Lunar Navigation
Japan's Experience and the Future

SpaceOps 2010 Conference

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Lunar Probes Launched by Japan

- Jan 1990 Mu Space Engineering Spacecraft - A (MUSES-A)

  Learning of technologies concerning precise determination and control of satellite orbit, highly-efficient data transmission, etc

- (cancelled) LUNAR-A

  Japan's first lunar mission to observe moonquakes and heat flow by inserting penetrators into two locations on the lunar surface, etc

- Sep 2007 SELenological and ENgineering Explorer (SELENE)

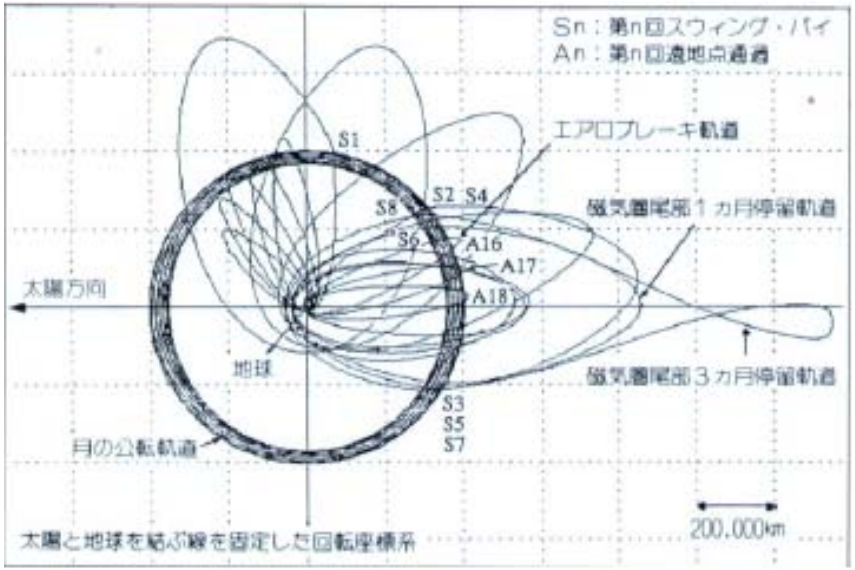
  obtain scientific data on lunar origins and evolution, develop the technology for future lunar exploration

Mu Space Engineering Spacecraft - A (MUSES-A) HITEN/HAGOROMO Mission Summary

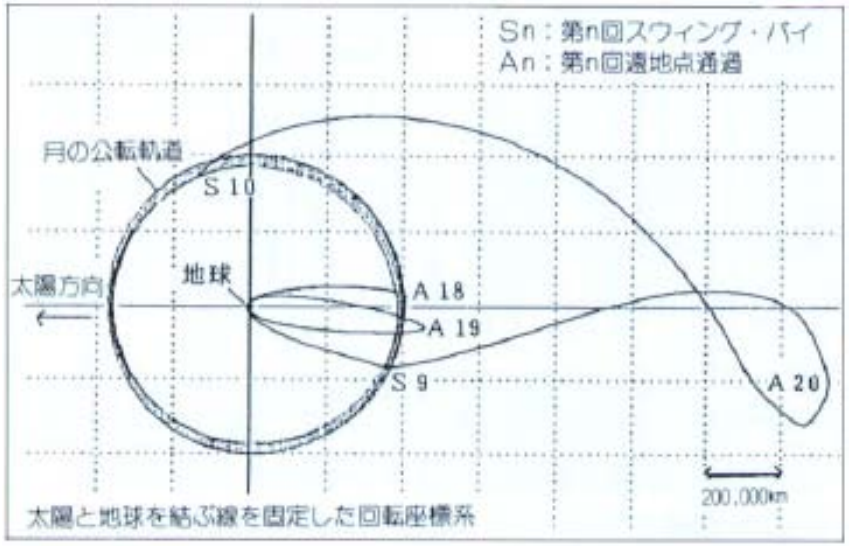
- ✓ MUSES-A was launched on January 24, 1990 and named 'HITEN'.
- ✓ Successfully conducted 10 lunar swing-by experiments and two aero-brake experiments at an altitude of 120km in the earth atmosphere.
- ✓ Had a grandchild satellite and released it during a moon approach at about a distance of 16,500km on Mar 19, 1990. The satellite was injected into lunar orbit and named 'HAGOROMO'.
- ✓ Marked its highest apogee altitude of maximum 1,530,000 km.
- ✓ In February 1992, HITEN entered lunar orbit.
- ✓ After completing its mission, HITEN hit the Furnerius Crater of the Moon on April 11, 1993.
- ✓ Usuda(USDC) and Uchinoura(USC) were tracking stations with NASA DSN early phase and contingency support.

MUSES-A Spacecraft and orbital operations

MUSES-A
Weight: 197kg Diameter: 1.4m Height: 0.79m
Spin stabilized



Lunar swing-bys and earth atmospheric aerobrakings



Maximum height of apogee: 1,530,000km

LUNAR-A

LUNAR-A was the first Japanese lunar exploration mission planned to be launched in 2004. Its mission plan was to explore the internal structure of the Moon by two penetrators to observe moonquakes and heat flow. The project was cancelled due to development problems in early 2007. The same navigation strategies were planned as executed in MUSES-A mission

Weight: 540kg
Size: 1.2mx1.2mx1.3m SA span: 3.8m
Penetrator: 80cm(L)x16cm(D)

Penetrator descending and penetration

SELENE(KAGUYA/OKINA/OUNA) Mission Summary

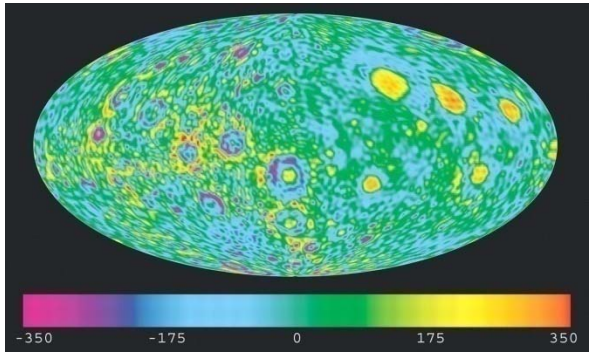
- ✓ SELENE's mission objectives are to obtain scientific data on lunar origins and evolution, and to develop the technology for future lunar exploration. The scientific data will be also used for exploring the possibility of future utilization of the Moon.
- ✓ SELENE consists of a main orbiting satellite(KAGUYA) and two small satellites (Relay Satellite(OKINA) and VRAD Satellite(OUNA)). The orbiters carry instruments for scientific investigation of the Moon.
- ✓ SELENE was launched on September 14, 2007 at Tanegashima Space Center and injected in lunar polar orbit. OKINA and OUNA were separated during the orbital height adjustment and KAGUYA was finally injected in 100km altitude orbit.
- ✓ KAGUYA completed its mission and intentionally impacted the moon on June 10, 2009.

