PROCEEDINGS OF SCIENCE

Lunar Subsurface Ice Detection with Cosmic Rays

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Evidence of water ice deposits in the Permanently Shadowed Regions (PSRs) on Mercury have engendered investigations for ice in the Moon's PSRs. However, continued radar investigations into the Moon's polar regions lack conclusive evidence for ice in radar backscattering data due to volume scattering and surface roughness. These previous radar experiments have ruled out shallow regions for ice deposits, but not at depths > 5 m. The radio signature produced in ultrahigh energy (UHE) particle showers, known as the Askaryan signal, offers a novel approach to probe deeper than previously achievable in search for buried ice deposits. Due to the linear polarization of the Askaryan signal, the dielectric properties of an ice layer would manifest as a polarity flip relative to direct measurement. The Cosmic Ray Lunar Sounder (CoRaLS) is a proposed lunar orbiter mission that will leverage the polarity flip in the Askaryan pulse upon reflection to determine the existence, location, and ice purity of these deep subsurface ice deposits.

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1. Introduction

The radio pulse emitted from cosmic-ray showers is a detectable channel that has allowed experiments such as ANITA, and in the future PUEO, to discern the cosmic-ray background from potential Ultra-High Energy neutrino events [12, 13]. The discerning feature between cosmic-ray and neutrino events is the flipped polarity that a cosmic-ray signal has after a reflection off the Antarctic ice. This idea could potentially be extended to using cosmic-rays for remote sensing of airless planetary bodies, such as the Moon. Due to the lack of atmosphere, cosmic-rays are able to penetrate beneath the surface before initiating a shower.

The discovery of large deposits of buried ice beneath Mercury's poles [1] has motivated interesting investigations into the existence of similar ice deposits beneath the Moon's poles [7]. However, remote sensing techniques lack a clear coherent backscattering that can be attributed to water [6, 9, 10]. More direct experiments, such as LCROSS, were able to detect water content in the Cabeus crater down to ~6 m depth, currently the deepest depth that has been probed. This water content is expected to be sparsely distributed and amounts to ~8% by weight of the measured material [2].

However, current models for lunar water deposition predict that large-scale Mercury-like deposits of ice exist further down, >10 m [3], as can be seen in Figure 1. Since the previous methods that have been used lack the probing depth needed to reach these large deposits, different techniques worth being investigated. A Ground Penetrating Radar (GPR), such as the one used in the Chang'E missions have shown to be able to reach these depths [4, 8]. Unfortunately, GPR systems are extremely localized with a viewing area ~1 m, requiring a large number of GPR systems to map a larger area.

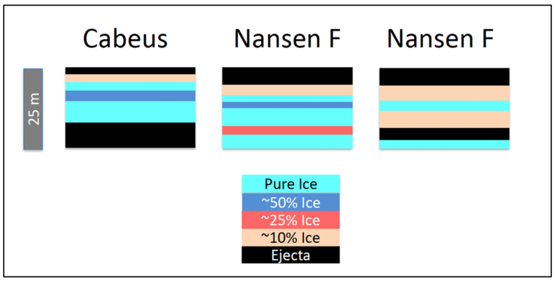


Figure 1: Cartoon of the ice models for the Cabeus and Nansen F craters. The two different Nansen F models are from two different runs of the simulation. Figure modified from [3].

On an airless body, such as the Moon, cosmic-rays ($E > 10^{18}$ eV) initiate showers within the first few meters. The current source produced by these showers can be thought of as a series of radar sources. Due to the isotropy of the cosmic-ray flux, these cosmic-ray radar sources provide an isotropic sampling of the Moon. A passive measurement of these cosmic-ray signals could allow a method for probing the entire lunar surface for ice deposits deeper than previous experiments have been able to achieve.

2. Detection Technique

The anticipated ice deposits on the Moon are predicted to be localized to the polar regions. The Permanently Shadowed Regions (PSRs), which are areas that never receive direct sunlight, providing thermal conditions for ice to exist for geological time-scales, are only located at the poles. Remote sensing of these PSRs has led to inconclusive results, likely due to surface roughness and

