# A Science Case for Microwave Wavelength Measurements

**Matt Siegler** (Planetary Science Institute and Southern Methodist U.)
(with substantial contribution by Jianqing Feng)
Decadal Survey on Planetary Science and Astrobiology:
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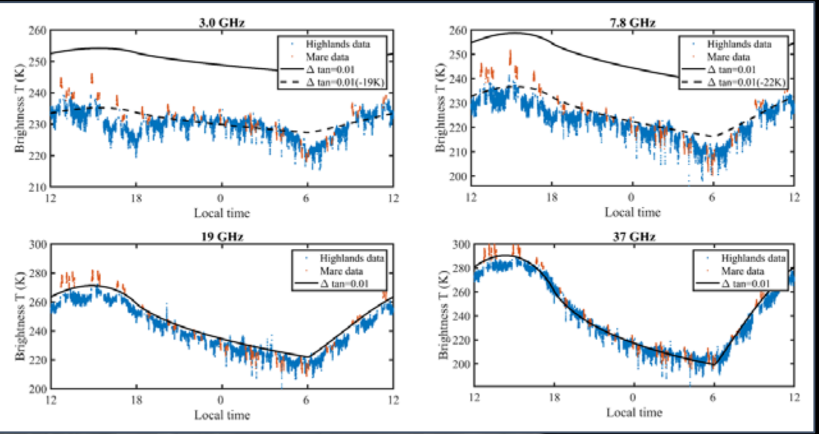
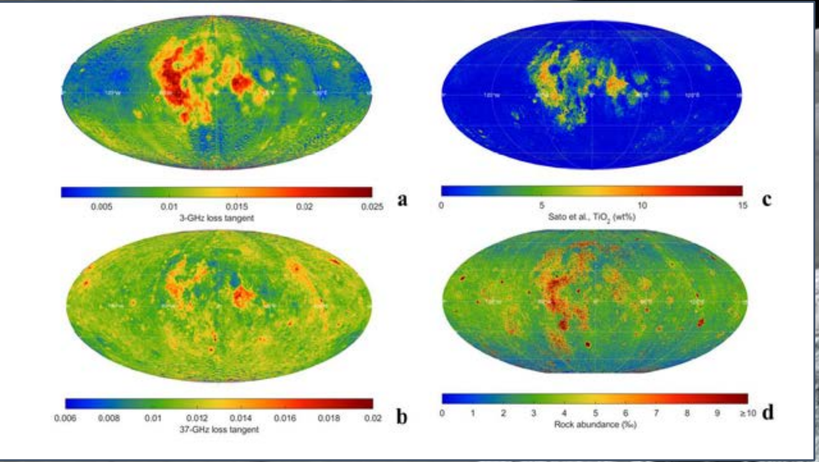
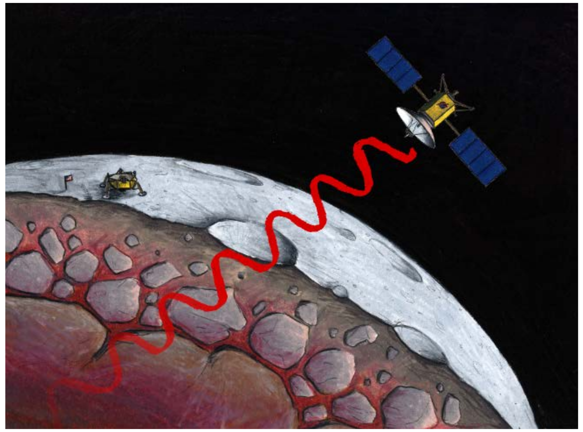
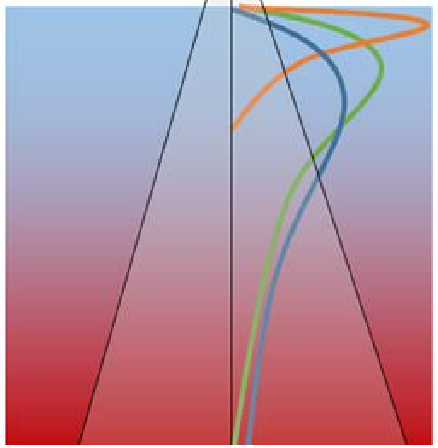


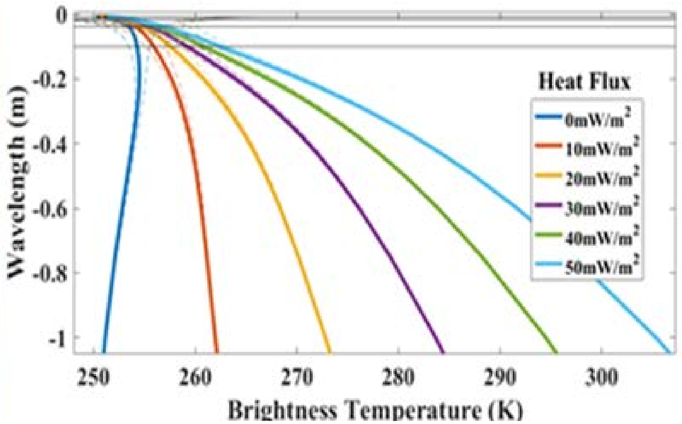




**Cosigners:** William Blackwell, David Blewett, Shannon Brown, Bryan Butler, Joshua Cahill, Simon Dicker, Adrienne Dove, Rebecca Ghent, Timothy Glotch, Paul Hayne, Karl Hibbits, James Keane, Stephen Keihm, Paul Lucey, Sidharth Misra, David Paige, Than Putzig, Edgard G. Rivera-Valentín, Christopher Ruf, Isaac Smith, Adrian Tang



**Microwave Radiometry:**
Any warm body emits microwaves from a depth determined by the:
(1) wavelength of the emitted microwave radiation,
(2) physical temperature, and
(3) the dielectric properties of the overlying material.





# What can we lean from microwave radiometry?

Microwave and radiowave (broadly ~1 mm to1m wavelength, 300 MHz to 300 GHz frequency) radiometry senses thermal emission from below the surface.

The strength of this emission depends on both the physical temperature of the material and the dielectric properties of material above it. It is commonly used for atmospheric sounding (weather satellites, but the liquid water on Earth prevents deep penetration. On the Moon (or Mars) one could “see” 10’s of meters into the subsurface.

This makes it an ideal tool for studying subsurface temperatures, thermal properties, density, and dielectric properties.

This has a groundbreaking potential to detect subsurface ice and measure geothermal heat without drilling and even from orbit.

# As a reminder, microwave radiometry of planets is not a new thing- it just hasn't left Earth orbit very often.

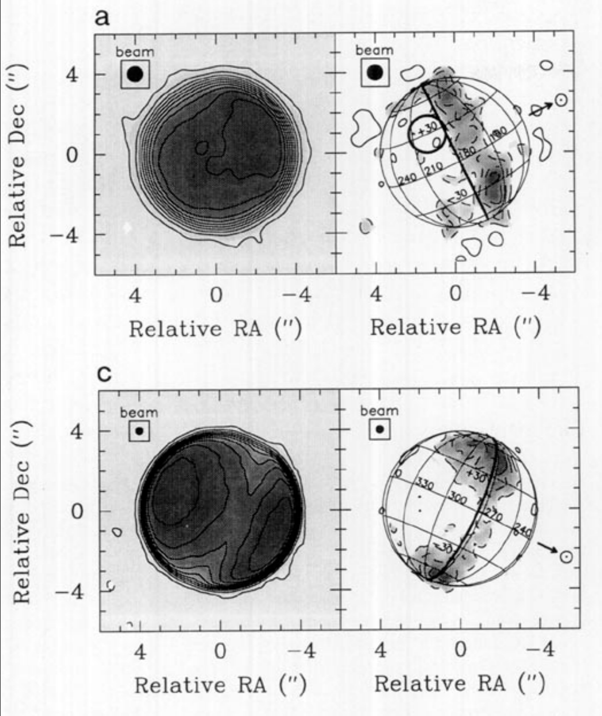
Some of our earliest thermophysical observations of the Moon were preformed in microwave (1.25cm, 24GHz , Piddington and Minnett, 1949) after wartime radio receiver development. Atmospheric windows prevented IR work.

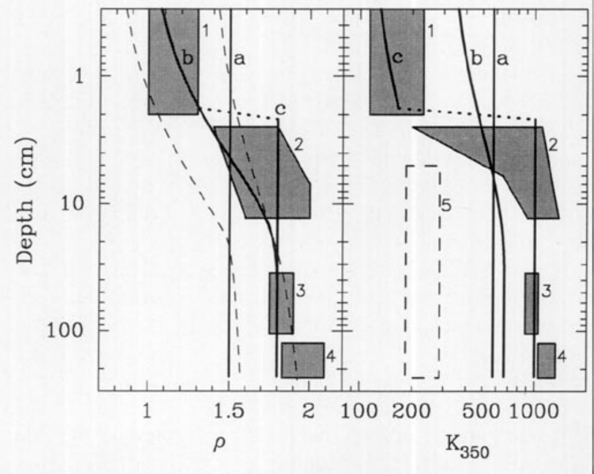
Muhleman (1971), Keihm & Gary (e.g. 1979) and others pressed this science further with Earth based observations and tried to push for orbital instruments to the Moon, but the 80s and 90's brought little in the way of lunar exploration opportunity.

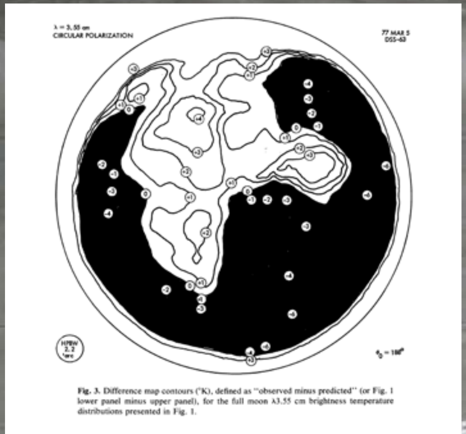
Passive measurements of Mercury (Mitchell and dePater, 1994) of Mercury gave us the first estimates of thermophysical properties there and provided the basic structure model applied to most lunar thermal modeling (e.g. Vasavada et al., 1999). Telescope data has also revolutionized Venus, Galilean satellites…

The JPL-built MIRO instrument flew aboard Rosetta with a 190 GHz (1.6 mm) and 562 GHz (0.53 mm) radiometer, measuring thermal properties of asteroids and comet 67P.

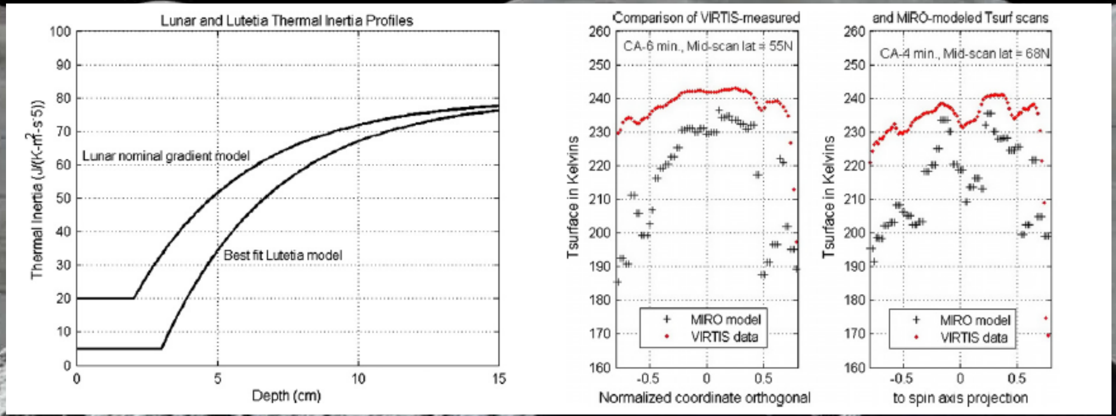
Juno's MRW instrument is looking at Jupiter's atmosphere and will fly by the Galilean Satellites in the extended mission. Cassini's radar had a passive mode with great observations of Titan (Janssen et al., 2016).



Keihm and Gary (1979)

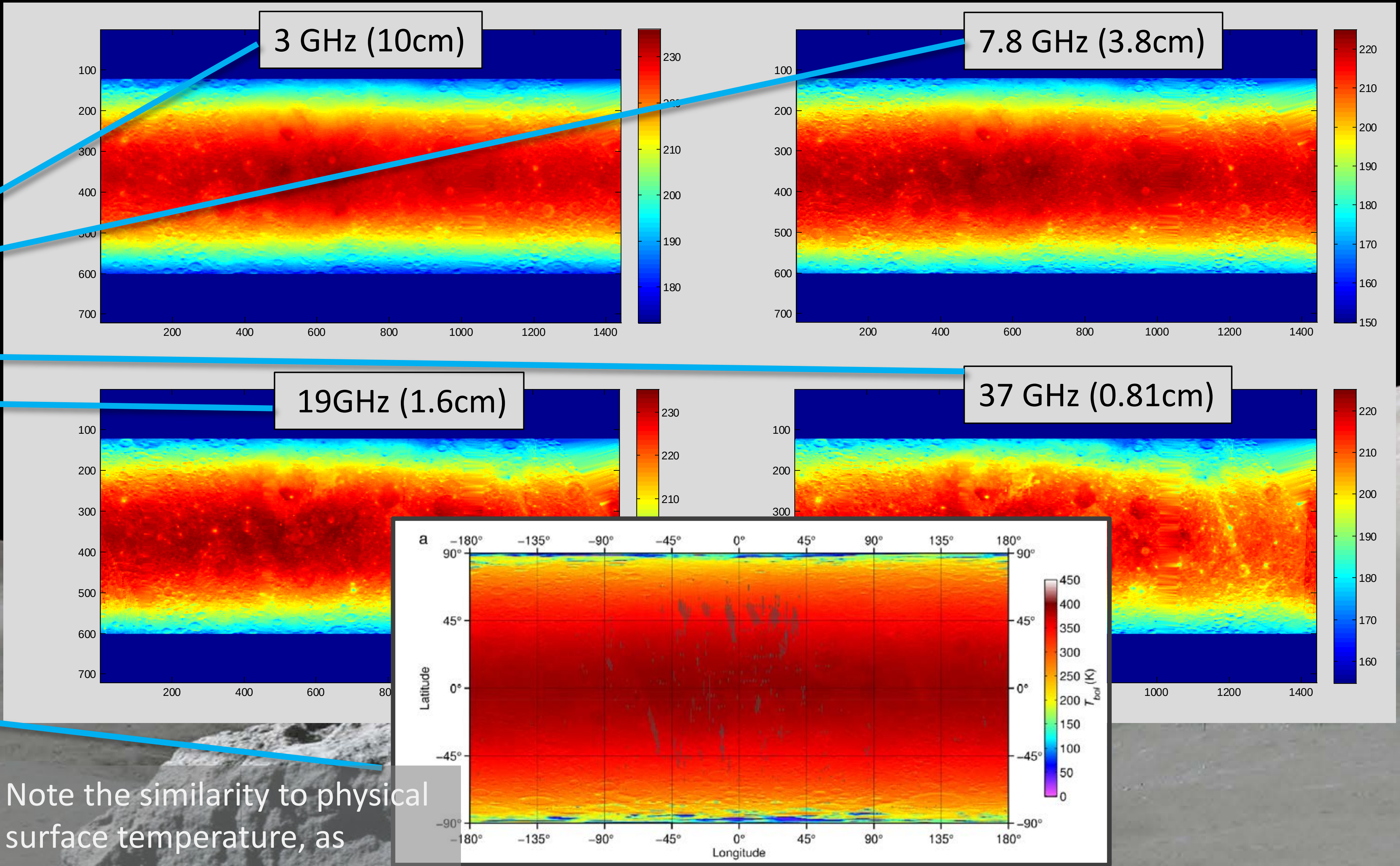



Keihm etal (2012)

Mitchell and de Pater (1994)

# A real revolution in lunar microwave came with the 2010 & 2012 Chang'E 1 and 2 orbiters

Both of the Chang'E orbiters carried a 3-37 GHz radiometer (MRM or often CLEMS)

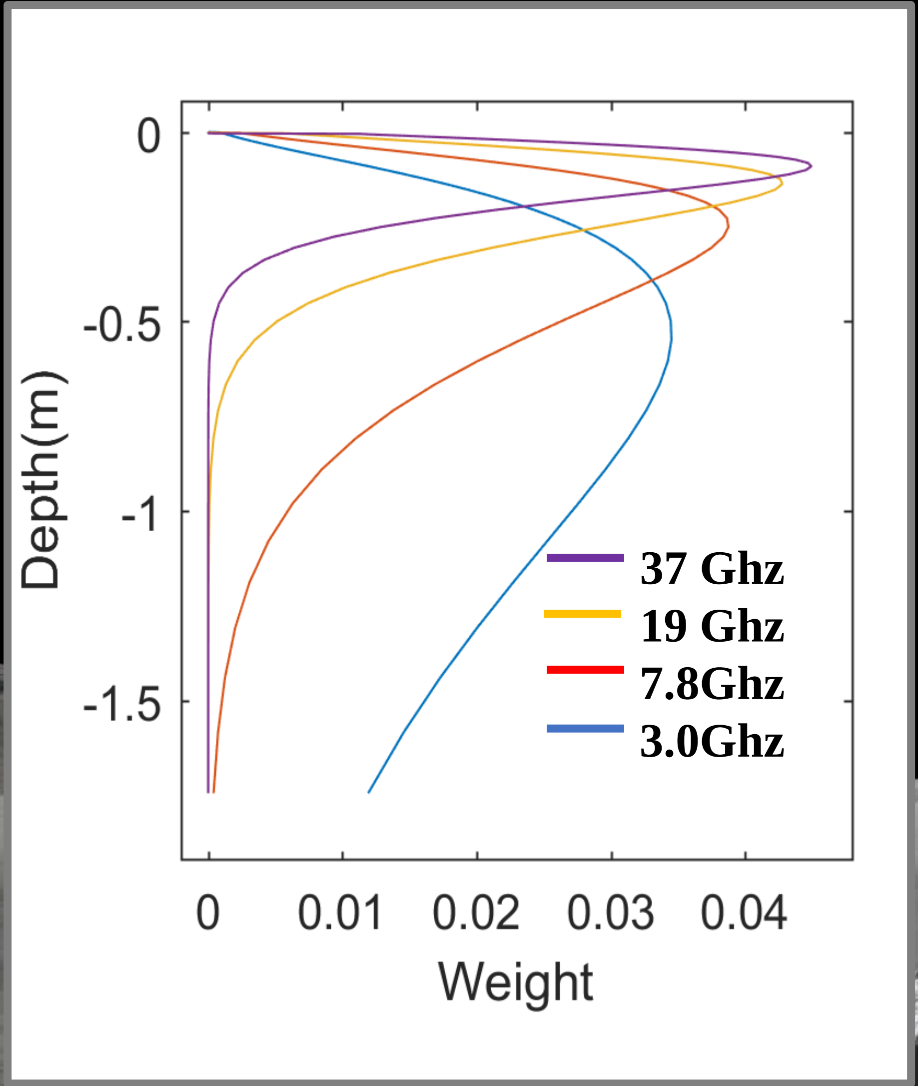



The Chang'E MRM instruments were effectively repurposed weather satellites so not designed with particular lunar science goals and has some difficult to navigate calibration issues, but opened a new window into the lunar surface and interior.

Note the similarity to physical surface temperature, as measured by LRO Diviner

From Williams et. al. 2017

# How does one translate microwave data to physical temperature – and what can we learn?




**<u>Simple rules of Microwave Radiometry</u>:**
**Any warm body emits microwaves from a depth determined by the:**

**(1) wavelength of the emitted microwave radiation,**

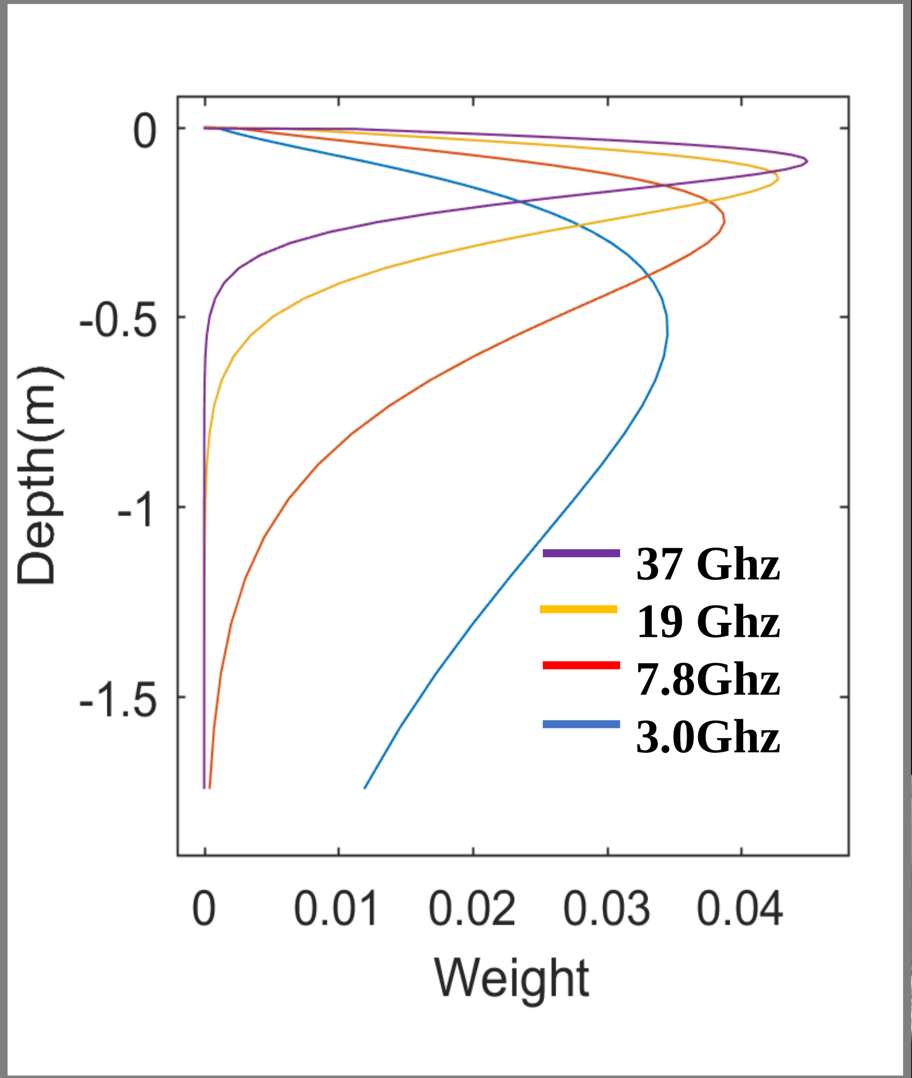
**(2) physical temperature, and**

**(3) the dielectric properties of the overlying material.**

**This allows us to sense temperature, density, composition (as it affects dielectric properties) both near the surface and far deeper.**

**Science goals:**
**Regolith thermophysics, Rock abundance mapping/landing safety, minerology (surface and subsurface Ti for instance), subsurface temperature (geothermal heat flux), and potentially buried ice**

# How does one translate microwave data to physical temperature – and what can we learn?




- More complicated rules of microwave radiometry:

$$w_i = (1 - s_i)\cdot(1 - e^{-2k_i d_i})\cdot(1 + \left|R_{i(i+1)}\right|^2 \cdot e^{-2k_i d_i})\cdot\prod_{j=0}^{i-1}((1 - \left|R_{j(j+1)}\right|^2)\cdot e^{-2k_j d_j})$$

Where $w_i$ is the weight coefficient of layer i,

$S_i$ is the single scattering albedo in layer i

$k_i$ is the absorption coefficient of layer i

$$k_i = 2\pi \frac{f}{c}\sqrt{\varepsilon}\tan\delta$$

"Loss tangent"

$R_{i(i+1)}$ is the reflection coefficient between layer i and layer i+1

$$R_{i(i+1)} = \frac{\sqrt{\varepsilon_{i+1}} - \sqrt{\varepsilon_i}}{\sqrt{\varepsilon_{i+1}} + \sqrt{\varepsilon_i}}$$

