EXPLORING RESOURCES ON THE MOON: TSUKIMI MISSION AND ASSOCIATED ACTIVITIES

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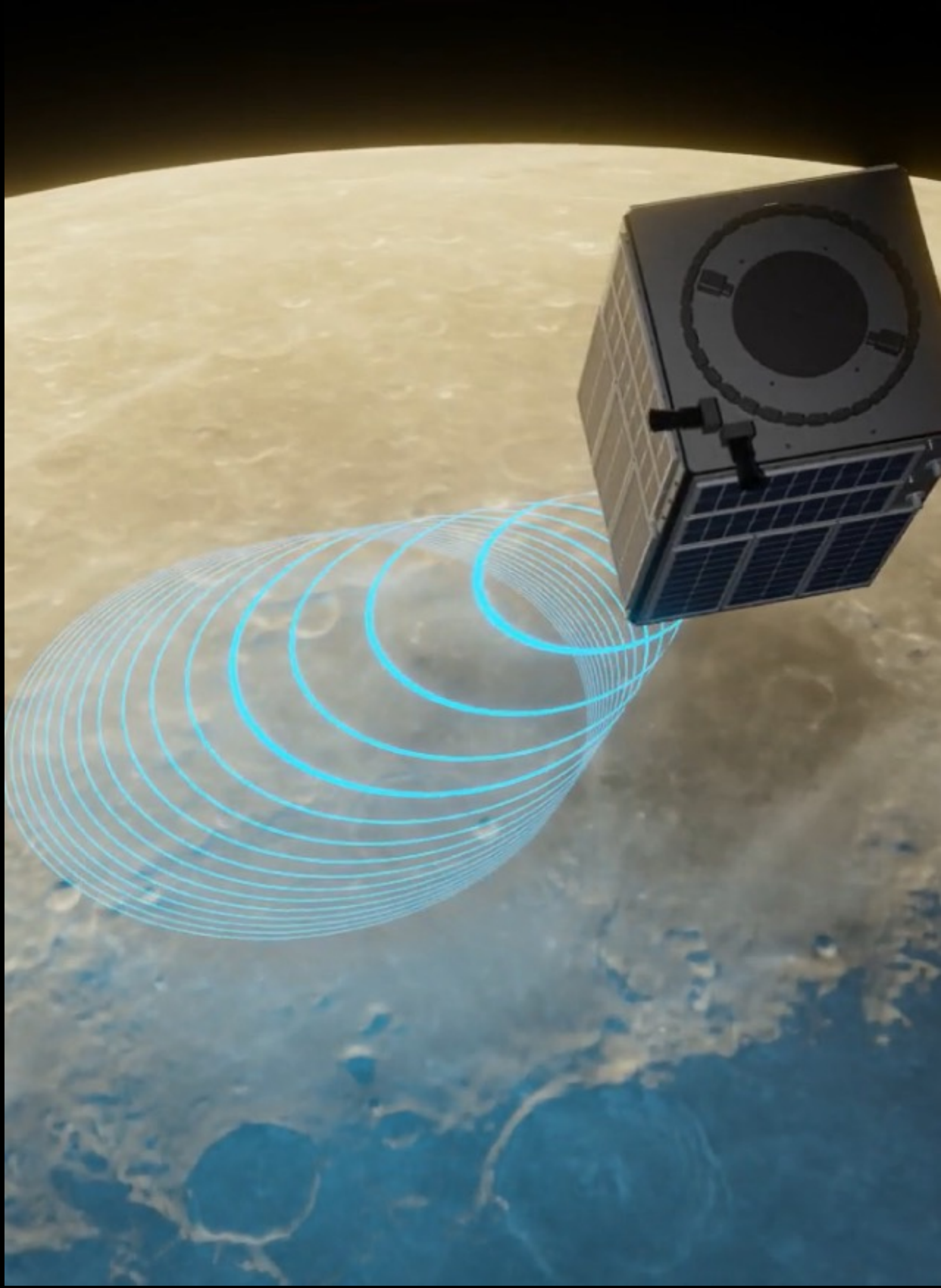
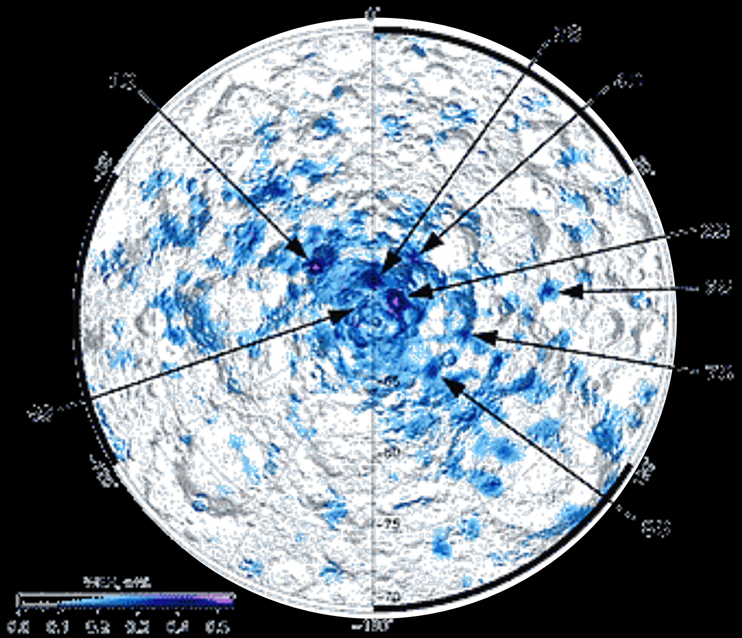
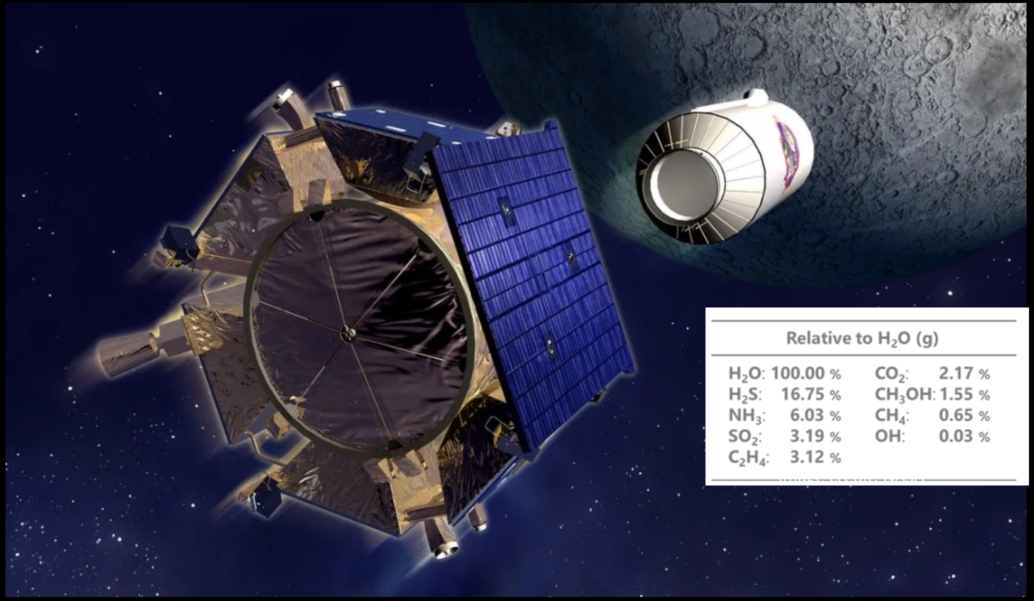


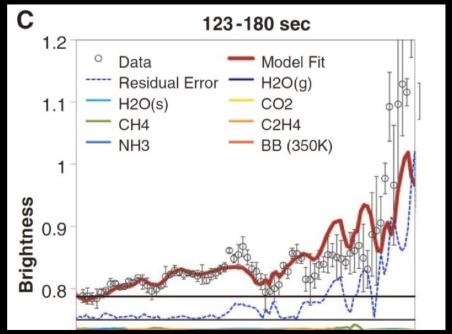
Volatiles on the Moon

LEND (e.g., Sanin et al., 2017)
Neutron Spectrometer
Water Equivalent Hydrogen

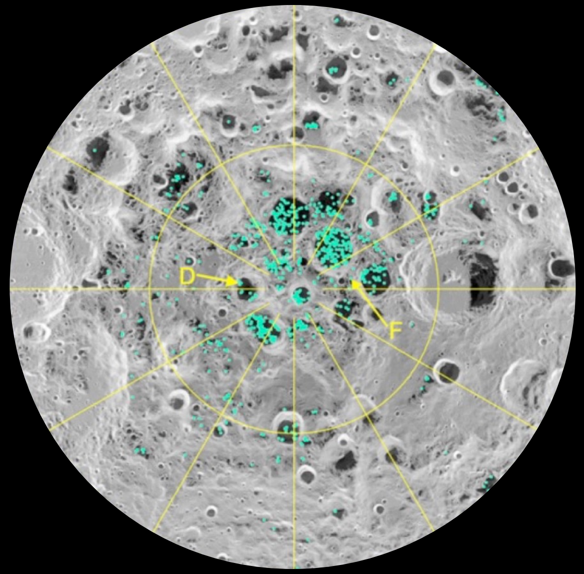


Direct impact experiment by LCROSS
(e.g., Colaprete et al., 2010)





Combination of M3, LOLA,
LAMP, Diviner data
(e.g., Liu et al., 2018)



