Measurements of radio propagation in rock salt for the detection of high-energy neutrinos

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Abstract

We present measurements of the transmission of radio/microwave pulses through salt in the Cote Blanche salt mine operated by the North American Salt Company in St. Mary Parish, Louisiana. These results are from data taken in the southwestern region of the 1500 ft. (457 m) deep level of the mine on our third and most recent visit to the mine. We transmitted and received a fast, high-power, broadband pulse from within three vertical boreholes that were drilled to depths of 100 ft. (30 m) and 200 ft. below the 1500 ft. level using three different pairs of dipole antennas whose bandwidths span 125 to 900 MHz. By measuring the relative strength of the received pulses between boreholes with separations of 50 m and 169 m, we deduce the attenuation of the signal attributed to the salt medium. We fit the frequency dependence of the attenuation to a power law and find the best fit field attenuation lengths to be $93 \pm 7$ m at 150 MHz, $63 \pm 3$ m at 300 MHz, and $36 \pm 2$ m at 800 MHz. This is the most precise measurement of radio attenuation in a natural salt formation to date. We assess the implications of this measurement for a future neutrino detector in salt.

Key words: salt, radio, microwave, transmission, attenuation, neutrino
PACS: 42.25.Bs, 91.55.De, 93.85.Fg, 95.85.Ry

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1 Introduction

The observation of cosmic rays with energy higher than the Greisen-Zatsepin-Kuzmin (GZK) cutoff at $\sim 10^{19.5}$ eV [1] implies a corresponding flux of ultra-high-energy (UHE) neutrinos, with energy in the $10^{17} - 10^{19}$ eV range [2]. These secondary neutrinos are created via photomeson production of cosmic rays on the 2.7 K cosmic microwave background. Detection of these neutrinos would provide unique information about the origin of primary cosmic rays and the nature of their sources.

Although predictions for the flux of UHE neutrinos differ by orders of magnitude, a reasonable set of parameters puts the rate of UHE neutrinos at the level of $10/km^2/\text{century}$ [2]. A detector volume of hundreds of cubic kilometers water equivalent is required to detect a significant number of neutrinos in this energy regime. Optical techniques are widely used in neutrino detectors, but the volume that can be instrumented is constrained by attenuation lengths of tens of meters at optical frequencies in detector media (such as ice), so optical detectors have limited sensitivity to rare high-energy events.

G. Askaryan first predicted coherent radio emission from ultra high-energy showers [4], and the effect has been confirmed in accelerator beam tests [5]. The energy of the coherent radio emission that results from the development of a negative charge excess in the shower depends quadratically on shower energy, and for showers with energy greater than $10^{16}$ eV, dominates the emitted
Cherenkov power spectrum.

Askaryan also proposed a few materials as detection media that occur naturally in very large volumes and are expected to have long attenuation lengths in the radio regime, including ice and salt. Radio attenuation lengths longer than 1 km have been measured in ice near the South Pole [3].

Formations of salt rock could therefore be a viable detector for high-energy neutrinos if attenuation in the radio regime is indeed low. Domes of rock salt occur naturally in many parts of the world, including the Gulf Coast region of the United States. In these formations, the salt originates from dried ocean beds which have been buoyed upward due to geological forces through a process called diapirism. Through this process, the salt becomes very pure as impurities are extruded. Such salt domes, with typical dimensions of several square kilometers by several kilometers deep, are thought to be good candidates for a neutrino detector. For a more detailed discussion of the dielectric properties of salt and the application to neutrino detection, see Reference [6].

2 Previous Measurements

There are two classifications of measurements that have been made of the radio properties of rock salt in salt domes. Ground Penetrating Radar (GPR) was used in the 1960’s and 1970’s to determine the size and structure of salt domes. This technique is based on sending a radar signal into the salt and
looking for reflections from interfaces in the salt structure. One can calculate the distance of the interface from the time delay of the reflected pulse. Although the primary purpose of the GPR measurements is to calculate interface distances, one can also extract an attenuation coefficient based on the detected signal voltage, the voltage of the transmitted pulse, and the distance over which the pulse traveled. Using the GPR technique to extract attenuation is complicated by the unknown reflection coefficient and geometry at the surface of reflection, but assuming a coefficient of 1.0 from a flat surface gives a conservative estimate.

