A Calibrated Lunar Microwave Radiative Transfer Model Based on Satellite Observations

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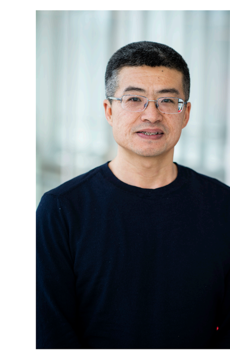


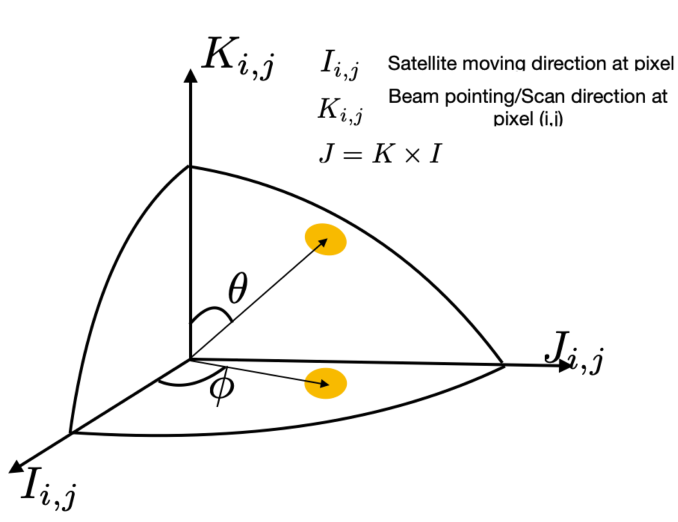
Introduction: As a potential external calibration reference for spaceborne microwave sounding instruments, accurate and reliable information of lunar disk-averaged radiance at millimeter band are important and fundamental. Based on study for 2-D lunar scans of the Advanced Technology Microwave Sounder (ATMS) on board the NOAA-20 satellite, the lunar radiance spectrum from 23 to 183 GHz at full moon phase has been reported in our previous work. In this study, the performance of a lunar microwave radiative transfer model (RTM) developed by Keihm was investigated. By taking the ATMS observations as the reference truth, the surface emissivity in the lunar RTM can be calibrated. The calibrated RTM model was then evaluated by independent satellite observation data sets from AMSU (Advanced Microwave Sounding Unit) and MHS (Microwave Humidity Sounder) instruments on several NOAA satellites. Results show that with the calibrated model, significant improvement can be made to reduce the uncertainties in the lunar microwave RTM simulations at millimeter wavelengths

Microwave Lunar Brightness Temperature Spectrum from Satellite Observations

The calibrated antenna temperature of Moon's disk at each data sample of the satellite observations, Ta_{moon}, can be modeled as function of disk-integrated lunar microwave brightness temperature, Tb_{moon}^{Disk}, antenna main beam solid angle Ω_p, and normalized antenna response G as below[1]:

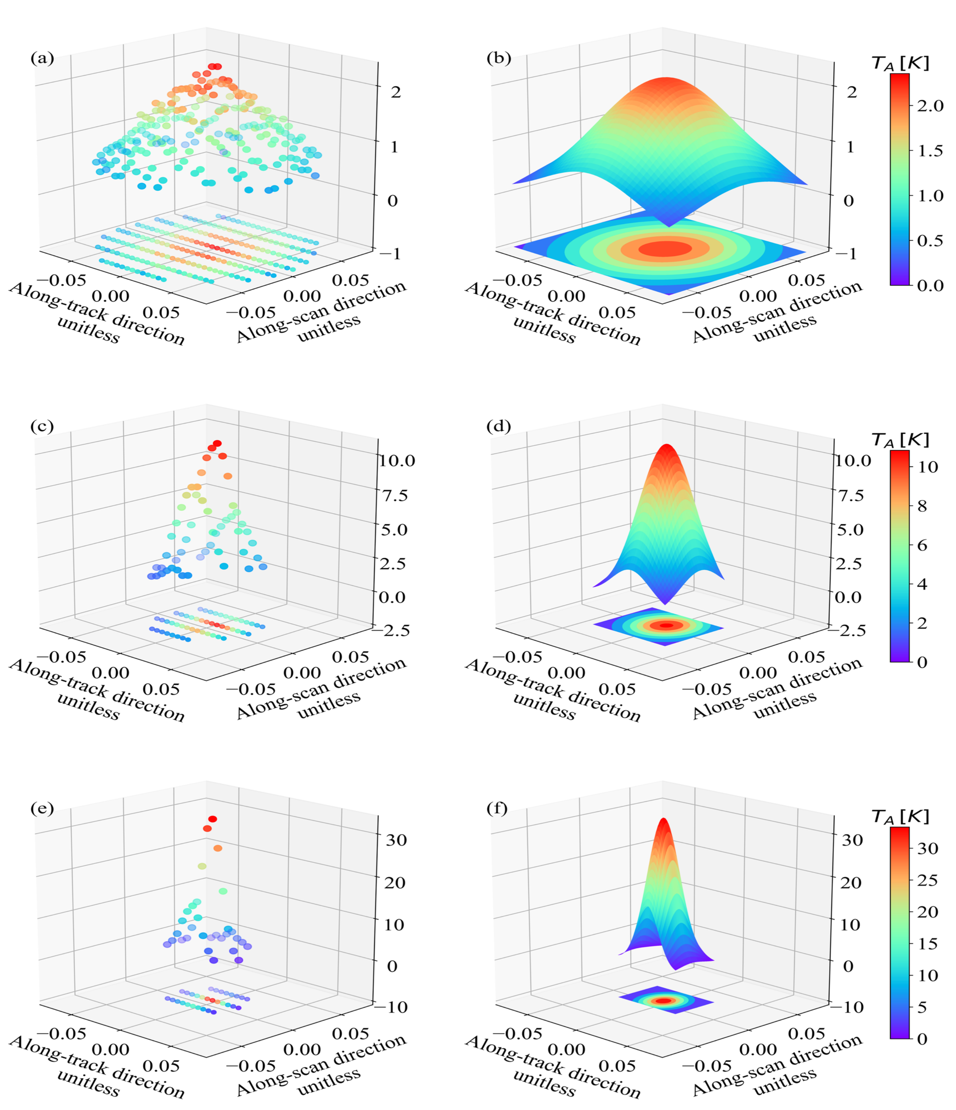
$$Ta_{moon}(\theta_{ifov}, \phi_{ifov}) = \frac{\Omega_{moon}^{max}}{\Omega_p} \cdot Tb_{moon}^{Disk} \cdot G(\theta_{ifov}, \phi_{ifov})$$

In equation above, θ, ϕ are zenith and azimuth angle of lunar disk center in polar coordinate system of antenna pattern, G is normalized antenna pattern, Ω_{moon}^{max} is the maximum solid angle integration of lunar disk over the surface of normalized antenna pattern when the Moon appears at the antenna beam center.

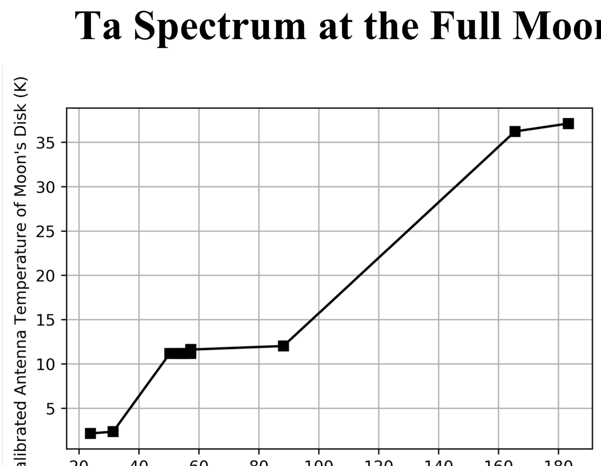


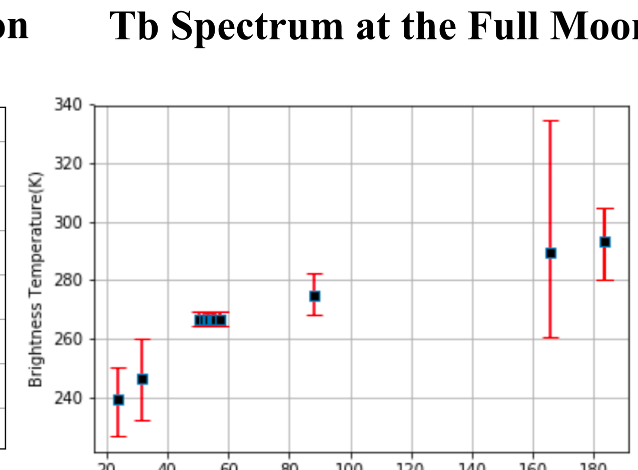
The microwave brightness temperature spectrum of Moon's disk in full-Moon phase can be retrieved from the well calibrated ATMS lunar 2-D scan observations at the frequencies range from 23 to 183GHz It shows the increase trend of Tb with frequency: Tb_{moon}^{Disk} increased from 240K at 23GHz to 296K at 183GHz.

