Microwave brightness temperature model of the Moon and implications for the calibration of meteorological satellite

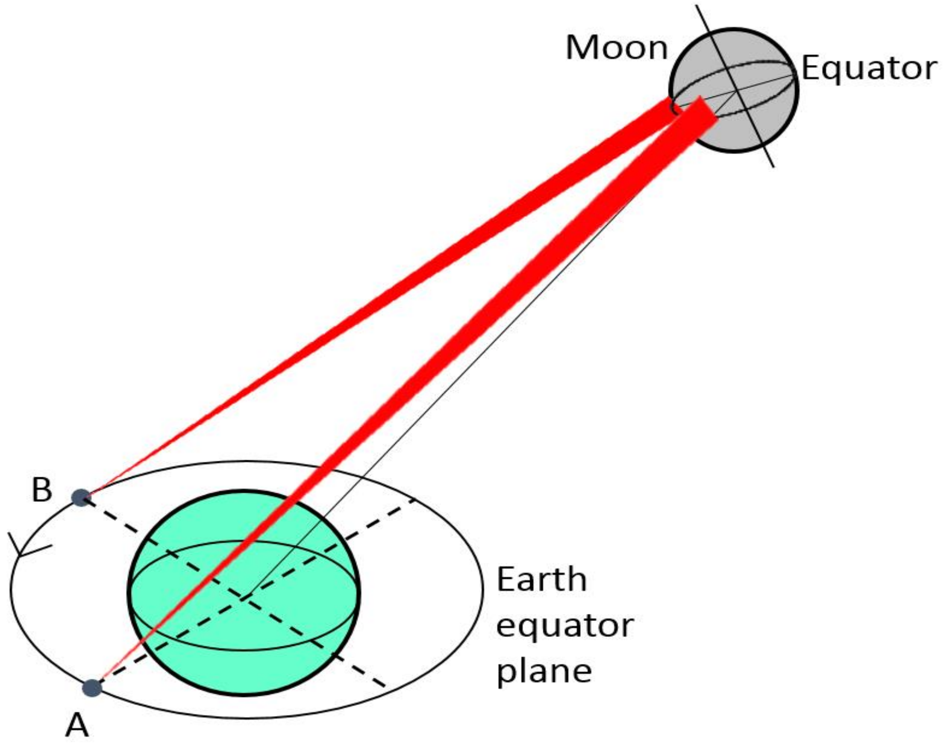
Niutao Liu

Key Laboratory of Information Science of Electromagnetic Waves (MoE)
Fudan University
Shanghai 200433, China
ntliu@fudan.edu.cn

FUDAN UNIVERSITY

Background

- The surface infrared and microwave radiations of the Moon change periodically with the solar illumination.
- The Moon can be observed by the meteorological satellite. The microwave radiation from the Moon is a potential calibration source for meteorological satellite (Yang et al., 2018, Burgdorf et al., 2019).
- The new generation of geosynchronous series satellite, Feng Yun-4M will carry the microwave radiometers, which can observe the Moon as well.

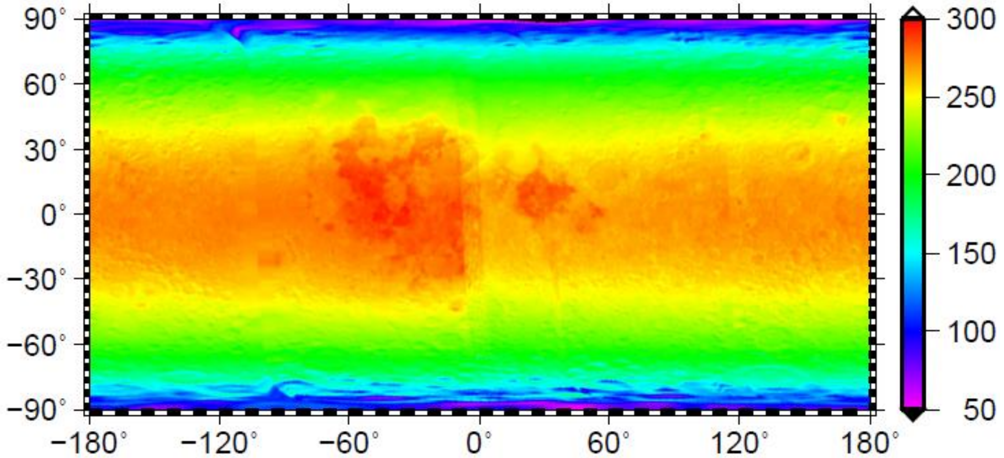


Background

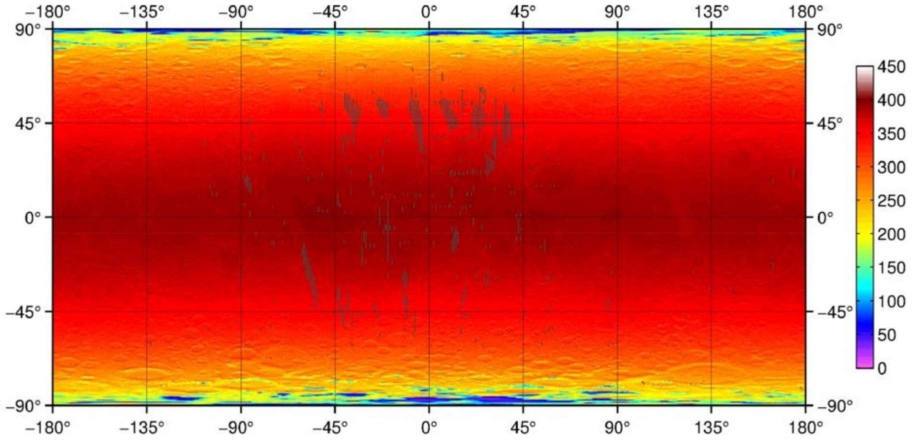
Models in early studies are mainly based on the Earth-based microwave observations of the Moon. The dielectric constant (especially the loss tangent) and thermal-physical properties of the Moon are from the measurements of lunar samples (Heiken, 1991).

Background

- The microwave observations of Chang'E-2 (2010) and infrared observations of Diviner provide new constrains on the dielectric and thermal-physical properties of the Moon (Fang 2014; Hayne 2017).



Chang'e 2 37GHz TB (Fang and Fa, 2014).



Diviner surface temperature (Williams, J. P., 2017).

Lunar microwave radiation model

From the radiative transfer theory, microwave brightness temperature (TB) is the cumulative contribution of the thermal emission at different depths (Keihm, 1984):

$$T_B(\theta_0) = [1 - \Gamma(\theta_0)] \int_0^{\infty} sec\theta_1 k_a(z) T(z) e^{-\int_0^z k_a(z) sec\theta_1 dz'} dz$$

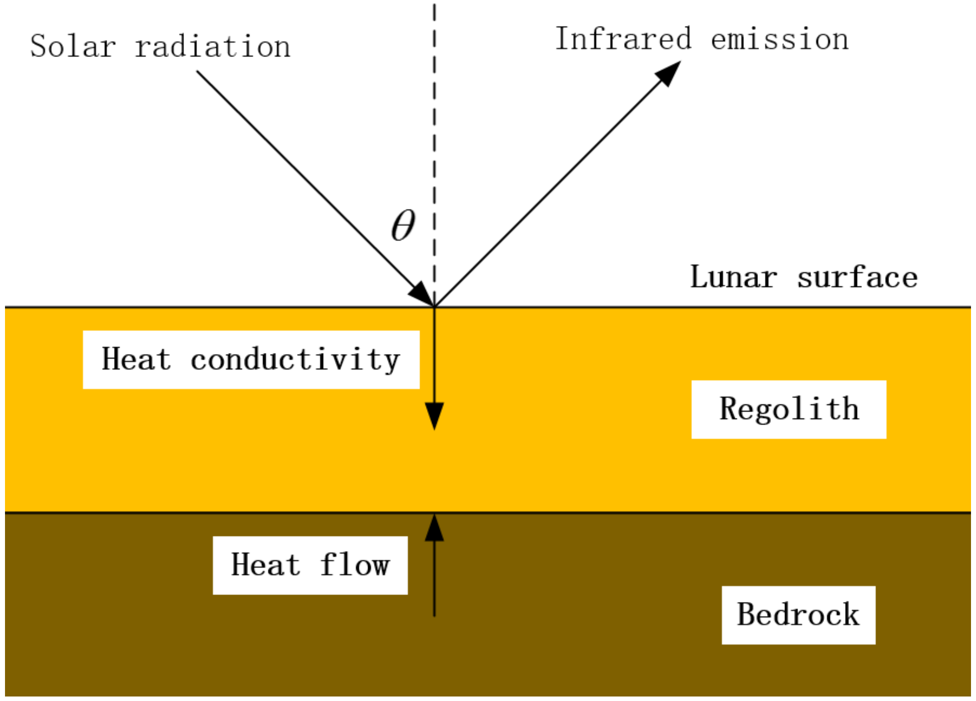
Where $\mathrm{k_a} = \frac{2\pi f\sqrt{\varepsilon'} tan\delta}{c}$ is the absorption coefficient. Γ is the Fresnel reflectivity.

