Validation of the Calibrated Microwave Lunar RTM Model by Using N20 and N21 Two-Dimension Moon Observations

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Summary of the Work

- 2D Moon scan observations from NOAA-21 was collected on 03/10/2023 during the special pitch maneuver test (PLT), when the Moon phase angle was around 34 degree after the full Moon (0 deg)

- The original Moon observations were processed and calibrated in MiCalPS, with reflector emission correction and satellite near-field correction being included

- It is found that due to the different data sampling rate, the NOAA-21 Moon antenna response is generally lower than NOAA-20, and the difference need to be addressed in Lunar Tb calculations

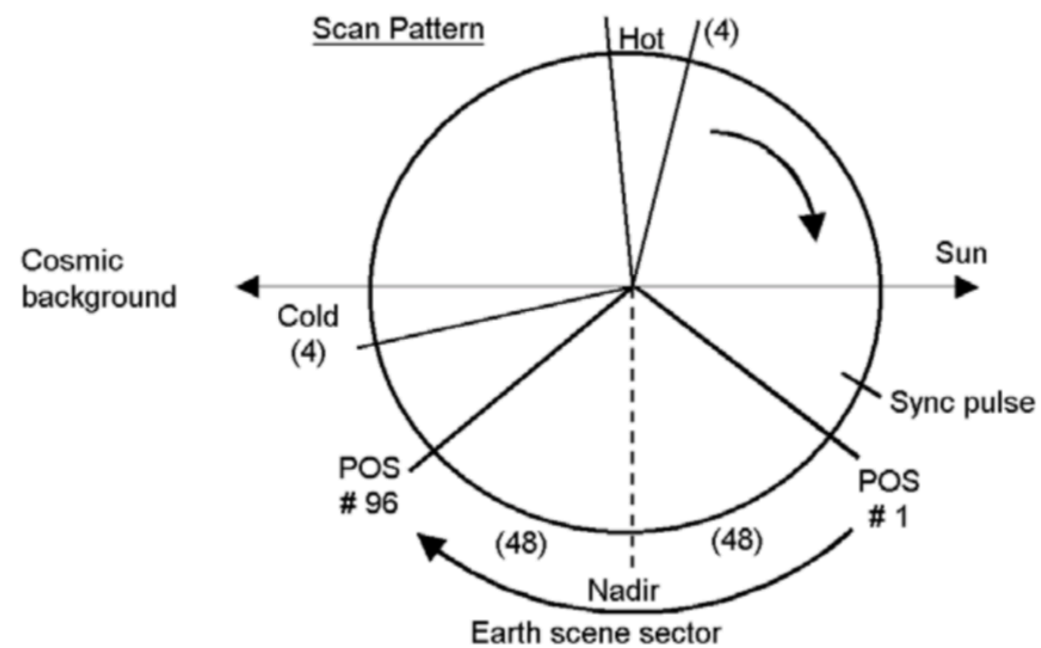
- Moon disk-averaged brightness temperature spectrum was derived from the calibrated antenna temperature, and compared with the lunar RTM simulations

ATMS Instrument Description

ATMS Spectrometric and Radiometric Specification

Ch	RF path			Center frequency [MHz]		Bandwidth [MHz]		NEDT [K]	Pol	Beamwidth [°]
	Ant	Feed	Rcvr	Value	Stab	Req	True	Req		Req
1	A	1	a	23800	<10	<270	1x270	0.5	V	5.2
2	A	1	b	31400	<10	<180	1x180	0.6	V	5.2
3	A	2	c	50300	<10	<180	1x180	0.7	H	2.2
4	A	2	c	51760	< 5	<400	1x400	0.5	H	2.2
5	A	2	c	52800	< 5	<400	1x400	0.5	H	2.2
6	A	2	c	53596±115	< 5	170	2x170	0.5	H	2.2
7	A	2	c	54400	< 5	400	1x400	0.5	H	2.2
8	A	2	c	54940	<10	400	1x400	0.5	H	2.2
9	A	2	c	55500	<10	330	1x330	0.5	H	2.2
10	A	2	d_1	57290.344 [f_0]	<0.5	330	2x155	0.75	H	2.2
11	A	2	d_1	f_0±217	<0.5	78	2x 78	1.0	H	2.2
12	A	2	d_2	f_0±322.2±48	<1.2	36	4x 36	1.0	H	2.2
13	A	2	d_2	f_0±322.±22	<1.6	16	4x 16	1.5	H	2.2
14	A	2	d_2	f_0±322.±10	<0.5	8	4x 8	2.2	H	2.2
15	A	2	d_2	f_0±322.±4.5	<0.5	3	4x 3	3.6	H	2.2
16	B	3	e	88200	<200	2000	1x2000	0.3	V	2.2
17	B	4	f	165500	<200	3000	2x1150	0.6	H	1.1
18	B	4	g	183310±7000	<30	2000	2x2000	0.8	H	1.1
19	B	4	g	183310±4500	<30	2000	2x2000	0.8	H	1.1
20	B	4	g	183310±3000	<30	1000	2x1000	0.8	H	1.1
21	B	4	g	183310±1800	<30	1000	2x1000	0.8	H	1.1
22	B	4	g	183310±1000	<30	500	2x 500	0.9	H	1.1

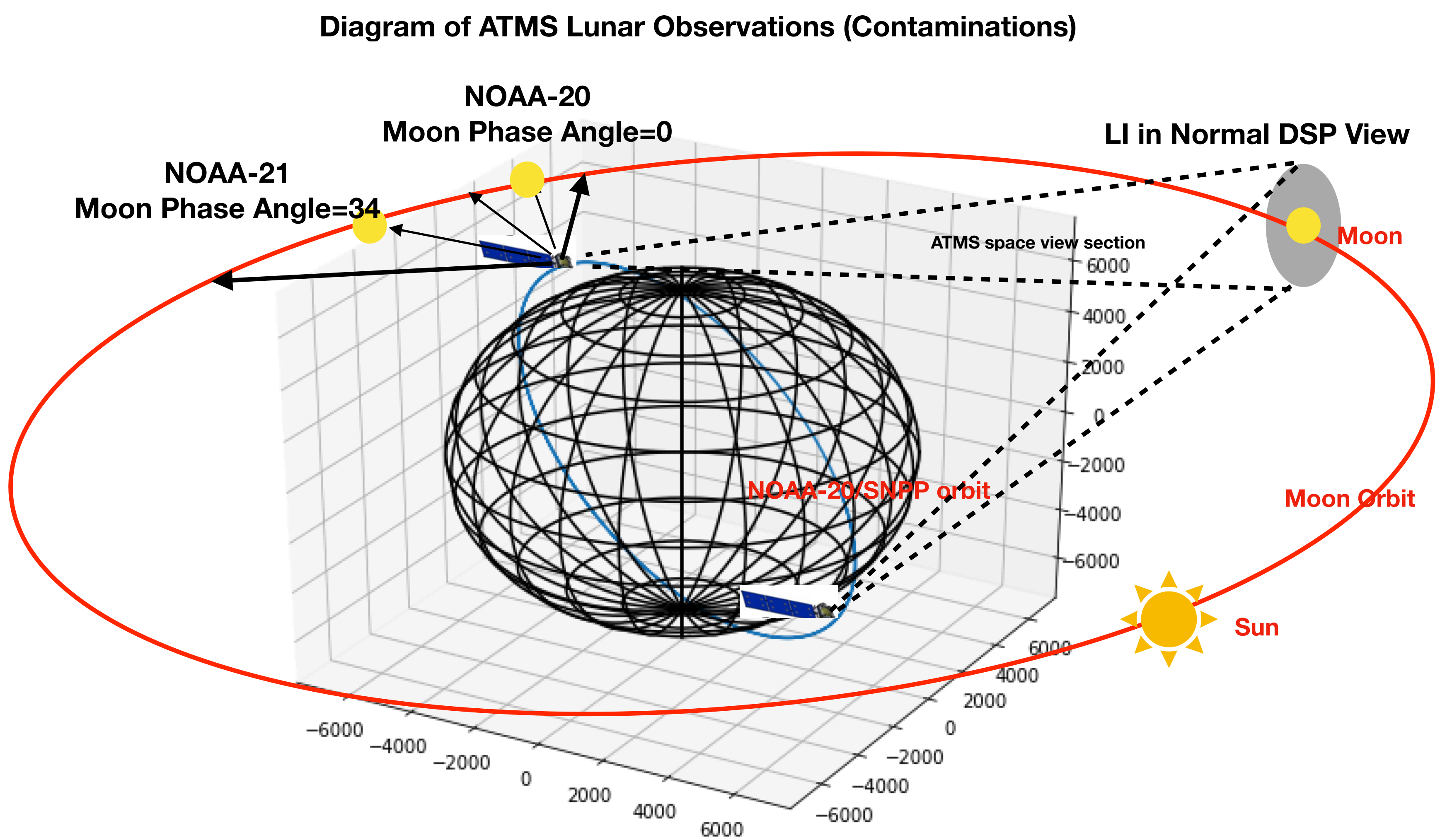
ATMS Scan Geometry



Integration time: 18ms
Scan rate for data sampling: 1.1deg/18ms

Two-Dimension Lunar Scan Observations from NOAA-20/21 ATMS

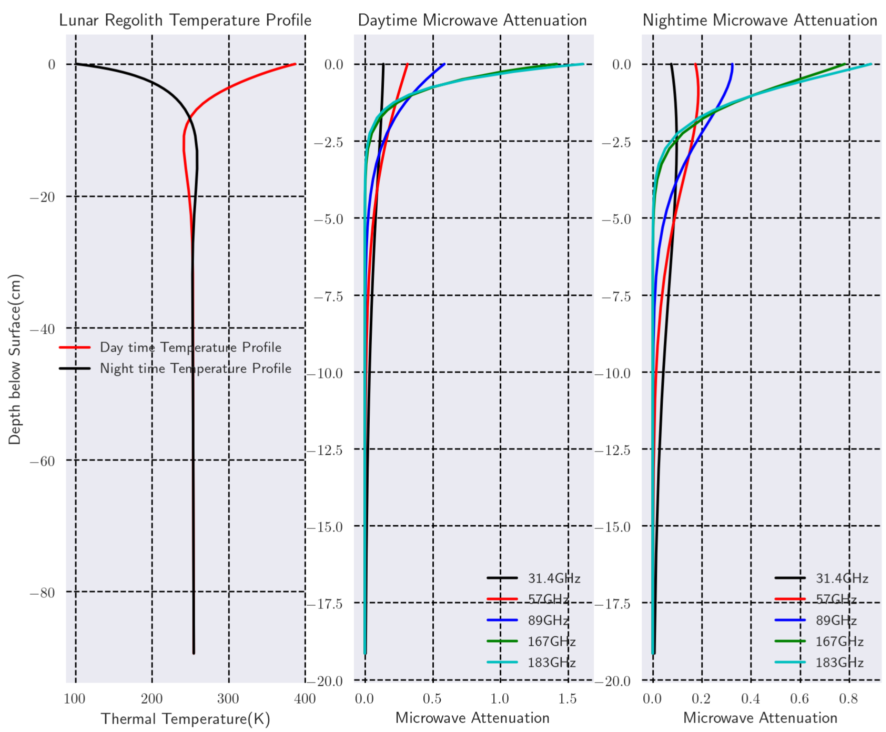
- For normal operation of JPSS ATMS, the Moon can be captured by space view when LI happens, and the Moon phase angle generally varies between 80 to 110 deg due to the stable orbit of JPSS satellites
- During pitch maneuver, the Moon can be captured for a wide range of Moon phase angles around the full Moon phase. For NOAA-21 ATMS , the Moon was captured between FOV20 and 40, around 3 days after the full moon when the Moon phase angle was 34 deg.
- For NOAA-20 ATMS, the Moon was captured between FOV60 and 80, on the day of the full Moon



