# Lunar, Martian, and Jovian Geodesy and Science Mission using VLBI and Astrometrical Technology

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# Mission flow for JAXA's Candidate Lunar and Martian explorers

2005 2010 2015 2020 2025

**SELENE** series for Moon

**SELENE (KAGUYA)**
three orbiters

**SELENE-2**
lander, rover, and orbiter

preparing AO

**MELOS** series for Mars

under discussing

**MELOS-1/2**
aircraft and/or network landers, and orbiters


**Launch years, configurations, and mission names are tentative except SELENE/KAGUYA.**

## Selenodetic, Areodetic & Radio Astronomical Mission Candidate

| | | | |
|---|---|---|---|
| selenodetic observations | | SELENE-# | PI |
| VLBI | d-VLBI : Differential VLBI | 2 | Kikuchi |
| | i-VLBI : Inverse VLBI | 2/3 | |
| LLR | Lunar Laser Ranging | 2 | Noda |
| ILOM | In situ Lunar Orientation Measurement | 3 | Hanada |
| areodetic observations | | MELOS-# | PI |
| FWD | Four Way Doppler | 1/2 | Harada & Iwata (tentative) |
| VLBI | i-VLBI : Inverse VLBI | | |
| radio astronomical observations | | SELENE-# | PI |
| LLFAST | Lunar Low Frequency Astronomical Telescope | 2 | Iwata |

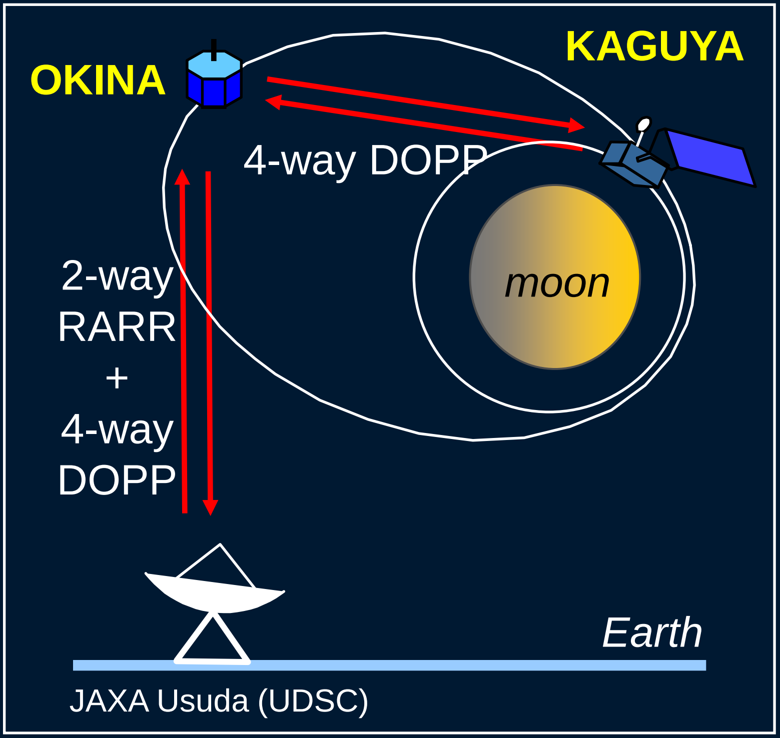
# Purpose of Selenodetic Observations

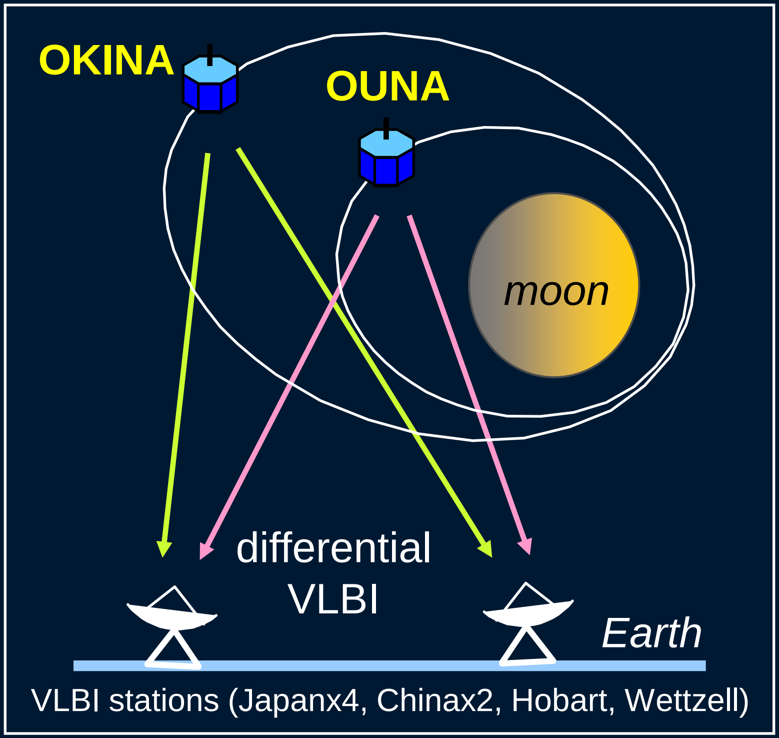
| selenodetic observations | | purpose |
|---|---|---|
| VLBI | d-VLBI : Differential VLBI<br>i-VLBI : Inverse VLBI | Gravity improvement |
| LLR | Lunar Laser Ranging | Libration (Lunar rotation variability) |
| ILOM | In situ Lunar Orientation Measurement | |

Questionnaires for the left mystery of the Moon

- Is there a core in the Moon ?
- Is the core metallic ?
- Is the metallic core liquid ?
- Is there an inner core center of the liquid core ?

# Former 4-way Doppler measurement & Differential VLBI by KAGUYA




Direct orbital determination for KAGUYA Orbiter above the far side using OKINA

V

Lunar gravity map above the **far side**

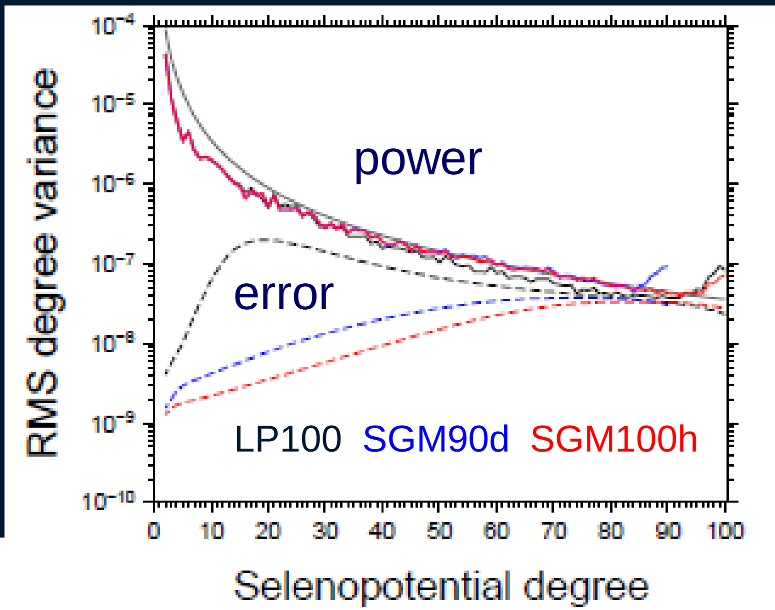
Multi-frequency, phase-delay differential VLBI observation for OKINA/OUNA

