Miniature Ground Penetrating Radar, CRUX GPR

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Abstract— Under NASA instrument development programs (PIDDP 2000-2002, MIDP 2003-2005, ESR&T, 2005), we have been developing miniature ground penetrating radars (GPR) for use in mapping subsurface stratigraphy from planetary rovers for Mars and lunar applications. The Mars GPR is for deeper penetration (up to 50 m depth) into the Martian subsurface at moderate resolution (0.5 m) for a geological characterization. As a part of the CRUX (Construction & Resource Utilization Explorer) instrument suite, the CRUX GPR is optimized for a lunar prospecting application. It will have shallower penetration (5 m depth) with higher resolution (10 cm) for construction operations including ISRU (in-situ resource utilization). The GPR is a short-pulse type system, which responds to interfaces between materials of differing dielectric permittivity.

Currently, the CRUX GPR (Technology Readiness Level 4) has miniaturized radar electronics (2 boards, 10 cm x 5 cm x 2 cm, 1W power, total 45g), with 2 batteries (9 V, 2 x 45 g) operating at 800 MHz center frequency. Field testing of the prototype has been conducted extensively. When deployed for lunar missions, the CRUX GPR data will help prospecting possible construction sites.

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1. INTRODUCTION

The success of future human missions will depend critically on the ability to identify optimal sites to conduct lunar and planetary surface operations (LPSO). As any terrestrial applications, subsurface stratigraphic information is vital for the evaluation of construction sites, in situ resource utilization (ISRU), and environmental management. CRUX GPR will certainly contribute for the purpose. Under NASA instrument programs (PIDDP 2000-2002, MIDP 2003-2005), we have been developing miniature ground penetrating radars (GPR) for use in mapping subsurface stratigraphy from planetary rovers for Mars applications. The Mars GPR is for deeper penetration (80 MHz center frequency) up to 50 m depth, into the Martian subsurface at moderate resolution (0.5 m) for a geological characterization. Under the CRUX task, we have been working on optimization of the GPR for a shallower lunar application; the center frequency has been adjusted for 800 MHz with smaller antennas (20 cm – 1m dimensions) to give a finer resolution of 10 cm, and a penetration depth of 5 m.

When deployed for lunar applications, the CRUX GPR data will help establish the extent to which drilling results may be extrapolated (i.e.; the homogeneity represented by a single bore hole log), and to prospect for other possible construction sites. Results from the drilling and other probes on board the CRUX instrument suite will help interpret the GPR data, such as reflection horizons, and in turn, provide interpolations of their results between drilling sites. Once characterized through drilling as ground truth, the GPR data will give the extent of subsurface homogeneity along the same stratigraphy, and guide the next drilling sites in search for different subsurface sampling.

For GPR, possible causes of stratigraphy are ice layers, regolith/bedrock interfaces and contrasts in sediment porosity (high porosity for uniform grain size; low porosity for varied grain size) and mineralogy (feldspars vs. mafic minerals). The first analytic procedure will be to utilize the drilling and ground probe results to estimate permittivity and thus to establish a calibration between echo time of return and depth. The second will be to establish the relative dielectric contrasts from the phase structure of the reflected wavelets. We will then use this information to interpret stratigraphic dips, thicknesses and layer homogeneities in order to determine the competency of a potential construction site.

2. CRUX GPR INSTRUMENTATION

As a part of the CRUX instrument suite, the CRUX GPR is a short-pulse type system, which responds to interfaces between materials of differing dielectric permittivity. The operation of GPR is simple, RF pulses are radiated into the ground through a transmit antenna and the RF reflections back from the stratigraphic interfaces are detected through a receive antenna, amplified and compiled as signal.s.

We have designed, fabricated and field tested the first version of CRUX GPR (800 MHz). A block diagram and fabricated CRUX GPR electronics board is shown in Fig. 1. As shown in the figure, the GPR protoype (Technology Readiness Level 4) has miniaturized radar electronics (2 boards, 10 cm x 5 cm x 2 cm, 1W power, total 45g), with 2 batteries (9 V, 2 x 45 g) and two resistively loaded dipole antennas (Tx and Rx, each at 1m length) or two RC-loaded Bowtie antennas (Tx and Rx, each @ 28 cm x 40 cm), operating at 800 MHz center frequency. Field testing of the prototype has been conducted extensively.