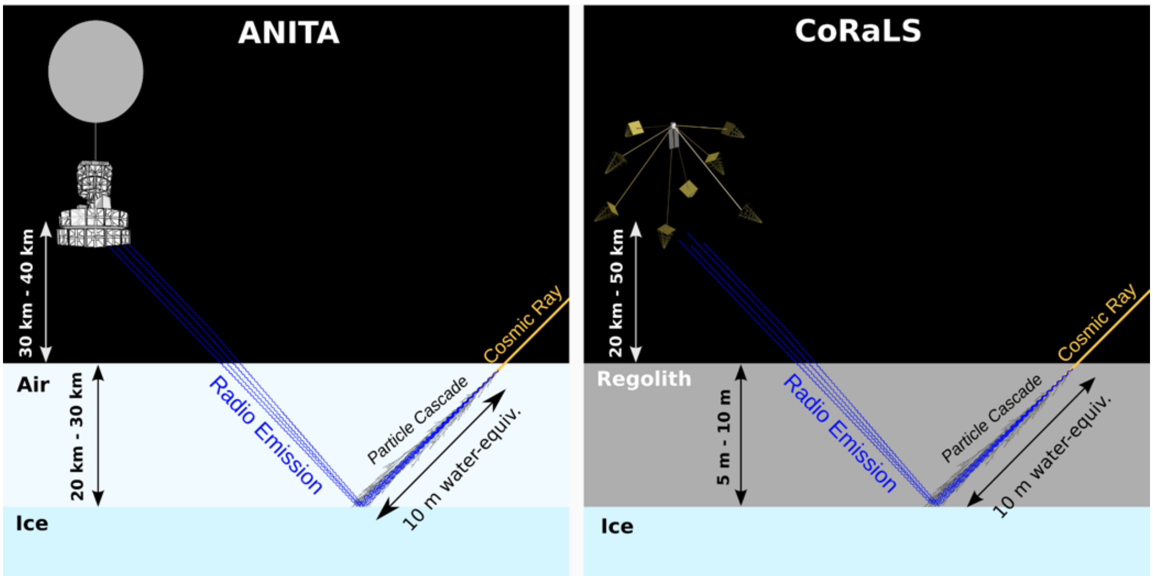


Figure 2: Side by side comparison of the cosmic-ray interactions for an extensive air air shower seen by ANITA (left) and a cosmic-ray shower in lunar regolith seen by CoRaLS (right). For ANITA the cosmic-ray shower travels 10m water-equivalent grammage over 10's of kilometers. Scaling by Lunar density, a cosmic-ray passes through the same grammage in 5-10 m

volume scattering [6, 7]. GPR has proven to be an efficient method for mapping beneath the lunar surface [4, 8], but inefficient for mapping large areas of the Moon. Cosmic-ray induced showers in the Moon's regolith can be viewed as a current source for a bistatic radar system. Due to the relative isotropy of cosmic-rays, these current sources would occur over the entire lunar surface at equal rates, allowing cosmic rays to be a natural radio source that can be exploited as a passive signal.

The radio pulse that is emitted from the Askaryan effect is a linearly polarized pulse that can propagate tens of meters in the regolith. If the pulse reflects off an ice layer, the reflected pulse will receive an inverted polarity. This polarity inversion would allow for an instrument to distinguish between reflections from ice and those from bedrock. This idea is analogous to how ANITA distinguished between neutrino signals and cosmic-rays that reflected off the Antarctic ice. Figure 2 shows how the cosmic-ray interaction in the Moon compares to an extensive air shower that would be seen by ANITA. For extensive air showers, the shower develops over the course of 10's of kilometers, amounting to roughly 10 m of water equivalent grammage. In the lunar regolith, a cosmic ray passes through roughly the same amount of material in the first $\sim$ 5 m. Data from 70 cm radar has set limits on contiguous ice deposits within the first 5 m [10]. Based on these limits and current models that predict substantial ice layers begin $\sim$ 10 m down [3], cosmic ray showers in the Moon will be able to develop prior to reaching these ice layers, leaving only the most extreme cases where a shower may develop through an ice layer, making it more difficult to detect.

Figure 3 shows 16 cosmic-ray events from ANITA. On the right shows the direct and reflected signals. The two direct signals were found to be above the horizon while all the reflected signals came from the Antarctic ice [5]. This also means detection of these signal can be used to point back to where it came from. Therefore an ANITA-like set-up could view the lunar surface. If an inverted pulse were received, it could be determined if its direction points back to a PSR, where ice