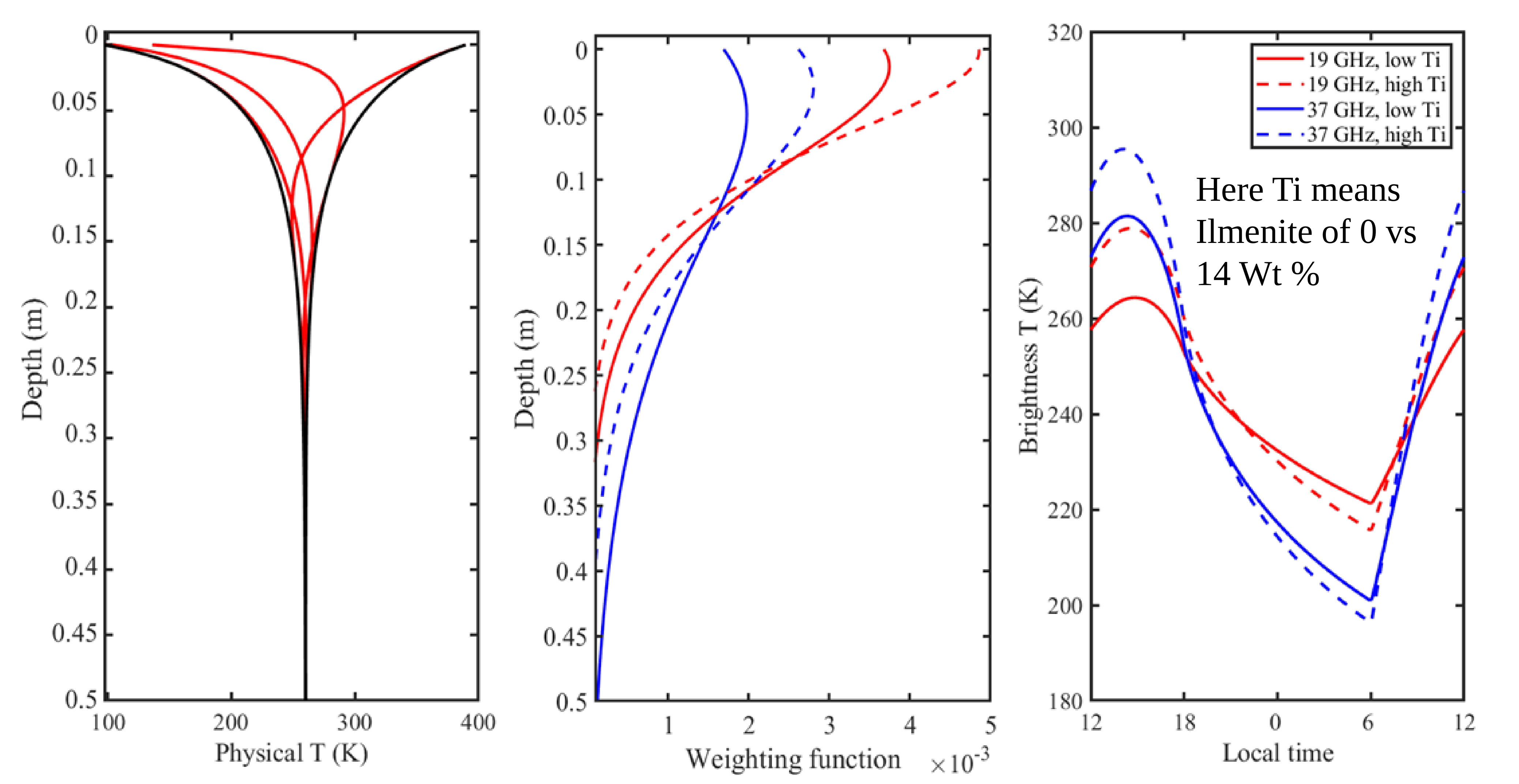
**The <u>Brightness Temperature</u>, *TB* is simply:**

$$TB = \Sigma\, T_i w_i$$

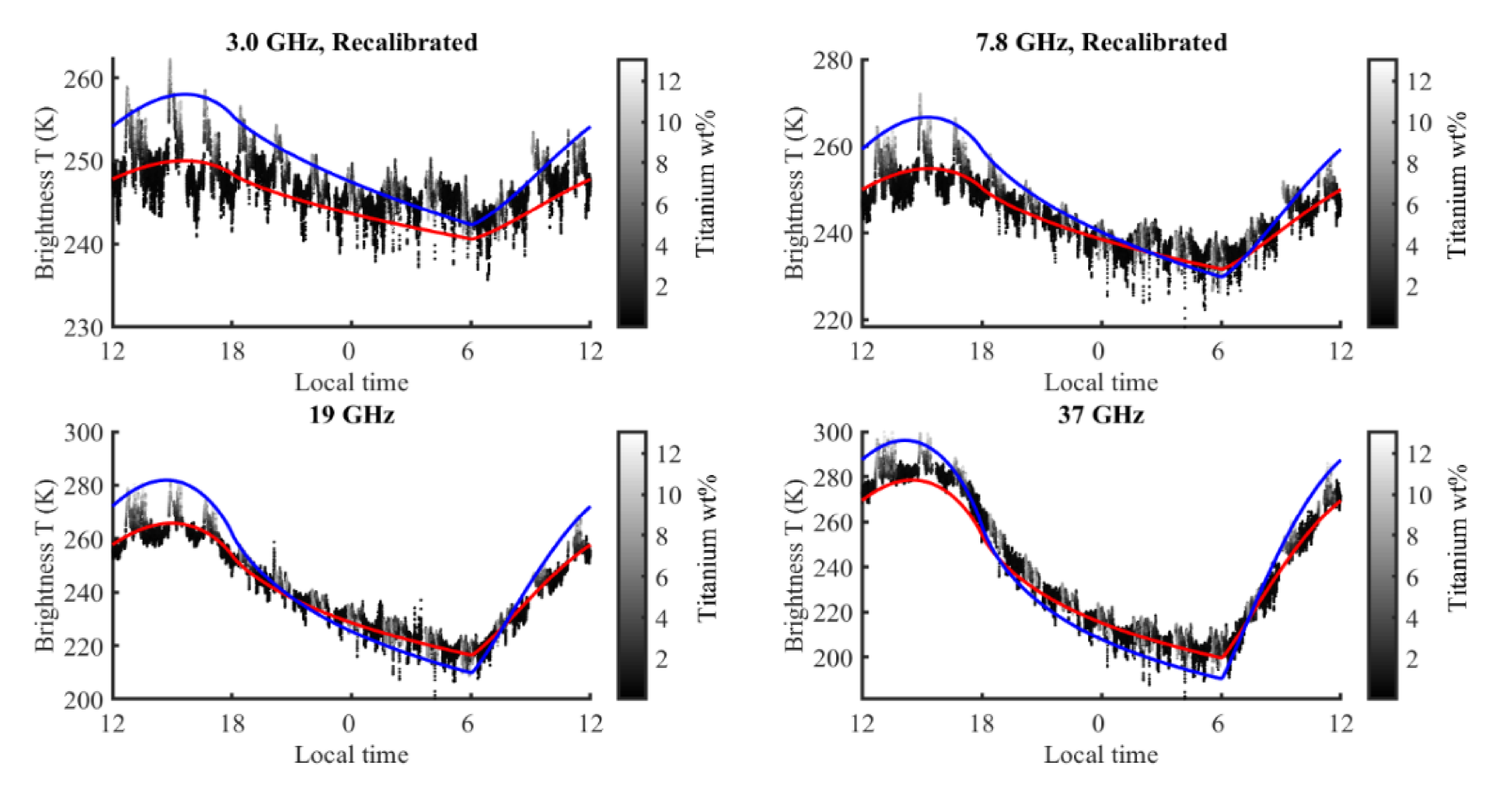
"Weighting function"

# Physical Temperature × Weighting Function = Brightness Temperature

$$T_b = \Sigma\, T_i w_i$$



# Microwave radiation should be sensitive to physical temperature, ilmenite ($FeTiO_3$) content (blue 14% $TiO_2$, Red 0% $TiO_2$), and density



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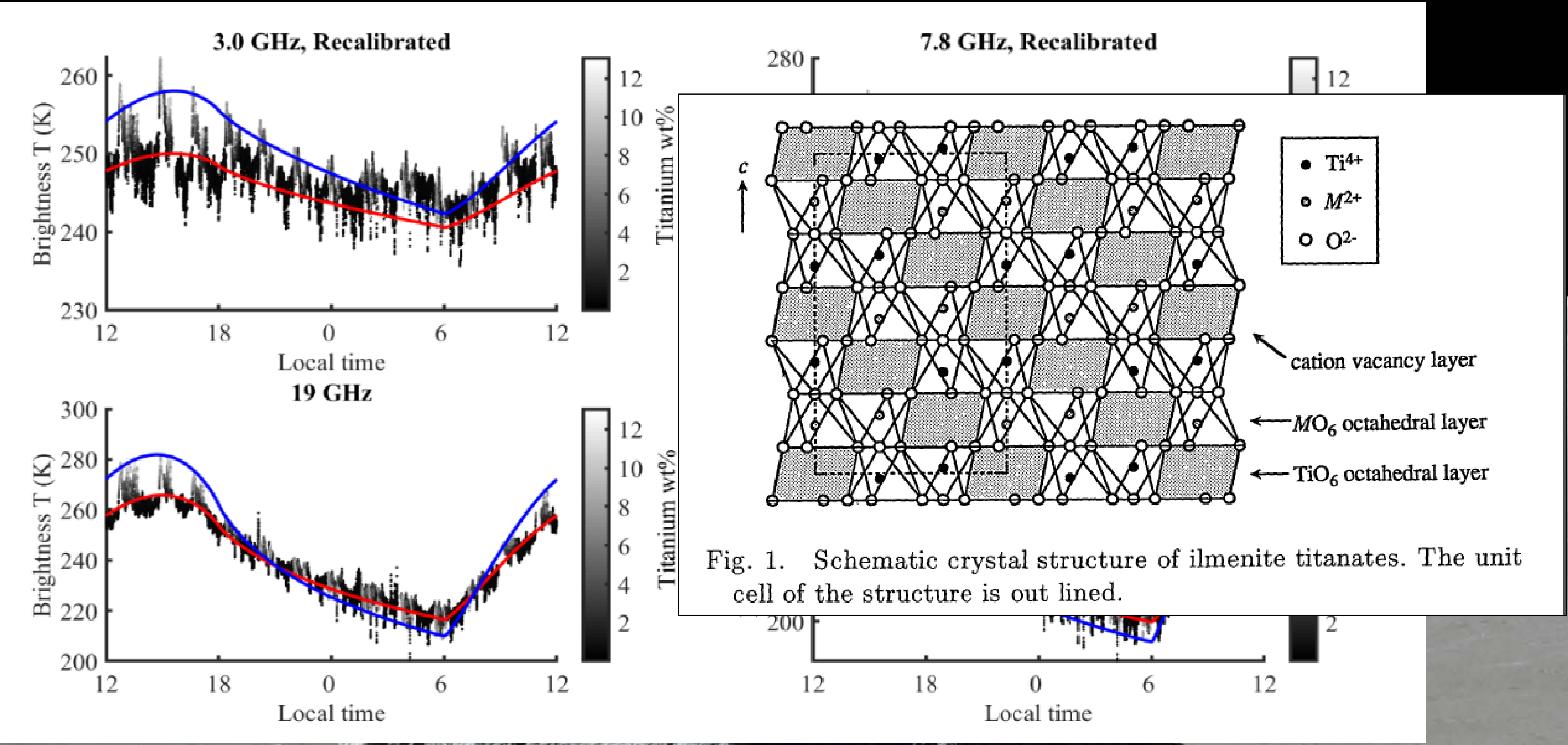
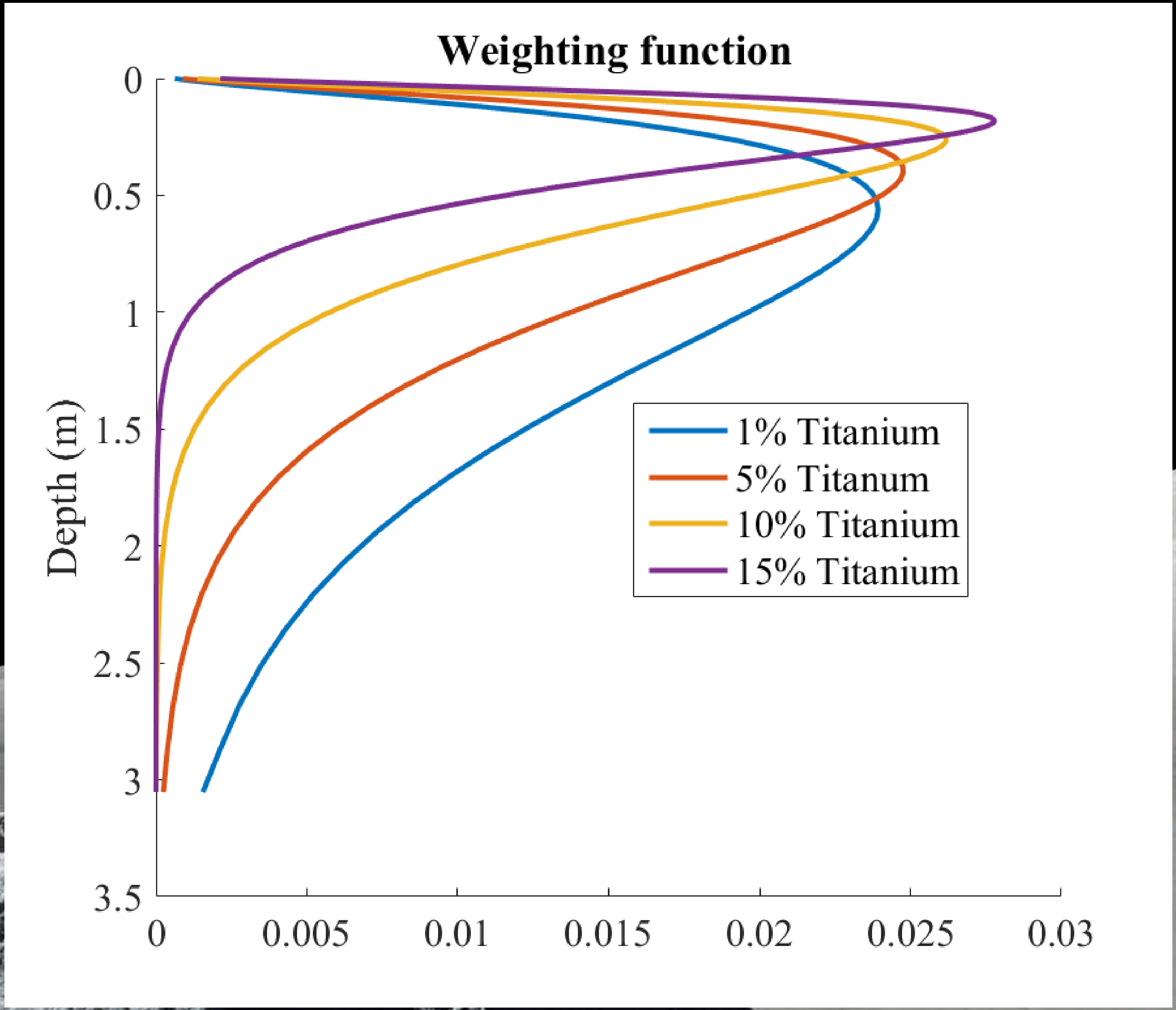


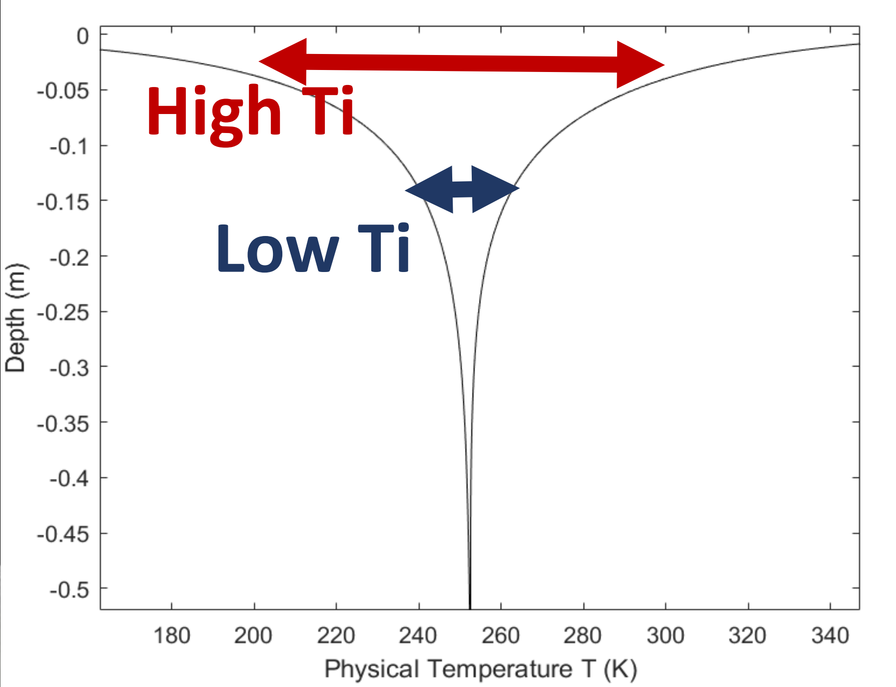

Fig. 1. Schematic crystal structure of ilmenite titanates. The unit cell of the structure is out lined.

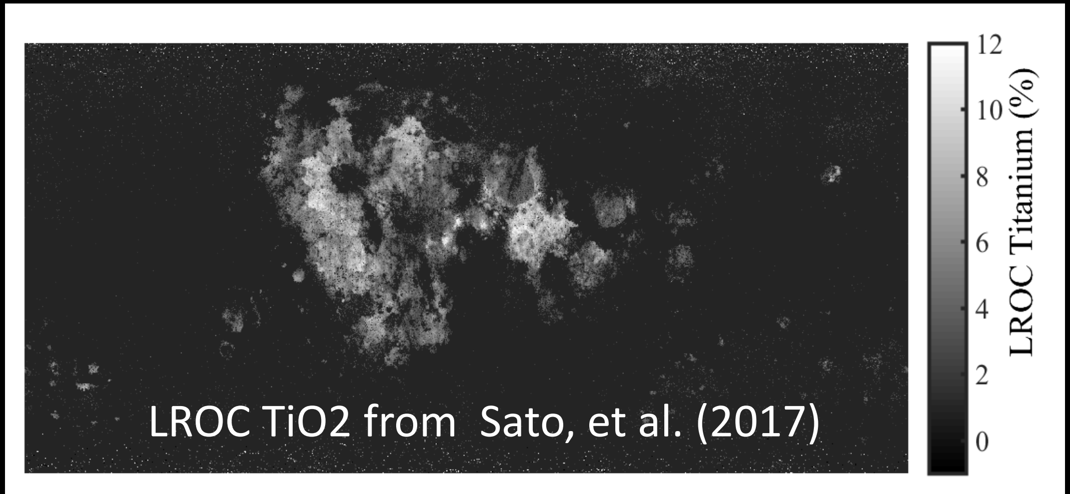
# Loss Tangent vs Ilmenite ($FeTiO_3$)

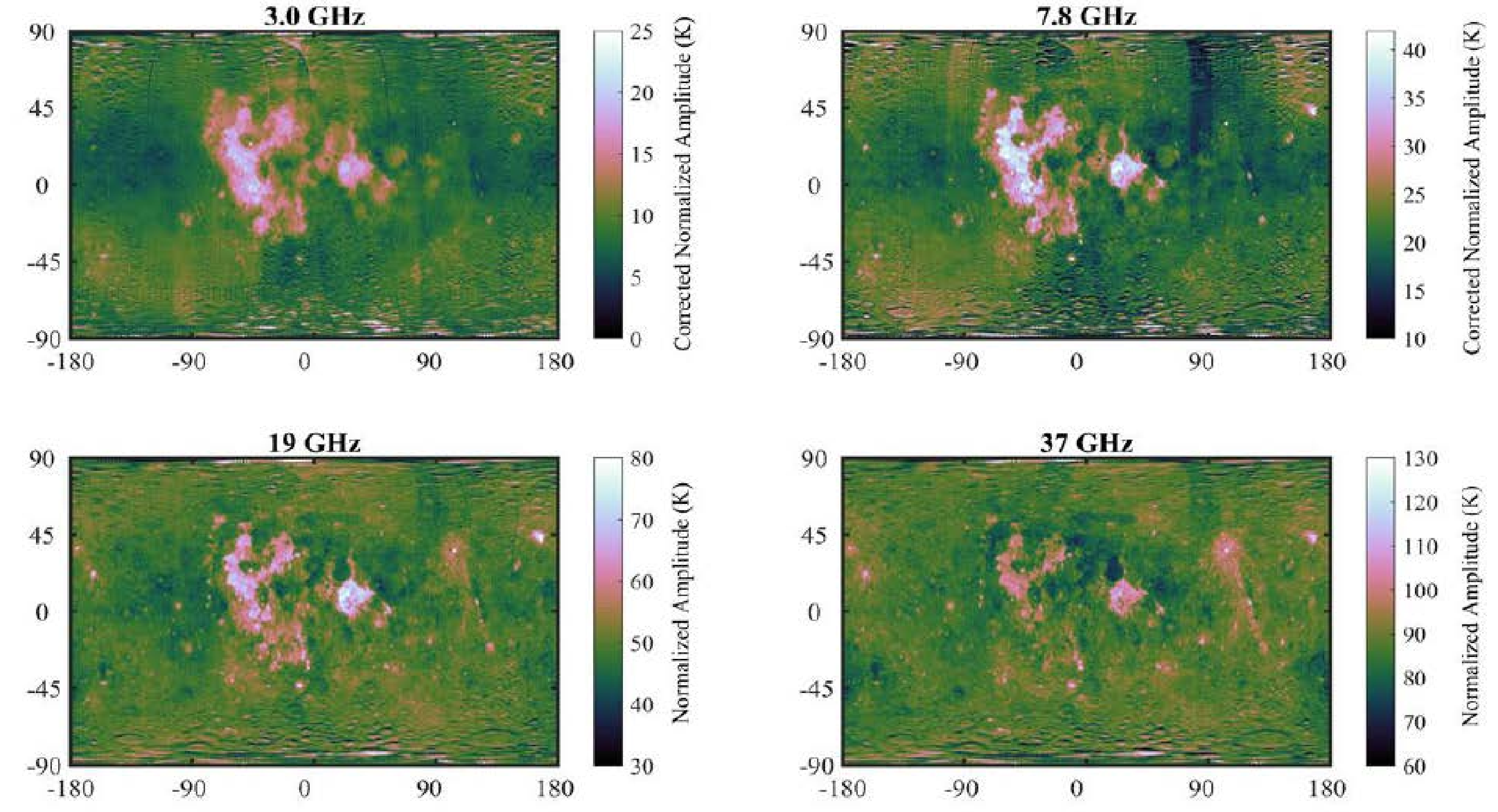
- The loss tangent is highly dependent on the amount of Titanium in the regolith.
- But in areas of low Titanium, the 3Ghz MRM channel (10cm wavelength) is getting a considerable amount of radiation from up to ~3-5m depth.



A high Ti area has a higher “delta Tb” at the same microwave frequency due to the high loss tangent of $TiO_2$ .




Using global Diviner models of subsurface temperatures, and diurnal amplitudes from the Chang’E data, we can constrain the variation of the loss tangent around the globe, which can tell us if Ti differs within the upper ~1m from LROC’s surface measurement.

# The Loss Tangent at various frequencies tells us about ilmenite and rock of different sizes and lets us calibrate the depth which each frequency is sounding.

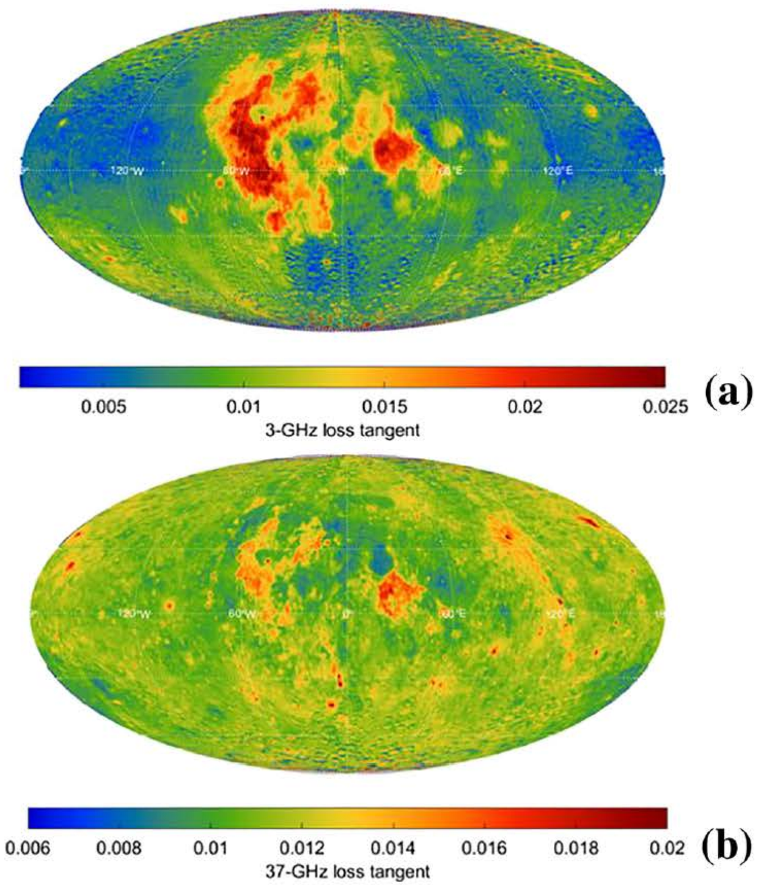



**Figure 9.** Our integrated loss tangent at (a) 3 and (b) 37 GHz as compared to (c) titanium as mapped by Sato et al. (2017) and (d) rock abundance as mapped by Bandfield et al. (2011).