Heat-conduction model

Heat conduction equation (Hayne, 2017)

$$\rho C\frac{\partial T}{\partial t}=\frac{\partial}{\partial z}\left(K\frac{\partial T}{\partial z}\right)$$

Where t is the time, T is the temperature and z is the depth.



Upper boundary:

$$K(z,T)\left.\frac{\partial T}{\partial z}\right|_{z=0}=TSI(1-A)\cos^{+}\theta-e\sigma T_s^4$$

Lower boundary

$$K(z,T)\left.\frac{\partial T}{\partial z}\right|_{z=-\infty}=-J_0$$

Thermal-physical parameters

Heat capacity (Hayne et al., 2017) :

$$C = C_0 + C_1 T + C_2 T^2 + C_3 T^3 + C_4 T^4$$

Here $C_0 = -3.6125 \text{J kg}^{-1}\ \text{K}^{-1}, C_1 = +2.7431 \text{J kg}^{-1}\ \text{K}^{-2}, C_2 = +2.3616 \times 10^{-3} \text{J kg}^{-1}\ \text{K}^{-3},$

$C_3 = -1.2340 \times 10^{-5} \text{J kg}^{-1}\ \text{K}^{-4}, C_4 = +8.9093 \times 10^{-9} \text{J kg}^{-1}\ \text{K}^{-5}$

Bulk density:

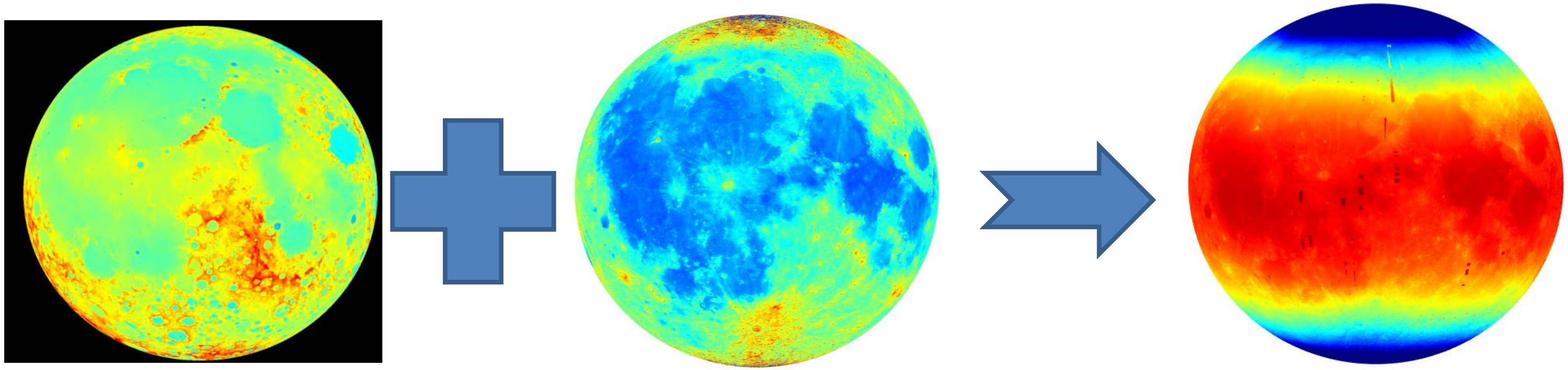
$$\rho(z) = 1800 - (1800 - 1100)e^{-z/H}$$

Heat conductivity:

$$K = K_c \left[1 + 2.7 \left(\frac{T}{350} \right)^3 \right]$$

Heat-conduction model

- Here is an example of the simulated surface temperature with DEM and reflectance data.

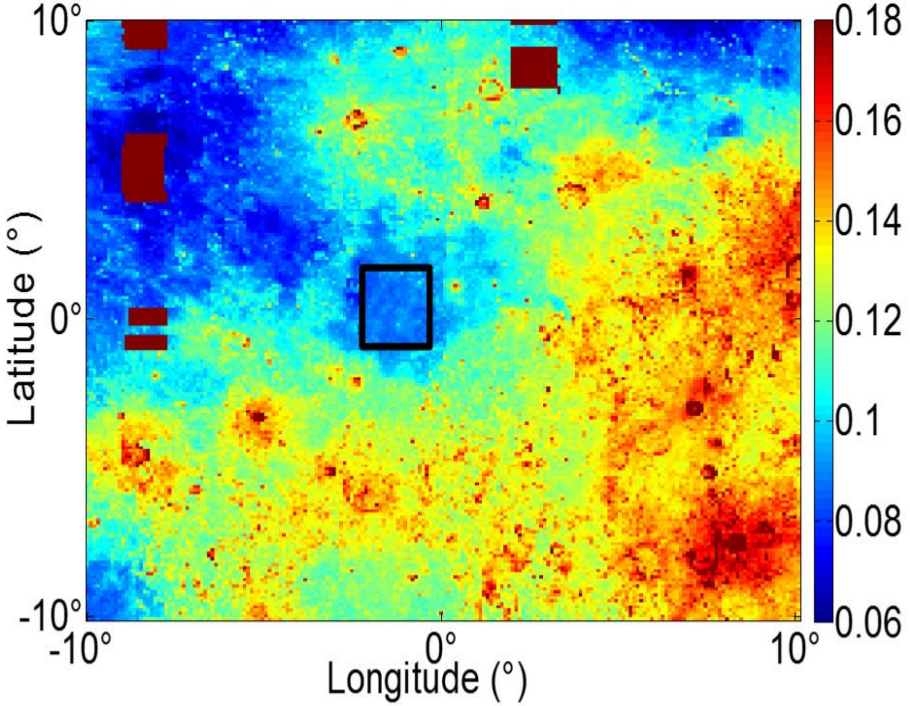


LOLA DEM

Clementine Reflectance

Surface temperature

Temperature simulation and validation



Solar reflectance of lunar center region (Liu et al., 2018)

