GSICS workshop, Jan.23, 2023, Online

A Validated Lunar Microwave Brightness Temperature Dataset for Microwave Sounding Instrument Calibration

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Jan.20, 2023

Outline

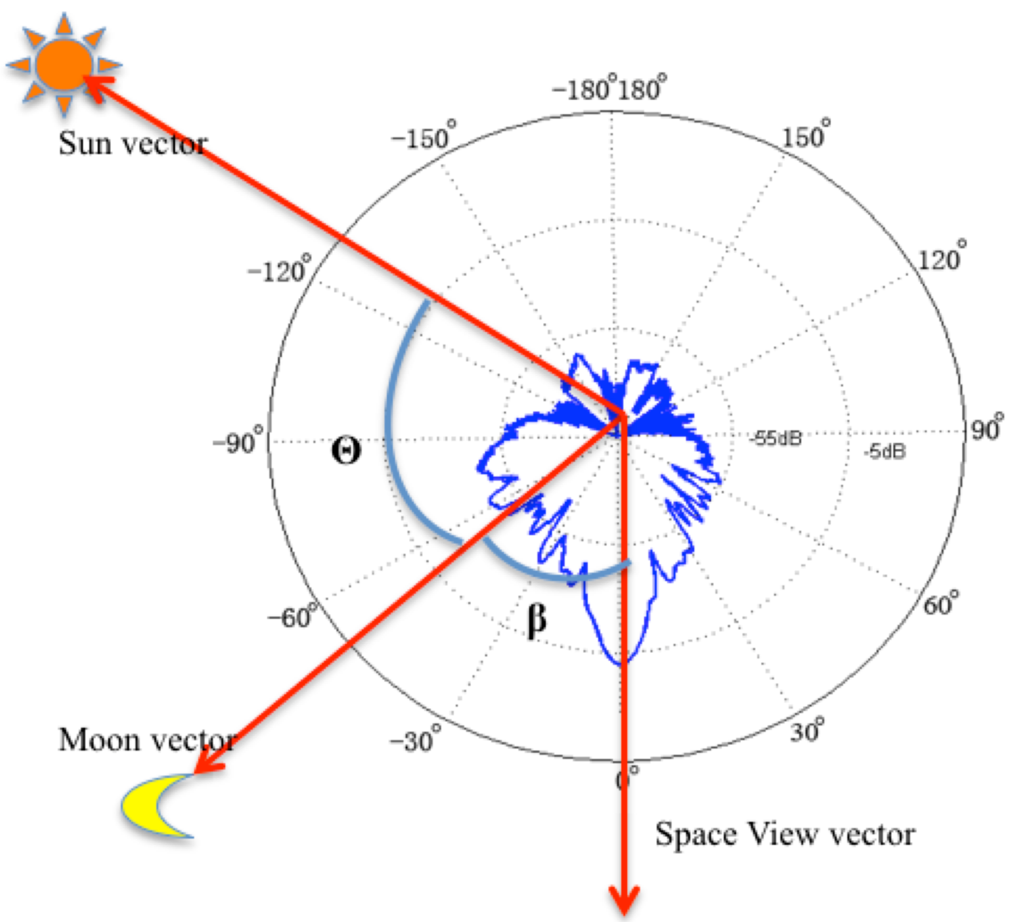
- Physical model for lunar observations from microwave sounding instruments
- The introduction of Keihm's lunar RTM model for calculation of disk-averaged brightness temperature
- The the disk-averaged brightness temperature spectrum from the 2-D scan full-Moon observations of NOAA-20 ATMS
- Calibration/validation of Keihm's RTM model with satellite observations
- The lunar disk-averaged microwave brightness temperature dataset and its application in on-orbit calibration
- Conclusion and discussion

1-D Lunar Model

Yang, H.et al., "Developing vicarious calibration for microwave sounding instruments by using lunar radiation". IEEE Geosci. Remote Sens. 2018, 56, 6723–6733

$$Ta_{Moon} = \frac{\Omega_{Moon}}{\Omega_{ant}} \cdot TB_{moon}^{Mo} \cdot e^{\frac{-(\alpha-\alpha_0)}{2\sigma^2}}$$

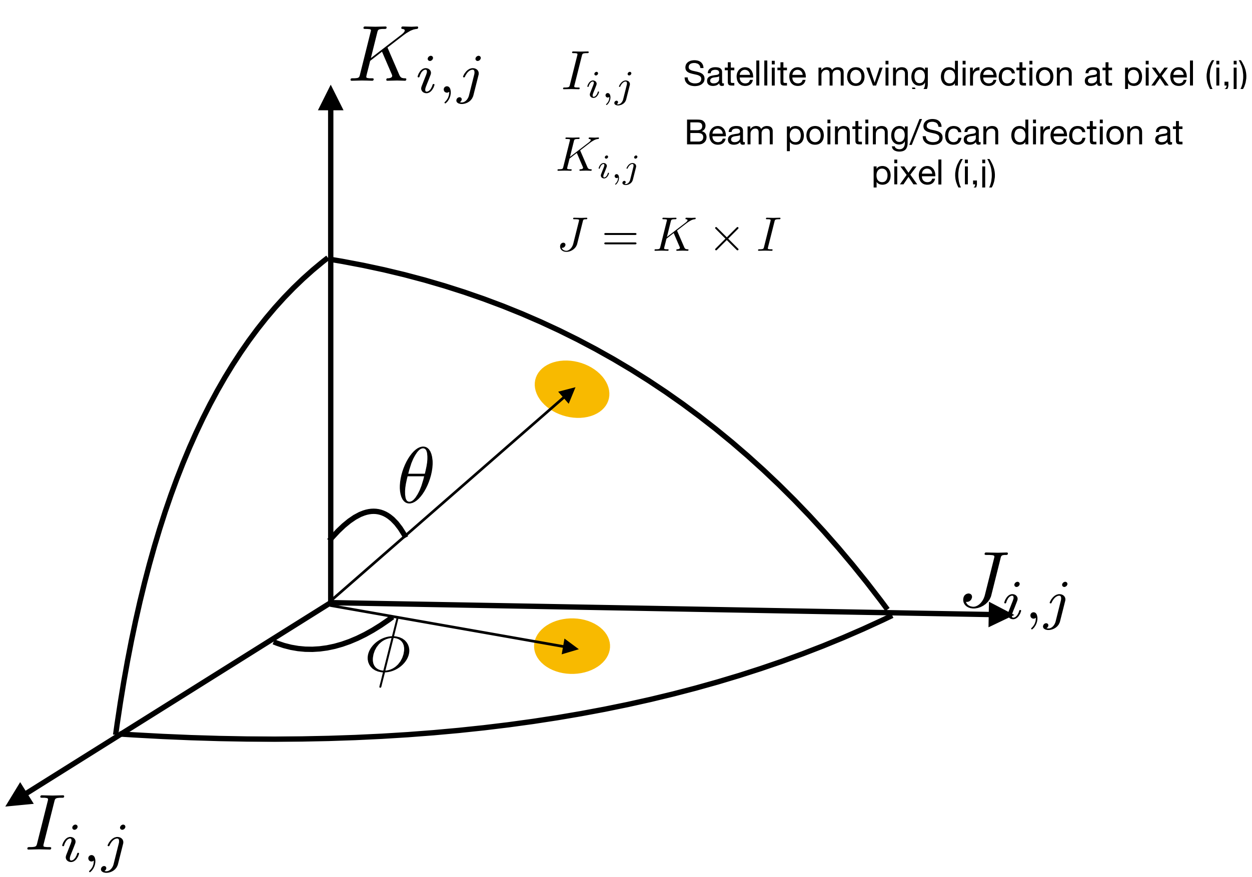
- 1D Gaussian function to calculate the antenna gain
- Experimental model to calculate the Moon-disk averaged Tb, with no consideration for phase shift in microwave band



2D Lunar Model

$$Ta_{Moon} = \frac{\Omega_{Moon}}{\Omega_{ant}} \cdot TB_{moon}^{RTM} \cdot e^{-(\frac{(x-x_0)^2}{2\sigma_x^2}+\frac{(y-y_0)^2}{2\sigma_y^2})}$$

- 2D Gaussian function to calculate the antenna gain
- Calibrated RTM model to calculate the Moon-disk averaged Tb, with consideration for phase shift in microwave band



Lunar Microwave Brightness Temperature Spectrum from NOAA-20 ATMS 2D scan Moon Observations

H. Yang et al., "2-D Lunar Microwave Radiance Observations From the NOAA-20 ATMS," in IEEE Geoscience and Remote Sensing Letters, doi: 10.1109/LGRS.2020.3012518.