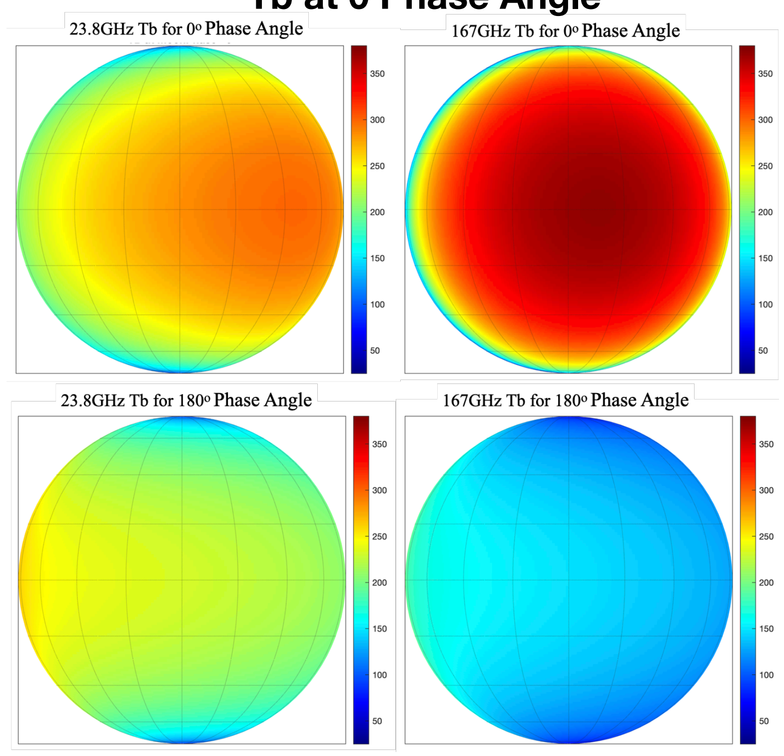
RTM Model Simulation for Lunar Microwave Emission

Yang H, Burgdorf M. A Calibrated Lunar Microwave Radiative Transfer Model Based on Satellite Observations. Remote Sensing. 2022; 14(21):5501. https://doi.org/10.3390/rs14215501

Lunar Regolith Temperature Profile and MW Thermal Emission Weighting Function



Calculated Moon Surface(Earth Side) Microwave Tb at 0 Phase Angle



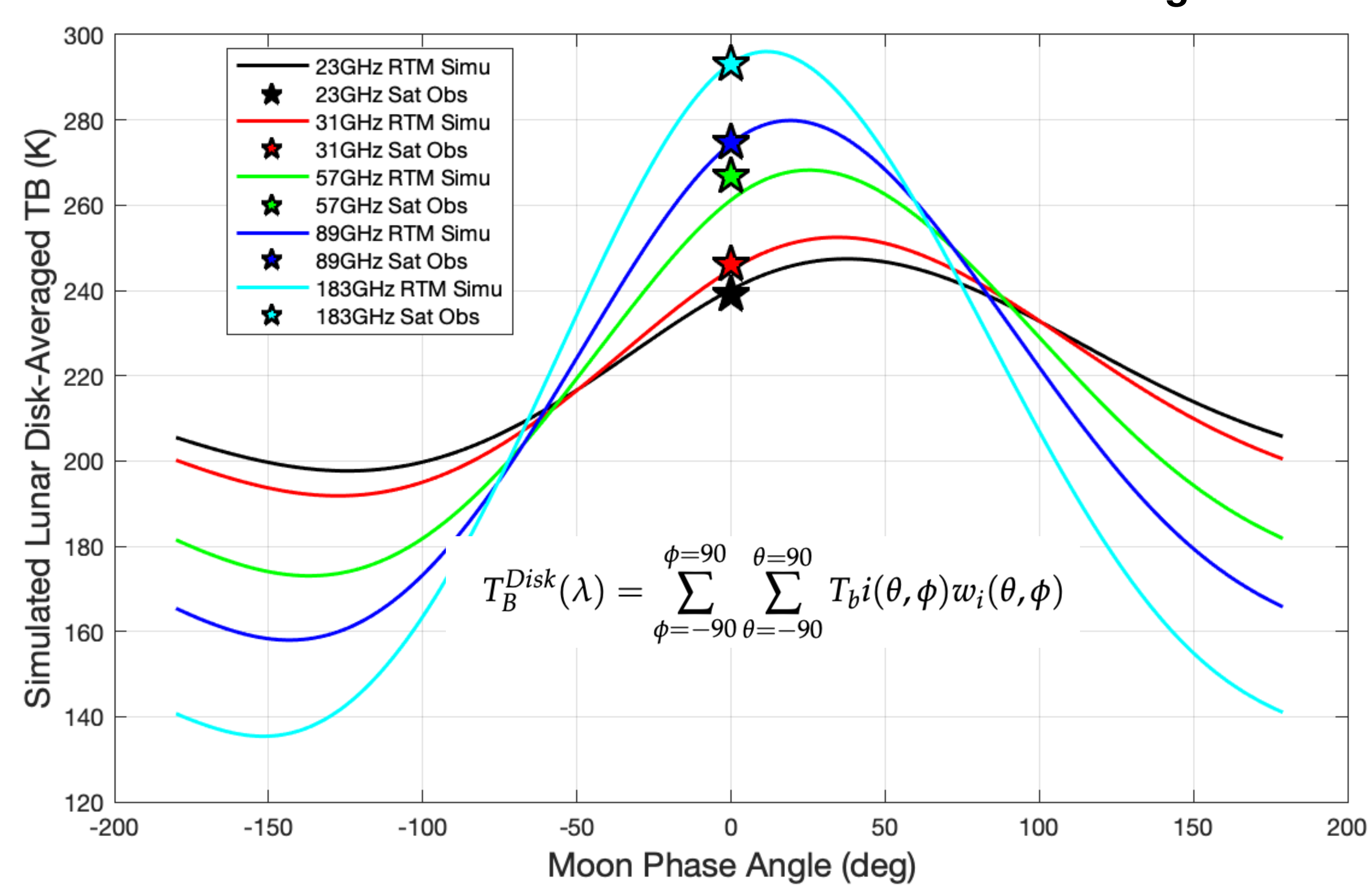
Calculation of Disk-averaged Lunar Tb

- No diurnal variation in deep layer
- More contribution from deeper layer in lower frequency band
- More contribution from deep layer during night time
- Magnitude of Phase-Lag decrease with the increase of frequency

(Keihm, 1984)

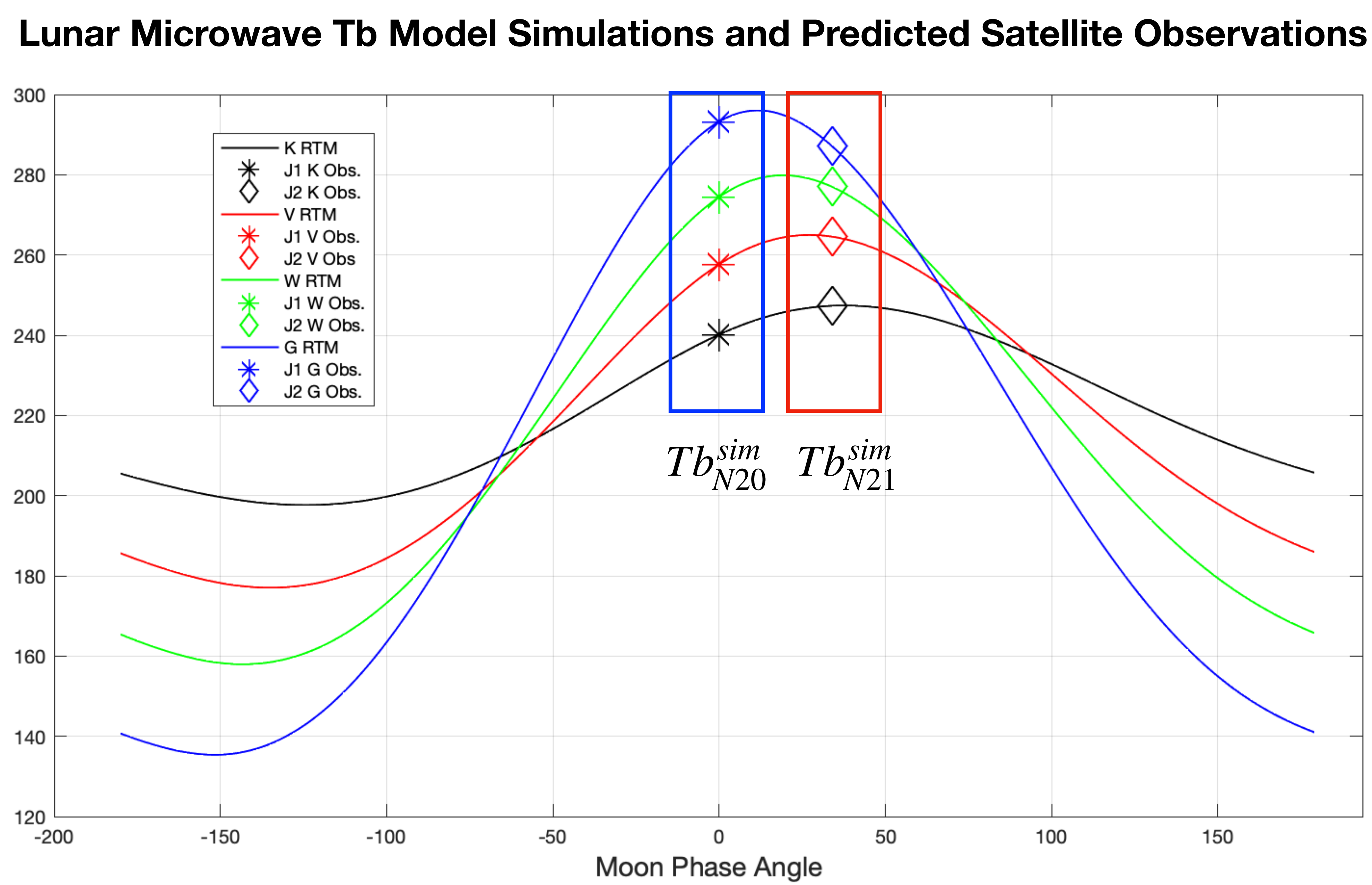
$$T_B(\lambda) = E_\lambda \int_0^\infty \kappa_\lambda \sec(\theta_i) \cdot T(z) \cdot e^{-\int_0^z \kappa_\lambda(z) \sec(\theta_i) dz} dz$$

Calibrated RTM Simulation for the Moon Disk-Averaged Tb



Prediction of the Disk-averaged Tb for NOAA-21 Lunar 2D Scan Test

- Lunar RTM simulation shows that for lower frequency channel of ATMS, the peak of the Moon disk-averaged Tb should appears around 3-days after the full moon, caused by the phase lag in lunar microwave observations
- For NOAA-21 Lunar observations, it is expected that the magnitude of lunar Tb should be higher than NOAA-20 in K to W band, and lower in G-band