The GPR block diagram (Fig. 1) shows a simplified representation of the basic functional blocks which provide for transmission, receive amplification, and "box-car" mode of sampling. The impulse GPR system transmits an 1.25 nsec monocycle pulse from the transmit antenna (Tx) at 250 kHz and receives through a separate receiving antenna (Rx) the echo signals which are reflected from dielectric boundaries in the ground. The signal received by the Rx antenna is amplified by roughly 100dB prior to being sampled. The Rx amplifier used is capable of 1GHz bandwidth (three-stage ERA-3SM amplifier). Between Tx and Rx boards, ferrite beads are placed on the connecting coaxial cable to create good isolation and minimized cross talking between the modules.

Sampling of the received echo waveform is achieved by means of a sample-and-hold that is triggered by a programmable silicon delay line (DS1023) under microprocessor control. By triggering the sample-and-hold after 1 nsec., 2 nsec., 3 nsec., ... 119 nsec., 120 nsec., the microprocessor can capture the full receive waveform (Fig. 1, bottom). At each delay interval, the sample-and-hold captures and averages roughly 2500 echoes onto a capacitor. In parallel with that process, the microprocessor samples the voltage on the hold capacitor using a 10-bit A to D converter. Sampling that voltage 64 times yields an equivalent of 16 bit sampling resolution. Through an optical fiber, the digital data are transmitted and stored on a lap-top PC.

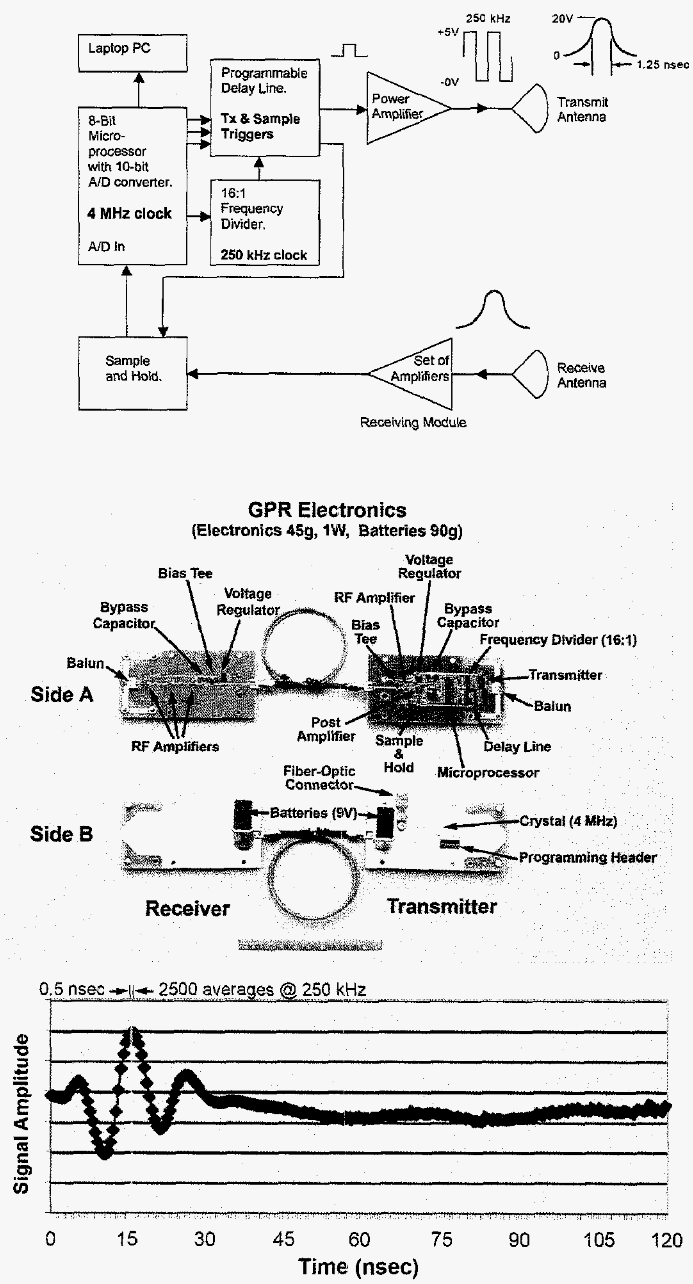

Figure 1 -Top, CRUX GPR Block diagram; middle, CRUX GPR Electronics board; bottom, "box-car" sampling mode.