Direct measurements of attenuation in rock salt have also been made. In 2002, measurements made at Hockley salt mine showed attenuation lengths consistent with being longer than 40 m at 150 and 300 MHz [6]. Their measurements were limited by the voltage of the pulser, which limited their transmission distances in the salt. We decided to follow the techniques of the direct transmission measurements but used a high voltage pulser so that we could transmit through longer distances of salt.

3 Cote Blanche Salt Mine

We made measurements of the dielectric properties of salt in the mine located in the Cote Blanche salt dome in St. Mary Parish, Louisiana in August 2007. We chose this dome because GPR measurements that were made in the mine
suggested very low radio attenuation, including observations of reflections over
the longest distance of any mine measured [7].

The Cote Blanche dome is one of five salt domes in the area. The salt dome
extends from approximately 90 m below the surface to 4270 m below the
surface. At a depth of 1100 ft. (335 m), the salt extends 1700 m east to west
and 2100 m north to south. At 2000 ft. (610 m) deep, the horizontal cross
section has nearly doubled in size. The total volume of salt in the dome is
estimated to be 28-30 km$^3$ [8,9,10,11].

The dome has been actively mined since 1965 using the conventional “room
and pillar” method. The mine consists of a grid of 30 ft. (9 m) wide by
30 ft. (9 m) high drifts (corridors) spaced by 100 ft. by 100 ft. (30 m by
30 m) pillars of salt, and has three levels at depths of 1100 ft., 1300 ft., and
1500 ft. (335 m, 396 m, and 457 m). Each level covers several square kilometers.
Current mining operations are on the 1500 ft. deep level.

The measurements described in this paper are from the third trip that we
made to the Cote Blanche mine. In May 2005, on our first visit to the site,
with M. Cherry and J. Marsh from Louisiana State University, we established
the viability of the experimental setup and measured field attenuation lengths
along a corridor (within 10 meters of a wall) on the 1300 ft. level of the mine,
of approximately 10-15 m at 150 MHz and 300 MHz [12]. In September 2006,
on a return visit to the mine, we transmitted and received signals horizontally
across a single pillar of salt, both with antennas placed against the walls and with antennas inserted 4 m into the ceiling in shallow boreholes. We measured attenuation lengths of 24.6 ± 2.2 m in the frequency range 50-150 MHz, 22.2 ± 1.8 m at 150-250 MHz, and 20.5 ± 1.5 m at 250-350 MHz. We also measured an average index of refraction of \( n = 2.4 \pm 0.1 \) \[13\].

The attenuation lengths that we measured were inconsistent with previous GPR studies of the Cote Blanche mine (see Section 7). The relatively short attenuation lengths that we measured through the walls of the pillar could be due to the method used to mine the salt. The miners carve out corridors in the salt by cutting a horizontal slice out from under the wall and then blasting the section above the floor so that the salt can be removed, and then proceed to a new section of salt further along the corridor. The data from our first two trips were consistent with a model of very lossy salt (approximately 10 m attenuation length) in the region closest to the walls of the pillar and longer attenuation lengths (quoted above) in salt more than about 10 m from the wall.
4 Method

4.1 Experimental Setup

Figure 1 shows the region of the 1500 ft. deep level of the mine where we made our measurements, and Figure 2 is a diagram of the experimental setup. The miners drilled three 2.75 inch (7.0 cm) diameter boreholes into the salt of the floor of the 1500 ft. level of the mine. Boreholes 1 and 2 were 100 ft. (30 m) deep, while Borehole 3 was 200 ft. (60 m) deep. At the first two boreholes, drilling was stopped at 100 ft. once the driller encountered methane gas. We used a fast, high-power, broadband Pockel’s cell pulser model HYPS from Grand Applied Physics with a peak voltage of 2500 kV and a 10%-90% rise time of 200 ps to generate radio pulses. There was 5 ft. of LMR 240 cable and 200 ft. of LMR 600 cable leading to the transmitting as well as from the receiving antennas, and the antennas were lowered by hand into the salt.