Volatiles on the Moon

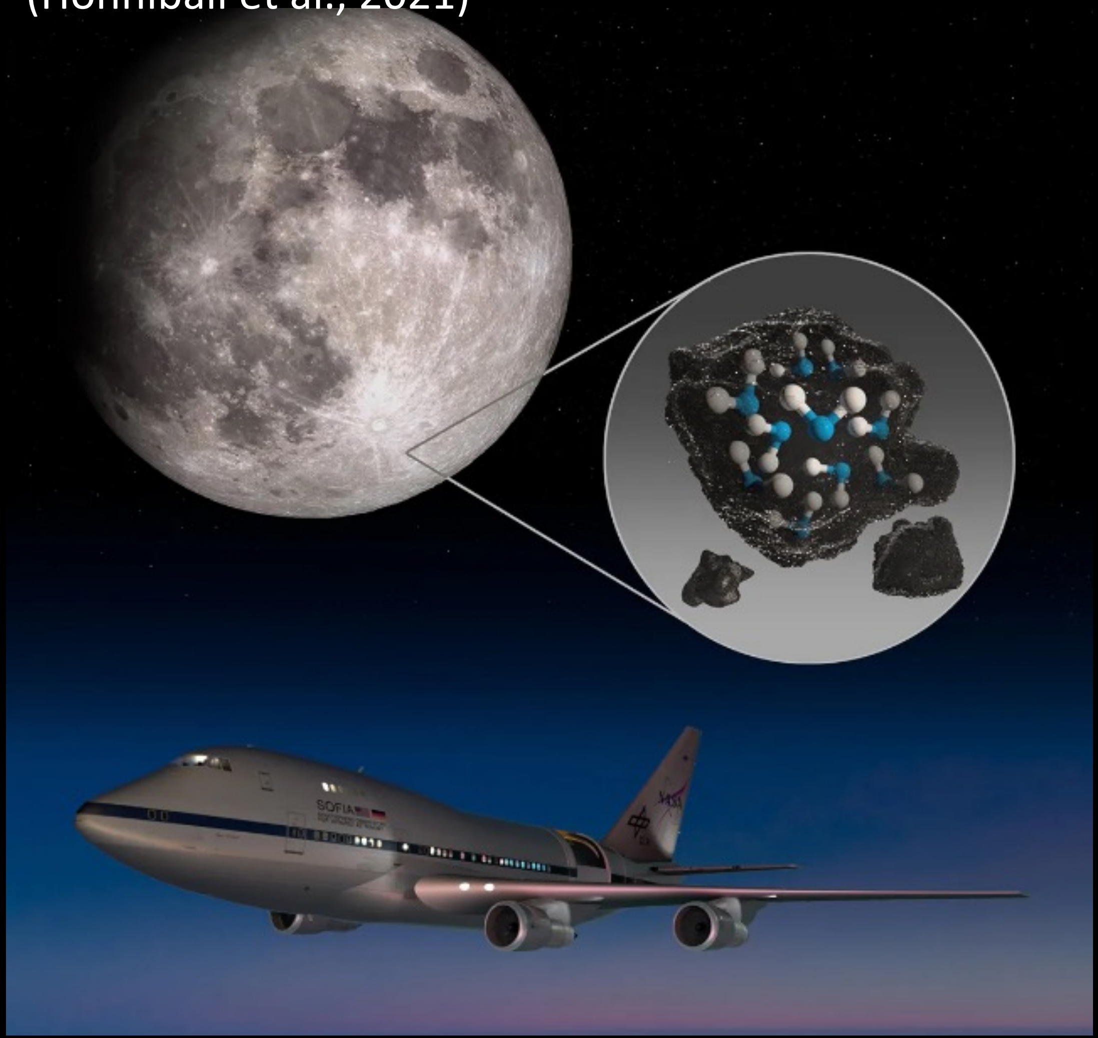
CHACE, neutron mass spectrometer on the Moon Impact Probe (MIP) experiment on Chandrayaan-1 (Sridharan et al., 2010)

(Image from Sridharan et al., 2010)

Direct evidence for water in the sunlit lunar exosphere

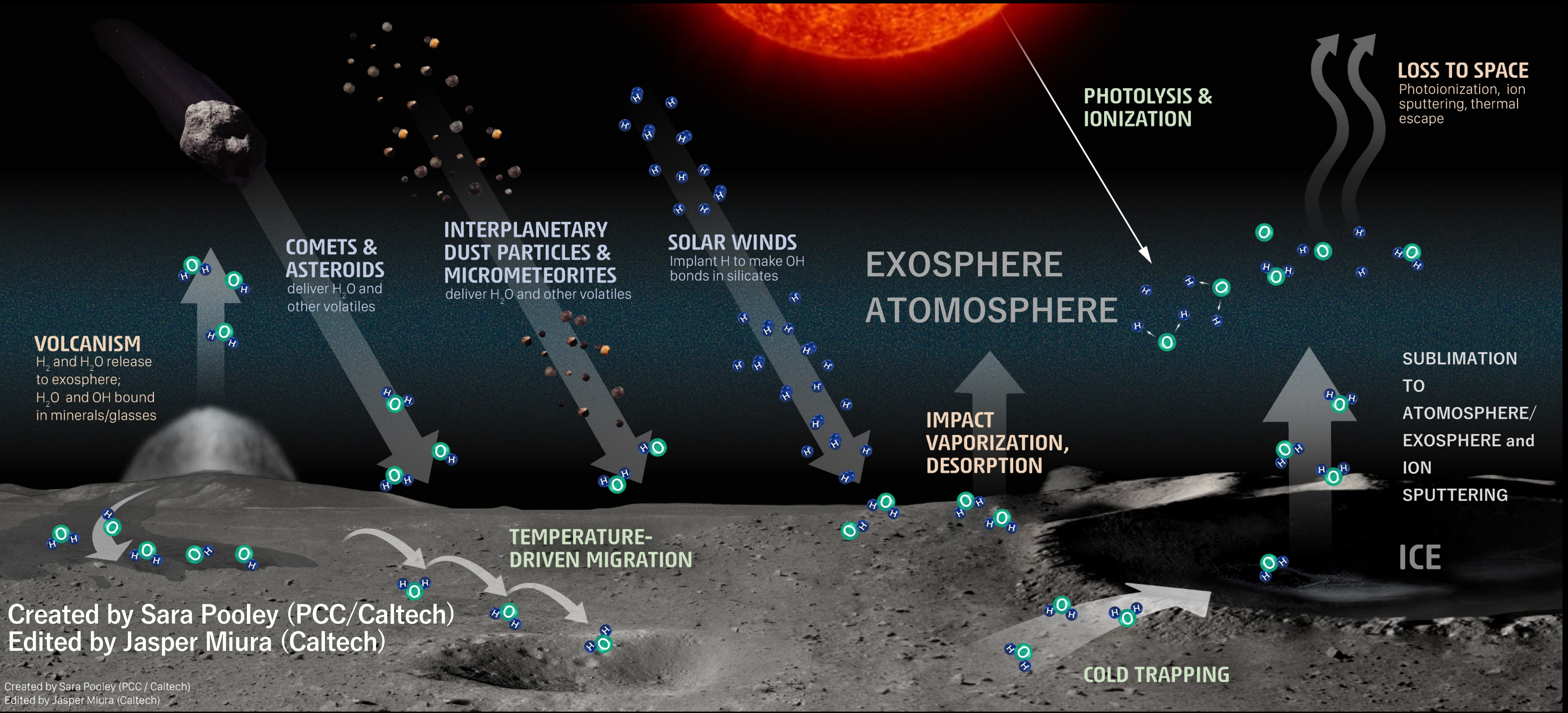
Atmosphere in the night 10-10 Pa@120K
In the sunlit H2O partial pressure ~10-5Pa

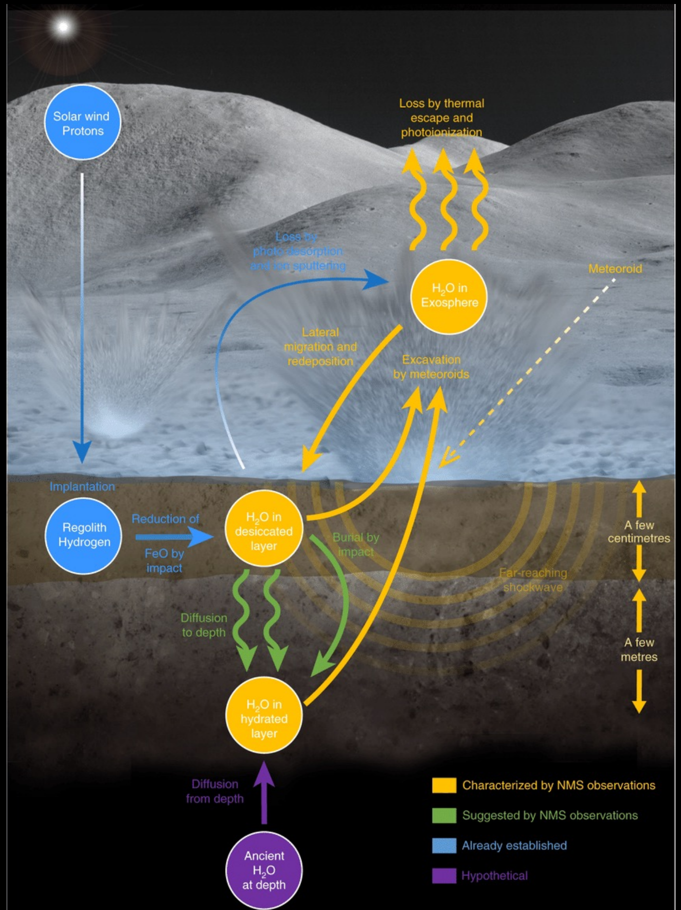
SOFIA (Stratospheric Observatory for Infrared Astronomy)
100-412 ppm water on the lunar surface
(Honniball et al., 2021)



