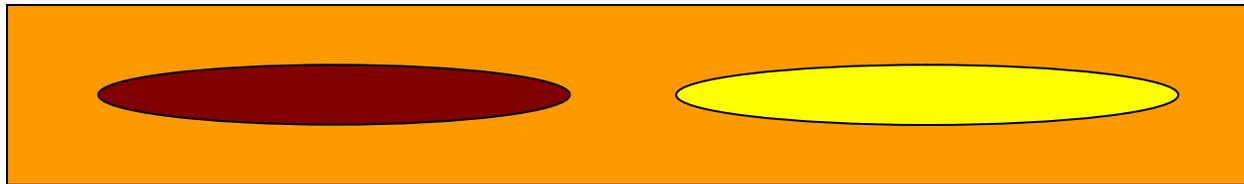
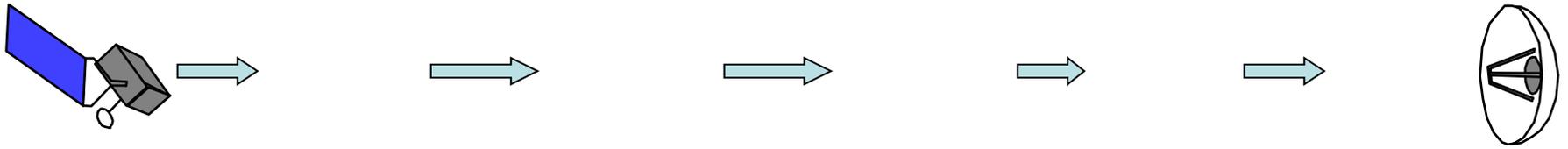
重力

内部構造を探るのに非常に強力



衛星による重力測定

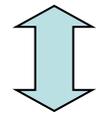
- 衛星の軌道 (速度・位置)を電波で計測して重力の分布を求める



レンジング
ドップラー効果
VLBI

視線方向の距離
視線方向の速度・加速度
視線と垂直方向の位置

地下の
密度異常
内部構造



月の進化
表裏の違い

衛星の軌道 (速度・位置)を電波で計測して重力の分布を求める

これまでの月重力測定

探査機が裏側にいるときは直接追尾できない
裏側の重力場の精度が非常に悪い

「かぐや(SELENE)」は裏側を含む月重力を高精度で測定します。

Q どうやって月の裏側の重力は求めるの？

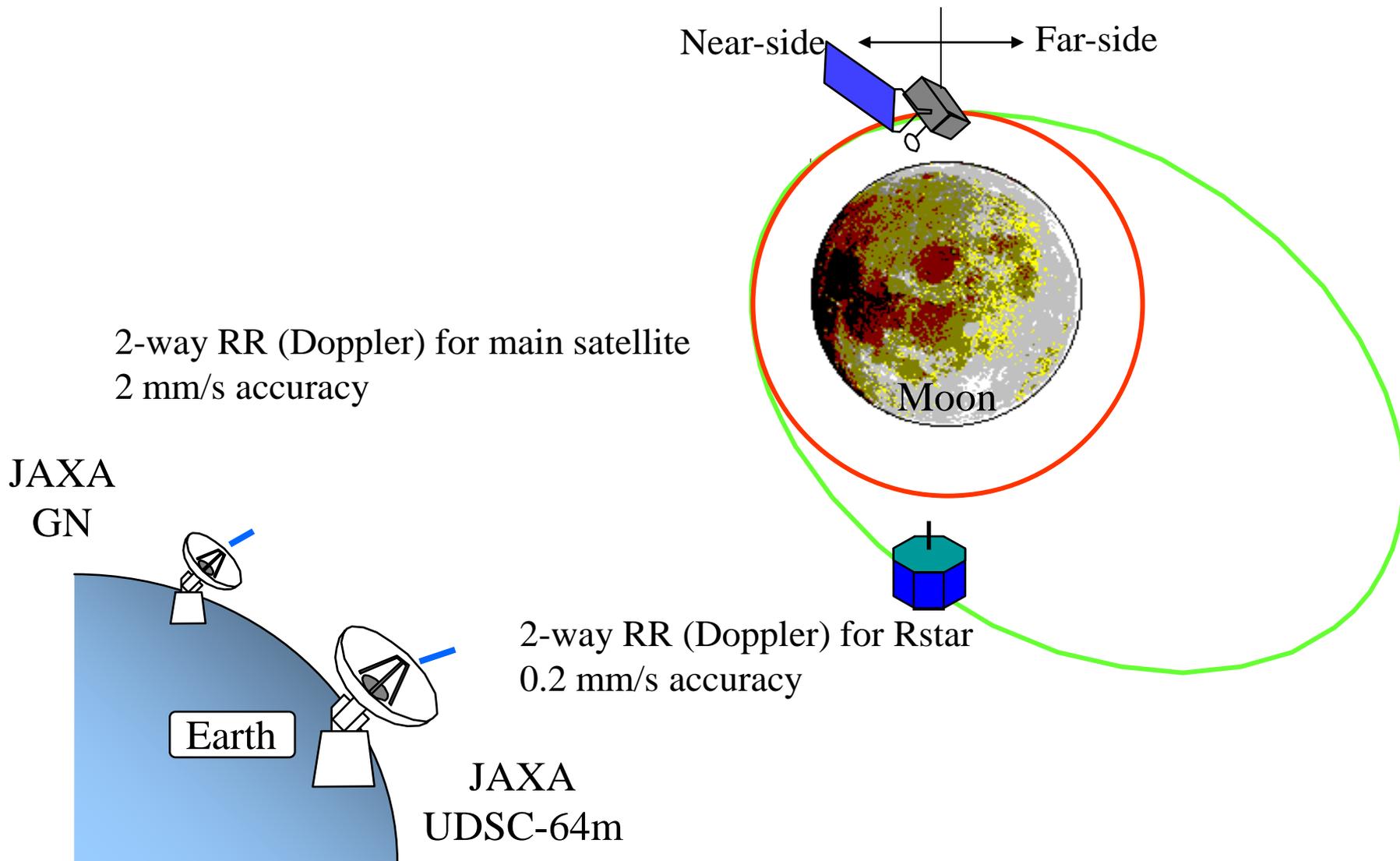
A リレー衛星を使います

Q 重力の解析に必要な地形データは？

A レーザー高度計で測定します

さらにVRAD (VLBI RADio source)衛星を使い、
衛星の軌道を正確に決めて、重力場の精度を高くします

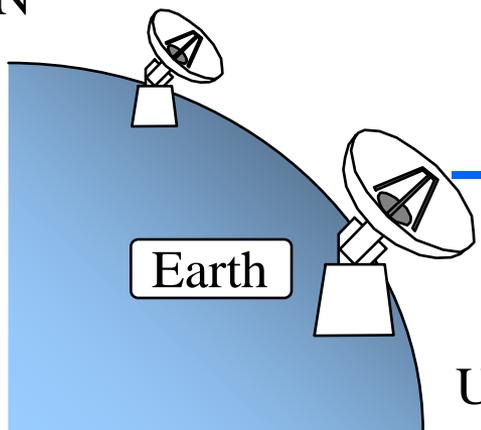
2-way Doppler測定



4-way Doppler 測定

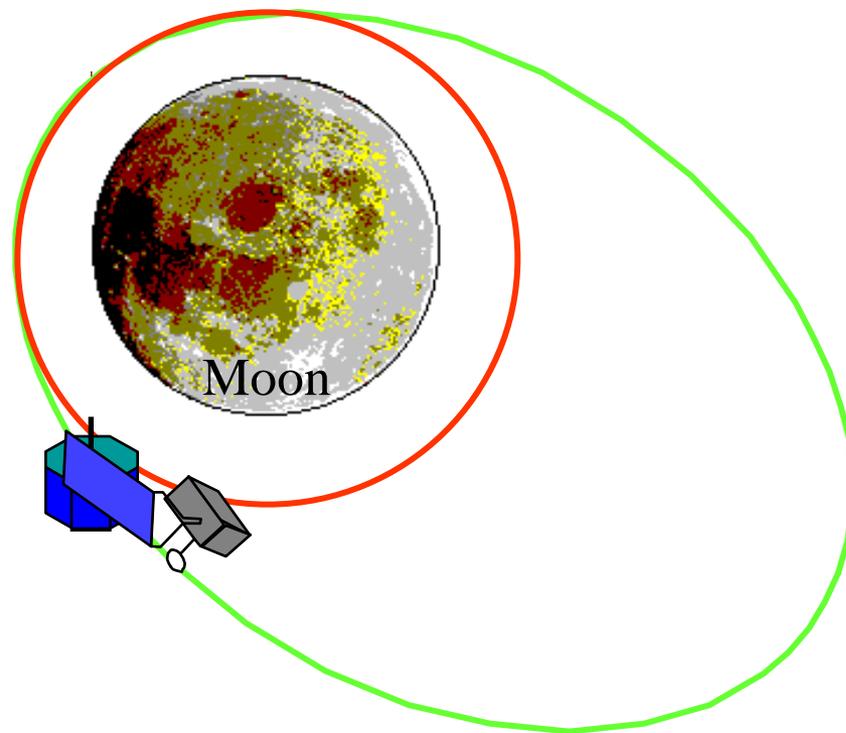
First direct observation of
Far-side gravity

JAXA
GN



JAXA
UDSC-64m

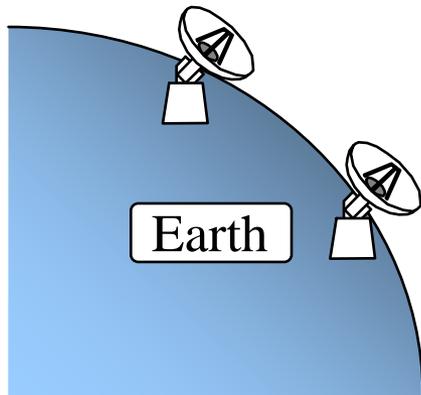
Near-side ← → Far-side



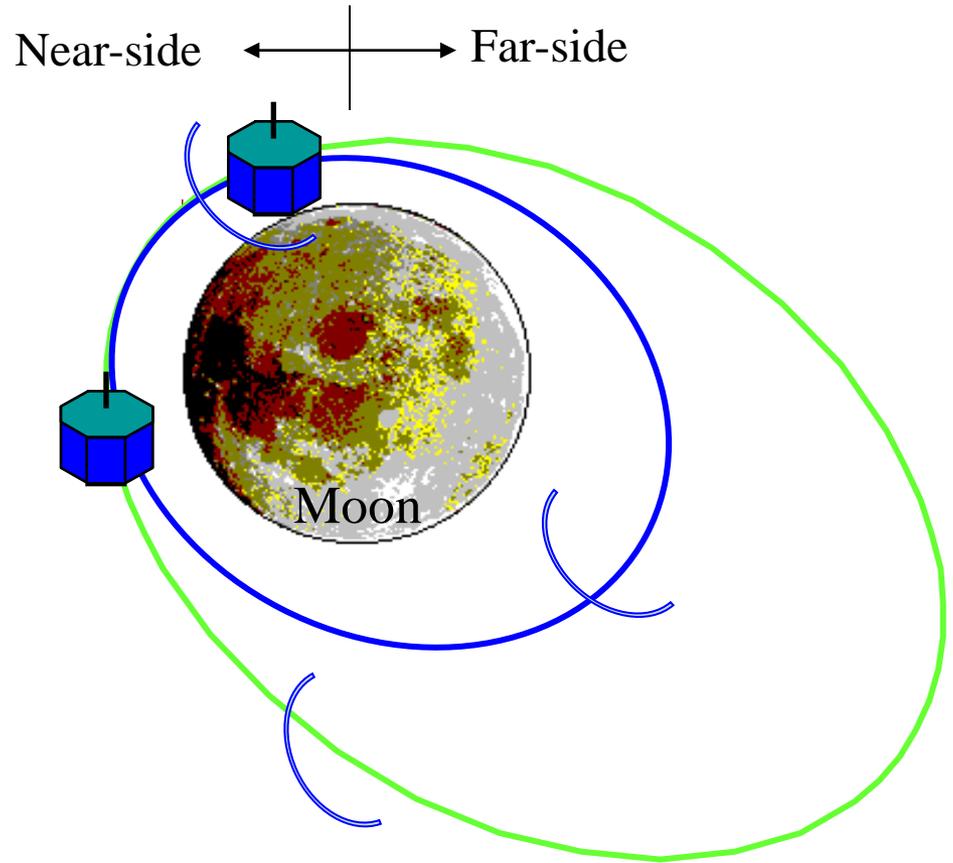
4-way RR (Doppler) for main satellite by way of Rstar
1 mm/s accuracy

相对VLBI 測定

Differential VLBI between Rstar and Vstar
Antenna switching every 120sec
1 mm accuracy as doubly differenced
1-way range



VLBI stations
(VERA, Shanghai, Urumqi, Hobart, Wetzel)



VLBI => 惑星科学

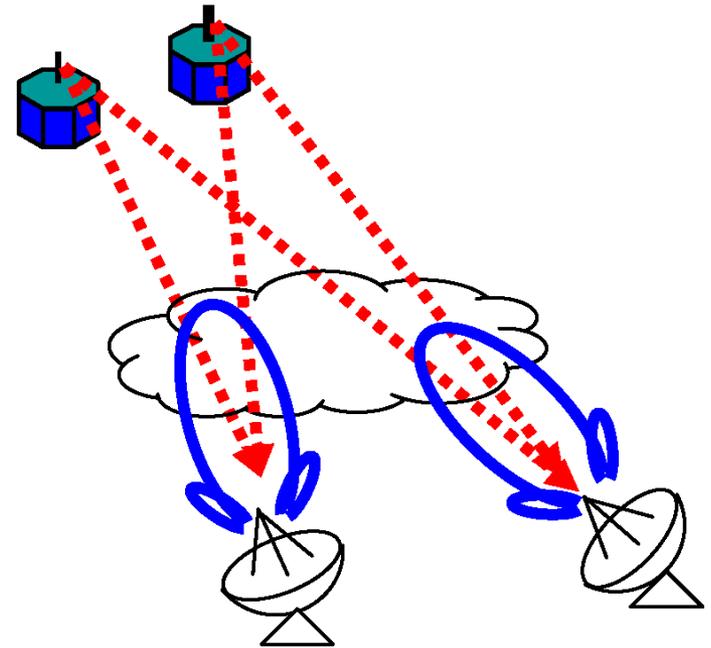
- 探査機の位置決定にも有効
- とくに視線方向の速度成分が無いときは、ドップラーは使えない
- (月の表と裏の境界)

- 活躍例 ホイヘンス(タイタン突入機)

- もし、旧ソ連の金星探査にVLBIが使われていたら、着陸地点はわかっていたはず。

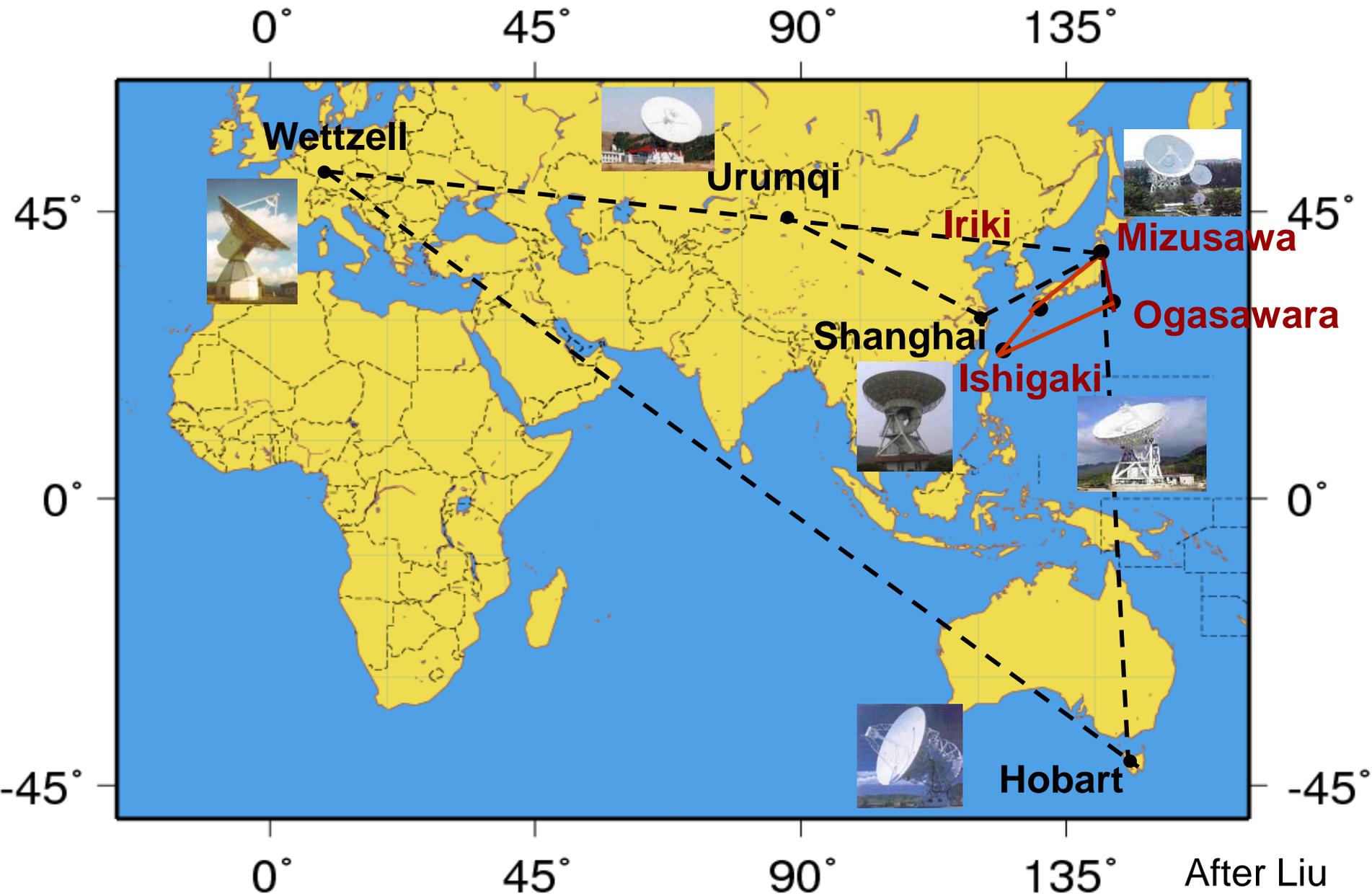
2つの衛星を複数のアンテナで

- 2ビーム
- 衛星が接近したときに、1つのアンテナで同時に観測可能
- 高精度の位置決定が可能
- 電離層などの影響を除去可能

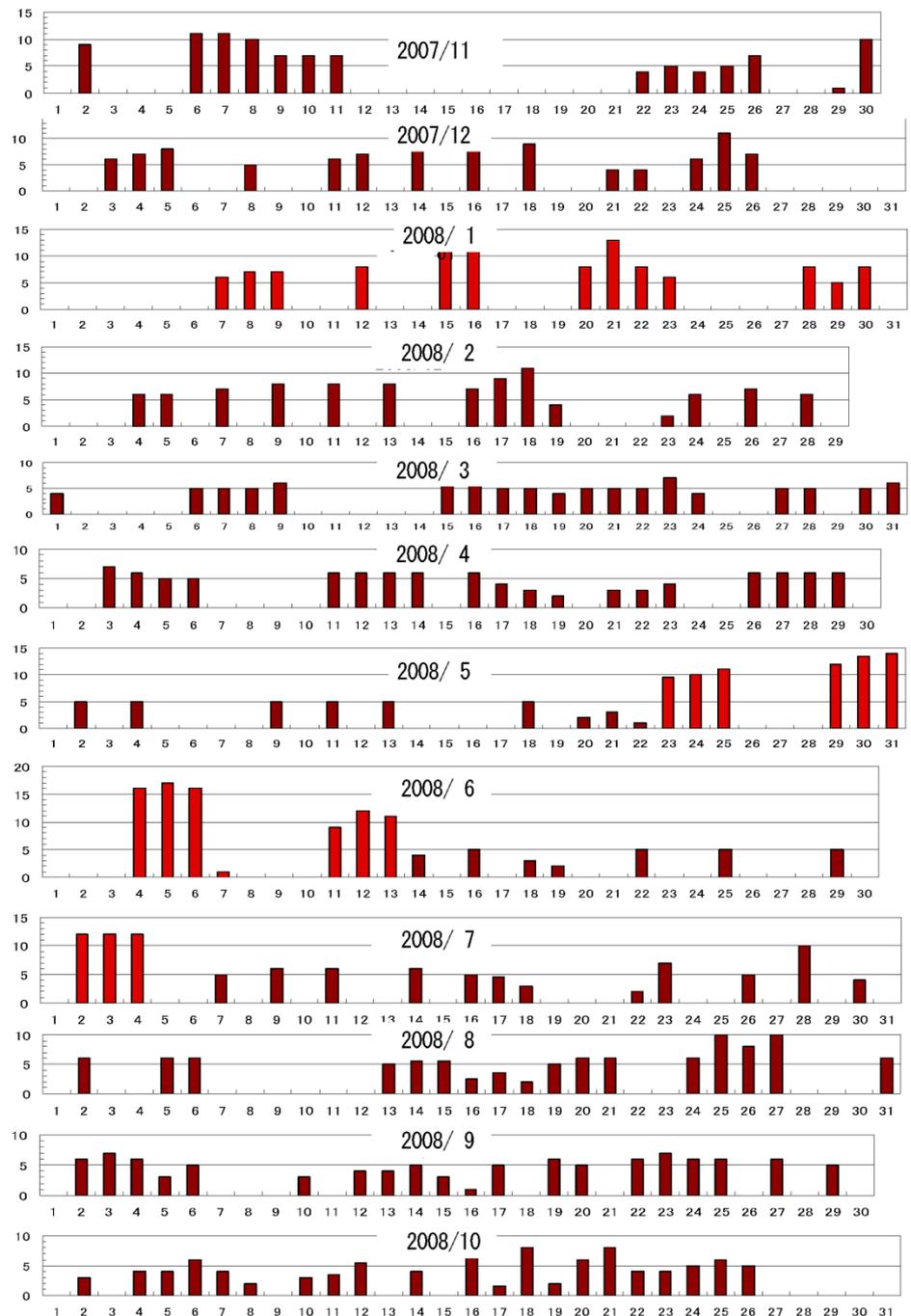


もともと、VERA (VLBI Exploration of Radio Astronomy) は、(パルサー + 星) を同時観測により、星の相対位置を正確に決める目的で、2ビームを導入した。