We made most of our measurements using three pairs of dipole antennas. We measured the 3 dB points of each antenna when they were in a borehole in the salt to determine the in-band frequencies. The 3 dB points of the transmission of the low frequency (LF) antenna pair (Raven Research RR6335), are 50 to 175 MHz in salt. For the medium frequency (MF) antennas, which we custom made, the 3 dB points are 175 and 500 MHz in salt. The high frequency (HF) pair (Shure Incorporated UA820A) has a transmission band
between 550 and 900 MHz in salt.

We used a Tektronix TDS694C oscilloscope to record the received signal pulse.

We used a pulser with synchronized outputs to trigger both the high-power pulser and the oscilloscope. This allowed us to look in a fixed time window for the signal and reduce noise by averaging many waveforms.

The transmitting antenna was always lowered into Borehole 1, and the identical receiving antenna was either in Borehole 2, which was 50 m away from the transmitter, or Borehole 3, which was 169 m away from the transmitter. We took data at 10 ft. (3 m) incremental depths in the boreholes. The setup used to measure transmission between Boreholes 1 and 2 was identical to the setup used to measure between Boreholes 1 and 3 so that we could make reliable relative measurements without requiring an absolute system calibration. Because the transmission band of each antenna was relatively broad, we were able to make measurements between 125 and 900 MHz in salt.

4.2 Attenuation Lengths

Figure 3 shows an example waveform of the received pulse at Borehole 2 and Borehole 3 using the MF antennas, and Figure 4 shows the Fourier transform of the same waveforms. To calculate the attenuation length, we first cut the recorded waveforms in a time window around the pulse to eliminate any reflections and reduce contributions from noise. The width of the window is
Fig. 1.

Fig. 2.
Fig. 3.

35 ns for the LF antennas, 30 ns for the MF antennas, and 12 ns for the HF antennas.

We expect to record reflections from interfaces within the salt and from the salt-air boundary. We were able to see reflections from the 1500 ft. corridor with the receiver at either borehole. The time window that we use for the analysis extends no more than 20 ns after the peak of the pulse to ensure that we eliminate the possibility of interference from any reflection off of the corridor for depths of 50 ft. and deeper.

We sum the total power in frequency bands that are 50 MHz wide for the LF and MF antennas, and 100 MHz wide for the HF antennas which had a larger bandwidth. We subtract the noise contributions in each band. The noise power
is taken from a sample waveform for each antenna type in a time window of the
same length as the pulse window but earlier in time than any pulse appears.
The noise subtraction had a small effect on the calculated attenuation length
because the signal to noise ratio was high in the band of the antenna.

We define voltages $V_{12}^i$ and $V_{13}^i$ to be the square root of the power in the $i^{th}$
frequency bin between Boreholes 1 and 2 and Boreholes 1 and 3 which span
distances $d_{12}$ and $d_{13}$ respectively. Since we used the same system regardless
of the location of the receiver, the voltages received in the boreholes from the
transmitter are related by:

$$\frac{V_{13}^i}{V_{12}^i} = \frac{d_{12}}{d_{13}} \cdot \exp \left[- \frac{(d_{13} - d_{12})}{L_i} \right]$$

(1)
where $L^i_\alpha$ is the field attenuation in the $i^{th}$ frequency bin. Inverting this equation gives an expression for the field attenuation length in each frequency bin:

$$L^i_\alpha = \frac{(d_{13} - d_{12})}{\ln \left( \frac{d_{12}V^i_{12}}{d_{13}V^i_{13}} \right)}$$  (2)