The calibrated antenna temperature of the Moon's disk of each data sample in a ATMS lunar scan, Ta_{moon}, is the radiance received from the Moon's disk integrated over a 18-ms sampling time along the moving path, which can be modeled as a function of the disk-integrated lunar microwave brightness temperature (Tb_{moon}^{Disk}), the antenna main beam solid angle (Ω_p), and the normalized antenna response (G) as follows:

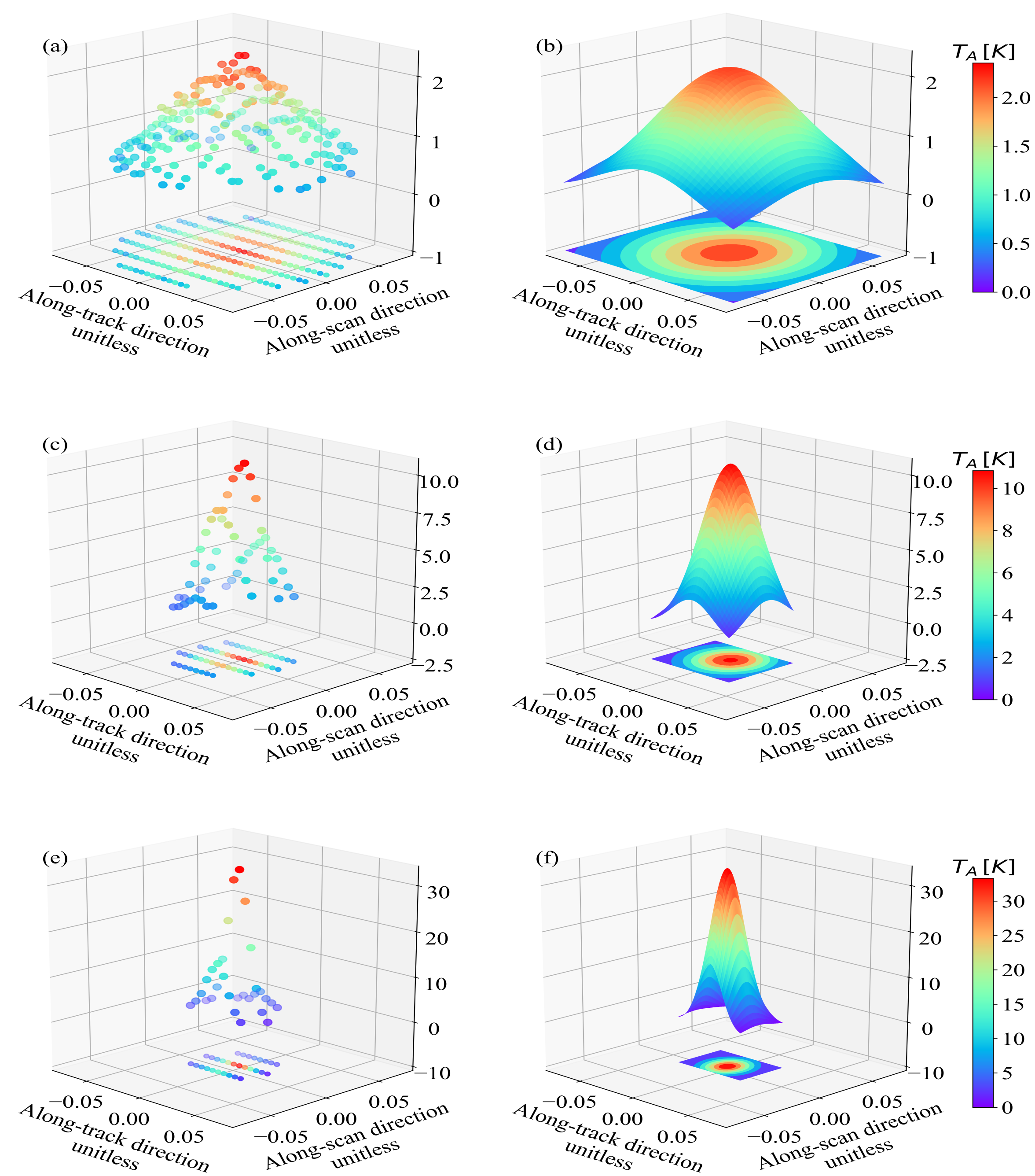
$$Ta_{moon}(\theta_{ifov}, \phi_{ifov}) = Tb_{moon}^{Disk} \cdot \frac{G(\theta_{ifov}, \phi_{ifov})}{\Omega_P}.$$

For lunar observations at each scan position, the antenna response can be simulated as the solid-angle integration of the lunar disk over the instrument integration time along the moving path of the Moon on the surface of the normalized antenna pattern, expressed as follows:

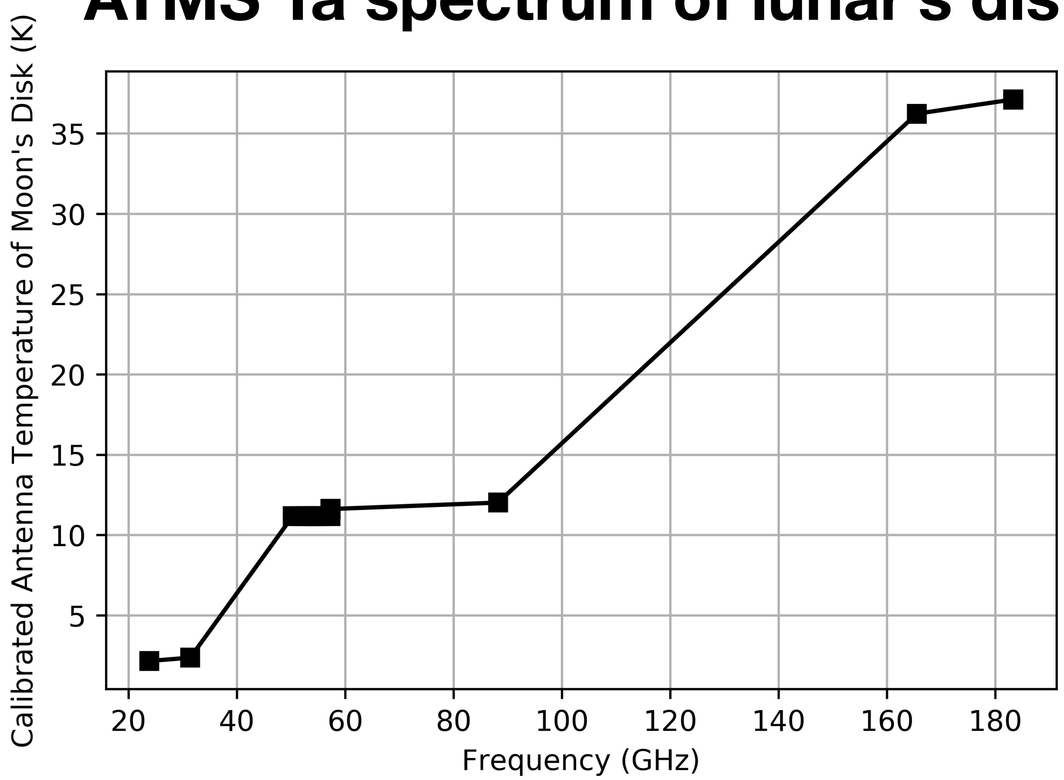
$$G(\theta_{ifov}, \phi_{ifov}) = \Omega_{moon}^{ifov}$$
$$= \frac{1}{\mathcal{L}} \int_{\frac{-\tau}{2}}^{\frac{\tau}{2}} dl \int_0^{2\pi} \int_0^{\alpha_{moon}} G'(\theta', \phi') sin\theta' d\theta' d\phi'$$

With the lunar solid angle calculated at each scan position, a linear regression model can be established to relate the calibrated lunar antenna temperature with the calculated antenna paramters as follow: For the *ith* lunar observation sample (where i=1,2,... n),

$$y_i = \alpha + \beta x_i + \epsilon_i$$



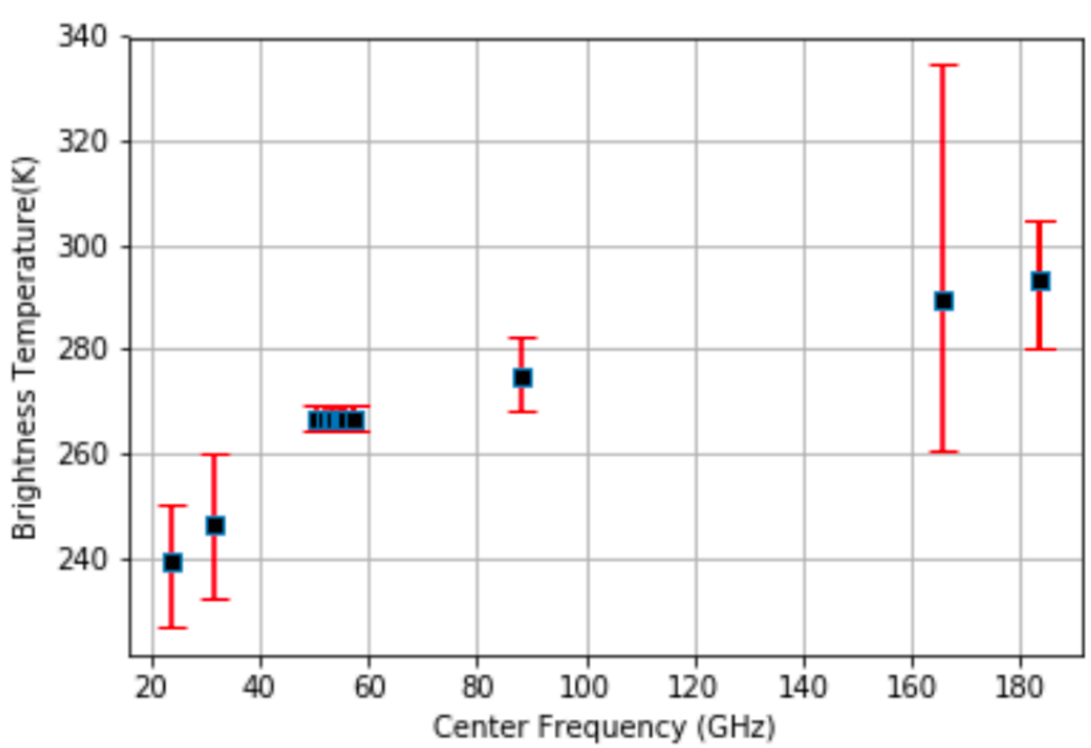
ATMS Ta spectrum of lunar's disk



Antenna parameters and Calibrated Peak Antenna Temperature of the Moon

Band	Center Frequency (GHz)	Ω_P	Ω_{moon}^{Max}	Ta_{moon}^{Max}(K)
K	23.8	32.98	0.23	2.1
Ka	31.4	33.32	0.23	2.4
V	50.3–57	5.68	0.21	11.3
W	88.2	5.22	0.21	12.7
G1	165.5	1.54	0.16	33.0
G2	183.31	1.52	0.16	33.8