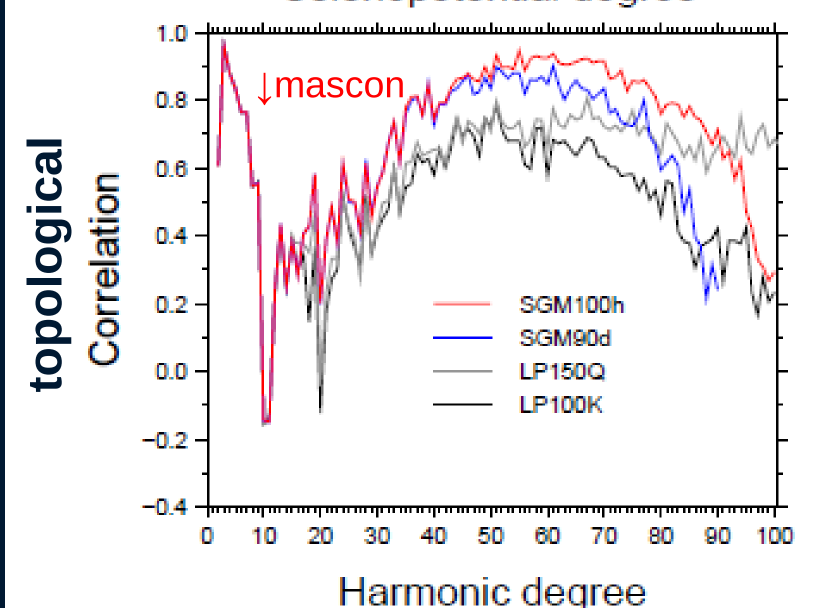
V

**Precise positioning** with the accuracy of ~20cm *cf*. RARR ; ~100m

*ex*. Matsumoto *et al*., this GM.

# Scientific goal for SELENE and post-SELENE




## degree of gravity *vs*. structure

SELENE (KAGUYA)

higher : local surface / inner structure

mechanism of isostasy

mascon (anomaly mass concentration)

dichotomy of inner structure

physical parameters of the core

lower : global structure

post SELENE

Matsumoto, *et al*. (2010)

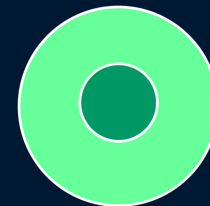
# Physical parameters of core obtained from MOI

former LLR
**0.394±0.002**
V
Radio Navigation; RARR（LP75G）
**0.3932±0.0002**
V
*ex*. Fe-core assumption
radius；320+50/-100km
(Konopliv *et al*., 1998)
V
improved by KAGUYA-VRAD
**0.393444±0.000096**
> accuracy of core density；20%
(Goossens *et al*., 2009)

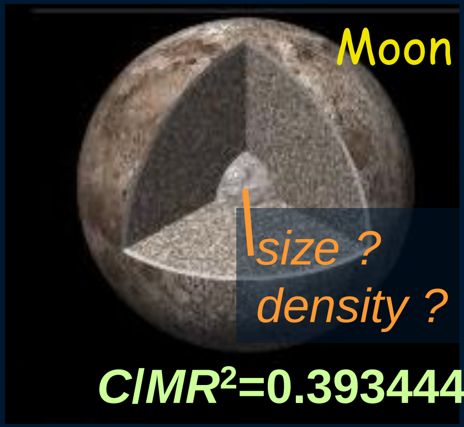
**V**
**improving the reliability by using radio sources settled on the lunar surface.**

