A Laser Radar for Probing Salt

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ABSTRACT

A plot of the optical absorption coefficient, k, as a function of frequency (or wavelength in micrometers) discloses a drop of 5 orders of magnitude in the absorption per unit length for pure NaCl in the region 60 to 5 micrometers (microns). The absorption coefficient rises again in the optical region reaching a maximum in the ultraviolet region. Insofar as we have been able to determine from a vigorous literature search, pure salt has such a low absorption coefficient in the region from 1 to 10 micrometers (near infrared) that it has never been measured. Manufacturers of optical equipment have know this for a long time and use salt as an integral optical part of spectrophotometers, for example.

The low absorption coefficient in the 1 to 10 micrometer region means that salt can transmit near infrared waves (at about 2 to 3 micrometers) almost as well as VHF radar waves. Thus a laser radar might be an alternative means of probing into salt for the detection of discontinuities, i.e. anything that is not salt. Laser radars have a number of advantages over ordinary pulse or CW-FM radars.

1. The peak power outputs available are much higher than for ordinary radars, e.g. 10^9 watts versus 10^3 watts.

2. Antenna gains ($G = KA/\lambda^2$) are much higher because of the very short wavelength used despite the small radiating area A, and G is important because it appears in the radar range equation as G^2. Thus any improvement in G (over the ordinary radar) is enhanced by the squaring. Antenna gains of 10^6 are common in lasers, compared with 10 to 15 for radars.

3. Very short pulse widths are obtainable with a laser radar. Nanosecond pulses are available whereas radar pulses less than 100 ns are difficult to obtain.

4. A laser radar avoids the large bulky antennas needed to obtain even a small amount of antenna gain in the VHF radiowave region. In practice, the inverse problem is expected to arise with a laser radar. The beam width is inherently so narrow (order of 10 milliradians) that it will have to be widened, but this is no problem.

5. Although high laser radar peak powers can be obtained, the pulses are of short length and so average powers can be quite low while still having reasonable pulse repetition frequencies.

Consequently, a laser radar has many advantages for probing salt. However, these advantages could be nullified if the structure of salt is such that it scatters the laser light in many directions. If this occurs the laser radar in salt would be analogous to bright white headlights in a thick fog.

INTRODUCTION

This paper will look at the radar equation which includes the attenuation of the waves by the salt and see what might be done to probe into salt better, deeper, and more accurately, for any discontinuity in the salt utilizing one of the two windows in salt, namely the infrared window. To do this it is proposed that a *laser* radar be used. One must initially determine where in the infrared range one should transmit and how such a laser radar might compare with a VHF radar operating in the other window of salt.

First it must be determined whether salt will permit the transmission of EM waves in the optical of infrared frequency region. It is known that pure salt is transparent. It is also known that salt in mines is not identical with the pure salt crystals seen on display in salt company offices or museums. Unterberger (1974) has shown that salt has a window, or low spot in its attenuation curve, (tan δ vs frequency) in the 10^6 to 10^9 Hz range. Much prior research on salt propagation has been done in this range and radar returns were achieved from reflections at distances up to a mile in salt. At 10^9 Hz the attenuation curve for salt continues upward until it reaches a peak in the infrared at 60 microns (or micrometers) wavelength where interatomic vibrations cause absorption. The attenuation then dips and the salt becomes so transparent in the 1–8 micrometer range that the attenuation or absorption constant is unknown. Note the drop by 4 orders of magnitude (Fig. 1) from wavelengths of 60 micrometers to about 9 micrometers. The dotted line is interpolation. As the wavelength shortens, salt again starts to absorb caused by the electronic transitions in the ultraviolet region. In the visible region, salt is transparent. This fact is often utilized in the optical manufacturing industry where, for example, salt crystals are used in spectrophotometers. Note that an uranium-doped calcium fluoride laser at 1.06 micrometer