Credits: NASA/Daniel Rutter

Current understanding of lunar volatiles





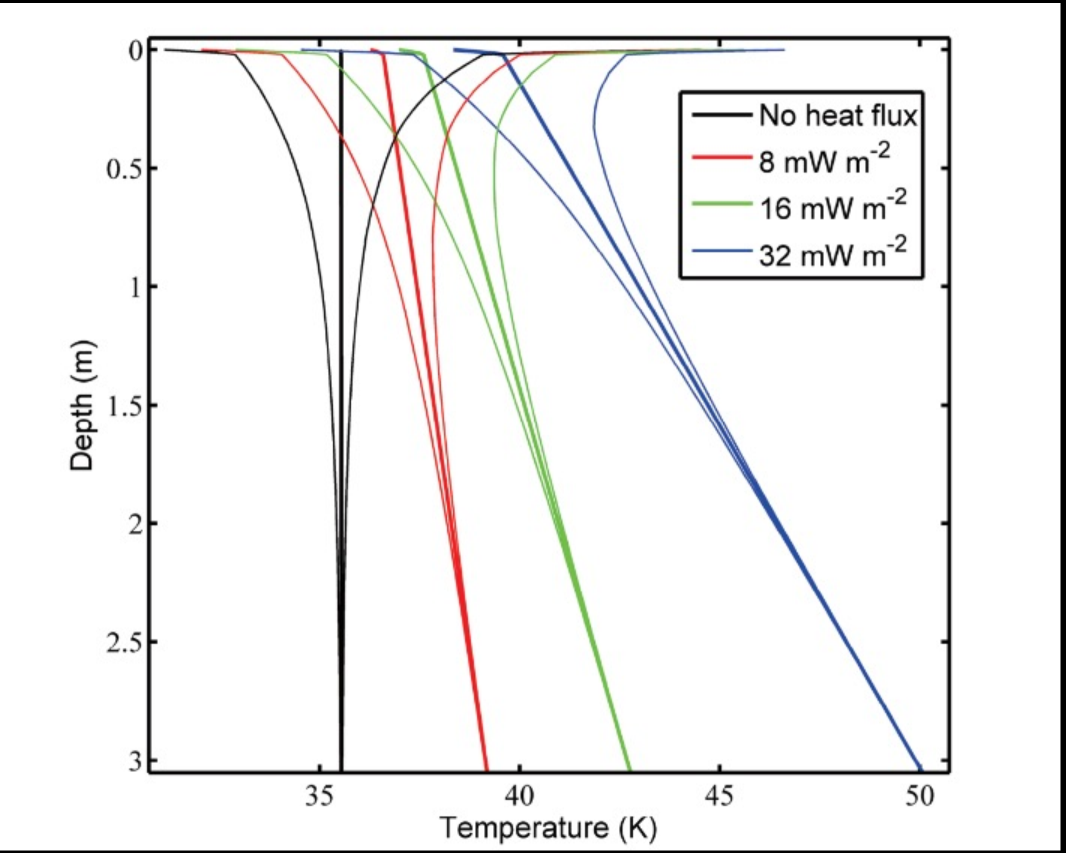
Benna et al. (2019)

Vertical migration of trapped volatile in regolith

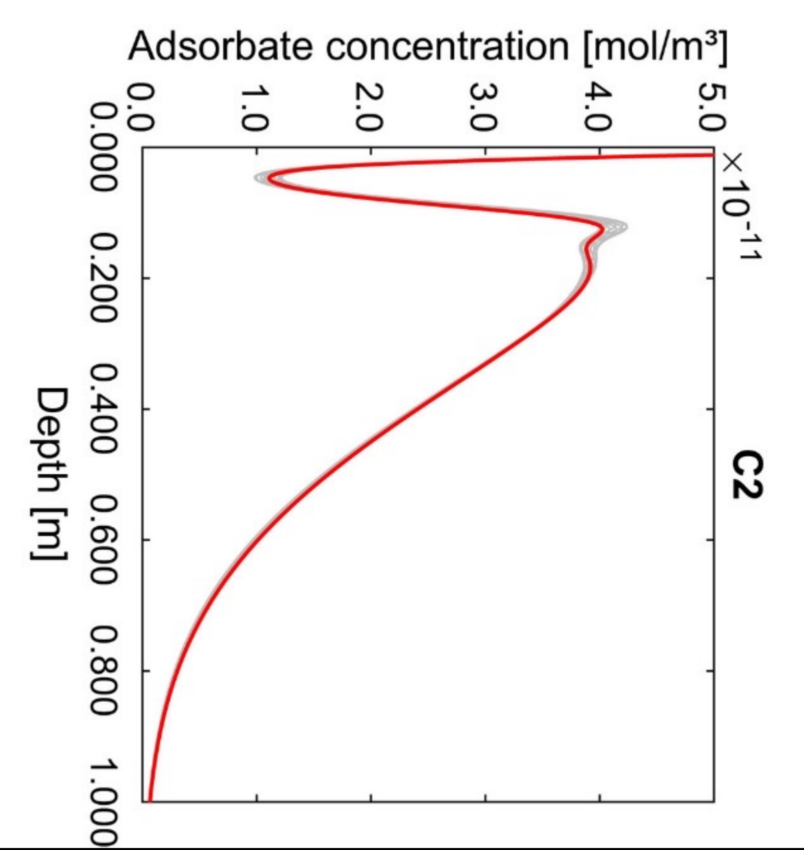
Shallow subsurface is complicated…

Water ice may exist on the Moon, particularly cold region such as PSA. Model-calculated temperature profile indicates that the "maximum" temperature is likely to be lowest in shallow depths

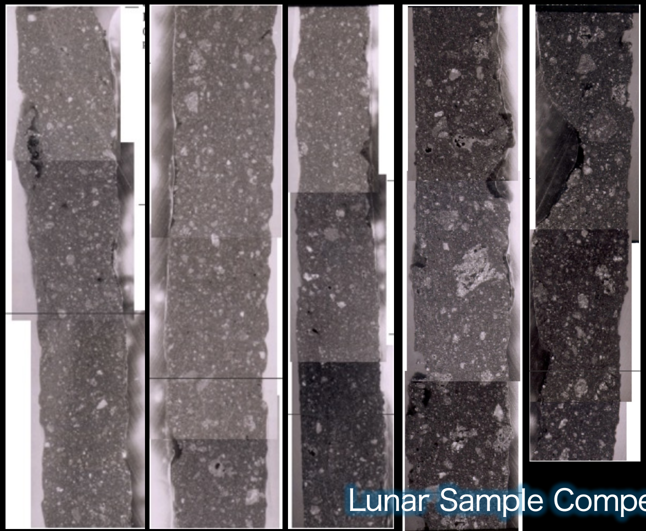
Maybe the top 10-30cm is the best candidate to look for volatile



(Page et al., 2010)



Reiss et al., 2021



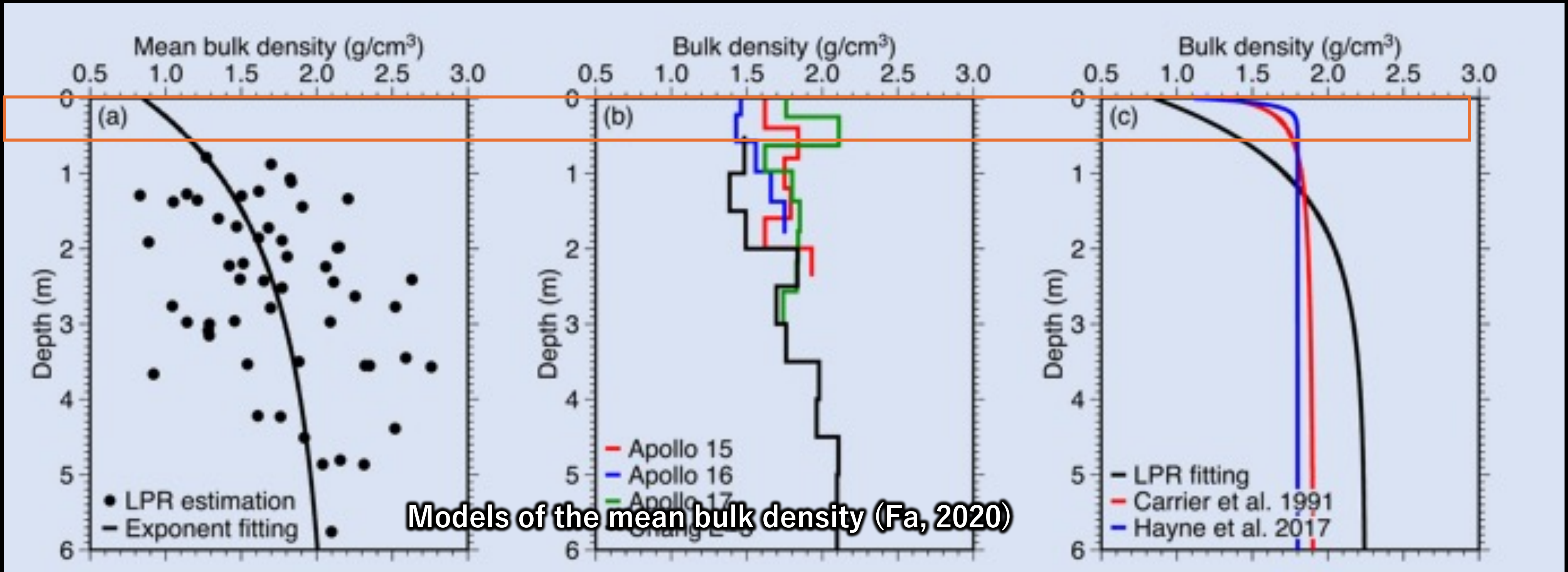
Apollo's core samples indicate a wide range of subsurface density distributions.

Estimated bulk density of the Apollo lunar soil

Collection site	Bulk density (g/cm^3)	Source	Bulk density (g/cm3)	Source
Apollo 15	1.36 – 1.85	Carrier et al., 1972	1.62 – 1.93	Carrier, 1974
Apollo 16	1.40 – 1.80	Mitchell et al., 1972	1.47 – 1.75	Carrier, 1974
Apollo 17	1.57 – 2.29	Mitchell et al., 1973	1.74 – 1.99	Carrier, 1974

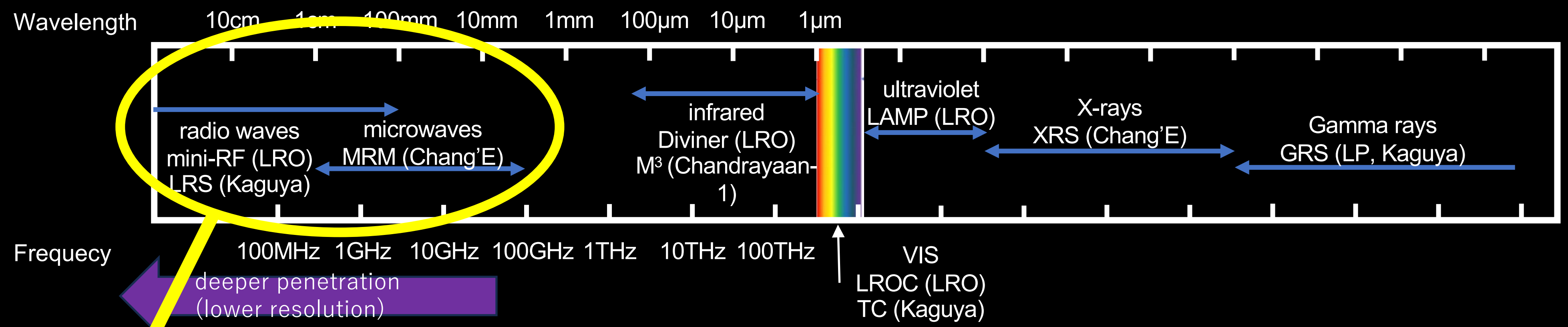
And in fact, the density structure at shallow depths needs to be constrained