NOAA 20 ATMS 2D Lunar Observations



Ta Spectrum at the Full Moon **Tb Spectrum at the Full Moon**





Radiative Transfer Model for Lunar Microwave Brightness Temperature Simulation

Microwave brightness temperature of lunar emission can be calculated as convolution of microwave electrical loss with lunar regolith temperature profile over different depths[2]:

$$T_B(\lambda) = E_\lambda \int_0^\infty \kappa_\lambda \sec(\theta_i) \cdot T(z) \cdot e^{-\int_0^z \kappa_\lambda(z)\sec(\theta_i)dz} dz$$

Where K is the thermal conductivity and T is the thermal profile of the lunar regolith. The details of the numerical solution of Eq.3 and the model parameters can be found in [2][3]. For this study, by solving a thermal conduction equation, a profile with 23 layers extending from the lunar surface to 98 cm under the regolith was generated at each latitude of the Moon from -90 to 90 degree.

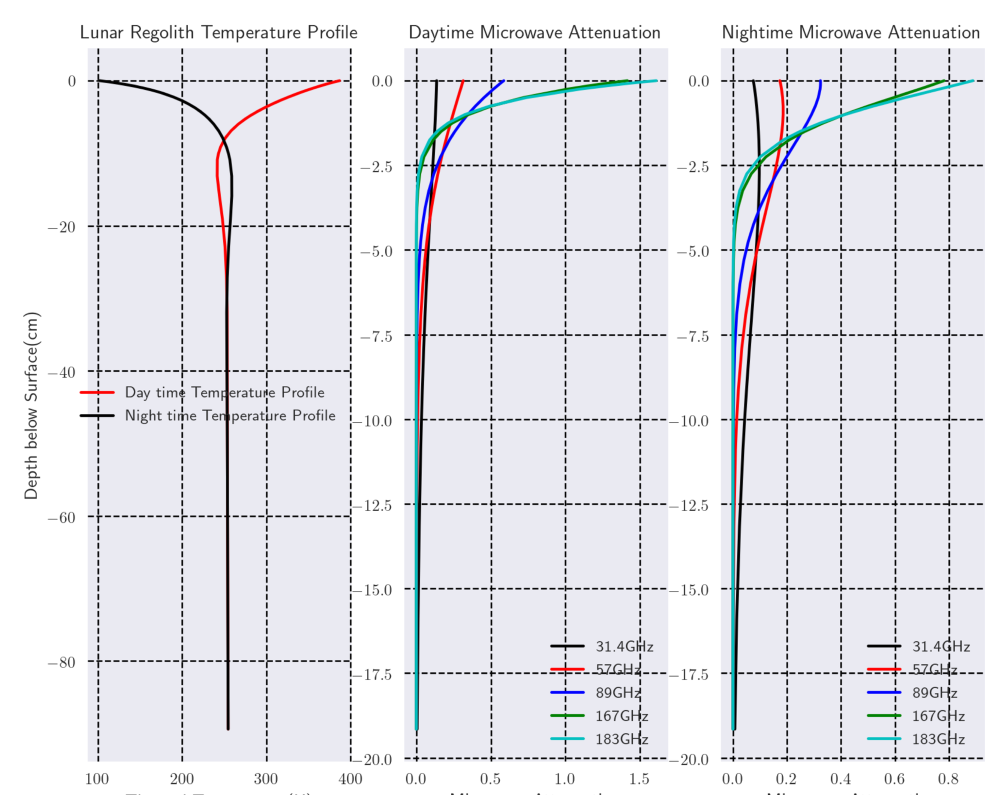
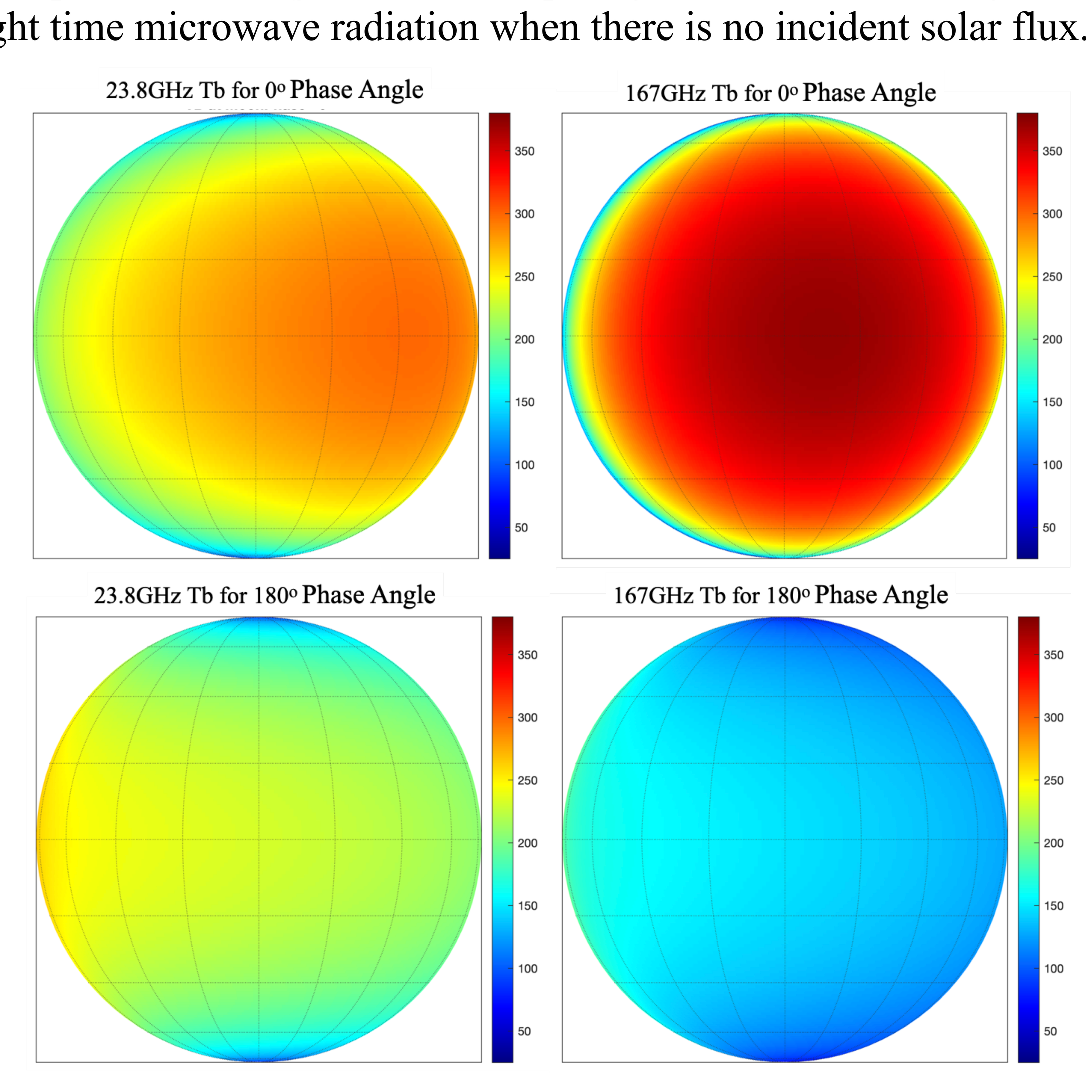
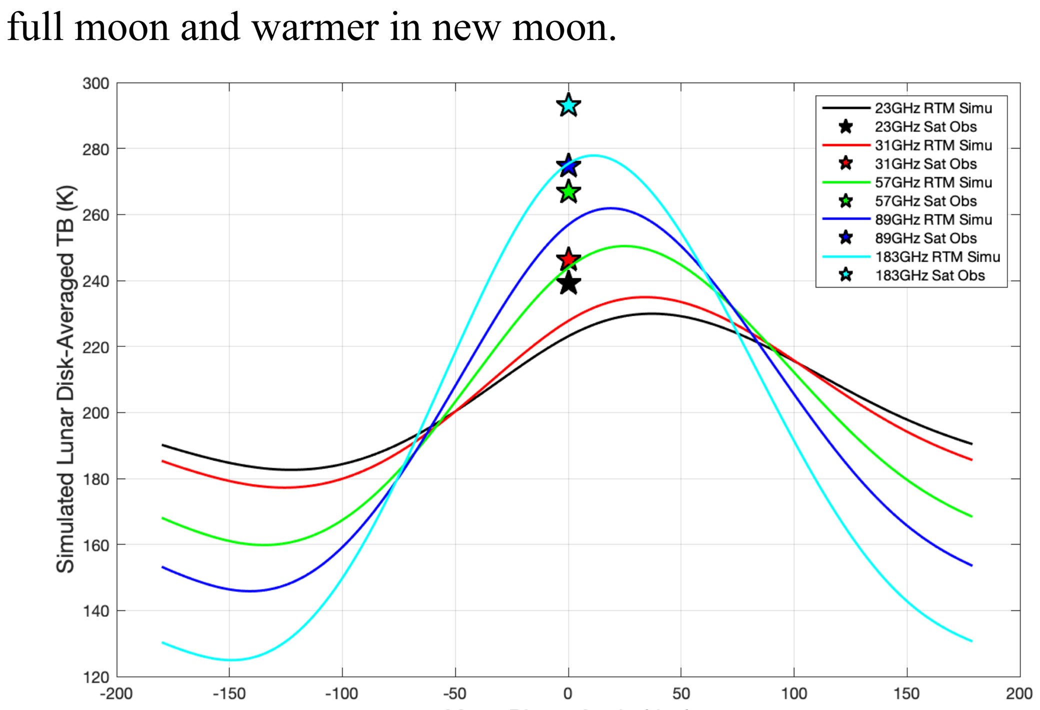