5 Uncertainties

The main source of systematic uncertainty on the measurement of the field attenuation length at a given depth is due to the position of the antenna within the hole. In previous trips to Cote Blanche, we discovered that a small variation in position of the antenna led to a significant change in the voltage received through the salt [13]. We estimate the size of this uncertainty as the root mean square variation between neighboring depths of the peak-to-peak voltage of the recorded waveform at each depth (excluding the 10 and 20 ft. depths):

$$\delta V = \frac{1}{N} \sqrt{\sum_{i=0}^{N-1} (V_i - V_{i+1})^2}$$  (3)

where $N$ is the number of depths included here. Using this method, we estimate the uncertainty on the voltage measured due to the position of the antenna in the hole to be 24%.

We also include an uncertainty due to the exact choice of the time window that contains the pulse. We estimate this uncertainty as the root mean square
variation of the total power in the pulse as we slide the time window by 1 ns.

When the power at a given frequency is small, this uncertainty dominates (up to 50% in voltage), but in the frequency band of the antenna, the uncertainty is small (less than 10% in voltage).

There is also an uncertainty on the distance between the holes. We measured the distance between Boreholes 1 and 2 with a measuring tape, and then used relative timing of received pulses to extrapolate the distance between Boreholes 1 and 3. The uncertainty on these distances include a contribution from system timing ($\pm$3 ns), one due to the measurement of the distance between Boreholes 1 and 2 ($\pm$1 ft.), and one due to a depth-dependent potential deviation of the boreholes from vertical ($<\pm$3 ft.). The maximum uncertainty on the distance between the transmitting and receiving antennas is always less than 2.1%.

6 Results

6.1 Antenna Transmission

Using the same pulser that was used for the attenuation measurements, we measured the fraction of power reflected from each antenna while it was in a borehole so that we could deduce the fraction transmitted and frequency dependence. For this S11 measurement, we inserted a coupler (Minicircuits
ZFDC-20-4) between the pulser and antenna and recorded the reflected signal through the coupled port. After measuring the reflection from the open cable (with the setup identical but with only the antenna removed), the ratio of the power in the two pulses is the fraction reflected from the antenna. The transmitted fraction is deduced by taking the sum of the reflected and transmitted power fractions to be unity. Figure 5 shows the transmission of an MF antenna as a function of frequency. The transmission did not change significantly when we changed the depth of the antenna in the hole.

6.2 Attenuation Lengths

Figure 6 shows the attenuation length in the frequency bin centered on 250 MHz as measured with the MF antennas plotted versus depth. We took measure-
ments at 10 and 20 ft. depths, and the values we calculate for the attenuation length at those shallow depths are consistent with attenuation lengths at greater depths; however, we only report the results from 30 ft. and deeper since the deeper measurements are more likely to be of unfractured, clear salt. At 30 and 40 ft., as much as 1/4 of the power in the waveforms received at Borehole 3 may be due to power from a reflected pulse (based on measurements at greater depths) but we still include those points here. We do not observe a depth dependence in attenuation length.

Measured field attenuation length at 50 ft. and 90 ft. depths are shown in Figure 7 as a function of frequency. The LF antennas were not easily lowered beyond 75 ft. depth, so we include data from those antennas at 75 ft. instead
of 90 ft. If the salt had a constant loss tangent, we would expect that the attenuation length would decrease with increasing frequency as $\nu^{-1}$, where $\nu$ is the frequency of the radiation [6]. We fit the points in Figure 7 to a power law of the form:

$$L_\alpha(\nu) = a \cdot \left(\frac{\nu}{1 \text{ GHz}}\right)^b$$

and the best fit values are $a = 32 \pm 2$ m and $b = -0.57 \pm 0.06$, with a $\chi^2$/dof=25.6/36. Although it is clear that the attenuation length is falling with increasing frequency, it does not follow the $\nu^{-1}$ expectation, which hints at a non-constant loss tangent, consistent with measurements at the Hockley mine [6]. In Table I, we list the measured attenuation lengths at a few frequencies of interest based on the best fit values from this fit.