N20/N21 Post-Launch Pitch Maneuver Test

NOAA-20 Pitch, 01/31/2018

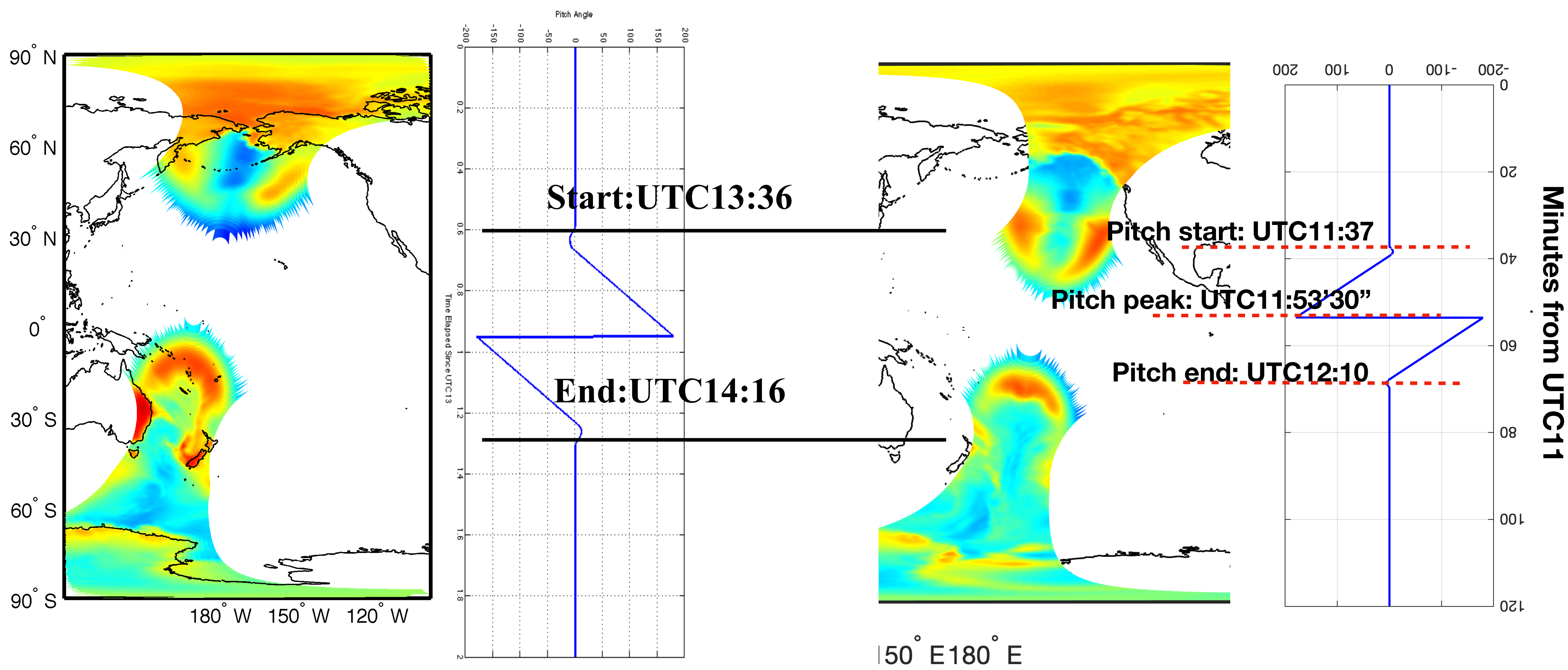
Satellite pitch slew rate: 0.1785 deg/sec

Moon Phase Angle=0°

NOAA-21 Pitch, 03/10/2023

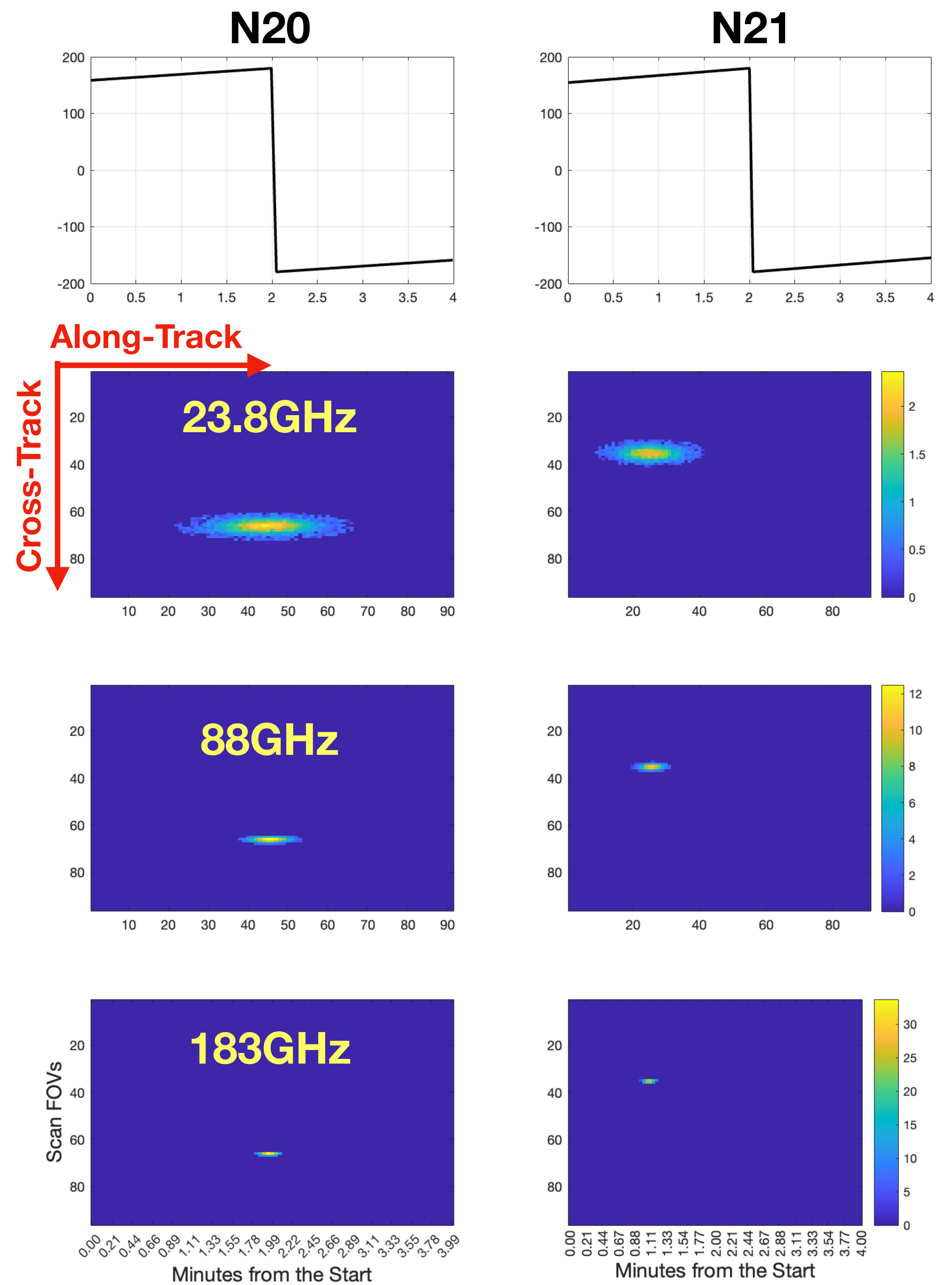
Satellite pitch slew rate: 0.2114 deg/sec

Moon Phase Angle=34°



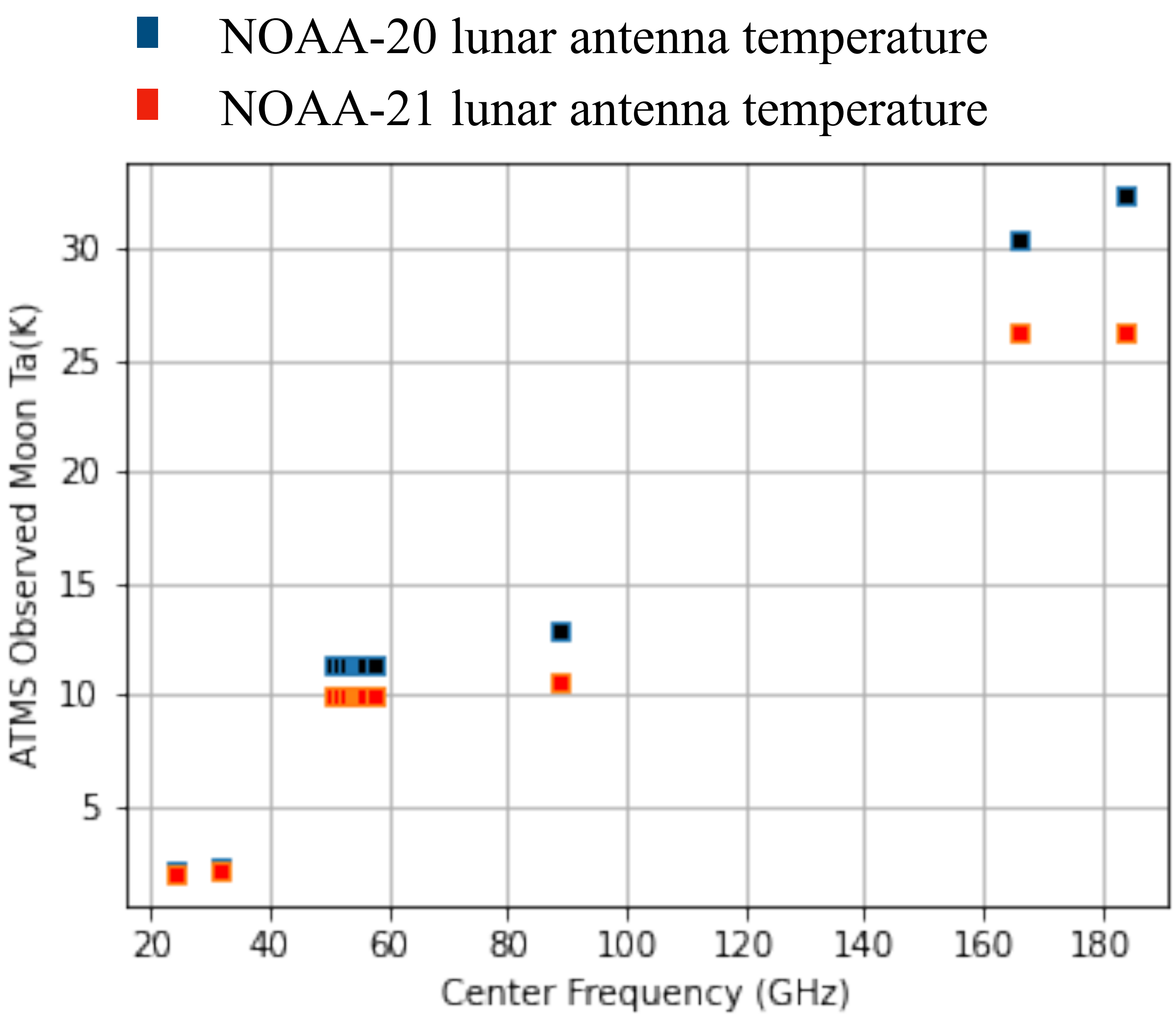
Calibration for ATMS Lunar Observations

- Only ±45 scan lines around the peak pitch angle were used for the study to reduce the impacts from the Earth contamination
- Reflector emissivity determined from OMPS pitch maneuver was used to make the reflector thermal emission correction for lunar calibration
- Satellite near-field contamination determined from the full-cycle pitch observation was used to make the near-field contamination correction for lunar calibration
- Due to the higher slew rate of N21 pitch maneuver, the sampling rate of N21 ATMS lunar is lower than N20, fewer Moon scan samples were obtained from N21



Comparison of ATMS Lunar Ta spectrum between NOAA-20 and NOAA-21

- Antenna temperature calibration results show that NOAA-21 lunar Ta is generally lower than NOAA-20, and the difference increase with frequency
- Note that to derive the Moon disk-averaged Tb, the antenna should be corrected separately for NOAA-20 and NOAA-21