Tb spectrum of lunar's disk



Retrieved Disk-integrated Tbs

Band	Center Frequency (GHz)	Tb_{moon}^{Disk}(K)	Lower Boundary of 90% Confident	Upper Boundary of 90% Confident
K	23.8	239.1	224.2	253.4
Ka	31.4	246.2	229.5	262.2
V	50.3–57	266.7	263.9	269.6
W	88.2	274.7	267.1	284.0
G1	165.5	289.7	222.7	336.3
G2	183.31	293.1	277.2	306.1

Theoretical Model for Microwave Emission of the Moon

S.Keihm, "Interpretation of the Lunar Microwave Brightness Temperature Spectrum: Feasibility of Orbital Heat Flow mapping", ICARUS 60, PP.568-589, 1984

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

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

Boundary Layer Condition:

$$\frac{\partial T}{\partial z} = Q/K$$ **,Q=0.018Wm-2 is the geothermal constant**

microwave absorption Term

$$\kappa_\lambda = (2\pi/\lambda)\sqrt{\epsilon'} \tan\Delta$$

Surface Emissivity is calculated with Fresnel Equation:

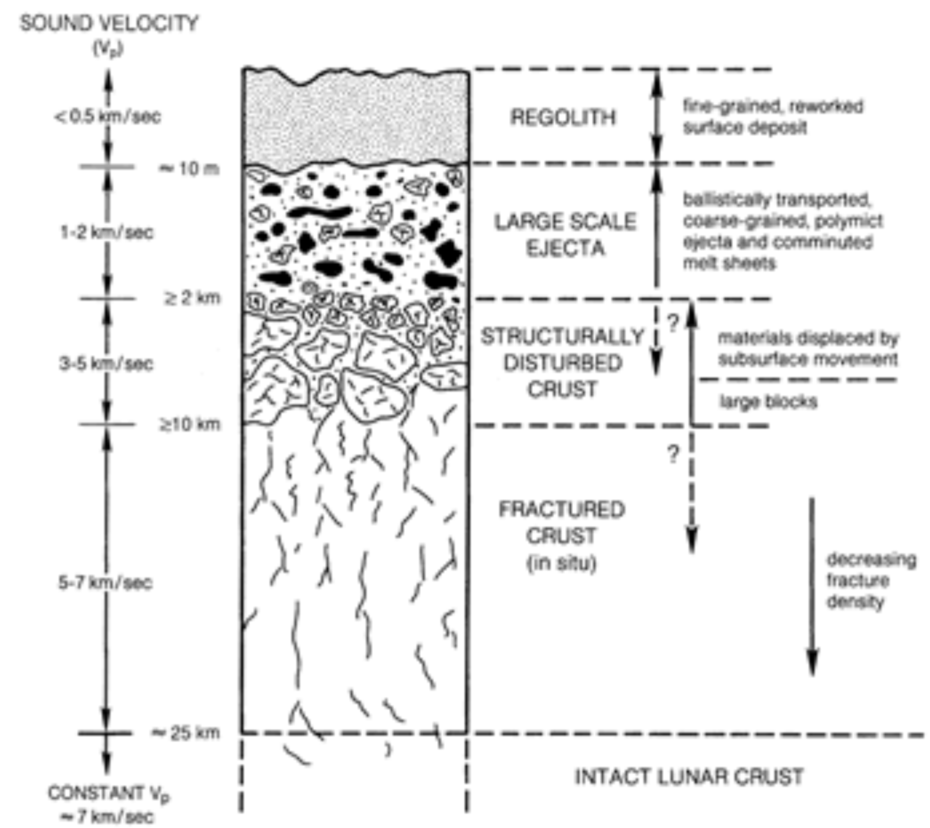
$$E_\lambda^p = 1 - R_\lambda^p$$

$$R_h = \frac{\sqrt{\epsilon'}cos\theta_i - cos\theta_0}{\sqrt{\epsilon'}cos\theta_i + cos\theta_0}$$

$$R_v = \frac{\sqrt{\epsilon'}cos\theta_0 - cos\theta_i}{\sqrt{\epsilon'}cos\theta_0 + cos\theta_i}$$

Lunar Surface Structure

Heiken, G.H., Vaniman, D.T., & French, B.M. eds, **Lunar Sourcebook**, Lunar and Planetary Institute, Houston, 1991.



- Lunar regolith temperature profile is calculated from the heat equation
- Dielectric constant calculation model is developed based on empirical fit to the Apollo sample measurements
- Parameters of thermal conductivity profile is derived based on Apollo 15 heat flow site

Temperature Profile of Lunar Regolith

Paul O.Hayne et al., "Global regolith therm-physical properties of the moon from the diviner lunar radiometer experiment", JGR Planets, 2017

The physical temperature profile,T(z), can be derived by solving the one-dimension heat equation at each latitude from -90 to 90 deg of the Moon disk

$$\rho c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial z}(K\frac{\partial T}{\partial z})$$

Density profile: $\rho(z) = \rho_d - (\rho_d - \rho_s)e^{-z/H}$

Thermal conductivity profile:

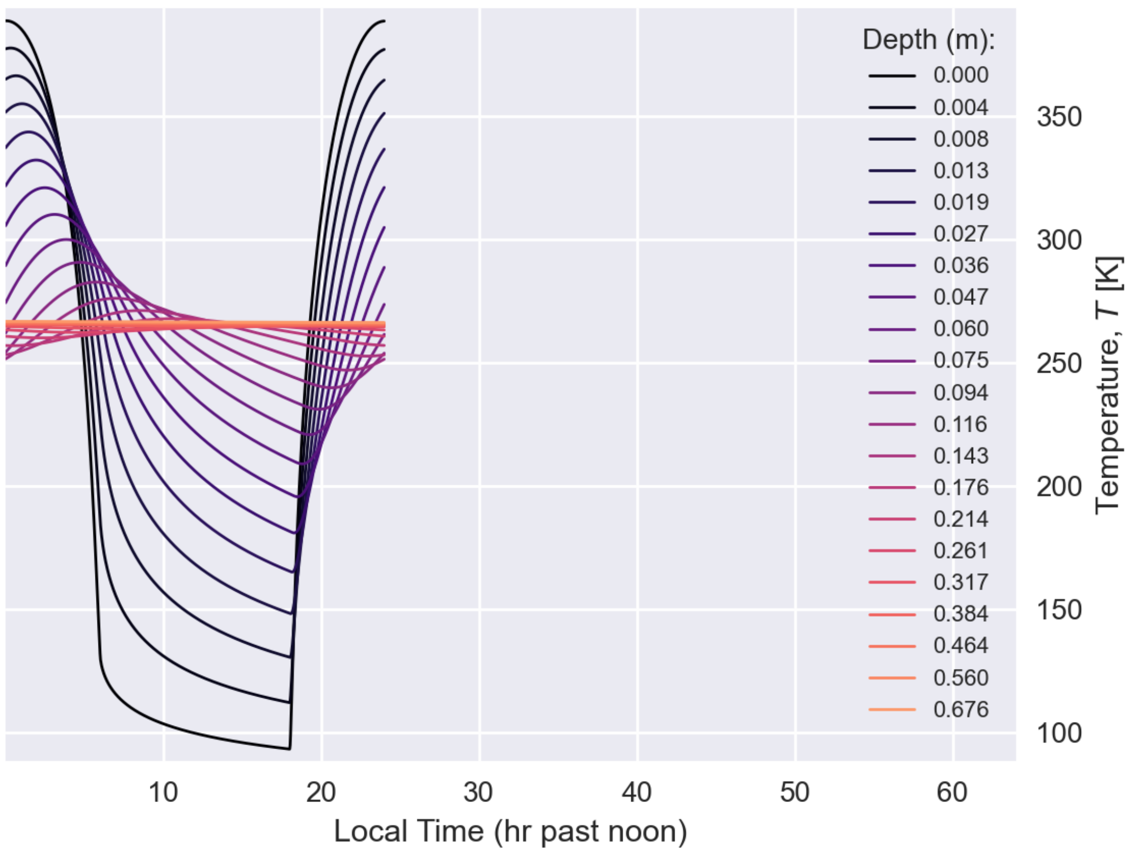
$$K(z) = [K_d - (k_d - K_s)\frac{\rho_d - \rho}{\rho_d - \rho_s}] \cdot [1 + \chi(\frac{T}{350})^3]$$

Boundary Conditions

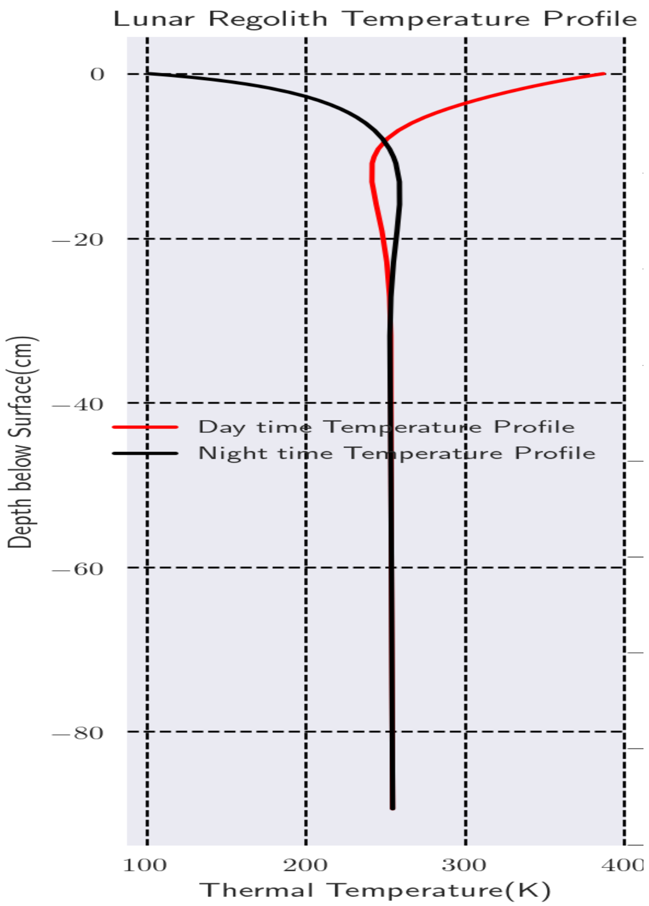
$$K\frac{\partial T}{\partial z}\bigg|_{z=0} + Q_s = \bar{\varepsilon}\sigma T_s^4$$