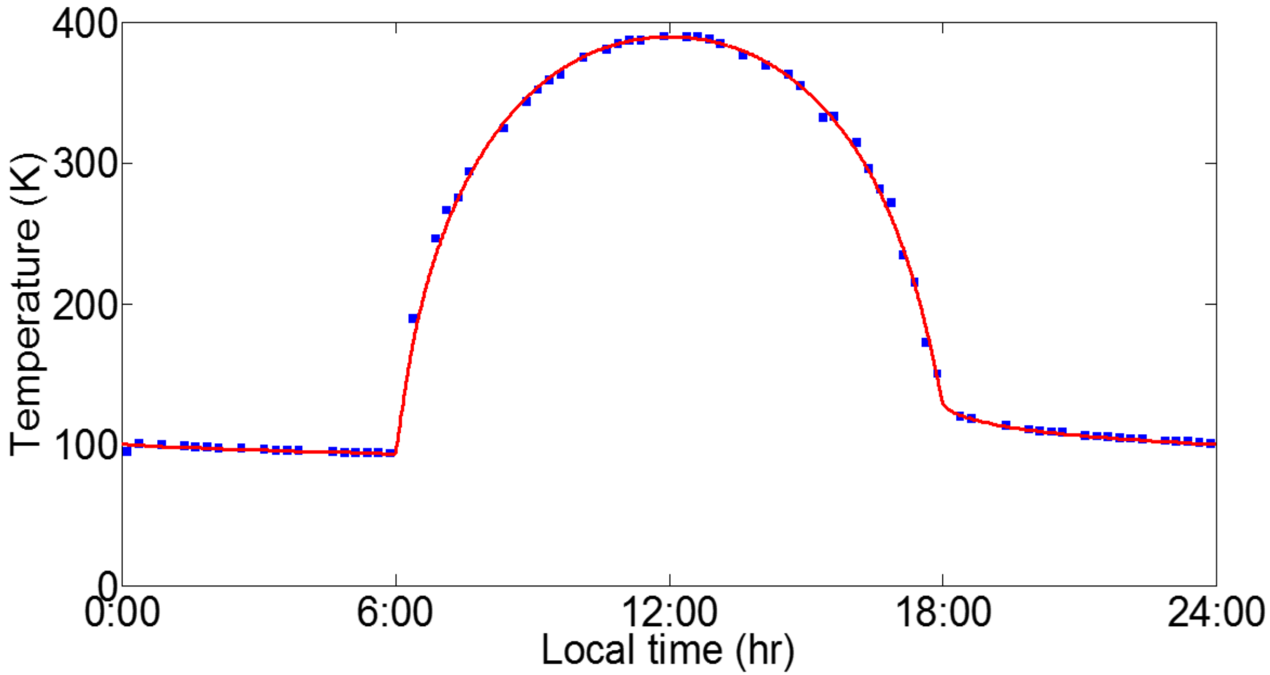


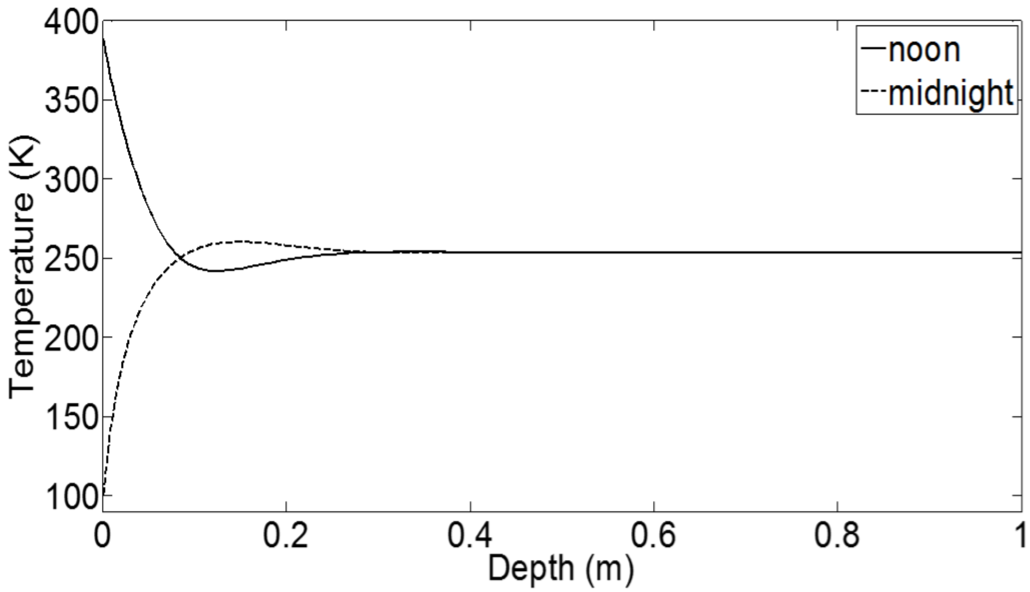
Fig. 3 Validation of the heat conduction model. The solid red line is the simulated surface temperature and the blue points are the average temperatures of Diviner data (Liu et al., 2018) .

Diviner data inside the black box are chosen to validate the heat transfer equation. The average $A_0 = 0.09$. Diviner T_7 channel (25-41μm) data are used for validation (2012, Vasavada, A. R., JGR).

FUDAN UNIVERSITY

Temperature simulation and validation

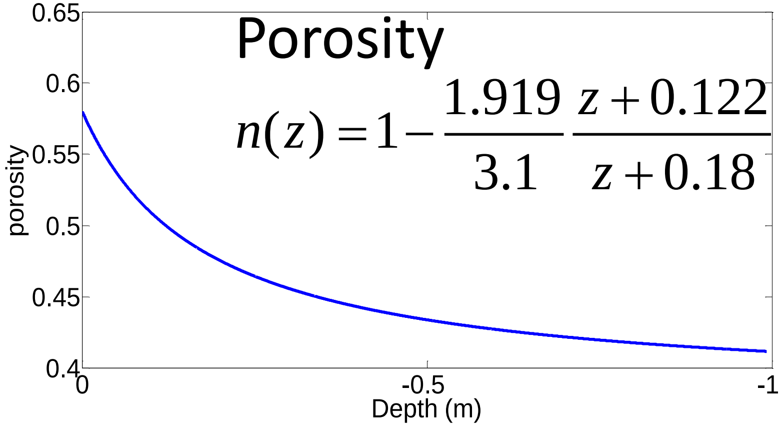
- The temperature at 1.3 m is about 256K by the Apollo 17 probe 2. The simulated temperature is 255K at the same place.
- The validations of temperatures at surface and deep layer make sure the simulated temperature can be used to calculate the microwave radiation.



Temperature profile of the equator center at noon and midnight (Liu and Jin, 2020)

Liu, Fa, and Jin, Brightness Temperature of Lunar Surface for Calibration of Multi-Channel Millimeter-Wave Radiometer of Geosynchronous FY-4M, IEEE TGRS, 2018

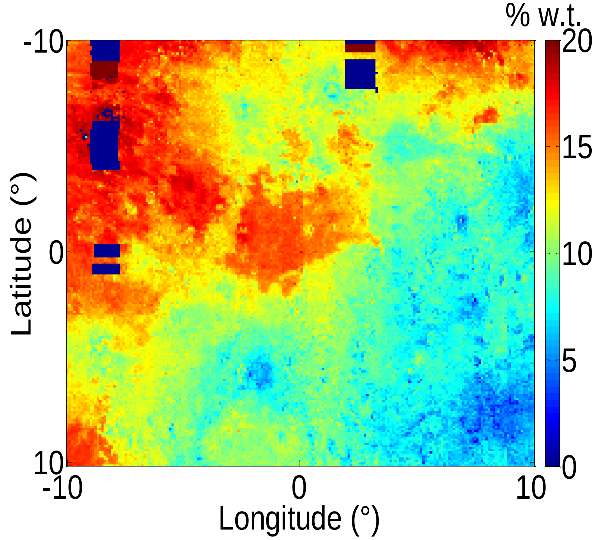
- Permittivity in radiative transfer model:

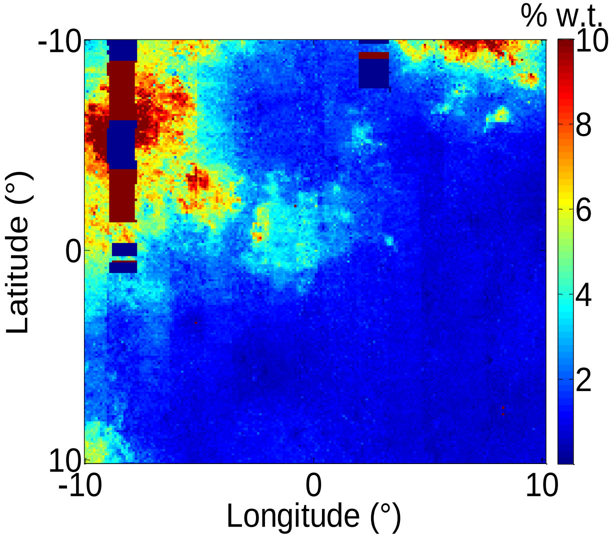


Maxwell-Garnett formula (Fa, 2012)