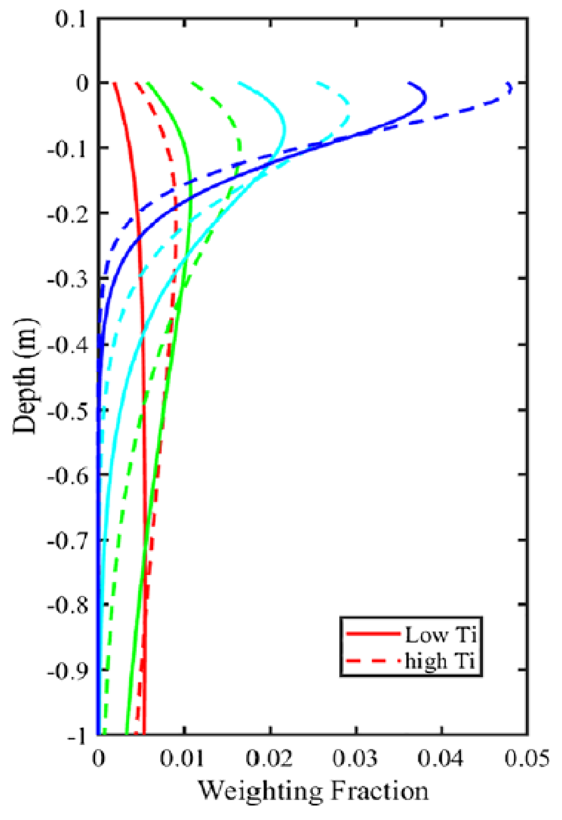


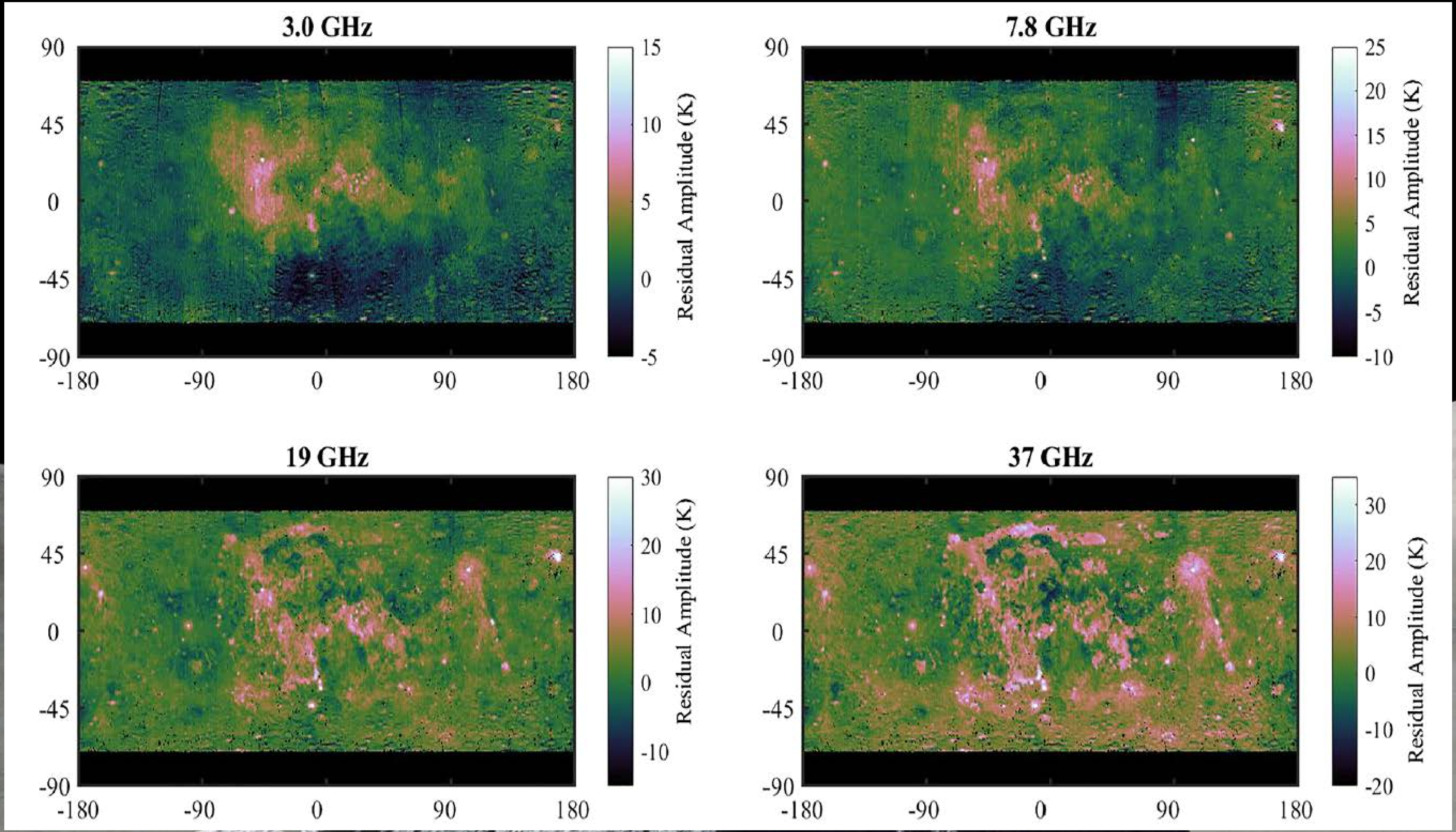

**Table 4**

*Depth at Which the Weighting Function for Each MRM Channel Peaks and the Depth at Which It Receives 99% of its Energy for Highlands and 8% $TiO_2$ Mare*

| Channel | Highlands peak depth | 8% $TiO_2$ mare peak depth | Highlands 99% depth | 8% $TiO_2$ mare 99% depth |
|---|---|---|---|---|
| 3.0 GHz | 0.184 m | 0.128 m | 5.572 m | 2.466 m |
| 7.8 GHz | 0.111 m | 0.073 m | 1.910 m | 1.017 m |
| 19 GHz | 0.050 m | 0.029 m | 0.677 m | 0.442 m |
| 37 GHz | 0.013 m | 0.002 m | 0.334 m | 0.262 m |

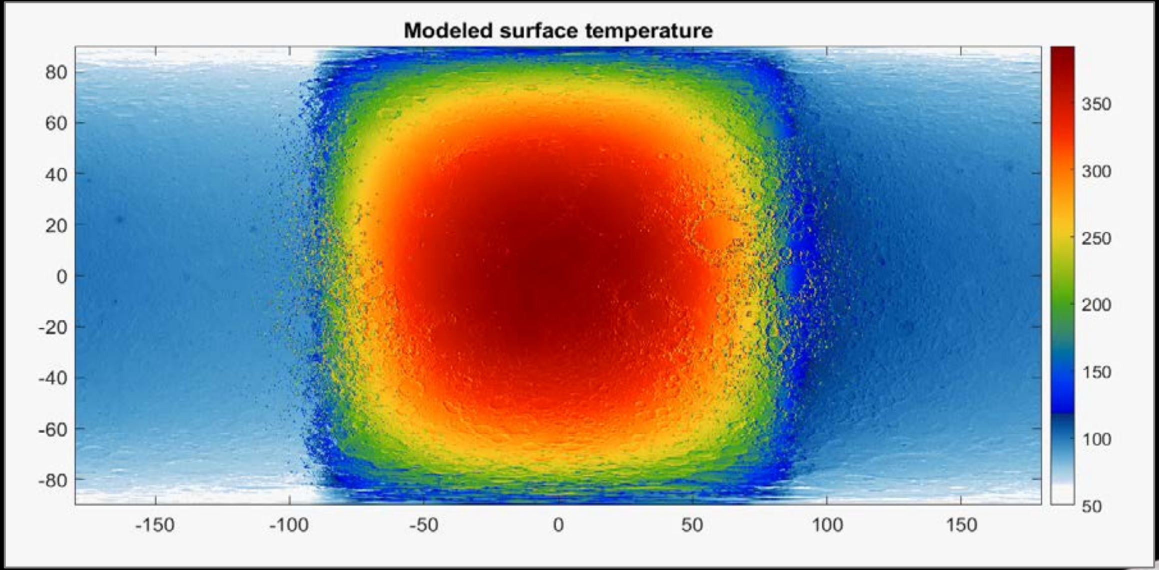
The Loss Tangent at various frequencies tells us about ilmenite and rock of different sizes

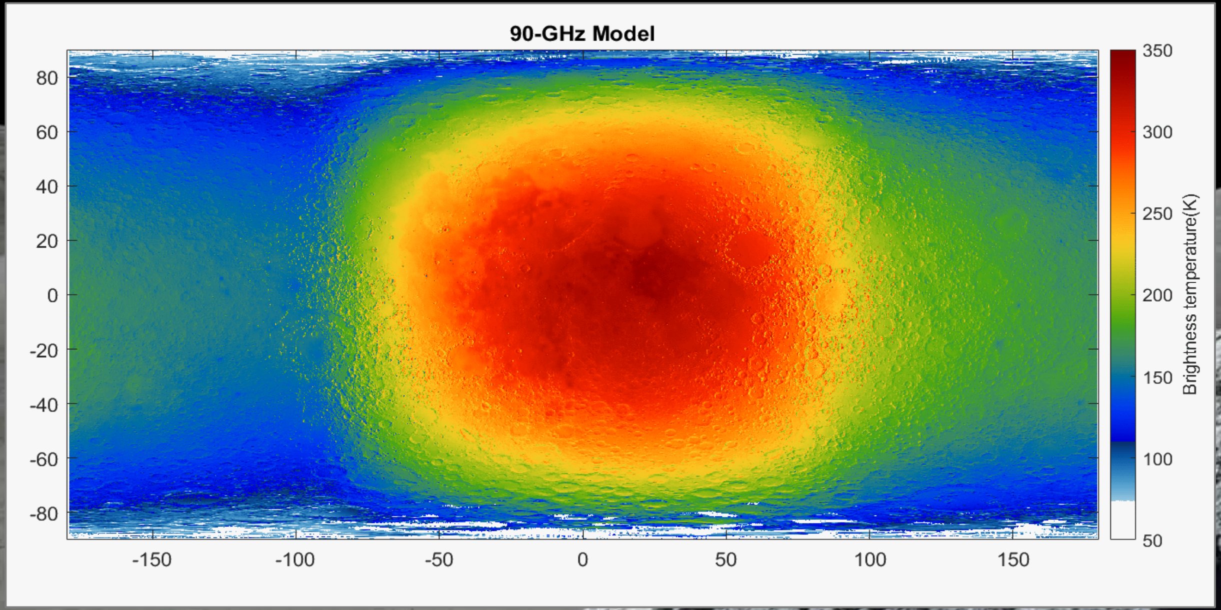
- Using fits to spectrally-measured (LROC) TiO2, we can view rocks of different sizes/depths

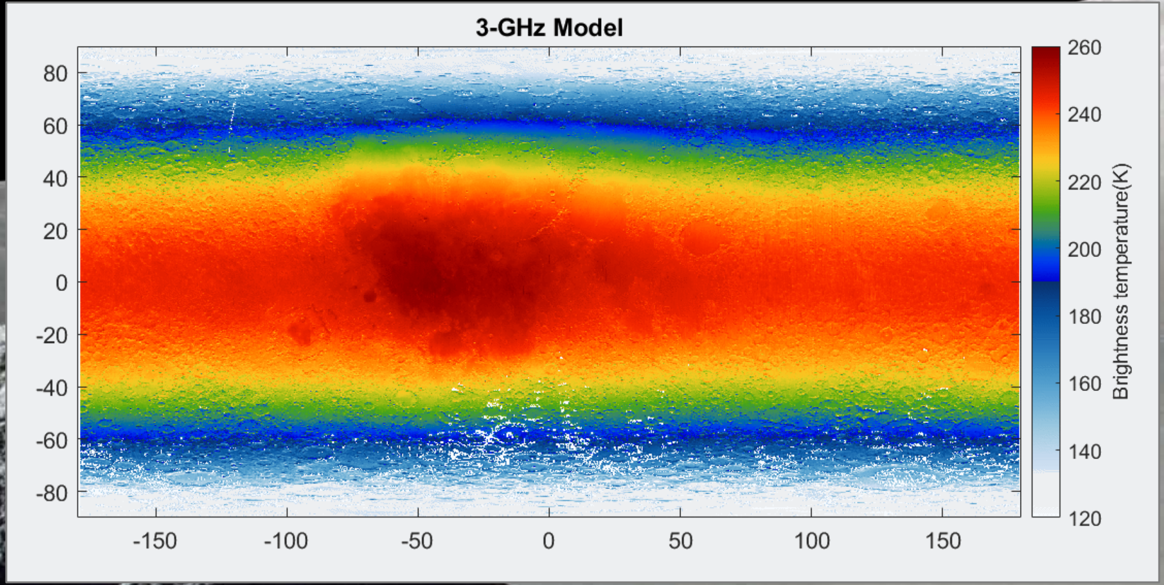


This allows the creation of fully synthetic microwave emission models based on currently know attributes (IR measured surface temperature, near surface thermal properties, measured loss properties) which we can compare with data to find new aspects IR can’t see , which include:

- Surface rocks smaller than ~30cm,
- Changes in properties deeper than ~20cm (buried rocks and as this also works in shadow, buried ice)
- Subtle variations in thermal and dielectric propertie
- Changes in deeper temperature (geothermal heat)



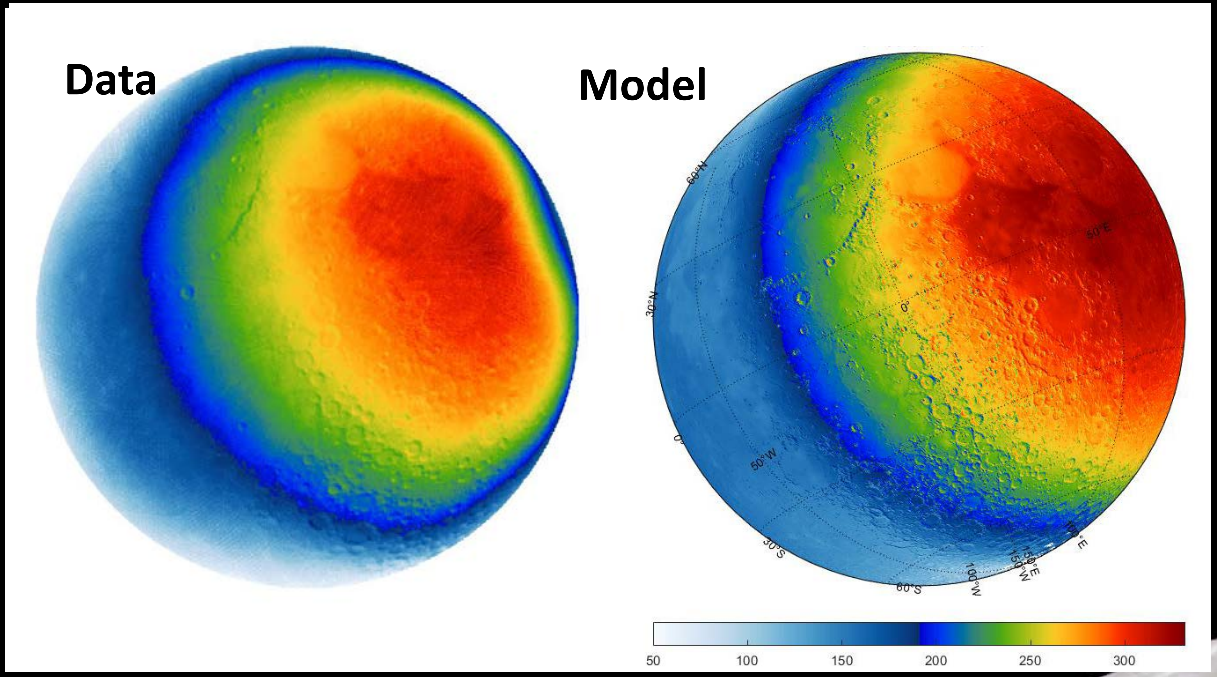

This is moving too, lower frequencies just change little with time

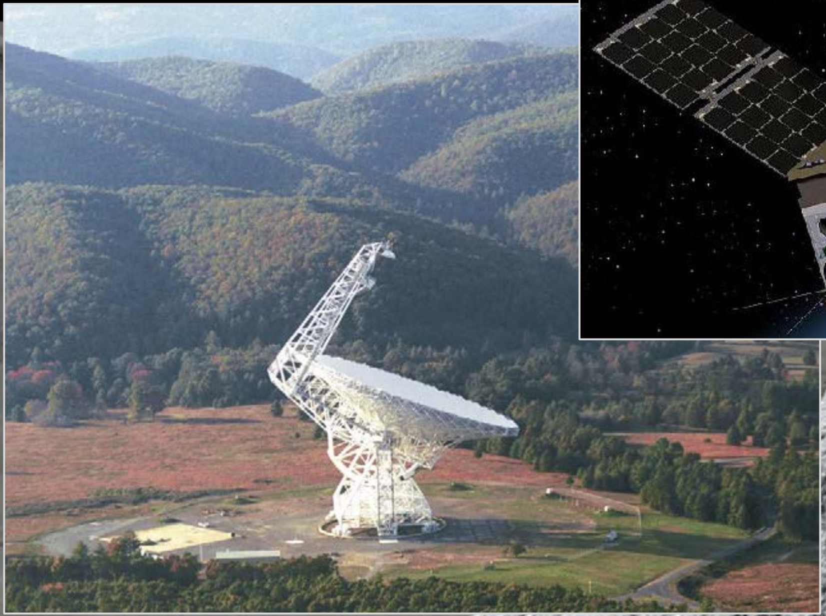
# Telescope measurements

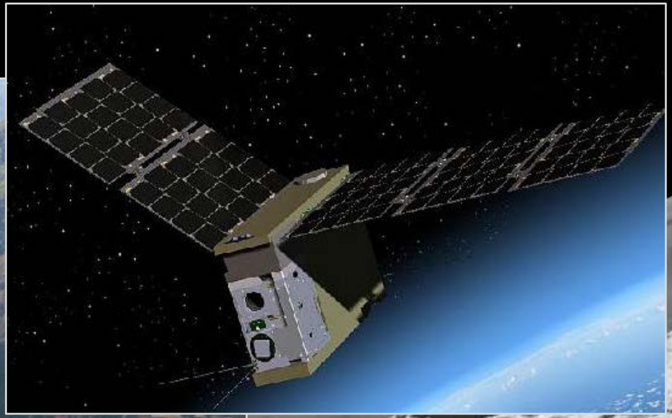
In an effort to expand the frequency range of characterized lunar microwave properties, we are also organizing a campaign of radio telescope measurements (VLA, Arecibo, Greenbank).

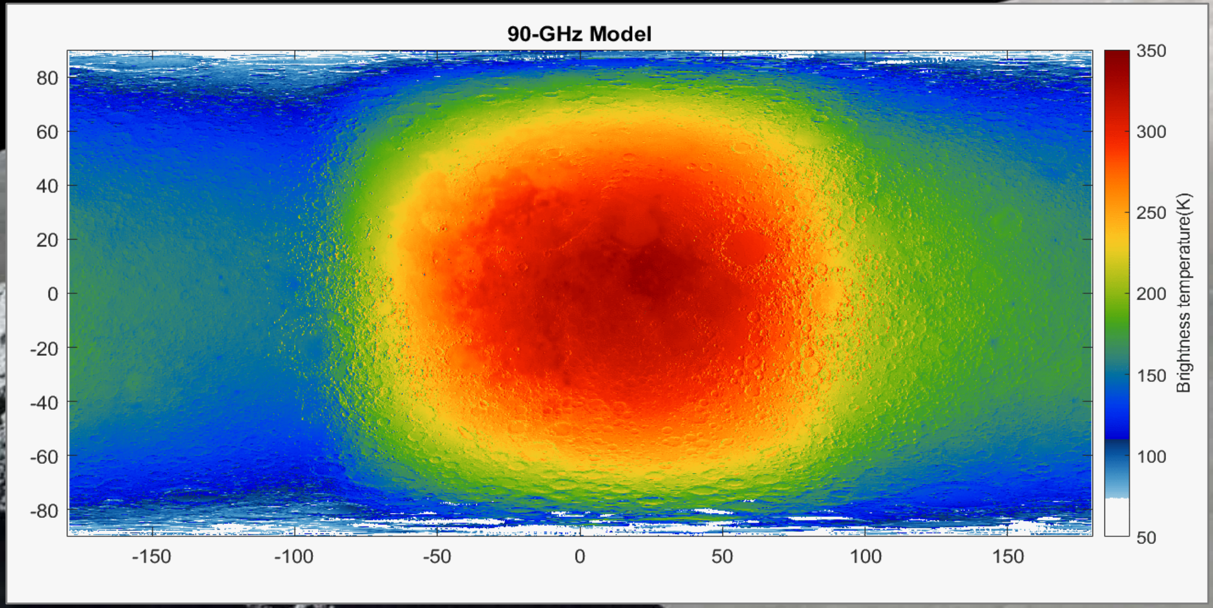
The new Mustang-2 system at Greenbank Observatory produced beautiful 90 GHz maps to which can predict what one might observe with a 90 GHz cubesat like a copy of the Tempest-D Earth–observing satellite might see.

These high-frequency data show us very near surface thermal and dielectric properties such as ejecta blankets as ray and should see evidence of surface frost in shadowed regions only observable from orbit.