$$Q_s = (1 - A)F_{\odot}$$

Diurnal variation of T

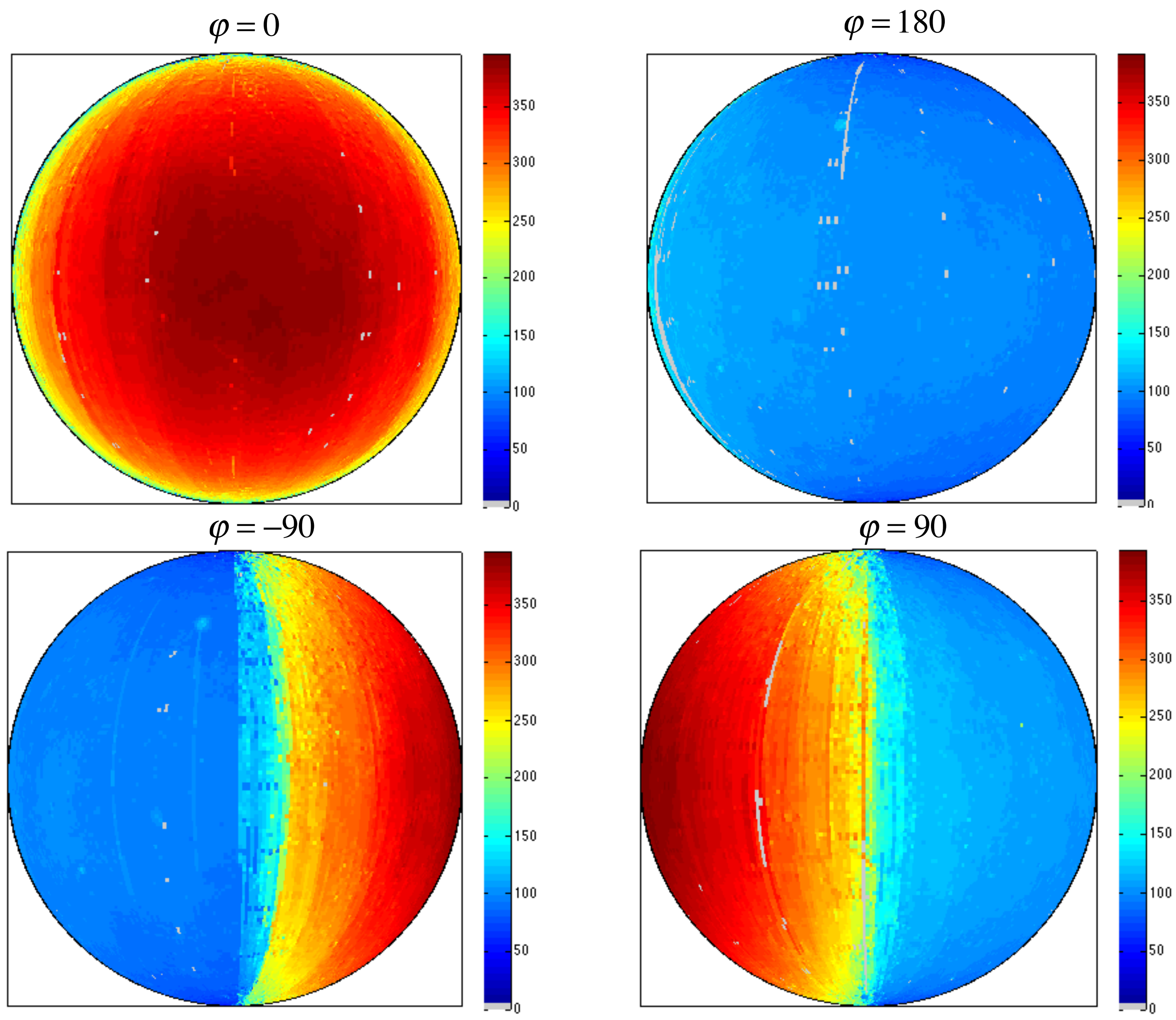


Profile of T up to 1 meter under Lunar Surface



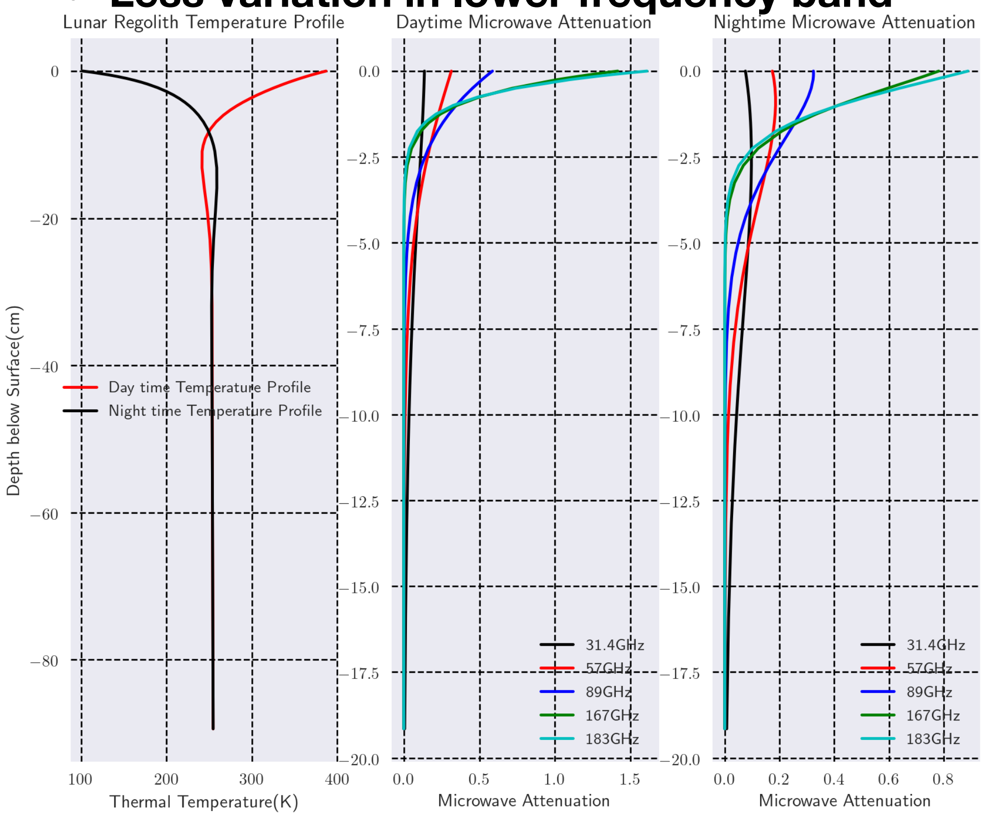
Moon surface temperature derived from the Diviner Lunar Radiometer Experiment instrument (DLRE) observations

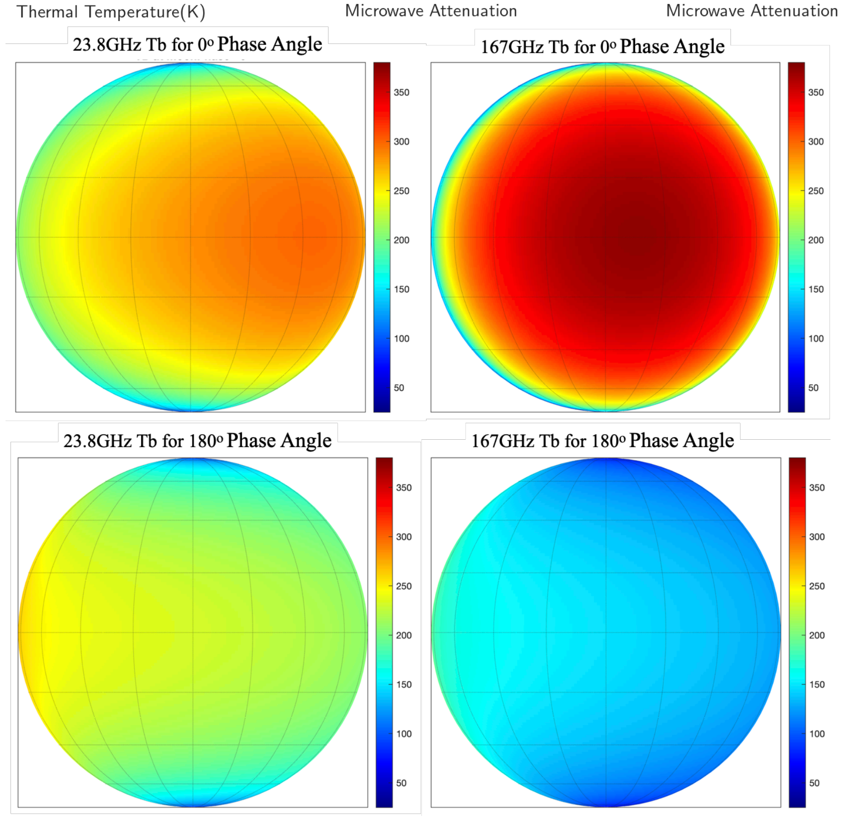
There is no phase angle shift in Tb observations because there is no penetration in infrared band



RTM Model Simulation for Lunar Microwave Emission

- **No diurnal variation in deep layer**
- **More contribution from deeper layer in lower frequency band**
- **More contribution from deep layer during night time**
- **Less variation in lower frequency band**