SELENE(KAGUYA/OKINA/OUNA) Mission Summary(2)

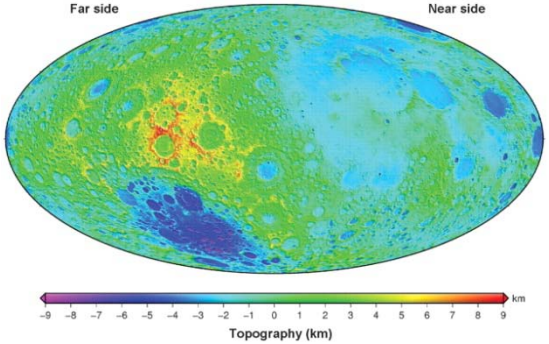
Main Orbitor:
Weight: 3 tons
Size: 2.1m x 2.1m x 4.8m
Attitude Control: Three-axis stabilized
Power: 3.5 kW (Max.)

Small Satellites: (RSAT & VRAD)
Weight: 50 kg
Size: 1.0 x 1.0 x 0.65 m
Attitude Control: Spin-stabilized
Power: 70 W

Major initial achievements



Free-air gravity anomaly map derived from 4-way Doppler data



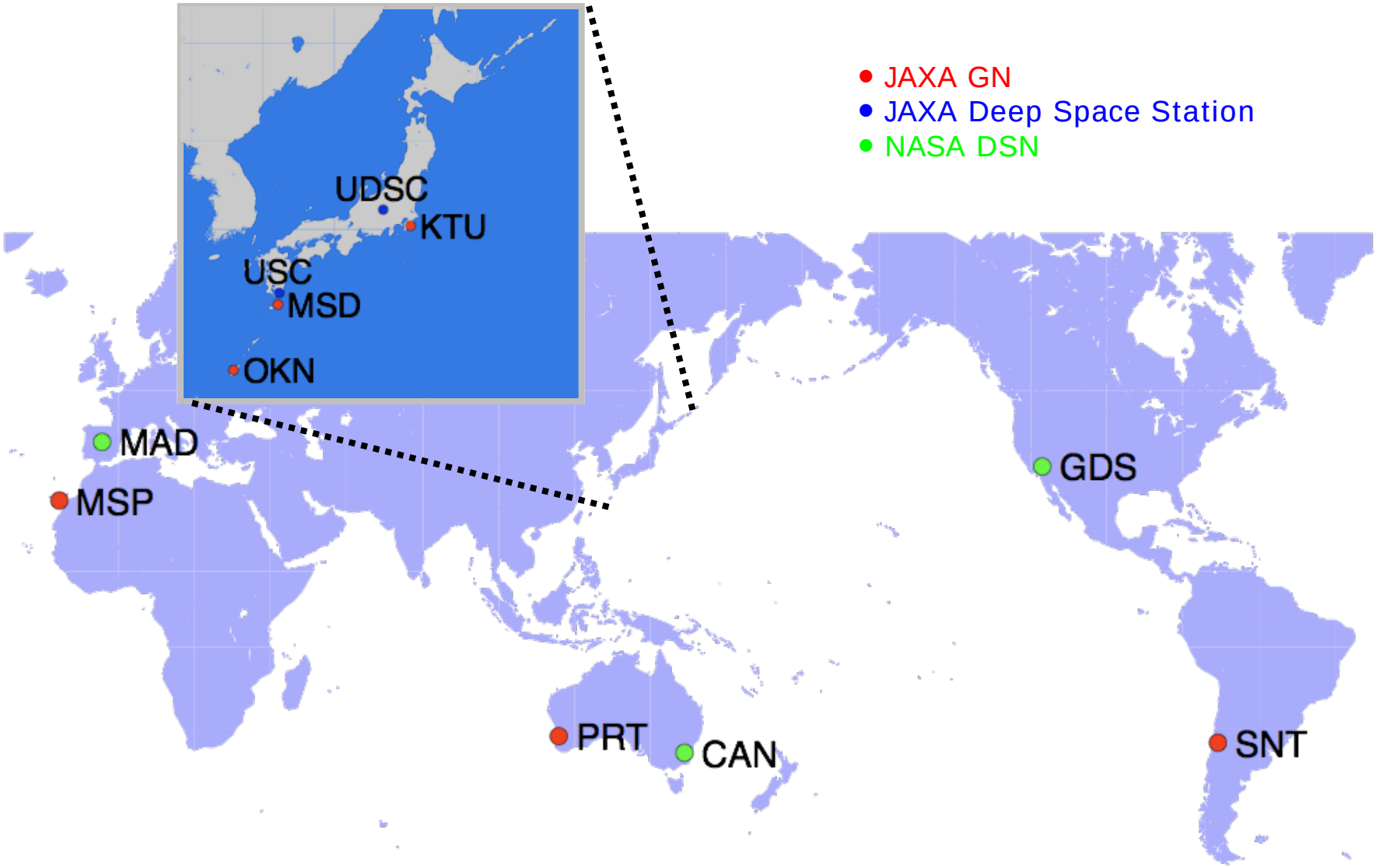
Lunar Global Shape and Polar Topography by LALT