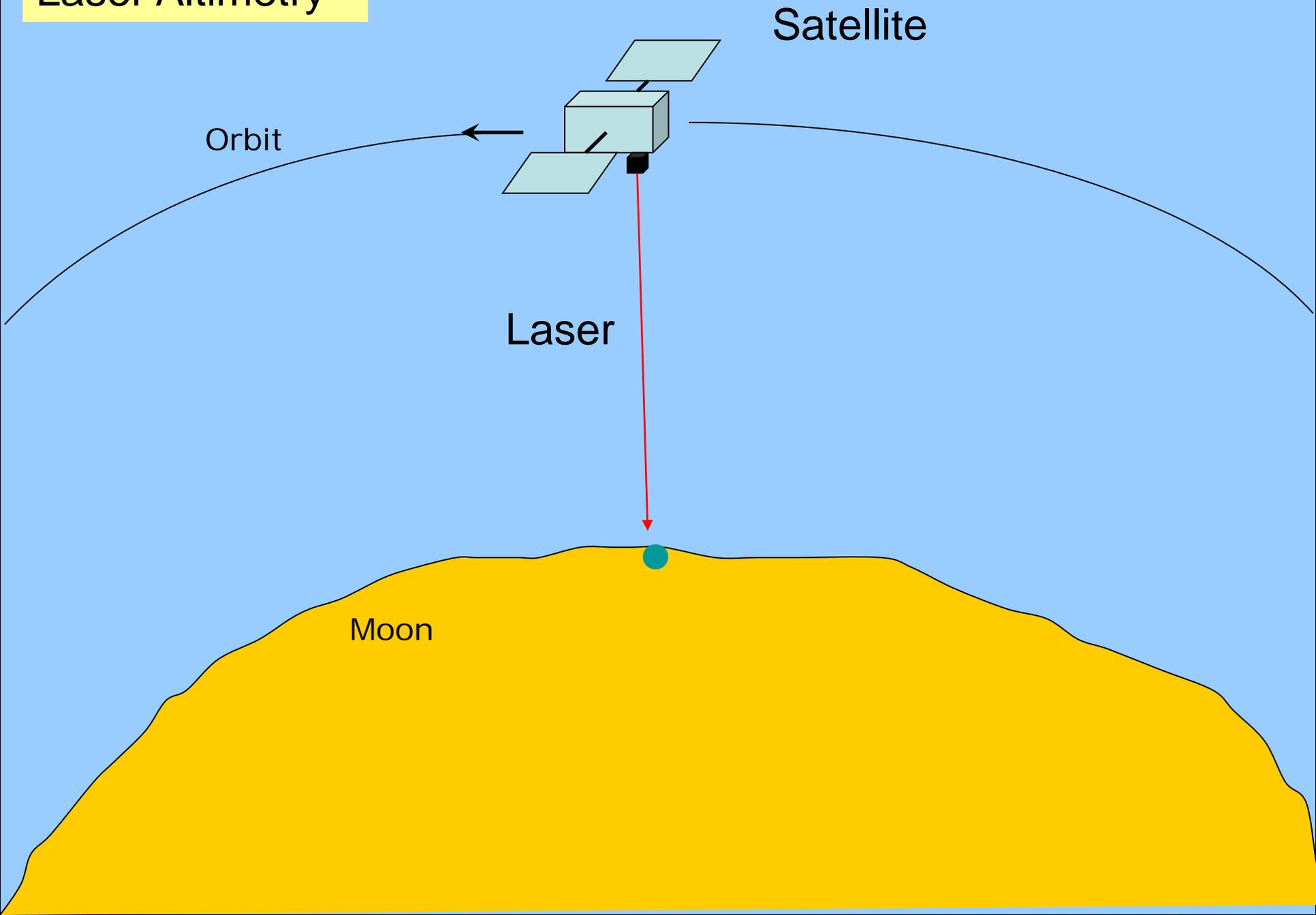
かぐや観測のためのVLBI電波望遠鏡



- VLBI観測
2007-11 to 2008-10
- エンジ色はVERA
- 赤は国際局
- 相対VLBI観測は09-2まで
- 「おうな」観測は09-6まで



Laser Altimetry



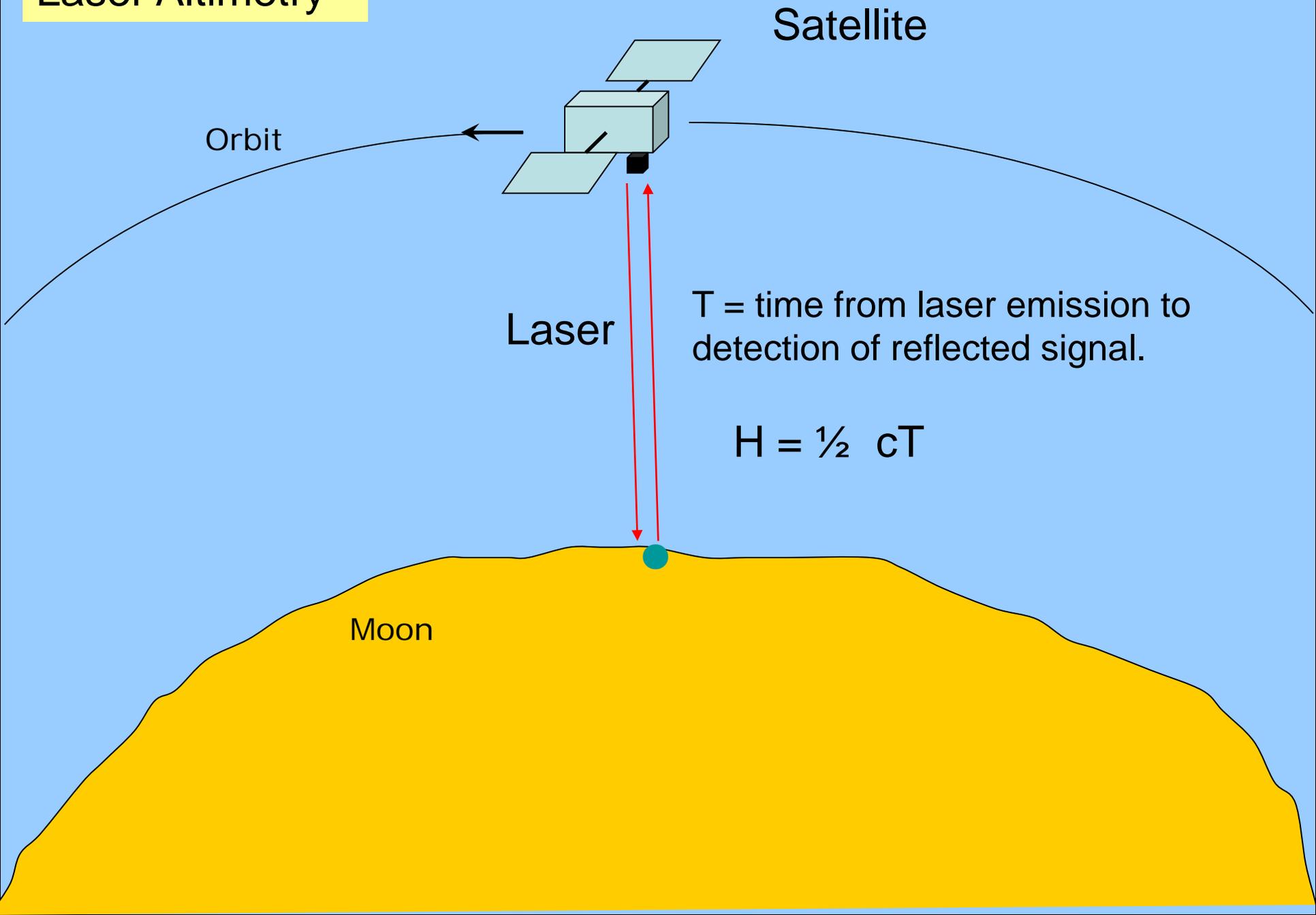
Satellite

Orbit

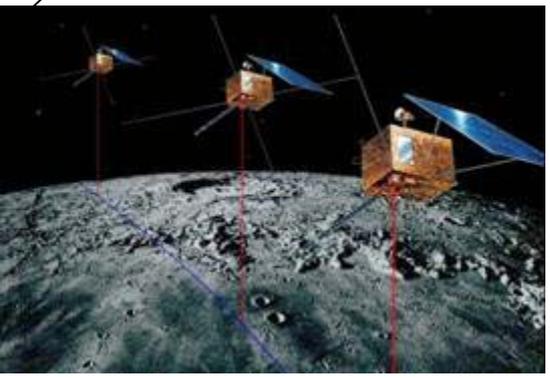
Laser

Moon

Laser Altimetry



月レーザー測距



軌道

時刻

軌道: 衛星位置
月重心座標系 (DE4XX)

衛星姿勢
LALT取付精度

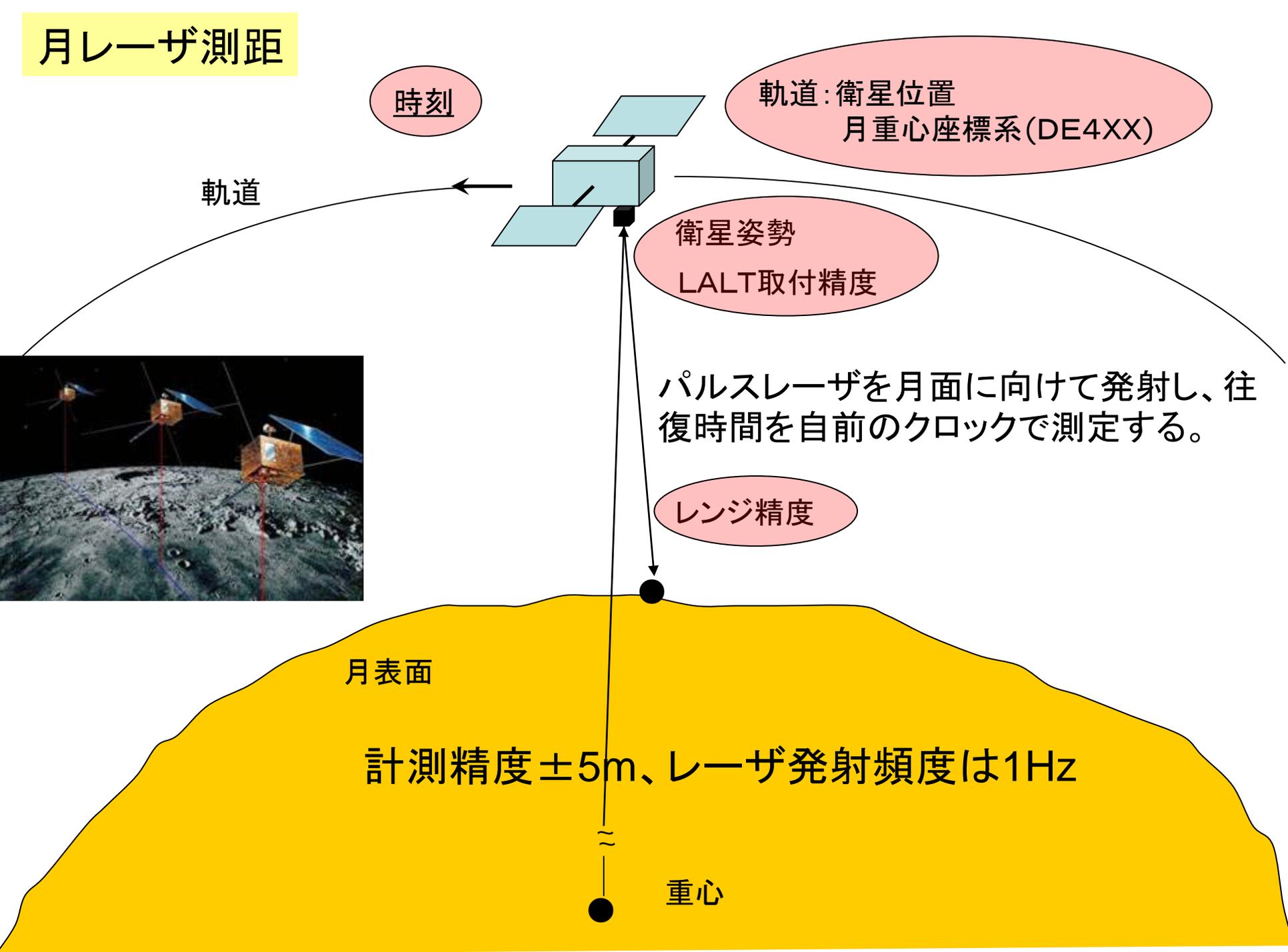
パルスレーザーを月面に向けて発射し、往復時間を自前のクロックで測定する。

レンジ精度

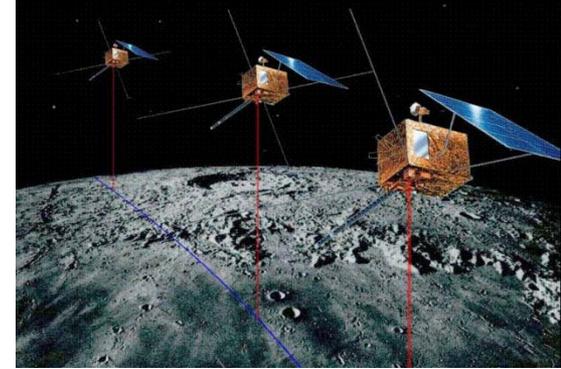
月表面

計測精度 $\pm 5\text{m}$ 、レーザー発射頻度は 1Hz

重心



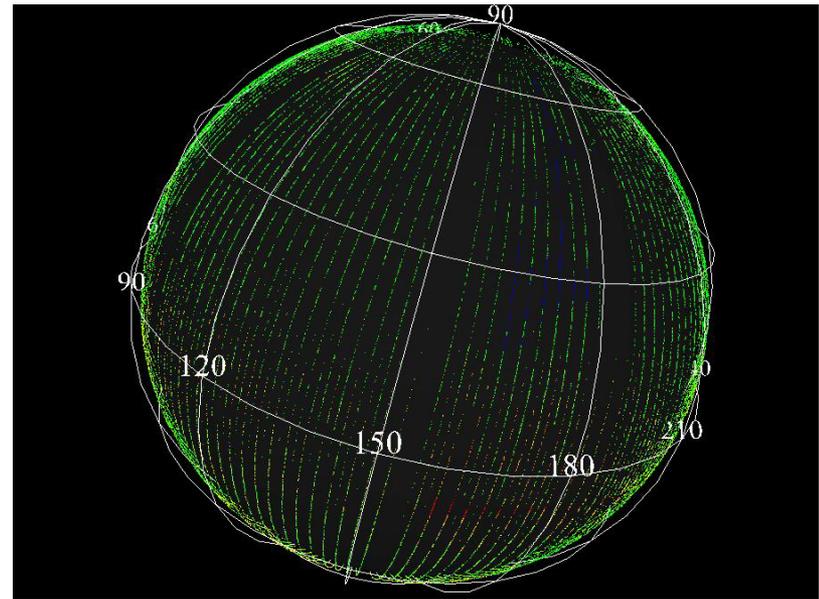
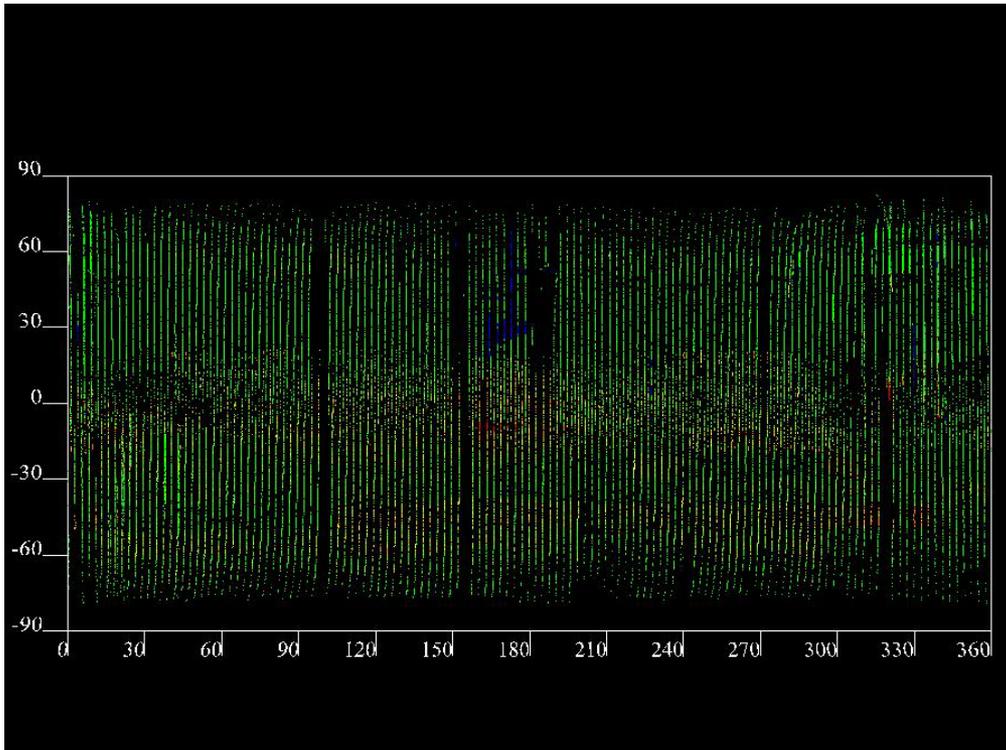
LALT概要



レーザー測距装置：パルスレーザーを月面に向けて発射し、往復時間を自前のクロックで測定する。

- 計測精度 $\pm 5\text{m}$ 、レーザー発射頻度は 1Hz
- ビーム拡散角 0.4mrad
- LD励起 / Qスイッチトリガ(LiNbO_3) / Nd:YAG
- パルスエネルギー 100mJ / パルス幅 15nsec .
- 口径 7.5cm 送信望遠鏡(ガリレオ式、倍率10倍)
- 口径 10cm 受信望遠鏡(カセグレン式)
- 受光素子: Si-APD+帯域 10nm バンドパスフィルタ

Clementineのデータは間隔大

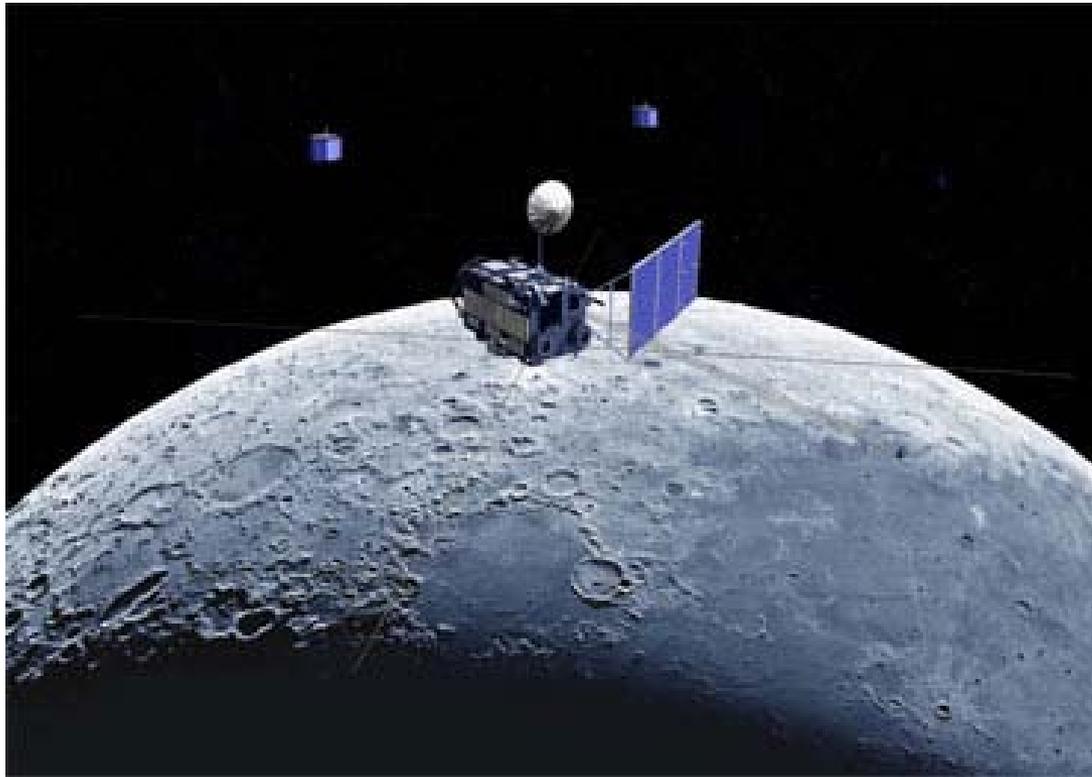


レーザー高度計 LALT

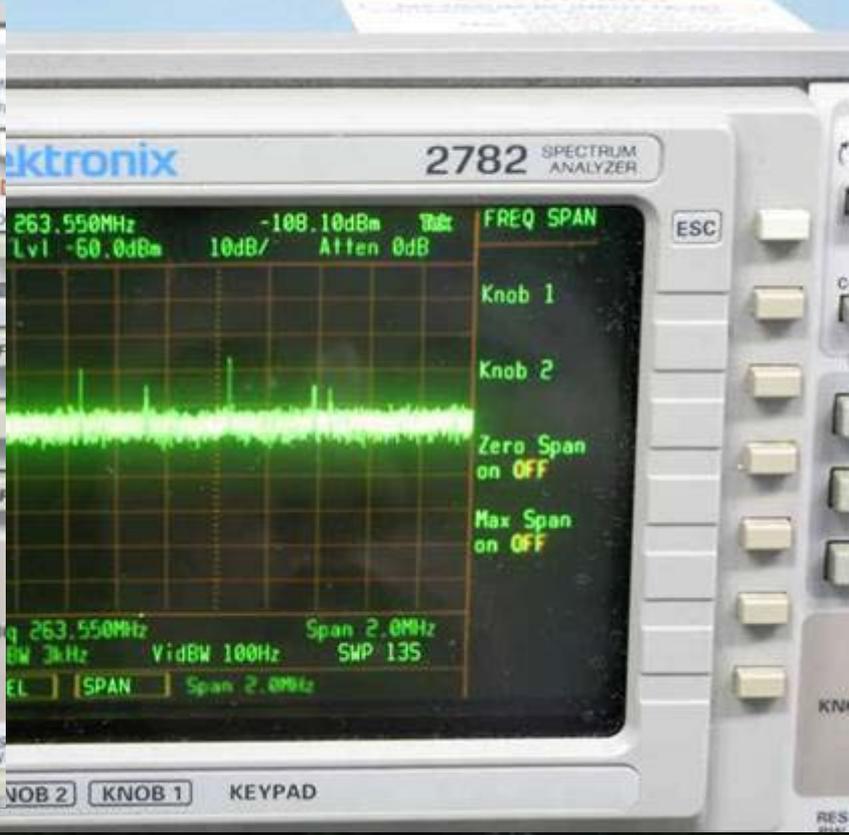
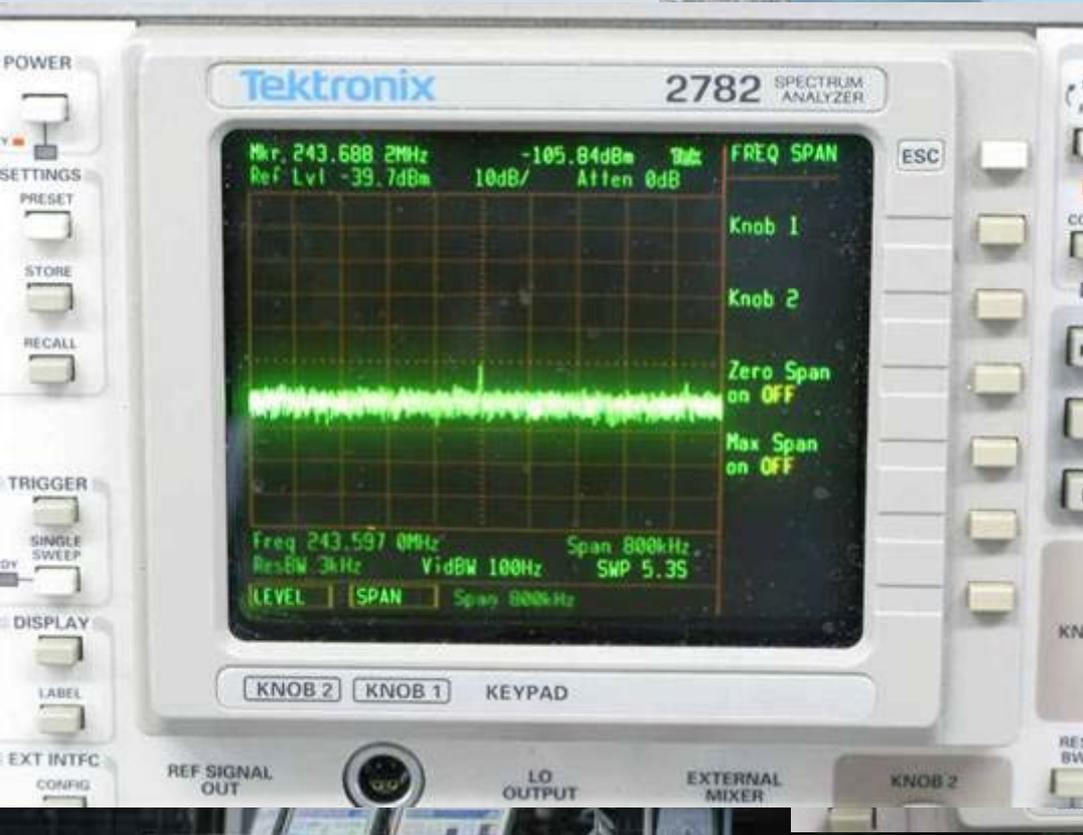




