Modeling Planar Dipoles on Lunar Regolith for a Radio Array on the Lunar Far-side.

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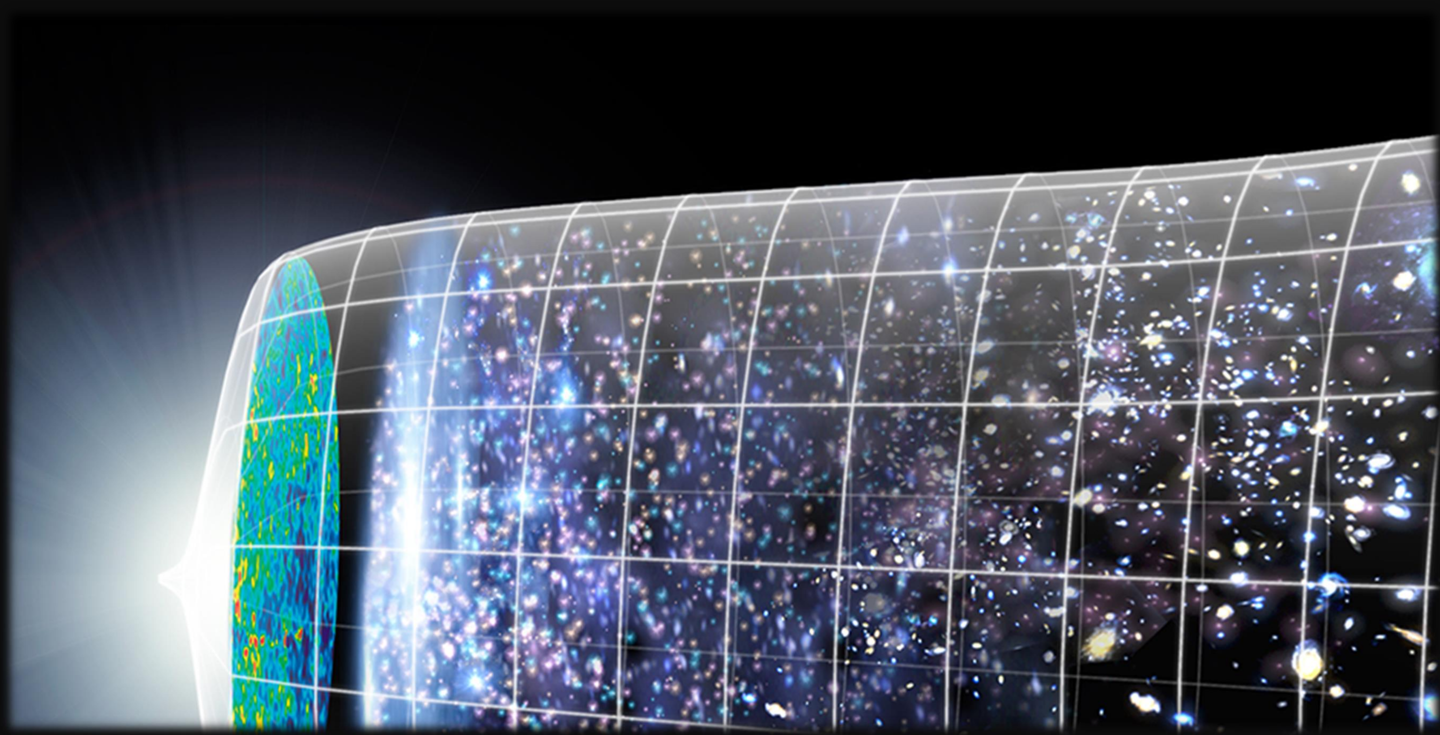
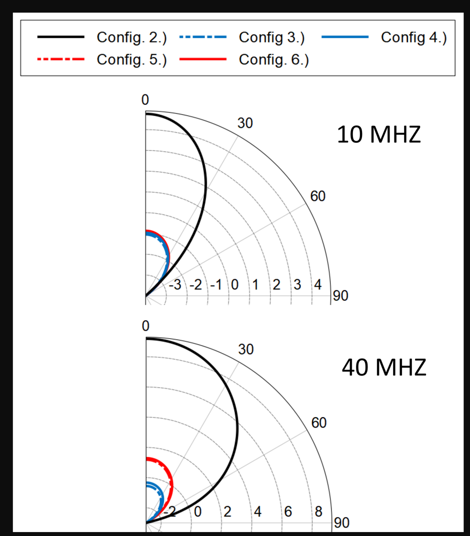
A low-frequency radio array telescope on the lunar surface can address two most pressing questions in astrophysics:



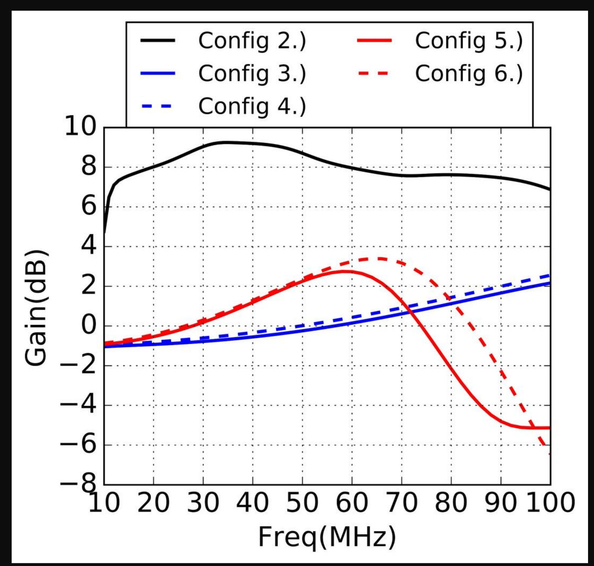
1) Detection of exoplanet radio emission to characterize exoplanet habitability and
2) Probing the growth of structure and thermal history of the universe during the cosmological dark ages using the 21cm line of hydrogen.

Existing radio astronomy antenna designs optimized for Earth-based arrays need to be modified for use in lunar radio telescope to cover the desired frequency range between ~1-30 MHz and to account for the properties of the lunar regolith.

Beam Pattern



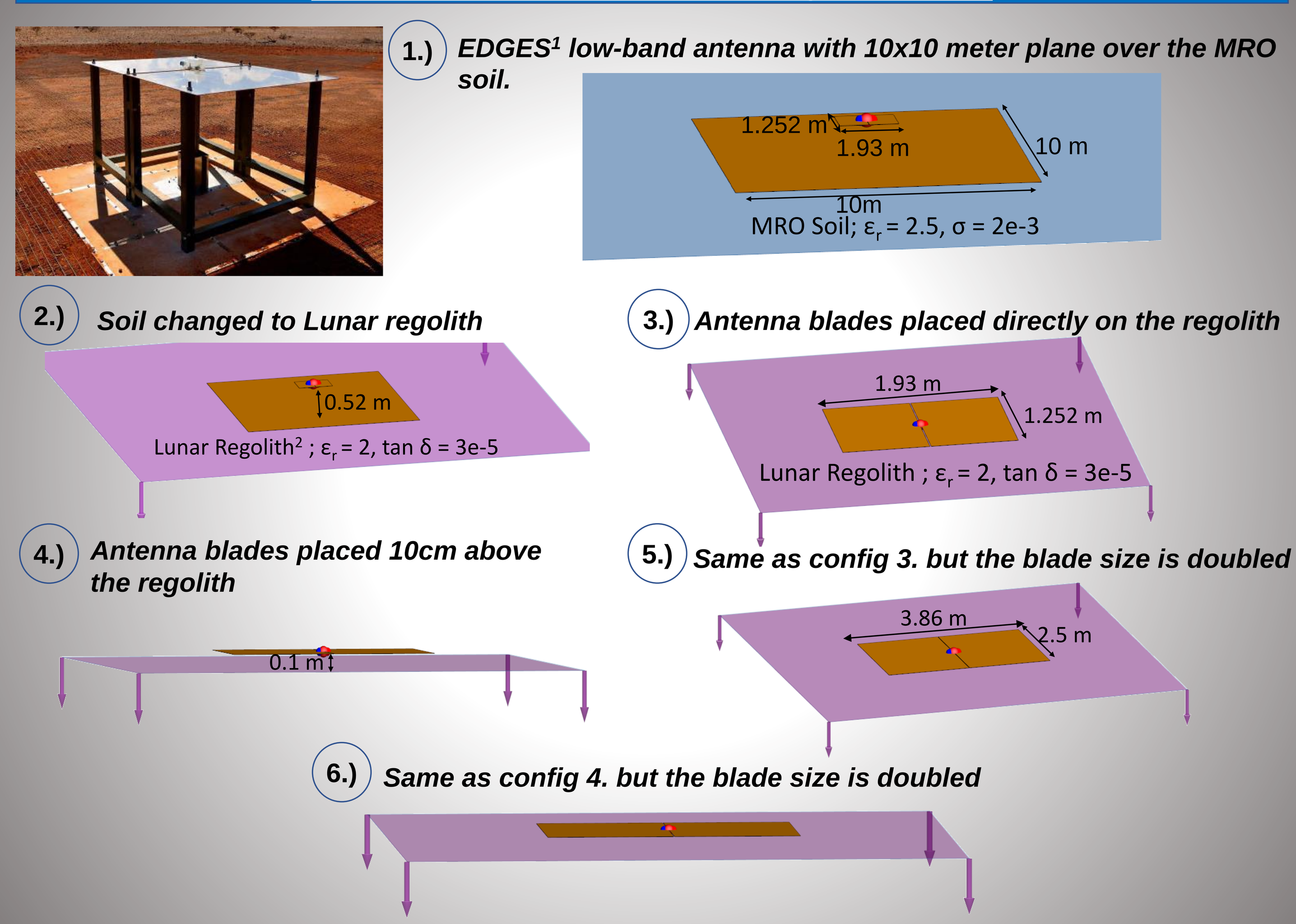
Top: Gain versus theta at phi=0 deg.
Bottom: Gain versus theta at phi= 90 deg. Gains are shown for each of the modeled antenna configurations.