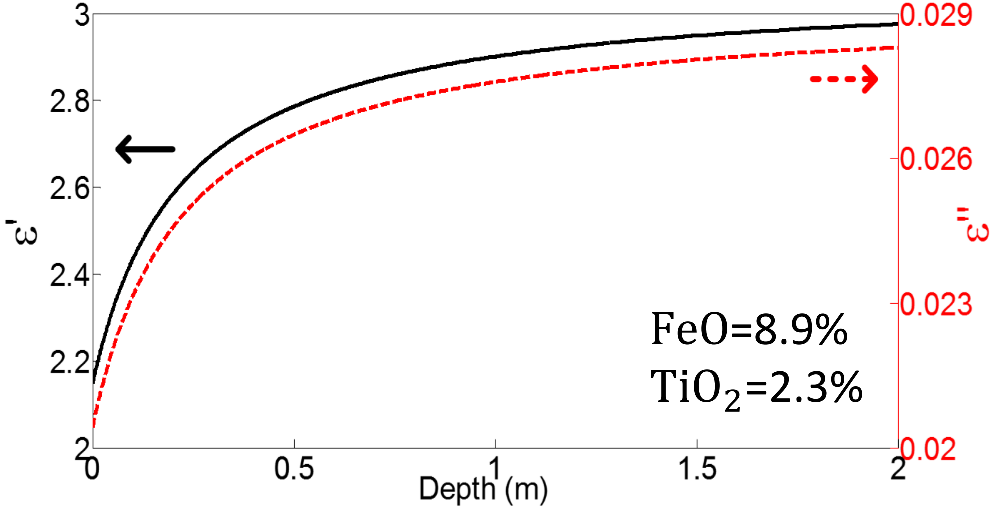
$$\frac{1}{1.7}\frac{2.75-1}{2.75+2} = \frac{1}{(1-n(z))g}\frac{\varepsilon'(z)-1}{\varepsilon'(z)+2}$$

Specific gravity $g = 27.3\text{FeO} + 11\text{TiO}_2 + 2773$





FeO content (Liu et al., 2019) TiO_2 content

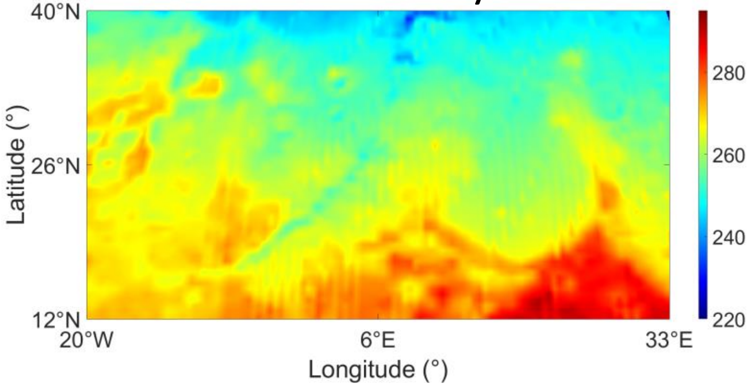


Dielectric constant with Maxwell-Garnett formula (Liu et al., 2018)

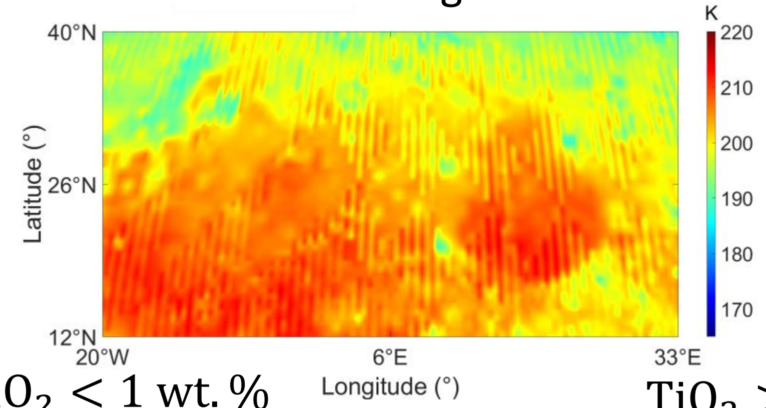
- The microwave radiation of lunar surface is very sensitive to loss tangent. A change of 0.003 in loss tangent results in a change of about 7 K in disk-integrated microwave TB at 89 GHz.
- The loss tangents were determined by measurements of lunar samples at 450 MHz on the Earth in early study (Heiken, 1991; Fa, 2012). But the number of lunar samples is very limited. The loss tangent has a wide range.

Loss tangent fitting

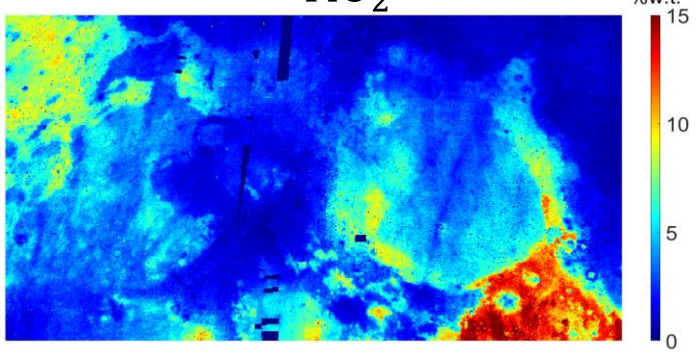
37GHz TB daytime



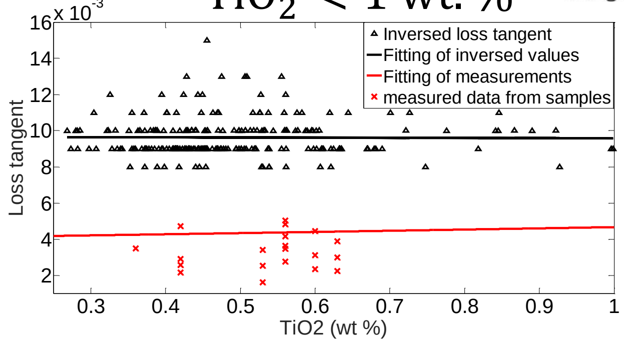
37GHz TB night



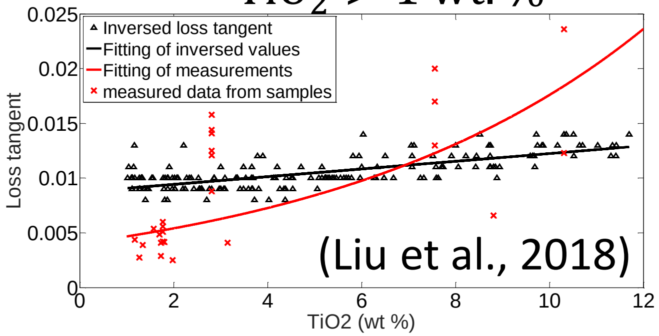
TiO_2



$TiO_2 < 1$ wt. %



$TiO_2 > 1$ wt. %



- The inverted tanδ are in the range of the measured values.
- The inverted values are fitted with TiO_2 because from the measurement of lunar samples, the influence of TiO_2 on tanδ is dominate.