The uncertainties on the distances between the holes is one that would move the measured attenuation length in the same direction at all measurement positions, so we do not include them in the fit. The uncertainties on the distances between the holes are small compared to the remaining uncertainties. If we vary the distances by their uncertainties and refit, the attenuation lengths change at most by $\pm 2\%$.

We have also averaged the attenuation length at each frequency over all depths of 50 ft. and deeper and over all antenna types, and plotted the results in Figure 8. This figure also shows the best fit power law function, with best fit values $a = 31.1 \pm 0.3$ m and $b = -0.68 \pm 0.04$ with a $\chi^2$/dof=13.3/12. For this
plot the uncertainties only include the scatter between measured attenuation
lengths using different antennas and at different depths in the same frequency
bin.

The attenuation lengths that we measured on this trip are significantly longer
than those that we measured on our previous trip to the same mine. The
measurements that we report here were made in boreholes that were drilled
into the floor of the lowest level of the mine, whereas the previous measure-
ments were made with holes drilled into the ceiling and against the walls of
the corridors. Because the method of mining consists of cutting under the salt
and then blasting the wall above the cut, any fractures that occur due to the
process would tend to propagate upward. This means that the salt in the floor
of the lowest level of the mine would tend to be less fractured and probably
exhibit less loss in the radio regime due to scattering.

6.3 Index of Refraction

We also calculate the index of refraction of the salt using the direct trans-
mission measurements that we made. The index of refraction is defined as
\[ n = \sqrt{\epsilon'}, \]
where \( \epsilon' \) is the real part of the dielectric permittivity. We calculate
the speed of transmission through the medium using the distance between
Boreholes 1 and 2 and the time of travel of the signal pulse through the salt.
The time of travel was measured by taking the difference between the time
Fig. 7.

Fig. 8.
that the pulse was generated and the signal was received and subtracting the known system delay.

Figure 9 shows the measured index of refraction at each depth. The index of refraction that we measure is consistent with $n = 2.45$, the index of refraction of rock salt. We estimate an uncertainty of $\pm 3$ ns on the absolute system timing and $\pm 1$ ft. on the distance between the holes. We also include the same uncertainty due to potential deviation of the boreholes from vertical that was described in Section 5 which contributed $< \pm 3$ ft. to the uncertainty.
At nearly every measurement position we observed at least one clear “reflected” signal in addition to the “direct” signal that traveled along the straight line between the transmitting and receiving antennas. Reflected signals can be easily distinguished from direct signals from their time of arrival at the receiver. They allow us to probe distances greater than that between our drilled holes, and to probe different salt regions as well. However, little is known about the loss in power incurred at the reflection, and reflected signals are often transmitted and received by the antennas at oblique angles, where the antenna response is less well understood.

With our antennas in Boreholes 1 and 2, the entirety of the shortest path between the receiver and transmitter was below the corridor where we were working, so we expected to see reflections from that corridor. We did observe signals that were consistent with this interpretation. The measured time differences between the direct and reflected signals while we were transmitting between Boreholes 1 and 2 were within approximately 10 ns of the expected time difference at all depths. These reflected pulses traversed as much as 256 ft. (78 m) of salt, and a discrepancy of 10 ns corresponds to approximately 4 ft. (1.2 m) in salt. With the antennas at the greatest depths, Most of the power in these reflected signal were out of the band of the antenna. We conclude that this power was reflected off of the input of the antenna and radiated from the
feed cable which was acting as a long-wire antenna. In addition, the expected beam pattern of a long-wire antenna is consistent with the angle of emission seen with these reflections.