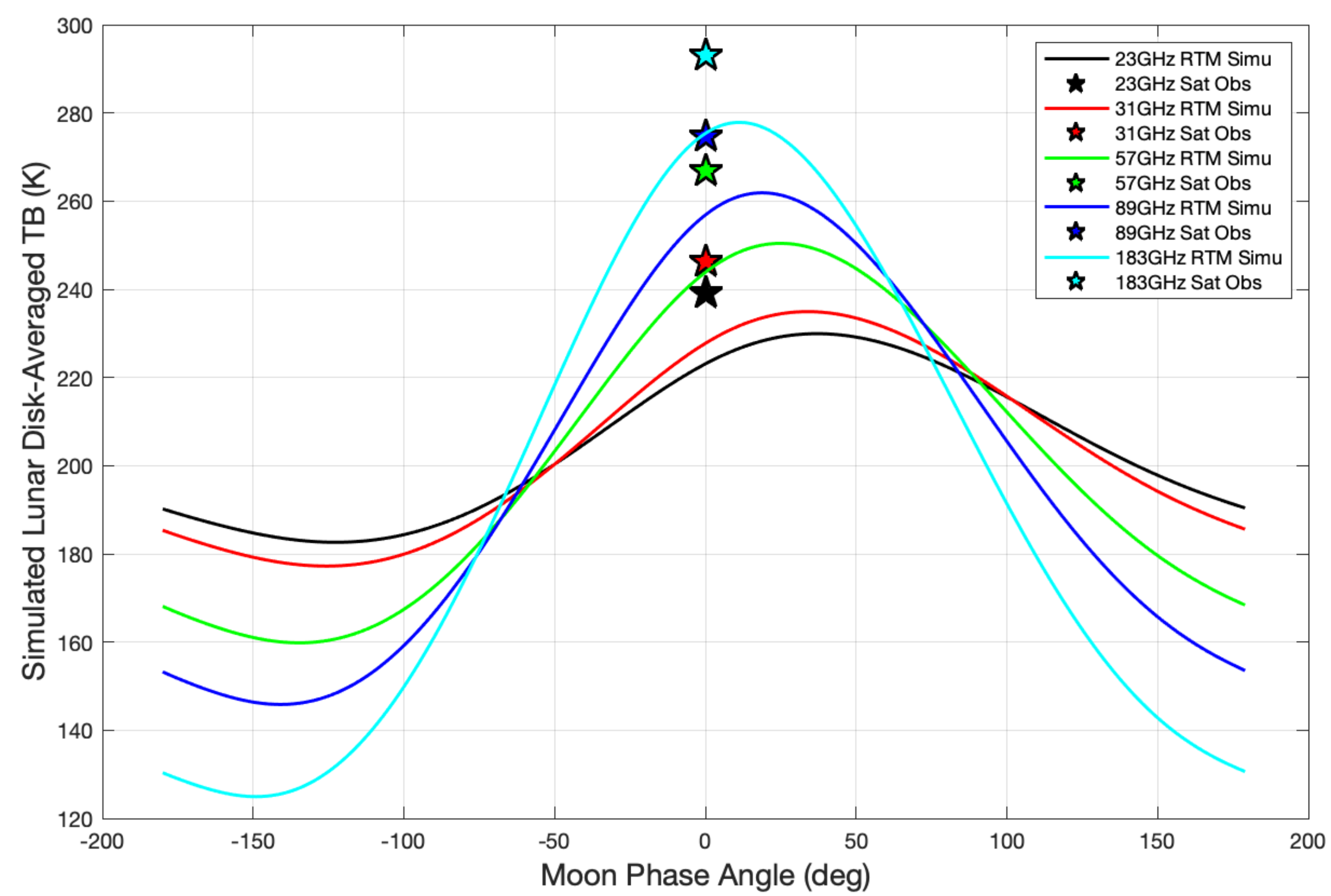




Calculation of Disk-averaged Lunar Tb

$$T_B^{Disk}(\lambda) = \sum_{\phi=-90}^{\phi=90} \sum_{\theta=-90}^{\theta=90} T_b i(\theta, \phi) w_i(\theta, \phi)$$

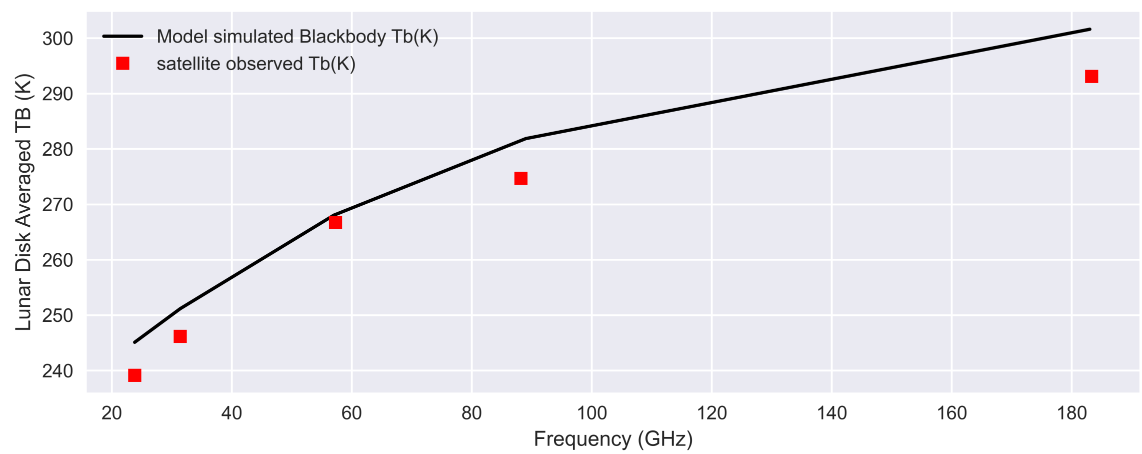
$$w_i(\theta_i, \phi_i) = \frac{\cos\theta_i \cos\phi_i d\theta\, d\phi}{\sum w_i(\theta, \phi)}$$

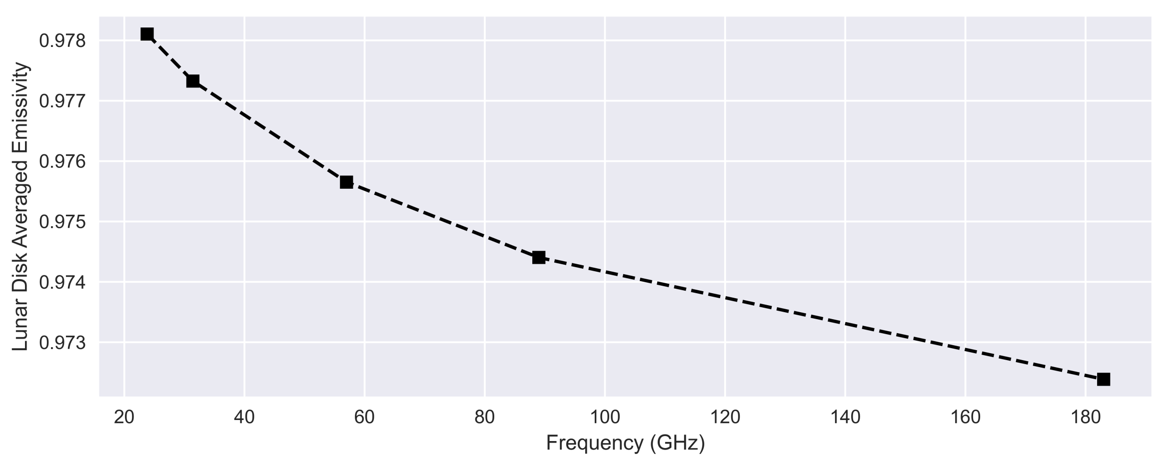


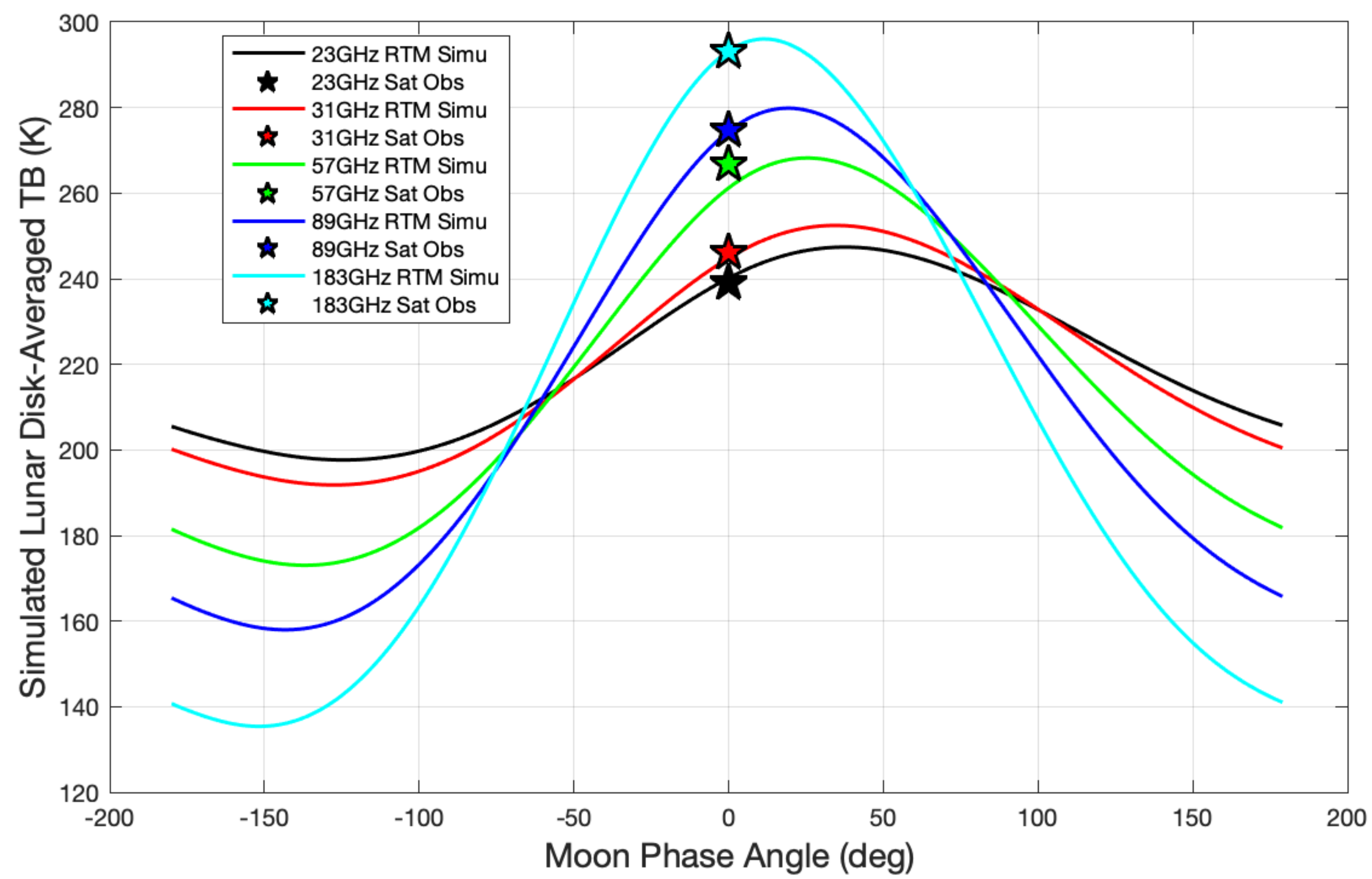
Calibration of the Lunar RTM Model with Satellite Observations