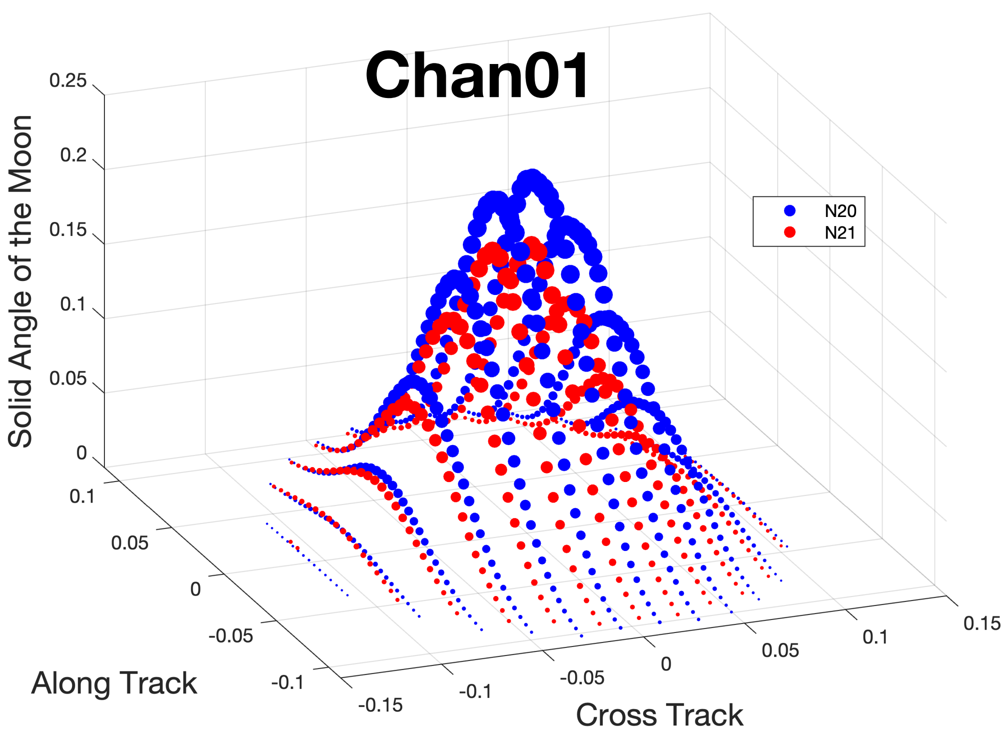
Band/Frequency (GHz)	NOAA-20	NOAA-21
K(23.8)	2.14	1.99
V(50~57)	11.39	9.45
W(88)	12.88	10.68
G1(166)	30.40	26.25
G2(183)	32.41	26.30

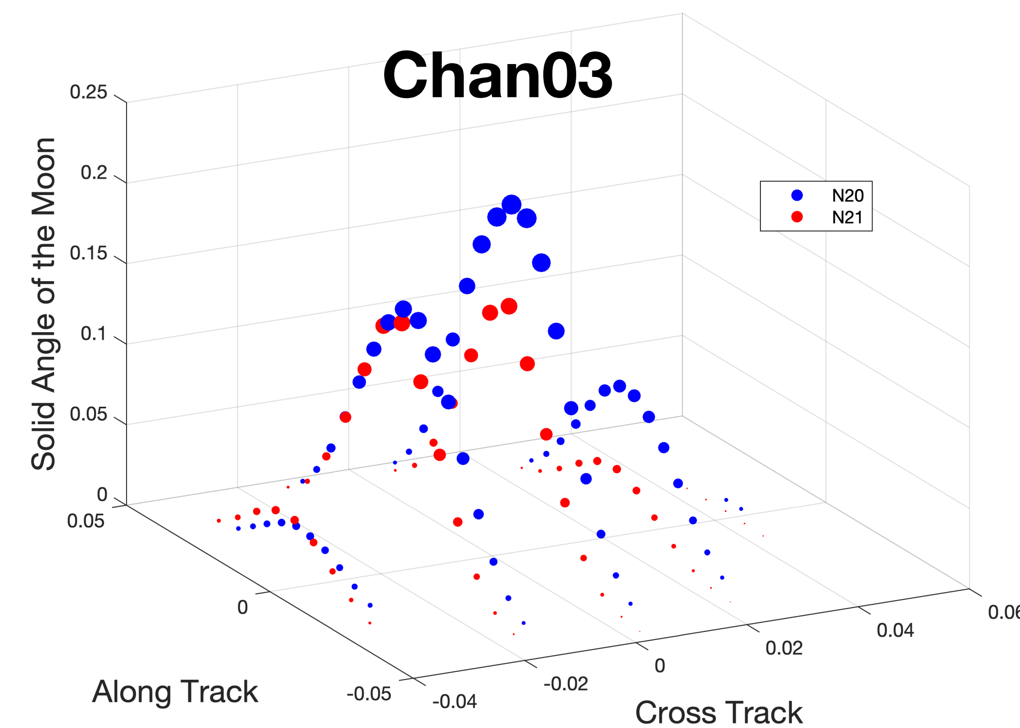
Difference in Antenna Responses for Moon Observations between N20 and N21

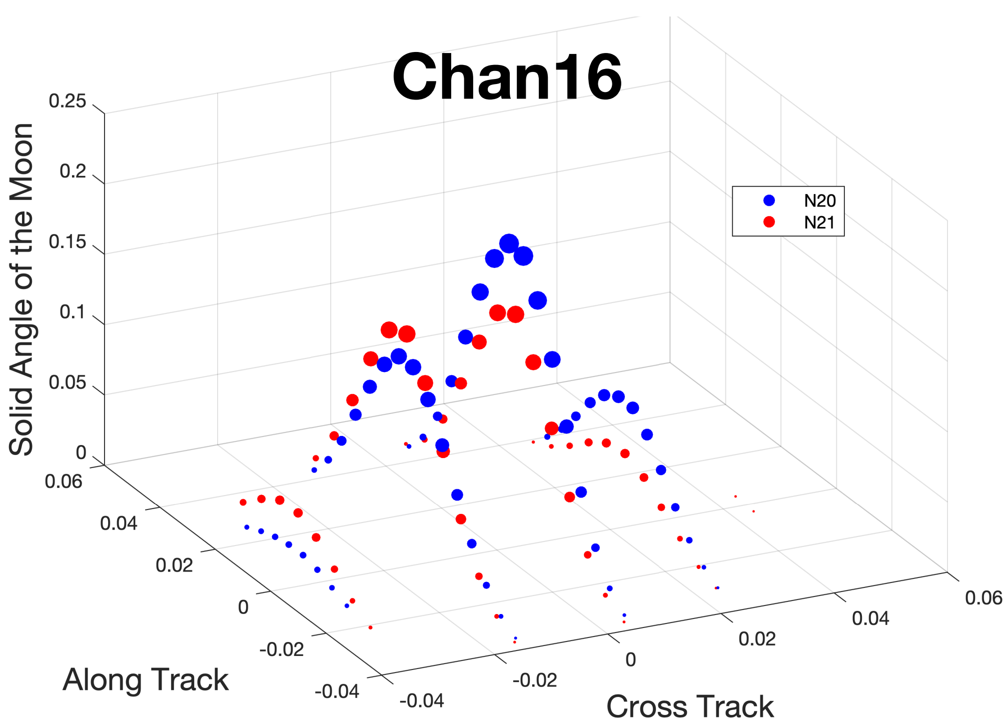
Due to the lower lower sampling rate of N21 ATMS Moon scan observations, the Moon was not well captured at the beam center. As a result, the Antenna Responses from N21 is weaker than N21, which need to be addressed for the Tb retrievals.

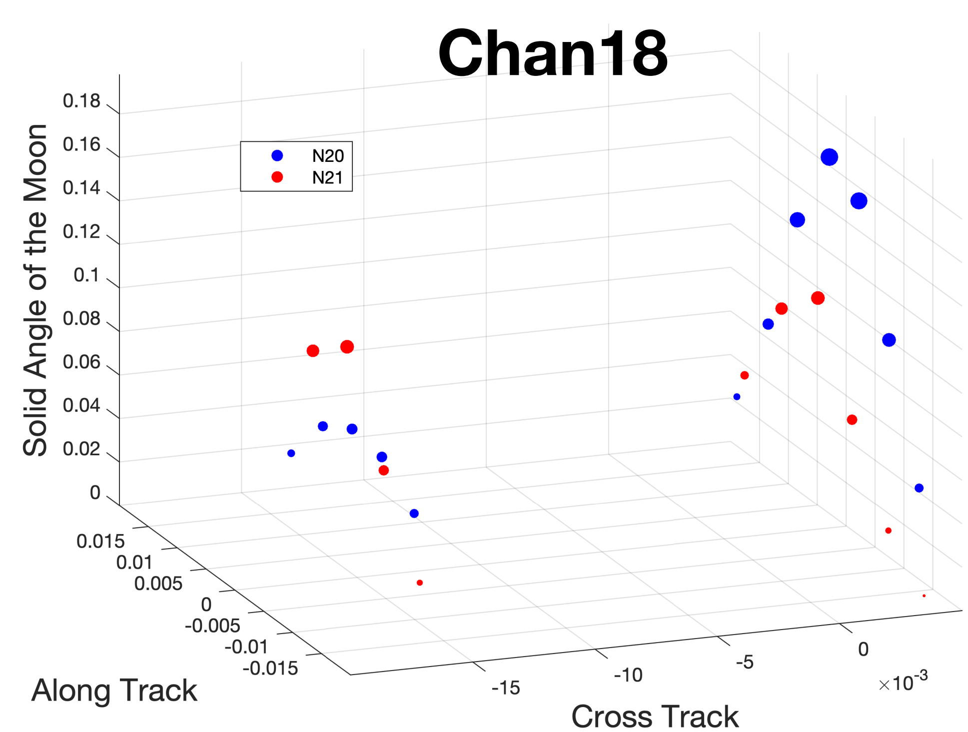
Solid Angle of the Moon:

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





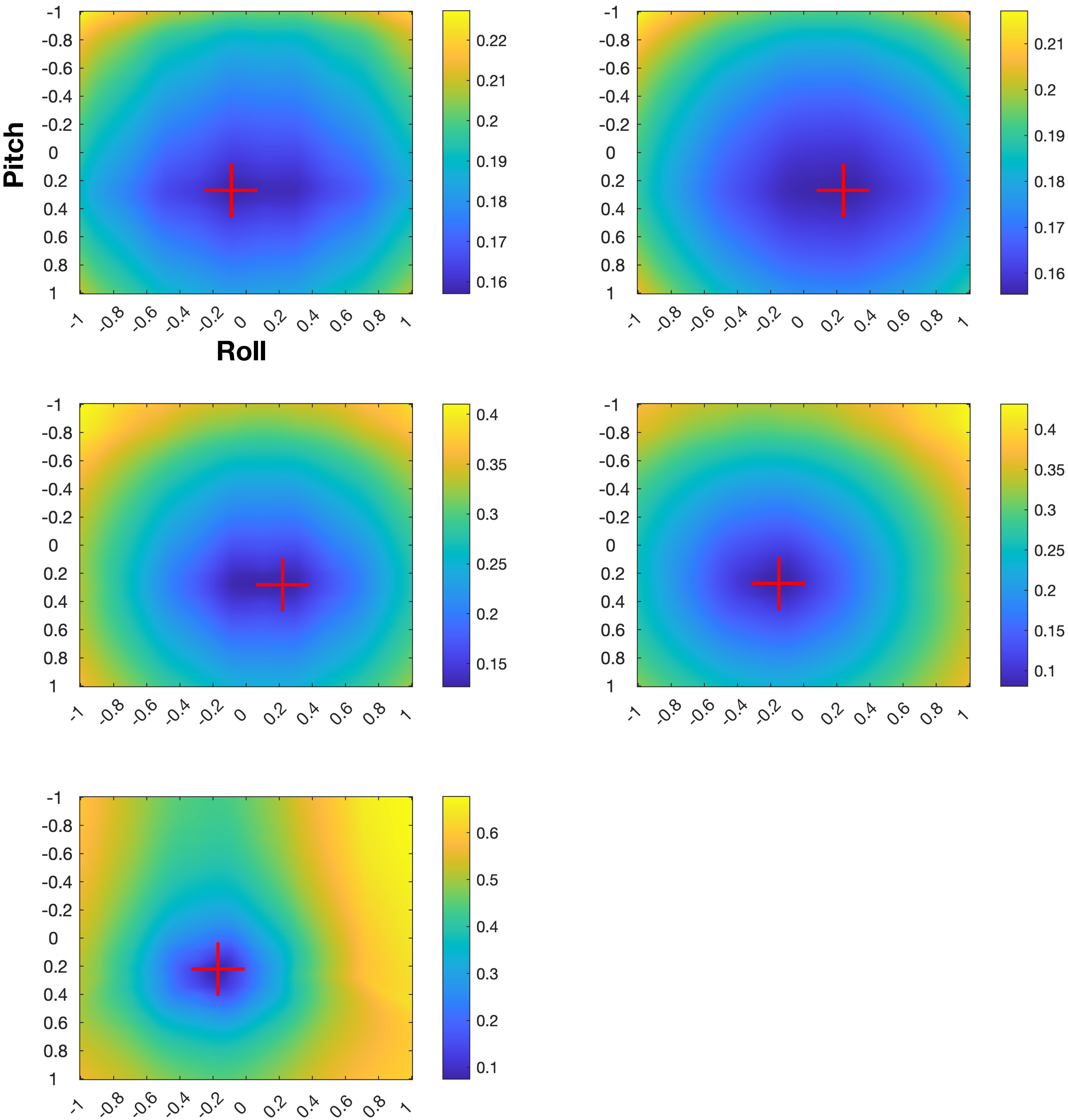




Beam Pointing Error Correction

- *Jun Zhou and Hu Yang, 2019, "On Study of Two-Dimensional Lunar Scan for Advanced Technology Microwave Sounder Geometric Calibration", Atmospheric Measurement Technique,* https://doi.org/10.5194/amt-2019-177