Earth Rise Shot by HDTV

SELENE Mission Instruments

	Observation	Instrument and Characteristics
Main Orbiter	Chemical elements distribution	**X-ray Spectrometer** (Al, Si, Mg, Fe distribution, spatial resolution 20 [km]) **Gamma-ray Spectrometer** (U, Th, K distribution, resolution 160 [km])
	Mineralogical distribution	**Spectral Profiler** (Continuous spectral profile λ= 0.5 to 2.6 [μm], spatial resolution 500 [m]) **Multi-band Imager** (UV-VIS-IR imager, λ= 0.4 to 1.6 [μm], 9 bands, spatial resolution 20 [m])
	Surface structure	**Terrain Camera** (High resolution stereo camera, spatial resolution 10 [m]) **Lunar Radar Sounder** (apparent depth 5 [km], resolution 100 [m]) **Laser Altimeter** (height resolution 5 [m], spatial resolution 1600 [m])
	Surface & Space environment	**Lunar Magnetometer** (Magnetic field measurement, accuracy 0.5 [nT]) **Plasma Imager** (Observation of plasmasphere of the earth, XUV to VIS) **Charged Particle Spectrometer** (Measurement of high-energy particles) **Plasma Analyzer** (Charged particle energy and composition measurement)
	Imaging	**High Definition Television camera** (Images of the earth and the lunar surface, for public outreach)
VRAD satellite	Gravitational field distribution	**VLBI Radio-source** on the VRAD satellite (lunar gravitational field) (VRAD = VLBI RADio source)
	Environment	**Radio Science** (Detection of the tenuous lunar ionosphere)
Relay satellite	Gravitational field distribution	**VLBI Radio-source** on the Relay satellite (lunar gravitational field) **Relay Sat. transponder** (Far-side gravity field using 4-way range rate from ground station to Orbiter via Relay Satellite)

SELENE Tracking Stations



SELENE Navigation Operation Summary (Nominal and extended phases)

1. Up to lunar orbit injection, NASA DSN supported SELENE operation.

2. Orbit Determination after lunar orbit injection

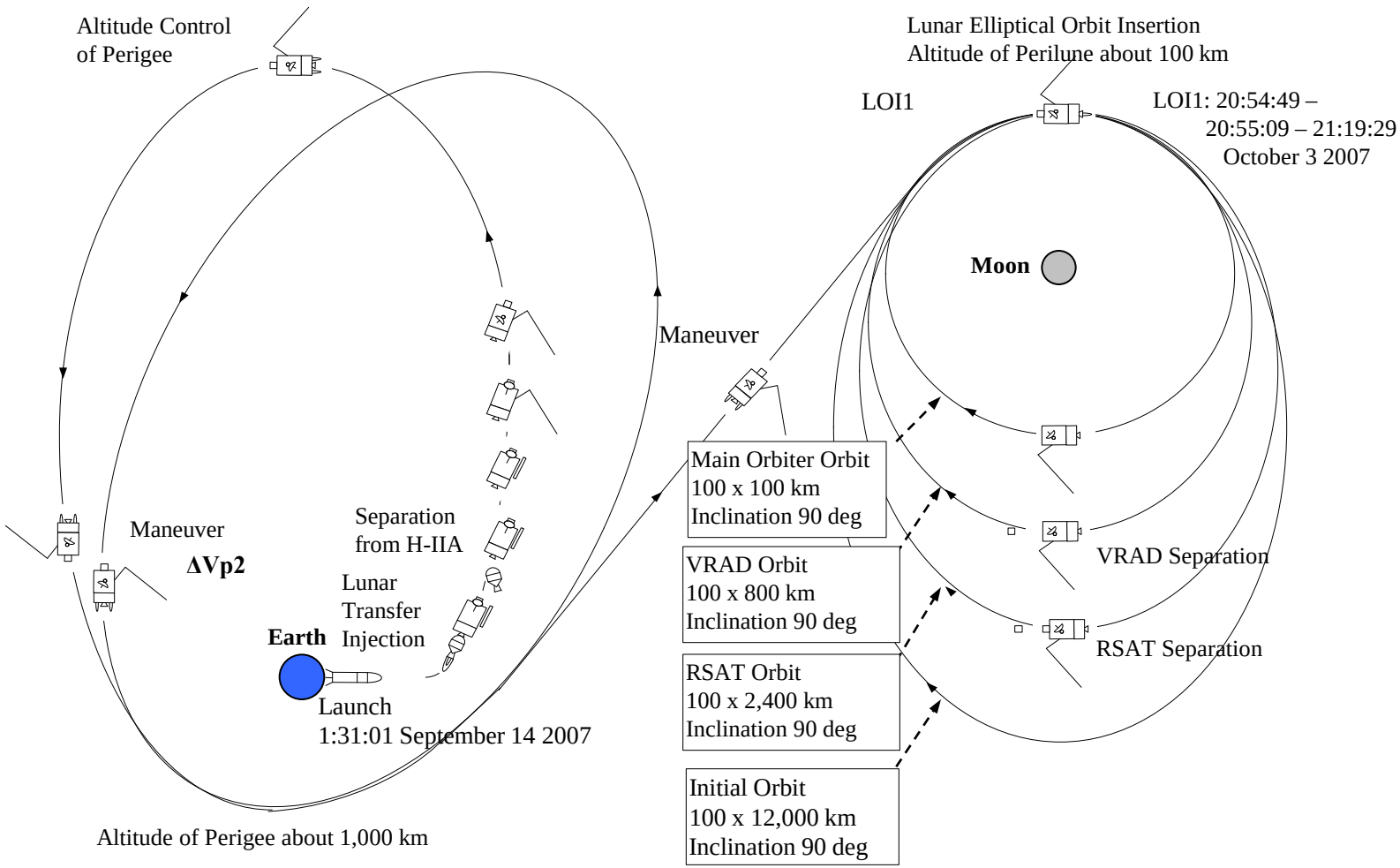
Spacecraft	Measurements	Data Arc	Ground Station	Note
KAGUYA	2-way S-band range, Doppler	12 hours (4RW mode) 6 hours (3RW mode) 6-12 hours (THR mode)	Φ10m (GN) Φ32m (USC) Φ64m (UDSC)	Gravity Model: LP100J Ephemeris: JPL DE421, DE405 OD: twice a week for Kaguya once a week for Okina, Ouna *4-way Doppler measurements are used for the gravity analysis
OKINA (RSAT)	2-way S-band range, Doppler	~ 7 days	Φ64m (UDSC)	
OUNA (VRAD)	2-way S-band range, Doppler	~ 7 days	Φ64m (UDSC)	