「かぐや」は「月」へ



国立天文台水沢VLBI観測所



リレー衛星放出成功

Oct.9, 9:35JST



放出前



放出後

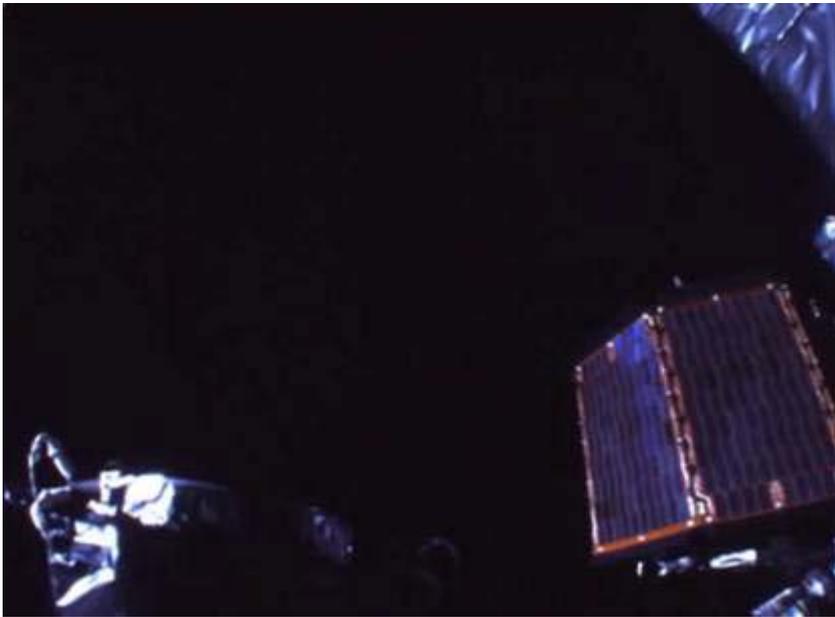


リレー衛星
分離成功

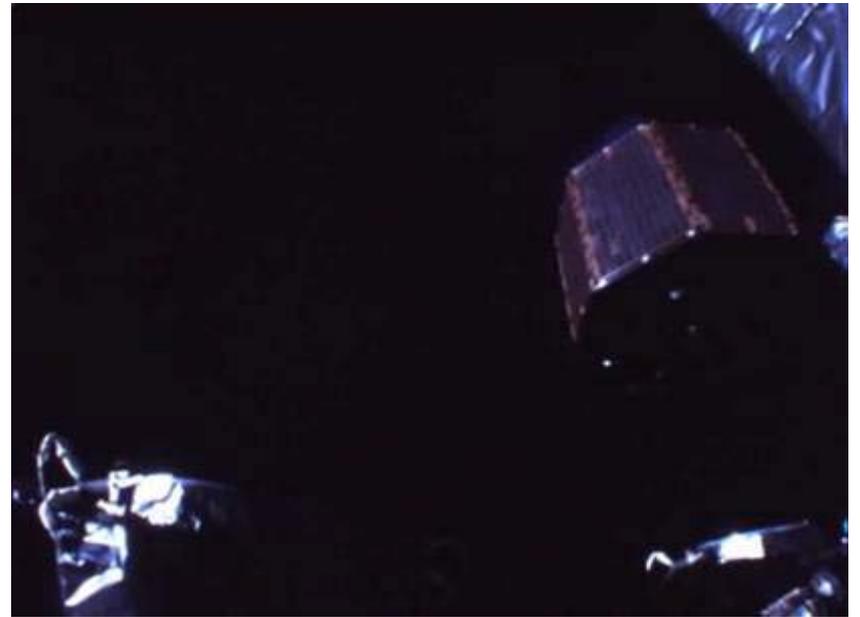
2007. 10. 9 天文台水沢

VLBIリレー衛星放出成功

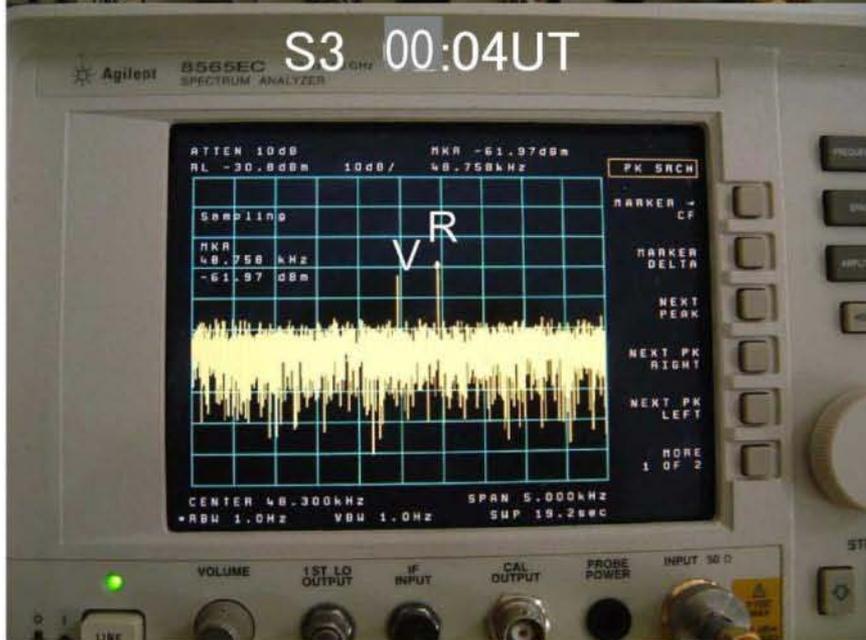
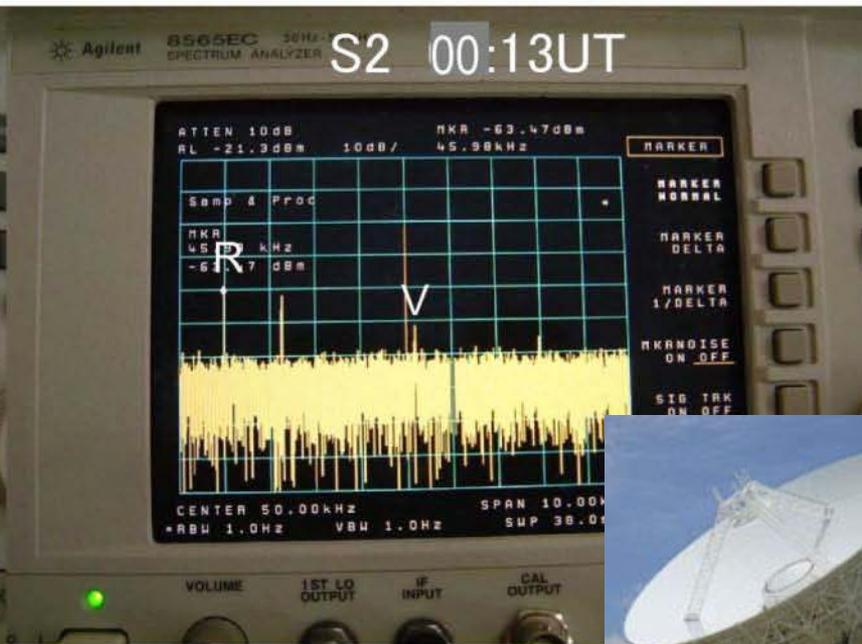
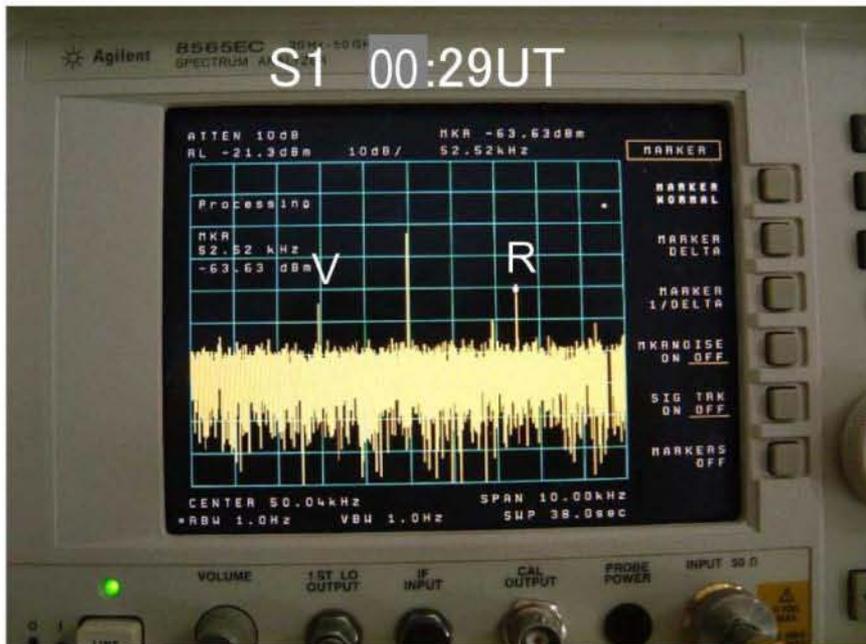
Oct.12, 13:28JST



放出前



放出後

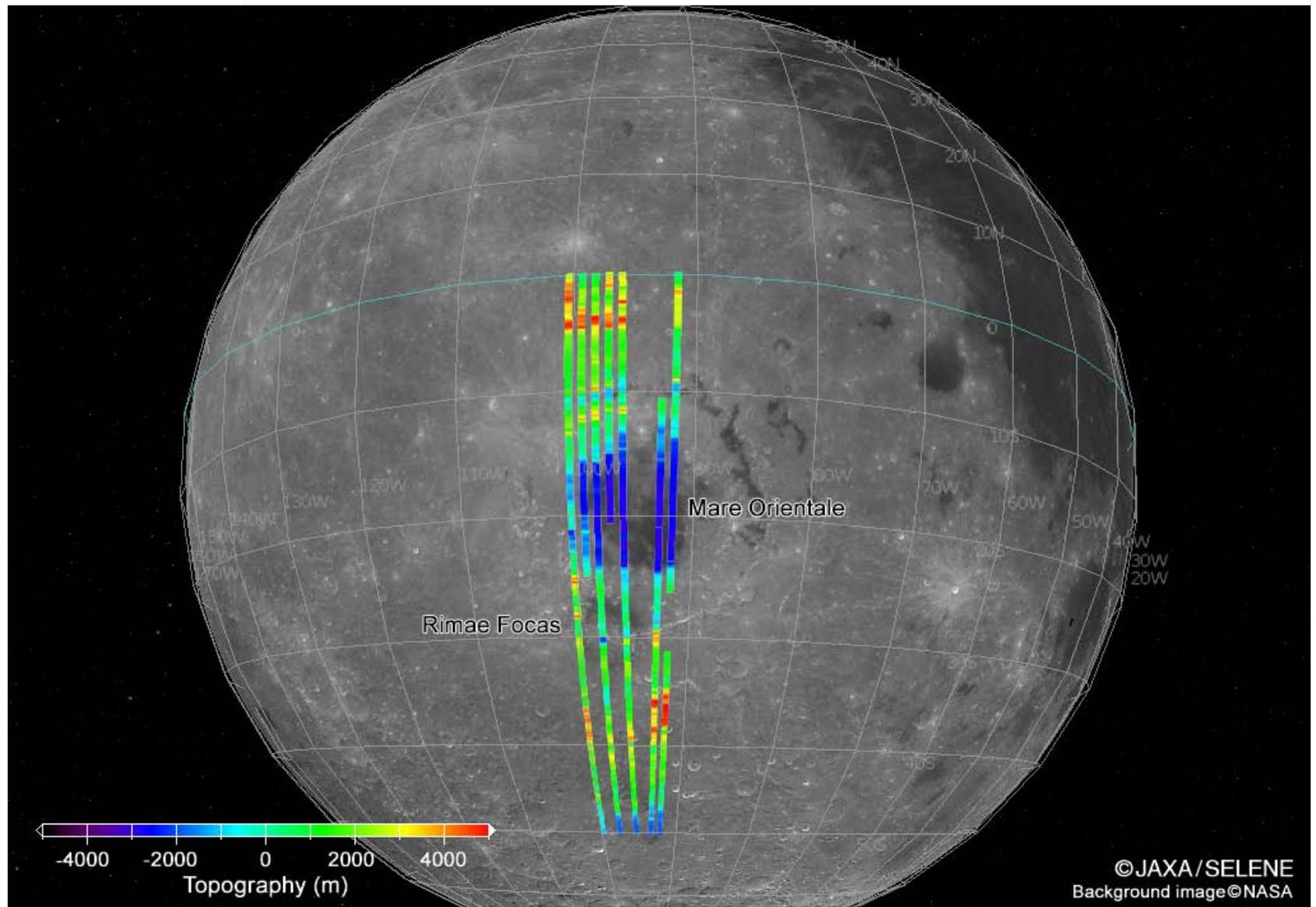


S-band Samebeam signal @ Ishigaki
2007.11.07

VERA石垣島局で受信された
「おきな」(Rstar)と「おうな」
(Vstar)のS帯の信号
(同一ビームVLBI観測時)

RISE受信ターミナルのコントロールは水沢RISE

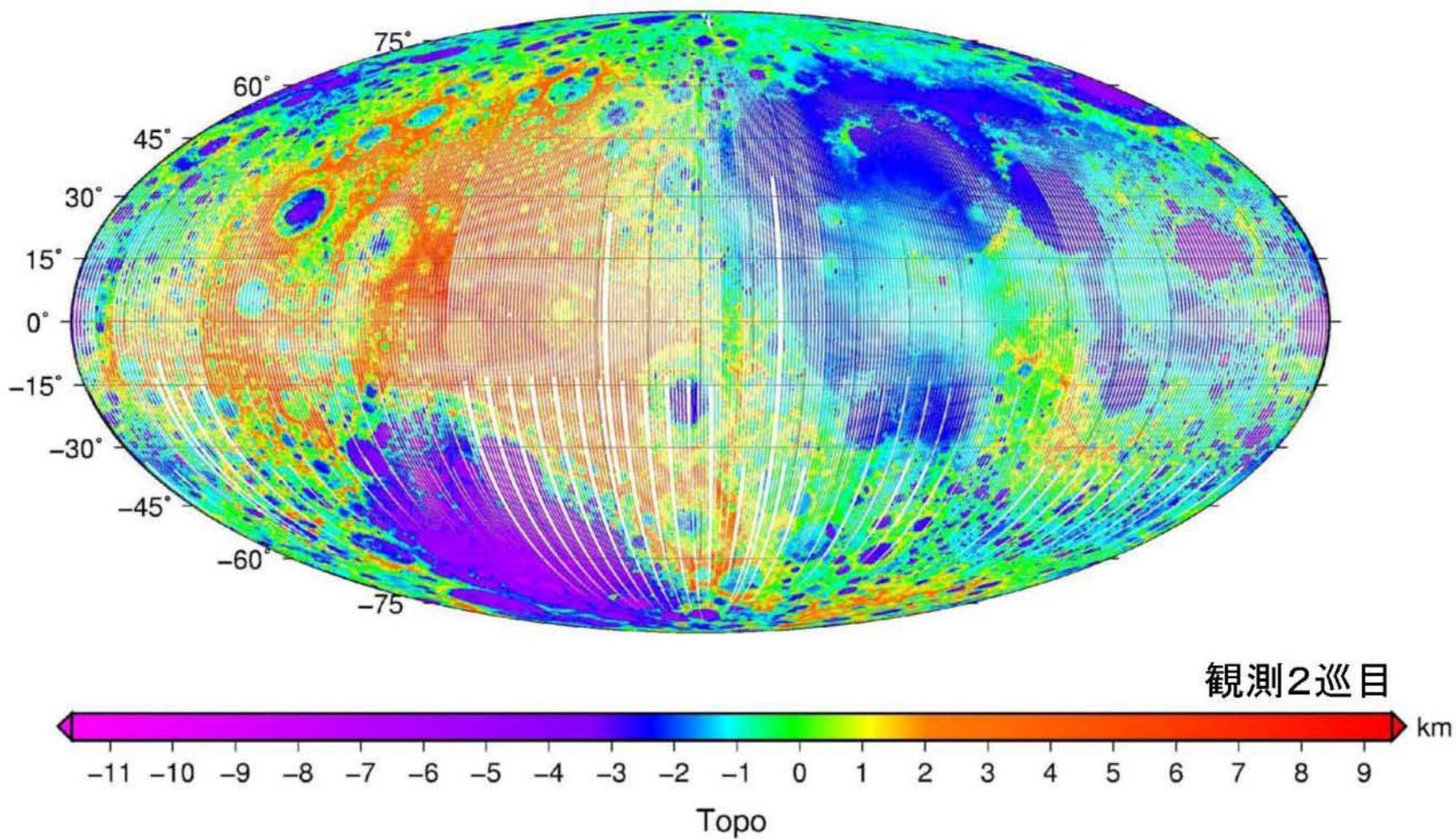




観測状況(全球)

LALT 2008.01.20 現在

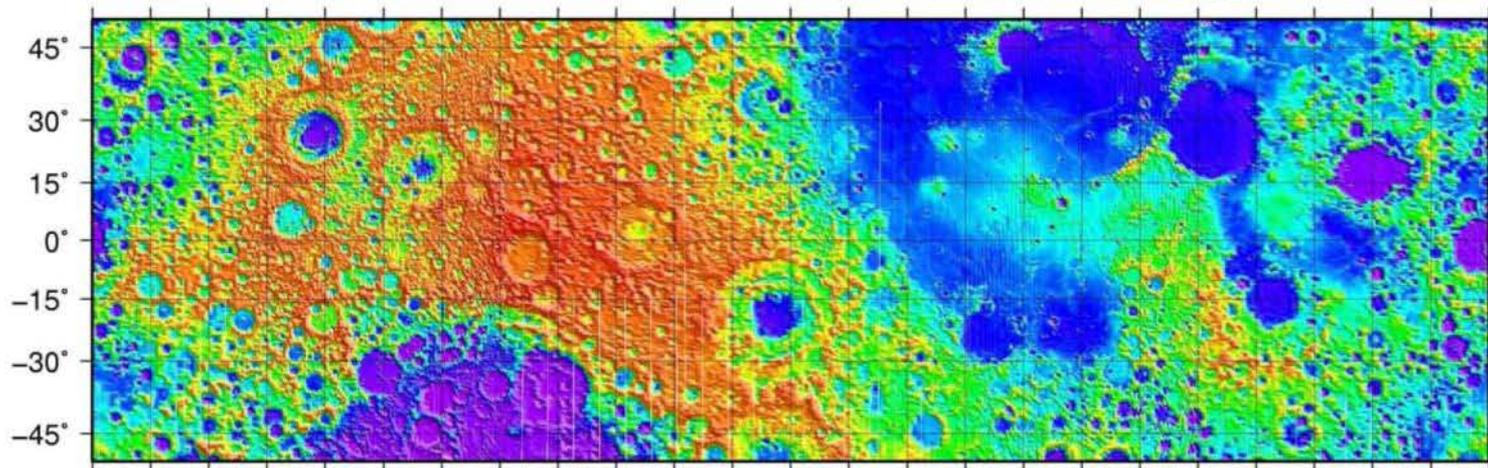
ALL-DATA



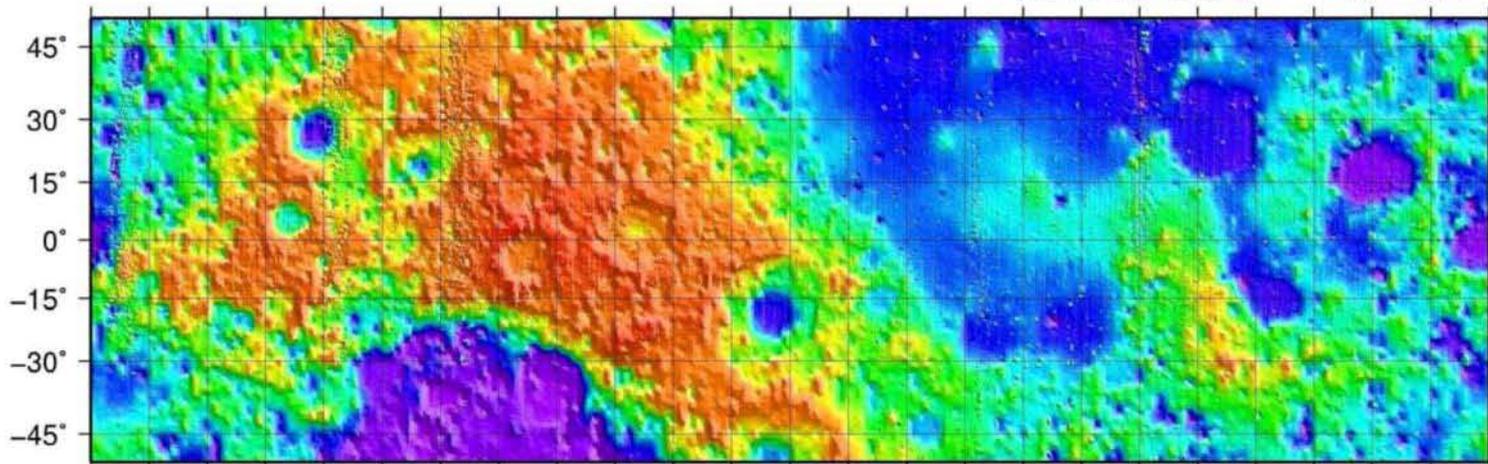
ULCN2005との比較

GMT 0.05度グリッド

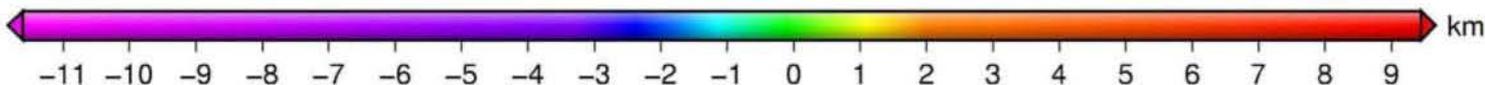
LALT 2008.01.20 現在 $\sim 1 \cdot 10^6$



ULCN2005 $\sim 2.7 \cdot 10^5$

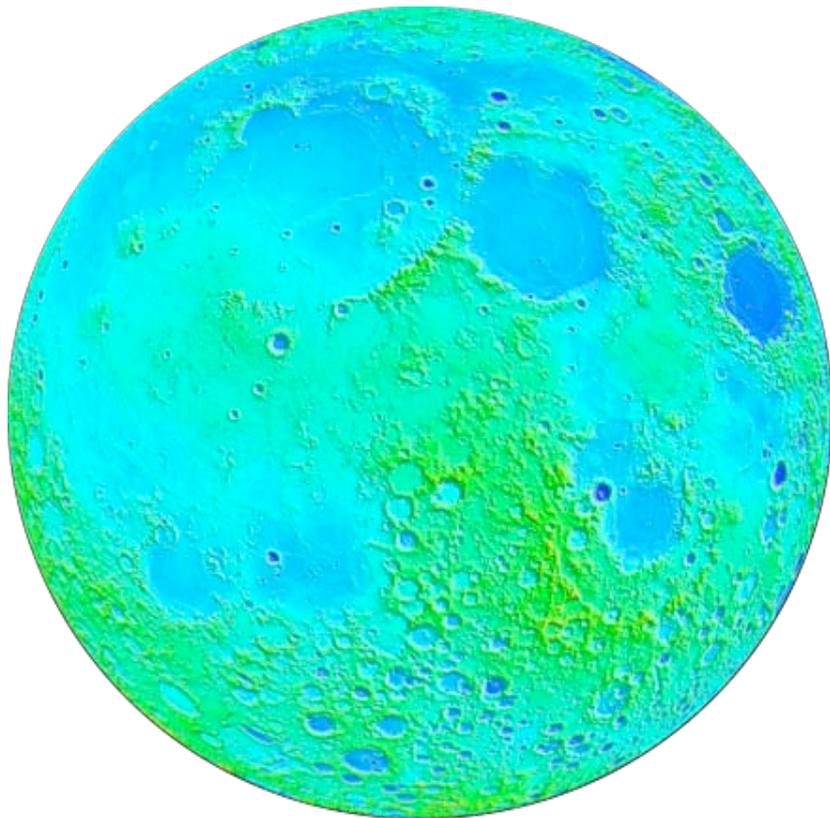


90° 105° 120° 135° 150° 165° 180° 195° 210° 225° 240° 255° 270° 285° 300° 315° 330° 345° 0° 15° 30° 45° 60° 75° 90°