With our antennas in Boreholes 1 and 3, the specular path of a reflection from the corridor level is not incident on a salt-air boundary, but nevertheless at depths greater than 50 ft. (where the reflections did not interfere with the direct signal) we did observe signals whose timing were consistent with reflections from the corridor level within 10 ns. In addition, with the antennas in Boreholes 1 and 3 we observed signals at all depths 30 ft. and deeper consistent with having reflected from 170 ft. above the corridor where we stood. The 1300 ft. level of the mine is of course nominally 200 ft. above the floor of the corridor. Therefore, we observed signals having traveled through as much as 624 ft. of salt when the MF antennas were 90 ft. and 150 ft. deep.

6.5 Beam pattern in salt

The deep holes provided to us by the Cote Blanche mine presented a unique opportunity to measure the beam pattern of our antennas while completely submerged in salt, although due to the distances involved, we did not probe a broad range of angles. With one MF antenna at 90 ft. depth in Borehole 1, we took data with the second MF antenna in Borehole 2 and at depths of 20 ft., 50 ft., 70 ft. and 90 ft., and in Borehole 3 at depths of 90 ft., 130 ft. and 150 ft.
The waveform at 20 ft. depth contained interference from a reflected signal, so that data was not included in this measurement. The remaining data probed the antenna beam pattern at angles of $-6.2^\circ$, $-4.1^\circ$, $0^\circ$, $7.0^\circ$ and $13.8^\circ$ with respect to the horizontal, defined to be positive when the antenna in Borehole 1 was deeper than the antenna in the other borehole. After correcting for $1/r^2$ power loss as well as salt attenuation loss based on our measured values, we plot the measured power at each position relative to that measured at $0^\circ$ in the same borehole. We use the same uncertainties as described in Section 5. The solid line in the figure is the expected beam pattern for a half-wave dipole in air:

\[
\frac{dP_{\text{Rel}}}{d\Omega} \propto \left[ \cos \left( \frac{\pi}{2} \cdot \frac{\sin \theta}{\cos \theta} \right) \right]^2. \tag{5}
\]

Although our uncertainties are large, we do not see a deviation from the half-wave dipole beam pattern. The data is also not inconsistent with the peak of the transmission being in the horizontal direction.

7 Review of Ground Penetrating Radar Data

Ground Penetrating Radar (GPR) measurements were made in the Cote Blanche mine and other salt mines in the 1970's by Stewart and Unterberger [7,14] to probe discontinuities in the salt and the location of the top of the dome. They used a single frequency waveform generator at 440 MHz, a pair
of high-gain antennas that were pointed into the salt of interest, and an oscilloscope to measure the time delay between the transmitted signal and any received reflections off of discontinuities deep within salt. To calculate the distance of the discontinuities, they used an index of refraction measured via transmission across a pillar of salt (their result implies $n = 2.62$).

They measured the location of the top of the Cote Blanche dome from within the mine by transmitting the signal vertically through the ceiling. Although the paper reports that attenuation of 2-3 dB per 100 ft. is typical for radar in dry salt in general, which would imply field attenuation lengths in the range 90-140 m, at one measurement station they report a multiply-reflected signal that had traveled through a total path length of 4080 ft. (1244 m) and stated
that it was the longest transmission distance observed in any mine. We have compiled information in Table II from the discussion of the specifications of the system used to make the measurements in References [7] and [14].

The power received, $P_{Rx}$, is related to the power transmitted, $P_{Tx}$, by the Friis formula:

$$P_{Rx} = P_{Tx} \frac{G_{Tx} G_{Rx} \lambda^2}{(4\pi r)^2}$$

(6)

where $G_{Tx}$ and $G_{Rx}$ are the gain of the transmitting and receiving antennas, $\lambda$ is the wavelength of the transmitted signal in salt, and $r$ is the distance between the antennas. Using the result of the Friis formula together with the GPR system specifications, we estimate that the minimum attenuation length allowed to detect the reflected signal over the longest distance observed (see Table II) is 138 m, assuming that they detected the signal just at the sensitivity threshold of their system.

This attenuation length is not inconsistent with some of our measurements in the same frequency range, although our results show generally higher losses. Note that if there are variations in the clarity of the salt, the longest observed path length quoted in their paper would be more likely to be from the clearest salt that they had sampled among all of their measurements. We only sampled one section of salt with these measurements.