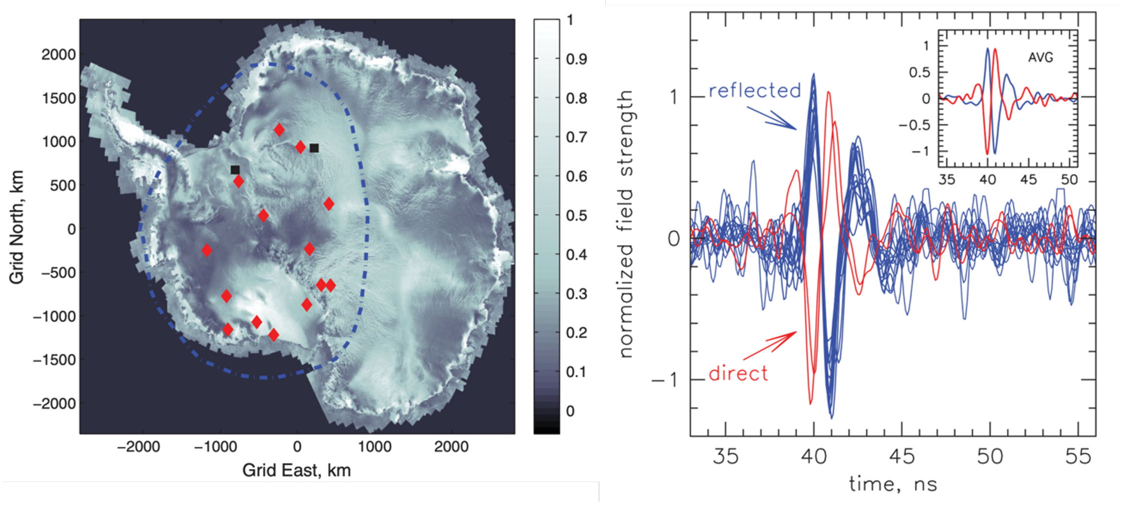


Figure 3: Direct and Reflected Cosmic Ray events Figure from [5]

is expected to exist.

3. Simulation Results

To model signal propagation we used an Finite-Difference Time-Domain (FDTD) simulation using a cosmic-ray shower-like current source to generate the radio pulse, this can be seen in Figure 4. In both cases it can be seen in the first panel the formation of the Cherenkov cone. The cosmic-ray shower develops over a few meters. In the second and third top panels the reflection off the ice layer can be clearly seen. The two reflected pulses are the reflections from the top and the bottom of the ice layer. A small direct pulse can be seen, the small magnitude of the direct pulse is due to the geometry of the cosmic-ray event; where the top of the Cherenkov cone experiences total internal reflection (TIR) when leaving the regolith. In the case of no ice, the signal will propagate down and reflect off the bedrock layer.

Figure 5 shows the waveforms of the FDTD simulations when they are propagated out to 25 km above the lunar surface. A 50 cm thick ice-regolith mixed layer what placed 6m below the surface, followed by a bedrock layer 12m below the surface. At 25 km altitude the strong reflections seen in Figure 4 can be seen, with opposite polarity coming from the regolith-ice interface being an inversion boundary. The time difference between these reflections can be used for estimating the thickness of the ice. The ice-purity of the layer is shown for a 100% pure, 74%, 47%, and 21% ice, the rest being a regolith. For all these cases the reflected signals are above the thermal noise implying if there exists strata that has 20% ice content or higher, this technique would be sensitive to those ice layers. If gigaton deposits of near pure ice exist, as lunar ice models predict [3], this technique would certainly be sensitive to these ice deposits.

4. Event Rates

The Cosmic Ray Lunar Sounder (CoRaLS) is a proposed ANITA-like payload that could fly on a lunar orbiter and would passively detect these cosmic-ray signals. The instrument would comprise