Unknow, but the most important depth for the volatile concentration

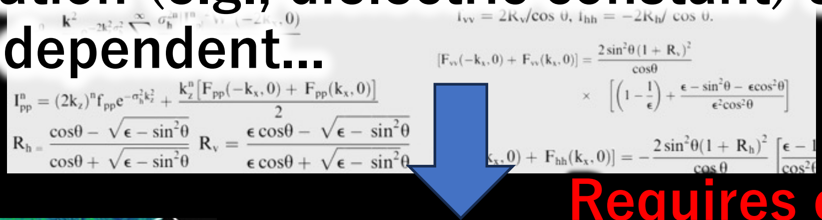


Models of the mean bulk density (Fa, 2020)

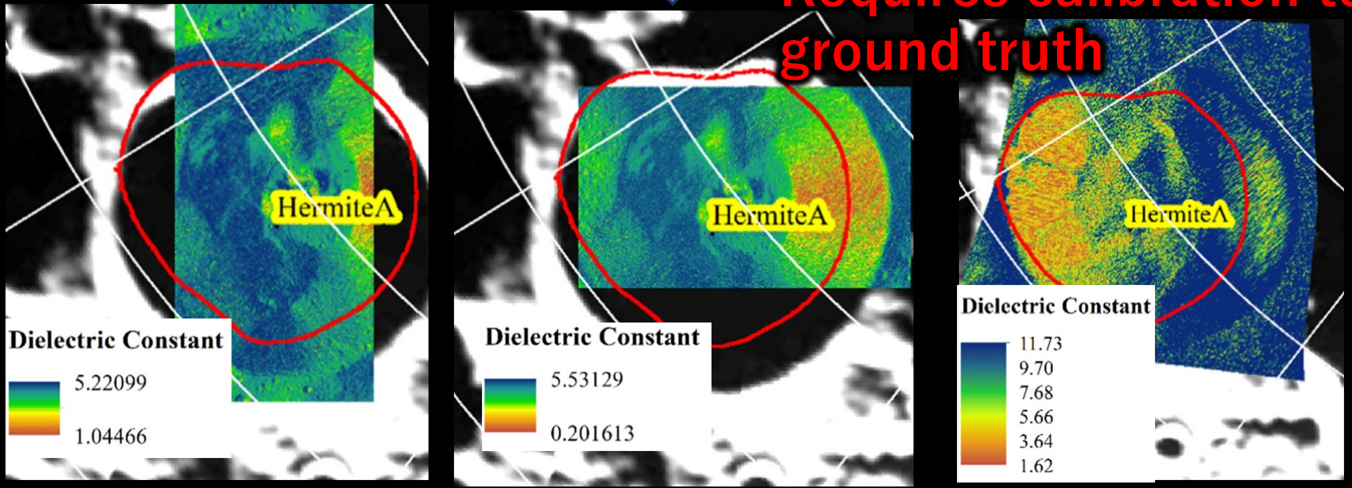
Even at shallow depths, the subsurface is difficult to observe remotely



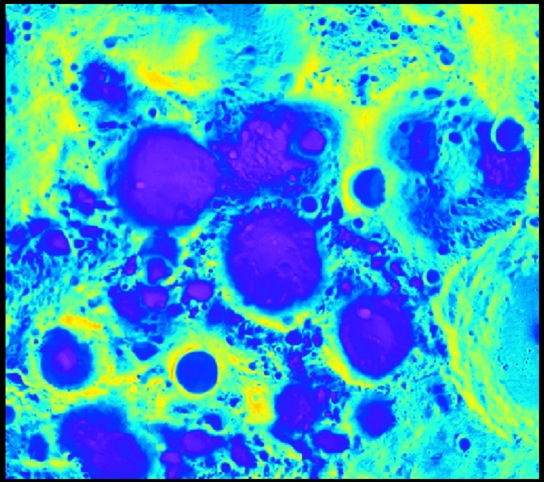
Great observational results are available and obtaining subsurface information (e.g., dielectric constant) seems possible, but highly model dependent…



Requires calibration to ground truth



(Singh et al., 2022)

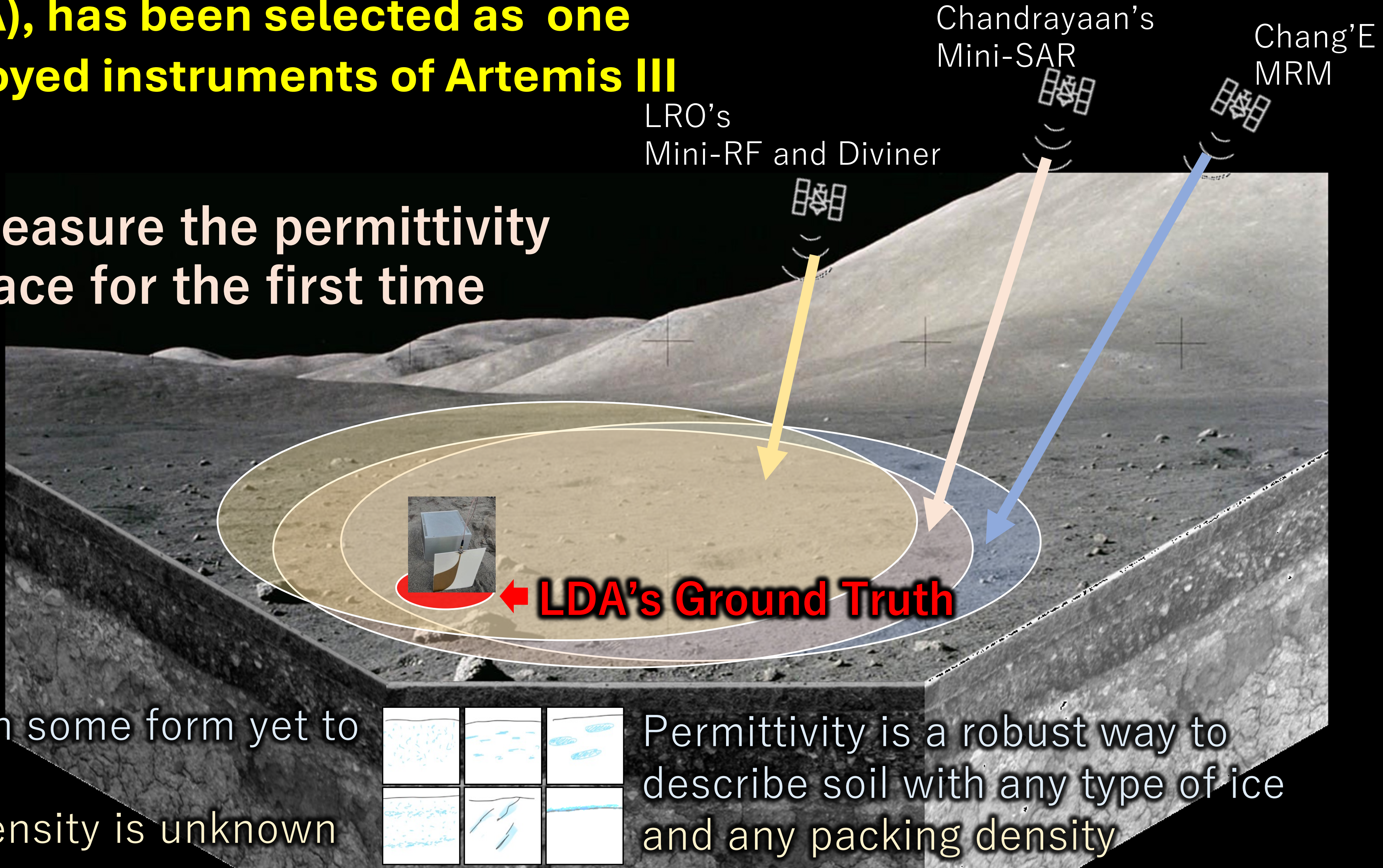


Diviner Polar Summer Avg Temp
(Williams et al., 2019)

Our instrument, the Lunar Dielectric Analyzer (LDA), has been selected as one of three deployed instruments of Artemis III

Good reference to previous electromagnetic observations

LDA will measure the permittivity of the surface for the first time

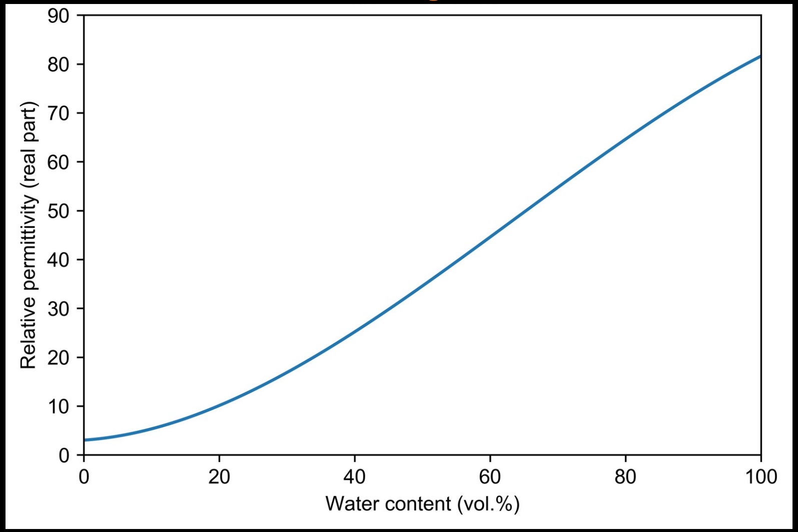


Ice may exist in some form yet to be determined
Soil packing density is unknown

Permittivity is a robust way to describe soil with any type of ice and any packing density