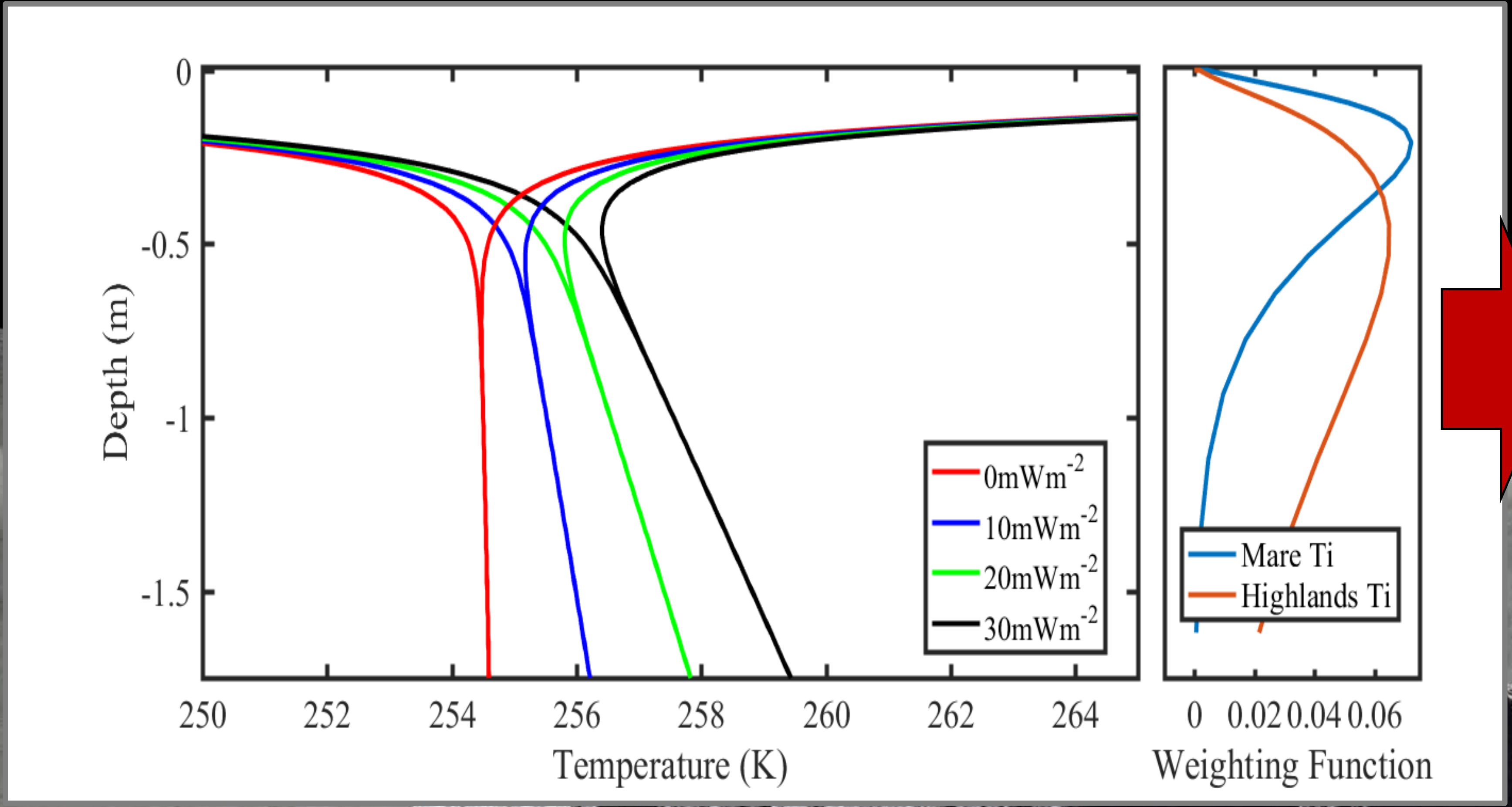


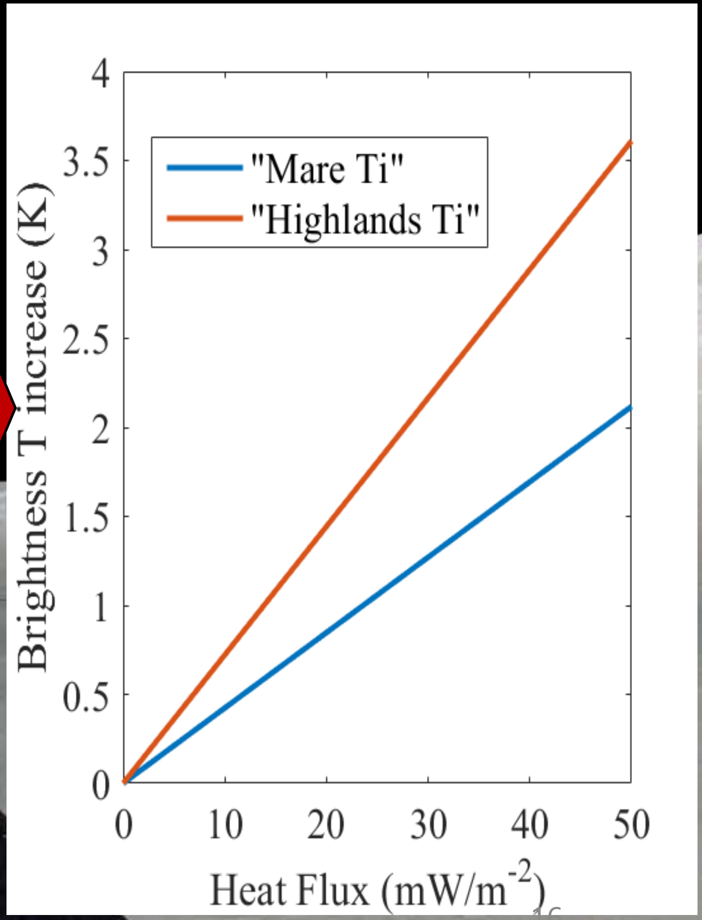
Telescope data can also help answer questions like:

Could lower frequency data constrain heat flux?

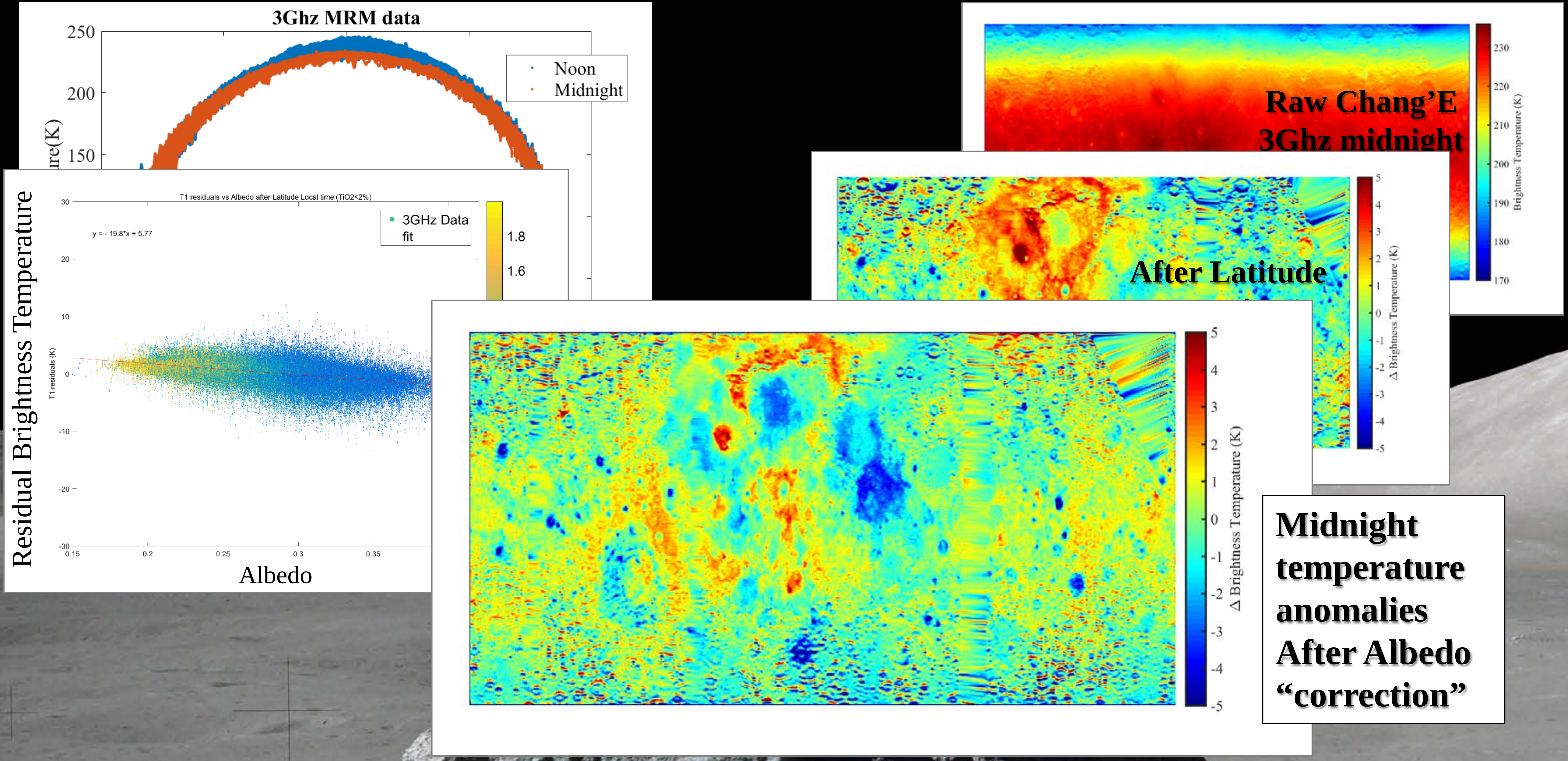
Using LRO-Diviner constrained subsurface temperature models for various geothermal heat fluxes, we can create a model of Brightness Temperature vas a function of geothermal heat flux.

Lower frequencies are seeing deeper and will see a larger temperature change for the same heat flux.

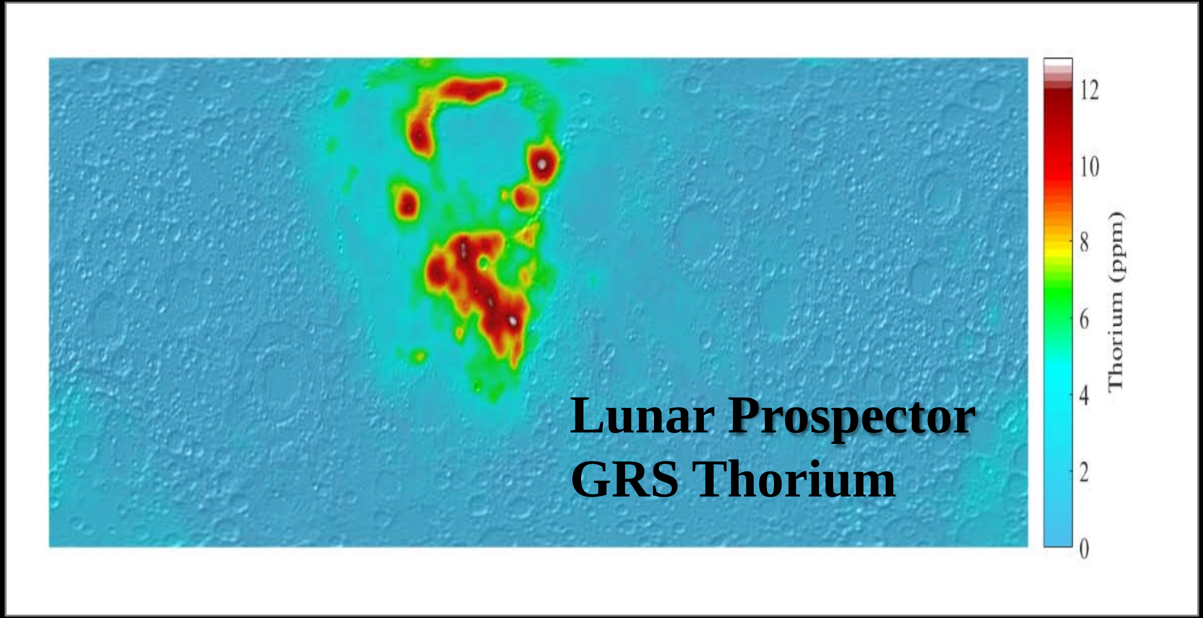


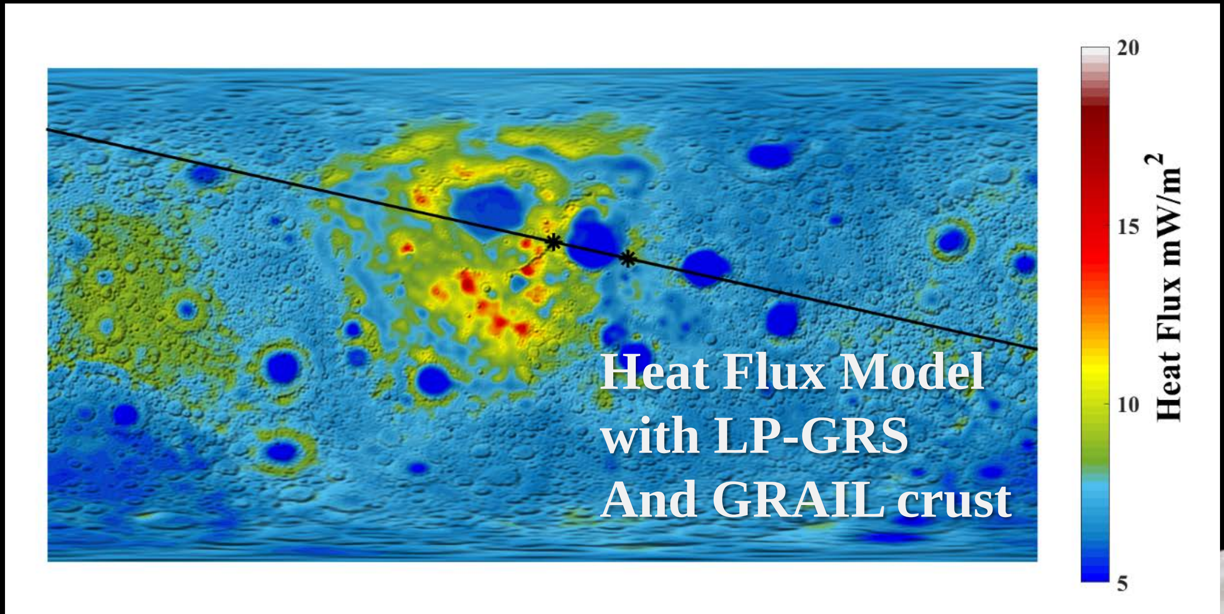



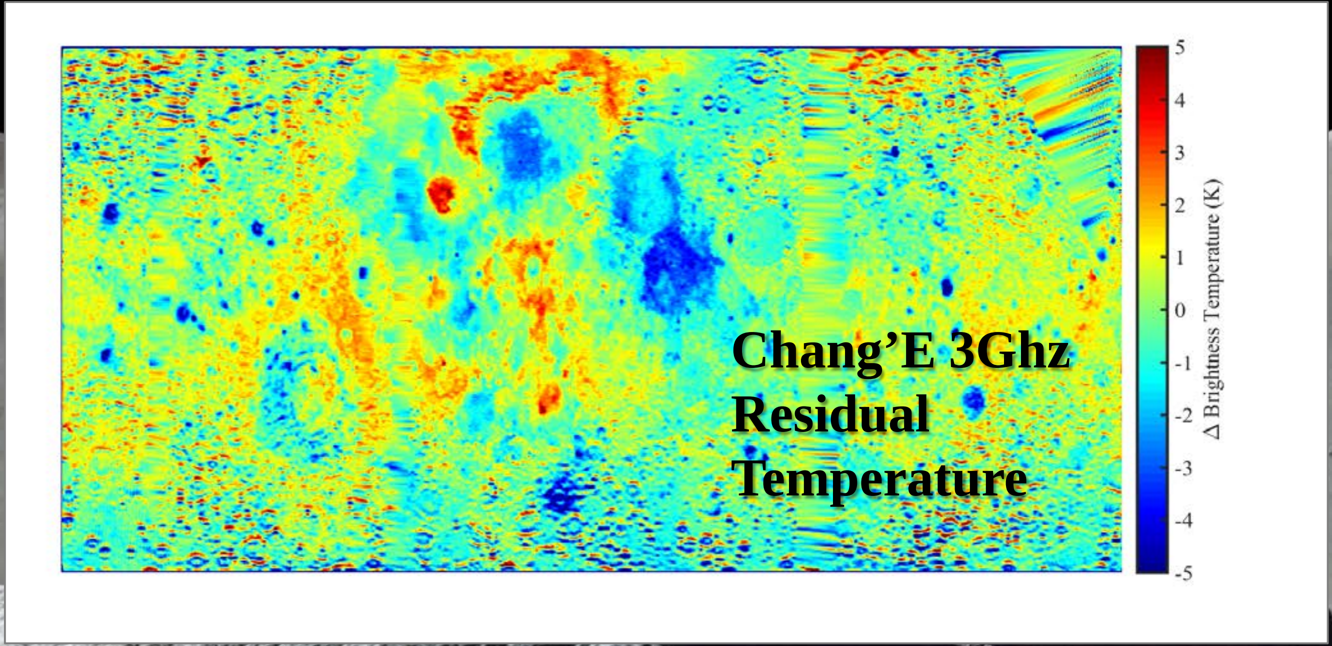
# Chang’E 3GHz data also shows a very interesting correlation with expected heat flux…



# This residual heat appears in much the same area as LP-GRS data shows enhanced Th

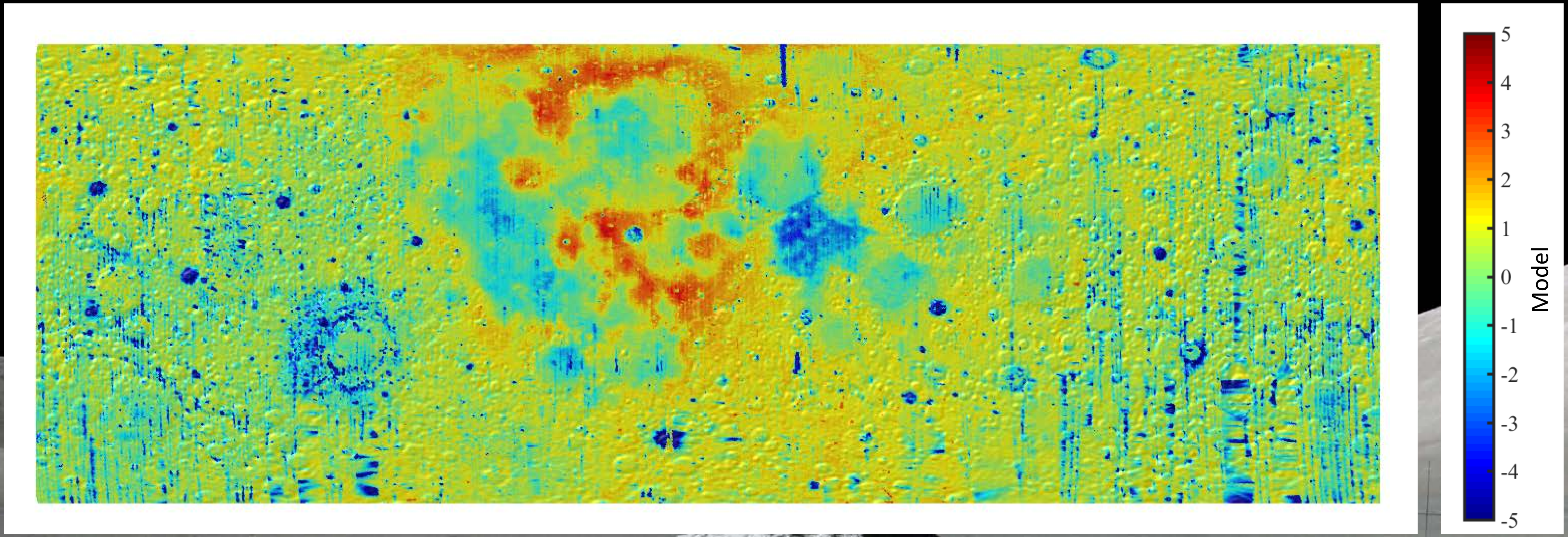


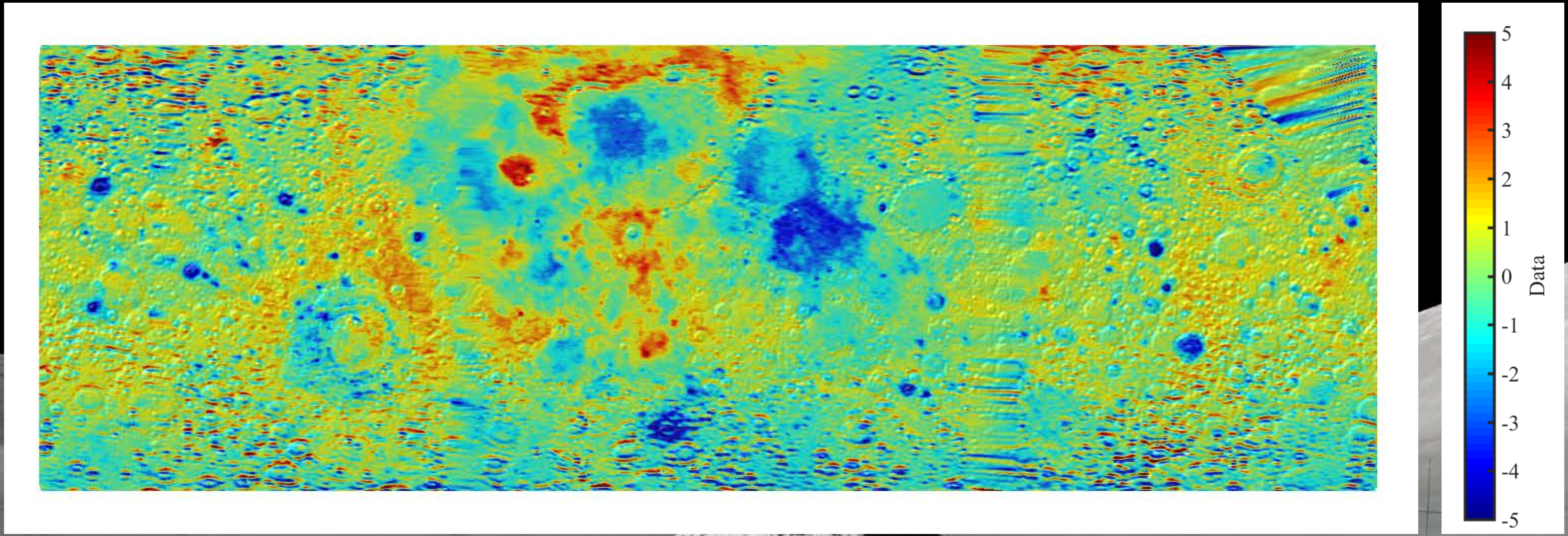

**Model heat flux includes Th concentrations (and correlated U and K) from LP [Lawrence 2006 /Paige, Siegler, Warren 2016], GRAIL crustal thickness and density models [Wieczoreck, 2013].**

We can make a forward model for Model with “all the bells and whistles” thrown in, including subsurface rocks from LRO-Mini RF CPR, etc with fits of their effect “by eye”… there isn’t really much theory to go on here. Right now the CPR is just a Tb amount I subtract, not an assumed rock depth.




Model

What we see is that the moon appear “hotter than expected” in regions where geophysical models would expect high heat flux.

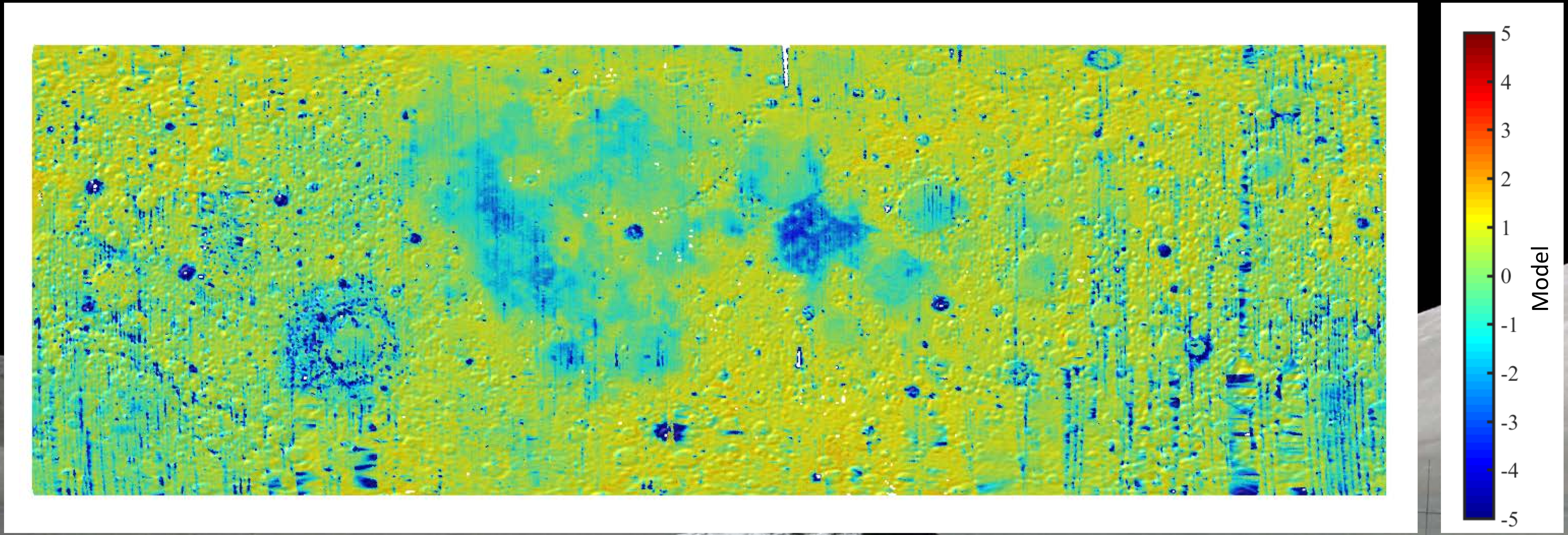



Data

Just to hammer the point home…

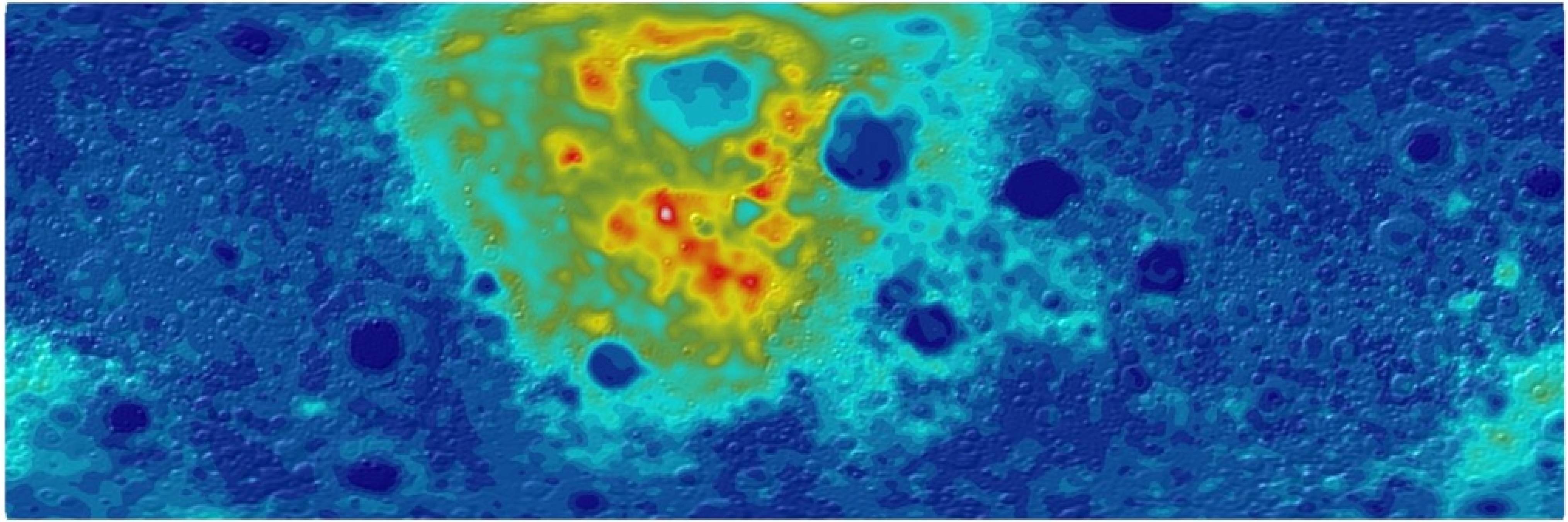
We see heat flux.