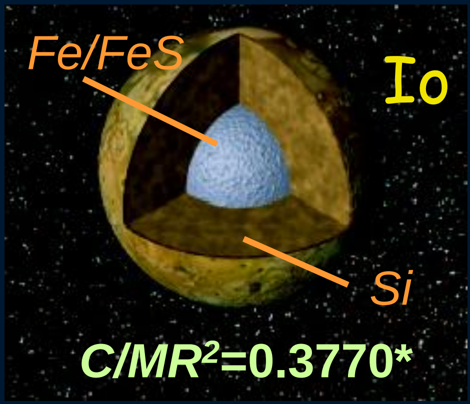
**MOI: Momentum of inertia**

***C / MR²* = ?**



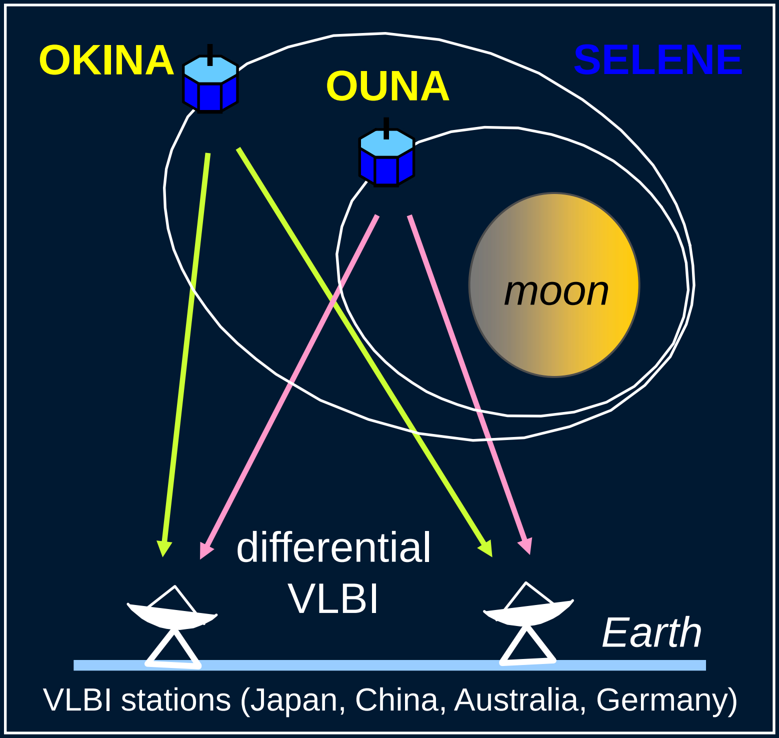
**<2/5 = core**

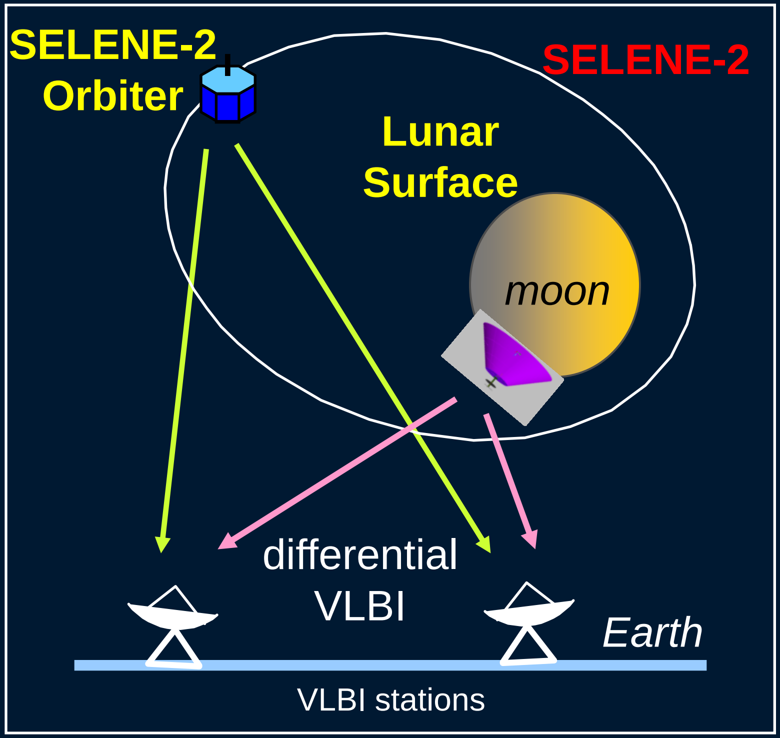



*) Heki (2004), Sasaki (1997), and references there in

# d-VLBI : Orbiter-Lander Differential VLBI by SELENE-2



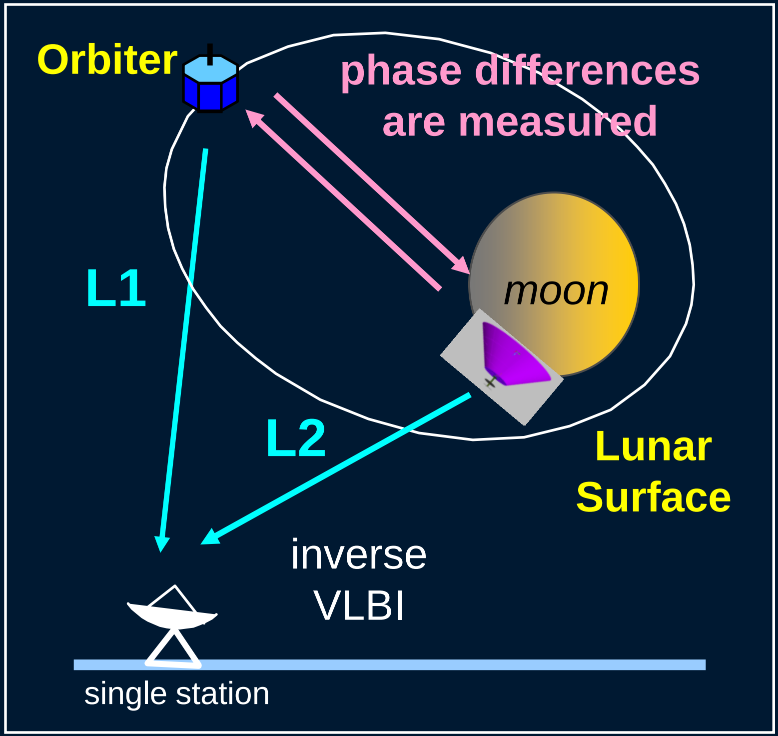




Differential VLBI between Lunar surface and Orbiter

V

**Libration** and Lunar rotation variability can be observed

# i-VLBI : Inverse VLBI by SELENE-2




<u>**sensitivity for positioning; σ(x)**</u>

**σ(x) = σ(⊿L); ⊿L = L1-L2**

**= 0.3 mm**

**under**

**σ(⊿τ) = 1ps = $10^{-12}$**

## Inverse VLBI

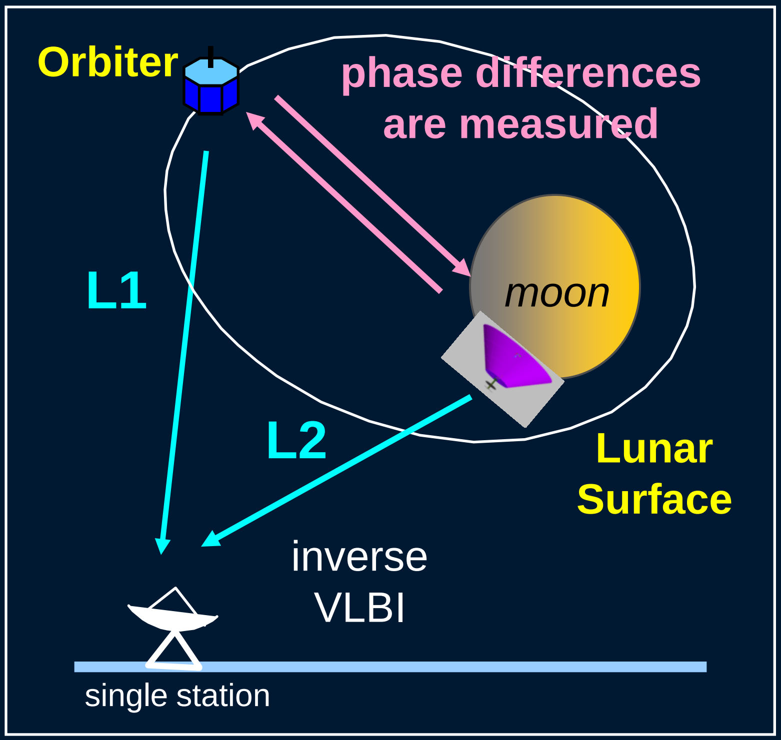
**after Kawano *et al*., *JGSJ*, 45, 181 (1999)**

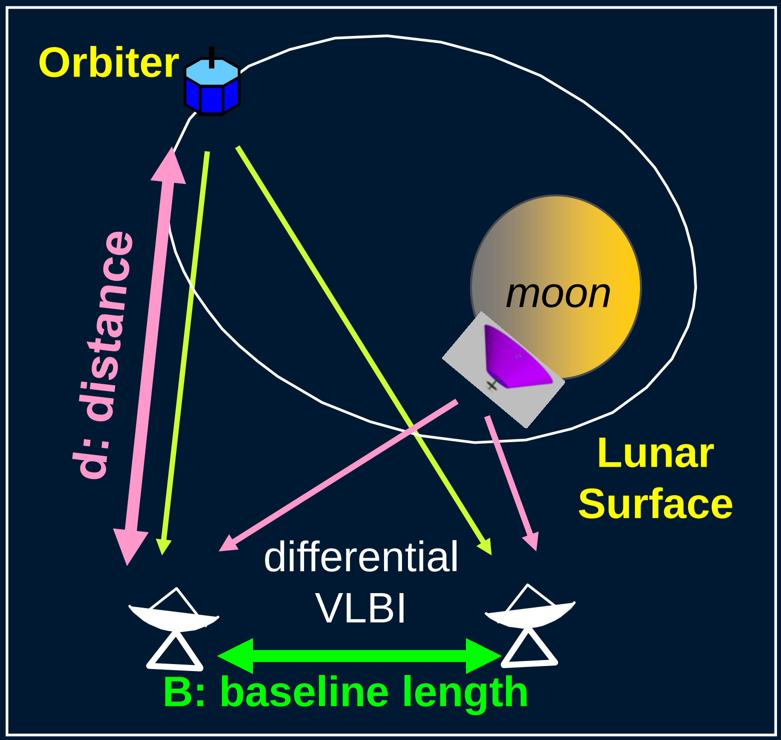
- Phase differences between two sources are measured by multi-frequency (in S-band) 2-way ranging.

- One station (not VLBI) on the ground observes these two sources (**L1**, **L2**).

- Sensitivity for positioning (**σ(x)**) is free from the distance of the sources.