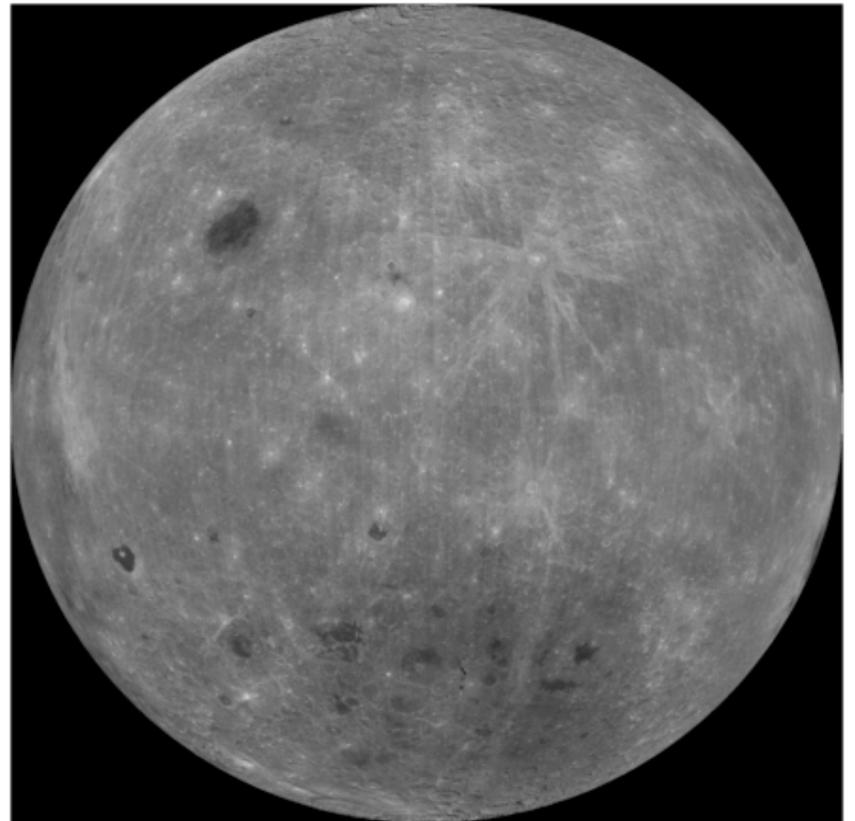


Topo

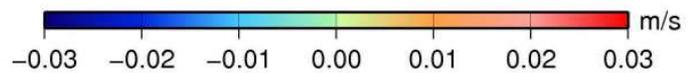
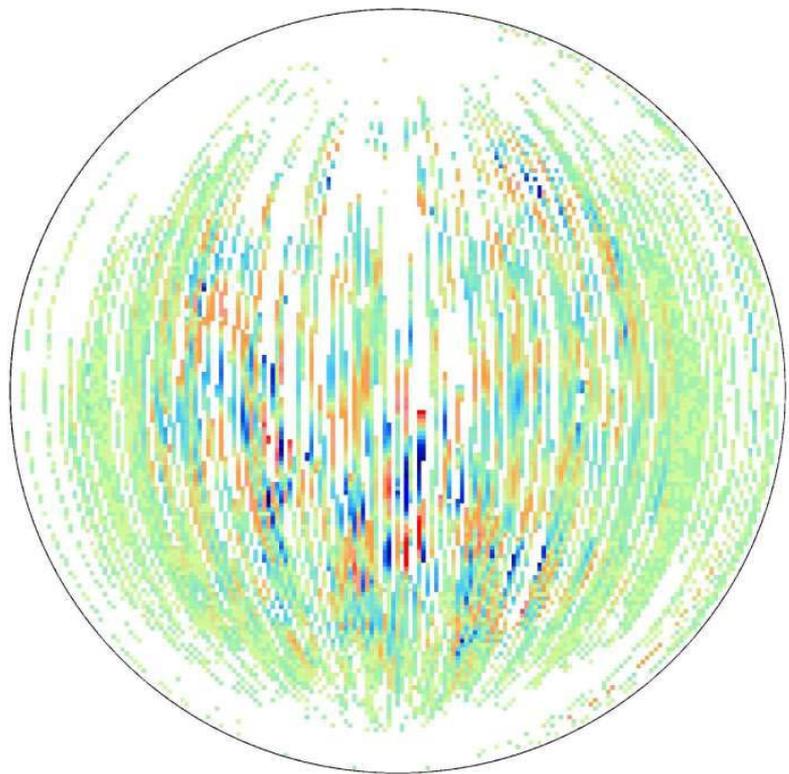
LALTで計測した月地形(表)



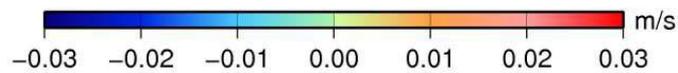
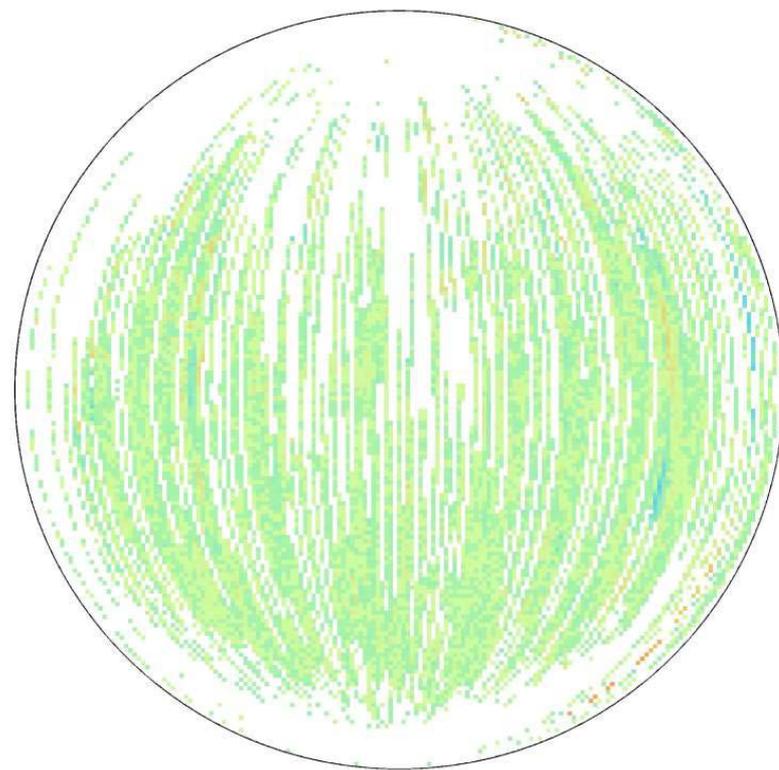
LALTで計測した月地形(裏)



4-way Dopplerによる月裏側の重力計測



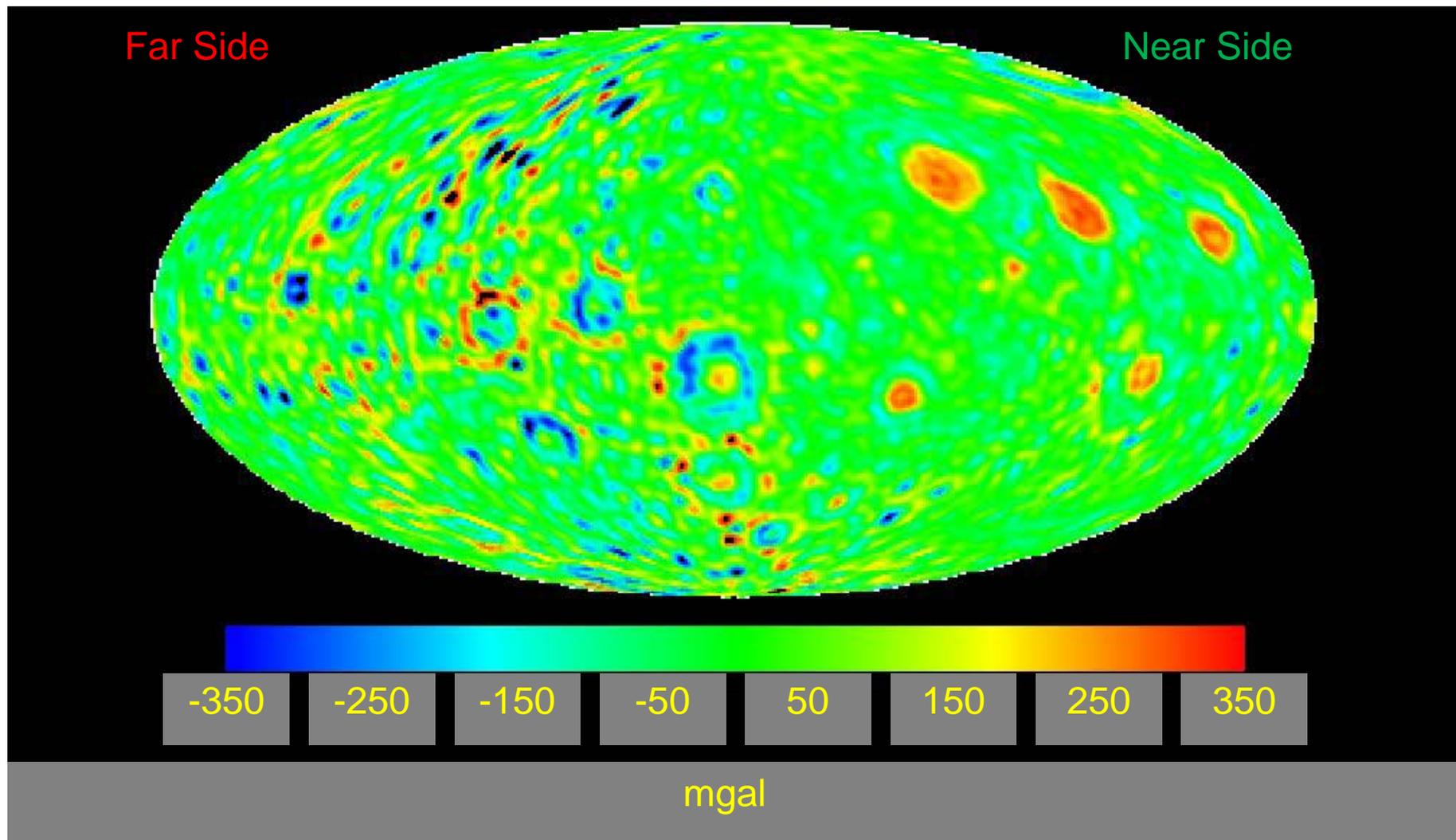
With respect to LP100K



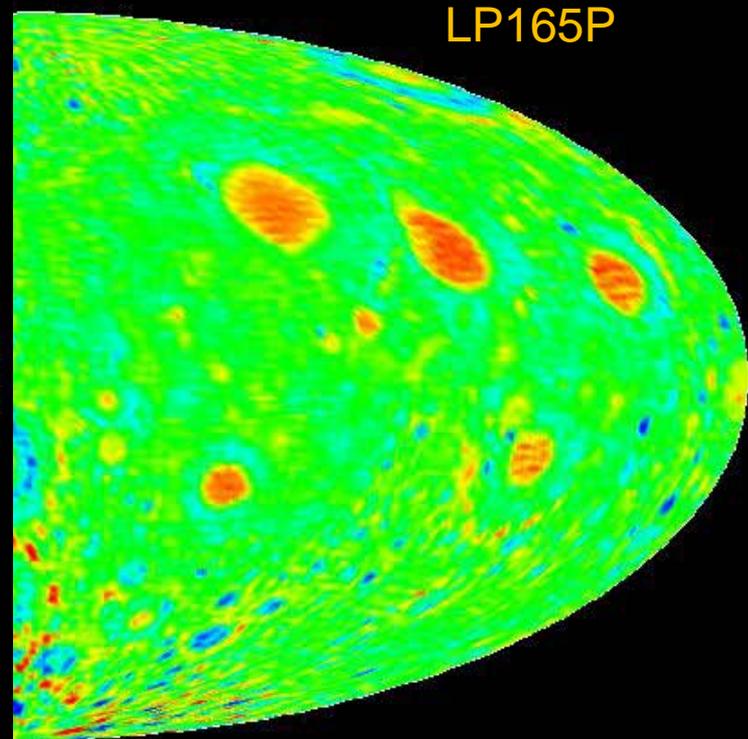
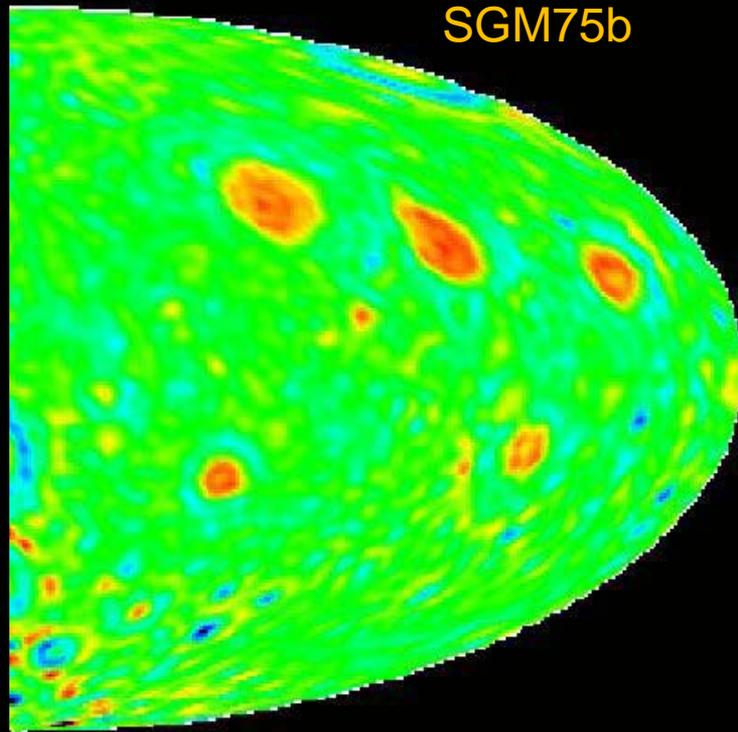
With respect to SGM90e

フリーエアークラフ重力異常: SGM75b

No VLBI data; Kaula's constraint

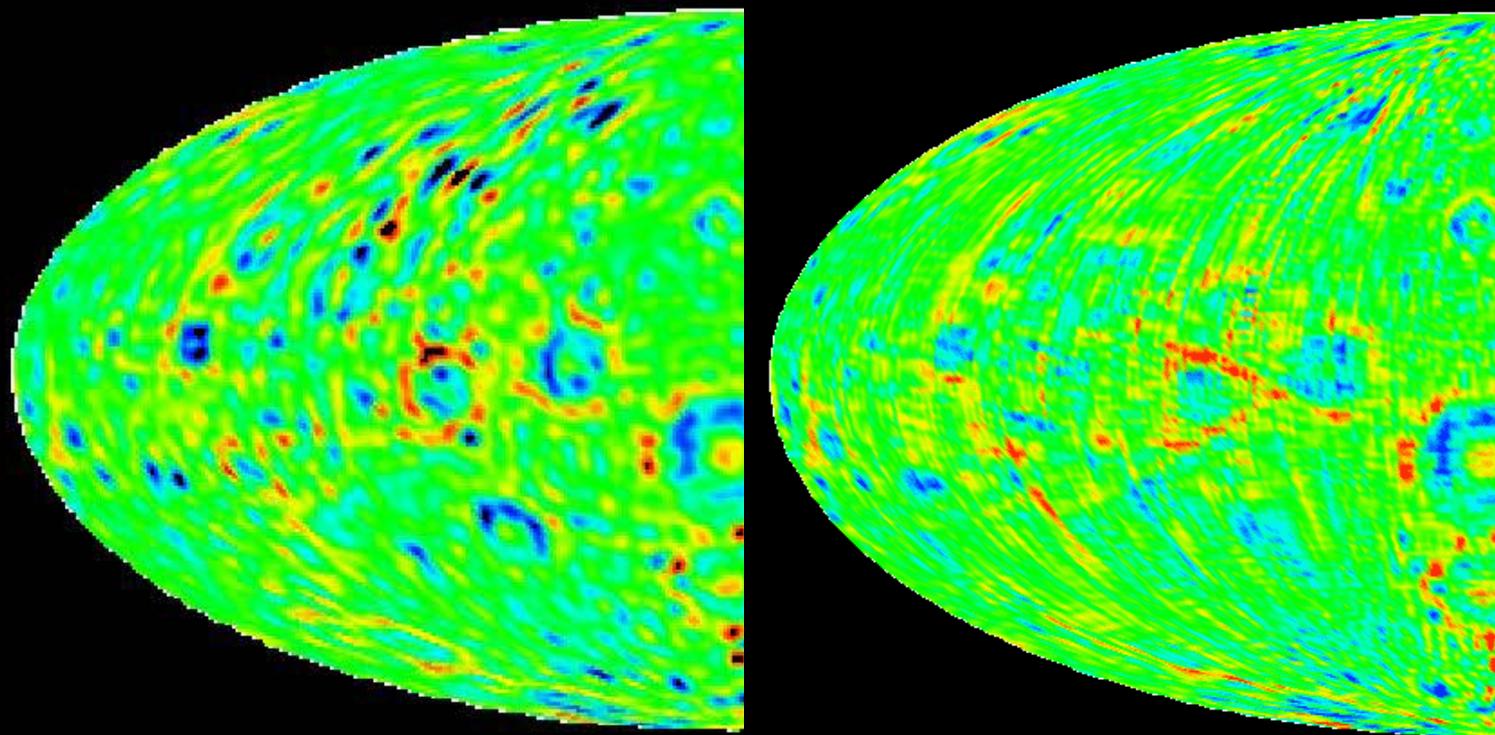


重力異常(かぐやvsLP)比較 表



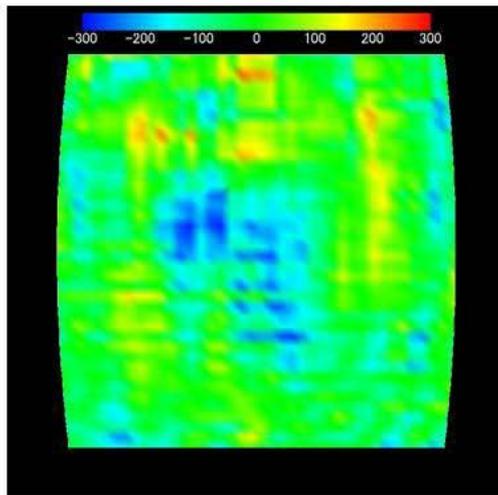
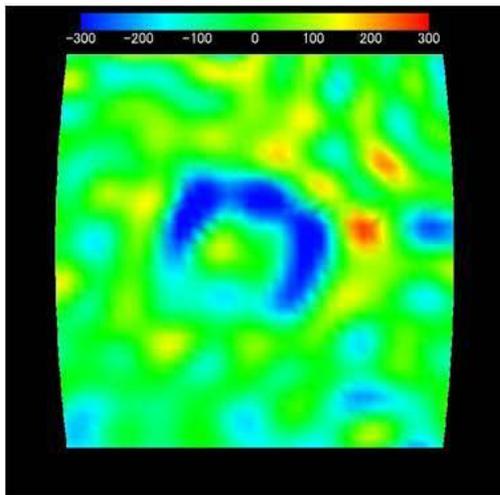
mgal

重力異常(かぐやvsLP)比較 裏



mgal

表と裏の重力の違い

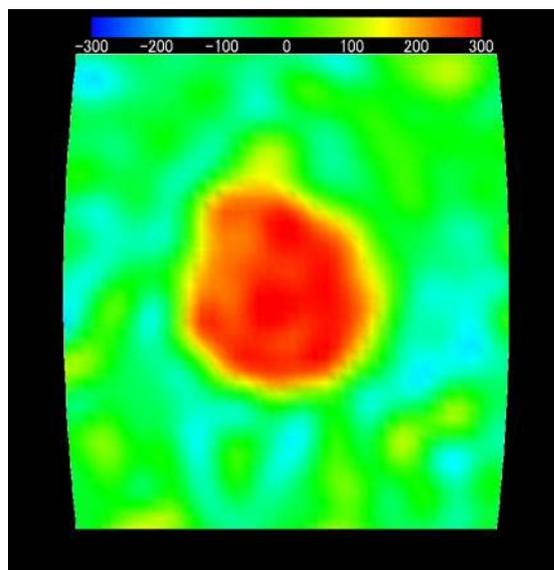


アポロ盆地 (かぐや)

(ルナプロスペクタ)