This is what the model looks like with zero heat flux (from surface Th).

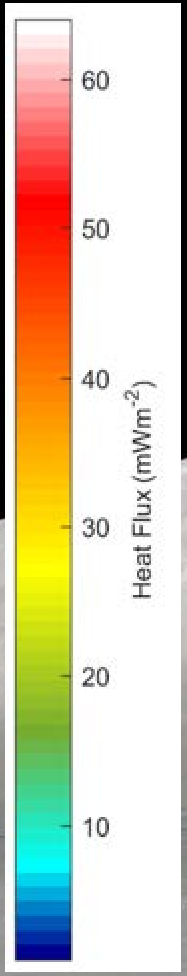



Model

All things considered, we can use the forward model to provide a best “fit” global heat flux, which can be tested again both future landed missions and potential orbital instruments like the Chang’E microwave radiometer ground based observations.

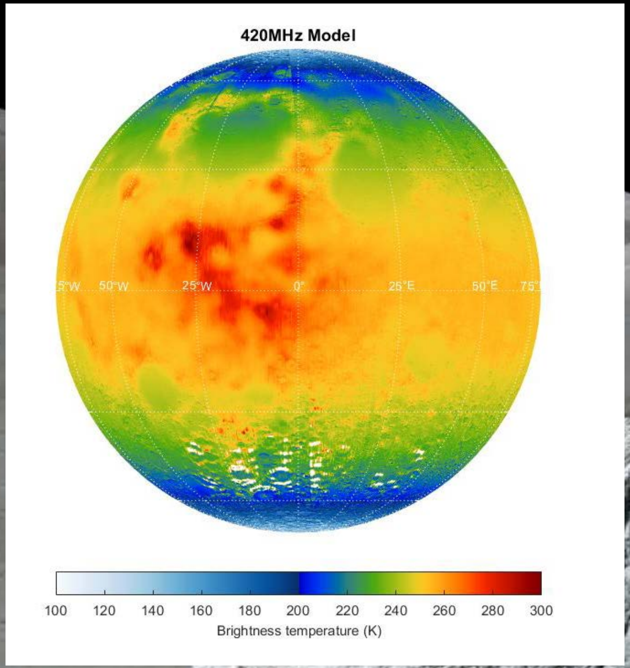


This “eyeball fit” model uses 70% surface 30% average “crust” material (e.g., Wieczorek and Phillips, 2000)

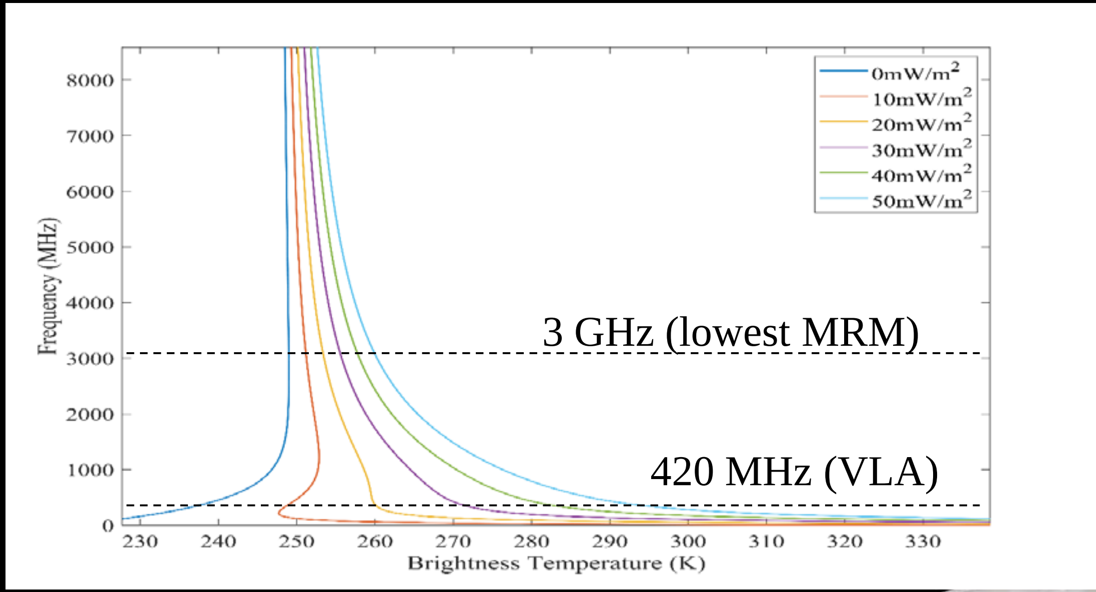


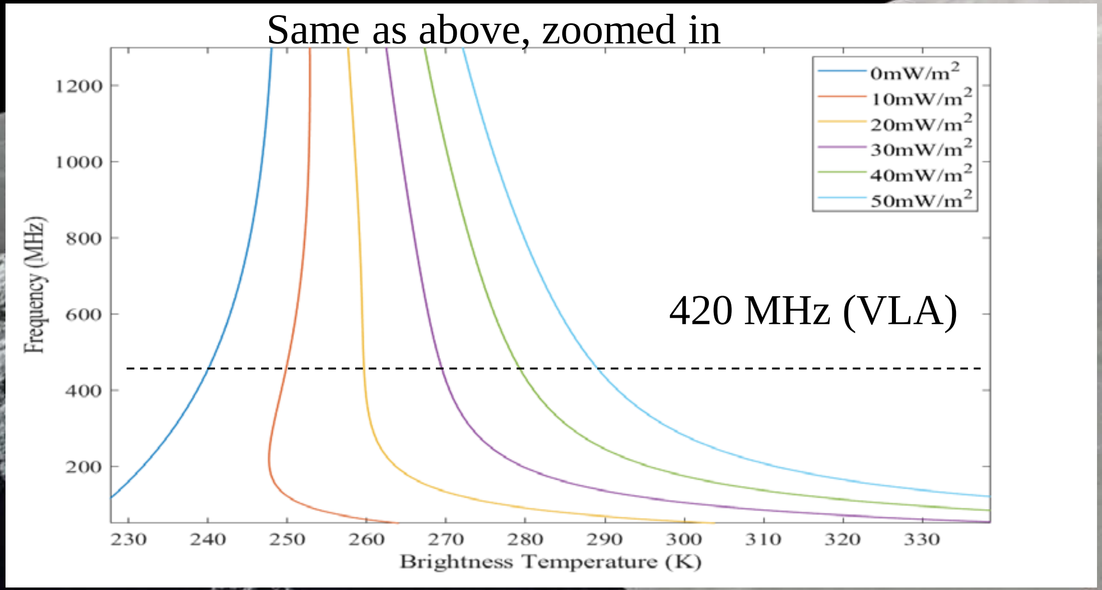

Model Heat Flux

# Lower frequencies should see an even more profound increase in Tb with heat flux




420 MHz Model assuming 60% GRS Crust



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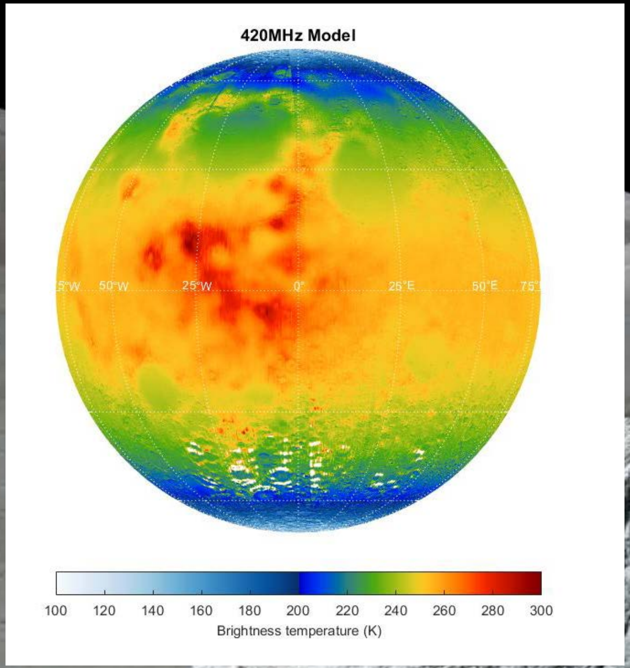


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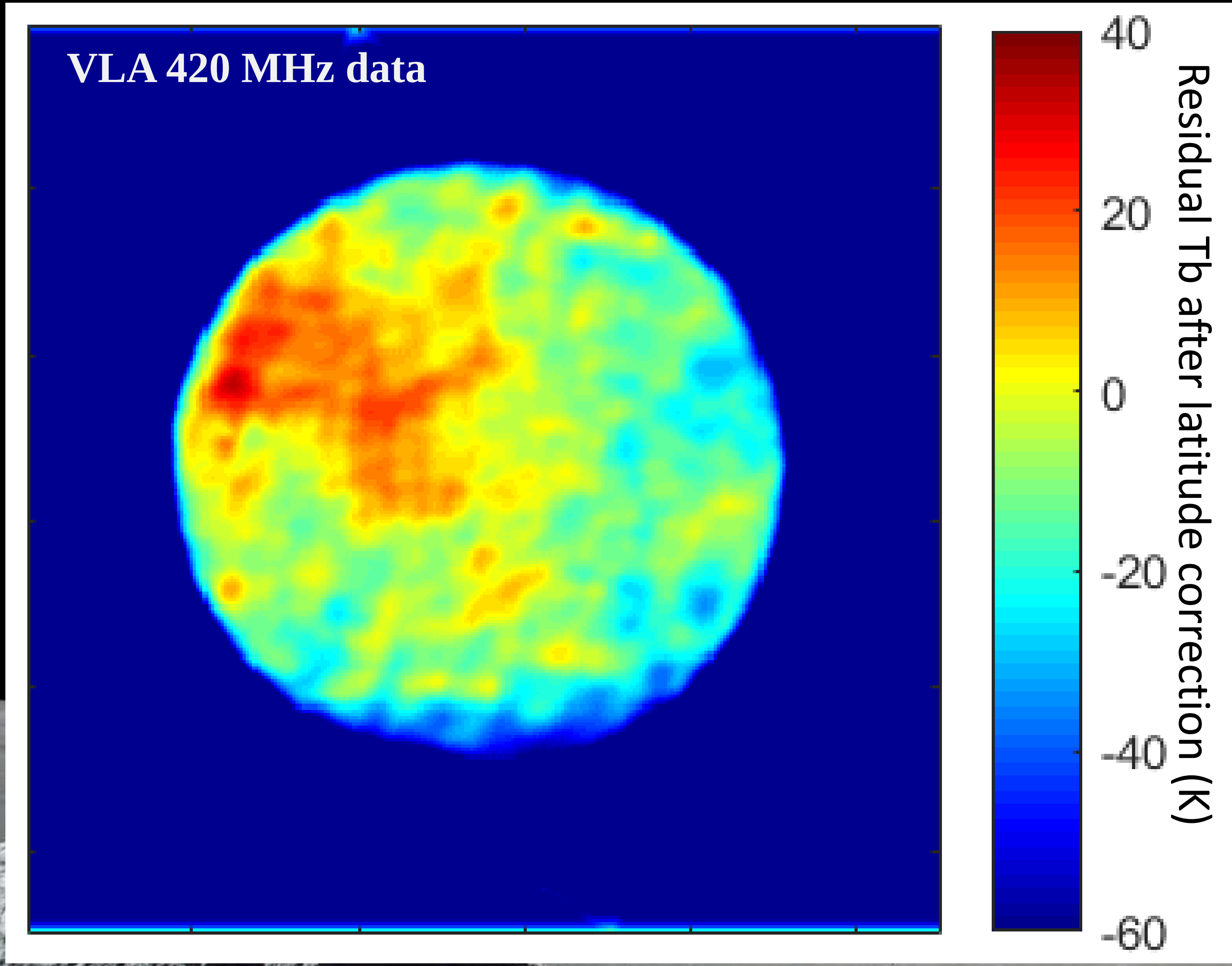
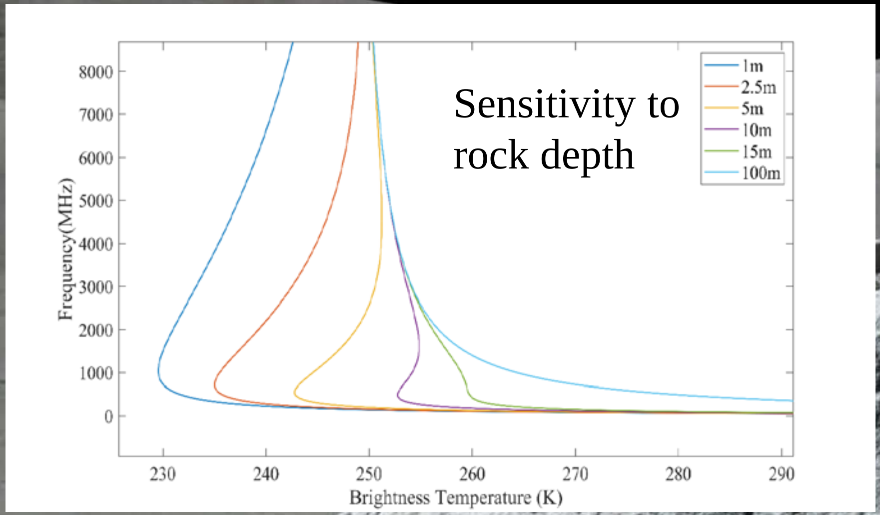


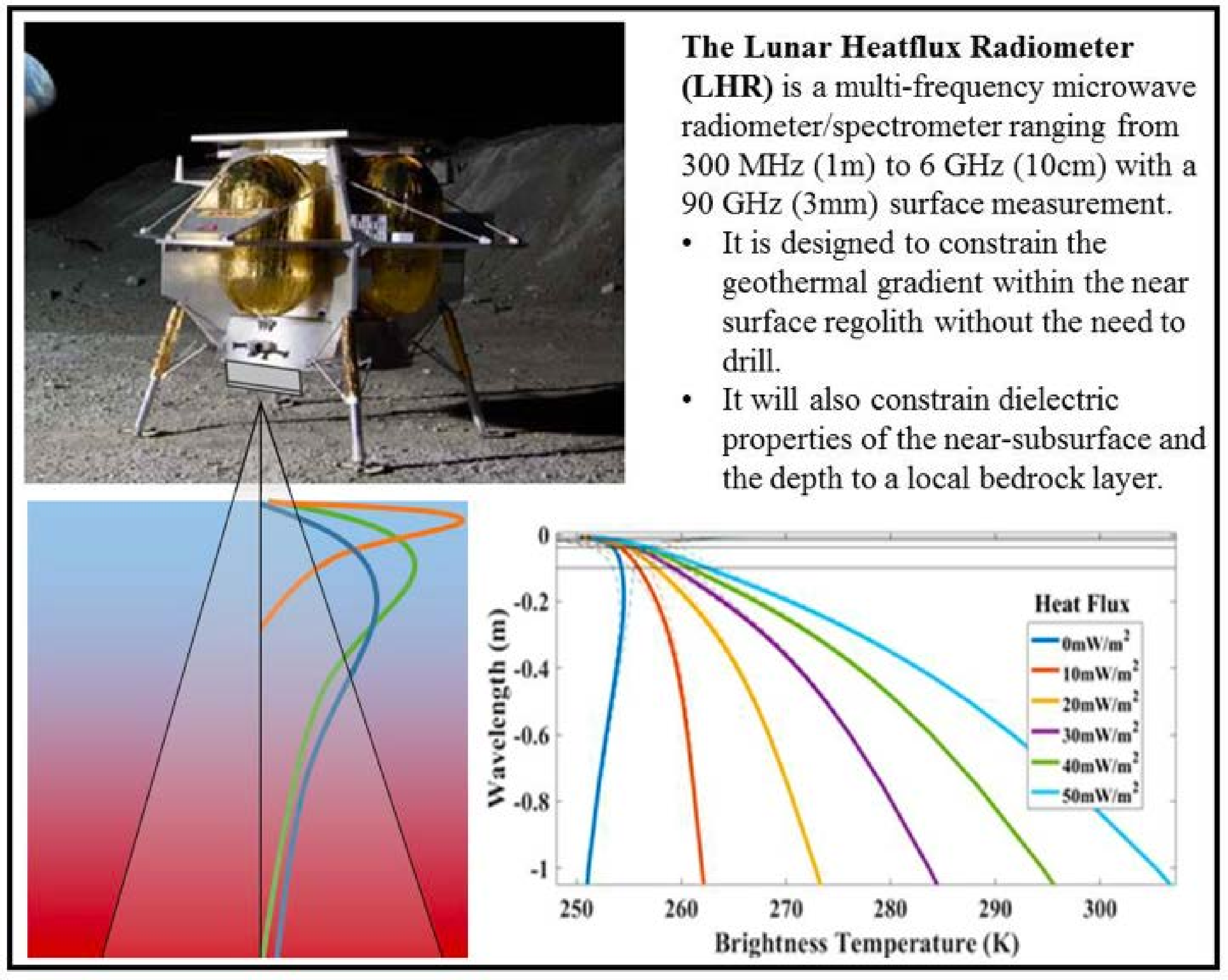
Not to advertise a specific instrument, but we are currently developing a 300 MHz – 90 GHz full-spectrum instrument at JPL through the NASA DALI program.

An instrument of this type could be designed for both landed and orbital operations on the Moon, Mercury, Mars….

This could be combined with an active sounding radar or GPR with a proper antenna design and back end electronics.

I am testing this concept as a new Participating Scientist with the Mars 2020 RIMFAX GRP that has a passive mode which we hope to calibrate.



# Conclusions: What can we lean from microwave radiometry?

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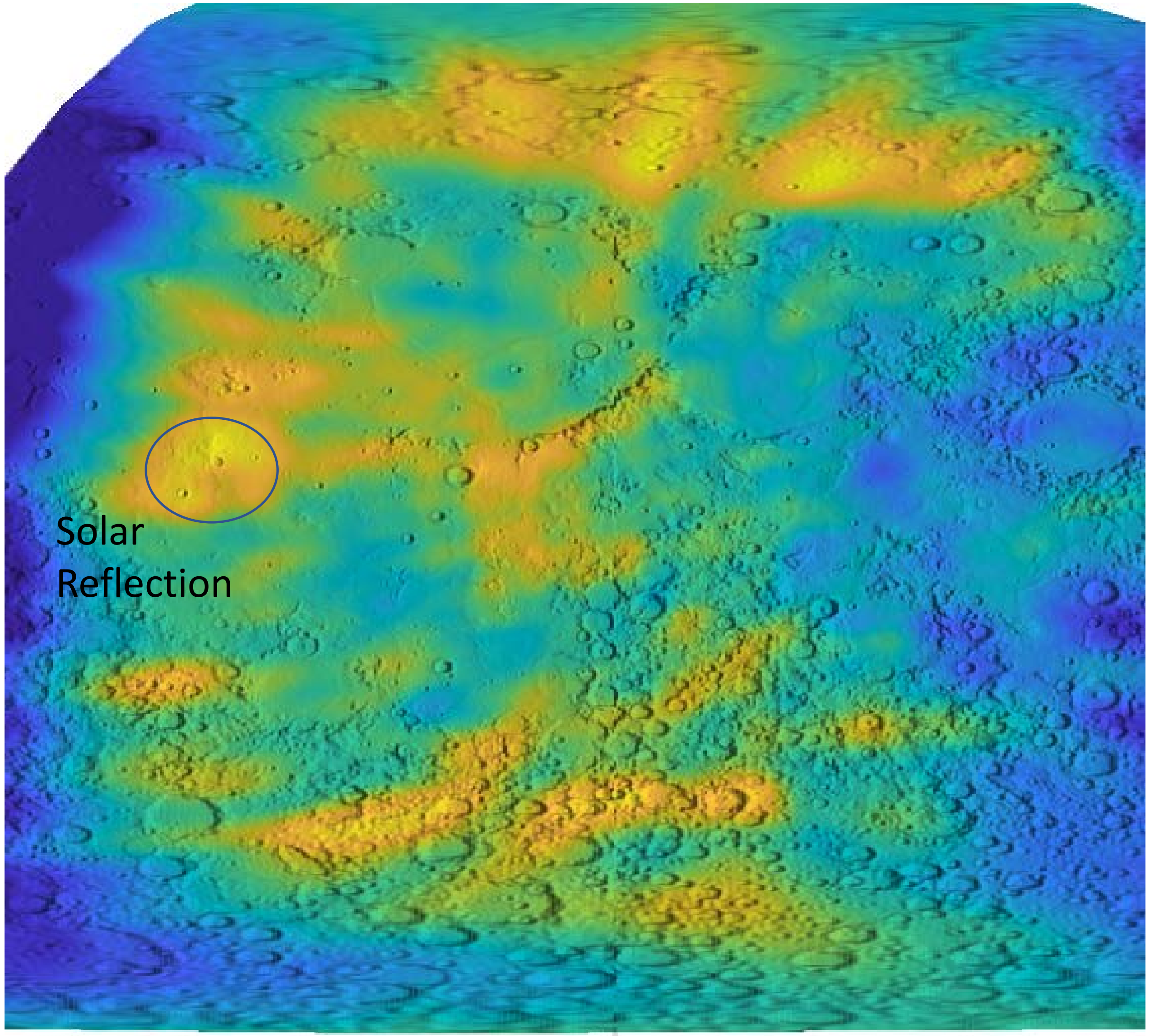
The strength of this emission depends on both the physical temperature of the material and the dielectric properties of material above it. It is commonly used for atmospheric sounding (weather satellites, but the liquid water on Earth prevents deep penetration. On the Moon (or Mars) one could “see” 10’s of meters into the subsurface.

This makes it an ideal tool for studying subsurface temperatures, thermal properties, density, and dielectric properties.