Frequency variation of the gain at zenith for each of the modeled antenna configurations.

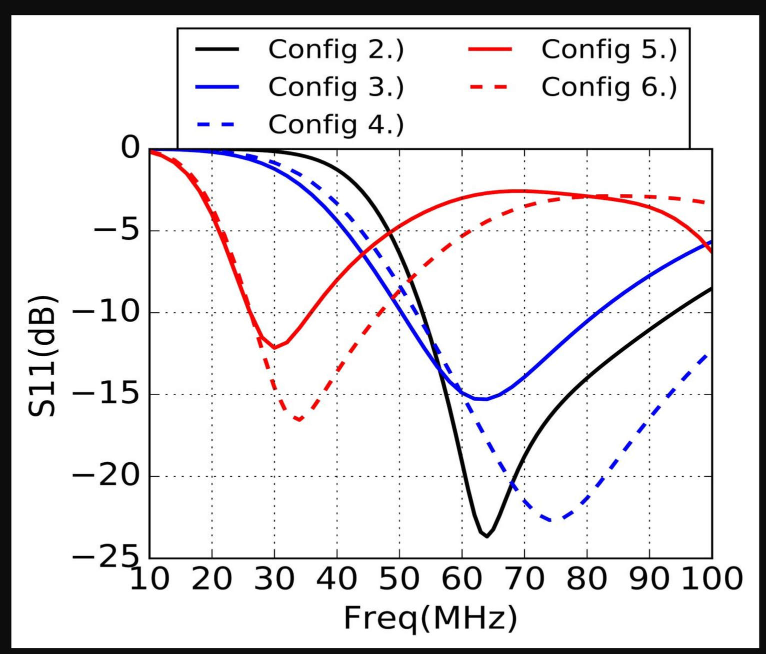
- The antenna beam is well-behaved and retains the smoothly changing beam pattern in angle & frequency characteristic of a dipole-based antenna, even without a ground plane.
- The gain reduces by ~ 85% without a ground plane. So the maximum is toward the nadir.
- The blade size is doubled to successfully improve the gain in the desired range.

Simulation Set Up Configurations



1. Bowman, J. D., Rogers, A. E. E., Monsalve. R. A., Mozdzen, T. J., & Mahesh, N. 2018, Nature, 555, 67
2. https://www.lpi.usra.edu/publications/books/lunar_sourcebook/pdf/LunarSourceBook.pdf

Reflection coefficient



The Reflection coefficient calculated with 50Ω ref Vs frequency for all the simulated antenna cases.

- At low Frequencies, the S11 decreases for the no ground plane cases compared to Config 2.)
- Simulations with the antenna blades 10cm above the regolith (configs 4&6) have a larger band-width where S11 < -10dB. (solid curves vs dashed curves)
- The cases of increased blade size result in better match at lower frequencies; 10-45 MHz (red curves Vs blue curves)

Antenna Efficiency

To answer the question of whether a ground plane is needed below the antenna, we first look at how much power reaches the receiver for each of the 6 configurations.

$$dT_{ant} = T_{sky} * gain(f) * (1 - S_{11}^2) \qquad gain(f) = (1/4\pi) \int\int G(\theta,\phi) d\theta\, d\phi$$

$$dT_{ant} = T_{ground} * loss(f) * (1 - S_{11}^2) \qquad loss(f) = 1 - gain(f)$$