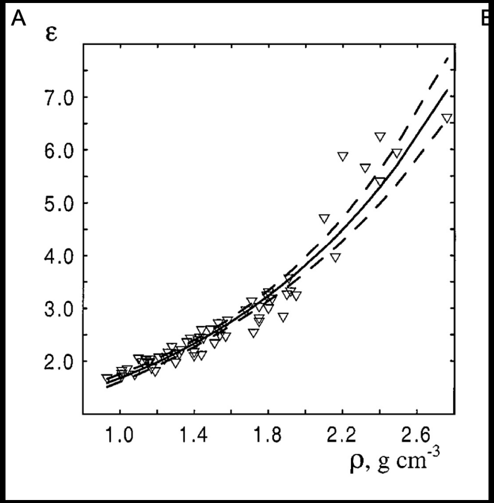
Permittivity and associated parameters

On Earth, liquid water

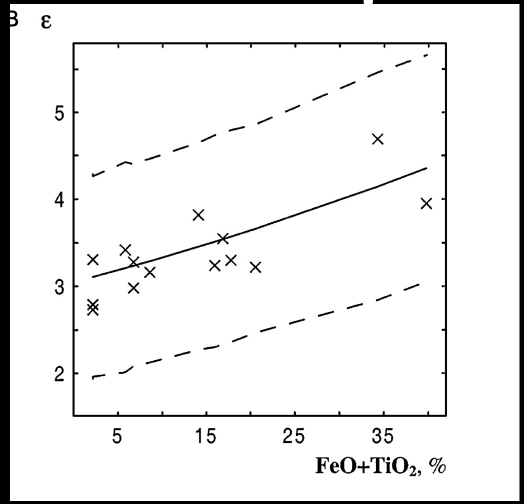


Topp et al. (1980)

Packing density

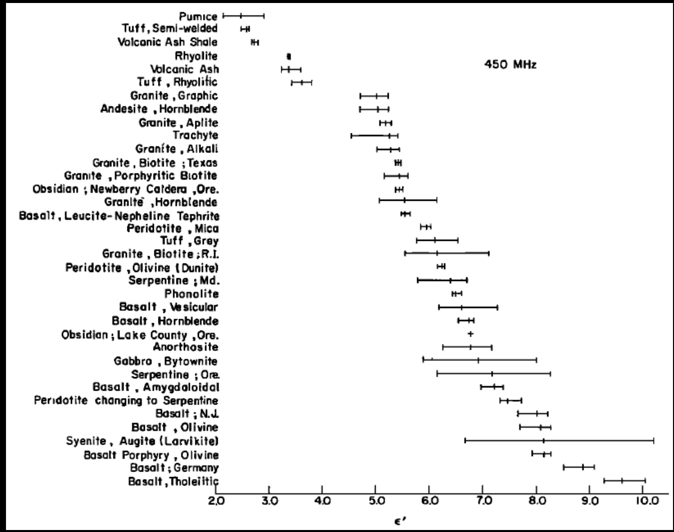


Elemental composition



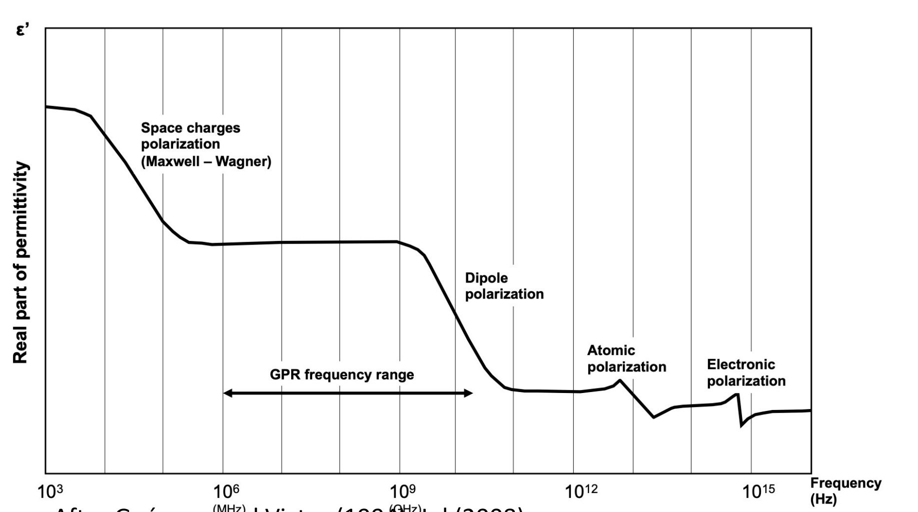
(Shkuratov and Bodarenko, 2001)

Materials



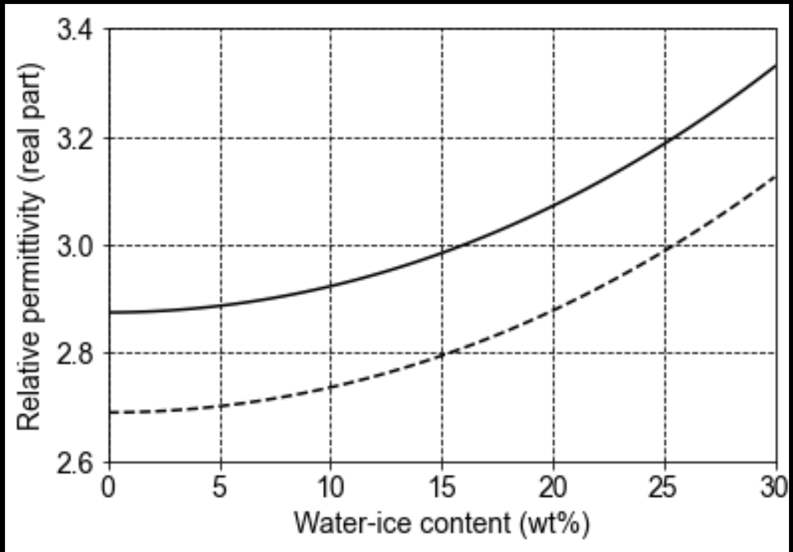
Campbell and Ulrichs (1969)

Frequency



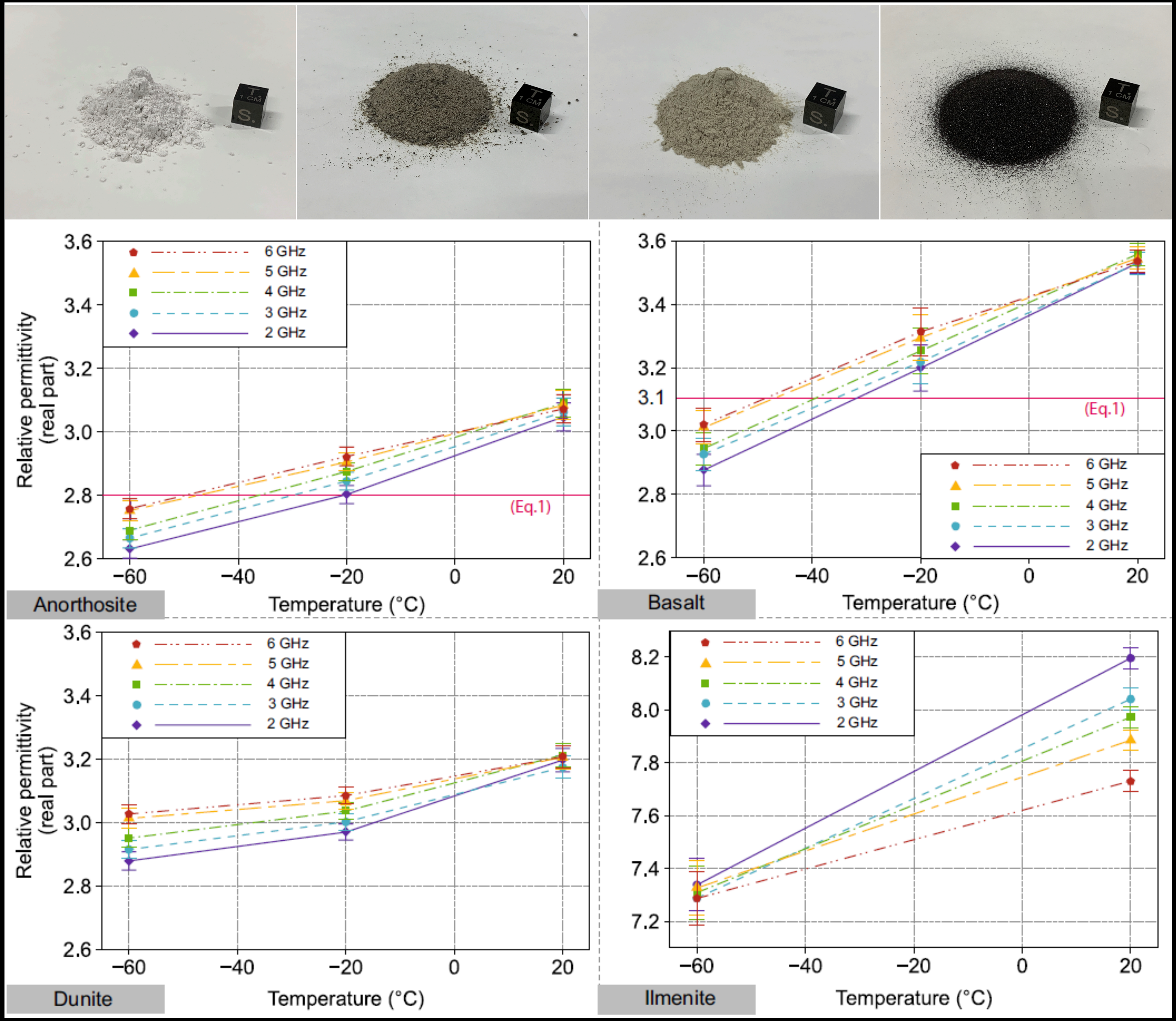
After Guéguen and Victor (1994), Jol (2008)

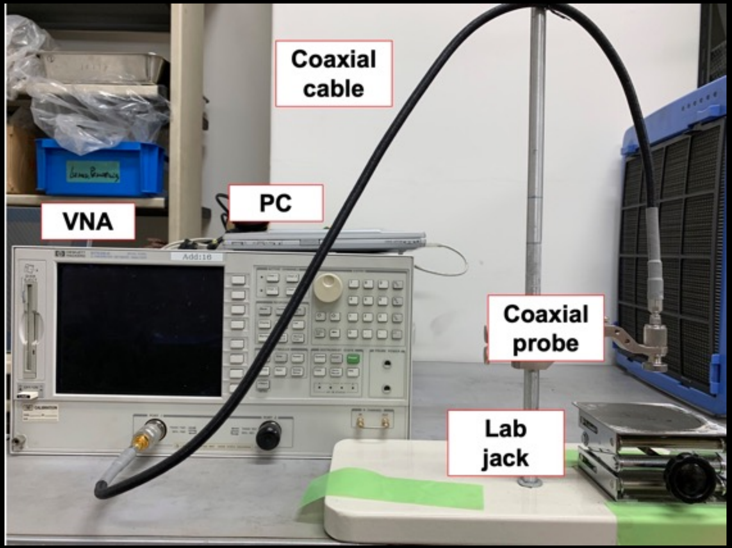
Ice content



We find the temperature dependences on permittivity depends on materials

Kobayashi et al., 2022





Theoretical Deby model indicates the permittivity will be close to the lowest at -60 ℃

