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Orbiting Lunar Ground Penetrating Radar SAR Feasibility

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Summary

This report aims to answer the question: "Will ground penetrating radar (GPR) be able to measure lunar subsurface resources from a 10km or above orbit?" Similarly, "Could a reasonable satellite-based system achieve the radar parameters required for lunar orbital GPR?" This report is not proposing a system but exploring if one is possible.

Based on the analysis contained in this report, the specifications for an orbiting ground-penetrating radar are difficult but reasonable. The example system is a high-power radar operating with 60 μs chip from 500-800 MHz with 6.6 kHz pulse repetition frequency. Operating in SAR mode, the radar would have an ideal 1-meter azimuth resolution and a 0.5 meter depth resolution, with penetration depth in the low-loss lunar regolith in the hundreds of meters. The best possible version of this system can have over 50 dB of SNR budget.

Analysis

Problem Setup

The geometry of the situation is depicted in Figure 1. A satellite carrying the theoretical GPR system is orbiting the lunar surface at r_{orbit} at speed v_{orbit} determined by (1). We assume the system is operating in SAR mode.

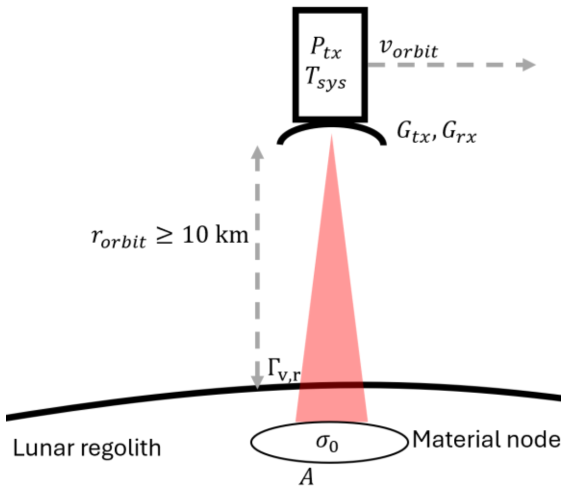

Figure 1: Radar setup

Under the surface, there is a node with backscatter coefficient σ_0 and area A.

Link Budget Equations

First, we perform an idealized analysis of the situation to determine how much antenna gain, transmit power, and processing gain is needed. If the return SNR has at least 0 dB, we assume it is at least possible to measure the response. [1] claims that the minimum SNR for recognition of planar interfaces is actually below -10 dB, but we will maintain 0 dB as a limit.

The simplified transmission equation we will use is based on the first reflection of the subsurface (1):

$$P_r = P_t \frac{G^2 \lambda^2 \sigma_0 A}{(4\pi)^3 (r_{orbit} + z)^4} \left(1 - \Gamma_{v,r}^2\right)^2 e^{-2\alpha_r z} \quad (1)$$

where:

- P_r, P_t: Power received and transmitted, respectively
- G: Antenna gain (assumed $G_t = G_r$)
- λ: Freespace wavelength
- z: Depth in lunar regolith
- $\Gamma_{v,r}$: Amplitude reflection coefficient from vacuum to regolith
- α_r: Attenuation coefficient [np/m] of regolith
- σ_0: Backscatter coefficient of material in regolith
- A: Area of target material

Similarly, we utilize an SNR equation ignoring noise sources other than thermal (2), and adding a term to address signal processing gain:

$$\mathrm{SNR} = \frac{P_r}{N_r} G_{proc} = \frac{P_r}{k T_{sys} B} G_{PCG} G_{SAR} \quad (2)$$

where:

- N_r: Noise of receiver
- k : Boltzmann's constant
- B : Bandwidth of receiver
- T_{sys} : Equivalent noise temperature of receiver
- G_{PCG} : Gain from chirp pulse compression technique
- G_{SAR}: Gain from SAR processing

The full equation is then (3), stated as an inequality to acknowledge the underestimate of noise and absence of inhomogeneous clutter:

$$\mathrm{SNR} \leq \; P_t G^2 G_{PCG} G_{SAR} \frac{\lambda^2 \sigma_0 A}{(4\pi)^3 (r_{orbit} + z)^4} \left[\left(1 - \Gamma_{v,r}^2\right)^2 e^{-\alpha_r z}\right] \frac{1}{k T_{sys} B} \quad (3)$$

Link Budget Calculations

First, we define the known or assumed parameters. Material parameters are taken as heuristic averages or "likely" parameters to encounter.