裏側

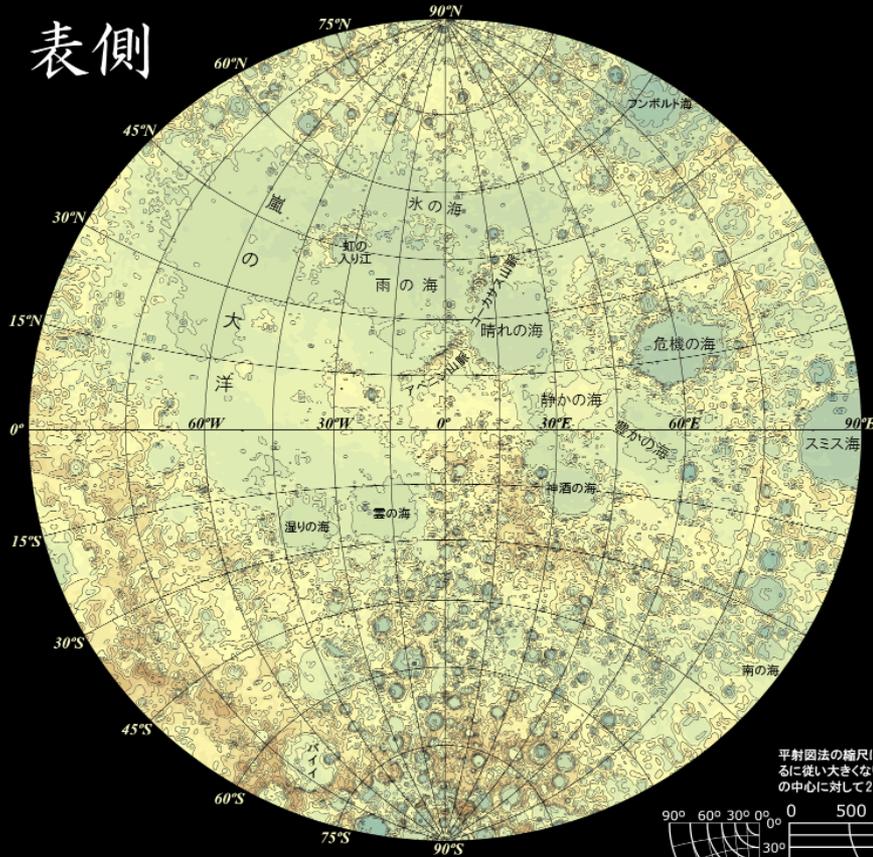
静かの海
(かぐや)
(表側)
マスコン



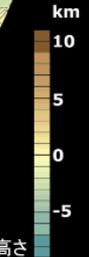
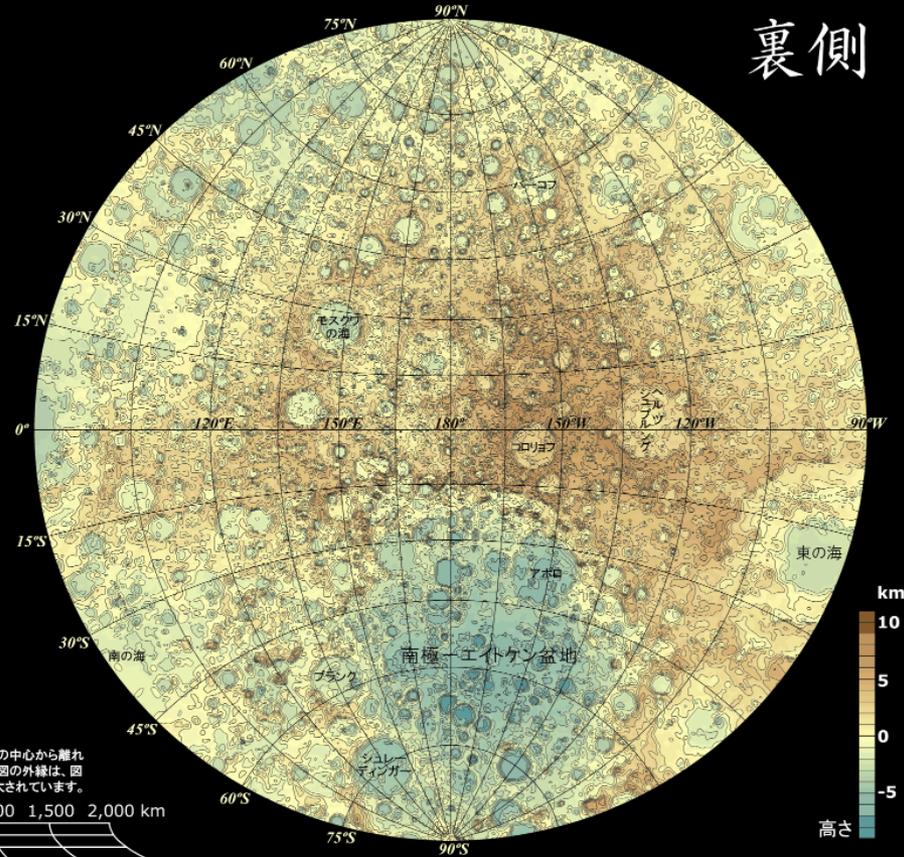


「かぐや」が見た月の地形

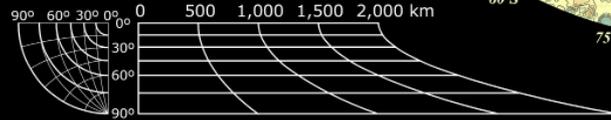
表側



裏側



平射図法の縮尺は、地図の中心から離れるに従い大きくなります。図の外縁は、図の中心に対して2倍に拡大されています。



この地図は、JAXAの月周回衛星「かぐや(SELENE)」に搭載したレーザ高度計(LALT)の観測精度5mの観測データをもとに作成しました。等高線間隔は1km、高さの基準は重心を中心とする半径1,737.4kmの球です。投影法は平射図法、経度0°は地球から見える月中心を通る子午線です。観測期間は平成20年1月7日~1月20日です。月の表側は玄武岩で覆われた平坦で薄暗い海が比較的多いに対し、裏側は大小さまざまなクレータで覆い尽くされており海はほとんどありません。

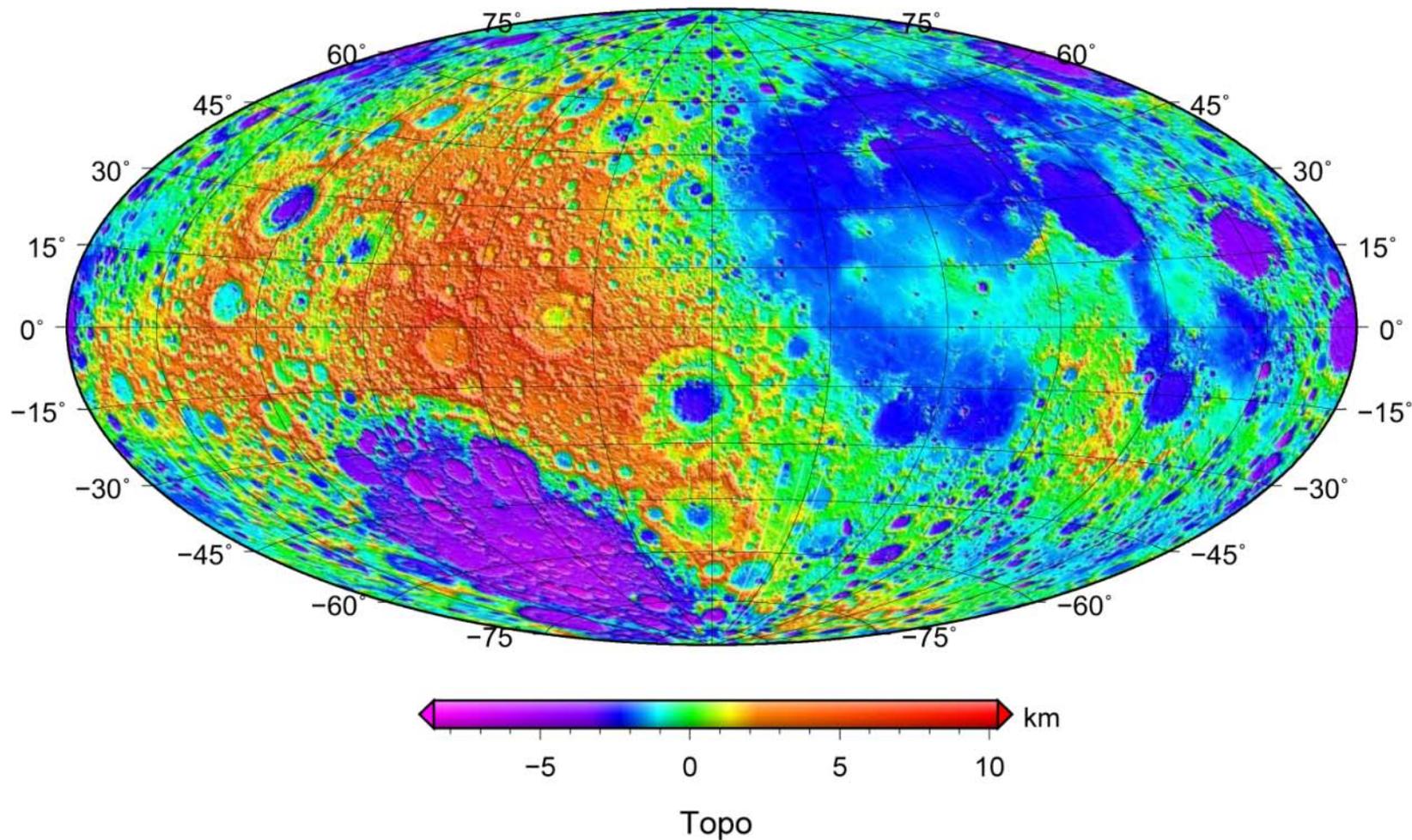
また裏側の南半球には、南極-エイトケン盆地と呼ばれる直径約2,500kmもある巨大な衝突盆地があり月面でも最も低い地域です。海は円形もしくは楕円形をしているものが多く、衝突盆地の窪みに溶岩が噴出して溜まったものと考えられています。しかし南極-エイトケン盆地は海にはなっていません。これは地殻の厚さや岩石の組成が表側と違うためではないかと考えられています。



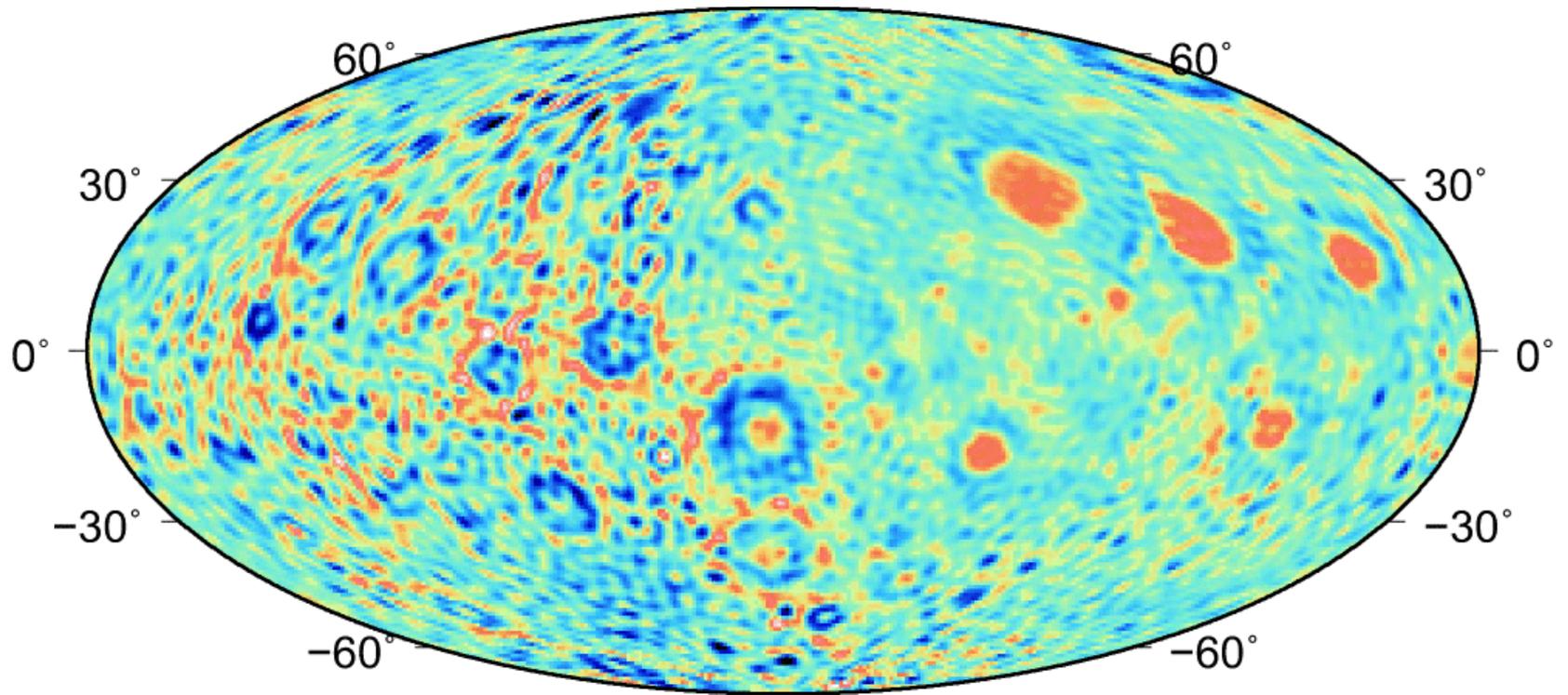
LALTのデータ処理・解析 自然科学研究機構 国立天文台
地形図の作成 国土交通省 国土地理院

レーザ高度計による地形(左が裏)

LALT 0.0625° GRID



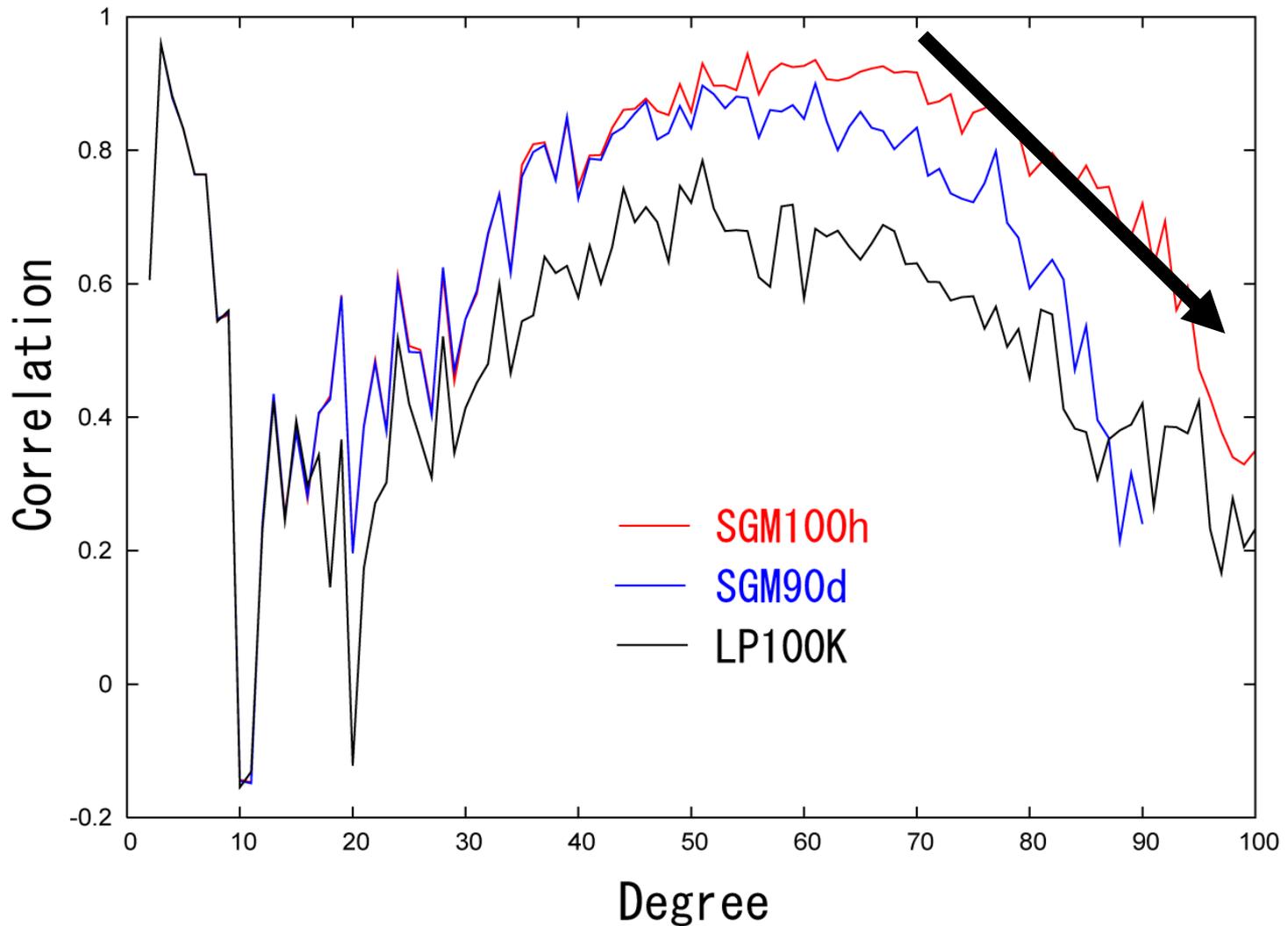
月全体の重力と地形



Video Time

重力と地形の関係は良くなった
→地形の凹凸の影響が大きい

Gravity-topography correlation

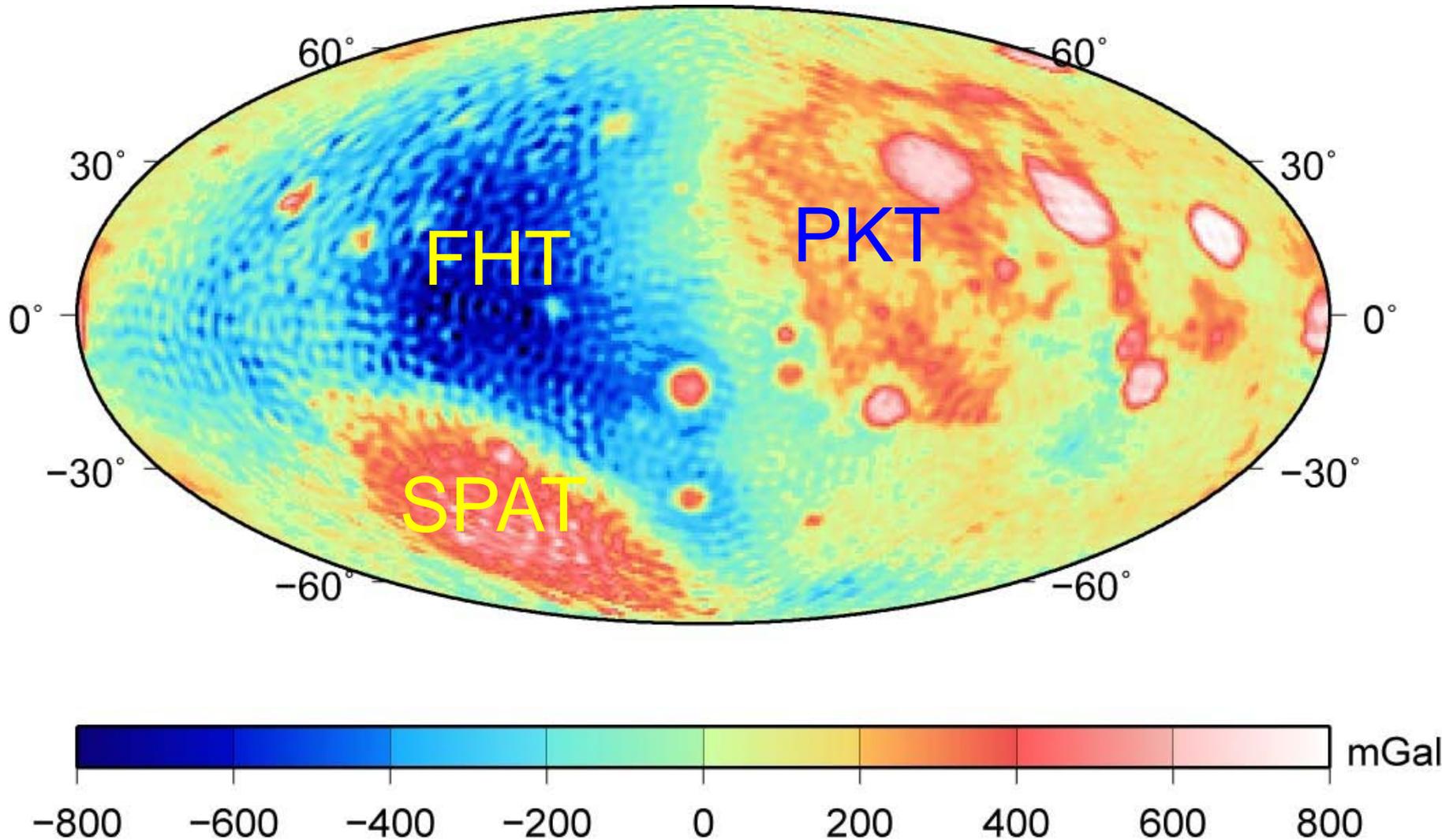


Bouguer anomaly

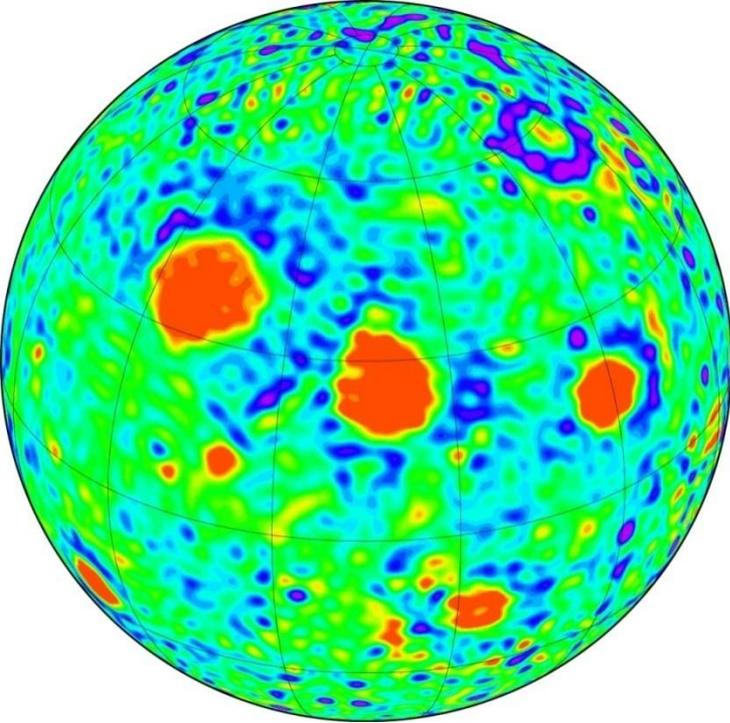
Crustal density = 2800 kg m^{-3}

Smooth crust-mantle boundary inside FHT and SPAT

Impact structures in FHT far-side are supported by lithosphere.