In order to replicate the low-loss results of the GPR technique, any further
measurements would have to be made with a portable high-power system capable of making measurements at many locations.

We made a brief attempt at making measurements using the GPR technique during our visit to the mine. Using the same high-power pulser and oscilloscope, we used a pair of directional antennas in an attempt to see reflections off of interfaces within the walls of the mine. We did see late reflected pulses, but we did not understand that data well enough to conclude whether the reflections that we saw came from within the salt, or were merely reflections down the corridor of the mine.

8 Simulation

We have run a simulation to estimate the sensitivity of an array of antennas embedded in salt with the attenuation lengths that we have measured here. As much as possible, we use the same parameters as the simulated array described in the Hockley paper for direct comparison [6]. The simulated array consists of $10 \times 10 \times 10$ dipole antennas with center frequency at 150 MHz and 50% bandwidth in a salt formation that is a cube 4 km on a side. We require 4 antennas hit with a signal-to-noise ratio of $4\sigma$. The previous study in [6] considered a 300 m attenuation length at 300 MHz and a $1/\nu$ dependence, whereas we have measured a $63 \pm 3$ m attenuation length at 300 MHz and the spectral index that we measure is $-0.57 \pm 0.06$. Reproducing the simulated
Hockley array, we expect 12 events per year compared to the order 10 events per year that they quote in their paper. Using the measured Cote Blanche attenuation lengths, we expect 1.4 events per year ultra-high energy neutrino flux [2], for a factor of 9 reduction in sensitivity due to a lower measured attenuation length, but still a non-negligible rate over a one year run time.

9 Conclusions

We have measured field attenuation lengths in the frequency range 125-900 MHz using broadband pulses transmitted and received by dipole antennas in boreholes drilled 100 ft. into the floor of the 1500 ft. deep level of the Cote Blanche salt mine. The best fit power law that describes the measured frequency-dependent attenuation lengths is given by

\[ L_\alpha = (32 \pm 2) \cdot (\nu/1 \text{ GHz})^{-0.57 \pm 0.06} \]  

with statistically dominated uncertainties. This is the most precise measurement of radio attenuation in a natural salt formation to date.

The main result of this paper is derived from data that we took on our third trip to the Cote Blanche Salt Mine. The data taken from the three trips indicates that the room and pillar system of mining leads to regions of salt near the walls and ceilings of the corridors with short attenuation lengths \((\sim 10\text{ m})\) which could be due to fracturing brought about by the explosives
used in that method. We find that the salt that is just under the floor of a

corridor does not suffer the same degradation, which may be due to the cut

along the floor that is made prior to the detonation of the explosives to blast

away the salt.

Although we expect there to be variation in salt properties between salt domes

as well as regions of salt within the same dome, we have compared our measure-

ments with previous measurements made at Cote Blanche and elsewhere. Our

result is not inconsistent with attenuation lengths measured at the Hockley

Salt Mine. We have attempted to compare our measurements with the longest

transmission distance reported by GPR experts in the same mine. Our data

generally showed greater attenuation than can be reconciled with that result.

However, due to the variation observed in our data, some of our measurements

do point to salt that could have been clear enough to be consistent. That we

strain to reconcile our numbers with the longest transmission distance reported

there may indicate that there are regions of the Cote Blanche mine with salt

that has less attenuation than in the regions where our measurements were

made.

We have modeled a SalSA array of $10 \times 10 \times 10$ dipole antennas in boreholes

that reach 3 km depth to assess the sensitivity of a neutrino detector in salt

with the attenuation lengths that we report here to compare with the simu-

lation study described in the Hockley attenuation length paper. We find the

lower best fit attenuation lengths measured at Cote Blanche reduce the sen-
sitivity of such a detector measured in terms of event rate by a factor of 9, but still maintain an expectation of order one event per year using a standard model for the expected ultra-high energy neutrino flux.