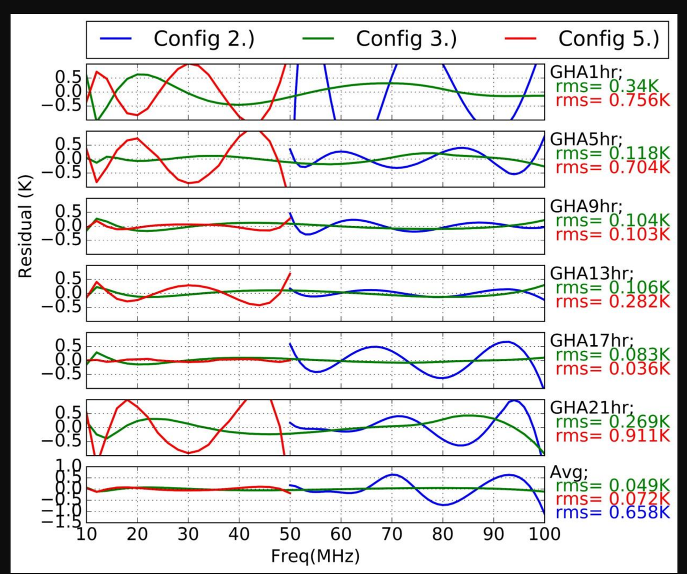
We assume the quiet sky temperature at 10 MHz is 130,000 K and at 40 MHz is 5,000 K

Configs.	dT_{ant} due to sky @ 10 MHz [K]	dT_{ant} due to sky @ 40 MHz [K]
1.)	214.5	1290
2.)	112.5	1123
3.)	49.4	559
4.)	97.1	629
5.)	1651	1030
6.)	1423	1188

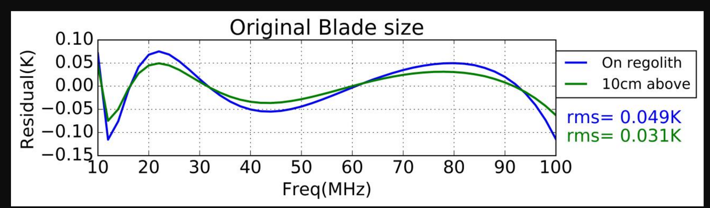
- The ground contribution will be: 240 K * (1-S11^2).
- At 10 MHz, the S11 of all the antennas is 0.9 or larger, thus the ground loss contribution to the uncorrected antenna temperature will not be larger than about 50K.
- Assuming a noise temperature of 200 K, the 2x scaled versions of the antenna are needed to achieve a SNR >1 at 10 MHz.

Simulated Spectra

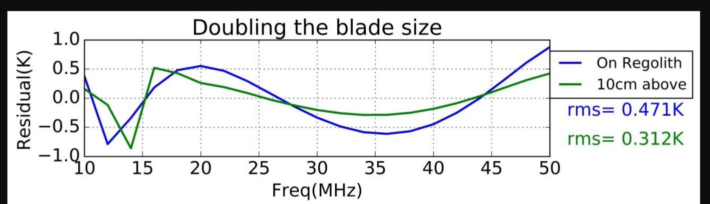
Simulated spectra is obtained by convolving the beam with scaled Haslam sky map[3]. Residue level and chromaticity is analyzed by fitting simple polynomials.



Comparison of residues after fitting a 5 term polynomial to the spectra generated with configurations 2.) , 3.) and 5.) for different GHAs. The residues are averaged over 2 hour bins.



Time averaged residues for original blade size configurations 3.) and 4.)

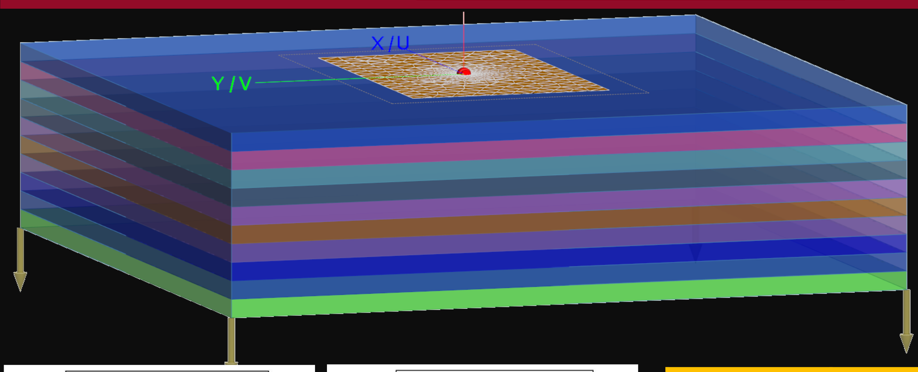


Time averaged residues for scaled up blade configurations 5.) and 6.)