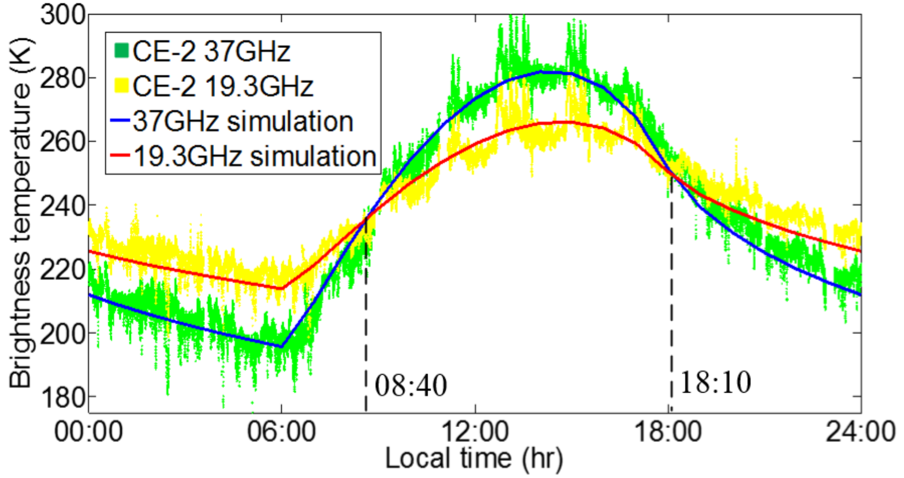
Fitted loss tangent:

$$\tan\delta = 3.516 \times 10^{-4} TiO_2 + 0.0087 \quad TiO_2 > 1\%$$
$$\tan\delta = -8.945 \times 10^{-5} TiO_2 + 0.0097 \quad TiO_2 < 1\%$$

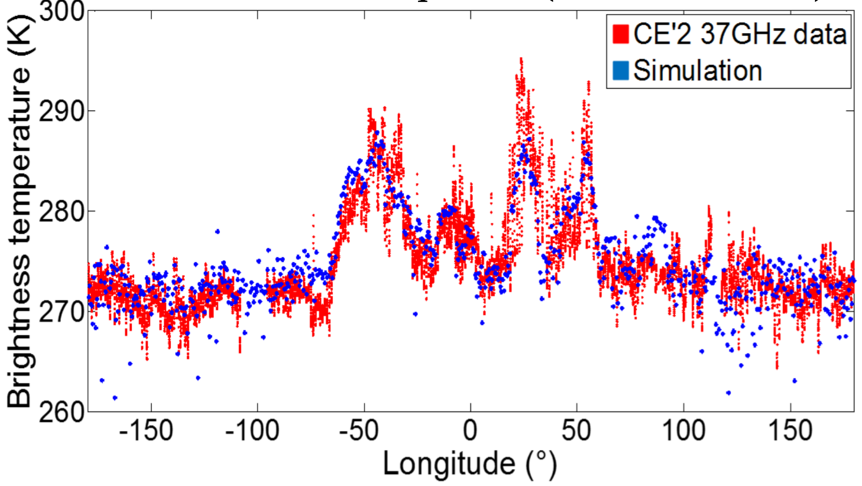
Microwave simulation and validation

- Maria with large loss tangents and TiO_2 abundance have high microwave brightness temperature during daytime in figures below.
- At high frequency (37GHz), the maximum TB is large and the local time of the peak TB is more close to 12:00 than low frequency (19GHz), because the penetration depths are different in right figure.

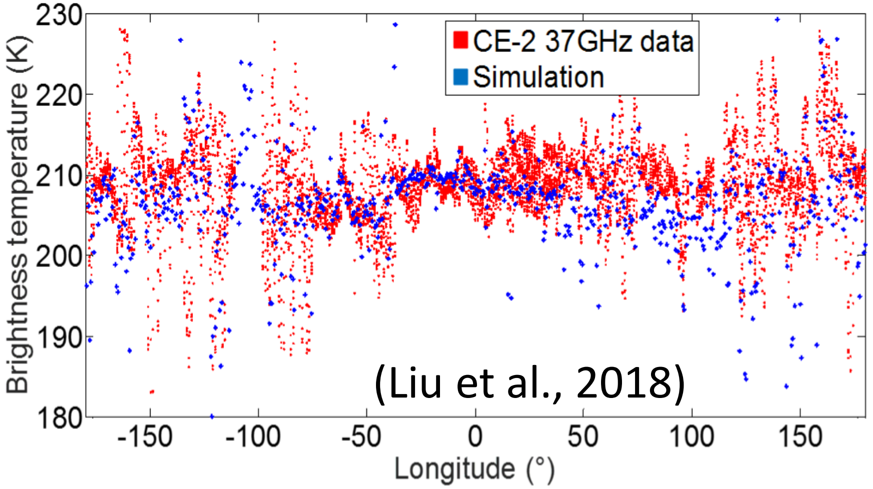
Simulation at equator (37GHz and 19GHz, all the day)



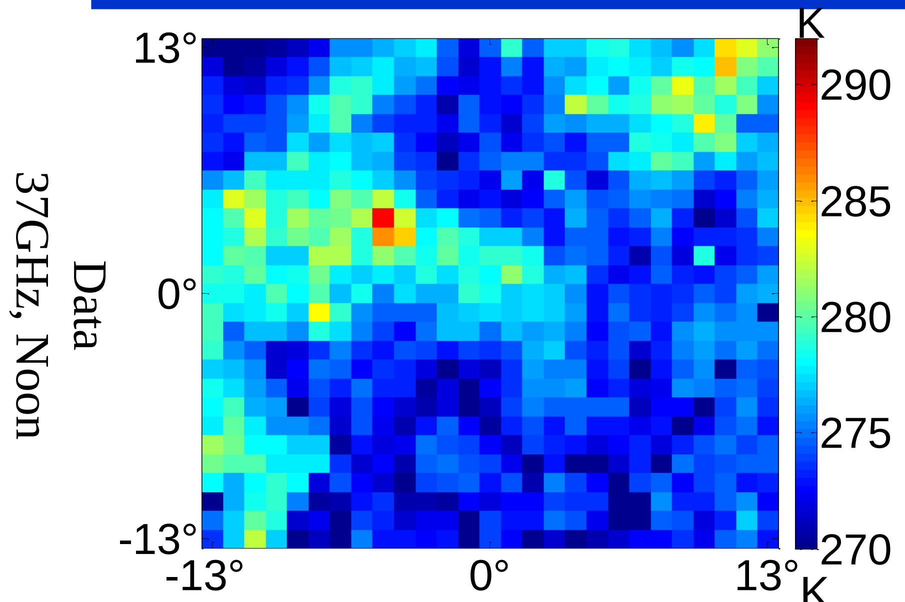
Simulation at equator (37GHz, noon)