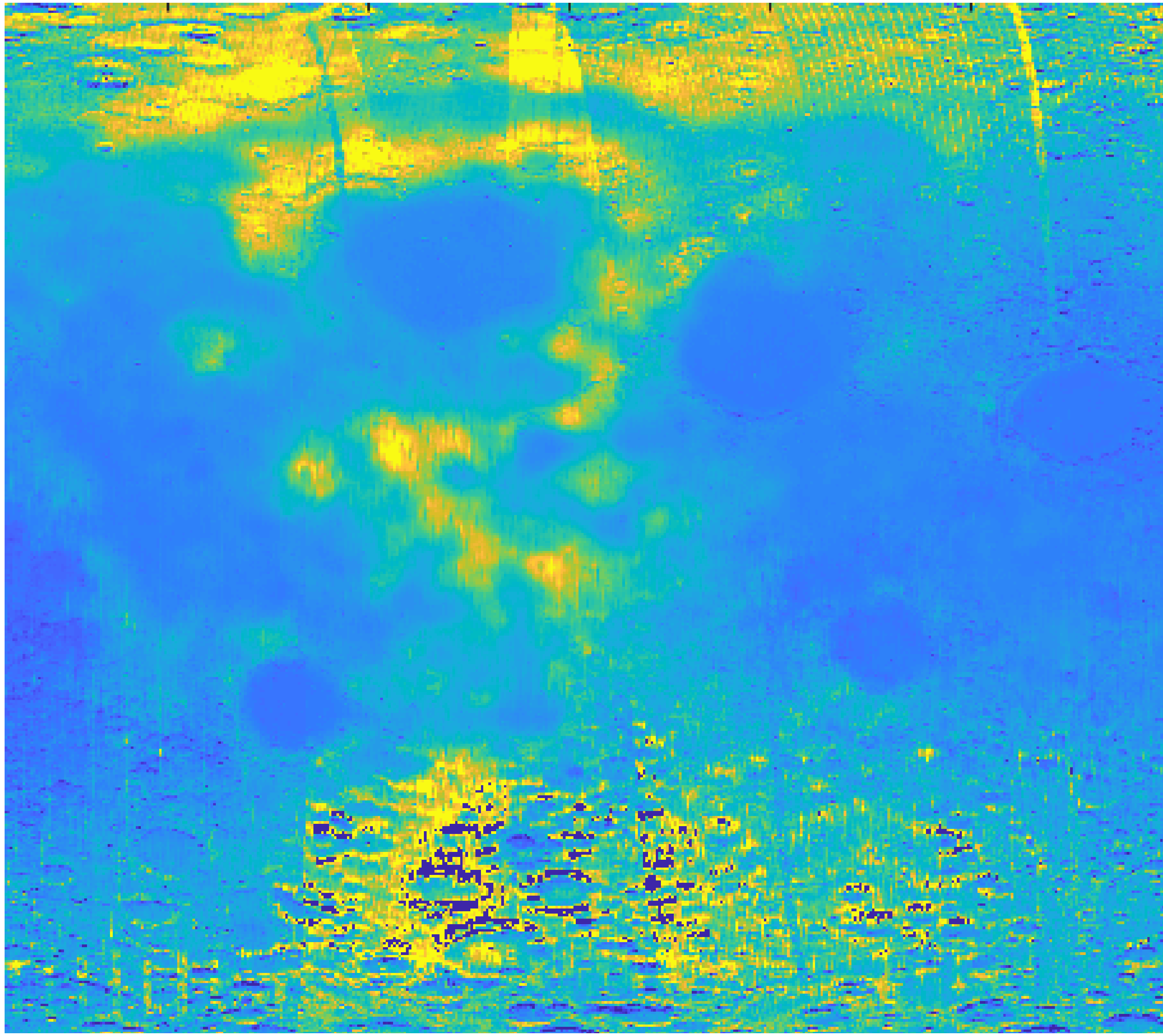
This has a groundbreaking potential to detect subsurface ice and measure geothermal heat without drilling and even from orbit.

# Thank you

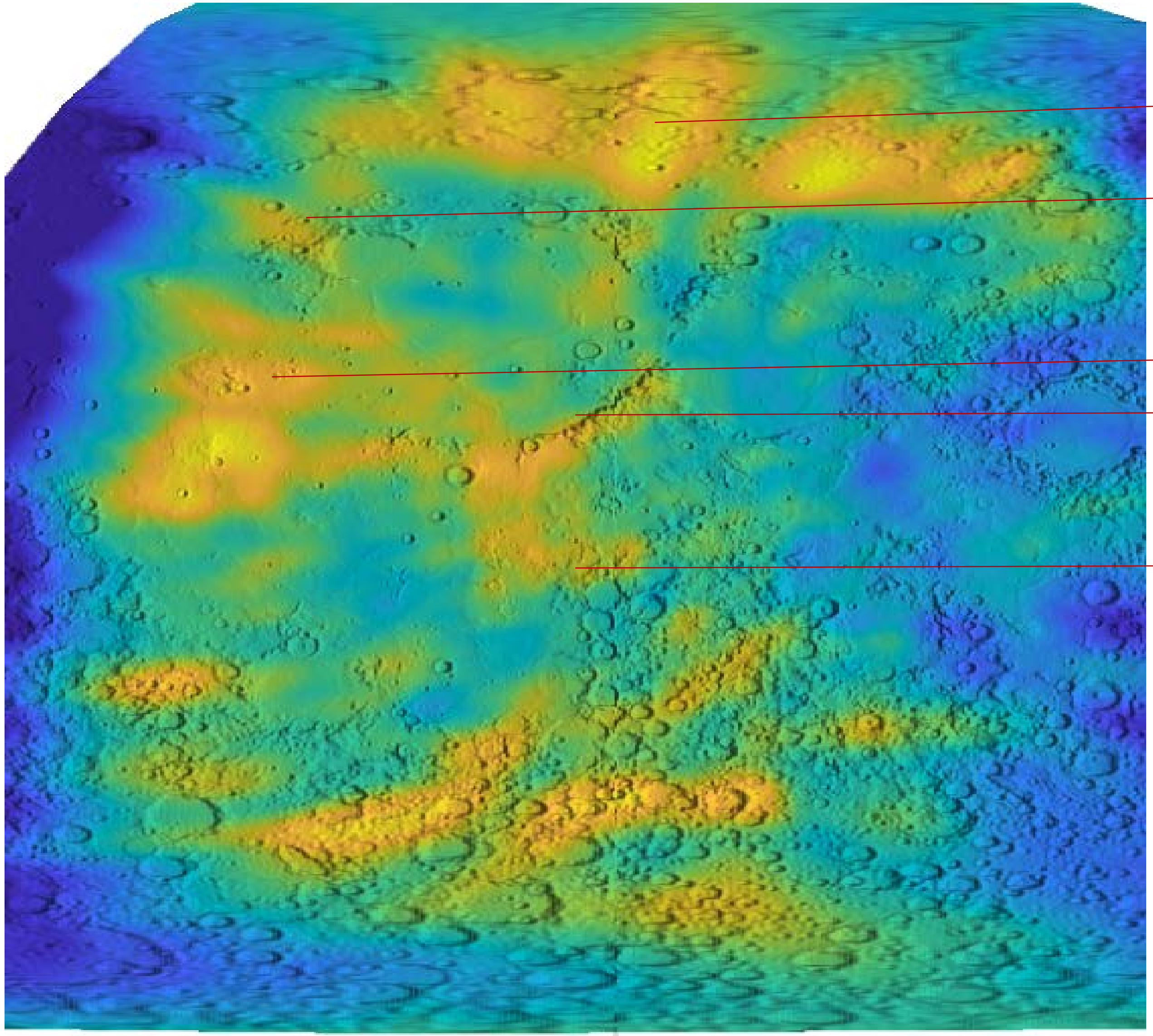
VLA 420 MHz Data



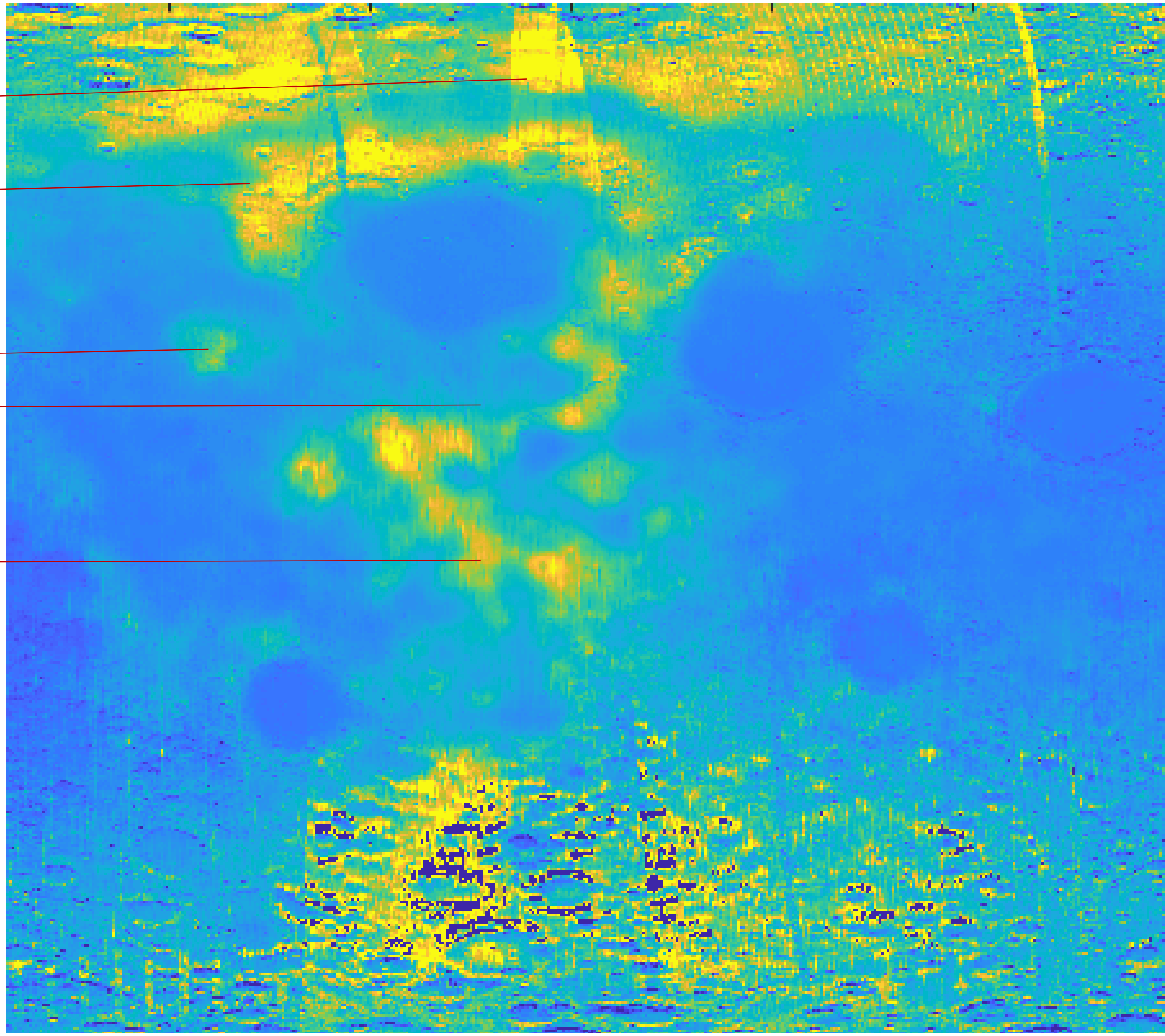

Model



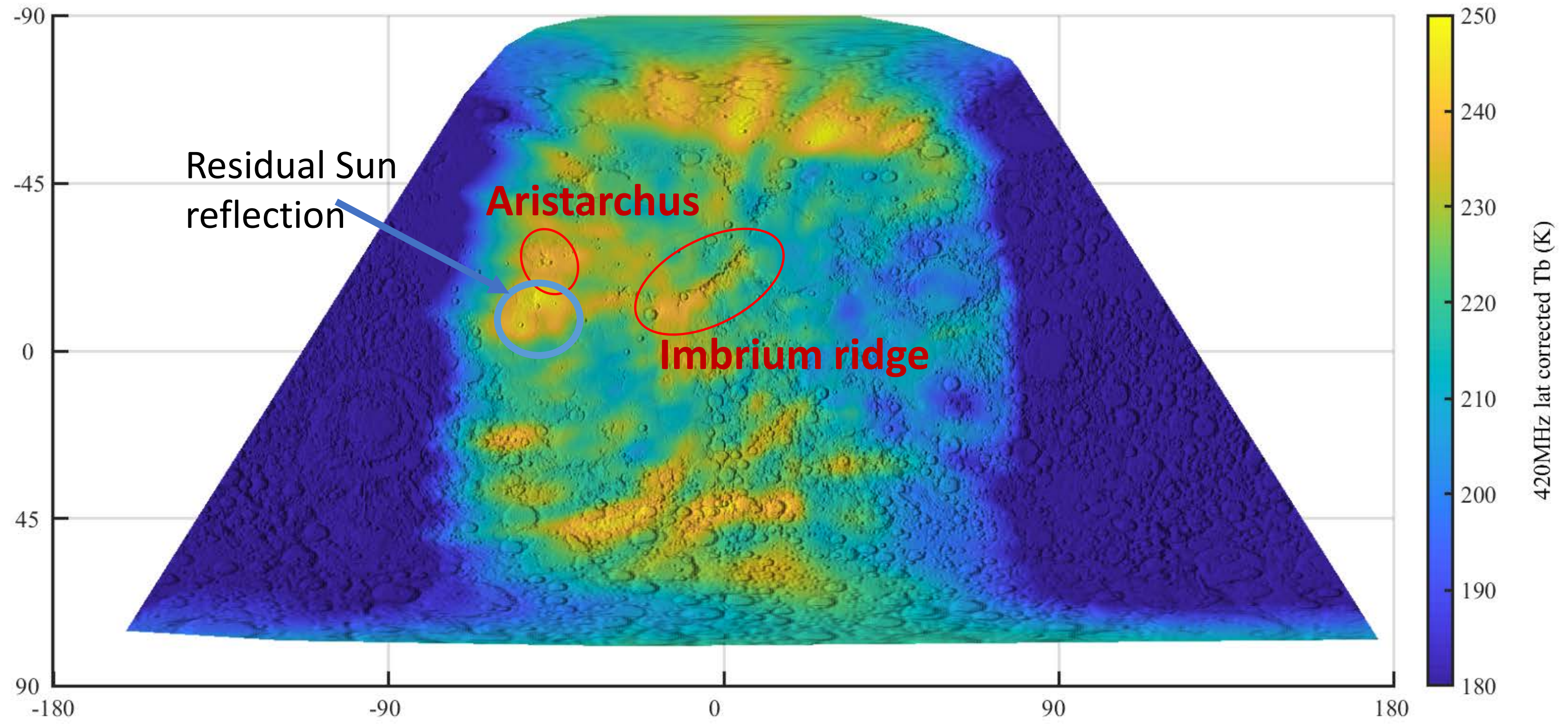
Data



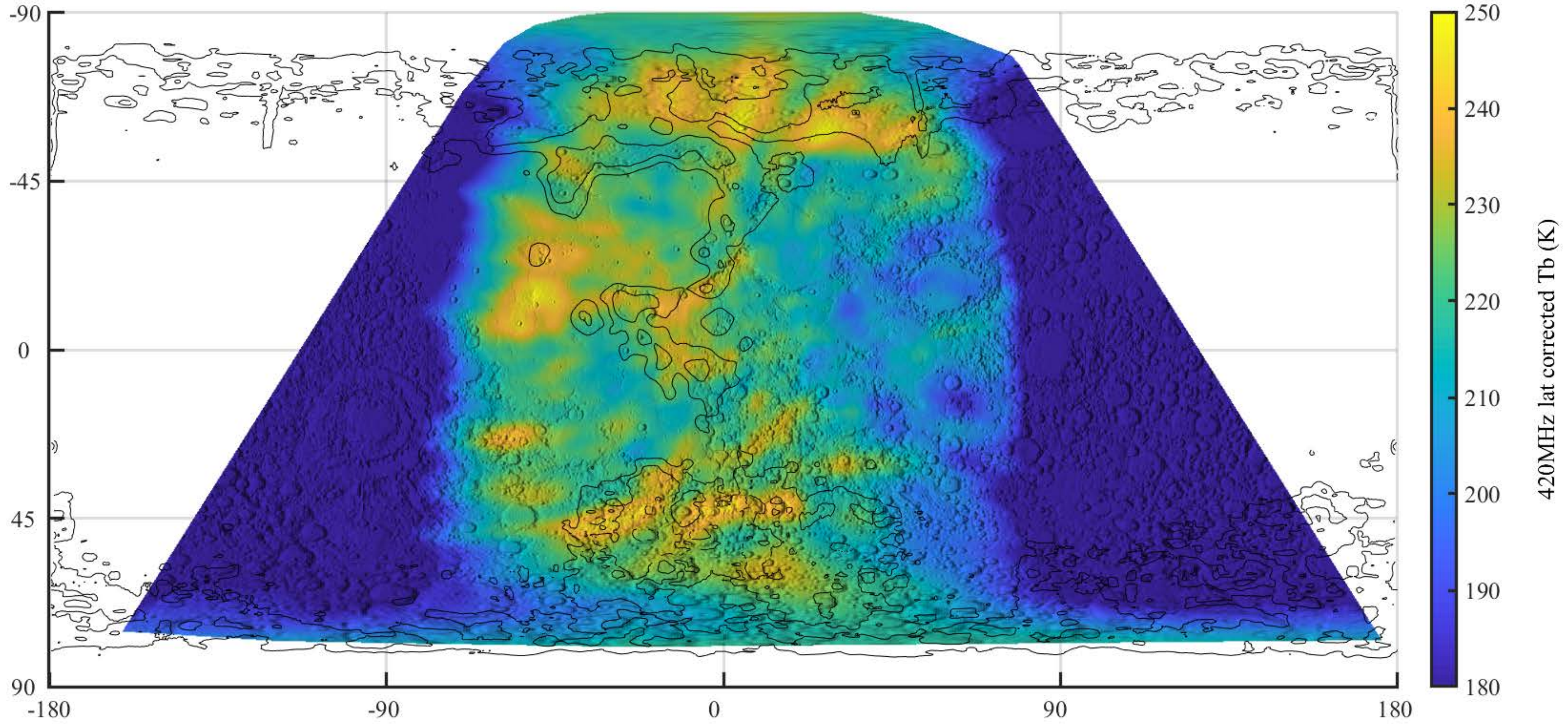
Model



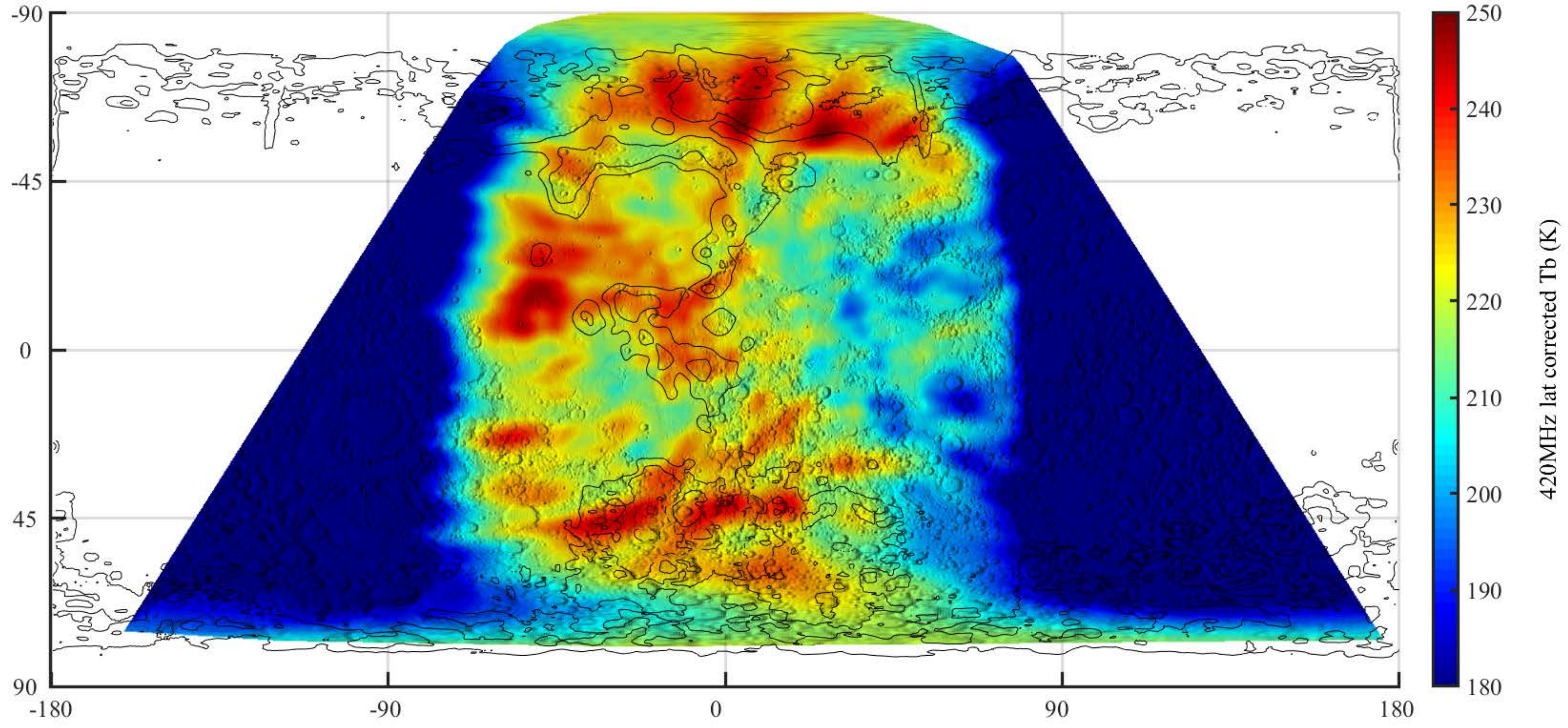
New Alignment data is shifted “up” by 10 in latitude

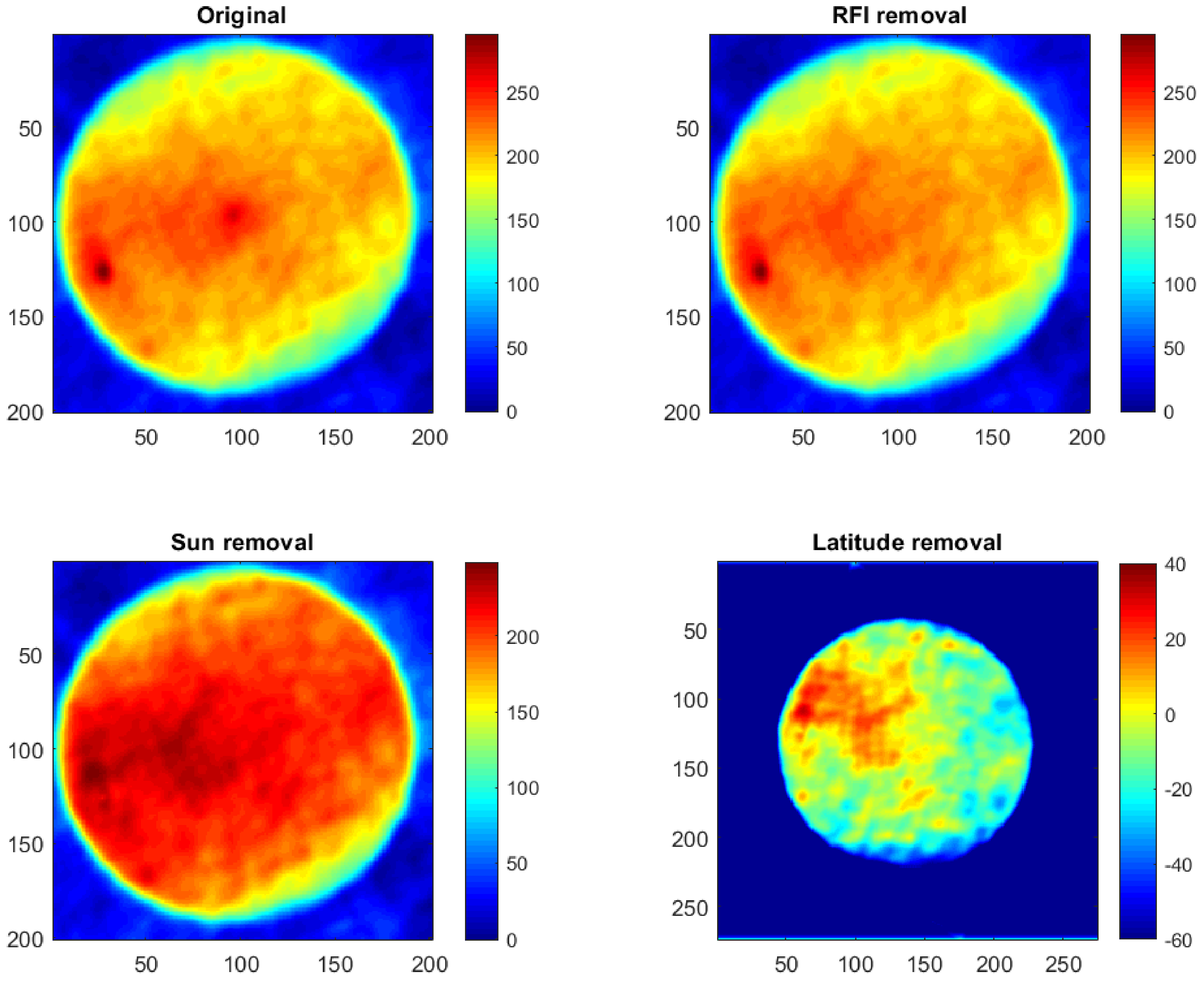


This lines up very well with Jianqing's model (contoured here)