3. CRUX GPR FIELD TESTING

The CRUX GPR prototype was field tested at 3 representative sites; (a) Quester gas pipeline site in Indio, CA. (b) Dumont Dunes, CA and (c) Hawaii Volcano's National Park, Hawaii. Comparisons to known subsurface structures for the test sites demonstrate that the system is capable of resolving fine-scale subsurface stratigraphy. In the field testing, two sets of antennas were used with the GPR electronics namely, resistively loaded dipole antennas and RC loaded bowtie antennas [1]. Both sets of antennas

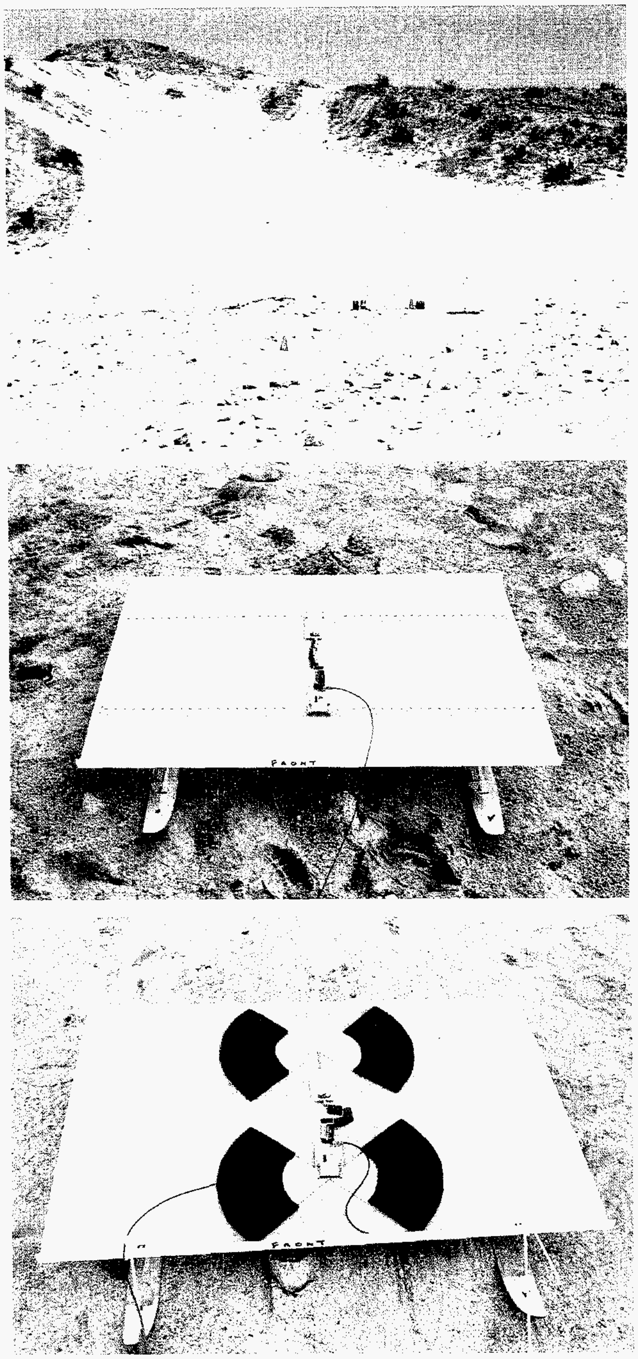

Figure 2 - Top, Indio CA field test site; middle and bottom; antennas (Tx and Rx) mounted on a sled used for the field testing. Middle, resistively loaded dipole antennas; bottom, RC loaded bowtie antennas [1].

gave pretty comparable GPR traces, with resistively loaded antennas slightly better performance. The bowtie antenna was impedance matched as described in Lestari et al [1], to reduce ringing and at the same time to increase efficiency. As shown in Figure 2, the antenna sled (66 cm x 98 cm) is mounted on a pair of cross-country skis (non-metal), traversed by a manual pull through a rope.

Initial testing of all our GPRs were done at the Quester gas pipeline site, since the two steel pipes are well known targets (1 m depth, 76 cm diameter, separated by 11.5 m between the two pipes). In Figure 3, the GPR traces show the metal pipes as two eyebrows.