NOAA-21 Lunar Geolocation Error Evaluation



Considering the facts that the magnitude of antenna response is very sensitive to position of Moon's center in the Field of View of antenna beam on observing direction. Especially when lunar appears at the center of FOV, where the gradient of antenna response reaches its maximum. Therefore by comparing simulated antenna response of lunar scans with the observation truth, the displacement of beam center can be identified.

$$\sigma(\xi_r,\xi_p) = \frac{1}{N-1}\sqrt{\sum_{i=1}^{N}(G(\xi_r,\xi_p)-G_{obs})^2}$$

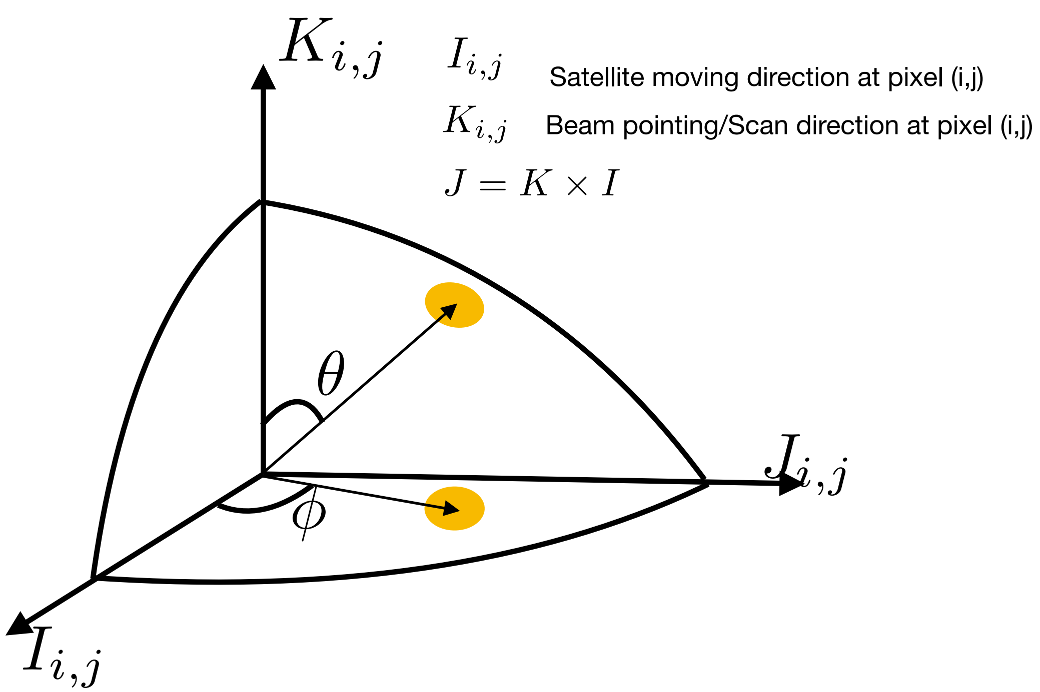
To calculate the antenna gain of the moon, the smearing effects need to be taken into account

$$G(\xi_r,\xi_p) = \frac{G_{imoon}}{G_{imoon}^{max}}$$

$$G_{imoon} = \frac{1}{L}\int_{\frac{-\tau}{2}}^{\frac{\tau}{2}} dl \int_0^{2\pi}\int_0^{\alpha_{moon}} G^{'}(\theta^{'},\phi^{'}) sin\theta' d\theta' d\phi'$$

Retrieval of Disk-Averaged Moon Tb from Calibrated 2-D Lunar 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 beam pointing error is corrected for the Tb retrieval
- The smearing effect has been taken into account to calculate the lunar solid angle
- Regression algorithm was used for the lunar Tb retrieval
- Observations from adjacent channels with closed frequencies were combined for the retrieval

Regression model for Tb retrieval

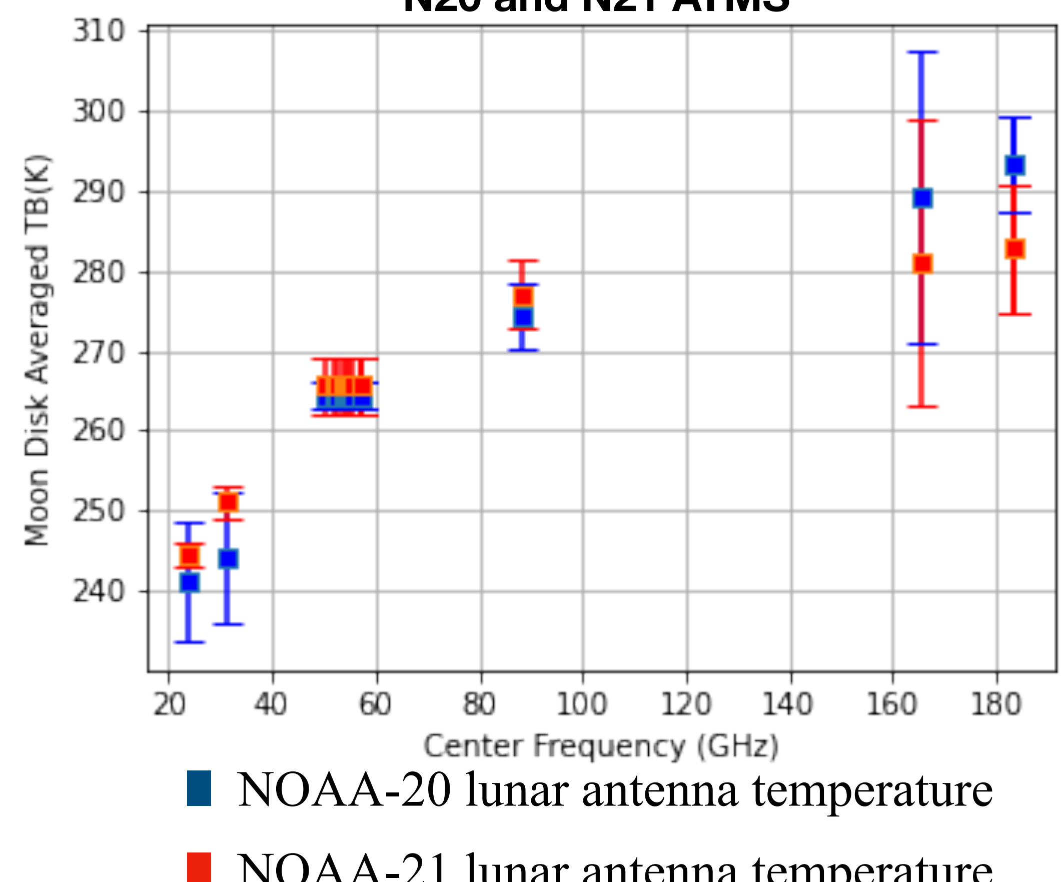
$$Ta_{moon}(\theta_{ifov}, \phi_{ifov}) = Tb_{moon}^{Disk} \cdot \frac{\Omega_{moon}^{ifov}}{\Omega_P}$$

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

Channel-Averaged Moon Tb

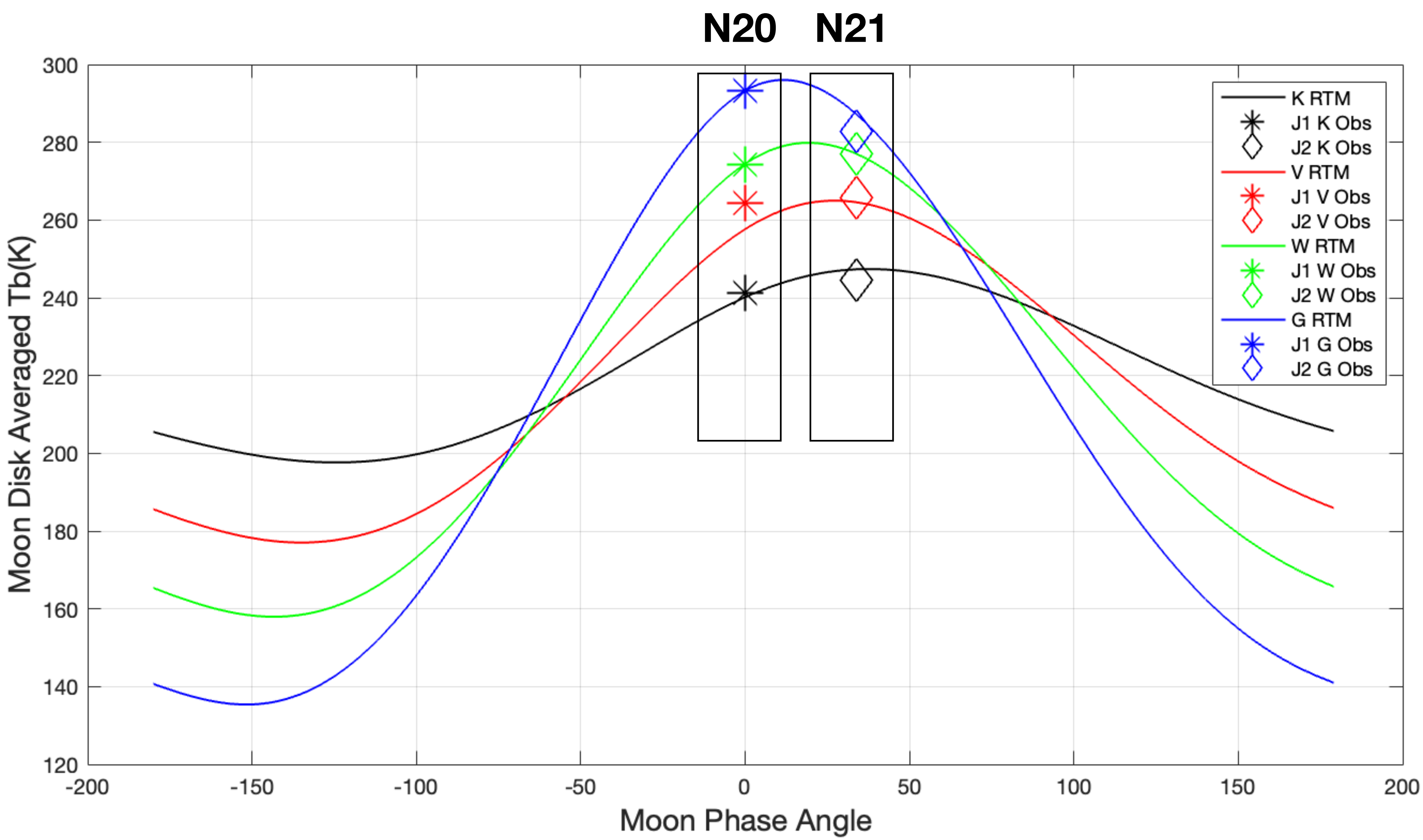
Band	Frequen	N20	N21
K	23.80	241.21	244.54
Ka	31.40	244.14	251.16
V	50.30	264.44	265.67
W	88.20	274.38	277.08
G1	165.50	289.19	281.03
G2	183.31	293.17	282.74