Mascon basins



LOS [*Muller and Sjogren, 1968*]

Detailed study by GLGM-2 [*Zuber et al., 1994*] and
LP165P [*Konopliv et al., 2001*]

topography;

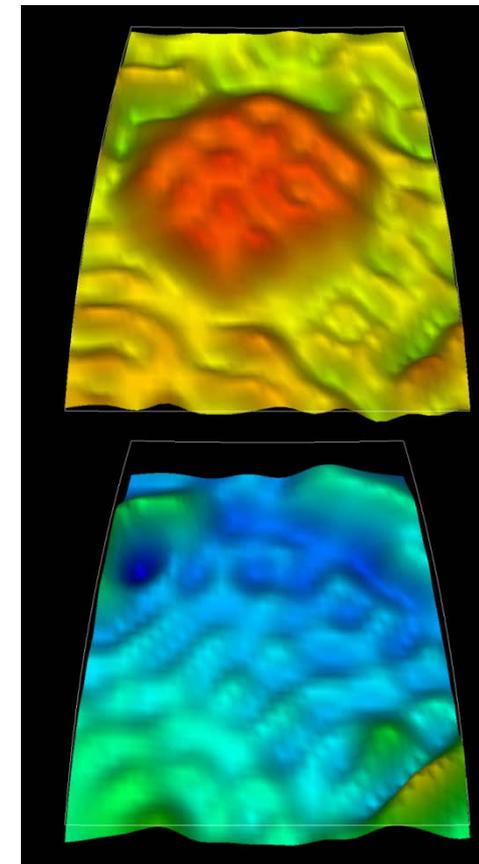
plateau shape with sharp shoulder

(b) Basaltic eruption (mare): Source depth = 200 – 300 km
[*Taylor, 1975*]

(c) Rim undistinguished in gravity

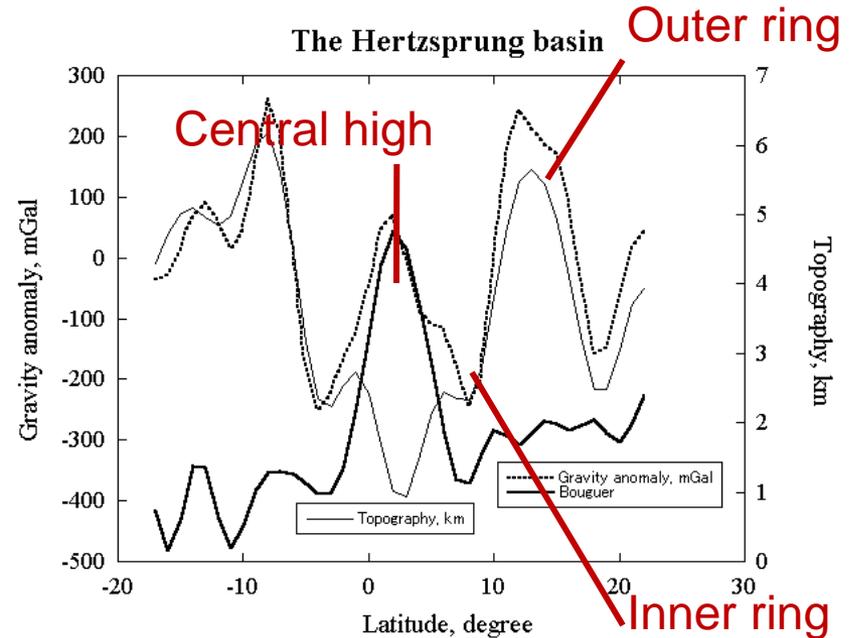
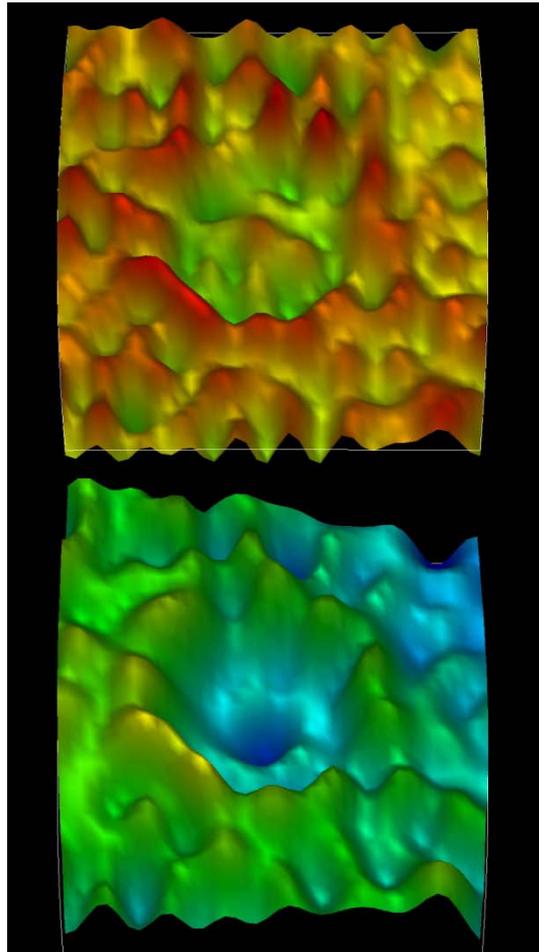
(d) Weak negative ring of $(\Delta g)_{FA}$

(e) $(\Delta g)_{FA} \sim (\Delta g)_B$ (Crisium, Nectaris, Smythii) or $(\Delta g)_{FA} <$
 $(\Delta g)_B$ (Serenitatis, Imbrium)



Mare Imbrium

Farside basins: Concentric structure



Outer ring: Topographic rim

Inner ring: Topographic depression

Central high: Density anomalies in the interior

Type I and II basins (>300km in diameter)
depending on the magnitude of central high:

Namiki et al. 2009

Classification: Major impact basins with gravity signatures

Type I basin

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

Concentrated but weak central gravity high

Central topography +

Mare volcanism rare

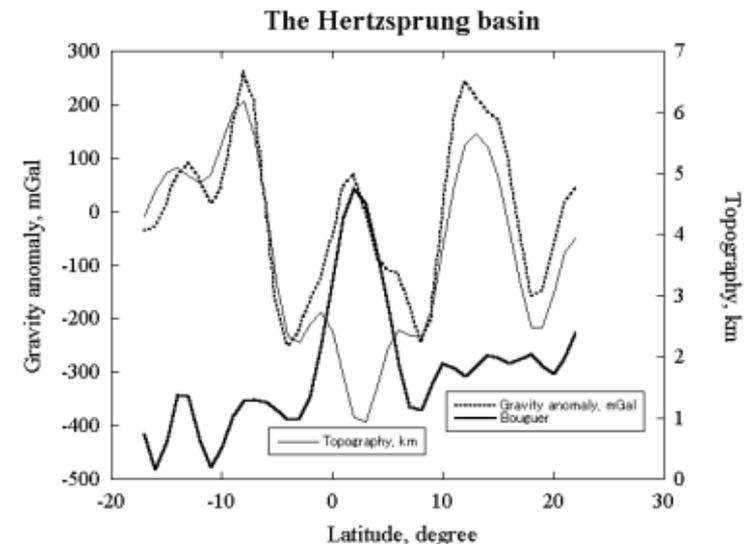
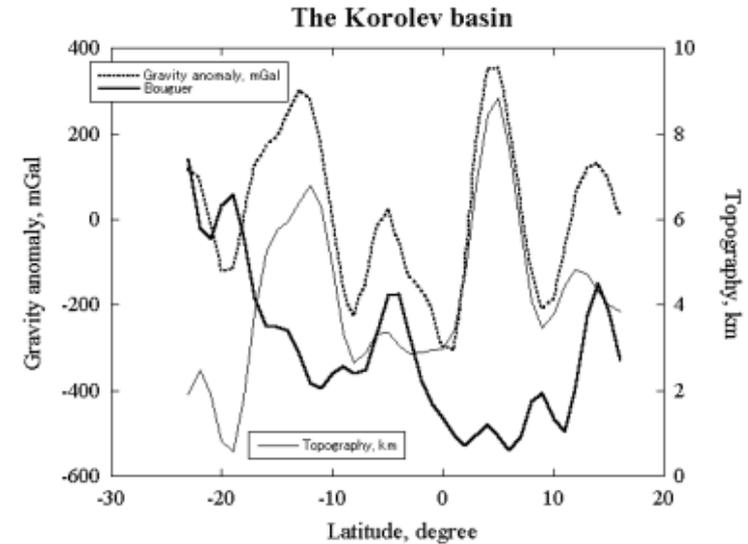
Type II basin

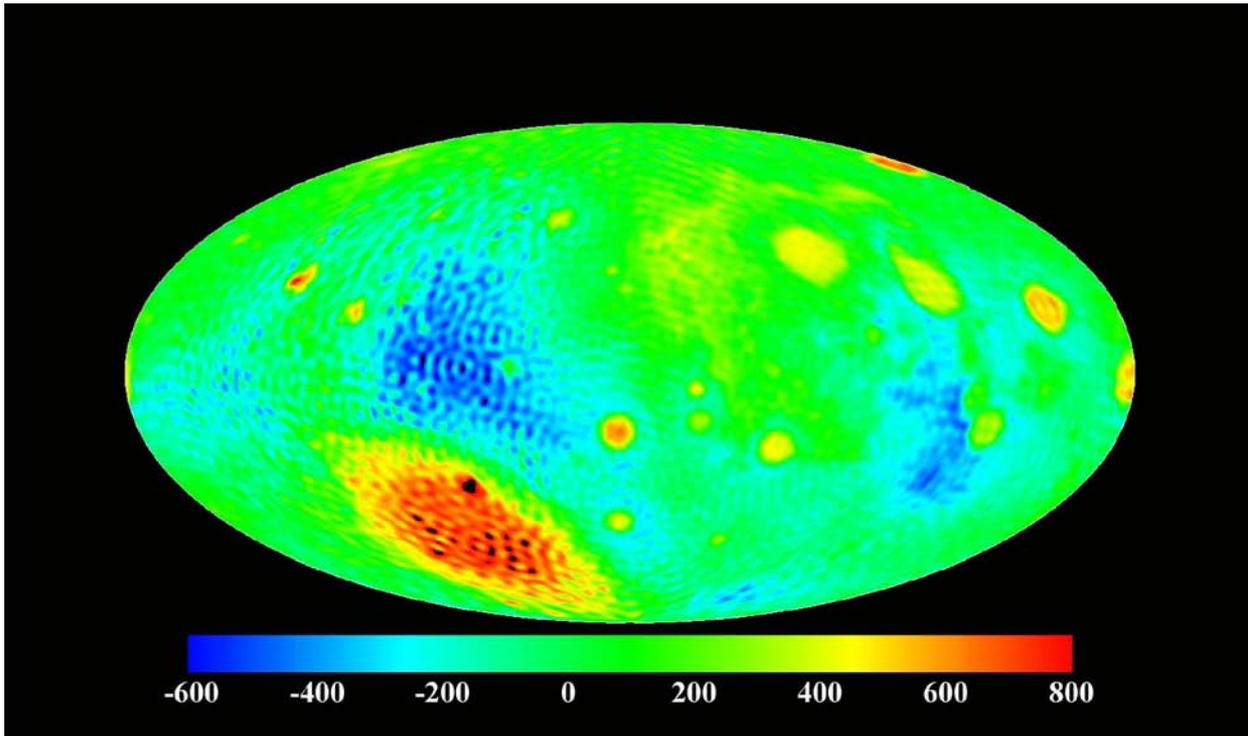
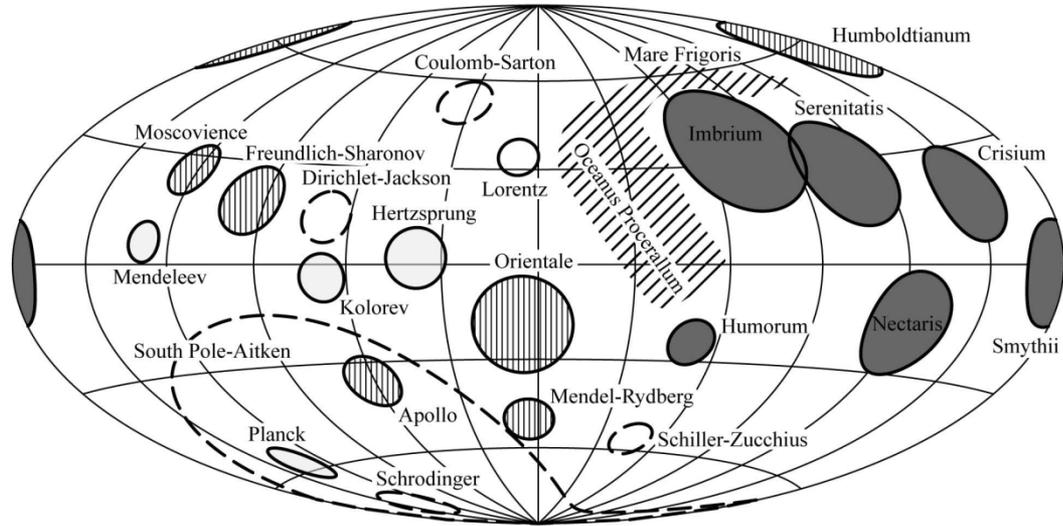
$$(\Delta g)_{FA} \sim (50-80\%) \times (\Delta g)_B$$