3. To keep the altitude at 100±30km, keeping maneuvers were conducted about every 2 months.

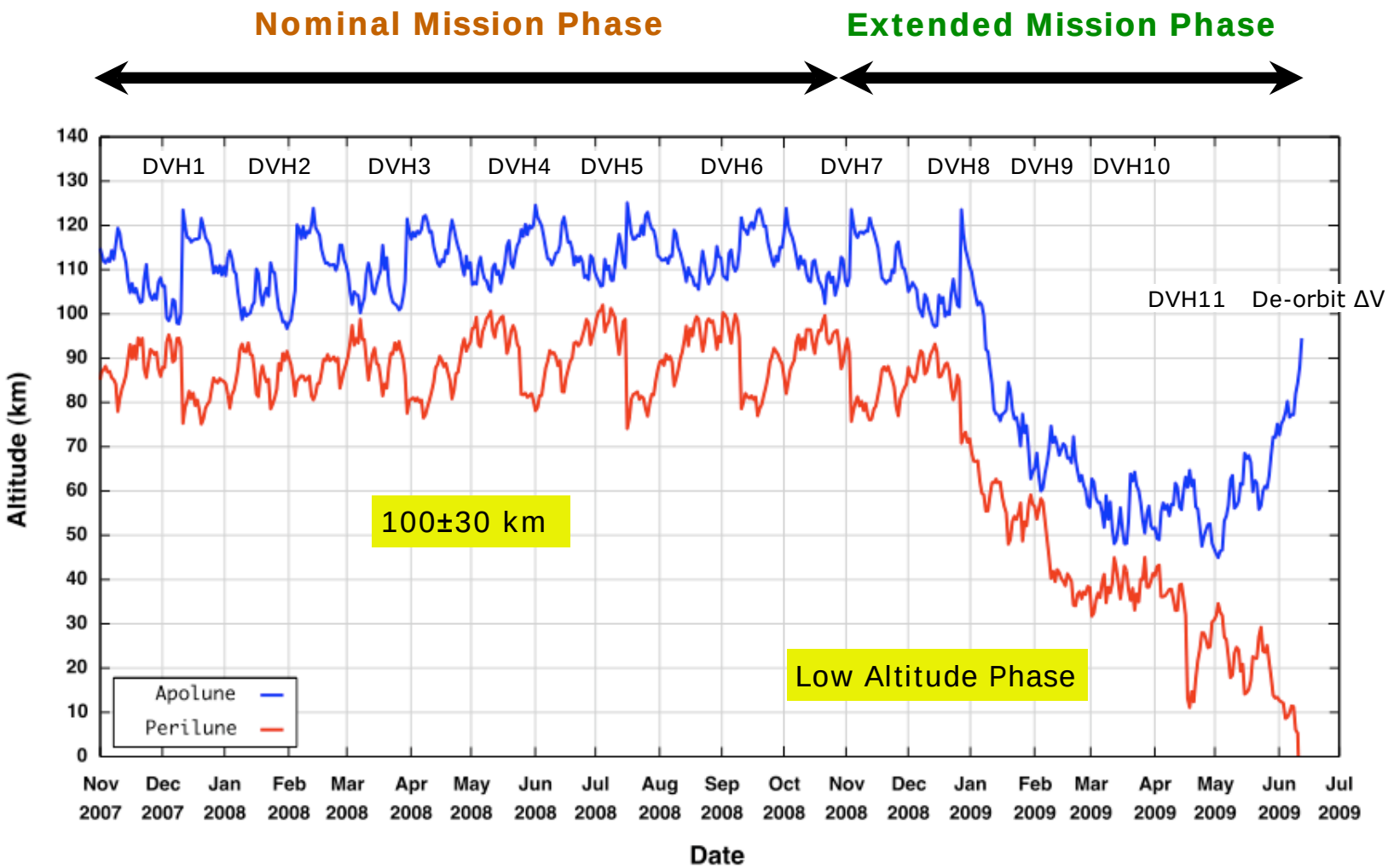
4. Tsukuba OD team also estimated the lunar gravity field using 4-way Doppler data successfully.

5. At the end of the extended mission, Kaguya made a controlled impact with the lunar surface. The impact point, altitude, and time were investigated with considering the detailed topography data.