Yang, H.; Burgdorf, M. A Calibrated Lunar Microwave Radiative Transfer Model Based on Satellite Observations. Remote Sens. 2022, 14, 5501. https://doi.org/10.3390/rs14215501

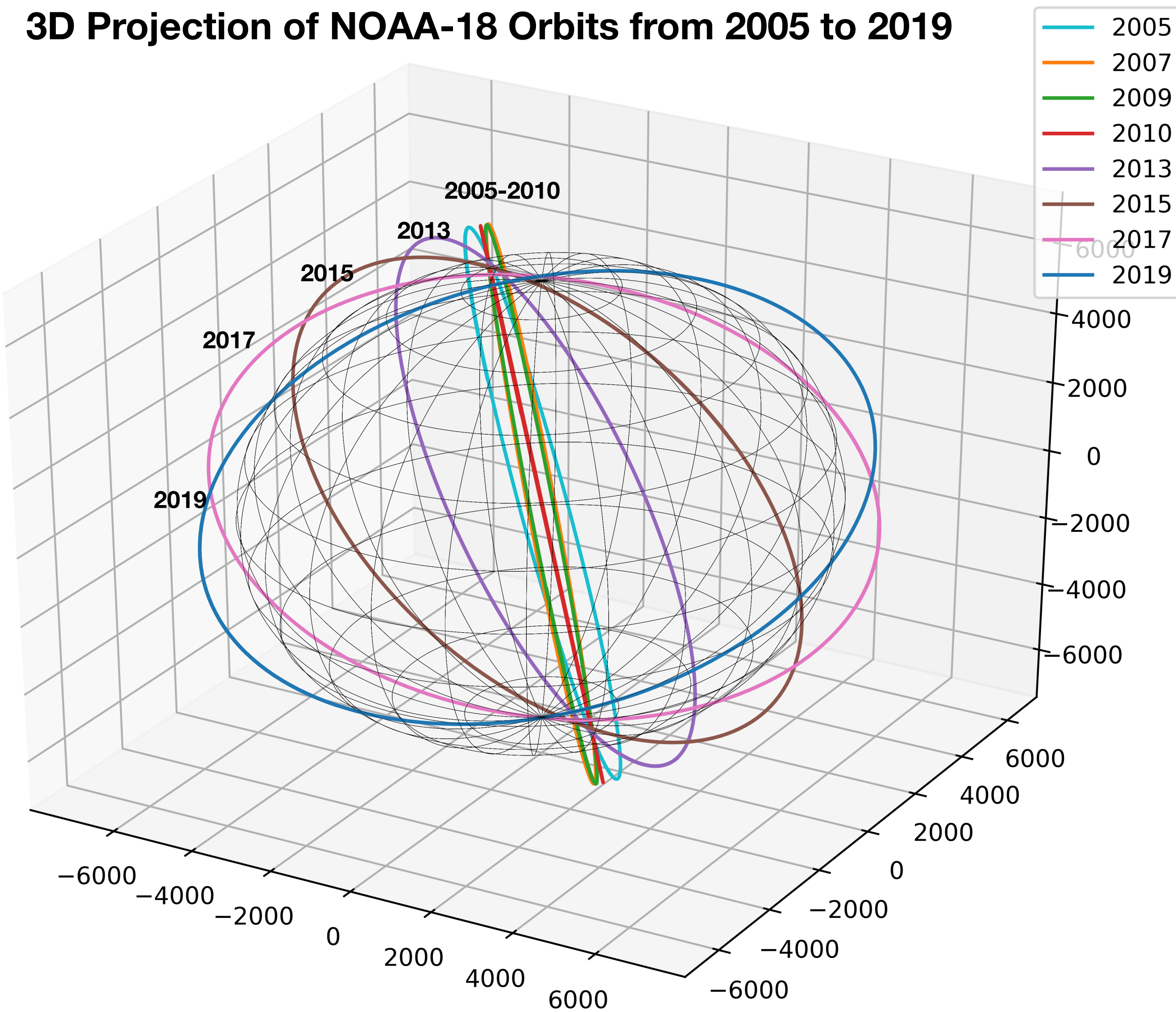
- In RTM simulation, only the "black body" emission are considered to reduce the uncertainty in the simulation when Fresnel reflection function is used.
- The Lunar disk Tb is calculated based on 1º by 1º resolution lunar simulation, with the normalized solid angle in satellite observation direction as sum weights for each pixel
- The frequency dependent feature of satellite derived lunar Tb spectrum is consistent with model simulations, the difference can be explained by the departure of real lunar Tb with "black body" simulations