Relatively large central high

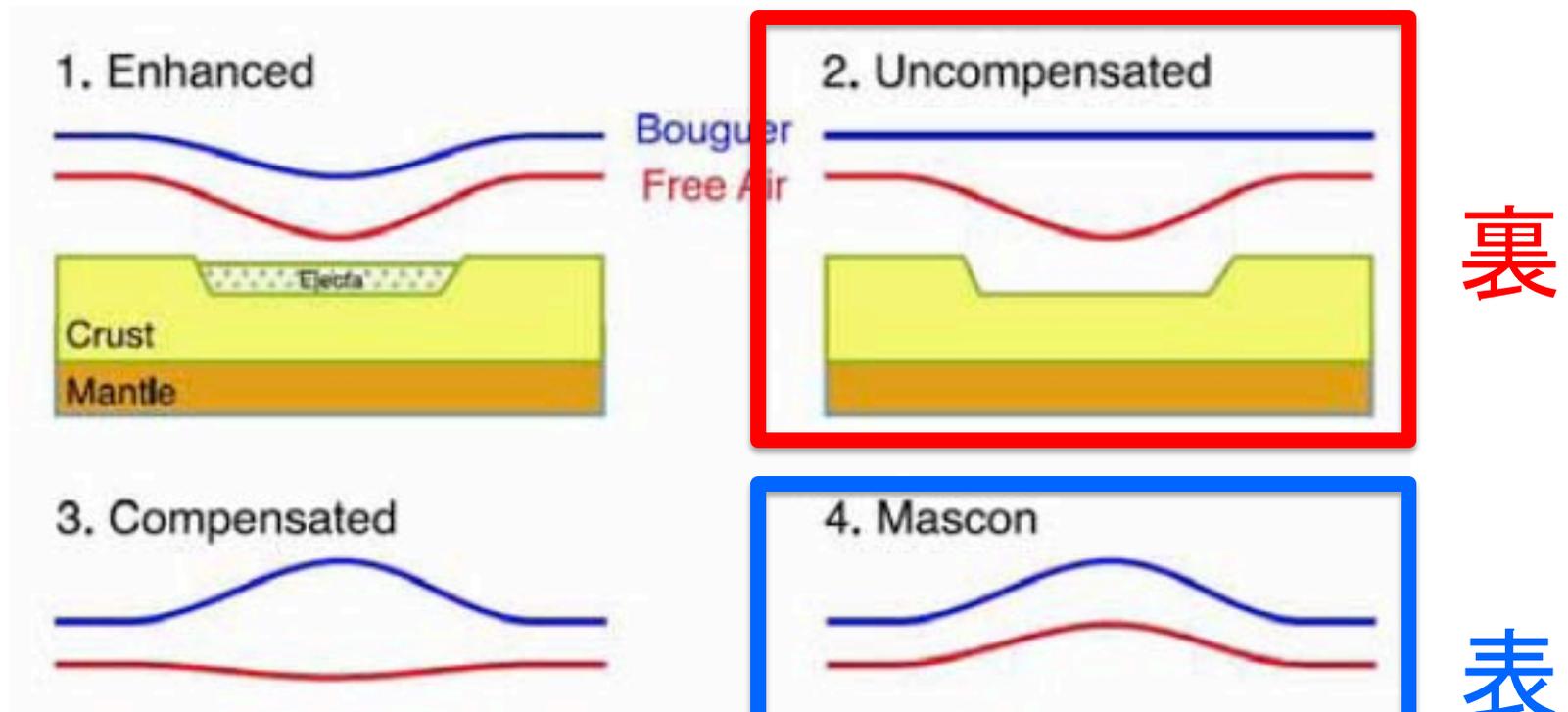
Central topography +

Associated with mare basalts



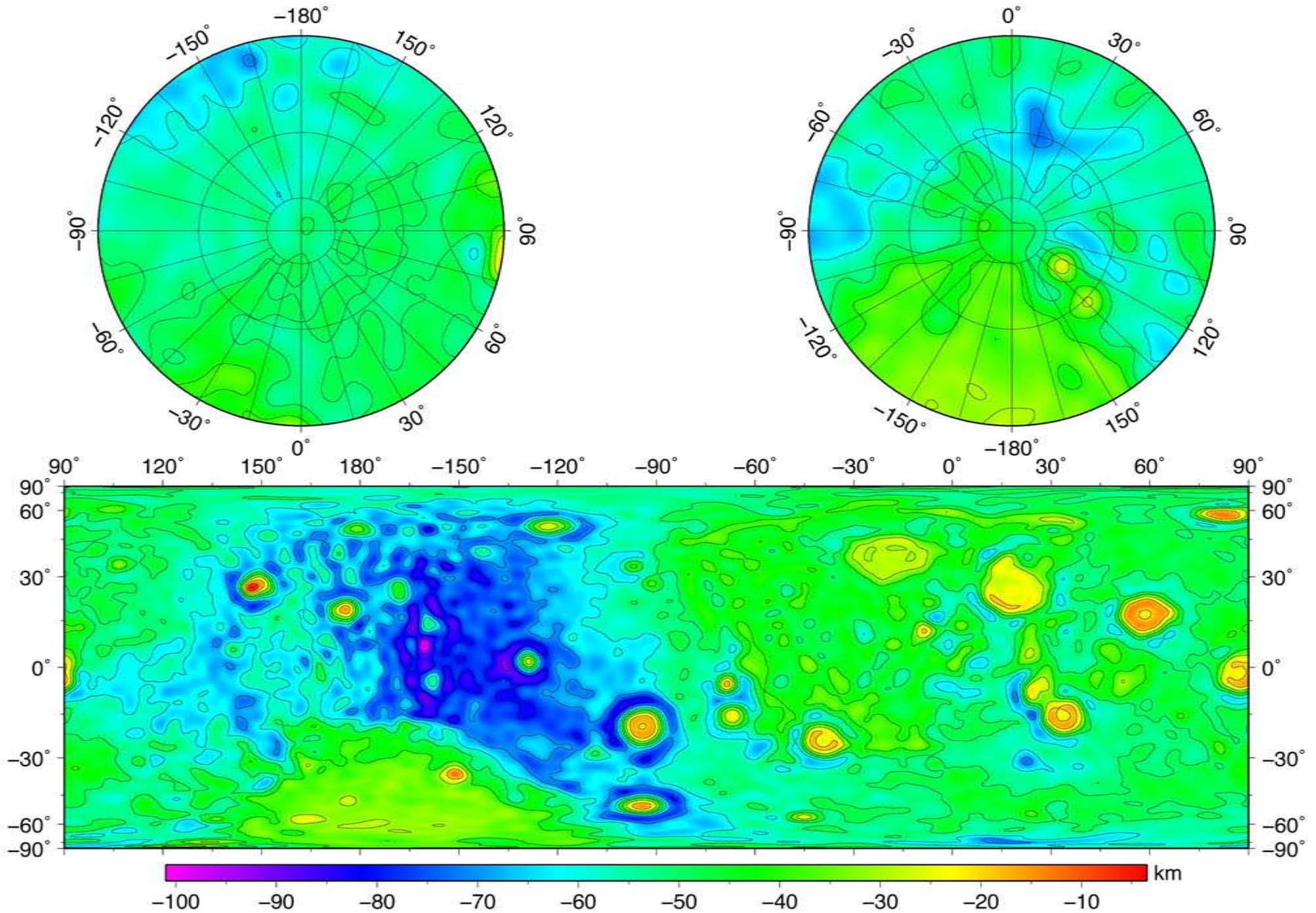


月の表と裏

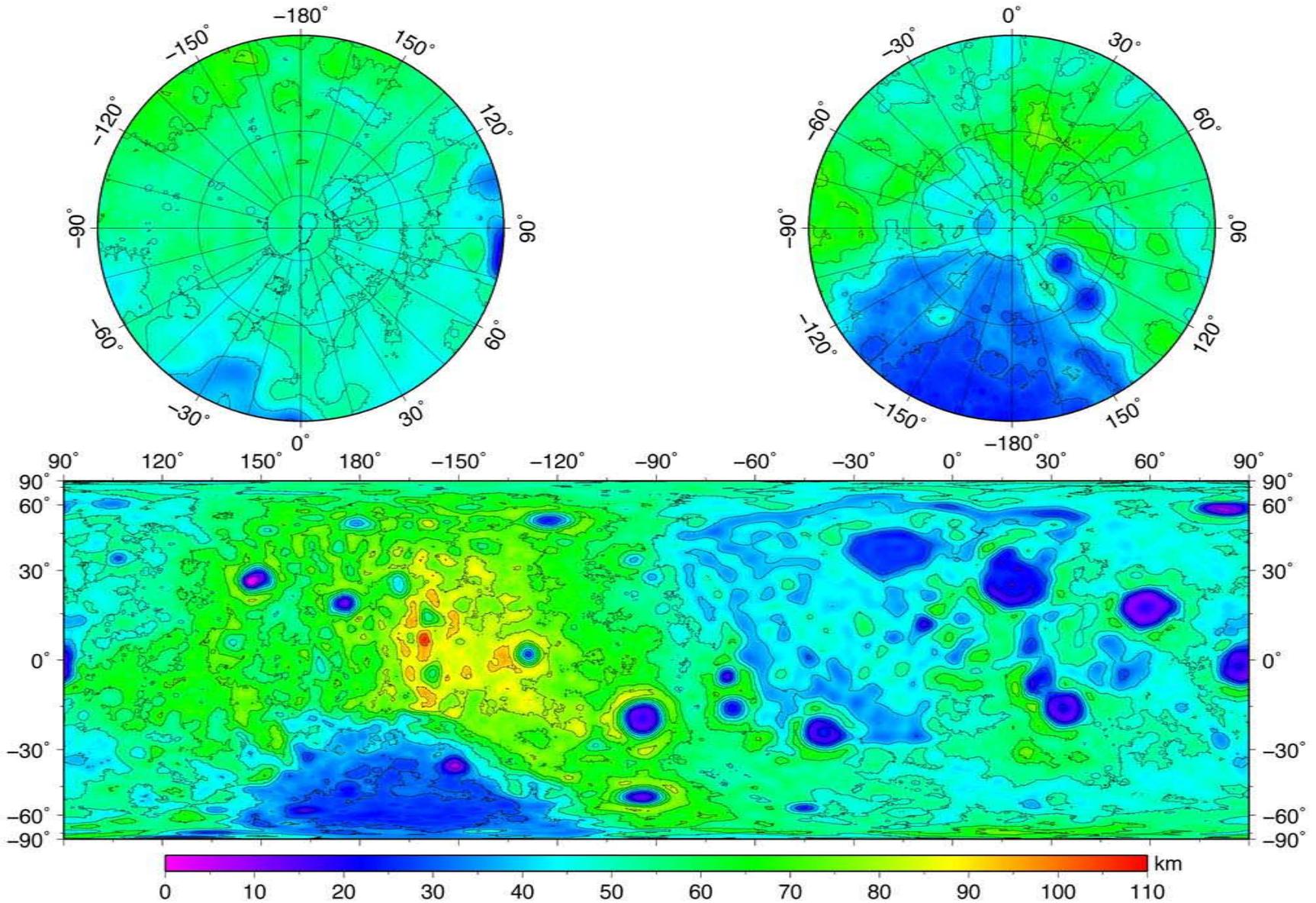


裏側は大規模衝突地形の凹凸がよく支えられている。
表側に比べると速く冷えて、硬くなっていた。

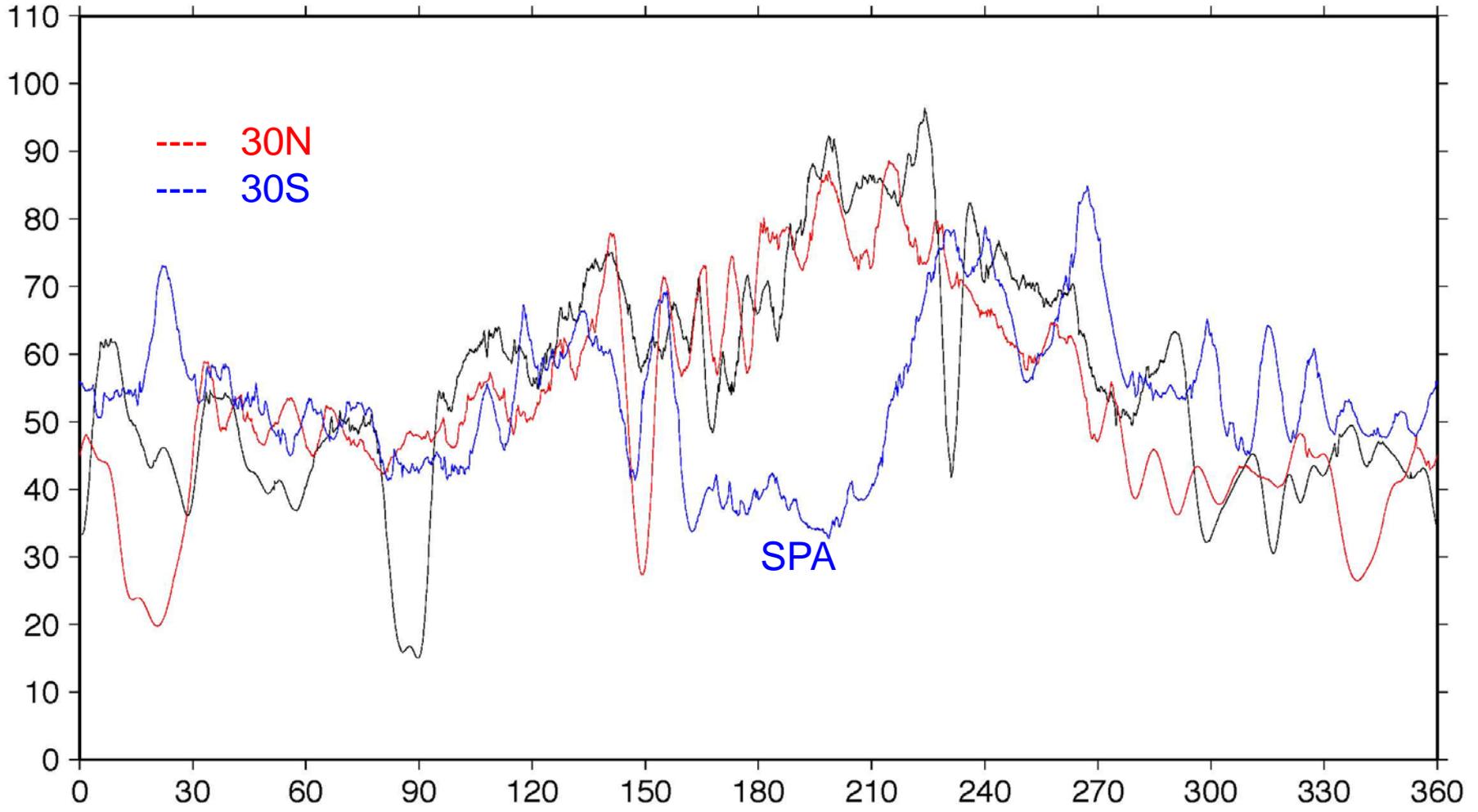
Moho Depth

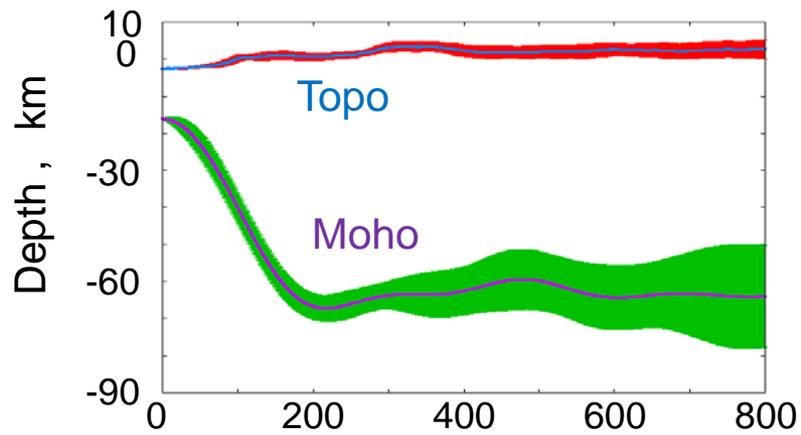
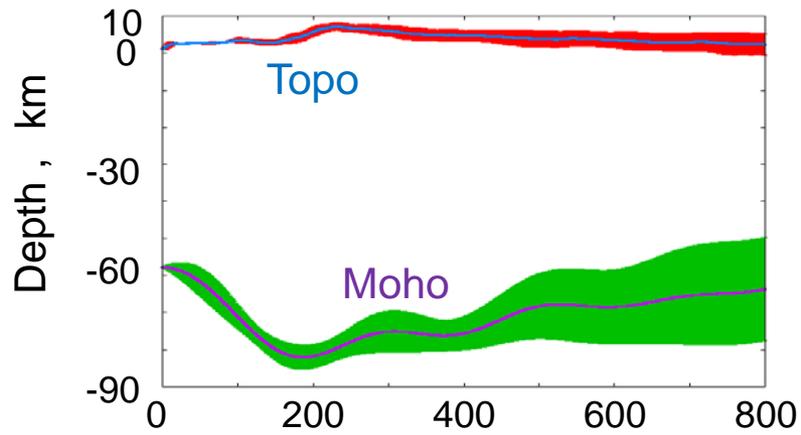
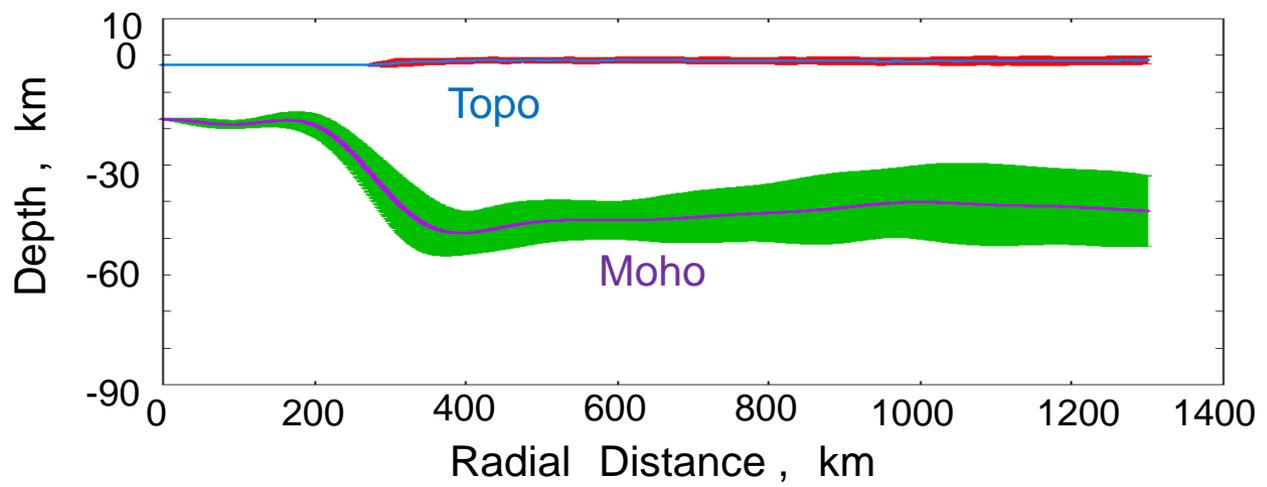


Crustal Thickness

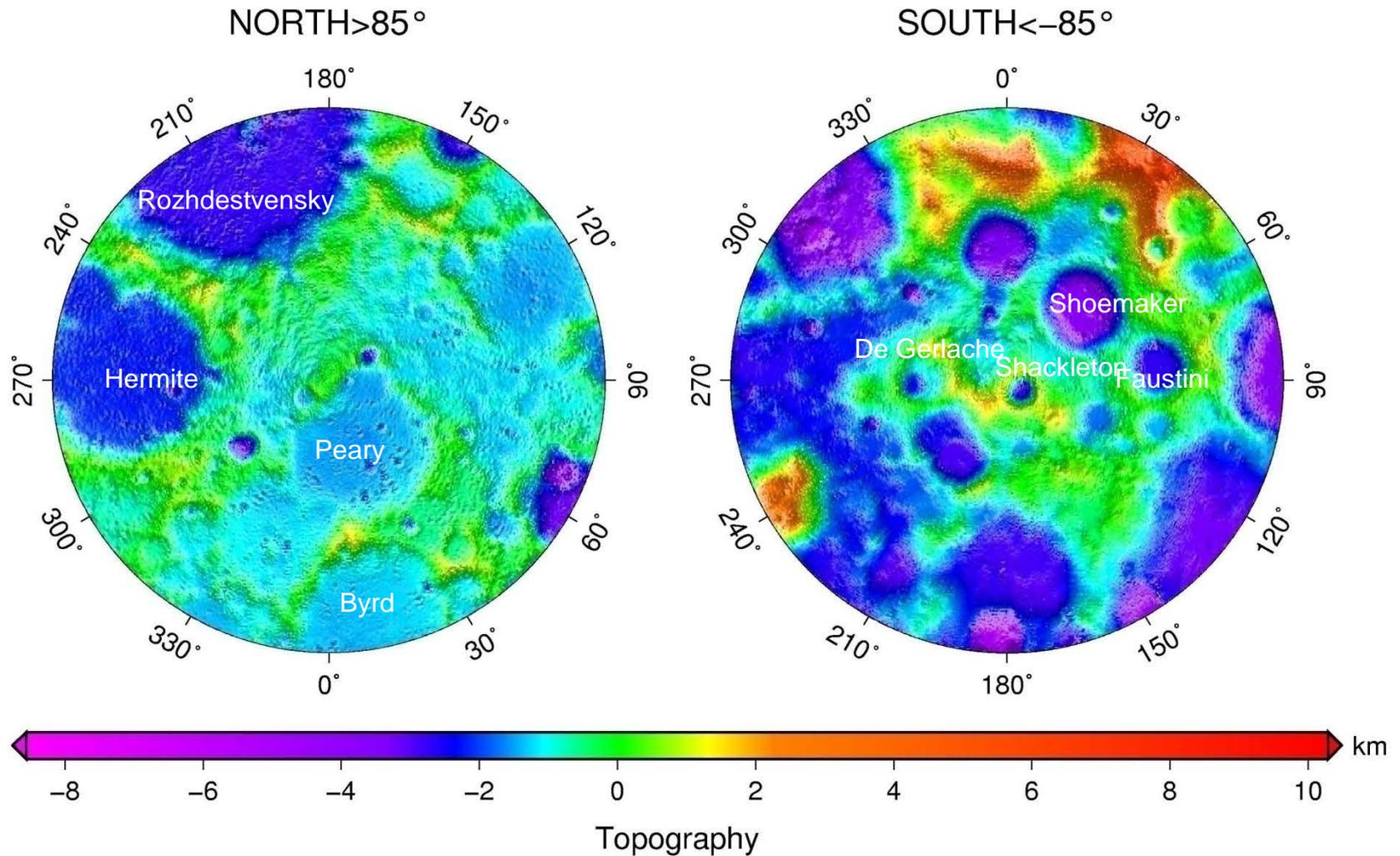


Crustal thickness variation





月の極域の地形図(北極から5度、南極から5度)



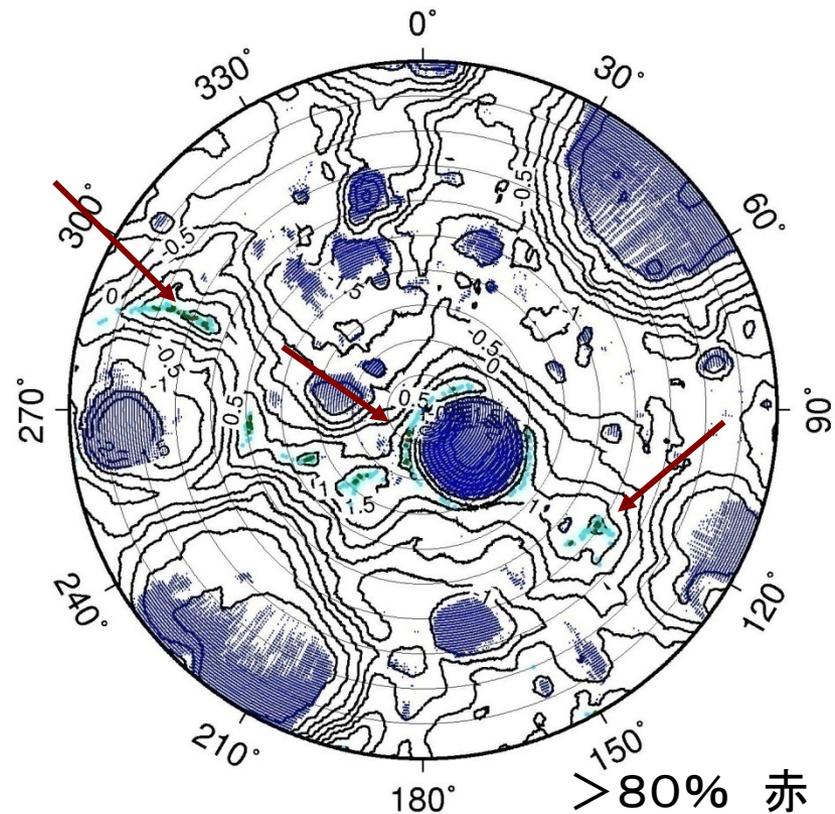
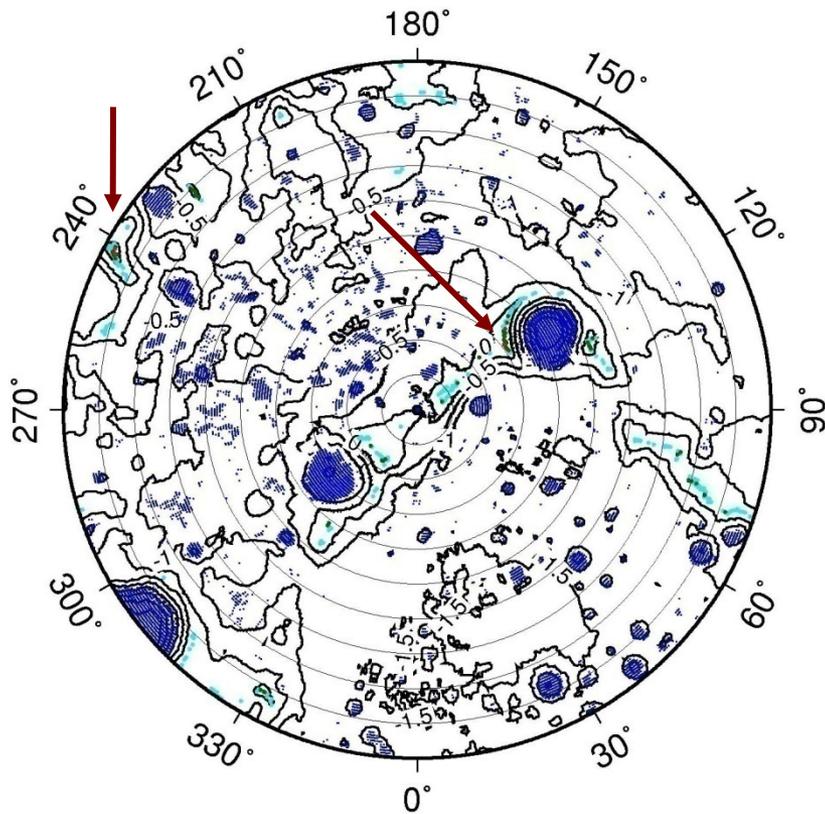
88度以北(以南)拡大図

北極

North > 88

南極

South < -88



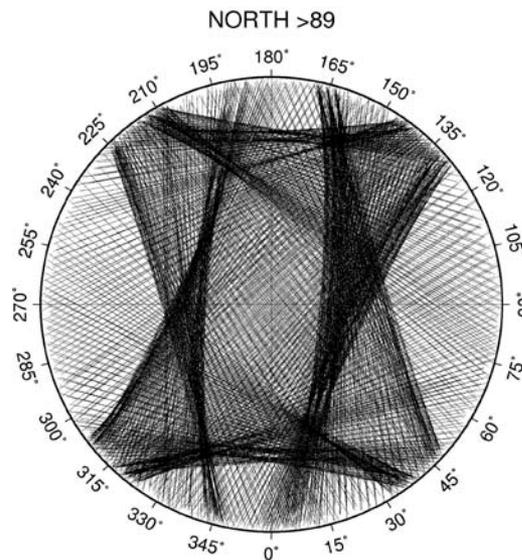
>80%	赤
70-80%	緑
60-70%	水色
0%	青

- 80%以上の領域はクレータリムの限られた部分のみに存在する(矢印)。

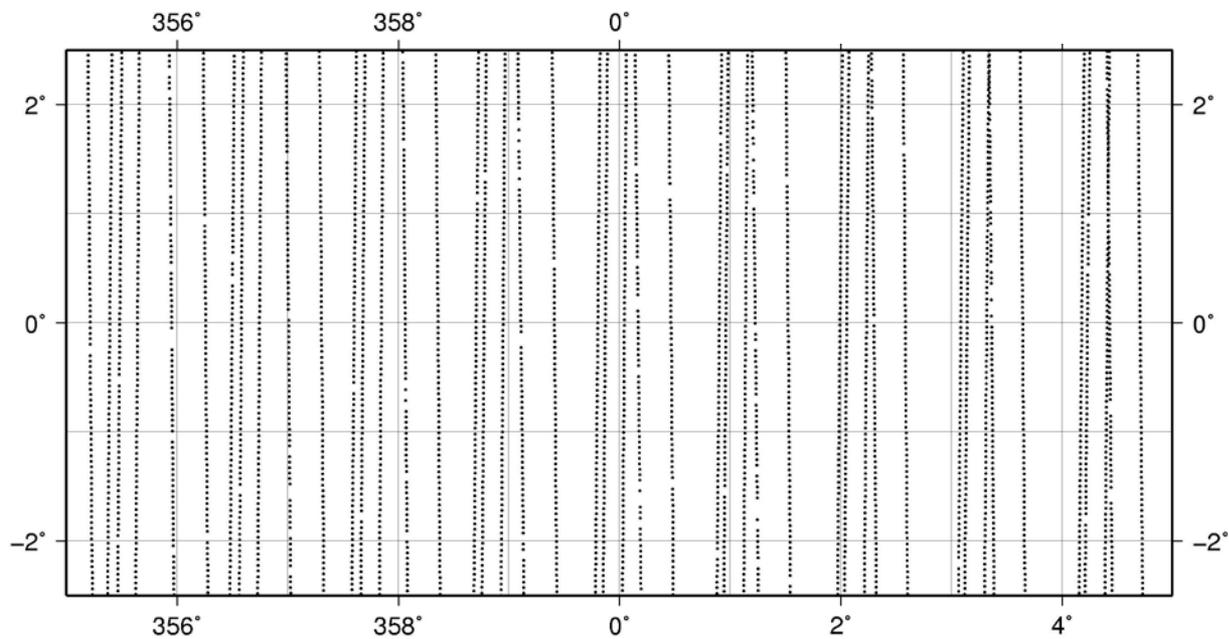
高度計の 観測点分布

Feb

North Pole (>89 deg)



Equatorial region



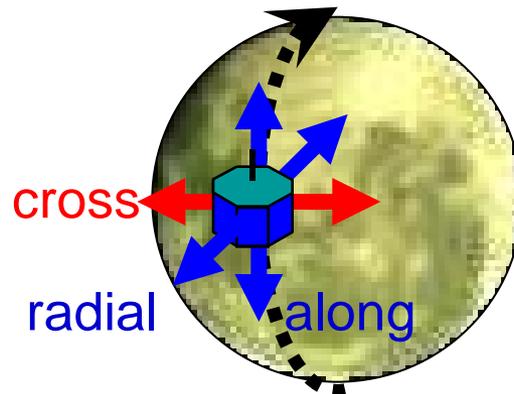
精密軌道決定に対するVLBIの寄与

Overlaps during Edge-on Geometry

おきな	R	A	C	計
DR	3.96	8.78	103.14	103.59
DRV	2.42	4.37	25.60	26.08
DRV-	2.73	5.61	13.44	14.82

おうな	R	A	C	計
DR	2.55	23.00	229.56	230.72
DRV	1.23	6.39	20.06	21.09
DRV-	1.30	5.74	8.01	9.94

(単位:メートル)



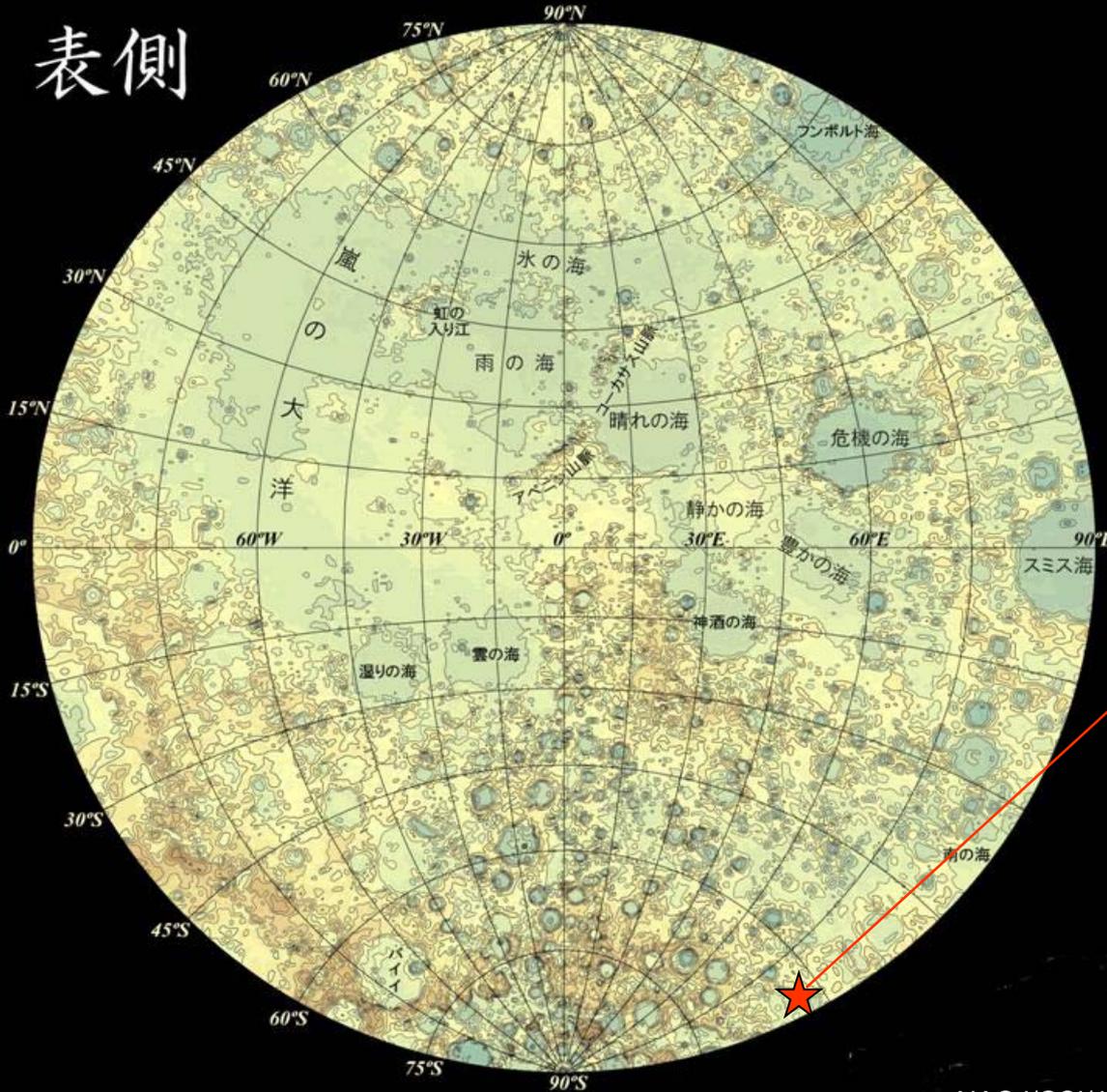
クロストラックで劇的な精度改善!