SELENE Lunar Orbit Injection



KAGUYA Orbit Altitude History



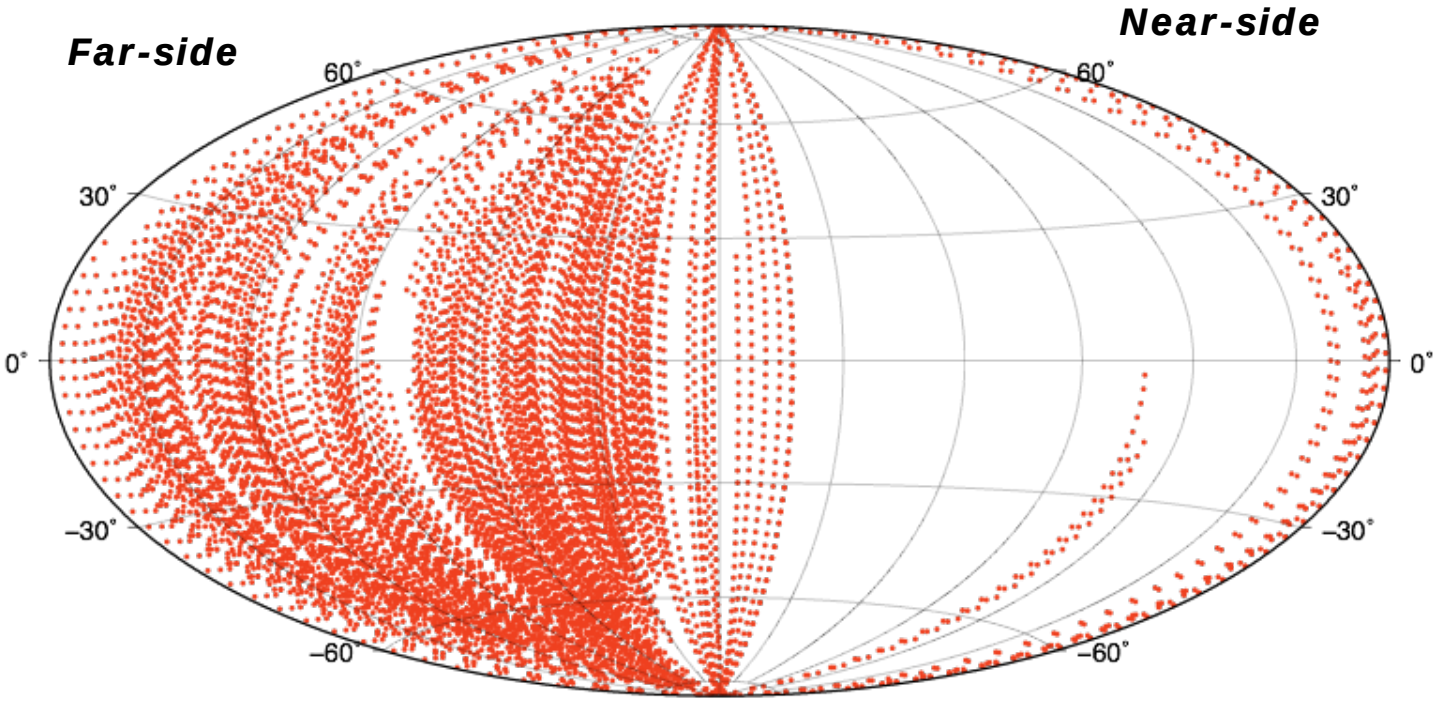
Lunar Gravity Estimation

- 2 groups worked on the estimation of the lunar gravity

- ***SELENE Gravity Model (SGM)*** --- Science Team
  - SELENE + Historical Tracking Data (Namiki et al., *Science* 2009)
  - SELENE + Historical Tracking Data + VLBI Data (Matsumoto et al.)
  - National Astronomical Observatory of Japan (NAOJ)
  - GEODYN II + SOLVE

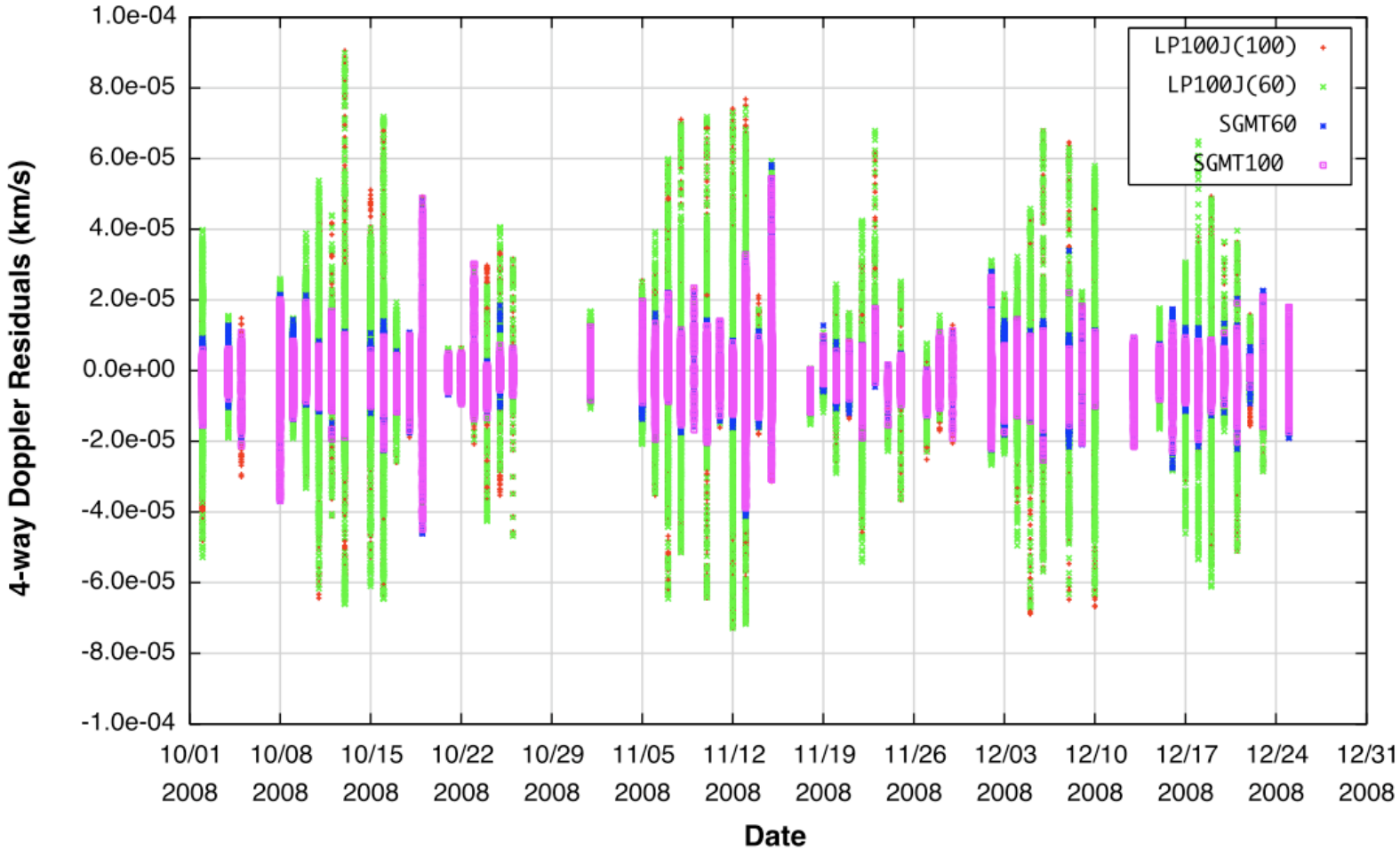
- ***SELENE Gravity Model -Tsukuba (SGMT)*** --- Tsukuba OD Team
  - SELENE Tracking Data
  - JAXA's gravity estimation software (newly-developed software)

Selenographical Coverage of Tracking Data (4-way Doppler)



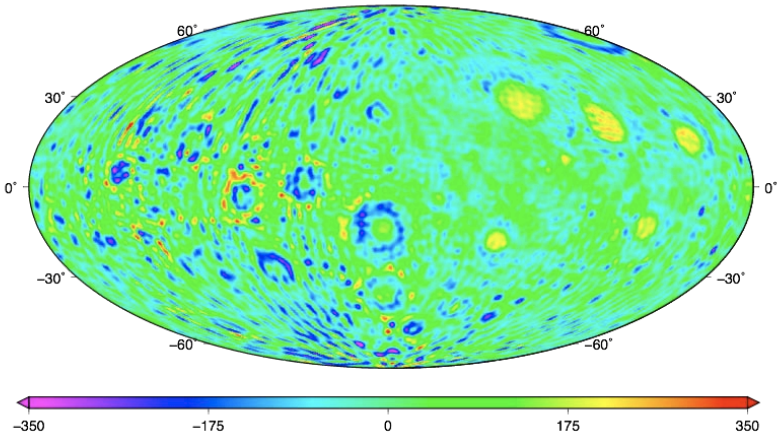
The sparse regions still exist at the northern hemisphere of the far-side.