Measurements of the permittivity at different temperatures between -60 to ~40℃ will help identifying the nature of the materials

This finding is especially important for an ice identification because the temperature dependencies exist for rock but not for ice

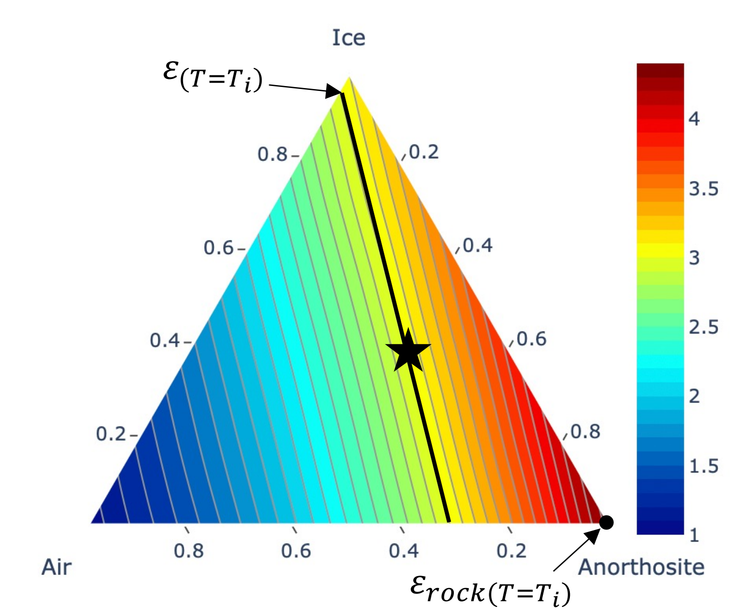
Mixing model of the permittivity for ice in regolith at different temperatures

$$\varepsilon_{(T=T_1)}^{\frac{1}{3}} = f_{rock}\varepsilon_{rock(T=T_1)}^{\frac{1}{3}} + f_{ice}\varepsilon_{ice}^{\frac{1}{3}} + (1 - f_{rock} - f_{ice})\varepsilon_{air}^{\frac{1}{3}}$$

$$\varepsilon_{(T=T_2)}^{\frac{1}{3}} = f_{rock}\varepsilon_{rock(T=T_2)}^{\frac{1}{3}} + f_{ice}\varepsilon_{ice}^{\frac{1}{3}} + (1 - f_{rock} - f_{ice})\varepsilon_{air}^{\frac{1}{3}}$$

$$\Rightarrow \varepsilon_{(T=T_1)}^{\frac{1}{3}} - \varepsilon_{(T=T_2)}^{\frac{1}{3}} = f_{rock}(\varepsilon_{rock(T=T1)}^{\frac{1}{3}} - \varepsilon_{rock(T=T2)}^{\frac{1}{3}})$$

→If we measure the permittivity at different temperature, we can determine porosity, packing density, water-ice content (★ in the figure on the right)



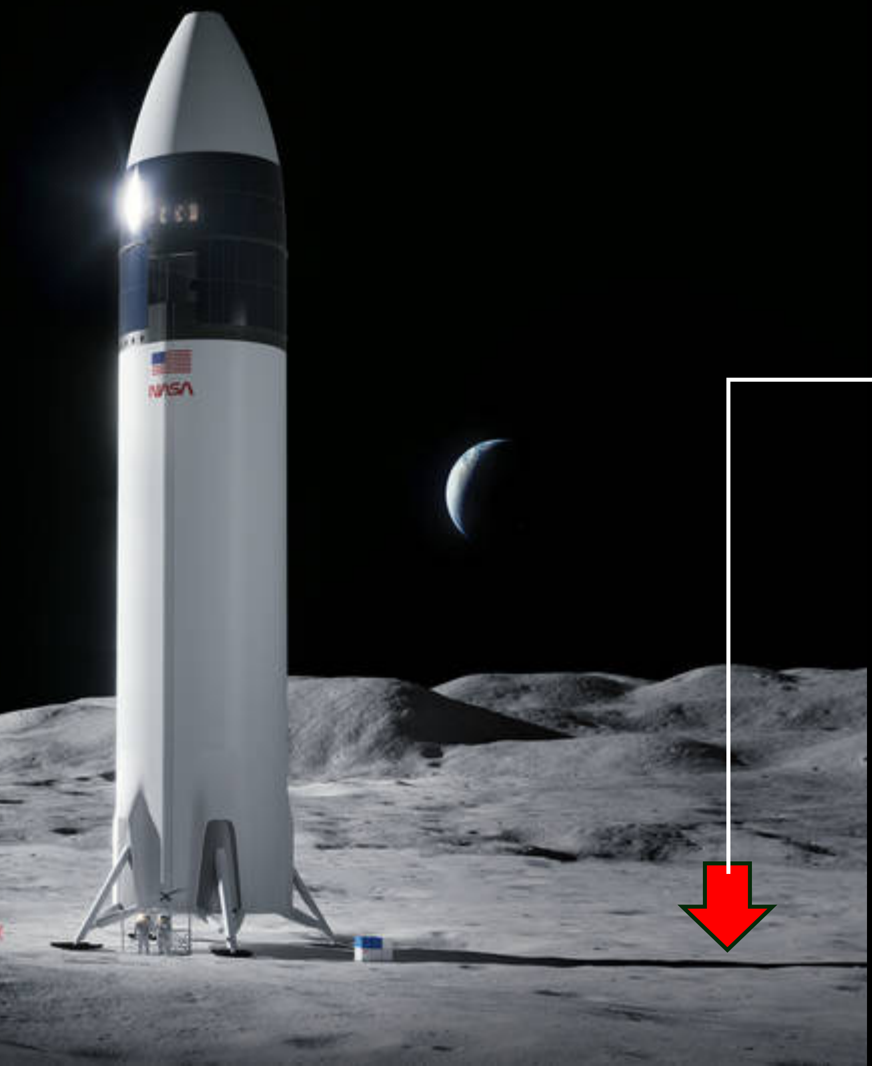
Error estimate

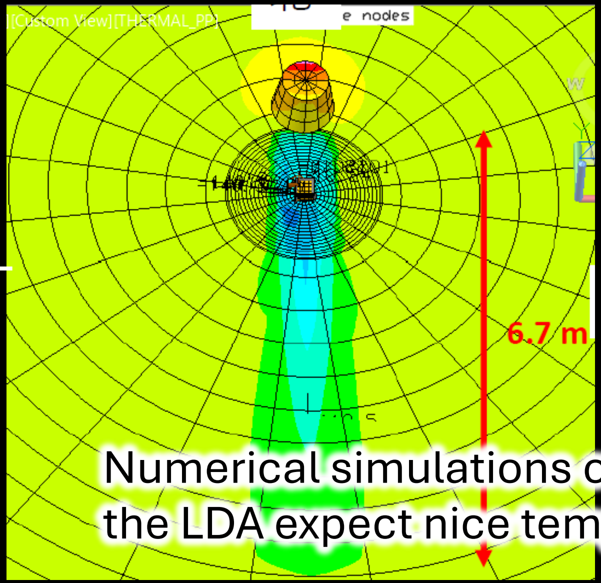
$$f_{rock} = \frac{\varepsilon_{rock(T=T1)}^{\frac{1}{3}} - \varepsilon_{rock(T=T2)}^{\frac{1}{3}}}{\varepsilon_{(T=T1)}^{\frac{1}{3}} - \varepsilon_{(T=T2)}^{\frac{1}{3}}}$$

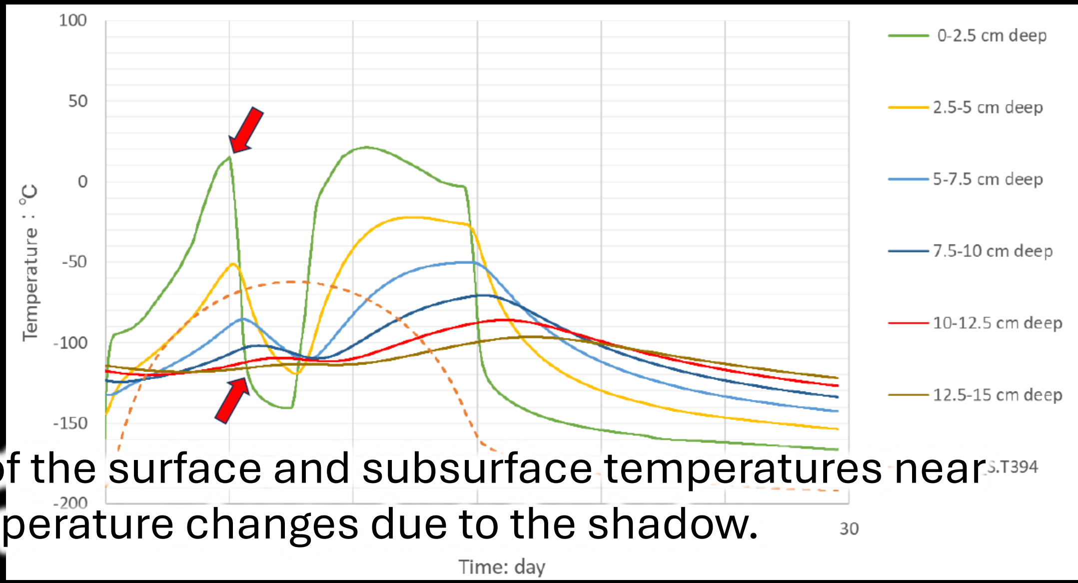
An accuracy of less than 2 wt% for the identification of water ice in regolith requires a permittivity accuracy of 0.05, best 0.01.