# i-VLBI : Inverse VLBI (left) *vs.* differential VLBI (right)




**sensitivity for positioning; σ(x)**

**σ(x) = σ(⊿L);  ⊿L = L1-L2**

**= 0.3 mm**

**under**

**σ(⊿τ) = 1ps = $10^{-12}$**

**sensitivity for positioning; σ(x)**

**σ(x) = σ(⊿L) * d / B**

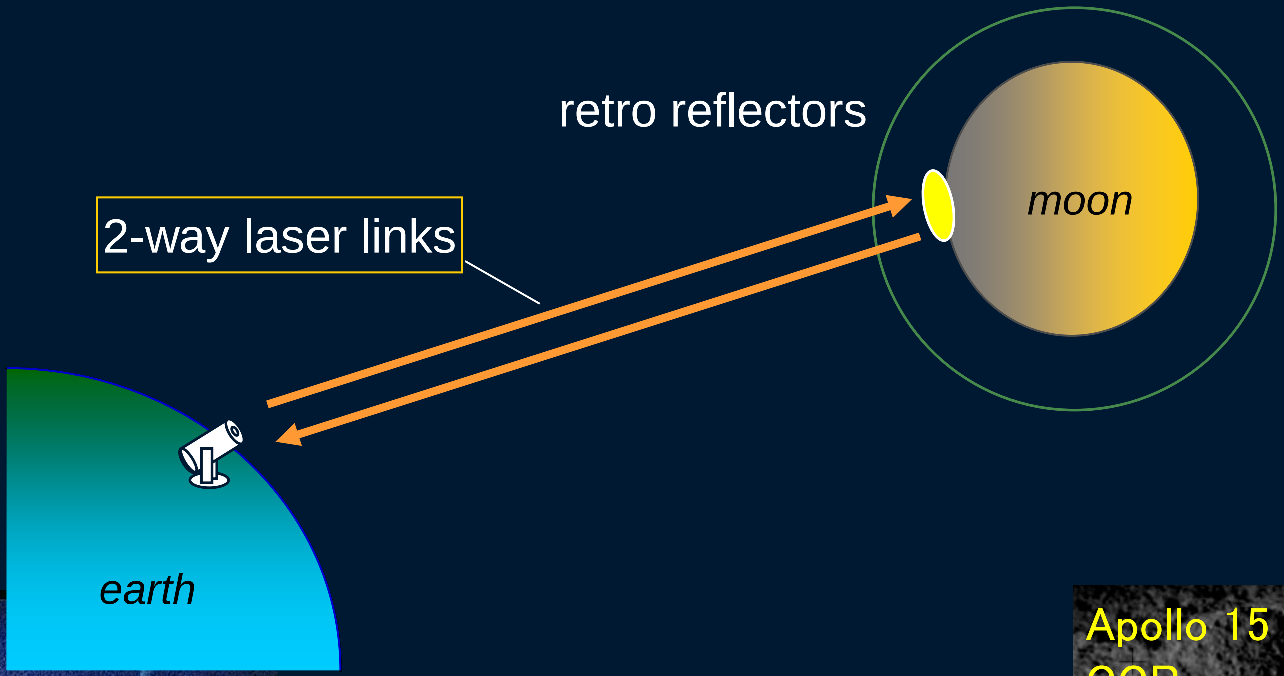
**= 6cm**

**under**

**σ(⊿L)=0.3mm**

**R=400,000km, B=2,000km**

# Configuration of LLR: Lunar Laser Ranging

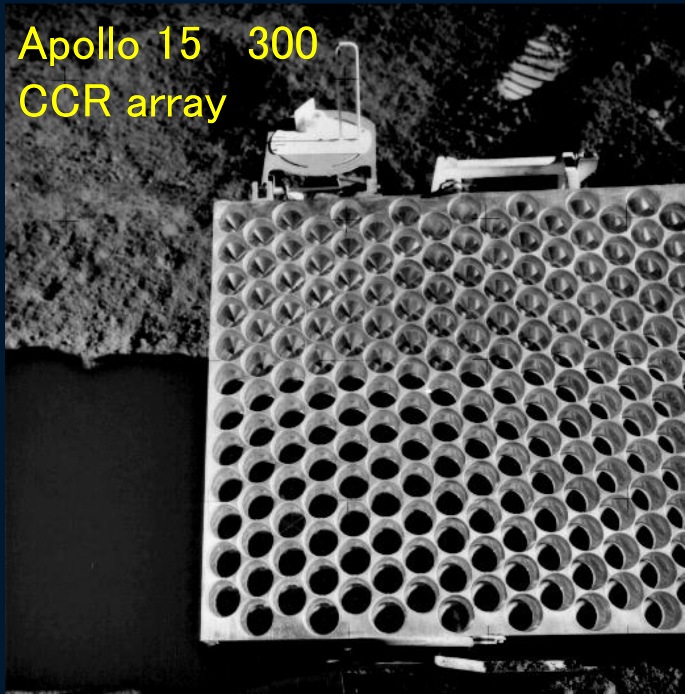



4 reflectors are ranged:

Apollo 11, 14 & 15 sites

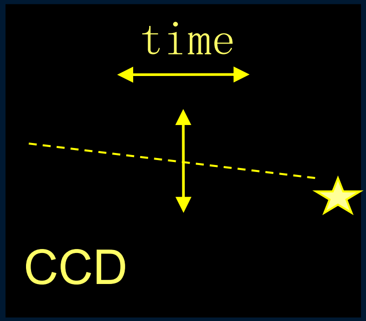
Lunakhod 21 Rover

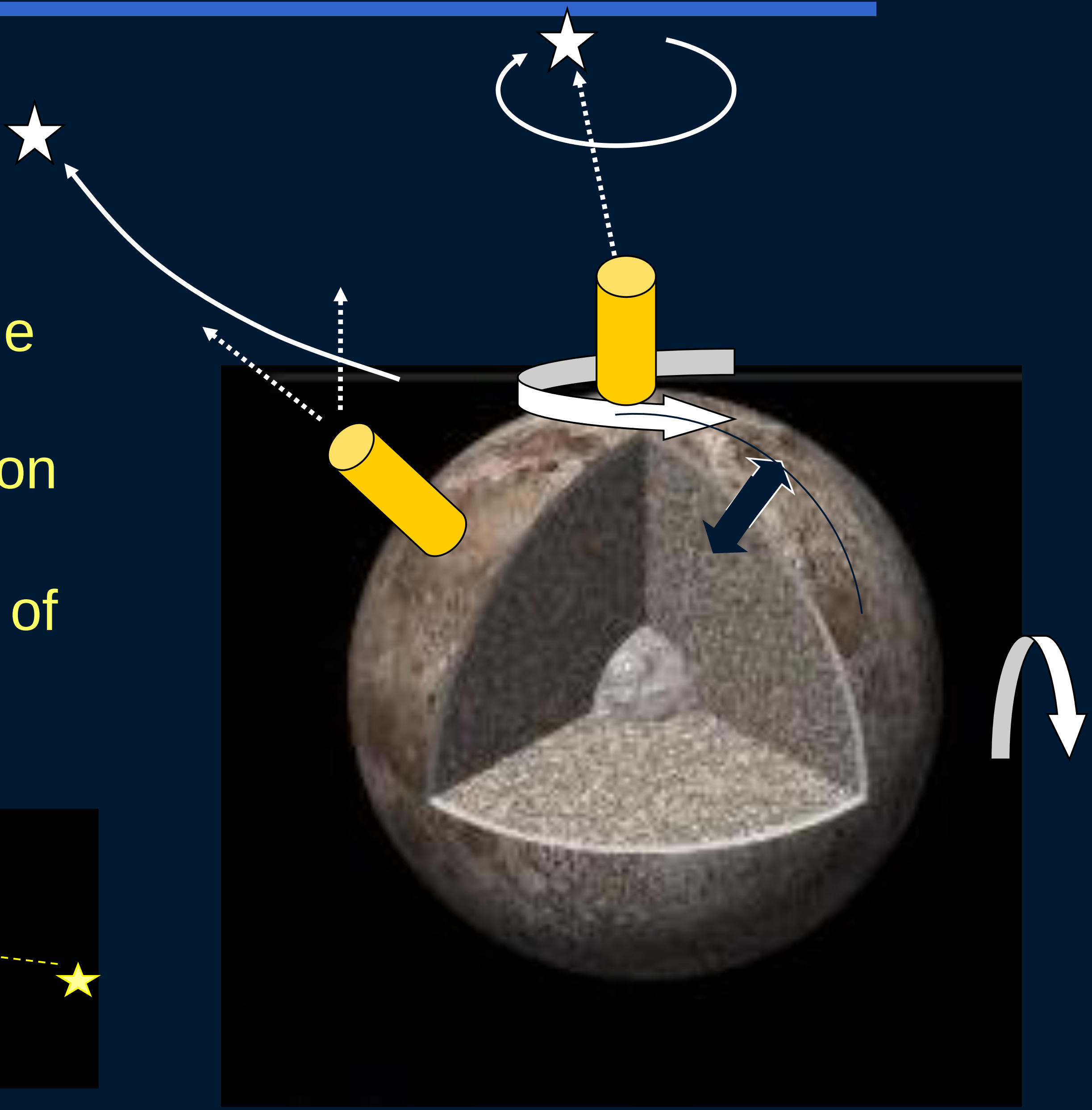
> settle one new site to improve accuracies