Table 1: Parameters

Name	Variable	Value	Notes
Lunar regolith complex permittivity	$\epsilon' - j\epsilon''$	$3 - j0.005$	Approximate
Lunar regolith attenuation coefficient	α_r	$\frac{\omega}{c}\sqrt{\frac{\epsilon'}{2}\left(\sqrt{1 + tan\delta^2} - 1\right)}$	$tan\delta$ from complex permittivity (ϵ''/ϵ')
Reflection coefficient from vacuum-regolith interface	$\Gamma_{v,r}$	0.268	Plane wave assumption, normal
Orbital radius	r_{orbit}	$\geq$ 10 km	Problem definition
Boltzmann constant	k	$1.38 \cdot 10^{-23}$ J/K	

Equivalent receiver noise temperature, includes receiver	T_{sys}	300K	250K – day-side lunar noise temperature 50K – Ultra low noise receiver
Receiver Bandwidth	B	300 MHz	System design – range resolution
Wavelength	λ	650 MHz	System design – penetration depth and horizontal resolution
Backscatter coefficient	σ_0	-20 to 0 dB	-20: weak target, 0: strong target. Assumed parameters, targets likely fall in this region if detectable
Area of target	A	1 m^2 to 100 m^2	Assumed fully illuminated due to large antenna beamwidth

With the parameters of Table 1, we can calculate the overall contributors to the link budget, which also defines the design space for the gain-adding elements.

Table 2: Link Budget Calculations

Name	Expression	Value	Notes
Spherical spreading	$\frac{\lambda^2}{(4\pi)^3 r_{orbital}^4}$	-199.7 dB	Dominant contributor, 650 MHz
Target reflectivity	$\sigma_0 A$	-20 .. 20 dB	Weak .. Strong (This is equivalent to RCS). **Note: Weaker targets could be obscured by clutter**.
Regolith coupling	$\left(1-\Gamma_{r,v}^2\right)^2$	-0.65 dB	
Loss per meter, regolith	$e^{-\alpha z}$	-0.085 dB/m	At 650 MHz
Noise Power	$kT_{sys}B$	-119 dBW	300 MHz BW, 300K T_{sys}
Total gain to make up	Combined as in (4)	-101.3 .. -61.3 dB	For SNR = 0, need $P_t G^2 G_{PCG} G_{SAR}$ to equal at least this

Example System to Meet Link Budget

From Table 2, we need to meet and exceed between 101.3 and 61.3 dB of gain using the expression $P_t G^2 G_{PCG} G_{SAR}$. In this expression, let's work left-to-right.

It is worth noting that an actually-realized system would likely want to collect HH, VV, HV, and VH polarizations in order to statistically de-clutter the image (full polarimetry). To avoid the resulting minutiae that would result from a discussion of that system architecture, we assume using a single transmitter and single receiver, and the eventual designer would figure out the H/V details.

Additionally, we are assuming that the SAR is a "first-class" sensor on this platform – i.e., heat management, power draw, and deployed antenna size can all be accommodated for the SAR. In reality this assumption may not be the case, but those can be engineering tradeoffs and is out-of-scope of this feasibility study.

Finally, a realistic implementation could be a solid-state phased array, but we also assume one transmit and one gain antenna for simplicity.

Transmit Power P_t

We want to use the highest transmit power possible, excepting power draw requirements and avoiding noisy transmitters that can eat into gain from G_{PCG} and G_{SAR}. Solid-state is a good candidate for a transmitter here, with the current state-of-the-art being GaN-on-SiC. Qorvo's website claims a 1.7 kW transmitter [2] capable of both CW and pulsed operations in the L-band. Therefore, it is reasonable to expect at least a 1.7kW could be achieved in the UHF 500 MHz – 800 MHz band. In dB-scale, 1.7kW is equivalent to 32 dB (dBW).

Antenna Gain G

We want to use the largest antenna possible for two reasons. First, as gain is squared in the equation, it disproportionally affects radar SNR. Second, a wider beam allows more clutter into the field of view, which would affect the imaging capability. From the SAR perspective, a larger beamwidth may be preferable if attempting to illuminate larger swaths of the moon at once. This depends on mission parameters.