Disk-Averaged Moon Tb Spectrum from N20 and N21 ATMS



Retrieved Disk-averaged Tb from NOAA-20 and NOAA-21 Lunar observations

- Disk-averaged Lunar Tb retrieval results from N21 show that they match well with the calibrated Keihm RTM model



Conclusion and Future Work

- NOAA-21 lunar 2D scan observations were processed and calibrated. It is found that due to a faster slew rate for N21 pitch maneuver, the Moon was not well captured at the ATMS antenna beam center

- After correction for the beam pointing error, the retrieved Moon disk-averaged brightness temperature from N21 matches well with the N20-calibrated RTM simulations

- Proposing for NASA to make Lunar 2D scan as a routine post launch test for future NOAA microwave sounding instruments

- Collect the microwave lunar data samples from different satellite platform to further evaluate the model performance at different Moon phase angles

- The dataset and the calibrated RTM model(CLRTM) can be accessed by requirement from Github: https://github.com/Tigeryang007/RTMlunar, contact info: huyang@umd.edu

Backup Slides

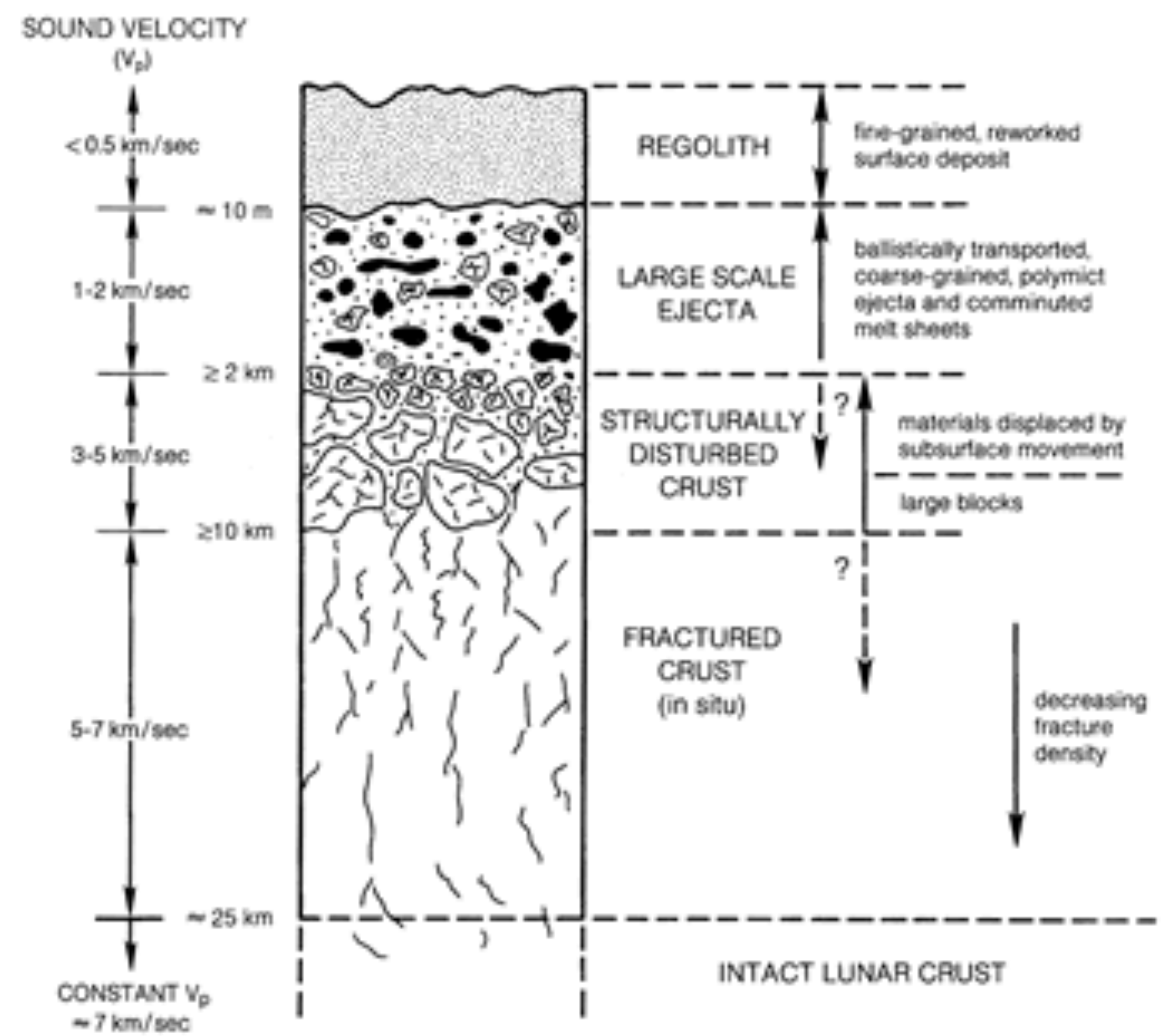
Theoretical Model for Microwave Emission of the Moon

(Stephen Keihm, ICARUS 60, 1984)

For a *purely absorptive* regolith, the correlation can be expressed simply as an integration of the depth-dependent emission, attenuated by the electrical loss to the surface. For a nadir observation,

$$TB(\lambda) = E_\lambda \int_0^\infty K_\lambda \cdot T(z) \cdot \exp\left[-\int_0^z K_\lambda dz'\right] dz$$