# ILOM : In-situ Lunar Orientation Measurement

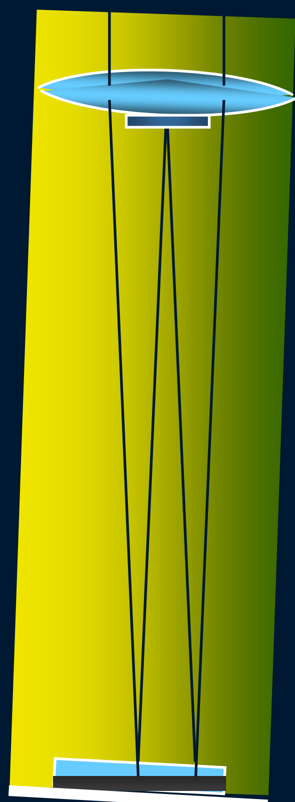
- Observation of the physical librations related to dissipation in the Moon
- with an accuracy of < 1 mas



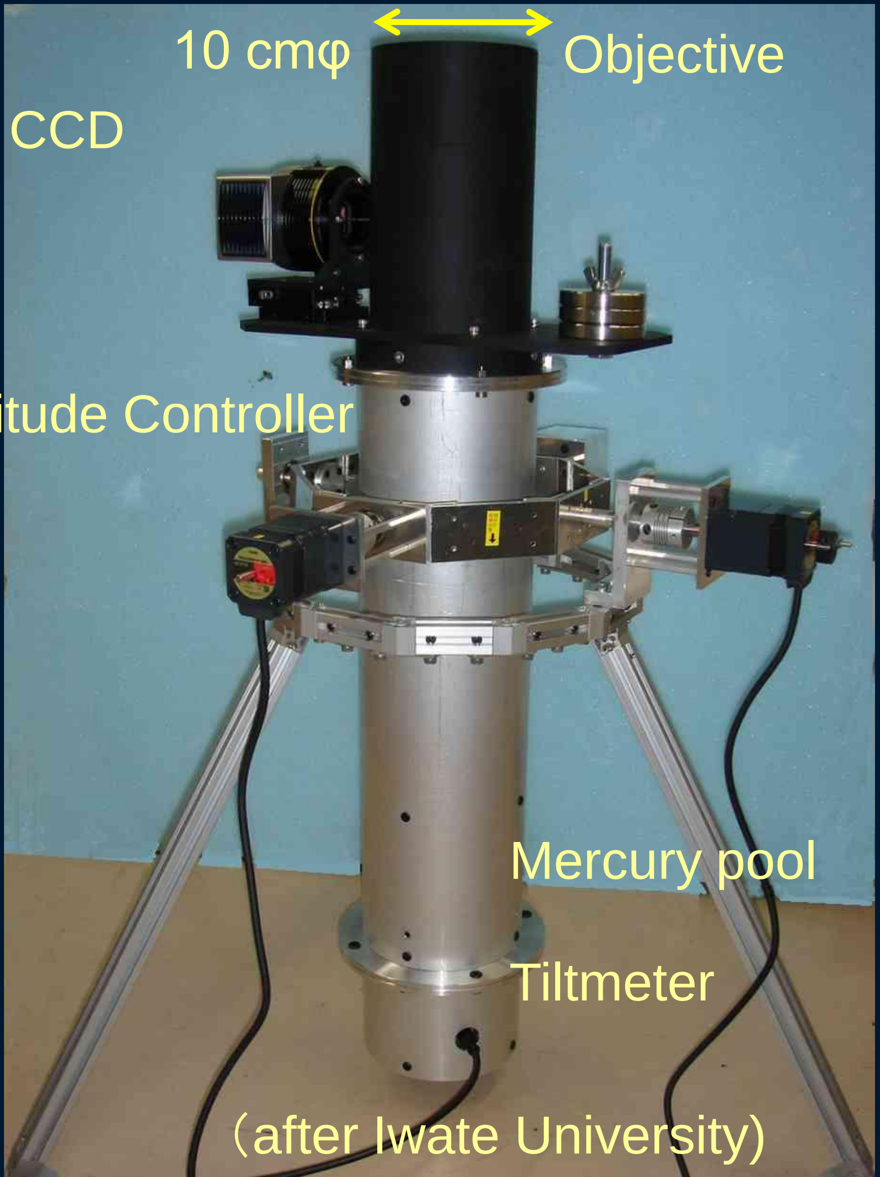



# ILOM telescope

**PZT (Photographic Zenith Tube) type telescope**



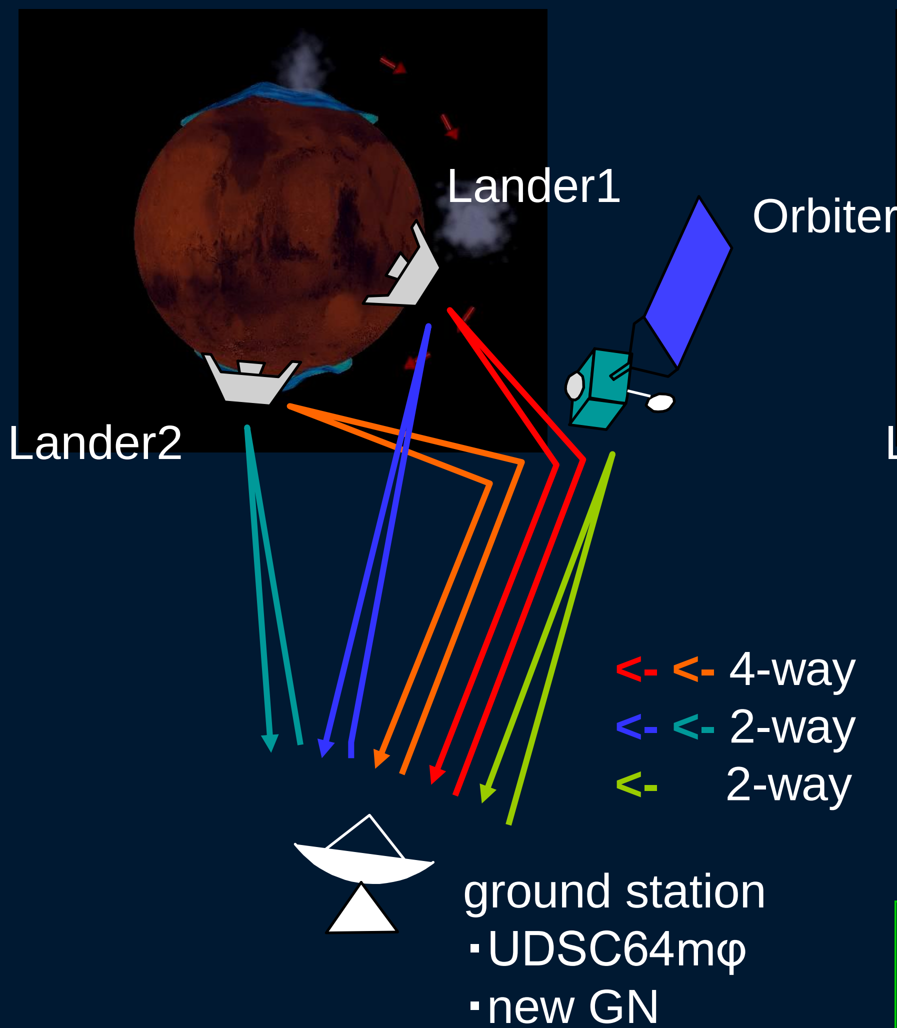

## Development of BBM



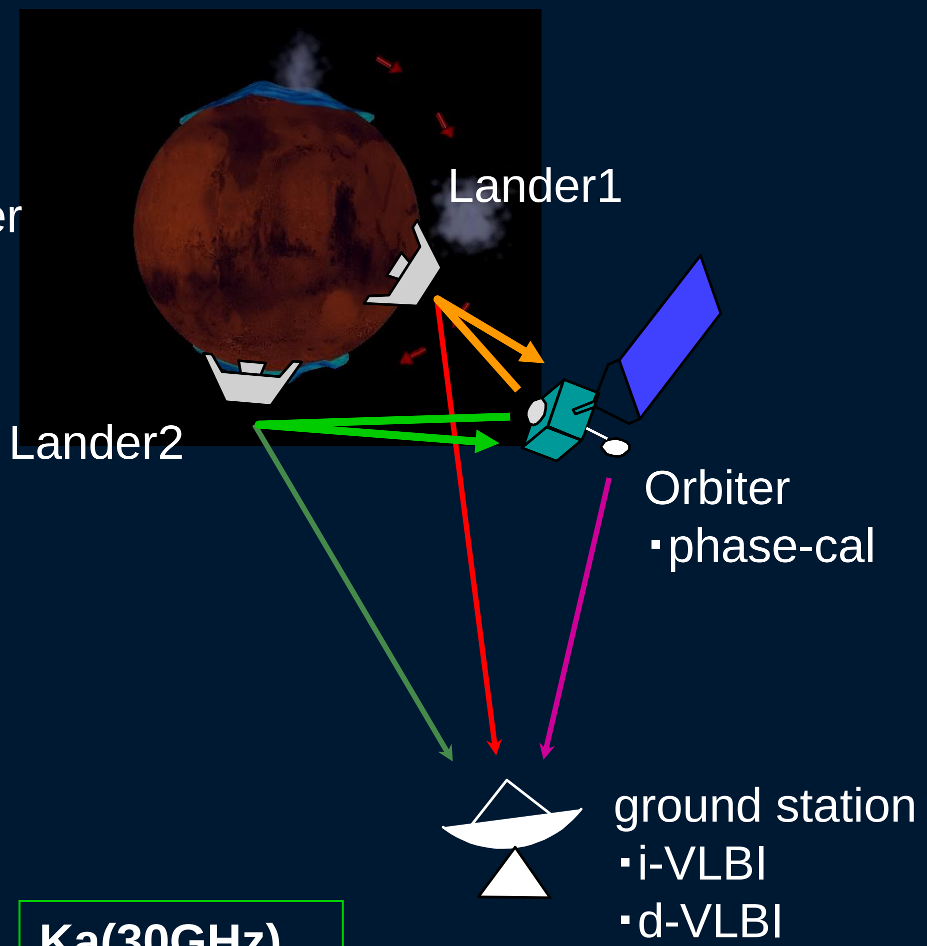
# Accuracy and subject for each selenodetic observation

| observations | accuracy | technical / theoretical subjects |
| --- | --- | --- |
| d-VLBI | 10 mas | - Accuracies are restricted by lunar ephemeris and terrestrial ionosphere. |