Figure above shows the temperature profile for local noon and mid night at the center of lunar front disk. Also presented are the corresponding microwave electric loss weights at different frequencies. It is seen that while the higher frequency is much more sensitive to the microwave emission at the near-surface layers above 2.5~cm, the emission from deeper layer have more contribution for the top of surface T_b of lower frequency bands, most notably for the night time microwave radiation when there is no incident solar flux.



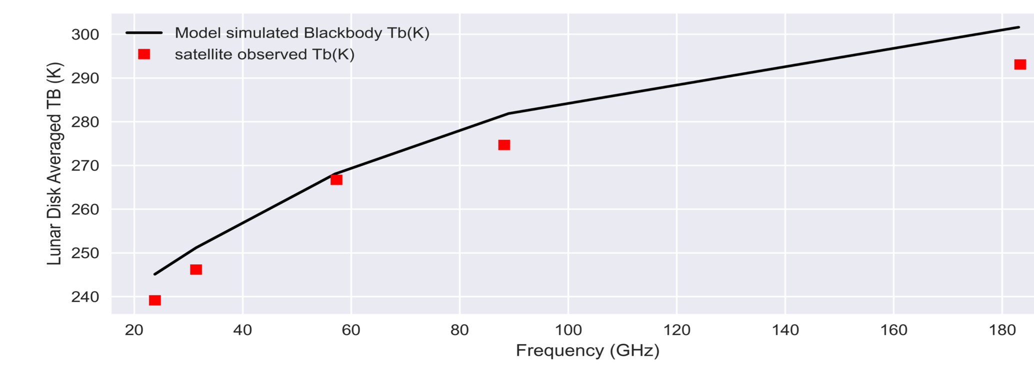
Above is the simulated front side lunar disk T_b of full Moon(local noon) and new moon (local mid night) for 23.8 and 167~GHz. It is seen that while the distribution of microwave T_b on lunar disk is impacted by latitude and local phase angle, there is significant phase shift in the T_b distribution at lower frequency. Also noticed is that compare to higher frequency, the T_b in low frequency is colder in full moon and warmer in new moon.