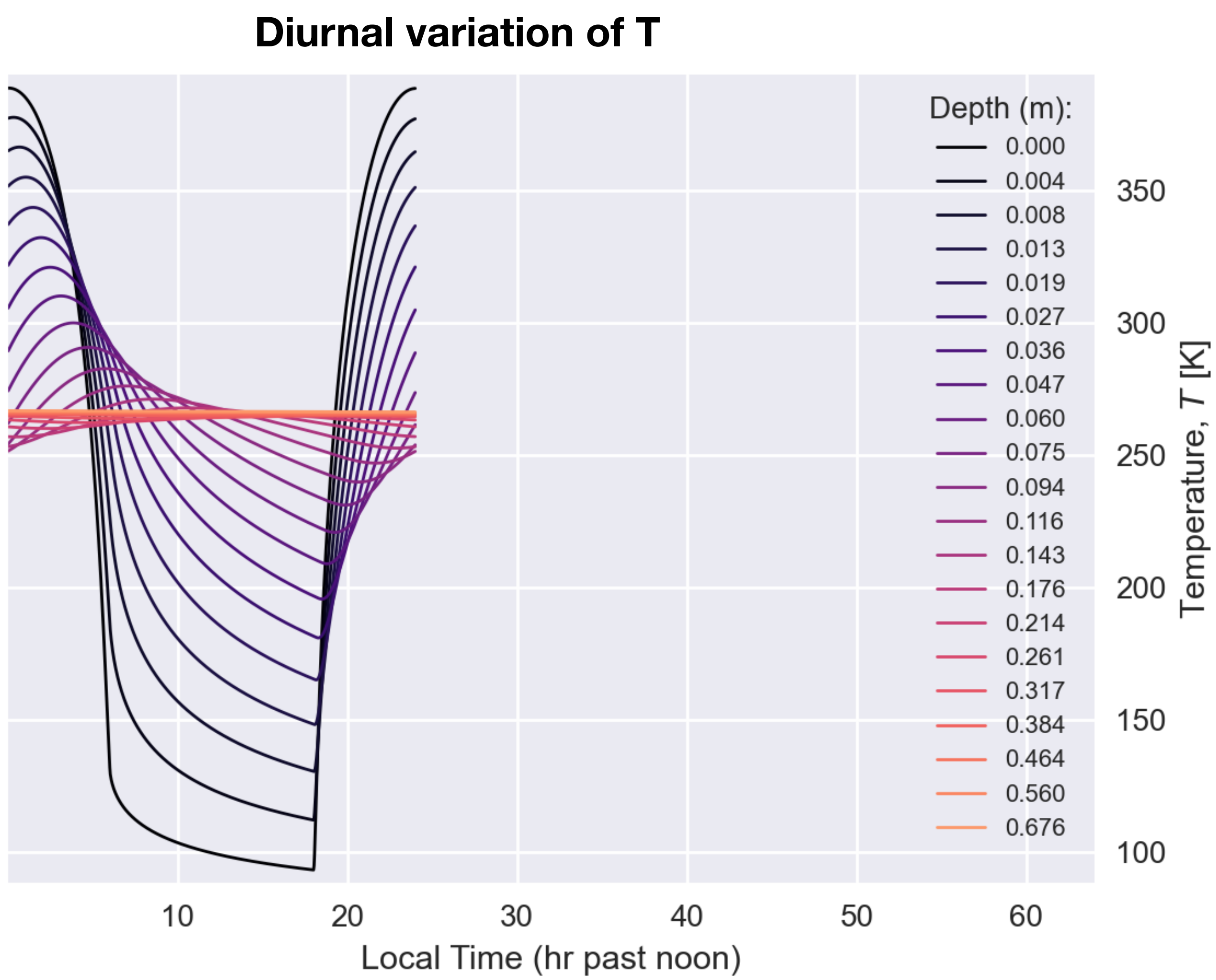
Lunar Surface Structure

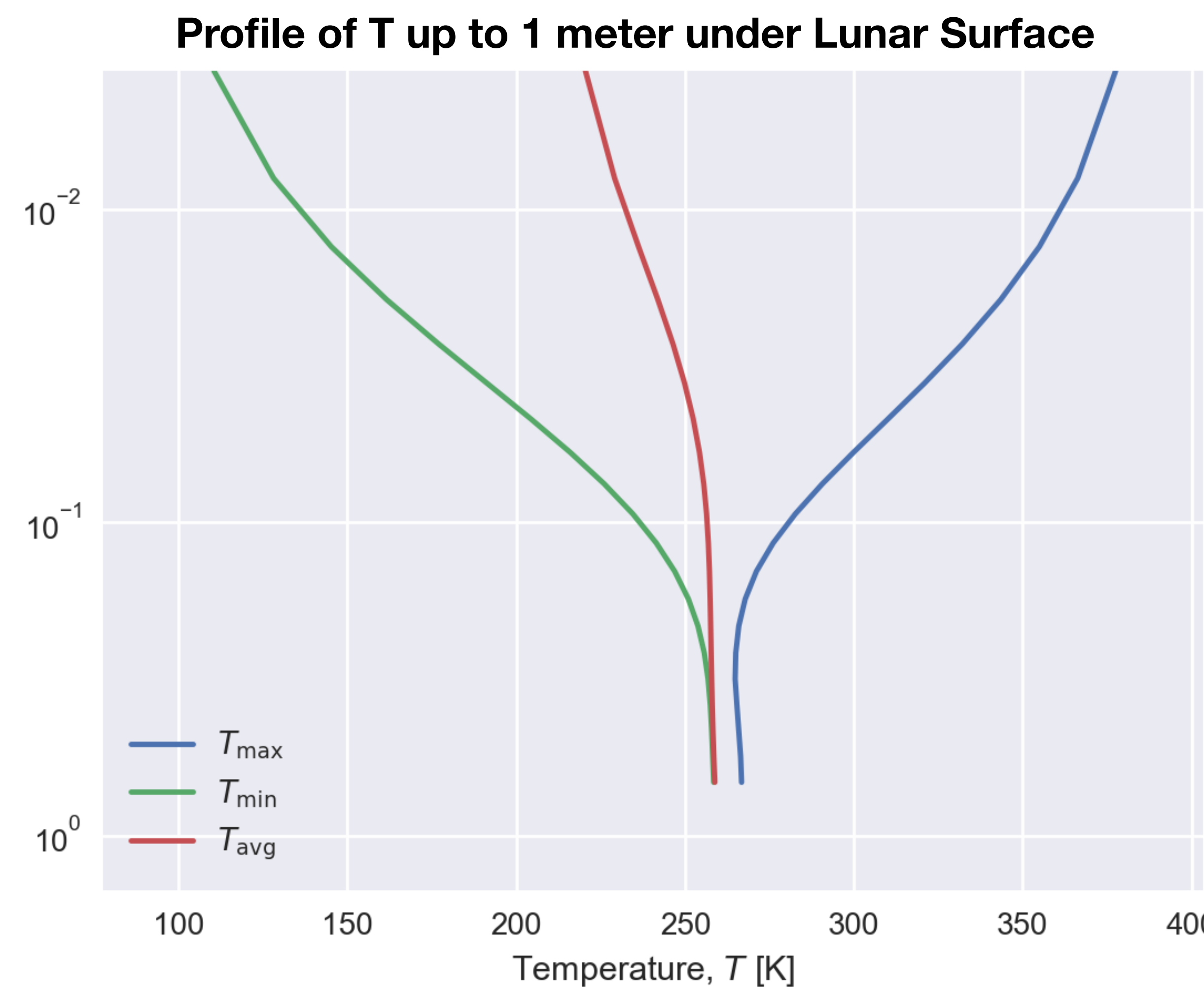


Heiken, G.H., Vaniman, D.T., & French, B.M. eds, **Lunar Sourcebook**, Lunar and Planetary Institute, Houston, 1991.

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





Calibration of the Keihm Lunar RTM

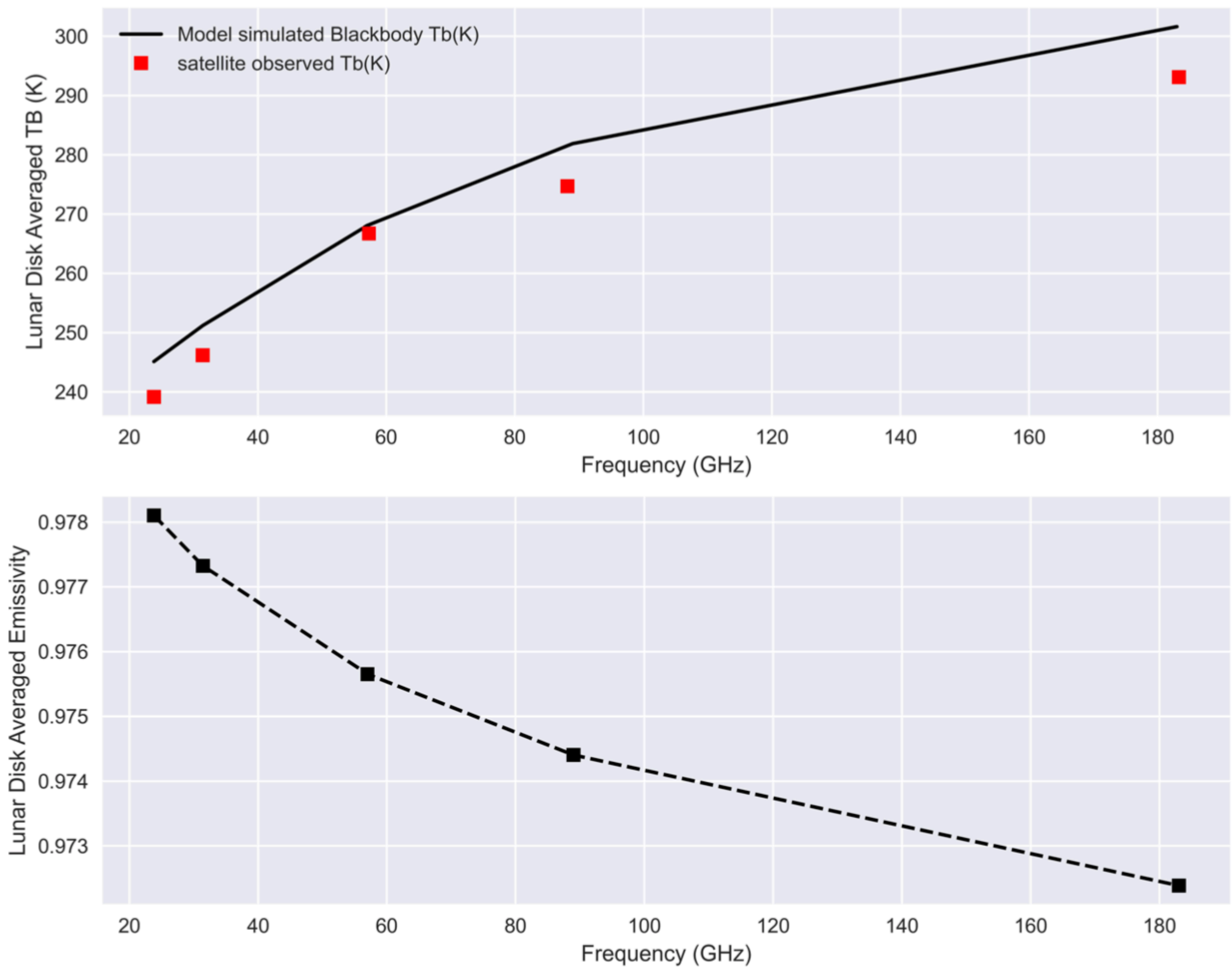
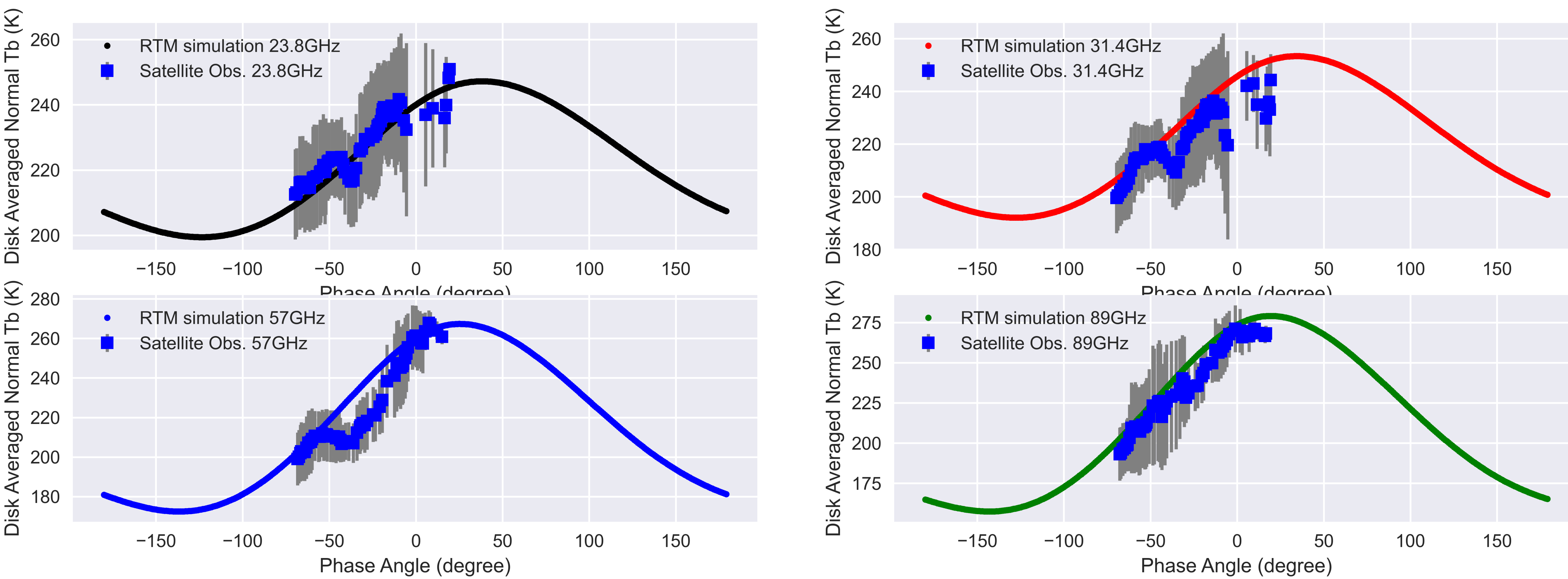
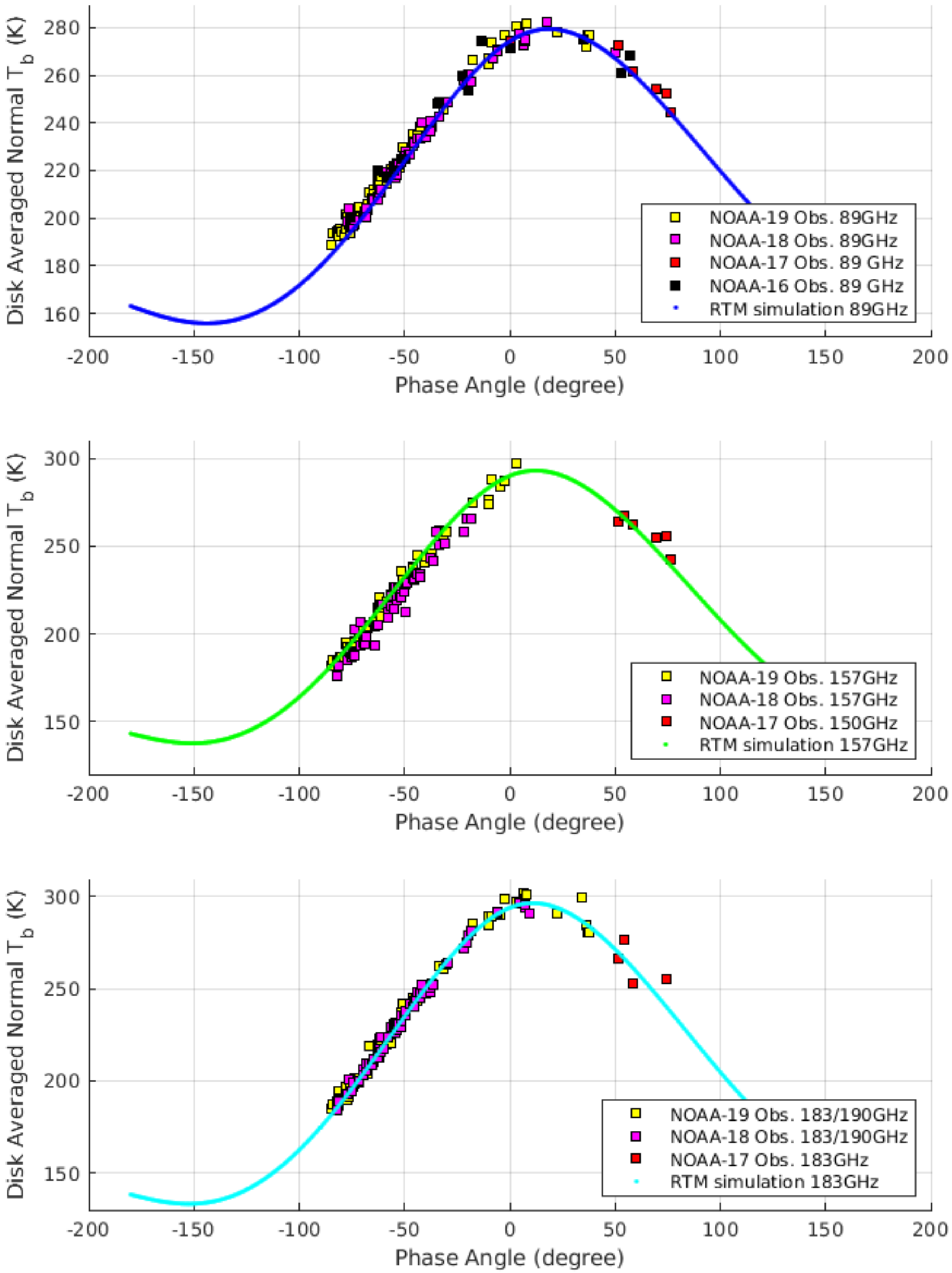


Figure 4. The disk-integrated lunar brightness temperature spectrum and effective emissivity at full-Moon phase.