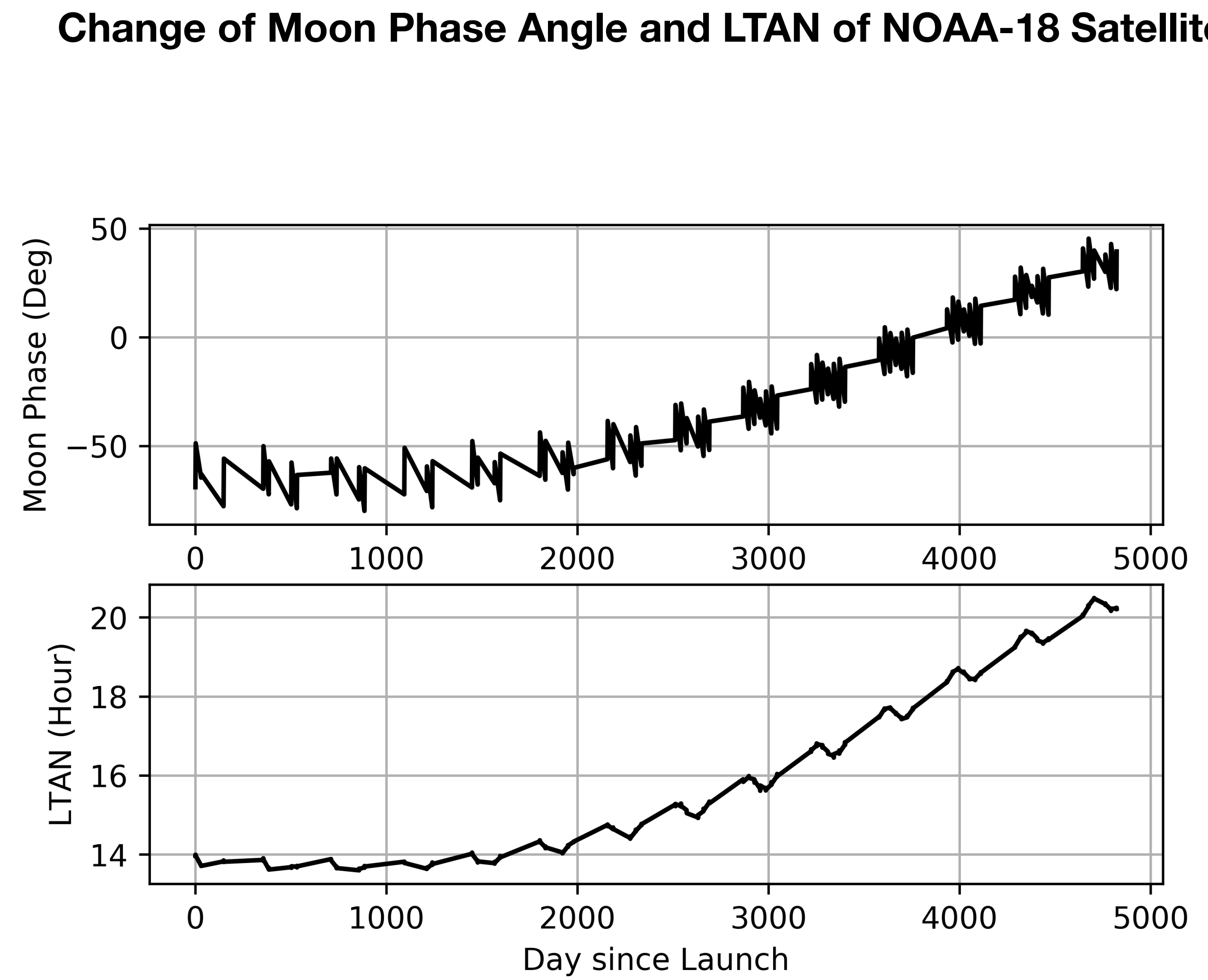




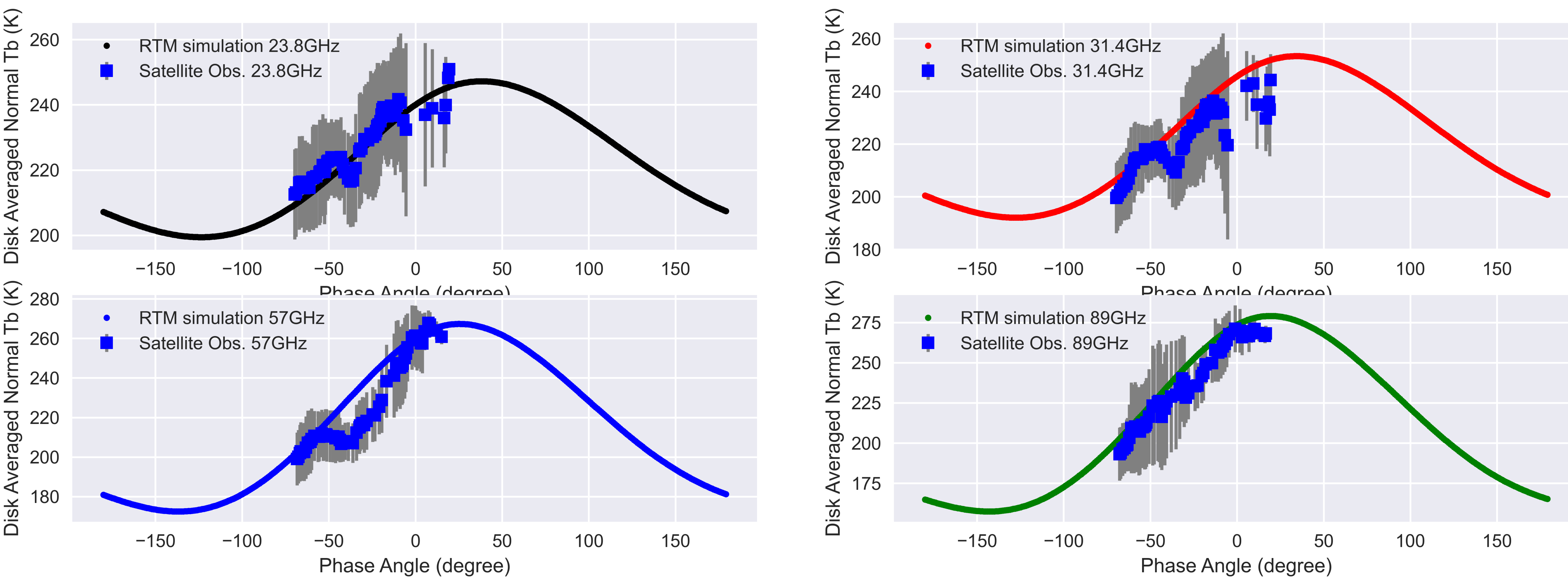


Validation of the Calibrated Lunar RTM Model with Lunar Observations from the Drifting-orbit Satellite

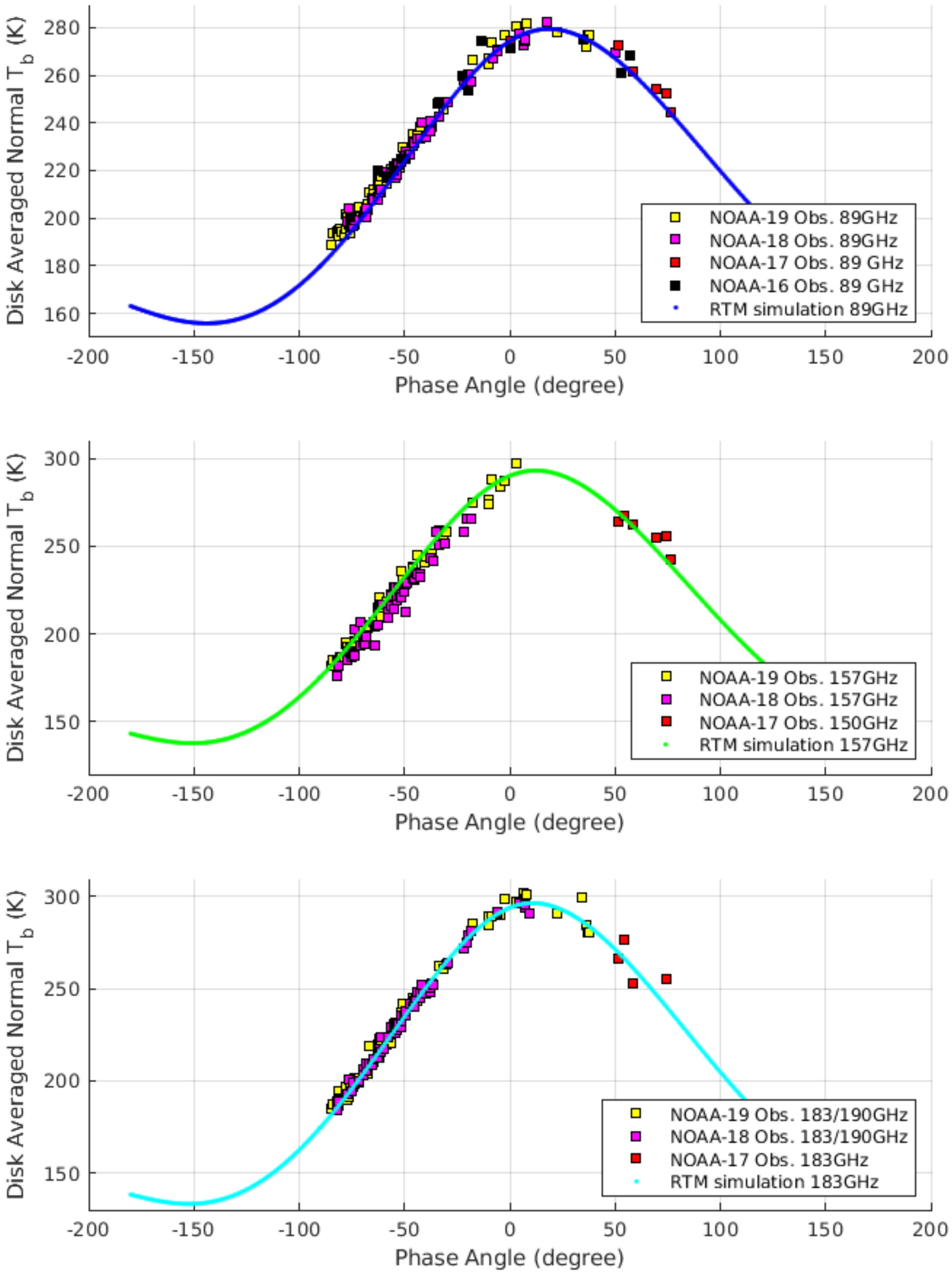




comparison of simulated and observed lunar disk averaged brightness temperature at different frequencies. Solid lines are the calibrated lunar RTM model simulations, the dots are the satellite observations, and the grey bar is the standard deviation of the satellite derived lunar-disk averaged TB



(Provided by M.Burgdorf)



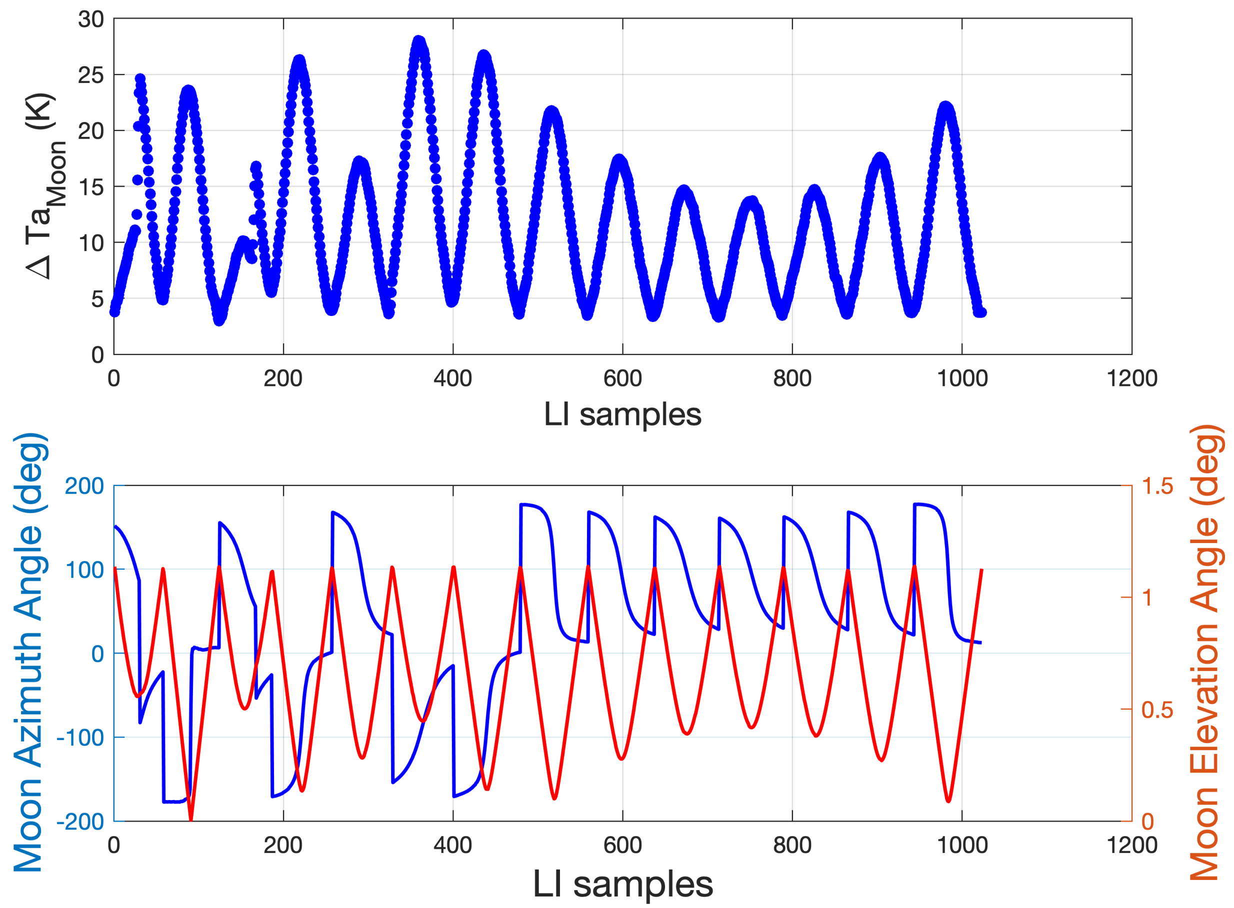
Comparison of simulated and observed lunar disk averaged brightness temperature at frequencies of 89~GHz and higher. Solid lines are our model simulations, the dots are the satellite observations with AMSU-B and MHS.