Residuals of 4-way Doppler Measurements

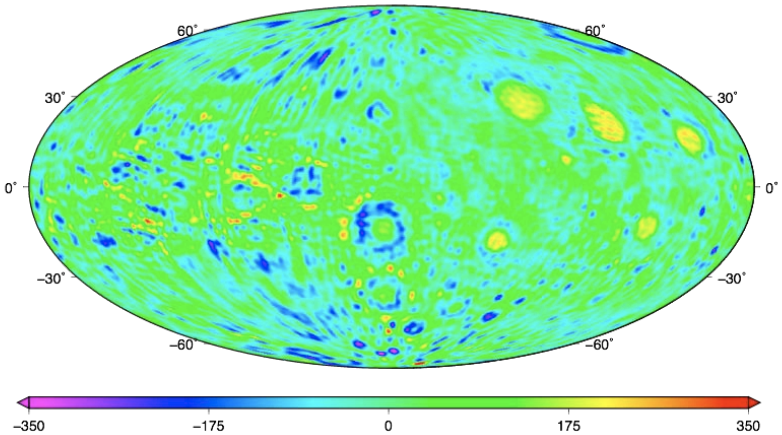


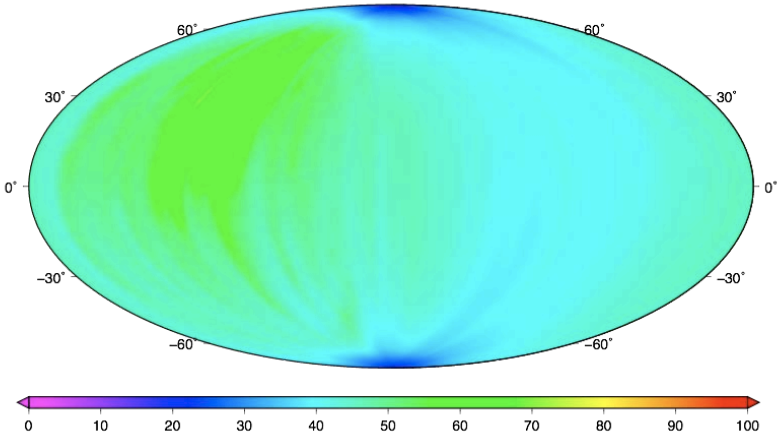
Free-air Gravity Anomaly Map / SGMT100

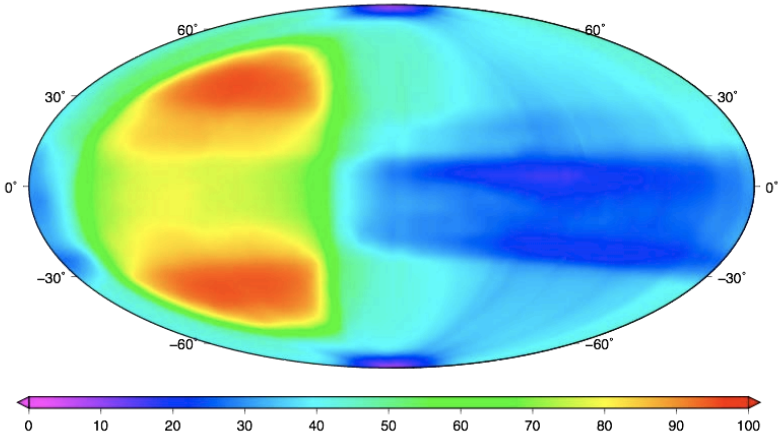
SGMT100



LP100J







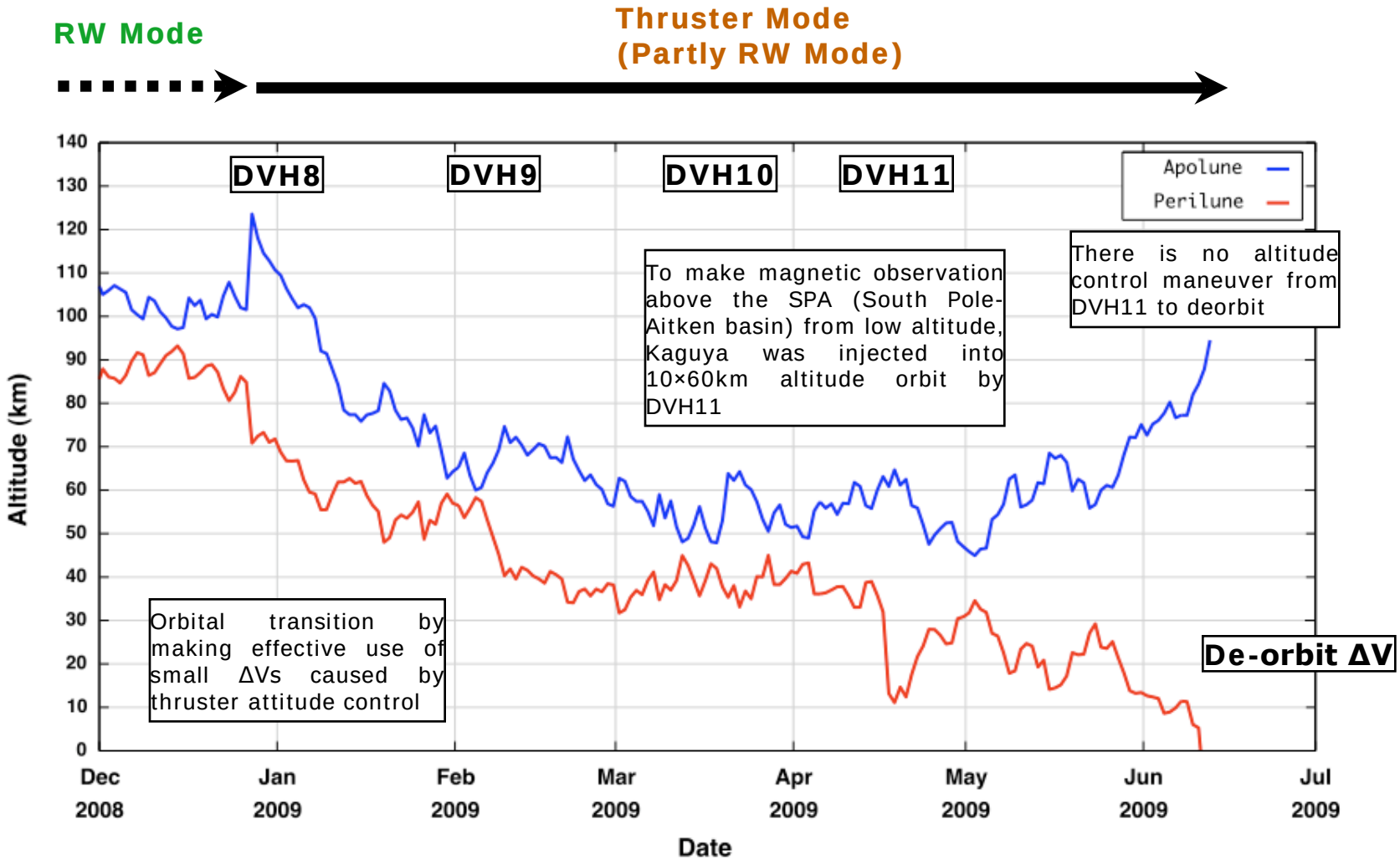
It is clear that the pattern of the gravity anomaly of located at the lunar far-side get better as compared with the LP100J