In order for a next-generation neutrino detector in salt that measures \( \sim 10 \text{ GZK events/year} \) to be feasible, attenuation lengths longer than the \( \sim 100 \text{ m} \) lengths reported here will likely be necessary. However, since this result is based on a limited region of the dome, and past GPR results in the same mine may have pointed clearer salt, there are reasons to be optimistic that there is clearer salt in other locations whose radio loss has not yet been precisely measured. For this to be pursued further, we believe that developing a portable radar system is a compelling next step so that the radio loss of the salt can be sampled in many locations on a single visit to a mine.

10 Acknowledgements

We are grateful to mine manager Gordon Bull at the North American Salt Company for supporting our project and his generosity in permitting us to carry out this work in the Cote Blanche mine on three separate visits. We would also like to thank Scott Fountain, Robert Romero and the other miners at Cote Blanche that provided us with constant assistance on our visits to make these measurements a success, and for drilling custom boreholes for us which make these measurements unique in the world. We would also like to
thank the High Energy Physics Division of the U.S. Department of Energy, the U.K. Particle Physics and Astronomy Research Council and the Royal Society for funding this project.

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Figure 1. Map showing section of 1500 ft. level of the mine where we made our measurements at Boreholes 1, 2, and 3. The letters and numbers follow the naming system for the corridors used by the mine. The hatched regions are the salt surrounding the corridors.

Figure 2. System diagram.

Figure 3. Pulses that propagated directly between the transmitter and receiver between Boreholes 1 and 2 between Boreholes 1 and 3 using the MF antennas at a depth of 90 ft. We plot voltage multiplied by the distance between transmitter and receiver for each pulse, which should be constant in the absence of any attenuation.

Figure 4. Fourier transforms of pulses in Figure 3.

Figure 5. Measured transmission for the custom-made MF antennas.

Figure 6. Attenuation length at 250 MHz measured with the MF antennas. The uncertainties are smaller for shorter attenuation lengths since variations in voltage have less of an impact when greater loss is observed.

Figure 7. Attenuation length shown as a function of frequency for two depths and all three pairs of dipoles.

Figure 8. Average attenuation length, shown as a function of frequency. The uncertainties shown in this plot are the scatter of the measured attenuation lengths using different antennas and at different depths.
Figure 9. Index of refraction measured at each depth.

Figure 10. Measurement of beam pattern while one MF antenna was at 90 ft. depth in Borehole 1 and the other was at various depths in Borehole 2 or 3. The square markers are measurements taken with the second MF antenna in Borehole 2 and the triangular markers with the second MF antenna in Borehole 3. The star denotes 0 degrees, where the attenuation is by definition 0 dB.
Table I
Measured attenuation lengths at a few frequencies of interest based on fitting the data at 50 ft. and 90 ft. depths to the power law function as described in the text.

| Frequency (MHz) | Measured Attenuation Length (meters) |
|----------------|--------------------------------------|
| 150            | 93 ± 7                               |
| 300            | 63 ± 3                               |
| 440            | 51 ± 2                               |
| 900            | 36 ± 2                               |

Table II
Specifications of the GPR system used in [7] and [14], and an estimation of the minimum attenuation length needed to see the longest path length reflection observed.

| System Specifications                  |
|---------------------------------------|
| Antenna Gain                          | 17 dB                                |
| Frequency                             | 440 MHz                              |
| Maximum Transmission Distance         | 1244 m                               |

| Attenuation Length Estimation         |
|---------------------------------------|
| Peak Power Output                     | 40 dBm 10 W                         |
| Loss from transmission (from Friis formula) | 61 dB 1.3 x 10^6                  |
| Power received (assuming no attenuation) | -21 dBm 8.0 x 10^-6 W              |
| System Sensitivity                    | -100 dBm 10^-13 W                   |
| Maximum attenuation allowed           | -79 dB 1.3 x 10^-8                  |
| Attenuation length                    | > 138 m                              |