Sat.	**Instr.**	**GHz**	**Mean Error** $Tb^{sat} - Tb^{effsim}$ **(K)**	**Mean Error** $Tb^{sat} - Tb^{Fresnel}$ **(K)**	**Std.(K)**
N15	AMSU-B	89	-0.7	18.5	9.2
N16	AMSU-B	89	-2.2	16.4	6.7
N17	AMSU-B	89	11	30.3	6.4
N18	MHS	89	4.9	22.5	3.6
N19	MHS	89	6.4	24.1	4.3
M-A	MHS	89	6.4	25.8	5.1
MB	MHS	89	2.8	22.2	3.4
MC	MHS	89	11.3	30.9	7.9
N15	AMSU-B	150	17	36.8	22.2
N16	AMSU-B	150	23.2	42	10
N17	AMSU-B	150	9.6	28.8	22.4
N18	MHS	157	-6.6	11.2	7.2
N19	MHS	157	1.6	19.4	5.2
MA	MHS	157	-2.7	16.8	9.1
MB	MHS	157	-6.1	13.2	4.2
MC	MHS	157	-2	17.6	8.7
N15	AMSU-B	183	10.2	30.2	16
N16	AMSU-B	183	10.4	28.6	10.4
N17	AMSU-B	183	-2.2	16.8	17.3
N18	MHS	183/190	4.4	22.1	4.1
N19	MHS	183/190	2.3	20.1	6.6
MA	MHS	183/190	4.7	24.1	6.1
MB	MHS	183/190	0.7	19.9	3.5
MC	MHS	183/190	13.3	32.8	13.7

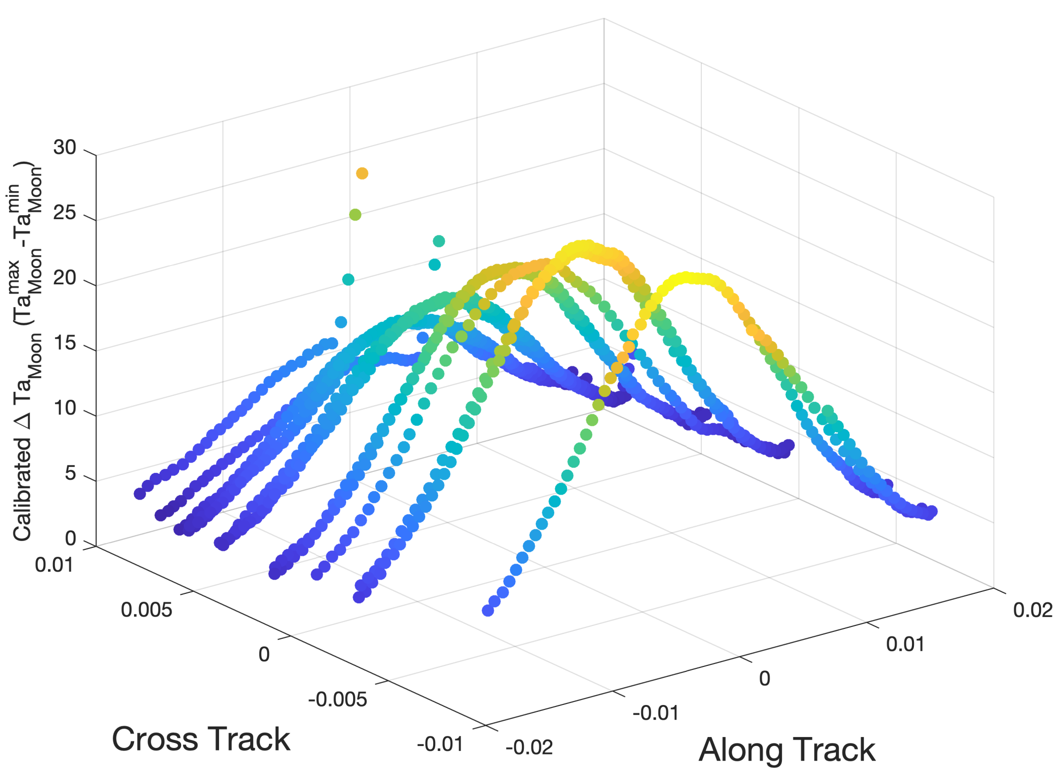
Application of the 2D Lunar Model in On-orbit Calibration

- LI samples are collected from NOAA 21 ATMS observations on 12/02, 2022
- The magnitude of lunar intrusion is sensitive to the location of the Moon in 2D FOV of ATMS, which is closely related to the antenna gain pattern

Calibrated Lunar Observation Samples at Chan.18

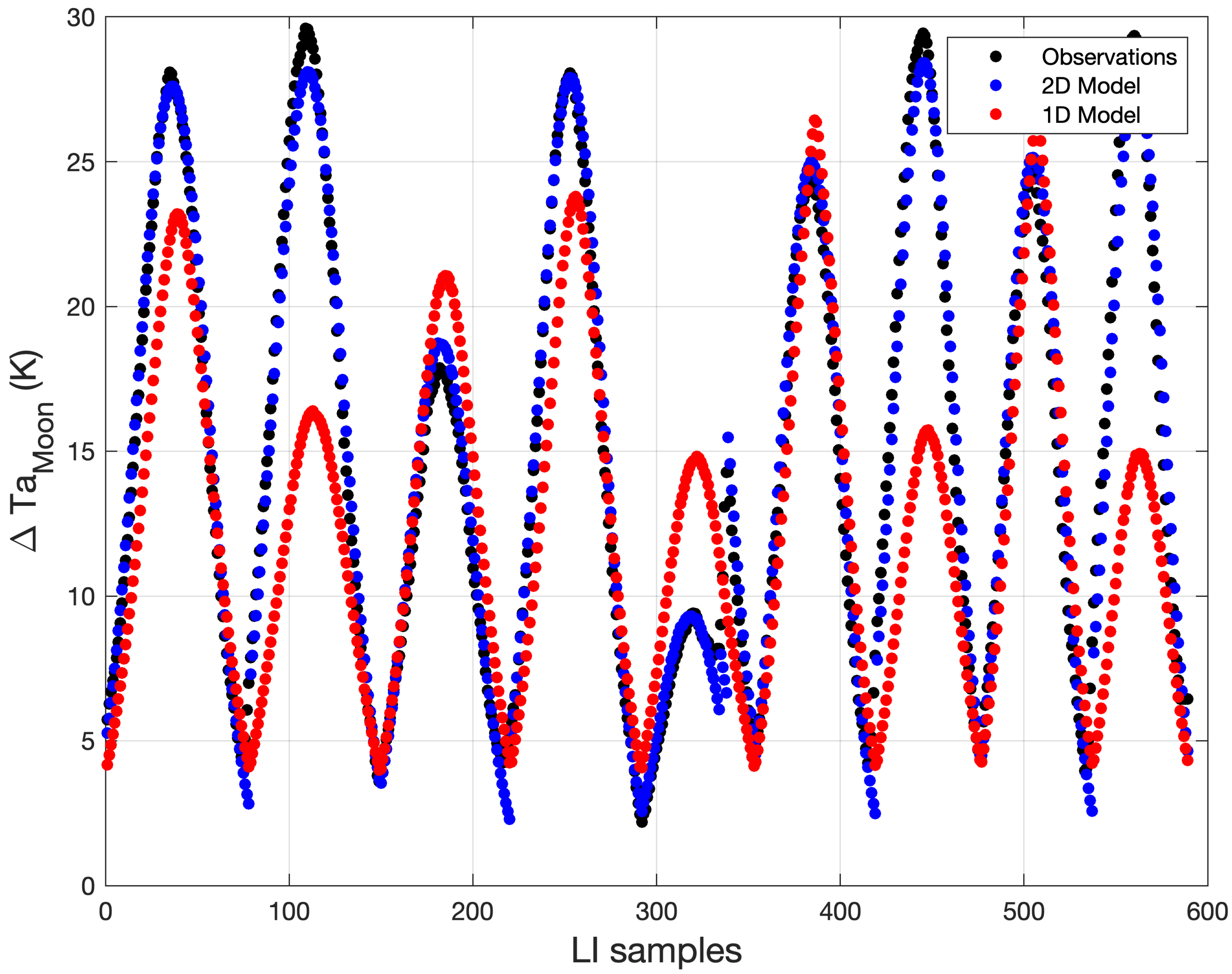


3-D plot



2D Lunar Model Validation

- The new 2D model was validated by using the LI samples collected on 12/03, 2022
- Compared to the 1D model, the accuracy of calculated lunar brightness temperature is improved, especially for W and G band, where the magnitude of LI is more sensitive to the location of the Moon in cold space view FOV



Conclusion

- Lunar microwave RTM model developed by Keihm was calibrated with NOAA 20 full moon scan observations
- Validation results show that the calibrated RTM model accuracy is largely improved and can be used for microwave lunar calibration
- A Moon disk-averaged brightness temperature dataset has been generated from the calibrated lunar microwave RTM model at 13 frequencies range from 23 to 204GHz for Moon phase from -180 to 180 with 1 deg resolution
- The dataset and the calibrated RTM model can be accessed by requirement from Github: https://github.com/Tigeryang007/RTMlunar, contact info: huyang@umd.edu