High-precision permittivity measurement at different temperature is the key to estimate the amount of the putative subsurface ice

For temperature variation, we'd like to ask the astronaut to place the LDA near the shadow, so we can measure the permittivity at different temperatures







Numerical simulations of the surface and subsurface temperatures near the LDA expect nice temperature changes due to the shadow.

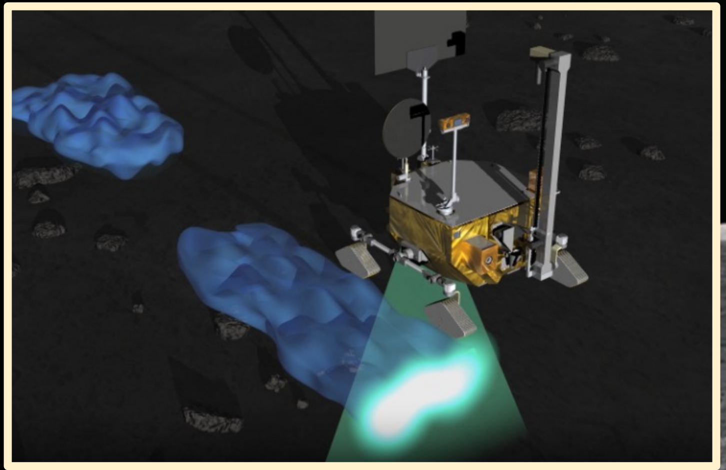
Original idea is to place the LDA in the shadow of the starship…

LDA will measure the permittivity of the surface for the first time

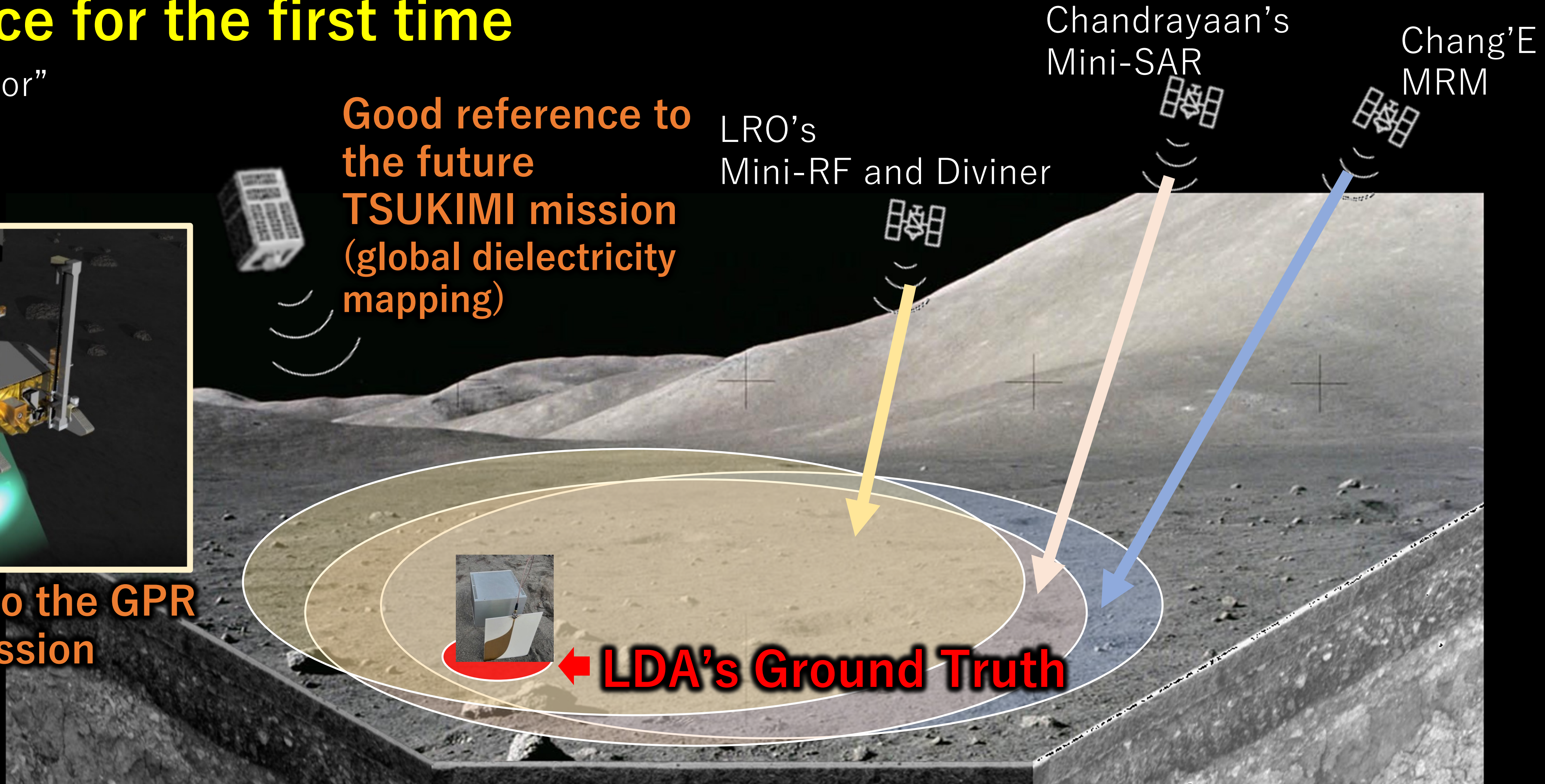
by using a “resonator”

Good reference to previous electromagnetic observations

Good reference to the future TSUKIMI mission (global dielectricity mapping)

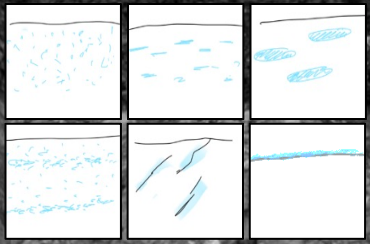


Good reference to the GPR of the LUPEX mission



Ice may exist in some form yet to be determined

Soil packing density is unknown

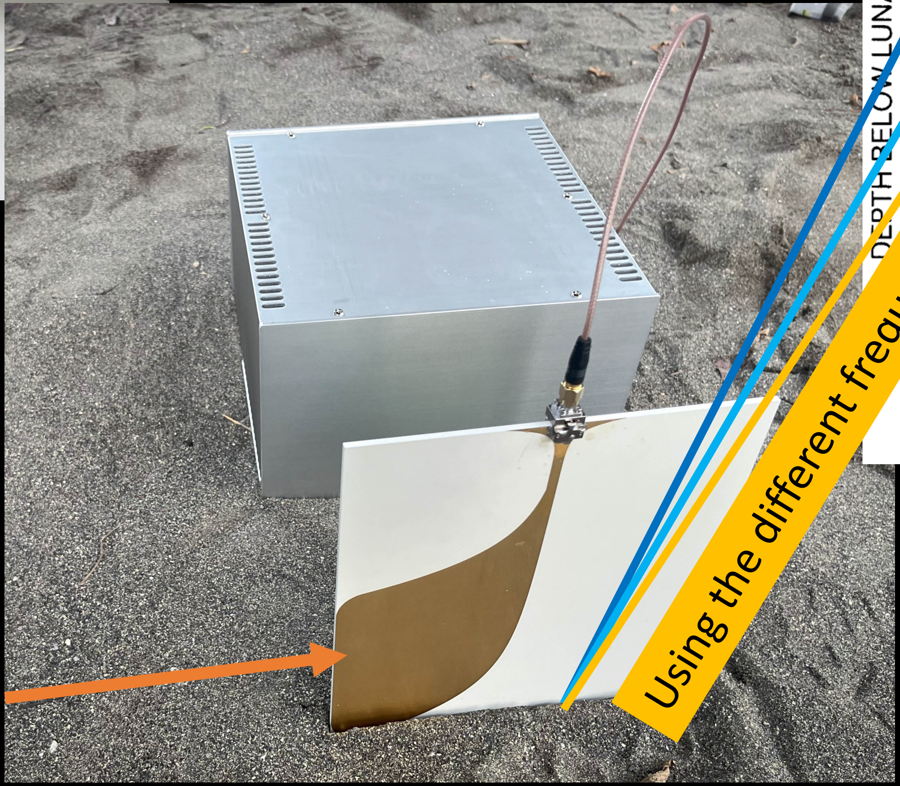


Permittivity is a robust way to describe soil with any type of ice and any packing density

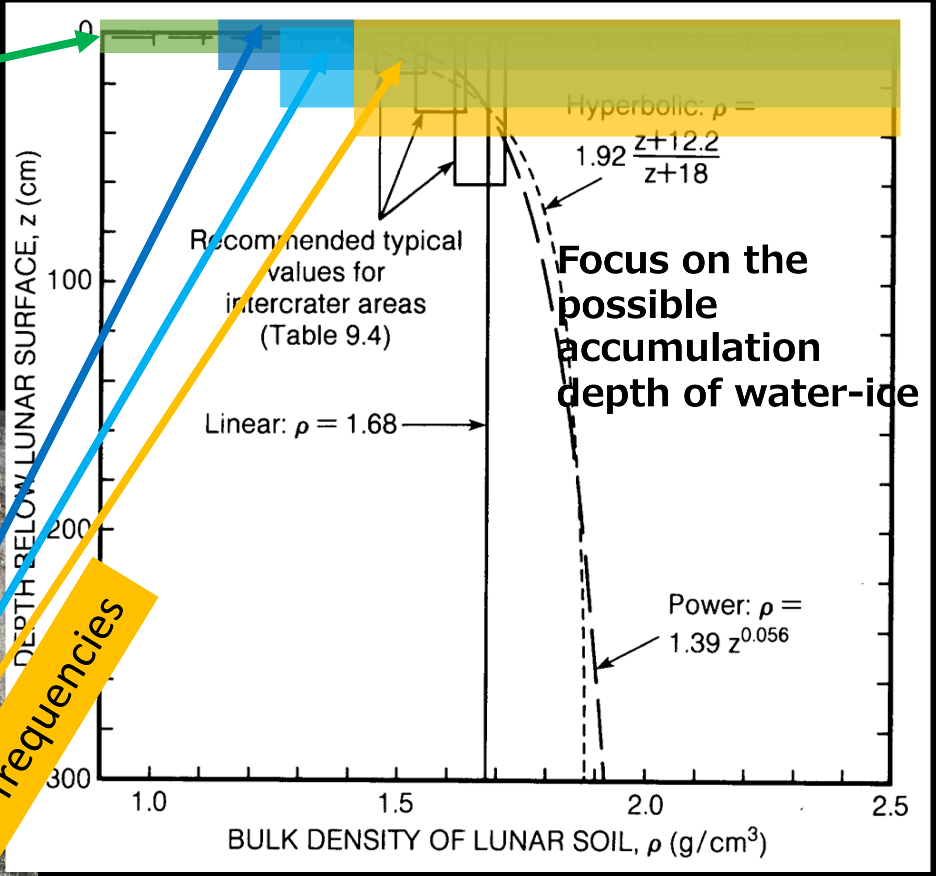
Outline of the Lunar Dielectric Analyzer (LDA)