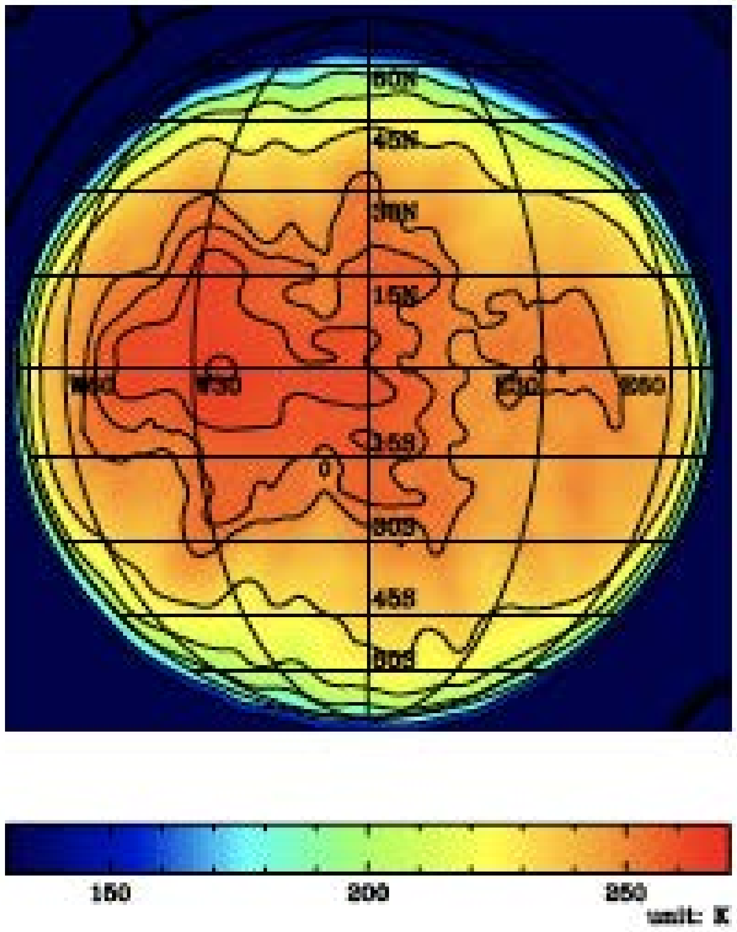
This lines up very well with Jianqing's model (contoured here)
(Same image, just a different colormap)

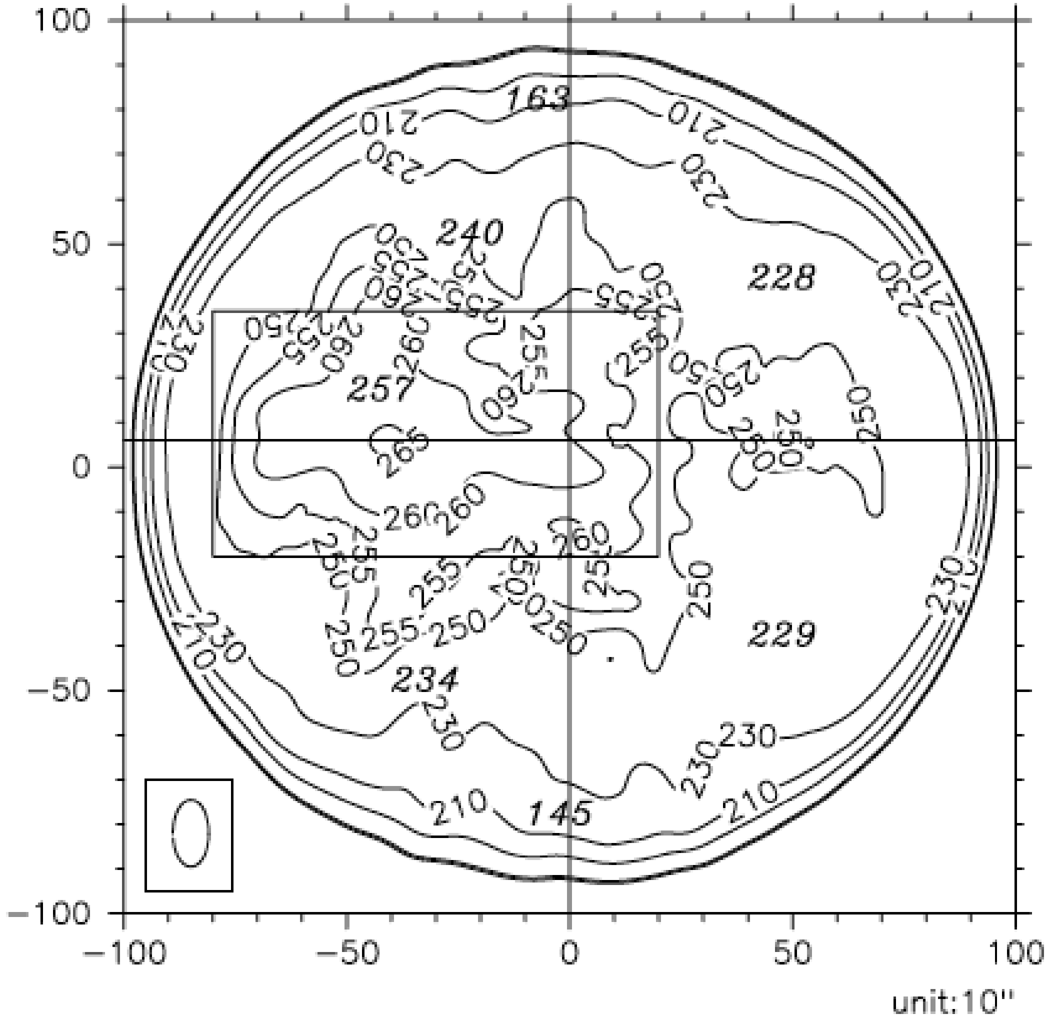


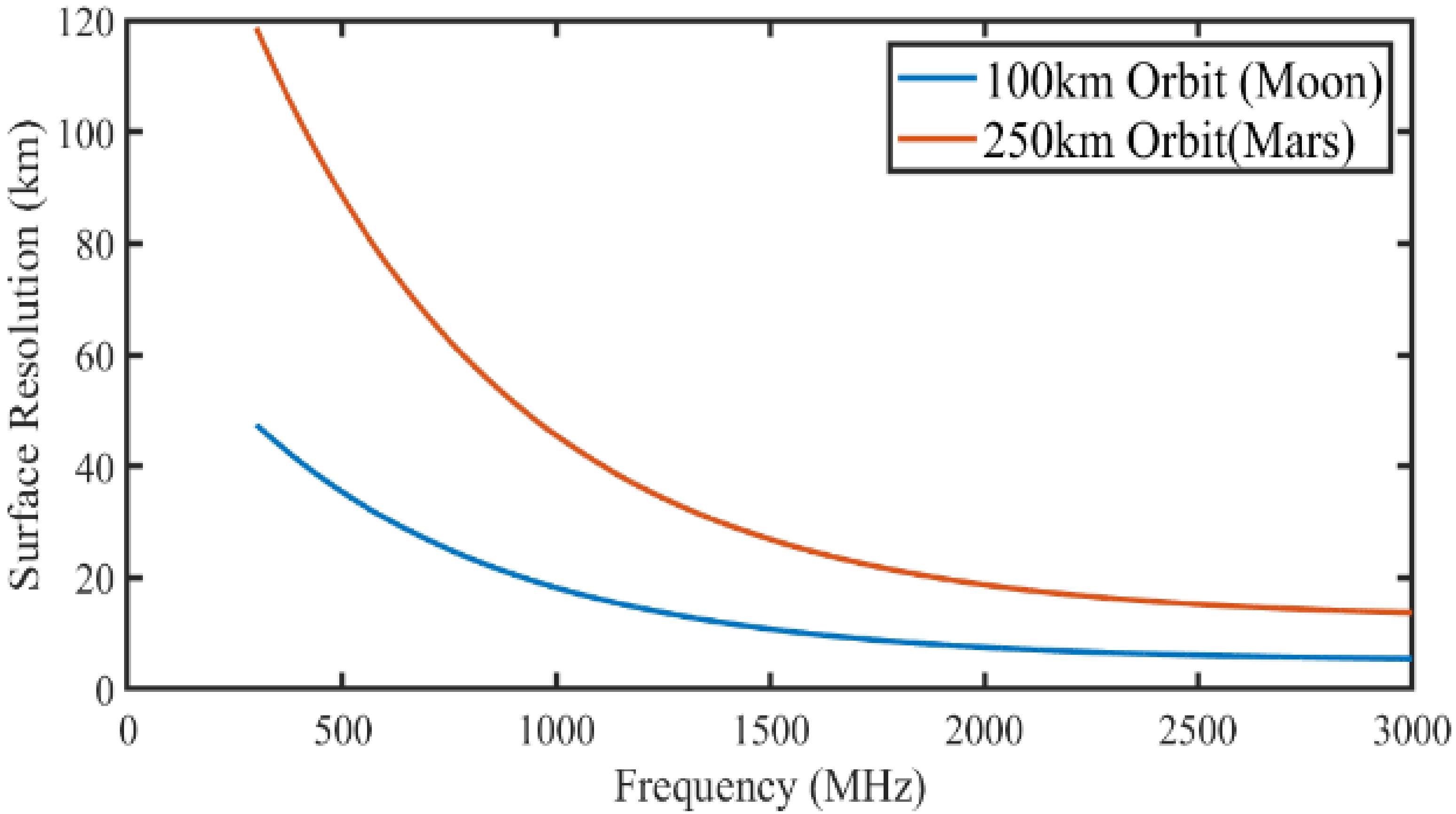


Original
RFI removal
Sun removal
Latitude removal

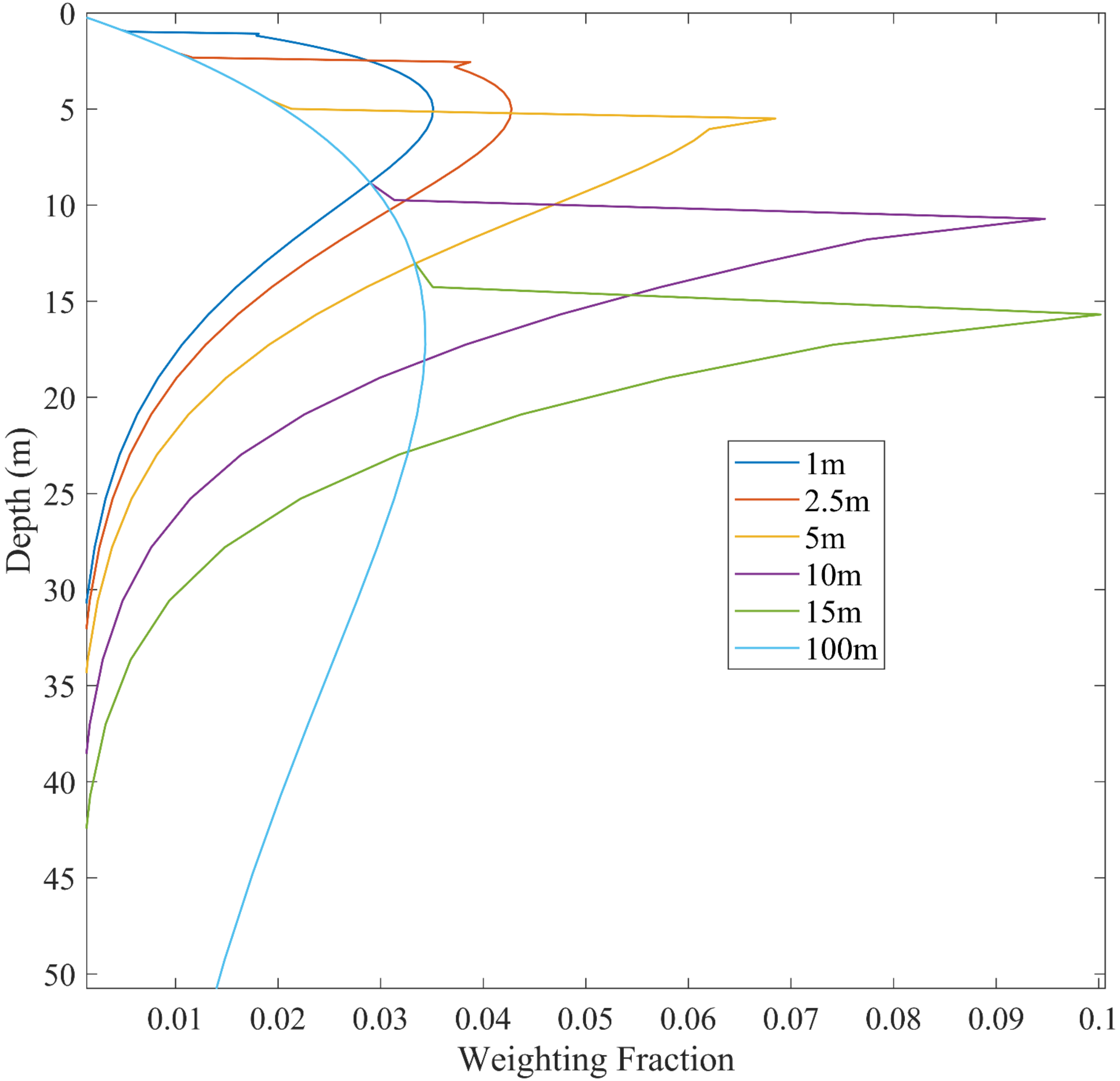
# Zhang et al., 2012 DRAO data at 1.4 GHz



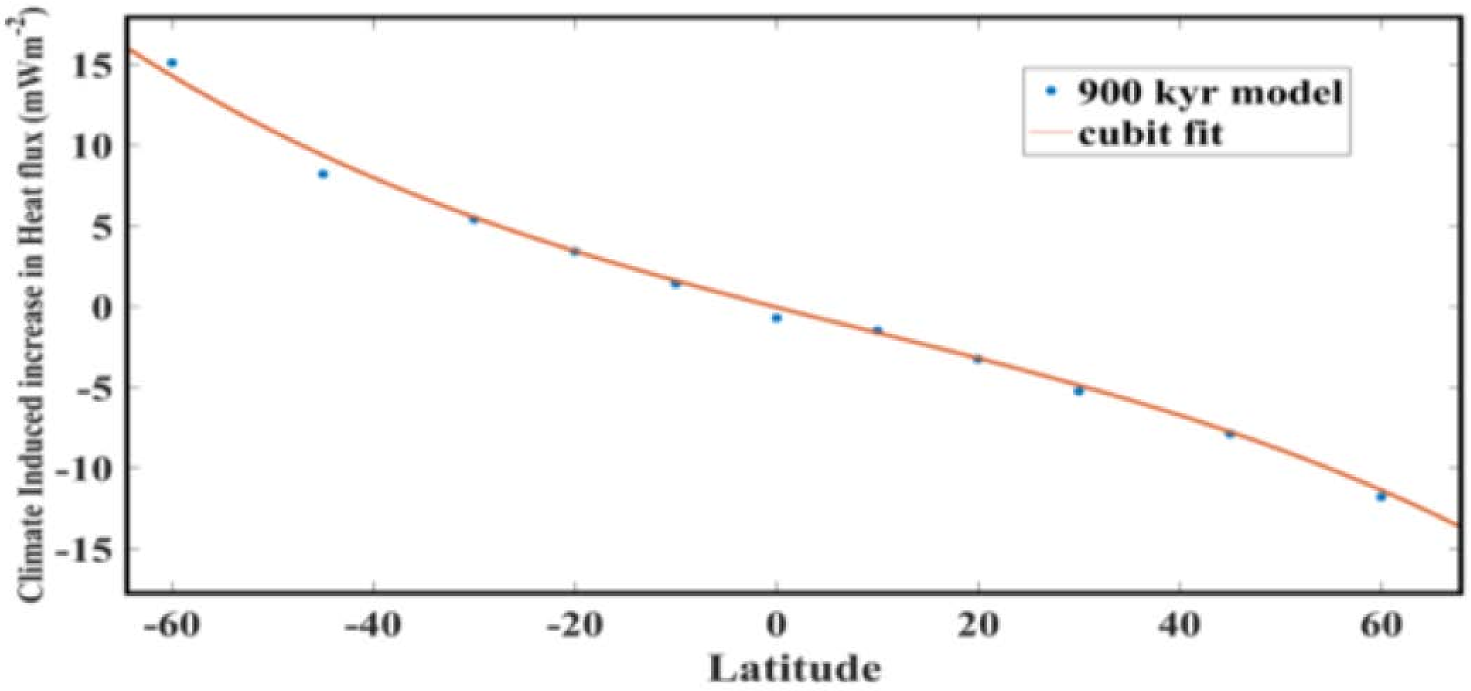





100km Orbit (Moon)
250km Orbit(Mars)
Surface Resolution (km)
Frequency (MHz)
0
20
40
60
80
100
120
0
500
1000
1500
2000
2500
3000



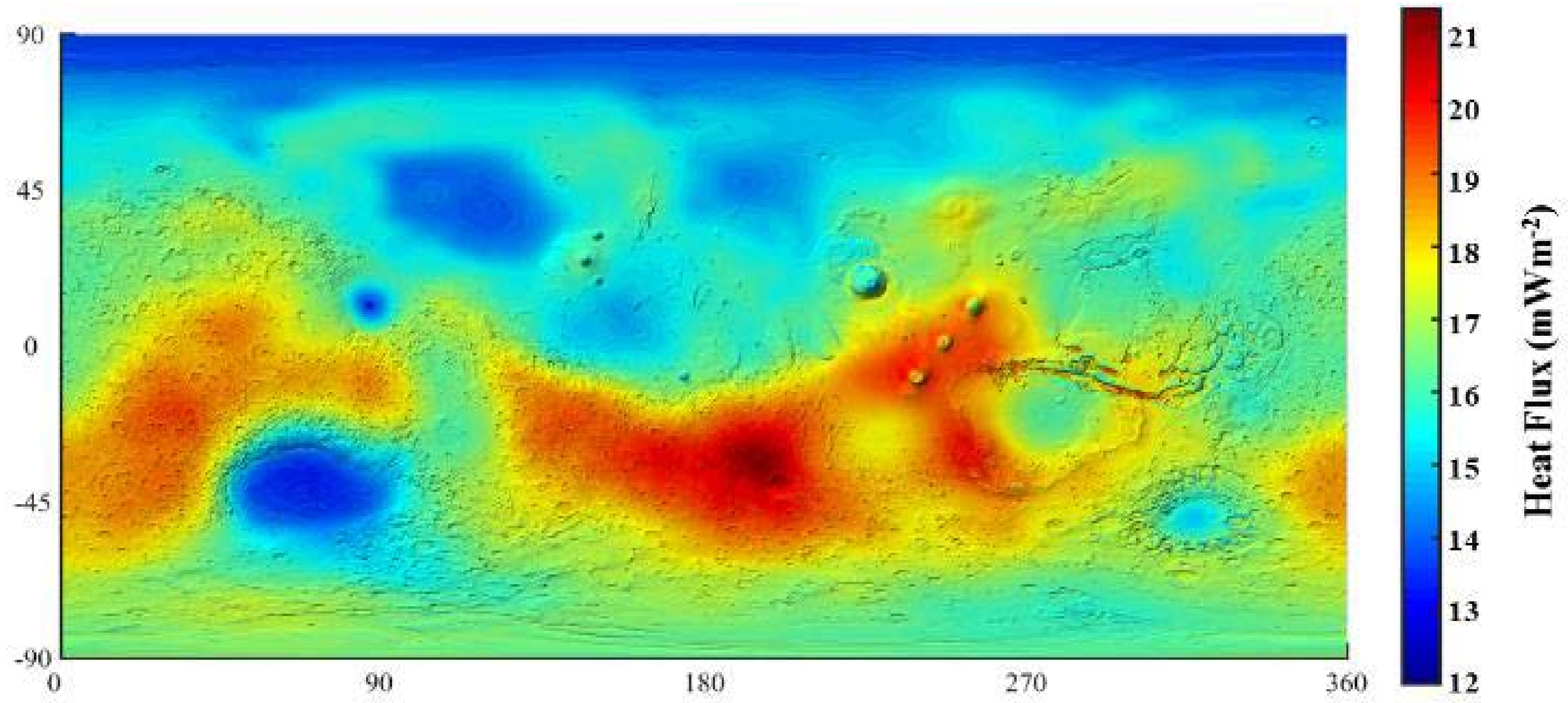
Depth (m)
Weighting Fraction
0
5
10
15
20
25
30
35
40
45
50
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
1m
2.5m
5m
10m
15m
100m



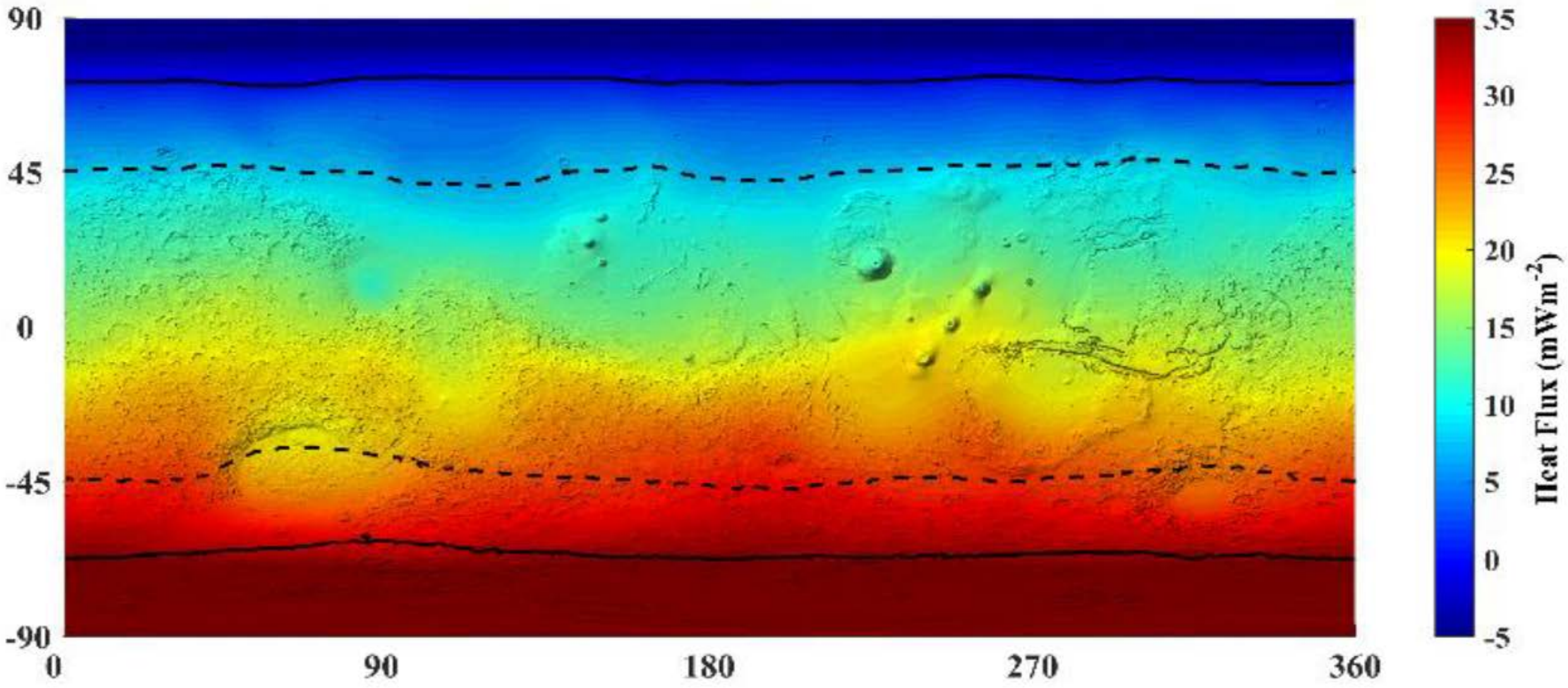

**We are also "lucky" that we are landing near the equator (which was chosen primarily due to constraints on a long term solar powered mission).**

**Had InSight landed at high latitudes, where precession scale temperature variations were much larger, this climate signal would have dwarfed the geothermal one and would have to be removed theoretically.**