We assume here a 2-meter dish, which gives a gain of approximately 20 dB using a 60% aperture efficiency. This is a beamwidth of 16 degrees. At an altitude of 10 km, this is a swath width of 2.8 km.

Pulse Compression Gain G_{PCG}

Pulse compression gain comes from correlating the received signal with the transmitted signal when the signal is modulated in a specific way that exploits the signal's bandwidth. A common modulation is a linear frequency modulation (LFM) chirp. The pulse compression gain can be calculated as (4):

$$G_{PCG} = \epsilon_{PCG} B\tau \tag{4}$$

where τ is the transmitted pulse length and we have included an ϵ_{PCG} efficiency factor ≤ 1 to note that realistic pulse-compression schemes do not achieve the full bandwidth-time product due to instability on the transmitter or other nonidealities.

Bandwidth is more limited by noise and hardware, so increasing the transmitter pulse length is a good way to increase the pulse compression gain. The maximum transmitter pulse length will be the inverse of the pulse repetition frequency (PRF). The PRF for SAR is determined by the velocity (5).

$$v_{orbit} = \sqrt{\frac{GM}{(r_{orbit} + r_{moon})}} = \frac{2.214 \cdot 10^6}{\sqrt{r_{orbit} + 1740 \cdot 10^3}} \ \text{(m/s)} \tag{5}$$

$$PRF \geq \frac{2v_{orbit}}{L} \tag{6}$$

Where L is the length of the antenna (2 meters) [3]. At 10 km, v_{orbit} is just above 1.67 km/s. By the doppler sampling criterion, (6) says that the PRF must be at least 1.67 kHz, ideally higher. Similarly, we would like to keep the radar's unambiguous range greater than r_{orbit}. This is not a hard requirement but would be nice. This specification results in (7). Note that this is a clear overestimate of maximum PRF, and is discounting slant angles.

$$PRF_{unambiguous} \leq \frac{c}{2r_{orbit}} \quad (7)$$

At 10km, we can keep the lunar surface in the unambiguous range if the PRF is less than 15 kHz. Therefore, the PRF must be between 1.67 kHz and 15 kHz. This is an engineering decision. We choose PRF = 6.68 kHz to 4x the Nyquist rate. Now, the maximum pulse length is 149 μs. It may be easier to transmit a pulse length of 60 μs, as the round-trip time length of a 10km altitude is 66 μs, and not transmitting while receiving may make implementing the receiver significantly easier, as well as allowing a duty cycle for heat recovery.

If we take $\tau = 60\mu s$, then the pulse compression gain is at a maximum 42.5 dB, or a time-bandwidth product of 18000. This is a high pulse compression gain, but we will take this number and acknowledge the practical difficulty of achieving the full pulse-compression gain.

SAR Gain G_{SAR}

SAR gain arises from coherent integration. Coherent integration can be arbitrarily increased over multiple target passes; but that is both impractical and demanding on the mission. Instead, we can calculate the SAR imaging gain from a single pass (8) [3]:

$$G_{SAR} = N_{SAR} = t_{illuminated} PRF = \lambda \frac{r_{orbit}}{L v_{orbit}} PRF \quad (8)$$

For our 10km, 1.67 km/s, 2-m dish, 650 MHz, 6.68 kHz system, we calculate G_{SAR} to be $9.23 \cdot 10^3$, or 39 dB.   Finally, we may complete our table of the gain-producing elements in Table 3.

Table 3: Link-budget gain-producing elements

Name	Expression	Value	Notes
Transmit power	P_t	32 dBW	GaN-on-SiC 1.7kW
Antenna gain	G, G^2	20 dB, 40 dB	650 MHz, 2-meter dish
Pulse compression gain	G_{PCG}	42.5 dB	60 μs, 300 MHz (**very high PCG**)
SAR Imaging gain	G_{SAR}	39 dB	1.4 seconds in main beam
Total		153.5 dB	Had to overcome -61.3 .. -101.3 dB

The total SNR budget ranges from 92 dB (strong target) to 52 dB (weak target). Alleviations in the system design could be made in the transmit power (1.7 kW to 170 W, a 10 dB decrease, is more realistic), nonidealities in the pulse compression gain and SAR gain, and other losses in the system (cable loss, signal processing loss). Similarly, the dynamic range of the receiver would require consideration. More alleviations could be made in using a less stringent receiver, as a 50K noise temperature receiver is very strict.