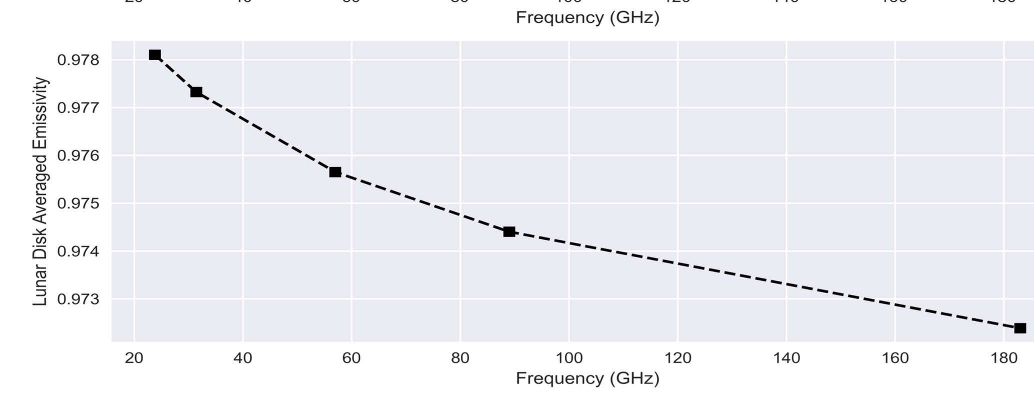


The phase shift can be clearly seen in disk-averaged T_b as shown in figure above, which can be explained by the larger phase lag in the longer wavelength due to the penetration depths characteristic of microwave radiation. The phase lag angle decreases from 36° in 23.8~GHz, 16° in 89~GHz to 9° in 183~GHz, which are close with those derived from satellite observations in our previous study [4].

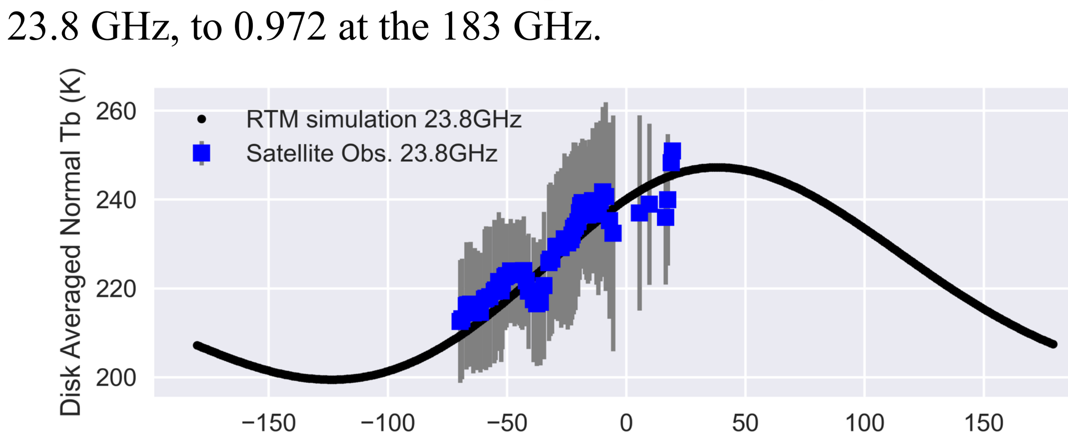
Calibration and Validation of the Lunar RTM Simulations

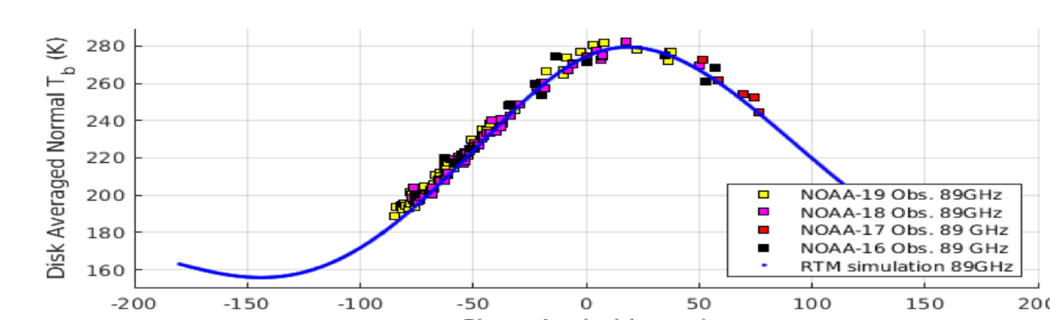
As noticed in the previous figure, the original RTM simulations with Fresnel surface emissivity has significant deviation from satellite observations. By taking the lunar disk-averaged T_b spectrum from NOAA 20 ATMS as the reference truth, the lunar RTM model can be calibrated to the satellite observations, with the lunar surface emissivity being calculated by comparing the "Black Body" RTM simulation with satellite observations.