New Gravity Model

Tsukuba OD Team Statement

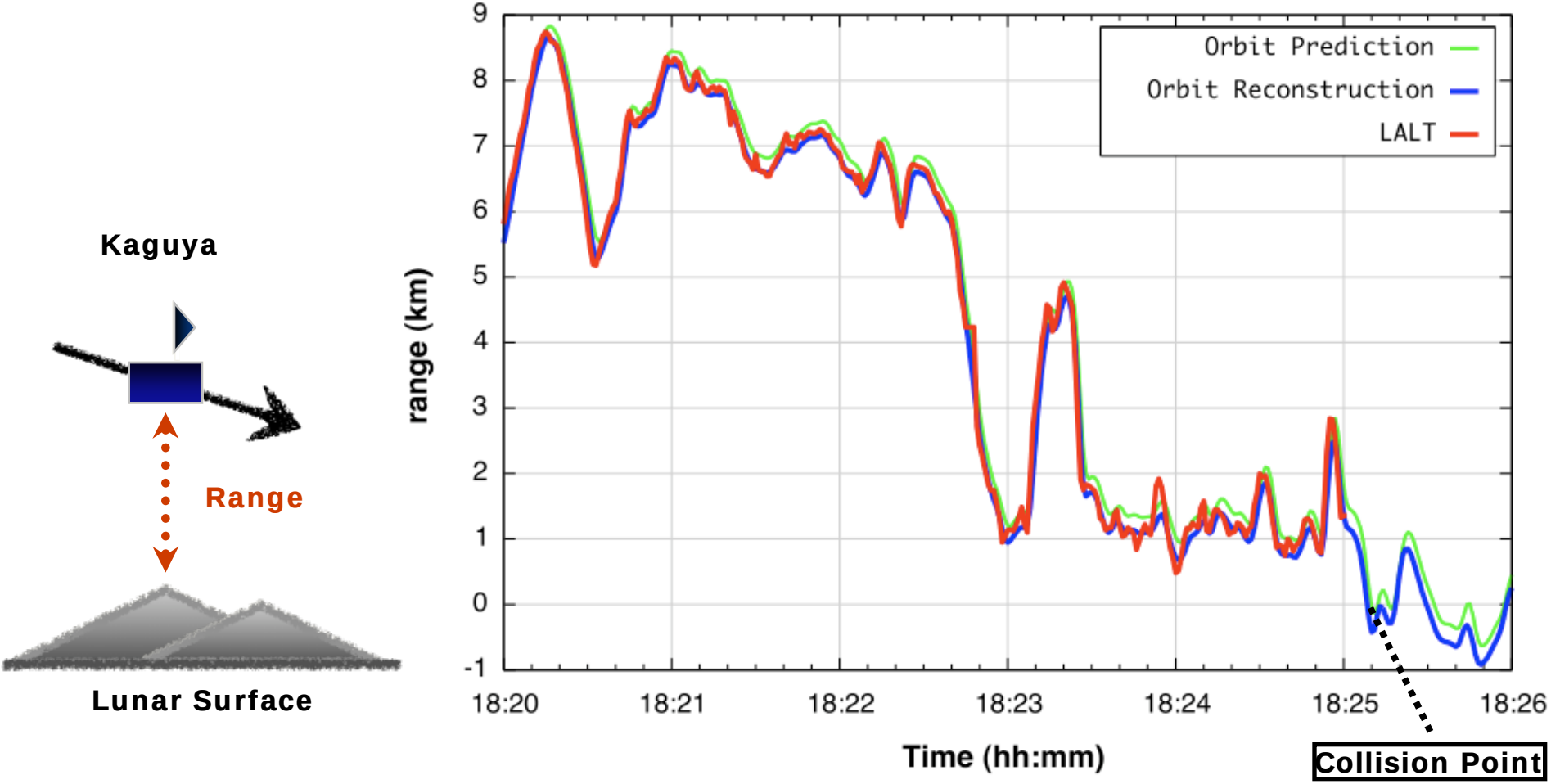
- ✓ It is clear that the residuals of 4-way Doppler measurements get smaller when we use the SGMT.
- ✓ At this time, the SGMT60 is better than LP100 (up to a degree and order 60 truncated model), but we cannot say for sure that SGMT100 is better than LP100 (100th degree and order) according to the results of the orbit determination and prediction analysis.
- ✓ In order to improve the orbit determination and prediction accuracy, we are going to modify the spacecraft dynamics model and to investigate the arc length and weight.
- ✓ Although, the residuals of the 4-way Doppler measurements get smaller, from the point of view of the orbit determination and prediction accuracy, it has significant scope to continue to improve.