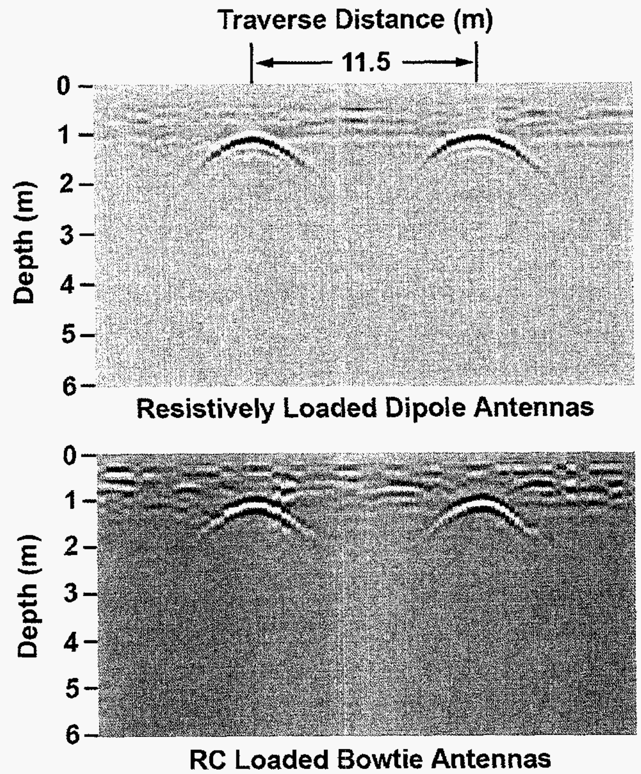

Figure 3 - Example of CRUX GPR data with two different antennas, at the Quester gas pipeline site in Indio, CA.

The CRUX GPR was tested at Dumont Dunes, CA. It is called "little Sahara" of California, located 50 km north of Baker, CA. It is established by wind blown sand deposited on an alluvial plain (basement) [2]. The sand dunes offer homogeneous media with little RF scattering, and ideal for GPR testing. As shown in Fig. 4, the GPR trace was obtained by traversing 130 m along the edge of the dune (from M to N). It shows the sand depth as the height above the basement. Our GPR data were recorded up to 60 nsec one-way trip, corresponding to 11.5 m at the dielectric constant of 2.55, a typical value for dry sand [3]. The original GPR data (Fig. 4 bottom) was manipulated to match the contour of the dune. The modified GPR traces show the flat basement at the bottom (Fig. 4, middle).

The GPR was also tested along the Kilauea Southwest Rift, in Hawaii Volcano's National Park [4]. This site is ideal due to the exposed layers that can be compared with stratigraphy obtained by GPR. Overall, GPR variations in unit thicknesses and contours are confirmed by exposed rift stratigraphy. The following are geological interpretation of the local area by our colleague, Steven Chemtob [5].