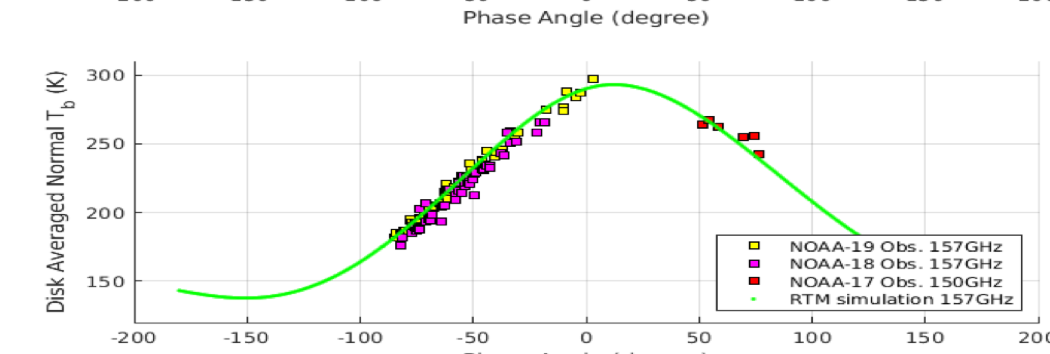


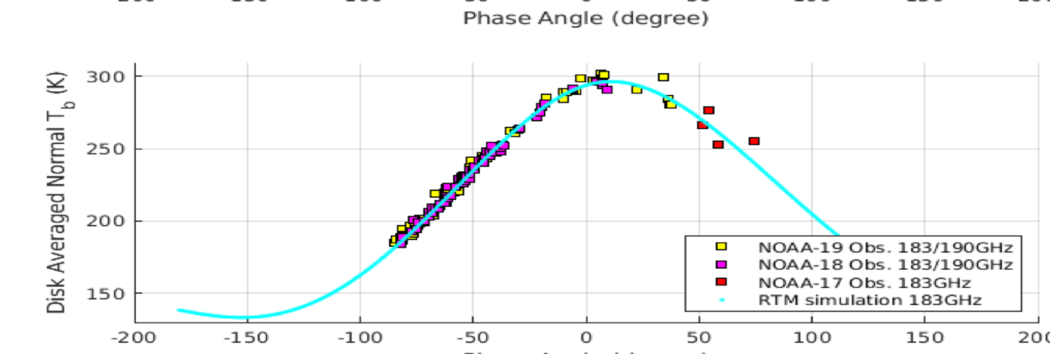


It shows that the disk-averaged lunar surface emissivity decreases with the increase of the detection frequencies, it changes from 0.978 at the 23.8 GHz, to 0.972 at the 183 GHz.









The satellite lunar observation samples from 15 years drifting orbit of NOAA-18 AMSU-A were collected and to compare with the model simulations for frequency from 23 to 89~GHz. For higher frequency from 89 to 183~GHz, the lunar observation samples from AMSU-B and MHS instruments of different satellites were collected and used on this purpose. Results show both magnitude and the phase shift angle matched very between the satellite observation and the calibrated RTM model simulations.

Conclusion and Discussion

Presented in this study is the calibration and improvement of the lunar microwave RTM model based on satellite observations. A multi-layer microwave emission model was firstly being used to simulate the radiation caused by electric loss in the lunar regolith, then the Moon surface emissivities were determined by comparing the model simulation with NOAA-20 ATMS lunar scan observations at the Full Moon phase angle. The calibrated RTM model was then validated against the satellite lunar observations independently collected from AMSU-A and AMSU-B/MHS onboard NOAA-16, 17, 18, 19 and Metop-A,B,C satellites. A significant improvement in the accuracy of the RTM model was observed in the frequency range of 22 to 183 GHz.

References

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2. S.J. Keihm, \emph{"Interpretation of the Lunar Microwave Brightness Temperature Spectrum: Feasibility of Orbital Heat Flow Mapping"}, ICARUS 60, pp. 568-589, 1984
3. Hayne, P. O., Bandfield, J. L., Siegler, M. A., Vasavada, A. R., Ghent, R. R., Williams, J.-P.,Paige, D. A. (2017). Global regolith thermophysical properties of the Moon from the Diviner Lunar Radiometer Experiment. Journal of Geophysical Research: Planets, 122, 2371–2400.
4. Yang, H.; Burgdorf, M. A Study of Lunar Microwave Radiation Based on Satellite Observations. Remote Sens. 2020, 12, 1129