| i-VLBI | < 3 mas | - Precise measurements for the phase delay in the space craft should be realized. |
| LLR | 10 mas | - Optical transponder will improve the lack of data.<br>- Accuracies are restricted by lunar ephemeris and terrestrial ionosphere. |
| ILOM | <1 mas | - The attitude instability caused by thermal deformation should be diminished. |

# Mars ; 4-way Doppler (left ) and i-VLBI (right) using MELOS




<- <- 4-way
<- <- 2-way
<- 2-way

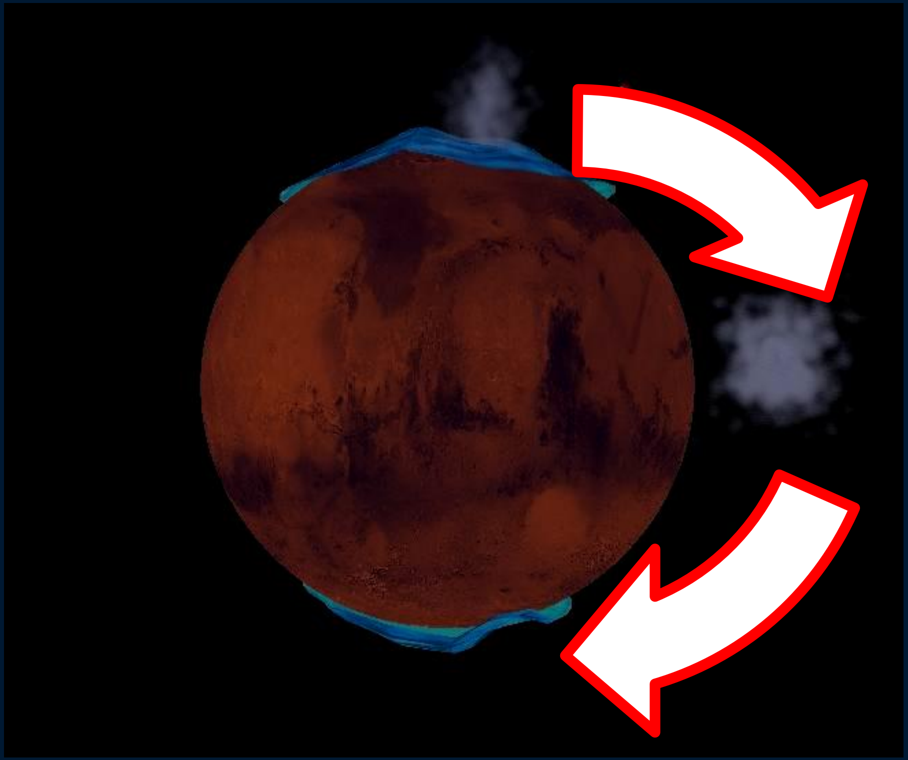



**Ka(30GHz), X, or S-band**

# Goal ; Mechanisms of Polar Motion & LOD Variation

The **atmosphere-cryosphere system** are the most important source.

LOD: length of day



**Loading by Atmosphere & Ice**

( **Moment of Inertia Perturbation** )