The material making up the layers at the Southwest Split is

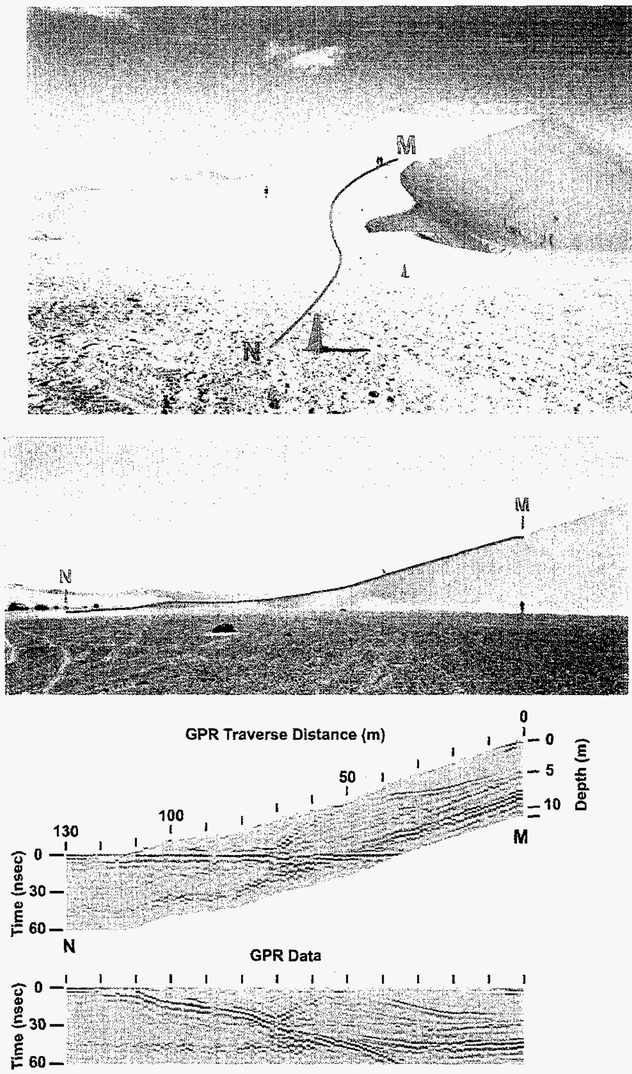

Figure 4 – Top, Dumont Dunes, CA (about 50 km north of Baker, CA), GPR field test site. The GPR was traversed from M to N, along the edge of the dune. Middle, GPR traverse showing the contour of the dune, bottom GPR data manipulated to match the contour of the dune, and the original GPR data. Notice the alignment of basement of the dune in the GPR trace as the original data are graphically adjusted to match the contour of the dune. The GPR trace shown is from resistively loaded dipole antennas.

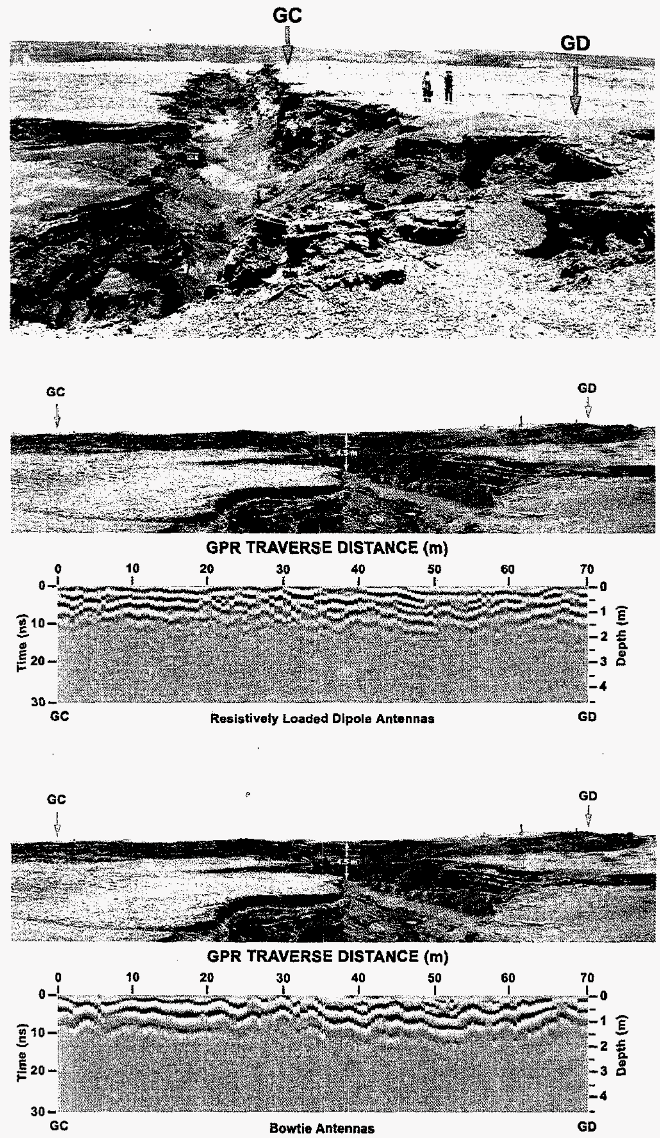

Figure 5 - Kilauea Southwest Rift, Hawaii. Top, GPR traverse was made along the rift, from GD to GC. Middle GPR Trace with resistively loaded dipole antennas, and bottom, with bowtie antennas. GPR traces show variations in unit thicknesses and contours that can be confirmed by exposed rift stratigraphy along the rift. The depth was calculated with dielectric constant, $\varepsilon' = 4$.

ash derived from numerous eruptions of Halema'uma'u. The mineralogy of the ash is characteristically basaltic, including pyroxene, plagioclase, olivine, magnetite, and hematite. The material is indurated by hydrated opaline silica, which has the appearance of a white coating. Human-modified landscapes in the region with silica cementations indicate that the cementations form over the time scale of decades. The ash particles are angular and poorly sorted, ranging in size from very fine to coarse, with frequent cobble-sized ejecta.