「かぐや」衛星の最後

- 「おきな」(リレー衛星)は2009年2月12日に月の裏側に落下
- 「かぐや」は低高度運用のあと、2009年6月11日午前3時30分に表側の縁に落下
- 「おうな」(VLBI衛星)は、月に落下しない

月周回衛星「かぐや(SELENE)」の 月面落下予測日時・場所について

表側



落下予測日時：
平成21年6月11日
午前3時30分頃
(日本標準時)

落下予測場所：
東経80度、南緯63度付近
(表側のGILLクレータ付近)

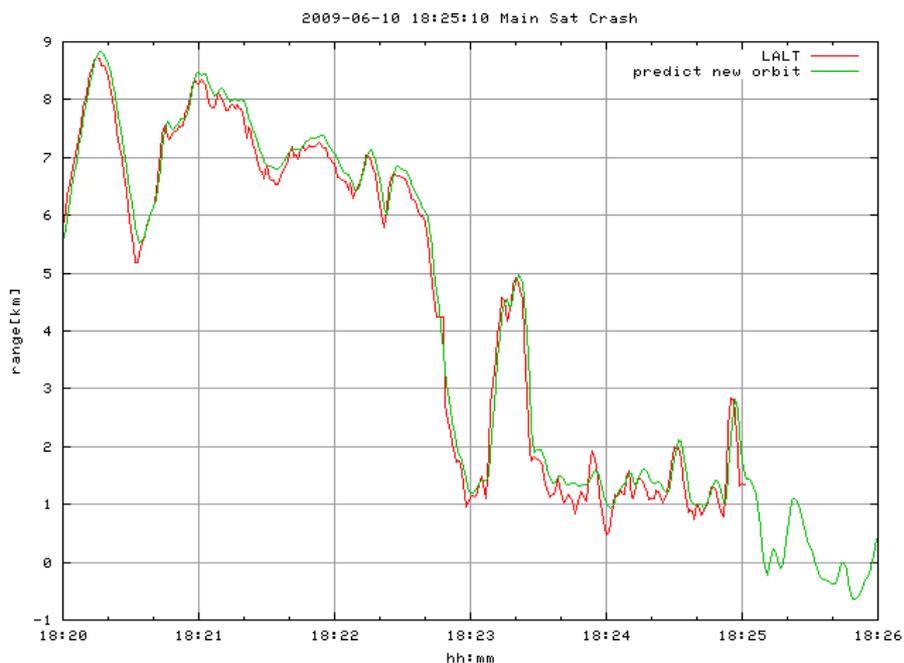
注:「かぐや」の落下予測時刻と位置
情報については、今後のさらなる軌道
解析、衛星の状況を踏まえて見直す
可能性があります。最新の情報は、
下記のプロジェクトホームページにて
お知らせしますので、適宜、ご覧くださ
い。

ホームページアドレス：
<http://www.kaguya.jaxa.jp>

高度計実測データ(赤)と
予測値(緑)「軌道高度—LALTグリッド
データ」

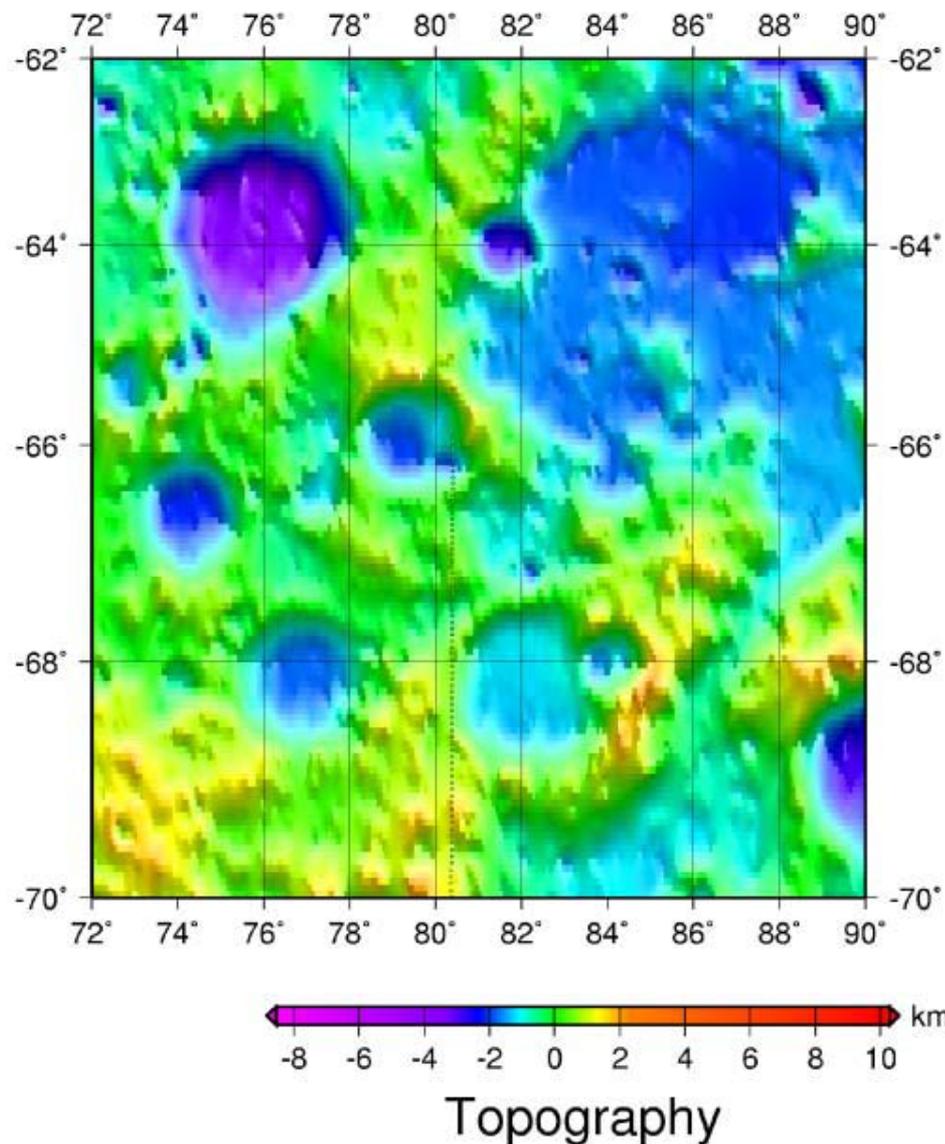
緑=0の点が予測衝突時刻UTC= 2009-
06-10T18:25:10

(Lon,lat) = (80.407 -65.460)



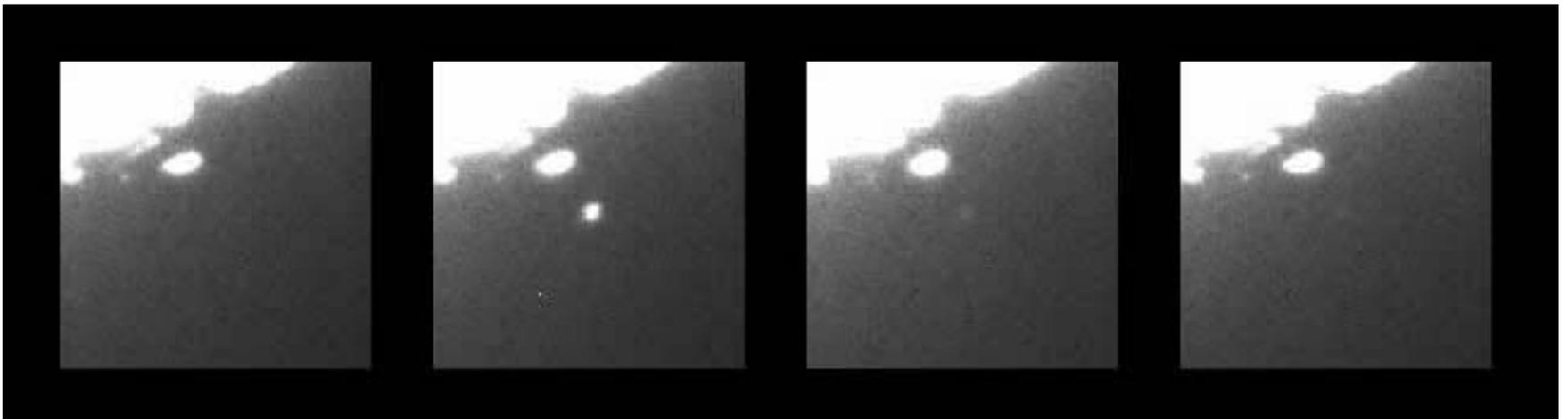
LALT最終データは
18:25:01.837

Footprint=衛星直下点として地図上にプロッ
トしたもの



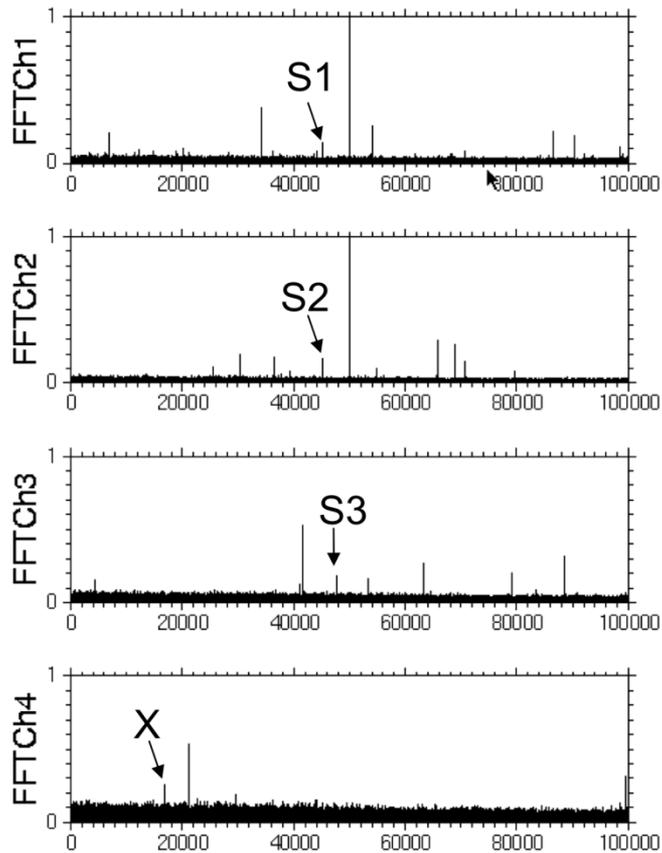
かぐや衝突の観測

- 水沢で、電波が消失するのはモニターした。
- 光学観測は、日本国内は天候が悪く、ほとんど観測できず。石垣島では晴れたが検出されず。
- オーストラリアのアングロ・オーストラリアン天文台の2.3ミクロンの観測(ヒドラジンのバンド)で、かぐやの衝突のタイミングで、閃光が観測された。



停波の確認 6/29 小笠原局

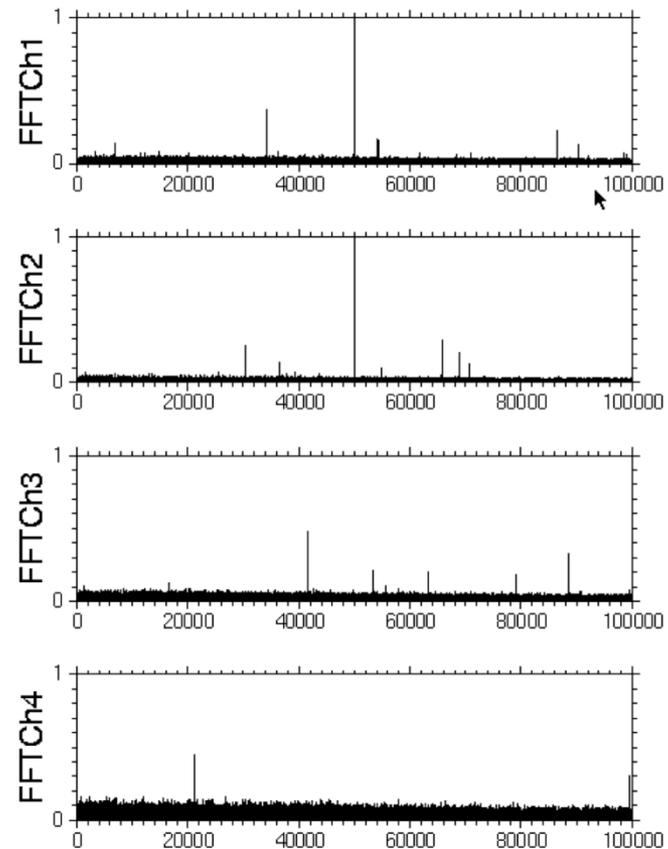
11:59:00UT



Spectrum for 10 msec of data with 1740 sec offset

/data/VERAOGSW_090629_113000.dat

12:01:00UT



Spectrum for 10 msec of data with 60 sec offset

/data/VERAOGSW_090629_120000.dat

VERA小笠原局

「かぐや」サイエンス現状

- 裏側・極域を含む月全球の重力場・地形図
- VLBI → 相関処理 → 軌道精度・重力場精度向上
 - 科研費で相関処理担当の技術支援員を雇用。
 - 同一ビーム観測データについては遅延時間推定まで完了。
 - 重力場データへの組み込みに目処が立つ。
- 論文
- Science誌2/13,重力 (Namiki et al)、地形論文(Araki et al)掲載
- VLBI精度論文(Kikuchi et al.)がRadio Science誌に掲載
- 極域日照率論文(Noda et al)がGeophys. Res. Lett.誌に掲載
- 地殻厚さ論文(Ishihara et al)がGeophys. Res. Lett.誌に受理
- 衛星アンテナ特性論文(Liu et al)がIEEE誌に受理
- 地殻組成論文(Ohtake et al.)がNature誌に9/9に出版
- 測地学会誌に特集号13本、ISTS-JSASS論文3本

Lunar Global Shape and Polar Topography Derived from Kaguya-LALT Laser Altimetry

H. Araki,^{1*} S. Tazawa,² H. Noda,³ Y. Ishihara,² S. Goossens,² S. Sasaki,² N. Kawano,² I. Kamiya,³ H. Otake,⁴ J. Oberst,⁵ C. Shum⁶

A global lunar topographic map with a spatial resolution of finer than 0.5 degree has been derived using data from the Laser Altimeter (LALT) on board the Japanese lunar explorer Selenological and Engineering Explorer (SELENE or Kaguya). In comparison with the previous Unified Lunar Control Network (ULCN 2005) model, the new map reveals unbiased lunar topography for scales finer than a few hundred kilometers. Spherical harmonic analysis of global topographic data for the Moon, Earth, Mars, and Venus suggests that isostatic compensation is the prevailing lithospheric support mechanism at large scales. However, simple rigid support is suggested to dominate for the Moon, Venus, and Mars for smaller scales, which may indicate a drier lithosphere than on Earth, especially for the Moon and Venus.

Knowledge of the lunar shape and topography is fundamental for our understanding of the internal structure and surface evolution of the Moon. However, laser topographic mapping of the Moon had been limited. Early experiments were carried out by the Apollo 15 to 17 spacecraft for limited areas below their near-equatorial orbits (1). More recently, laser altimeter on the Clementine obtained topographic data covering almost the entire South Pole–Aitken Basin (2). Its coverage did not reach beyond 80° latitude owing to the elliptic orbit of the spacecraft, and the spatial resolution is 20 to 60 km (3). A full topographic map, including the polar regions, ULCN 2005, was produced using photogrammetric analysis of Clementine images combined with data from historical control points on the Moon (4). However, the map is known to suffer from large systematic errors. Radar topography from Earth includes gaps due to limitations of viewing and illumination conditions, whose effects are especially evident in the polar regions (5, 6).

The LALT on board the Japanese lunar explorer Kaguya (SELENE) is designed to measure distances to the lunar surface from the altitude of 100 km (7). LALT measures the distance from the spacecraft to the surface of the Moon by transmitting Nd and Cr-doped yttrium-aluminum-

garnet (Cr-doped Nd:YAG) laser pulses every second. The beam divergence is 0.4 milliradian, resulting in the laser spot size on the lunar surface of typically 40 m from the orbiter altitude of 100 km. To exploit the instrument's nominal range resolution of 1 m, the range data are calibrated for thermal variations of the internal clock frequency and the instrument delay. The errors related to data quantization, thermal variation of the clock and electronics, and instrument delay measurement are estimated to be 0.55 m (1 SD) (8, 9). The first ranging tests were carried out

successfully on 25 November 2007, and the nominal mapping phase began on 30 December 2007. Topography data were produced by incorporating precise orbits for the Kaguya main orbiter. These orbits are calculated from two-way Doppler data by the GEODYN-II software using the latest lunar gravity model SGM90em (SELENE Gravity Model) that is an adapted version of the model SGM90d for the purpose of orbit determination (10–12). Orbit precision is determined from orbit differences during overlapping parts, showing that the radial orbit error is generally within 1 m (13) and the total positioning error (computed using the root sum square over the radial, along-track, and cross-track directions) is found to be ~50 m. Thus, the radial topographic error originated from the orbit repeatability is 1 m (1 SD), the instrumental error is 0.55 m (1 SD), and the instrument range shift is between +2.5 m and +12 m (8, 9), which are summarized 14.1 m (1 SD) as the final budget where the range shift is incorporated as 4 m (1 SD). In the same way, the horizontal topographic error originated from the orbit repeatability is 50 m (1 SD), the pointing error is 175 m (maximum), and the timing error is 1.5 m (maximum), which are summarized as 277 m (1 SD) as the final budget (14). Attitude and time-tag data are provided from the tracking and operation center of the Japan Aerospace Exploration Agency (JAXA). The number of geolocated points over the entire lunar surface is about 677×10^6 as of 31 March 2008 (15).

Figure 1 shows the topographic map obtained from LALT data. It clearly delineates the prom-

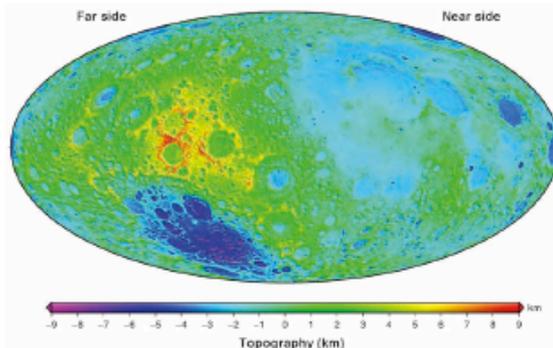


Fig. 1. Lunar global topographic map obtained from LALT altimetry data shown in Hammer equal-area projection. Lunar coordinates are based on the mean Earth/polar axis system. Reference of the height is a sphere whose radius is 1737.4 km and whose origin is set to the center of mass (19). The map center is 270°E, with the nearside on the right and the far side on the left. Full range of the topography is about 19.81 km. The highest point is on the southern rim of the Deiringer-Jackson basin (–158.64°E, 5.44°N, +10.75 km), and the lowest point is inside Antoniadi crater (–172.58°E, 70.43°S, –9.06 km) in the South Pole–Aitken Basin.

Farside Gravity Field of the Moon from Four-Way Doppler Measurements of SELENE (Kaguya)

Noriyuki Namiki,^{1*} Takahiro Iwata,² Koji Matsumoto,³ Hideo Hanada,³ Hirotoyo Noda,³ Sander Goossens,² Mina Ogawa,⁴ Nobuyuki Kawano,³ Kazuyoshi Asari,⁵ Sei-itsu Tsuruta,⁶ Yoshiaki Ishihara,⁷ Qinghui Liu,⁸ Fuyuhiko Kikuchi,⁹ Toshiaki Ishikawa,⁹ Sho Sasaki,² Chiaki Aoshima,² Kosuke Kurosawa,² Seiji Sugita,⁴ Tadashi Takano⁷

The farside gravity field of the Moon is improved from the tracking data of the Selenological and Engineering Explorer (SELENE) via a relay subsatellite. The new gravity field model reveals that the farside has negative anomaly rings unlike positive anomalies on the nearside. Several basins have large central gravity highs, likely due to super-isostatic, dynamic uplift of the mantle. Other basins with highs are associated with mare fill, implying basalt eruption facilitated by developed faults. Basin topography and mantle uplift on the farside are supported by a rigid lithosphere, whereas basins on the nearside deformed substantially with enaction. Variable styles of compensation on the near- and farsides suggest that reheating and weakening of the lithosphere on the nearside was more extensive than previously considered.

In the beginning of the space age, Apollo missions and their precursors discovered that the topography and crustal thickness of the Moon differed on the near and farsides (1). Post-Apollo global mapping missions such as Clementine, Lunar Prospector (LP) and Small Mis-

sions for Advanced Research in Technology-1 (SMART-1) further revealed that the near and farsides also differ in their chemical composition (2–4), which might be a consequence of asymmetric crystallization of a primordial magma ocean (5). Here, we present gravity data of the farside from SELENE (Kaguya) (6), which helps resolve the origin of this dichotomy.

The gravity field is a fundamental physical quantity for the study of the internal structure and the evolution of planetary bodies. The Moon was the first target of planetary gravimetry. In 1966, the Luna 10 mission began the study of the gravity field from observed orbital motion of the spacecraft. It was followed by Lunar Orbiter missions (LO) from LO to V and Apollo 15 and 16 subsatellites (A15/16ss) and more recently Clementine and LP. Muller and Sjogren (7) discovered large positive gravity anomalies called “mascons” within maria basins on the nearside. The elliptic orbit of the Clementine spacecraft improved the lower degrees and sectoral terms of the gravity field (8). The low circular, polar orbit of LP increased the spatial resolution of the nearside gravity field (9), and we will use the degree and order 100 model (LP100K) (9) for comparison with our model.

The most important problem of the previous lunar gravity models is the lack of direct observa-

(2–4), which might be a consequence of asymmetric crystallization of a primordial magma ocean (5). Here, we present gravity data of the farside from SELENE (Kaguya) (6), which helps resolve the origin of this dichotomy.

The gravity field is a fundamental physical quantity for the study of the internal structure and the evolution of planetary bodies. The Moon was the first target of planetary gravimetry. In 1966, the Luna 10 mission began the study of the gravity field from observed orbital motion of the spacecraft. It was followed by Lunar Orbiter missions (LO) from LO to V and Apollo 15 and 16 subsatellites (A15/16ss) and more recently Clementine and LP. Muller and Sjogren (7) discovered large positive gravity anomalies called “mascons” within maria basins on the nearside. The elliptic orbit of the Clementine spacecraft improved the lower degrees and sectoral terms of the gravity field (8). The low circular, polar orbit of LP increased the spatial resolution of the nearside gravity field (9), and we will use the degree and order 100 model (LP100K) (9) for comparison with our model.

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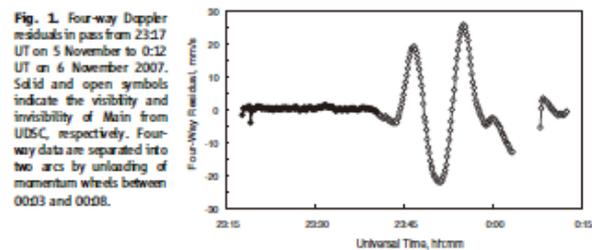


Fig. 2. Four-way Doppler residuals in ppm from 23:17 UT on 5 November to 0:12 UT on 6 November 2007. Solid and open symbols indicate the visibility and invisibility of Main from UES, respectively. Four-way data are separated into two arcs by unloading of momentum wheels between 00:03 and 00:08.

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