# Long term (orbital) changes acting as heat flux



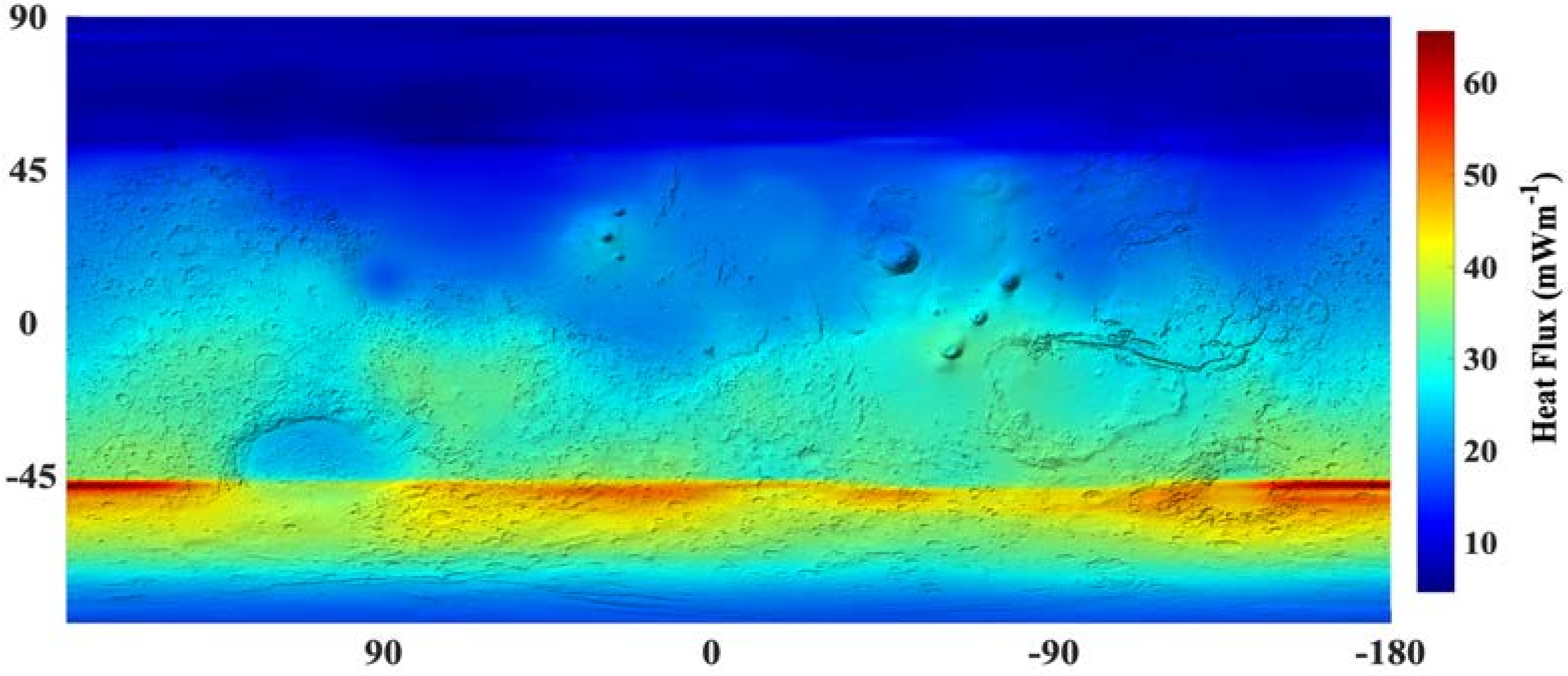
# Long term (orbital) changes acting as heat flux

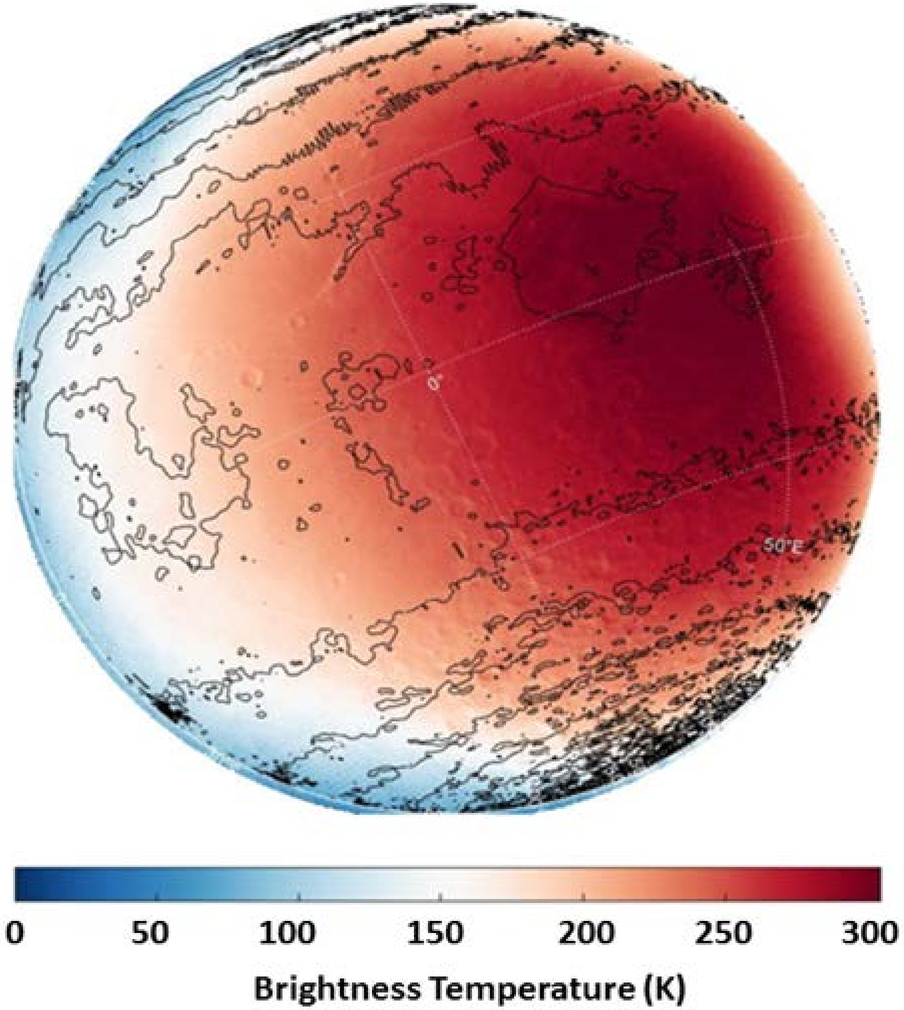


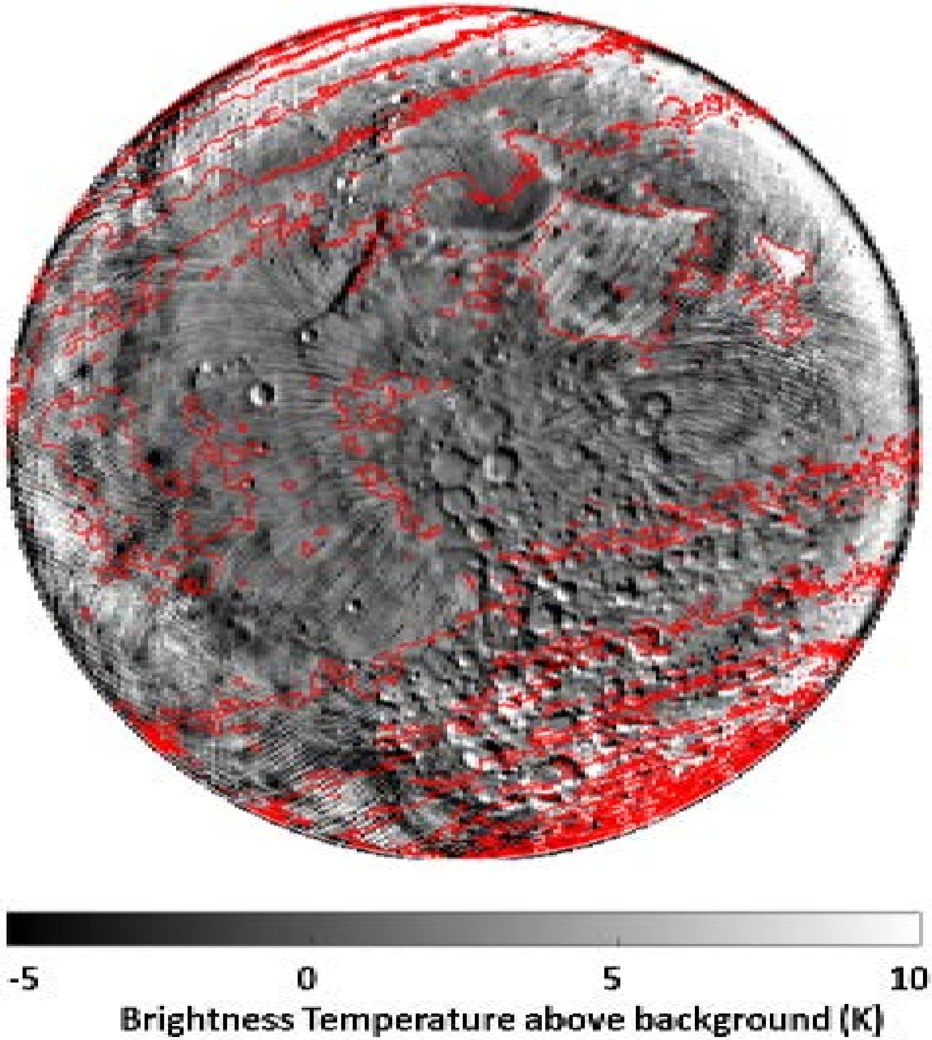

This is what the actual surface heat flux of Mars likely looks like.
20,000 years ago it would have been the opposite (hopefully I got the sign right!). Some places near the North pole should have negative surface heat flux.

The geothermal component I just showed you is included here, it is just hidden by the climate signal.

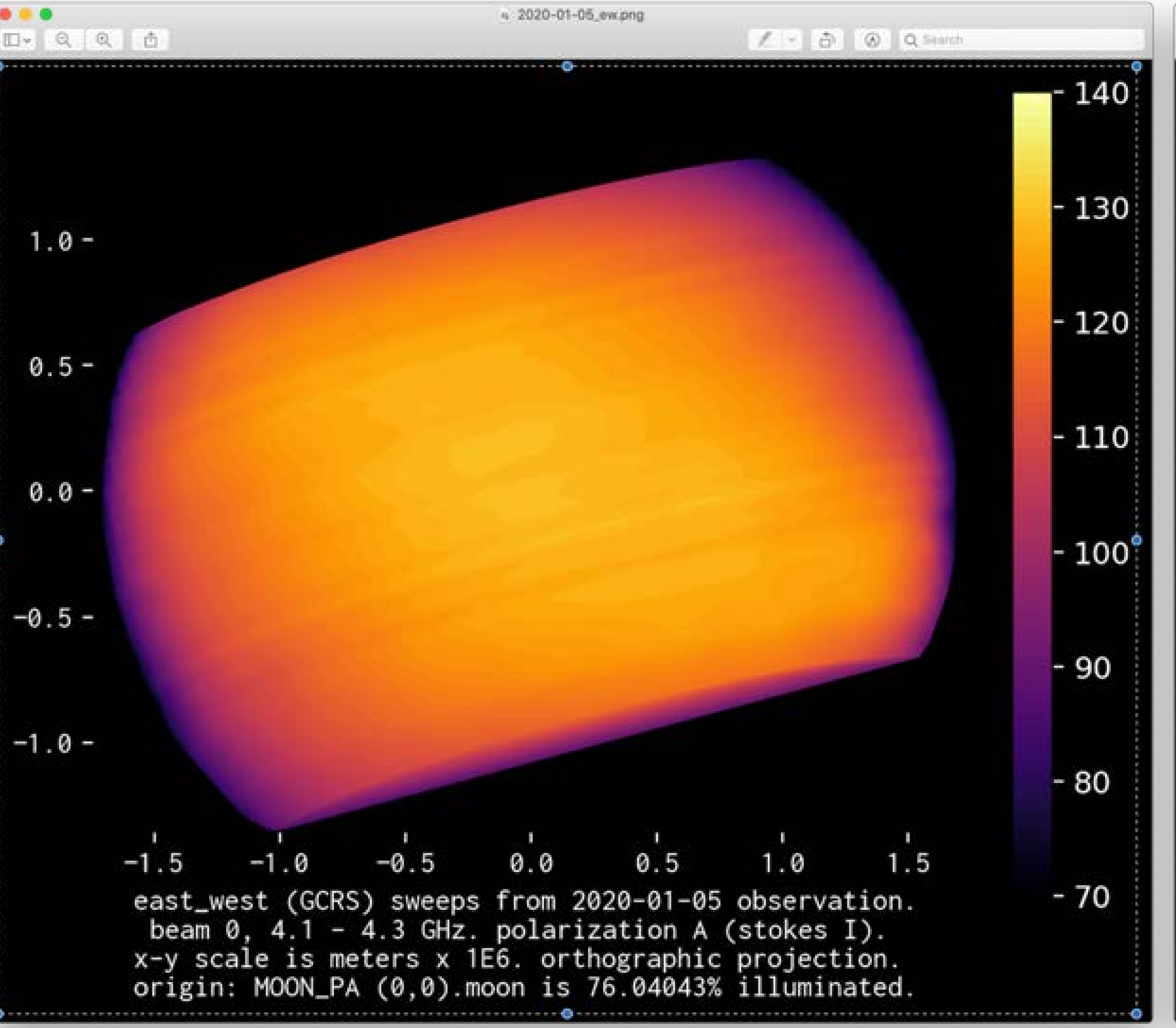
# Long term (orbital) changes acting as heat flux (including $CO_2$)

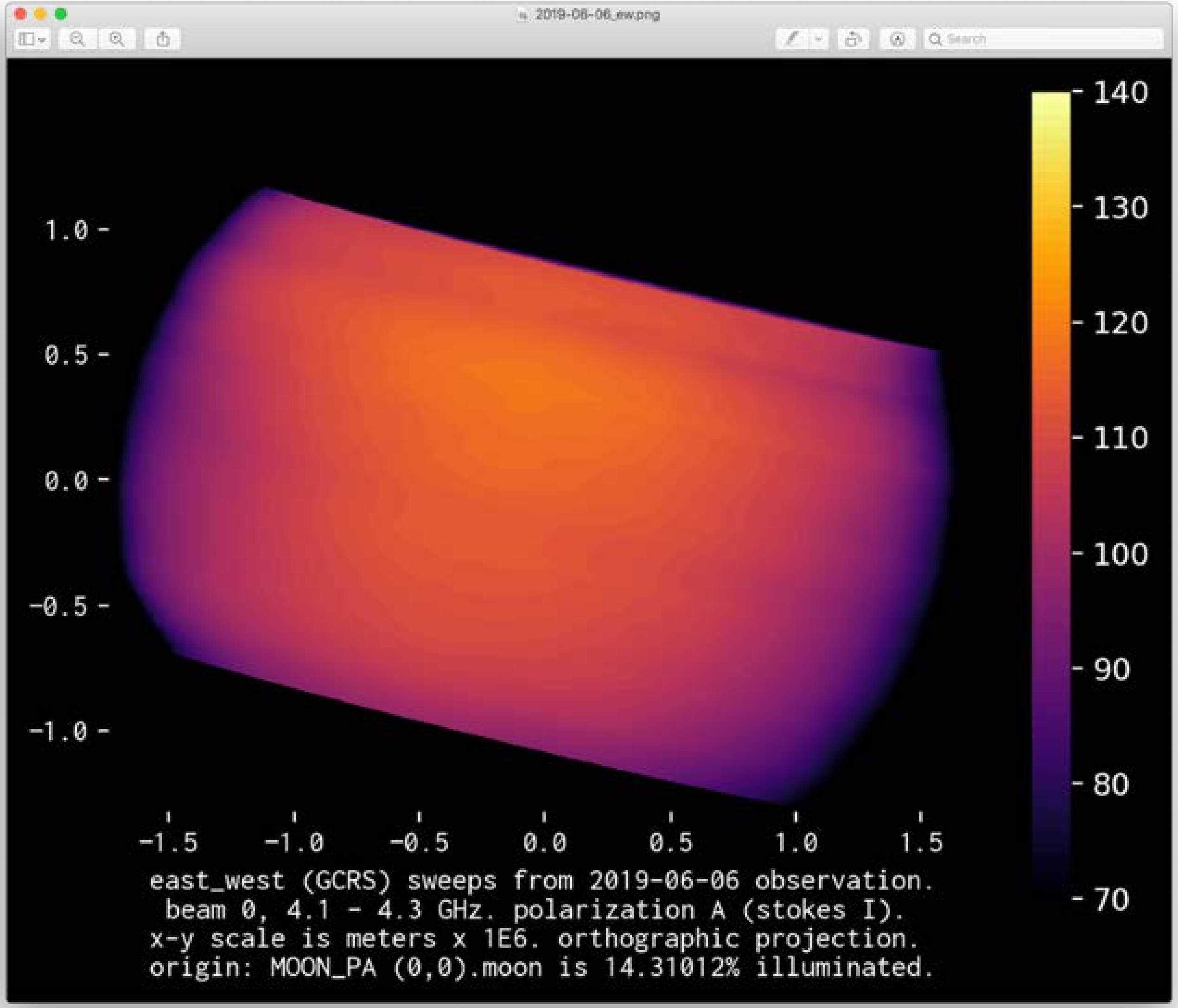


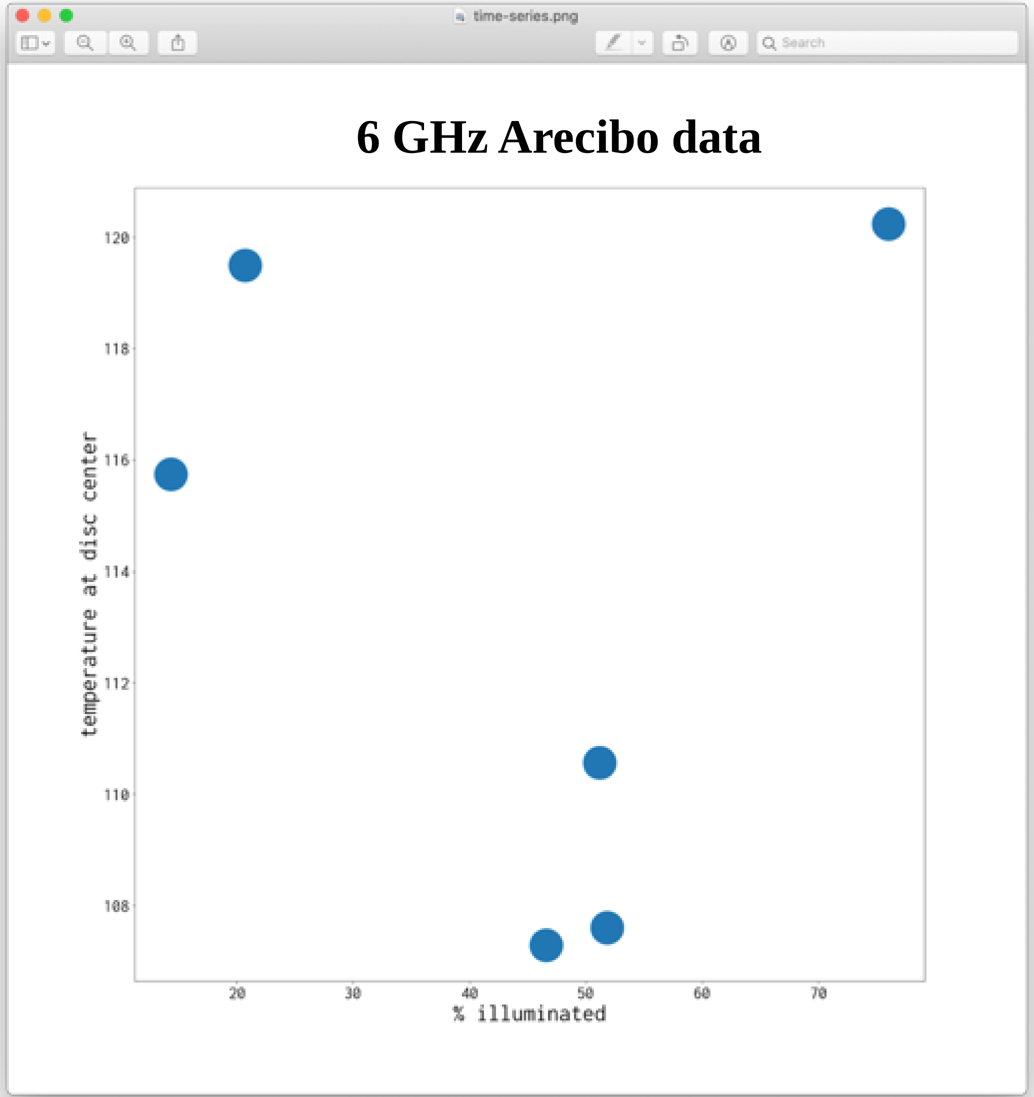

0°
50°E
0
50
100
150
200
250
300
Brightness Temperature (K)

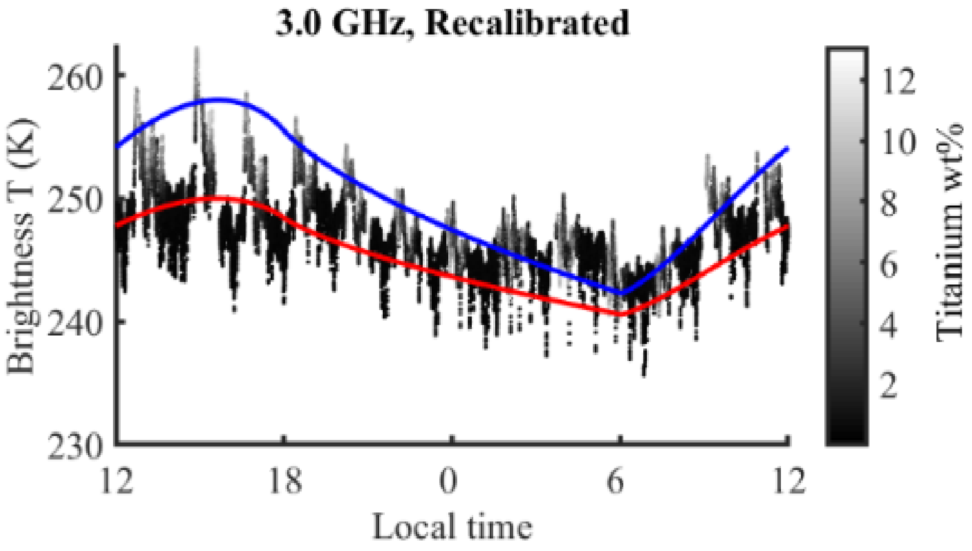

-5
0
5
10
Brightness Temperature above background (K)

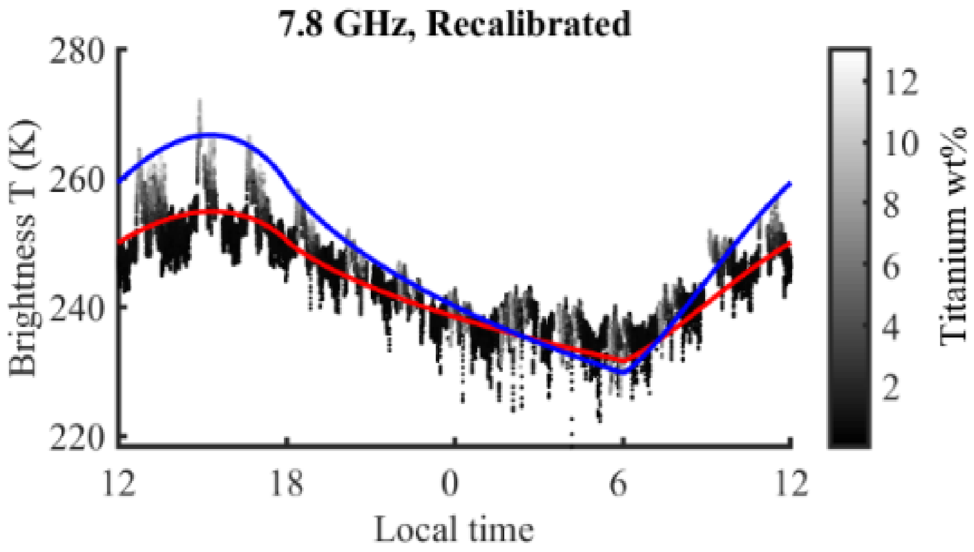
# Our Arecibo Data: 6 GHz – Taken by Edgard Rivera-Valentine




time-series.png
Search
6 GHz Arecibo data
temperature at disc center
120
118
116
114
112
110
108
20
30
40
50
60
70
% illuminated


3.0 GHz, Recalibrated
Brightness T (K)
260
250
240
230
12
18
0
6
12
Local time
Titanium wt%
12
10
8
6
4
2


7.8 GHz, Recalibrated
Brightness T (K)
280
260
240
220
12
18
0
6
12
Local time
Titanium wt%
12
10
8
6
4
2