- The simulations with the original blade size (configs 3&4) produce the lowest spectral structure.
- The model with the ground plane has the largest spectral variations.
- Raising the blades from the regolith surface reduces the chromaticity slightly.

3. Haslam C. G. T., Klein U., Salter C. J., Stoel H., Wilson W. E., Cleary M. N., Cooke D. J., Thomasson P., 1981, A&A, 100, 209

Regolith Variations



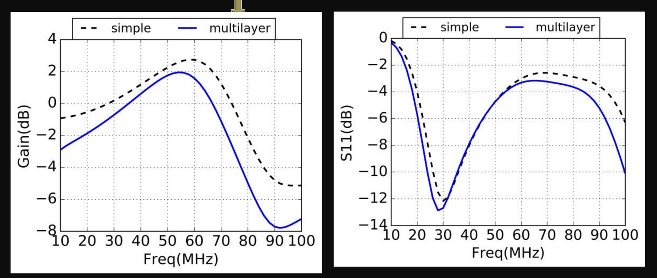
Regolith density variation with depth[4]:

$$\rho = 1.91 \frac{z + 12.2}{z + 18}\ g/cm^3$$

EM properties of the regolith[4]:

$$k = 1.919^{\rho}$$

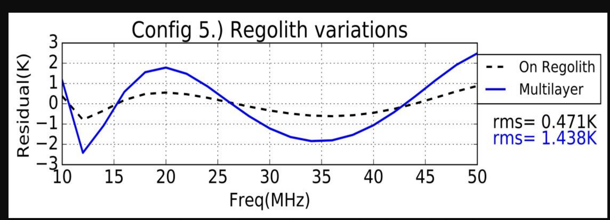
$$tan\delta = 10^{0.420\,\rho - 2.903} s/m$$



Frequency variation of (left)Gain and (right) Reflection coefficient for config 5 with two different soil conditions.

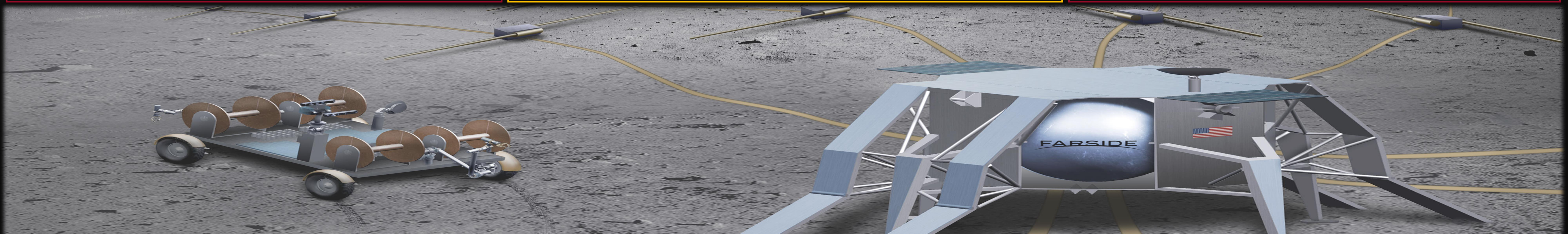
Configs.	dT_{ant} from sky @ 10 MHz [K]	dT_{ant} from sky @ 40 MHz [K]
Simple	1651	1030
Multilayer	1381	862.3

The multilayer simulation was tested for all the metrics:
- The gain reduces.
- The antenna efficiency decreases
- The chromaticity increases



Time averaged residues for scaled up blade configurations 5.) and 6.)

2. https://www.lpi.usra.edu/publications/books/lunar_sourcebook/pdf/LunarSourceBook.pdf



CAVEATS

•Calculations indicate that ideally, the scaled EDGES blade has enough efficiency to sense the sky at low frequencies ~ 10 MHz. But the S11 of this antenna is ~0.96 which means receiver signal could plummet drastically due to measurement and calculation errors.
•The beam chromaticity analysis carried out based on the simulated spectra was done assuming the antenna was placed at the MRO site.
•The analysis done for variations in the regolith electrical properties with frequency is preliminary.

CONCLUSIONS

1. From this preliminary analysis, we see no need to include a ground plane if we can trade off the gain with higher sky temperatures at low radio frequencies.
2. For antennas without ground planes, the antenna must be about twice the size of the EDGES low-band antenna to achieve sky-noise dominated performance at 10 MHz.
3. The scaled blade antenna configuration meets the required antenna efficiency and beam chromaticity.

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