Microstrip line resonator：
Monitor the resonant freq. change, corresponding to permittivity on the surface

Vivaldi antenna：
Acquire the dielectric properties from multiple depths using S11 parameter

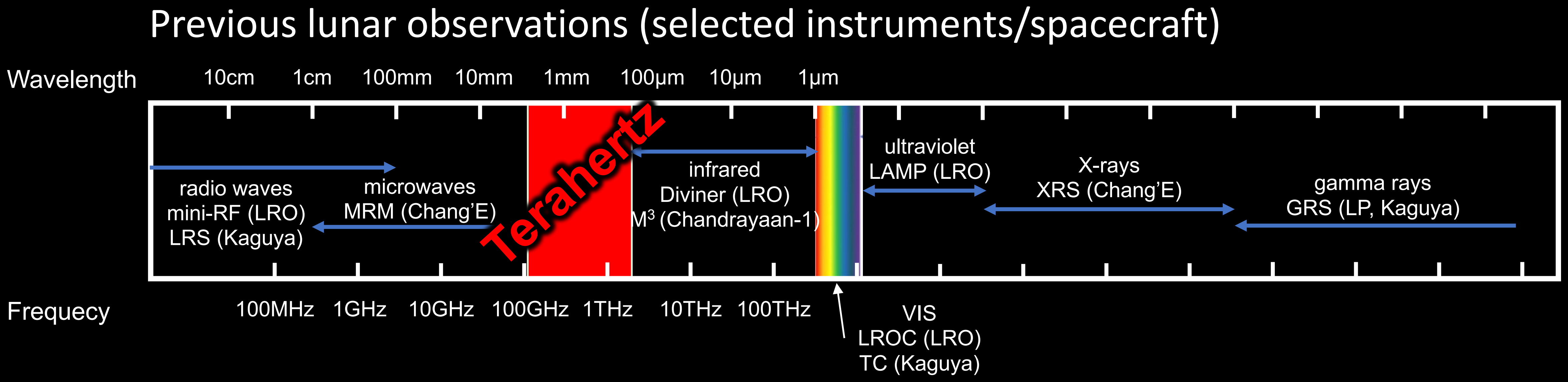


Density profile can be derived

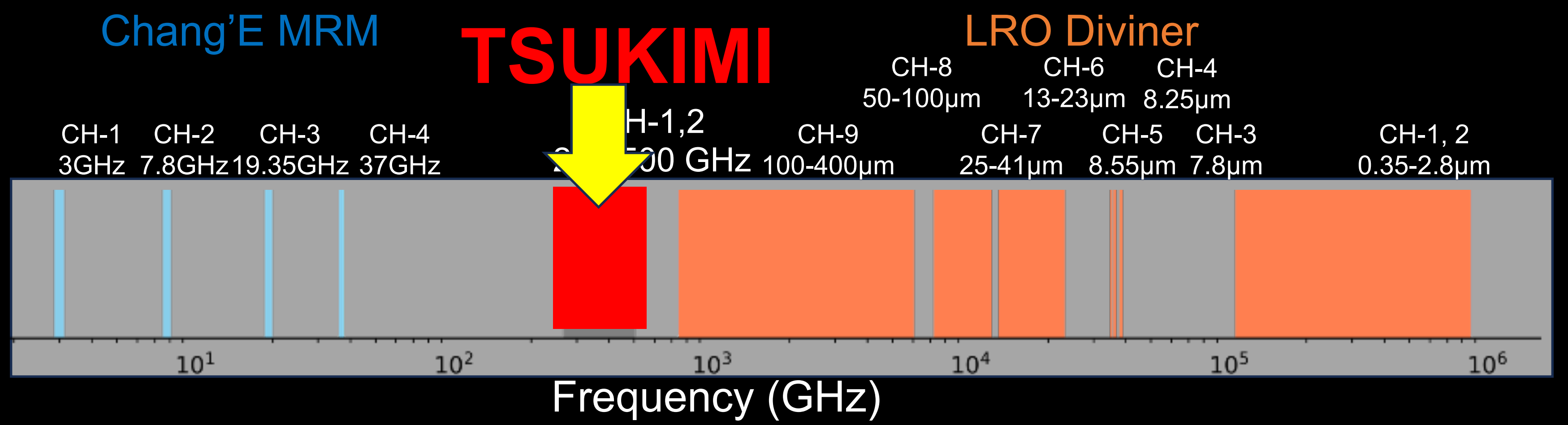


(Heiken, 1991)

Terahertz band remained largely unexplored

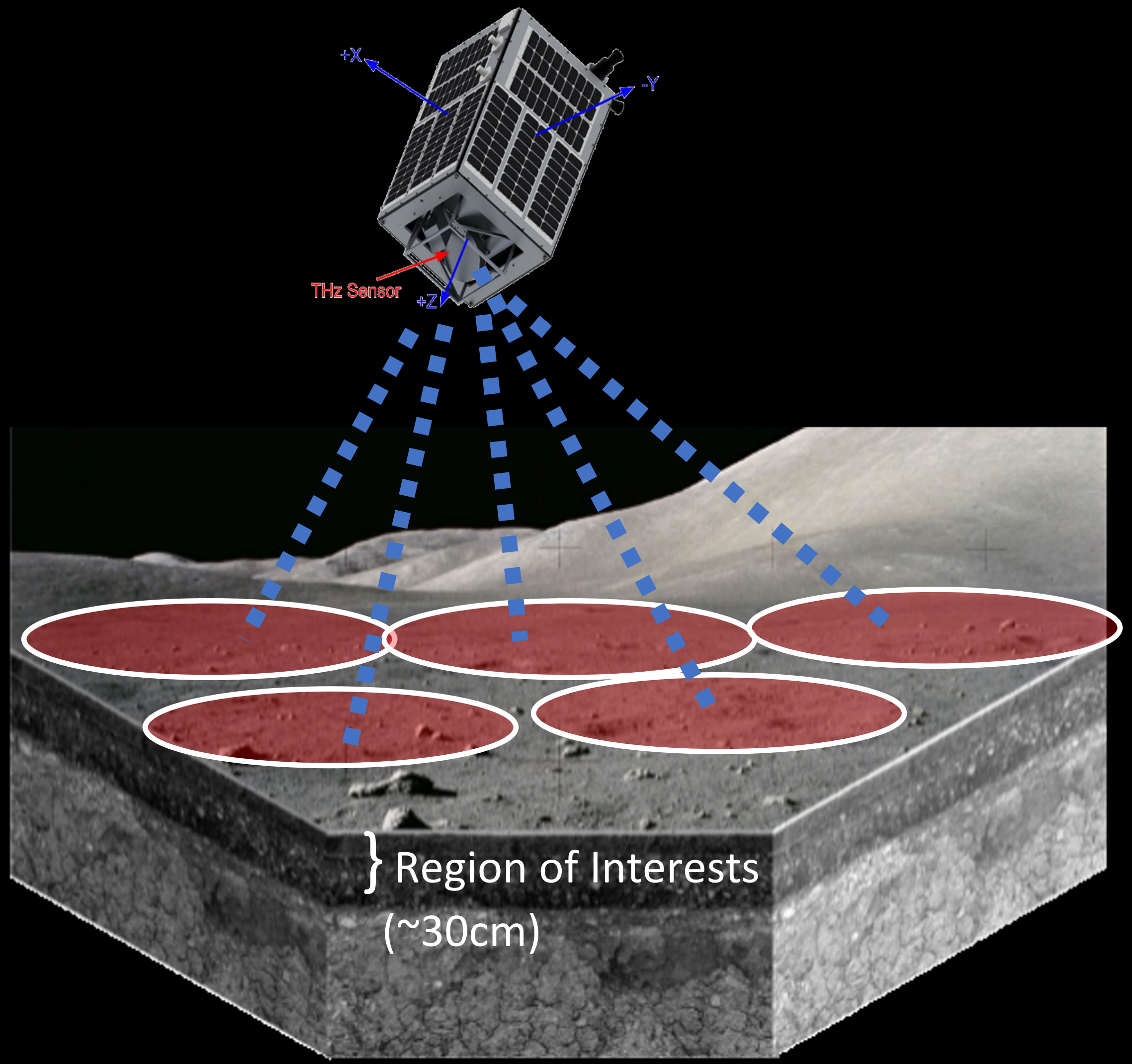


But, terahetz has recently become accessible due to technological advance



Complementary to the extensive remote sensing data already available

TSUKIMI（Lunar Terahertz Surveyor for Kilometer-scale Mapping) is a small satellite



- Spacecraft ~80cm-sized, ~100kg in mass
- Instrument is a successor of SMILES onboard IST
- Scheduled to be launched in FY 2027, and plan 1 year operation duration
- Measure the brightness temperature of the Moon in the **terahertz range**
- Map the heterogeneity of the lunar surface soil in terms of thermal diffusivity and apparent permittivity

Summary

- The LDA (Lunar Dielectric Analyzer) will be used by an Artemis III astronaut to measure the permittivity of the lunar surface near the polar region.
- Permittivity is an important key parameter for identifying ice and understanding packing density especially if we can measure at different temperatures.
- The permittivity value of LDA will be an important reference for past and future electromagnetic observations.
- TSUKIMI (Lunar Terahertz SUrveyor for KIlometer-scale MappIng) is a lunar orbital mission scheduled for launch in FY2027.
- TSUKIMI will measure the brightness temperature of the Moon in the terahertz region and map the heterogeneity of the lunar surface soil in terms of apparent dielectric constant.
- The relative changes in permittivity will be essential for identifying the concentrations and distributions of useful materials such as volatiles and metals.

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