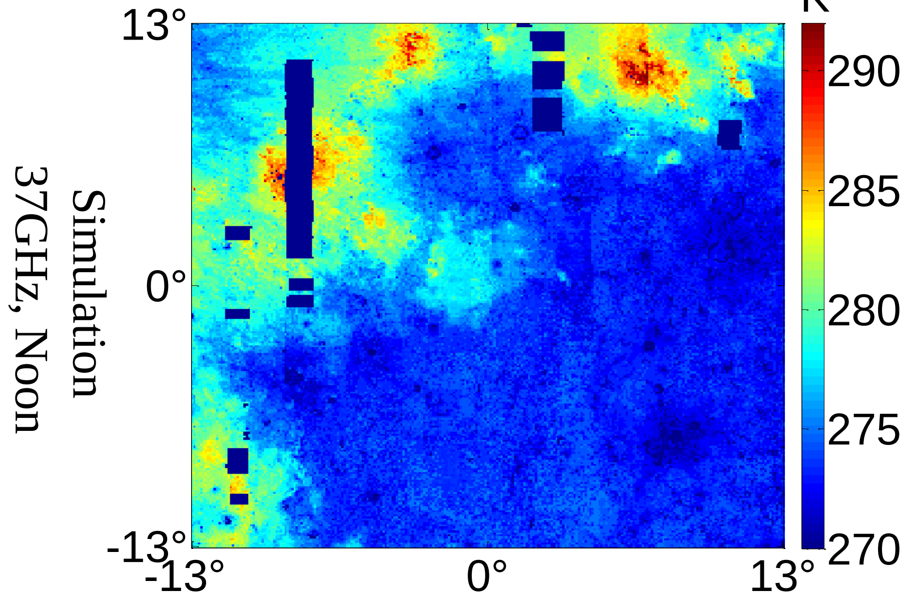


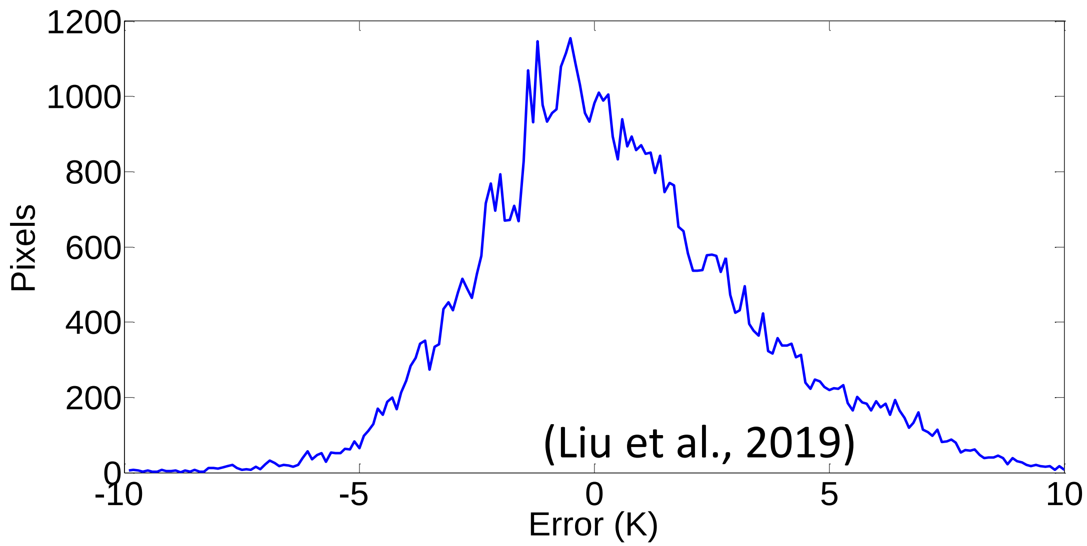
Simulation at 60° N (37GHz, noon)



Error analysis





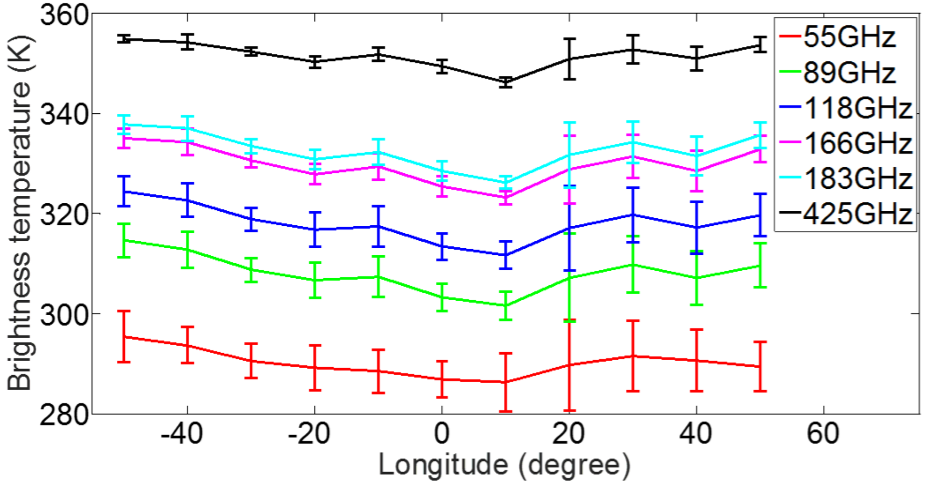


Error distribution

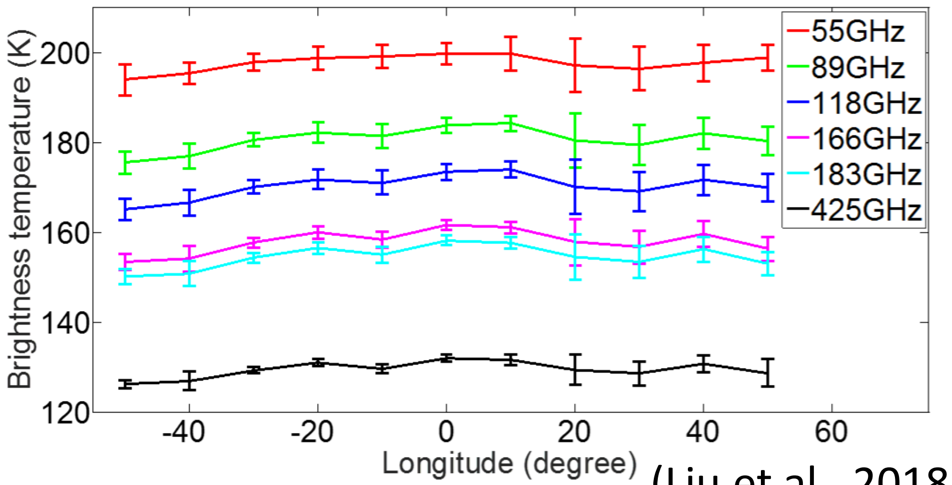
Error	Percentage
<3K	72%
<5k	90%
<10k	99.5%
The number of pixels (Without useless pixel):64902	

Calibration model for FY-4M

noon

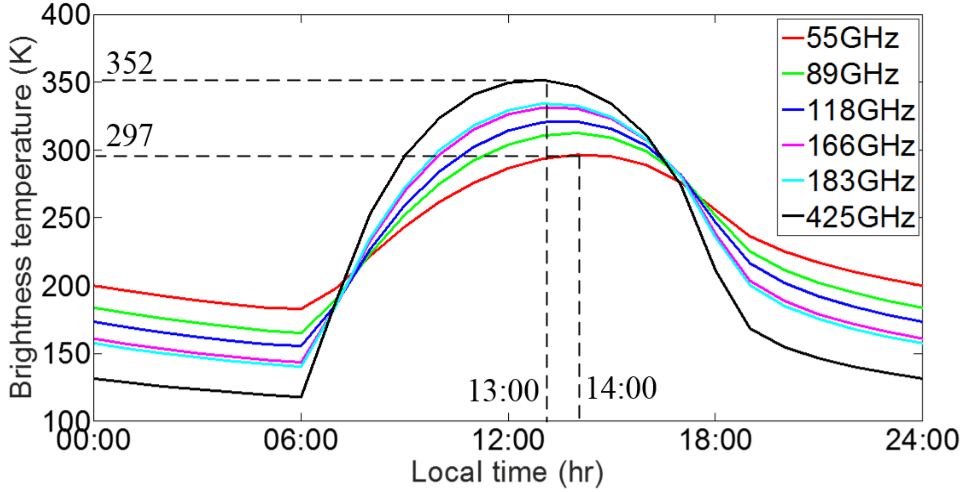


midnight



(Liu et al., 2018)