With these SNR budgets, penetration depths of several hundred meters into the low-loss regolith are in play. From an SNR, geometric, and practical perspective, the link budget implies that this mission is possible. Very likely, clutter will be the limit of such a practical system.

The simulation of excess SNR versus depth for a variety of targets is shown in Figure 2. We can see theoretical max penetration depths of hundreds of meters. In reality, clutter will likely limit performance to a fraction of that depth

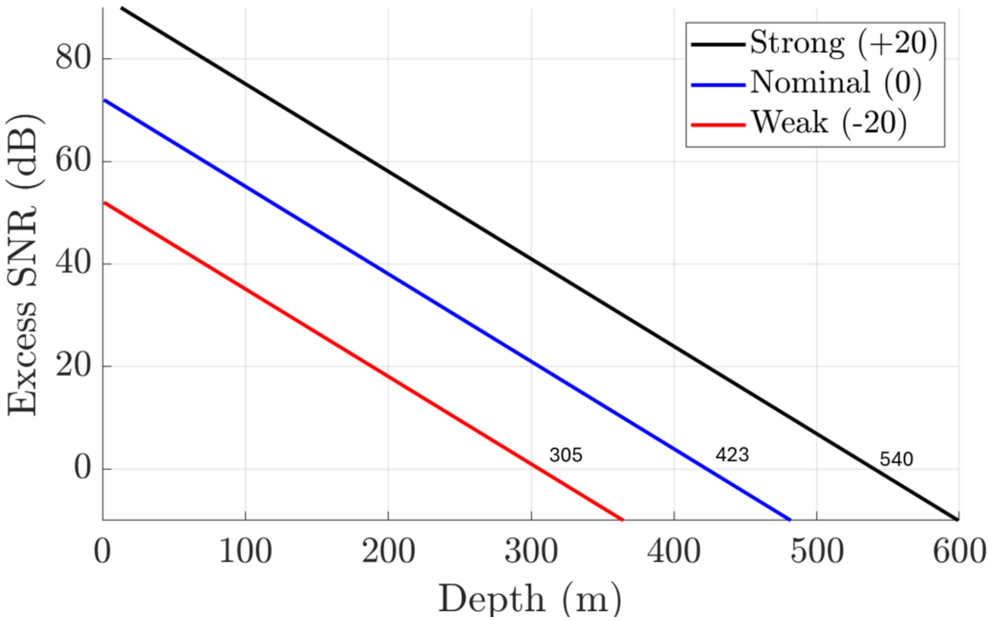

Figure 2. Excess SNR versus buried depth for proposed radar system

System Summary

The proposed system would be a high-power transmitter with a 2-meter antenna aperture, 60 μs chirp from 500-800 MHz, and a very good receiver. Ideally, the system is fully polarimetric and an electronically steerable array. The range resolution of this system would be 0.5 meters, and its azimuth resolution would be 1 meter, though realistically achieved resolutions would be poorer. This system could penetrate to depths in the hundreds of meters. To reduce clutter, this radar is best paired with a sensor able to accurately characterize the lunar surface, which would allow suppression of surface clutter. Another option is to increase the operation frequency to maintain bandwidth and reduce fractional bandwidth, as the lunar regolith mode is low-loss enough to support higher frequencies.

In conclusion, the proposed numbers are difficult to achieve but not impossible, and leave several magnitudes of power to account for nonidealities or engineering tradeoffs.

References

[1] Song, P., Gogineni, S., Galkin, I. A., Volakis, J., Soderblom, J. M., Hayes, A. G., et al. (2021). "Feasibility study of a high-resolution shallow surface penetration radar for space application." *Radio Science*, 56, e2020RS007118. **https://doi.org/10.1029/2020RS007118**

[2] *QPD1034*, Qorvo, https://www.qorvo.com/products/p/QPD1034 (accessed Jun. 9, 2025).

[3] J. V. Zyl, Y. Kim, "SAR Imaging Basics," in *Synthetic Aperture Radar Polarimetry*, JPL, Caltech, Pasadena, CA, JPL Space Science and Technology Series, Dec. 2010.

[4] A. W. Doerry, "Performance Limits for Synthetic Aperture Radar," Sandia National Laboratories, Albuquerque, NM, Jan 2001.