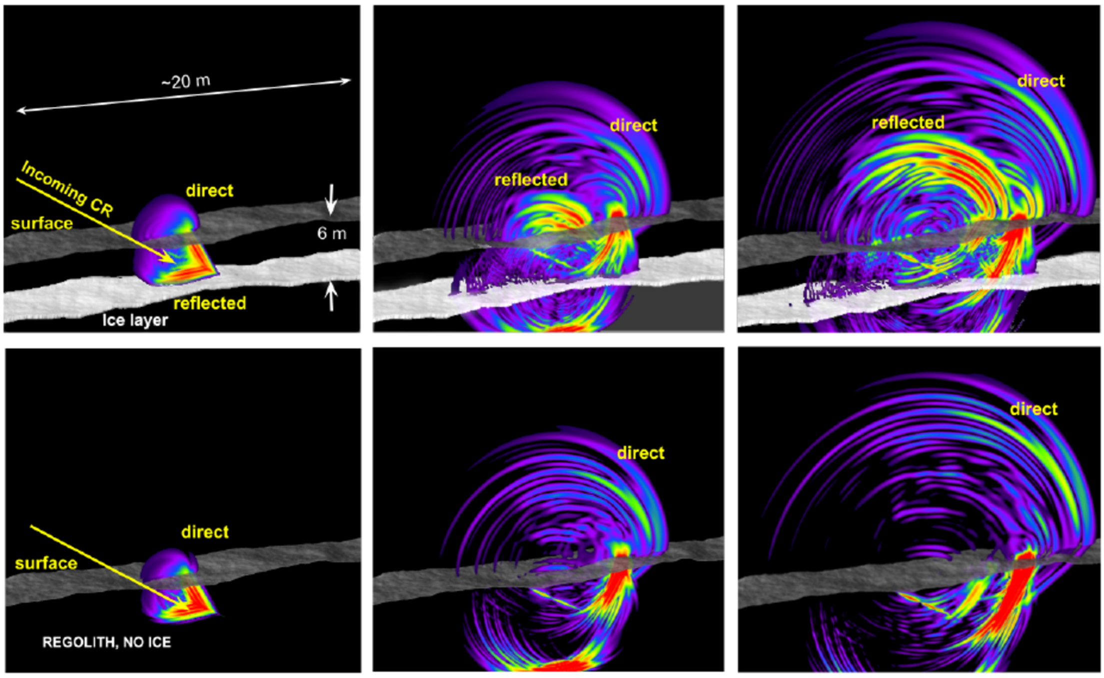


Figure 4: FDTD simulation of a cosmic-ray signal in the lunar regolith. The top three panels show different times of the same simulation where an ice layer was placed 6m below the surface. The bottom three panels show the same situation if no ice is present.

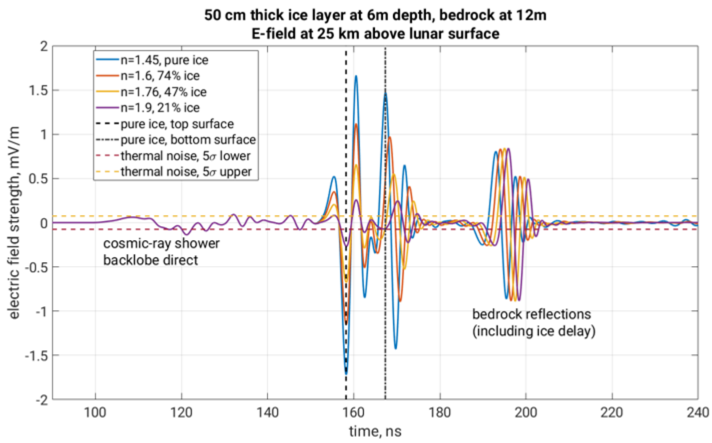
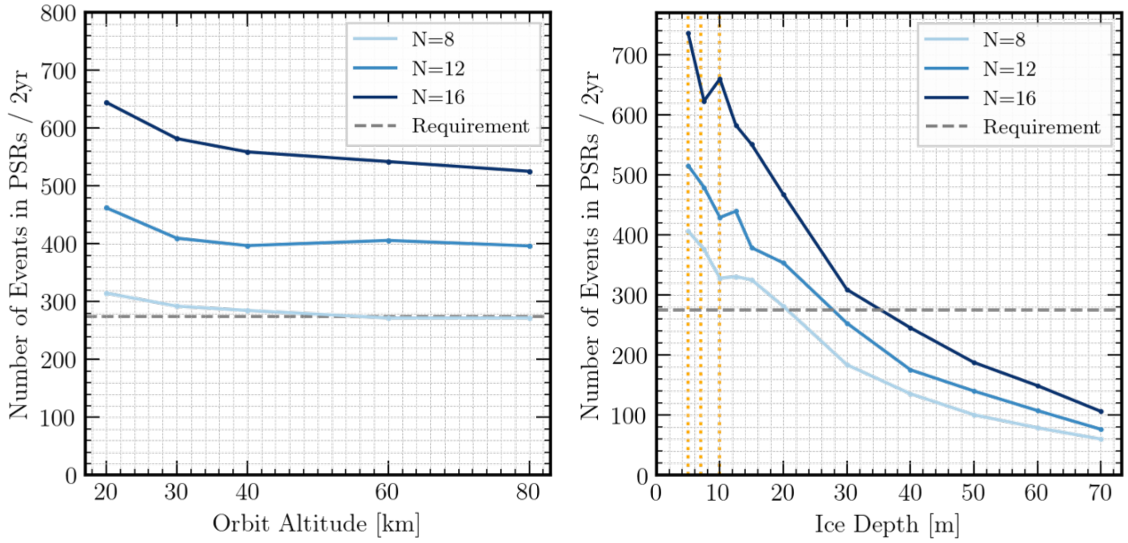


Figure 5: Waveforms seen at a payload 25 km above the lunar surface. Simulations done for different ice purity.

of an array of wide band antennas (150 - 800 MHz) with a trigger threshold of SNR ≥ 4. As an orbiter, the majority of the time the PSRs would not be in view. However, CoRaLS would still expect to detect ~ 100,000 cosmic-ray events in the lunar mare during a 2-year mission. The PSRs are $\sim 29,000$ km^2 distributed within 10° of the poles. The fraction of observed cosmic-rays that are PSR events decreases with altitude, as can be seen in Figure 6a. With a low lunar orbit, CoRaLS would expect to see ~ 275 PSR events with a minimum of 8 antennas. Detecting 275 PSR events gives a 95% confidence that at least one event is from the PSR probed by LCROSS, where trace



(a) Expected PSR event rate for CoRaLS as a function of flight altitude for three different numbers of antennas.