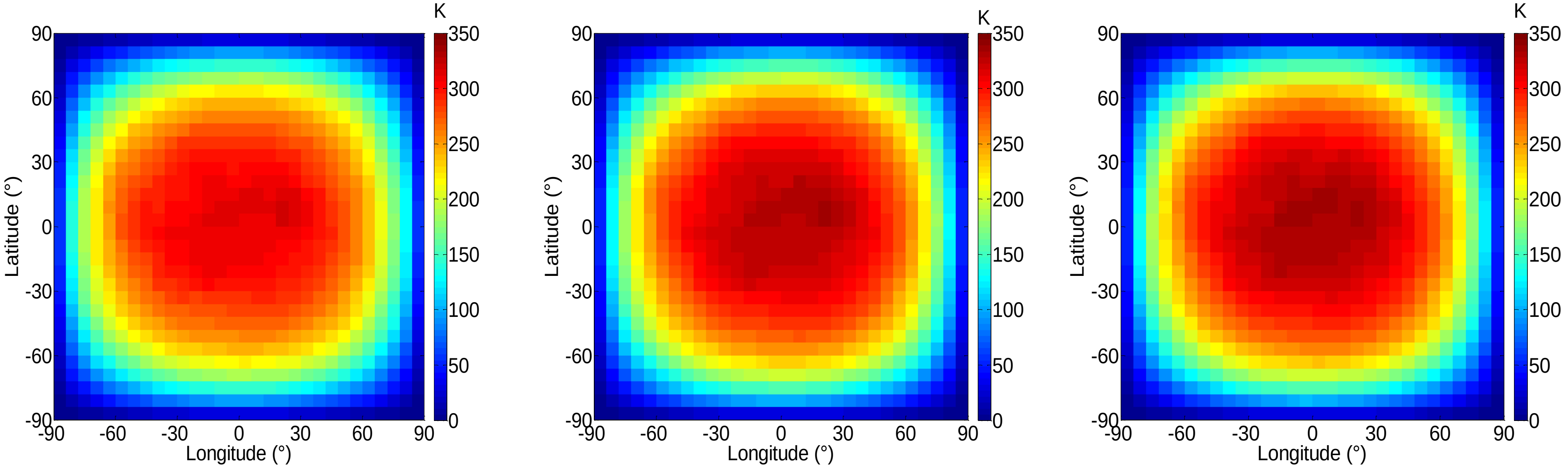
TB at lunar center region



Possible error by RMS in fitting loss tangent

Frequency (GHz)	Error by RMS in fitting (K)
425	1.8
183	3.2
166	3.4
118	3.7
89	3.8
55	3.4

Disk-integrated TB

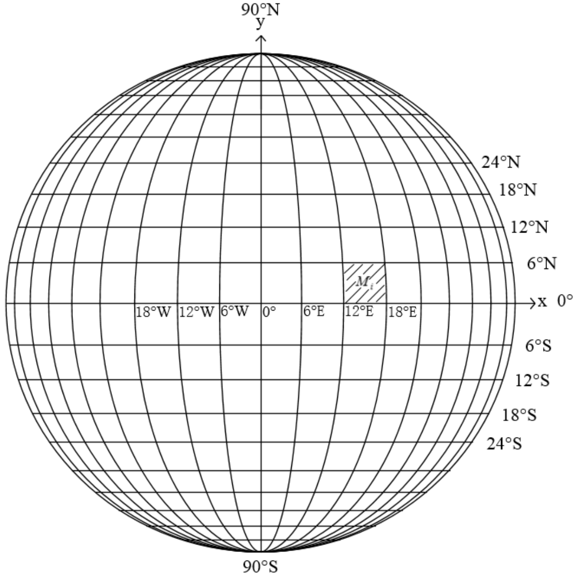


89GHz 157GHz 183GHz

Microwave TB of the near side

The disk-integrated TB of the nearside of the Moon: $\overline{T}_{BW} = \dfrac{\sum_i T_{Bi}(\theta_{0i}) G_i \cdot M_i}{\sum_i G_i \cdot M_i}$

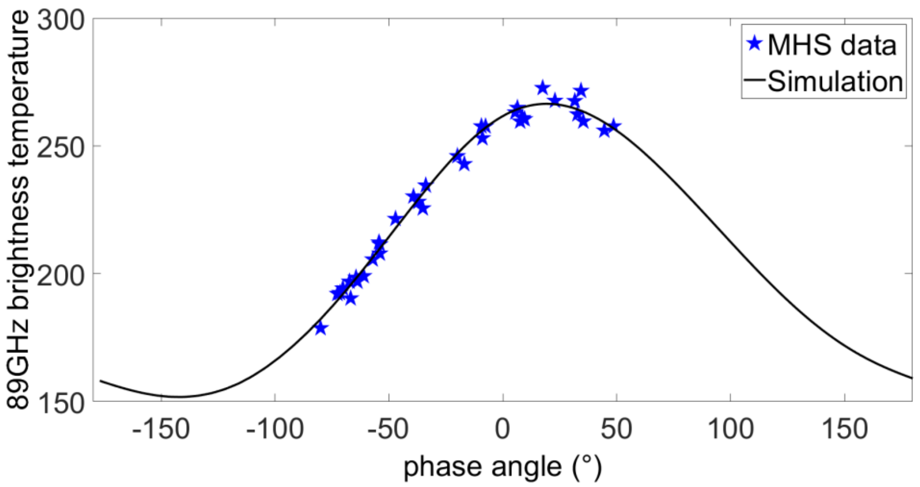
The antenna response function: $G_i = \dfrac{1}{2\pi\sigma^2} e^{-\frac{x_i^2 + y_i^2}{2\sigma^2}}$



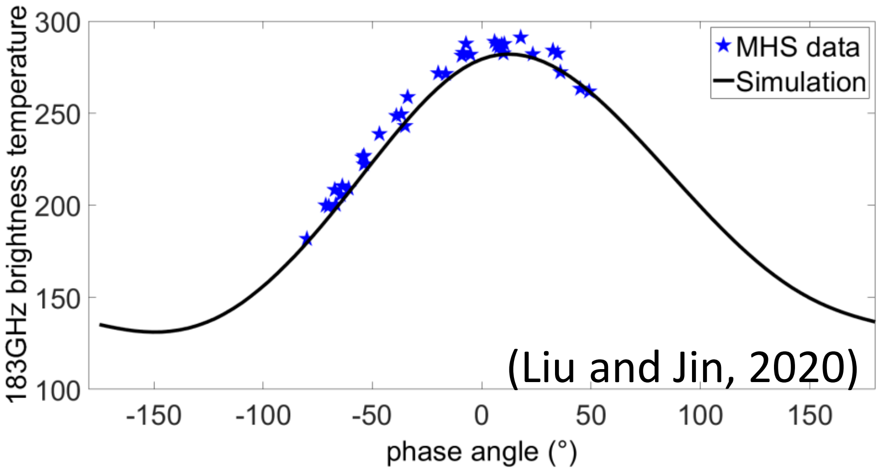
Divided sub-regions

(Liu and Jin, 2020)

Influence of FWHM



89GHz



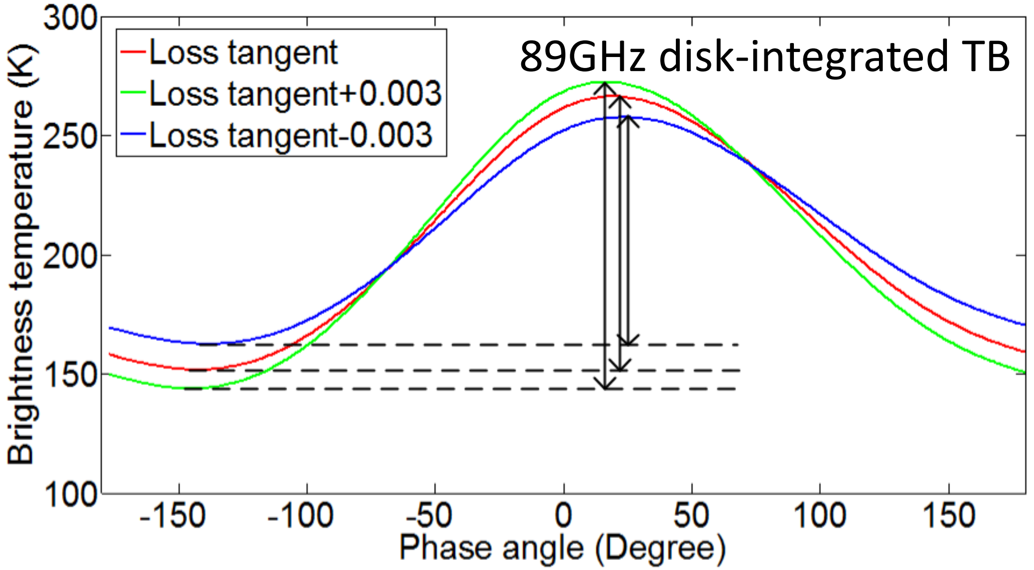
183GHz

Simulation and data analysis (Liu and Jin, 2020; Burgdorf, 2019)