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

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:

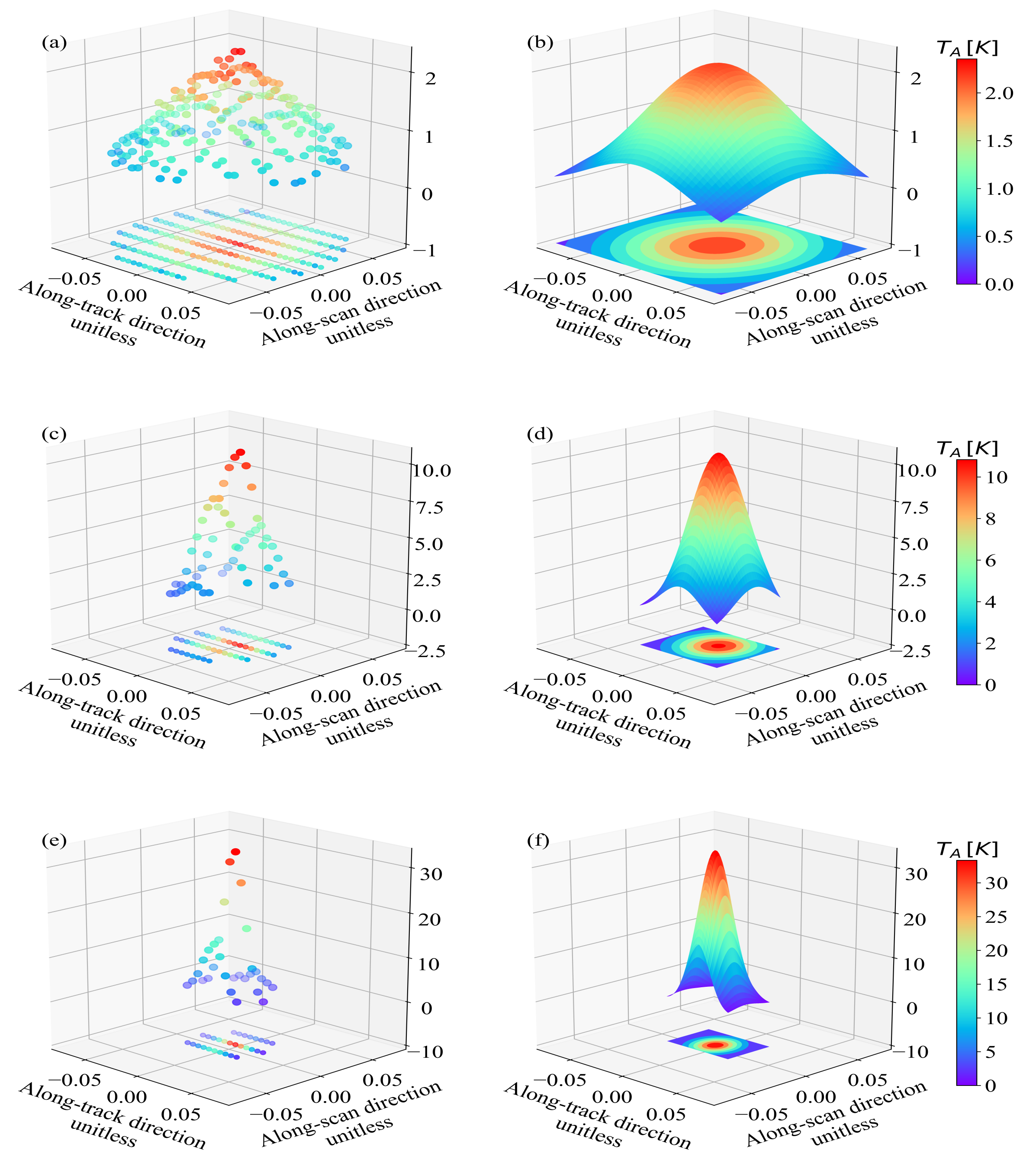
$$Ta_{moon}(\theta_{ifov}, \phi_{ifov}) = Tb_{moon}^{Disk} \cdot \frac{G(\theta_{ifov}, \phi_{ifov})}{\Omega_P}.$$

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),

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



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:

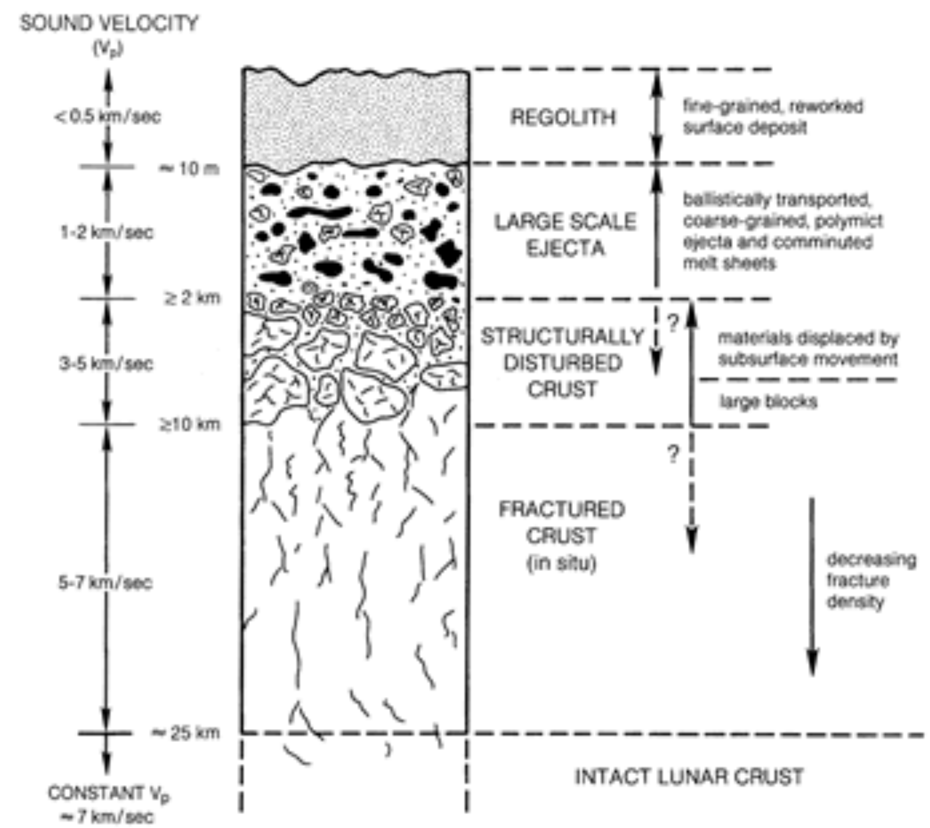
$$E_\lambda^p = 1 - R_\lambda^p$$

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

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

Lunar Surface Structure

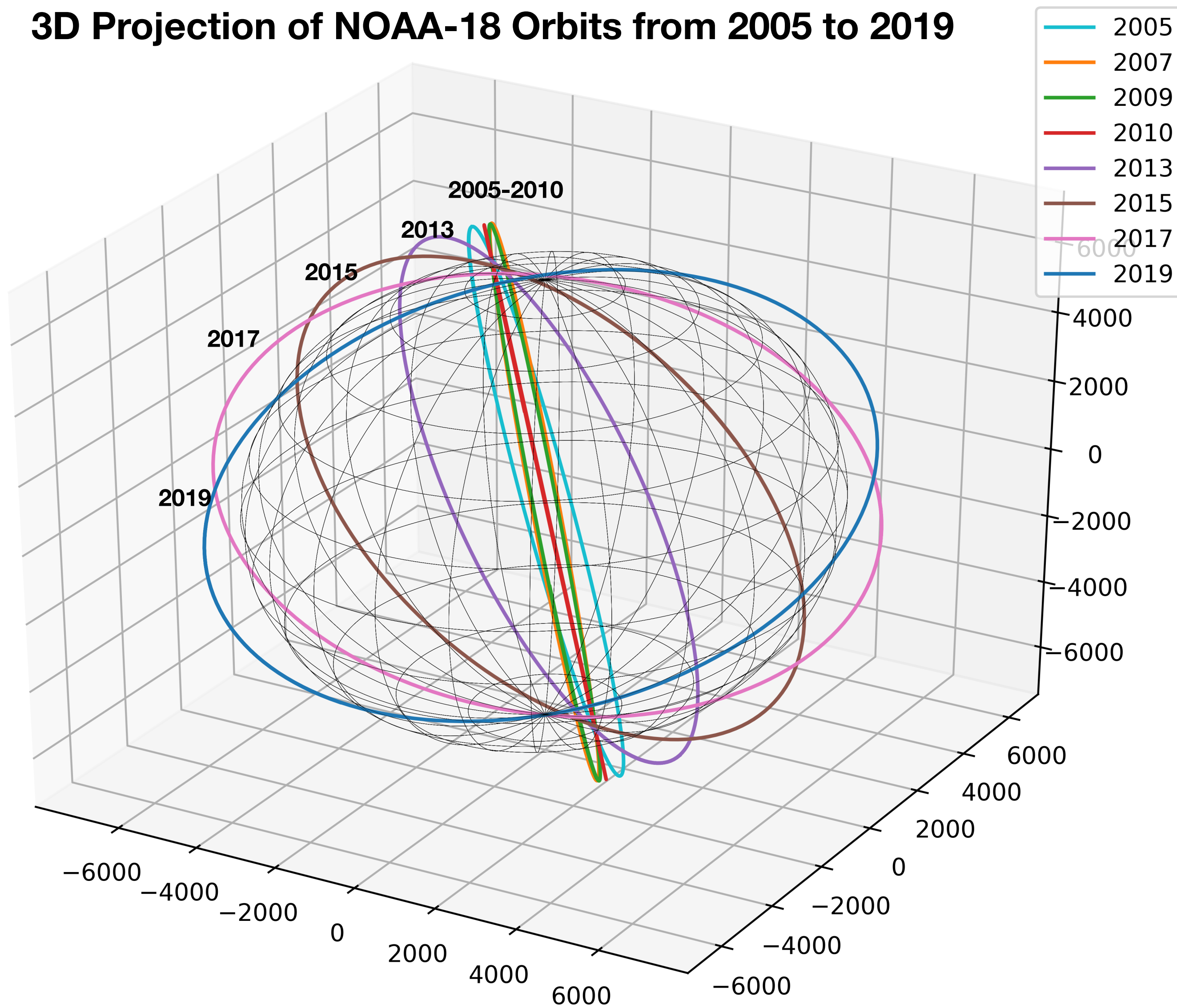
Heiken, G.H., Vaniman, D.T., & French, B.M. eds, **Lunar Sourcebook**, Lunar and Planetary Institute, Houston, 1991.



- 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

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

3D Projection of NOAA-18 Orbits from 2005 to 2019



Change of Moon Phase Angle and LTAN of NOAA-18 Satellite