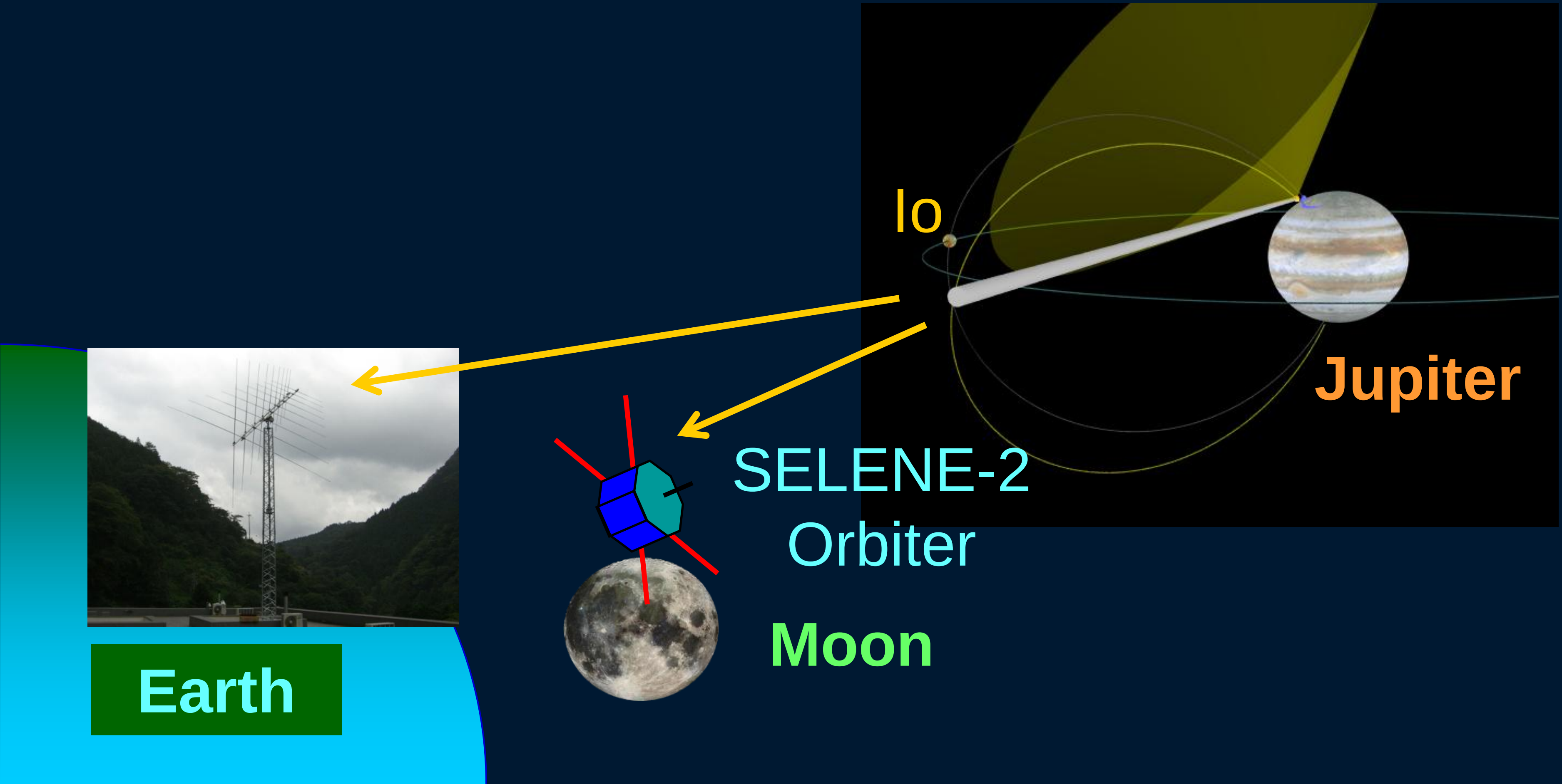
**Shear Stress by Wind**

( **Angular Momentum Interaction** )

# LLFAST : Lunar Low Frequency Astronomy Telescope

- Moon-Earth Space VLBI to observe Jupiter.

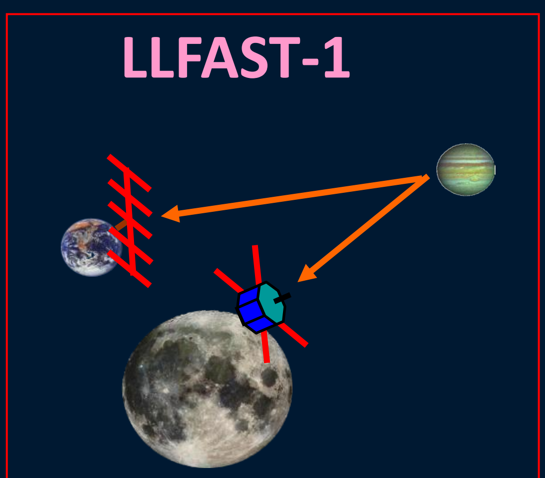
- The first step to realize future large interferometer on the lunar far side.

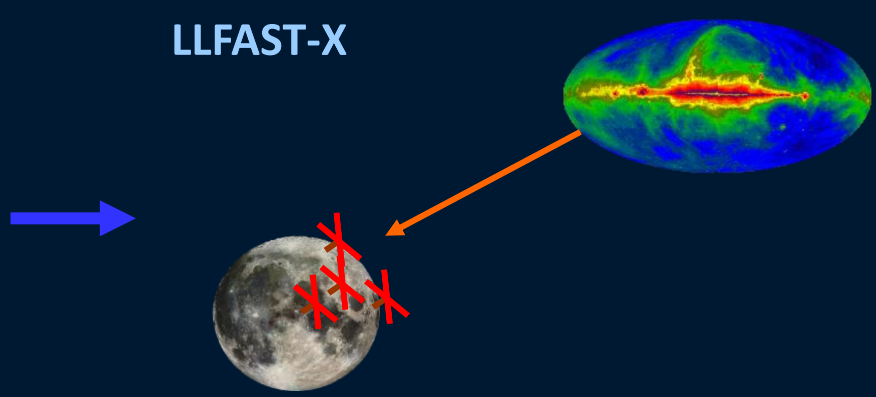


# Comparison of 1st and final observatory

| | 1st ; LLFAST-1 | final ; LLFAST-X |
|---|---|---|
| configuration | Moon (1 element)-Earth interferometer | Interferometer on the Moon (~100 elements) |
| site | **lunar orbit (SELENE-2 Orbiter)** | **far side; to avoid terrestrial interference** |
| frequency | **20 - 25 MHz *** | **0.1 – 20 MHz** |
| targets | **Jupiter**, Sun | galactic and extra-galactic objects, etc. |