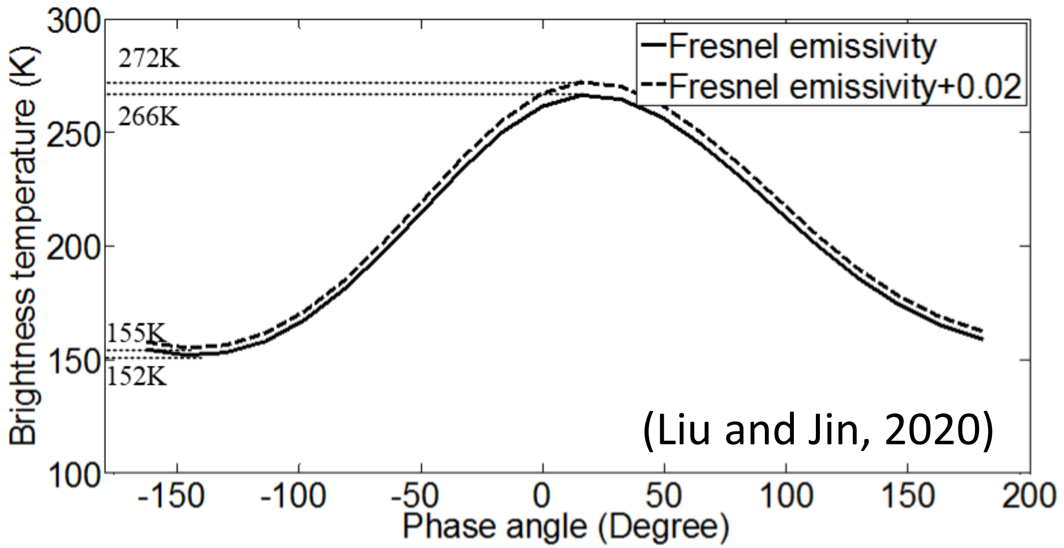
The simulated disk-integrated TBs are consistent with the data from microwave humidity sounders onboard NOAA-18 at 89GHz and 183GHz (published by Burgdorf, 2019). The phase angles of the peak TB are consistent with the data as well. At 183 GHz, the maximum TB is higher and the phase angle of the peak TB is more close to 0° than that of 89 GHz.

Liu and Jin, Average Brightness Temperature of Lunar Surface for Calibration of Multi-Channel Millimeter-Wave Radiometer from 89GHz to 183GHz and Data Validation, IEEE TGRS, 2020

Influence of loss tangent and emissivity



Influence of loss tangent

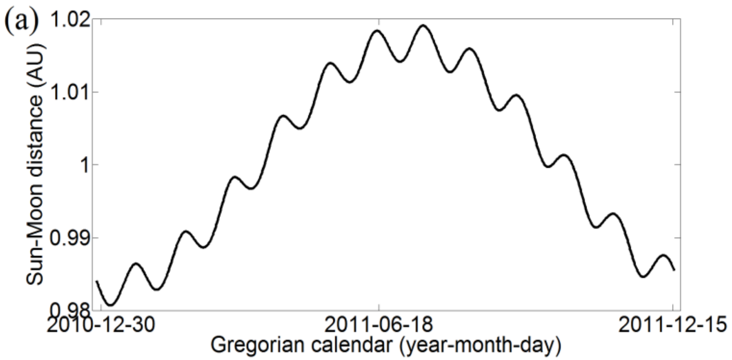


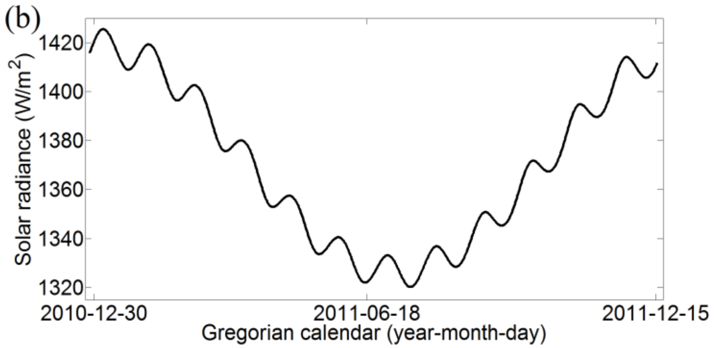
Influence of emissivity

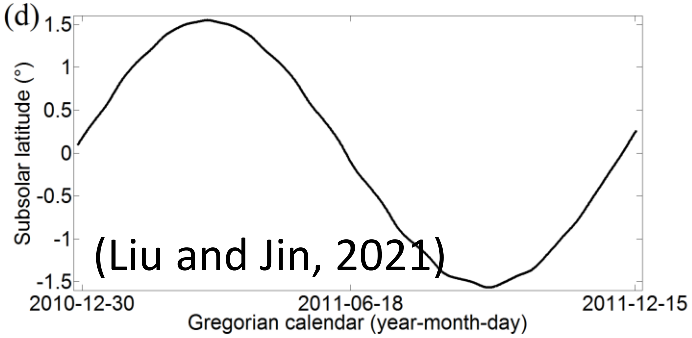
Loss tangent	Maximum TB	Minimum TB	TB difference	Peak phase angle
tanδ	266K	152K	114K	19°
tanδ +0.003	273K	144K	129K	17°
tanδ -0.003	258K	163K	95K	23°

- increase in loss tangent will enhance the peak TB and reduce the minimum TB. The phase angle of the peak TB will reduce as well.
- The increase in emissivity will enhance the TBs all the day.

Influence of solar illumination



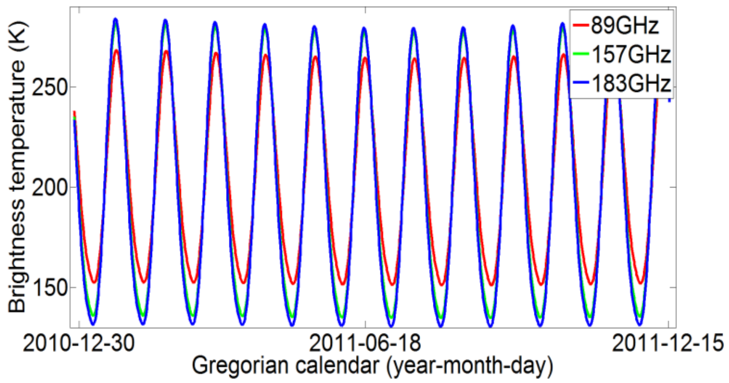




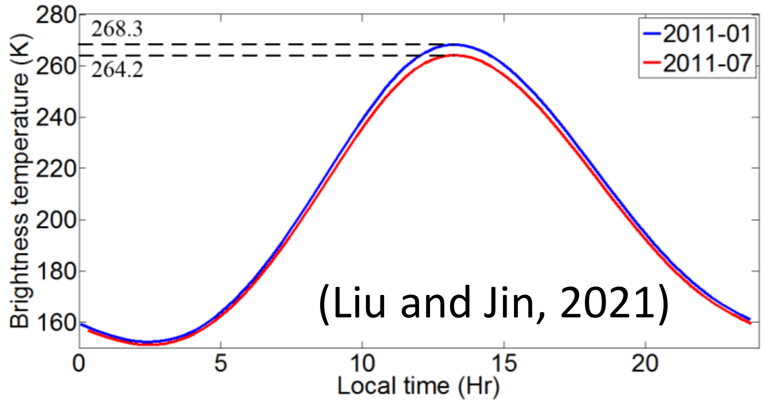
The real time solar irradiance can be derived as：

$$TSI = 1371/d^2$$

Where d is the distance between the Sun and the Moon.



disk-integrated TB at 2011



89GHz disk-integrated TB

The maximum TB at Jaunary 2011 is larger than that at July, 2011 by 4 K to 4.5 K at 89 GHz, 157 GHz, and 189 GHz in the low-right figure.

Liu and Jin, Calibration of the Space-borne Microwave Humidity Sounder Based on Real-Time Thermal Emission from Lunar Surface, China Science: Earth Science, 2021

Conclusion

- Microwave brightness temperature of the Moon could be a potential calibration source for meteorological satellites.
- More study about lunar thermal-physical and dielectric properties will be helpful in improving the model.

Thank you!

Q&A