(b) Expected PSR event rate for CoRaLS as a function of ice depth for three different numbers of antennas.

Figure 6: Event rate plots in the Permanently Shadowed Regions over 2-years. Figures from [11].

amounts of water had been discovered in the first few meters. With this many PSR events we would be able to either confirm or deny the existence of ice in the PSRs in the first few meters. However, the depth of an ice layer also impacts the number of PSR events we can expect.

The event rates for different depths of ice can be seen in Figure 6b. With the requirement of 275 PSR events, this limits CoRaLS probing depth to ~ 20 m with an 8 antenna configuration. Since the depth of an ice layer corresponds to its age, it can be seen that there is a slight dependence on the age of an ice layer down to 10 m. This is likely due to ice shallower than 10m are more likely to have the shower develop through the ice layer, making it difficult to detect.

5. Conclusions

The existence of ice in the Moon's PSRs is an interesting open science question. The lack of coherent evidence has been mainly attributed to surface and volume scattering effects [6, 7]. GPR systems have proven to be an efficient method of mapping the lunar subsurface but are restricted in their field of view. However, cosmic-ray showers develop over the first few meters of the regolith and produce a radio pulse via the Askaryan effect all over the moon. Detection of these signals would allow an instrument to map the entire lunar surface. The ANITA experiment was able to use the polarity of the radio pulse to determine cosmic-rays that reflected off the Antarctic ice. Similarly, in the presence of ice, the radio pulse in lunar regolith will receive an inverted polarity allowing a clear mark that cosmic-ray reflected off an ice layer. Using an ANITA-like configuration of an array of wide band antennas, the CoRaLS instrument could detect ~ 275 PSR events in a 2-year mission, down to depths of 20 m. Allowing CoRaLS to begin probing the parameter space where ice models predict large ice deposits to exist [3]. Over the course of a 2-year mission, CoRaLS would likely be able to confirm or deny the existence of substantial ice deposits in the first 20 m in the lunar PSRs.

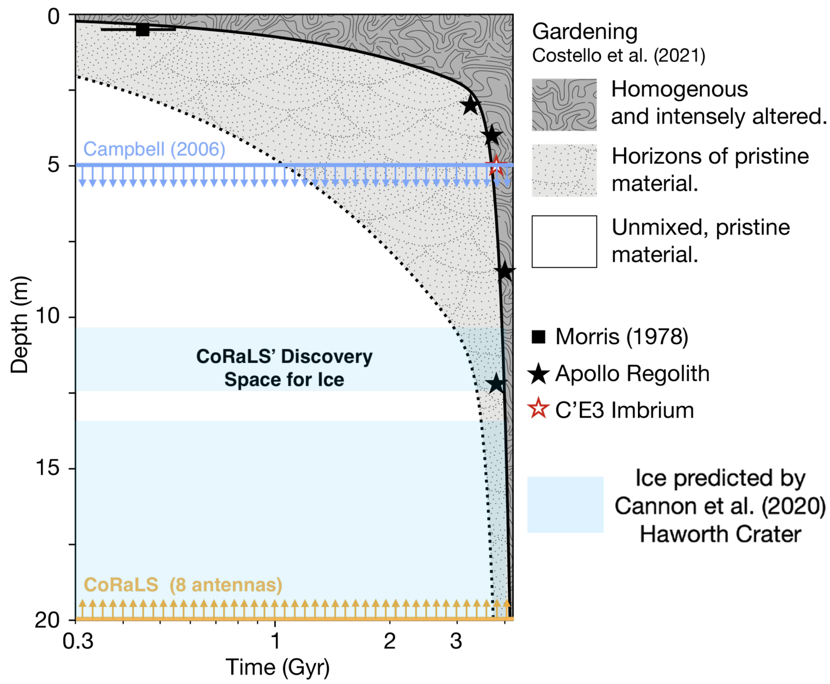


Figure 7: CoRaLS potential ice discovery space compared to the leading probing depth of 5m.

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