***) 15-20 MHz single dish**



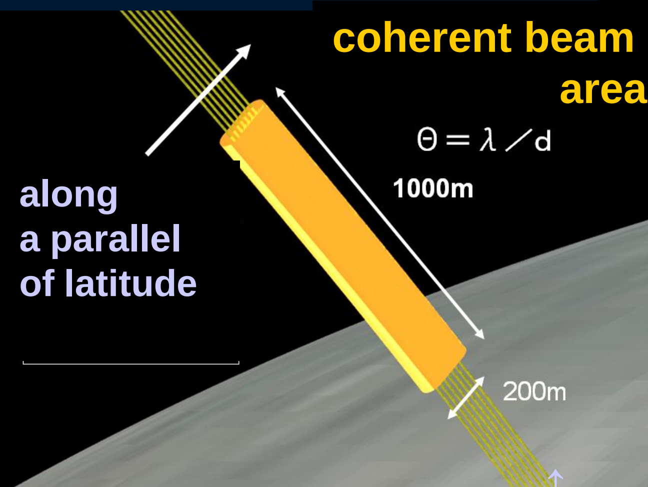



# Research for the mechanism of Jovian radio sources

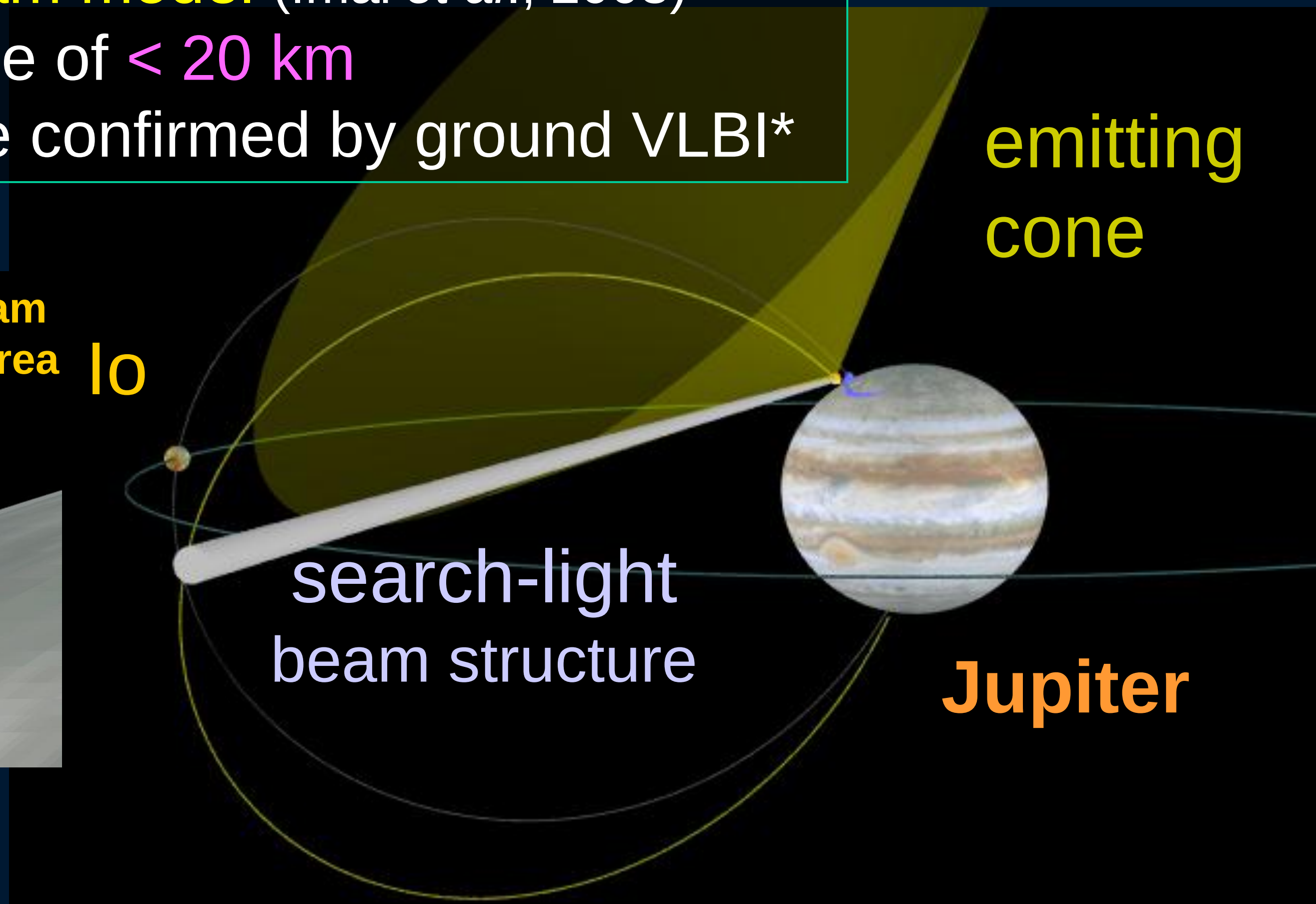
Observation results of modulation lane methods (Imai *et al*., 2002) and De effects;

- search-light beam model (Imai *et al*., 2008)
- radio source size of < 20 km
  which cannot be confirmed by ground VLBI*

*) resolution; 1,000 km



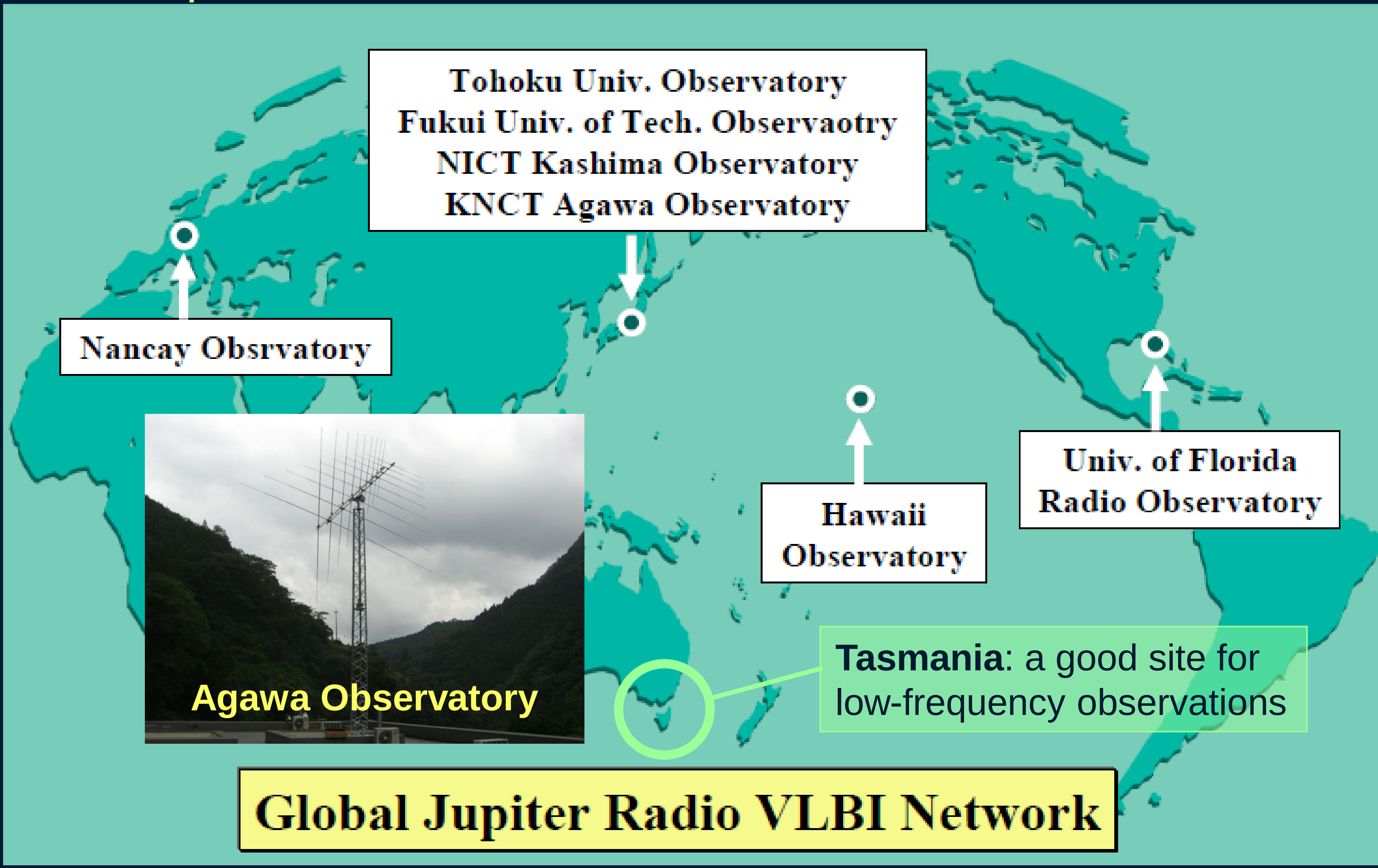

**radio sources of km-size**
(Imai *et al*.)




De: Jovicentric Declination of the Earth

# Candidate Ground Stations

Developments and test observations in 2007-2009



# Summary -

| observations | accuracy | future works for collaboration |
|---|---|---|
| selenodetic / areodetic observations | | |
| d-VLBI | 10 mas | -Seismological data is necessary to determine the core density.<br>- International collaborations for ground observation is necessary to improve accuracies. |
| i-VLBI | < 3 mas | |
| LLR | 10 mas | |
| ILOM | 1 mas | |
| FWD/i-VLBI | (0.3 mm) | |
| radio astronomical observations | | |
| LLFAST | 5 mas<br>(20 km) | - International collaborations for ground observation is necessary to increase chances to detect. |