Extended Mission and Controlled Impact Operation

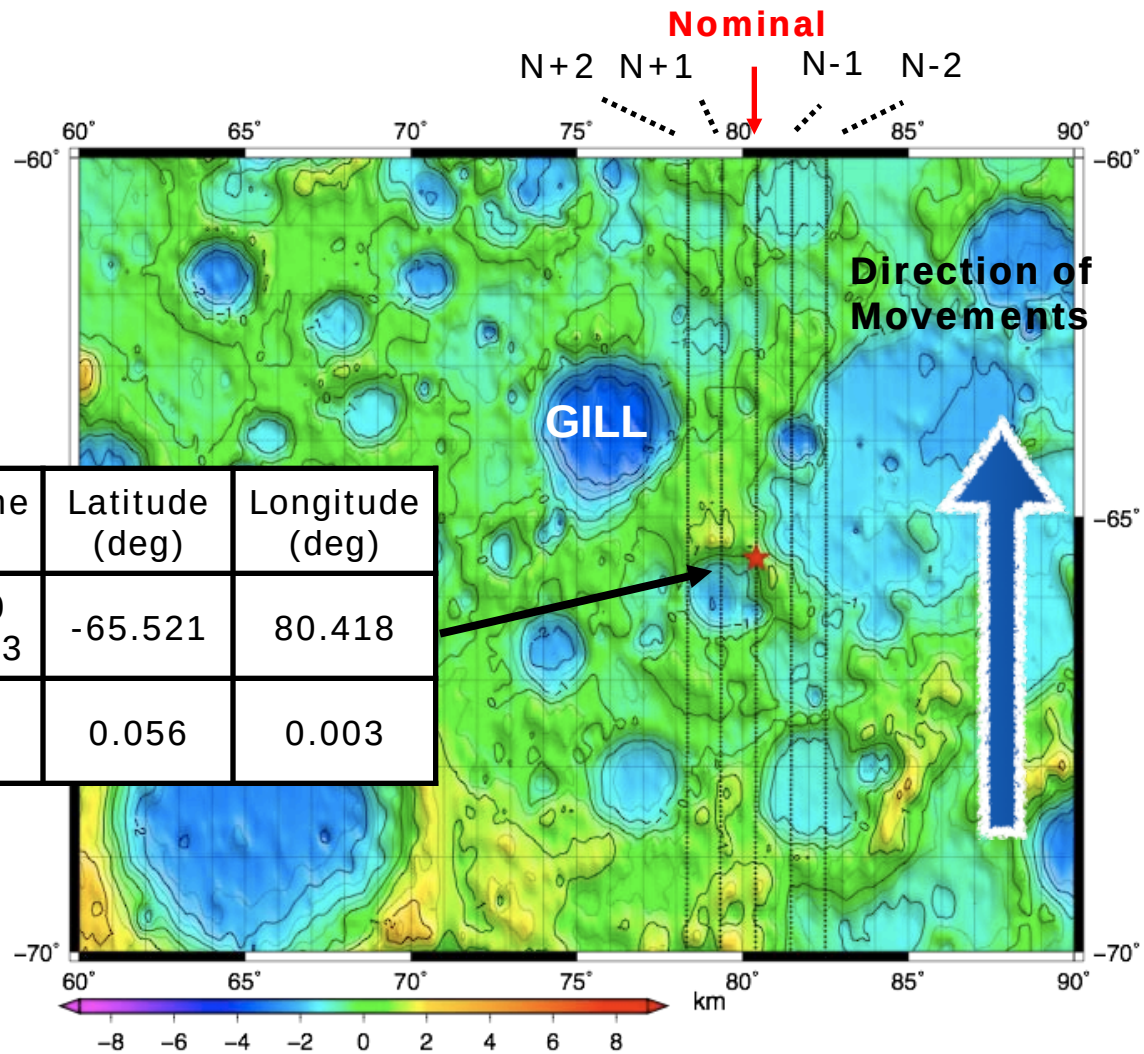


KAGUYA Controlled Impact

Prediction & Observed Result



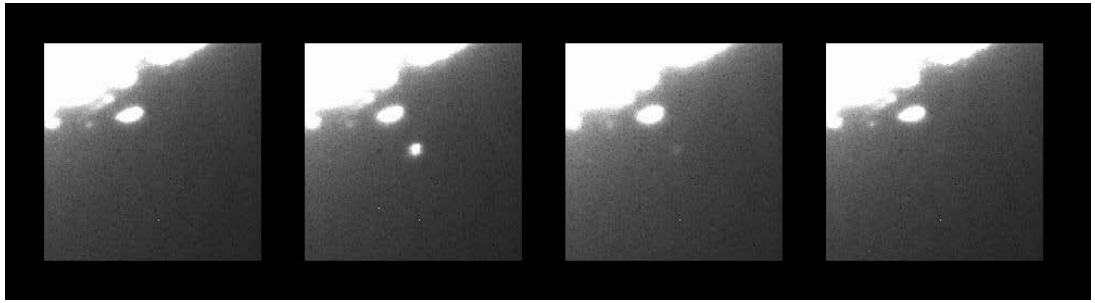
KAGUYA Impact Orbit and Impact Point



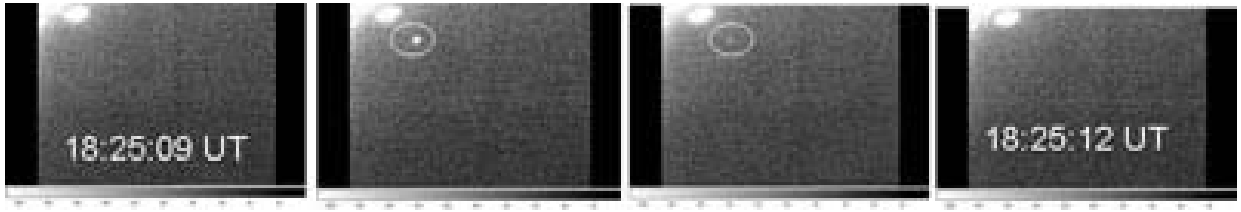
	Collision Time (UTC)	Latitude (deg)	Longitude (deg)
Nominal	2009/06/10 18:25:08.363	-65.521	80.418
error (3 sigma)	00:01.211	0.056	0.003

KAGUYA Lunar Impact observed

- Anglo-Australian Telescope (AAT), Australia



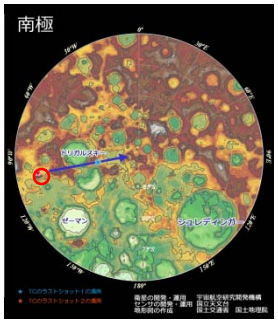
- Mount Abu Observatory, India



- TC last shot 3-D movie:

  12 minutes before the impact

  Height approximately 25km



Lunar Navigation: the Future

- In the short term, operating and planned lunar exploration missions seem to be operated in a traditional way: Spacecraft does not have a self navigation system, but is fully supported by ground navigation systems.
- In the circumstance of lunar exploration growth, the International Space Exploration Coordination Group(ISECG) was established in 2007 and studies on the architecture began.
- NASA has been intensively studying it's lunar communication and navigation architecture. Lunar Network(LN) which consists of 2 Lunar Relay Satellites(LRS) and 2 Lunar Communications Terminals(LCT) is proposed. Each LN element has a precise 'synchronized' clock and GPS-like navigation is realized.