As shown in Figure 6, the upper 4.5 m exposed in the rift zone are comprised of four main units. The lower ~1 m of the exposed section constitutes laminated deposits of fine-grained light-colored ash (A). These laminae have been lightly indurated by silica. The next ~1.75 m of the exposed section constitutes thinly bedded fine ash deposits with heavy opaline silica cementation (B). Ash beds in this unit range in thickness from 5-25 cm. The heavy silica cementation has given this unit a massive appearance and made it especially resistant. The next unit is ~1.75 m thick

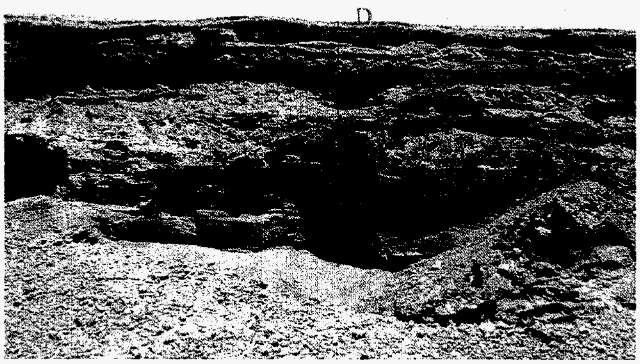

Figure 6 – Geological layers of the Kilauea Southwest Rift, where GPR data were obtained, in Hawaii Volcano's National Park.

and consists of thinly bedded ash deposits with some beds of larger cobbles (C). Bed thicknesses range from 5-25 cm. There are some cut-and-fill features present in the bedding. Some units are heavily cemented by opaline silica, but overall cementation is less strong than in the previous unit. The upper ~20 cm constitute a desert pavement (D). The surface is dominated by cobble-sized rocks of basaltic composition, with fine ash and aeolian dust trapped underneath. The pavement has been cemented by silica deposits. Our GPR data is penetrating up to 1.7 m depth, and that includes layers D and C in Figure 5.

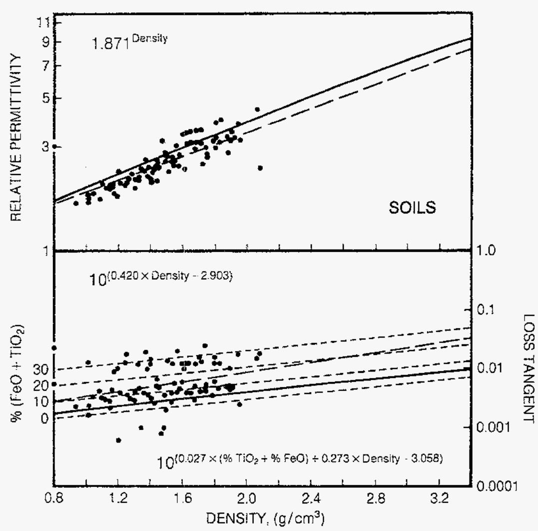

Figure 7 – Relative dielectric permittivity (ε') and loss tangent (tan δ) for lunar soils as a function of bulk density and % (TiO_2 + FeO), adapted from Heiken et al. [6]. Blue shades indicate the 3 density values used in Table 2.

4. Lunar Application of GPR

Dielectric properties of lunar materials are available from Appollo missions [6]. The properties of lunar materials are shown in Figure 7 as a function of density. In order to compare the GPR characteristics expected for lunar applications, the dielectric properties including attenuation of RF are summarized in Table 2. It shows that compared with soil on Earth, the dielectric characteristics of lunar materials are favorable for deeper penetration.

Table 2. Dielectric Properties #

		ε'	tan δ	dB/m @ 800 MHz
Moon [6]	ρ = 1.0	1.843	0.0032	0.31
	ρ = 1.5	2.502	0.0041	0.48
	ρ = 2.0	3.397	0.0054	0.72
Earth [3]	Sandy Soil Dry	2.55	0.0093	1.08
	Loamy Soil, Dry	2.46	0.0055	0.63
	Clay Soil, Dry	2.36	0.019	2.12
	Magnetite Soil, dry	ε'	tan δ	dB/m @800 MHz
		3.50	0.019	8.17
		μ'	tan δ_m	
		1.07	0.039	

For the moon data, the values of ε' and tan δ at 450 MHz were used for 800 MHz calculation, since 800 MHz values are not available. The values of tan δ are from 10% (TiO_2 + FeO). For Earth, the values of ε' and tan δ at 800 MHz were interpolated from available data [3].

5. Conclusions

We have developed a miniature GPR that has been extensively field tested. As a part of CRUX instrument suite, the GPR will contribute crucial subsurface stratigraphic information for the CRUX project.

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BIOGRAPHY

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