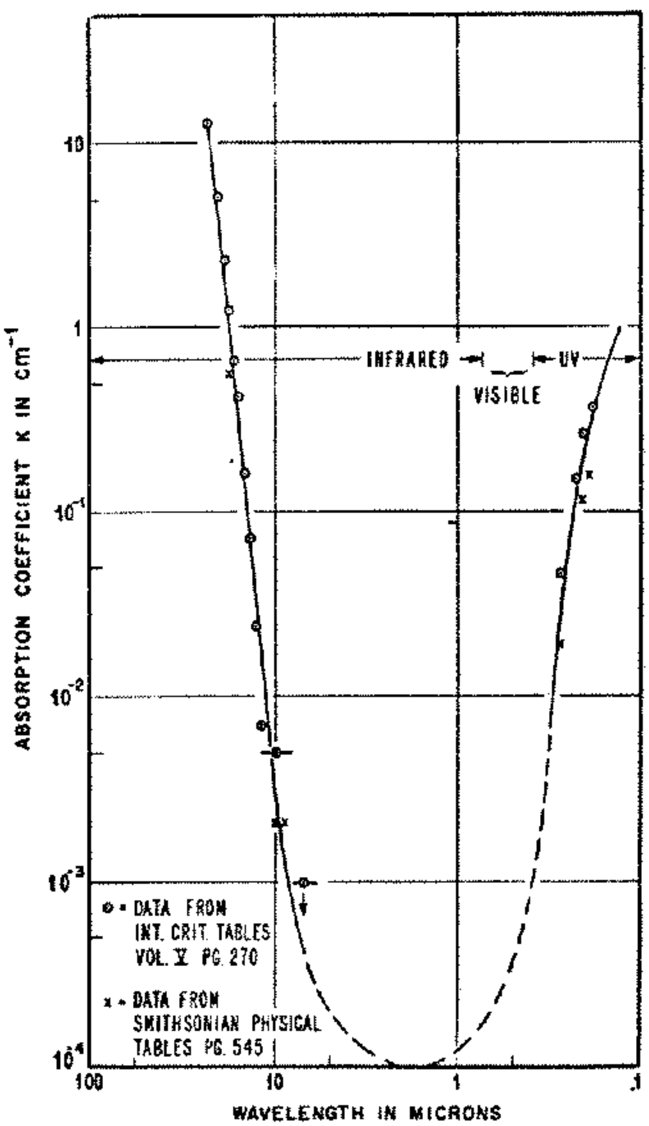

Figure 1. The Optical Window in Salt.

wavelength would operate in the middle of the transparent region of salt according to the graph (Fig. 2) which shows the transparency of salt plotted against wavelength for the ultraviolet, visible, and infrared region using data from the Smithsonian Physical Tables, (1956).

From electromagnetic wave theory, it is known that absorption must be accompanied by a change in the index of refraction so that the index of refraction can be used as a sensitive indicator for absorption. In Figure 3 four-significant-figure index of refraction data are plotted against wavelength. The index of refraction rises on the right because of the UV absorption and dips on the left because of the 60 micrometer absorption in the infrared region. Note that the flattest part of this curve is in the 1 to 5 micrometer region. Therefore it is at this frequency (or wavelength) that a laser radar should be used to probe salt because this is where salt is the most transparent.

A plot of the index of refraction (Fig. 3) of some impurities found in salt, particularly anhydrite, gives three indices for anhydrite at the wavelength of the sodium D-line. If it is not desirable to detect anhydrite impurities in salt with laser radar then the wavelength of laser radar might be chosen such that the index of refraction of anhydrite would coincide with that of salt.

From the data reviewed so far, one can conclude that there is a window in salt through which one might probe for discontinuities such as sand lenses, water, limestone, anhydrite, etc. just as one probes with VHF radar at much lower frequencies (and longer wavelengths) for similar discontinuities. At low (VHF) frequencies the reflections are caused by the change in the complex electric permittivity at the interface between salt and some other material. In the infrared region it is the change in the index of refraction of the salt and the impurity that will give rise to a reflection signal, whose range can be determined from timing the reflected laser pulse.

All the data cited are for pure salt, usually Harshaw Chemical Co. salt, grown from a melt. How does this compare with natural *in situ* salt? This is a difficult question to answer. Dr. William T. Holser, University of Oregon (Personal Communication) says that a Pittsburgh Plate Glass Co. engineer obtained 98% transmission in the infrared (wavelength unspecified) through a five foot salt core from Palangana Dome, Texas.

From Beer's law:

$$I = I_o e^{-kx} \qquad (1)$$

where I_o is the initial intensity of light at $x = o$, and I is the intensity after traveling a distance x, the absorption coefficient k of this salt is obtained:

$$k = 1.3 \times 10^{-4}. \qquad (2)$$

Note how well this compares with the bottom of the interpolated curve (Fig. 1). No data are available in the 0.8 to

9 micrometer region for the absorption coefficient of even pure salt because it transmits well i.e. it is so transparent. Usually solid and liquid substances are very absorbing in this region so that the optical instruments available to measure the absorption coefficient are designed to handle only a small thickness of sample. For example, the Beckman Model 21 Double Beam Infrared Spectrophotometer will not accommodate a sample longer than 5 inches.

COMPARISON OF VHF ATTENUATION CONSTANT α AND THE INFRARED ABSORPTION COEFFICIENT k

The IR intensity loss per unit length, k, is usually expressed to the base e, in nepers per centimeter. The equivalent of this in the VHF region is the attenuation factor, also expressed in nepers per centimeter. α, however, is associated with a decrease in the amplitude of the electric vector E of the VHF wave. The infrared, k, is associated with the intensity. Thus the two loss mechanisms are equated by:

$$k = 2\alpha = \frac{2\pi}{\lambda}\sqrt{\frac{\epsilon'}{\epsilon_o}\frac{\mu'}{\mu_o}}\ \tan\delta \tag{3}$$

Equating these at 440 MHz for the VHF radar in salt, where most of the data given in Unterberger (1974) were taken one obtains

$$k = .22 \tan\delta \tag{4}$$

This equation relates the two important factors governing the attenuation of the wave as it progresses through salt. Thus, if a tan δ of salt of 4×10^{-4} yields a satisfactory radar range in salt in the VHF region, which it does, then an infrared laser radar in salt of 1×10^{-4} neper/cm absorption coefficient should give equivalent performance insofar as attenuation is concerned. Remember that 1×10^{-4} is what was presumably measured for the five foot sample of Palangana salt dome salt.

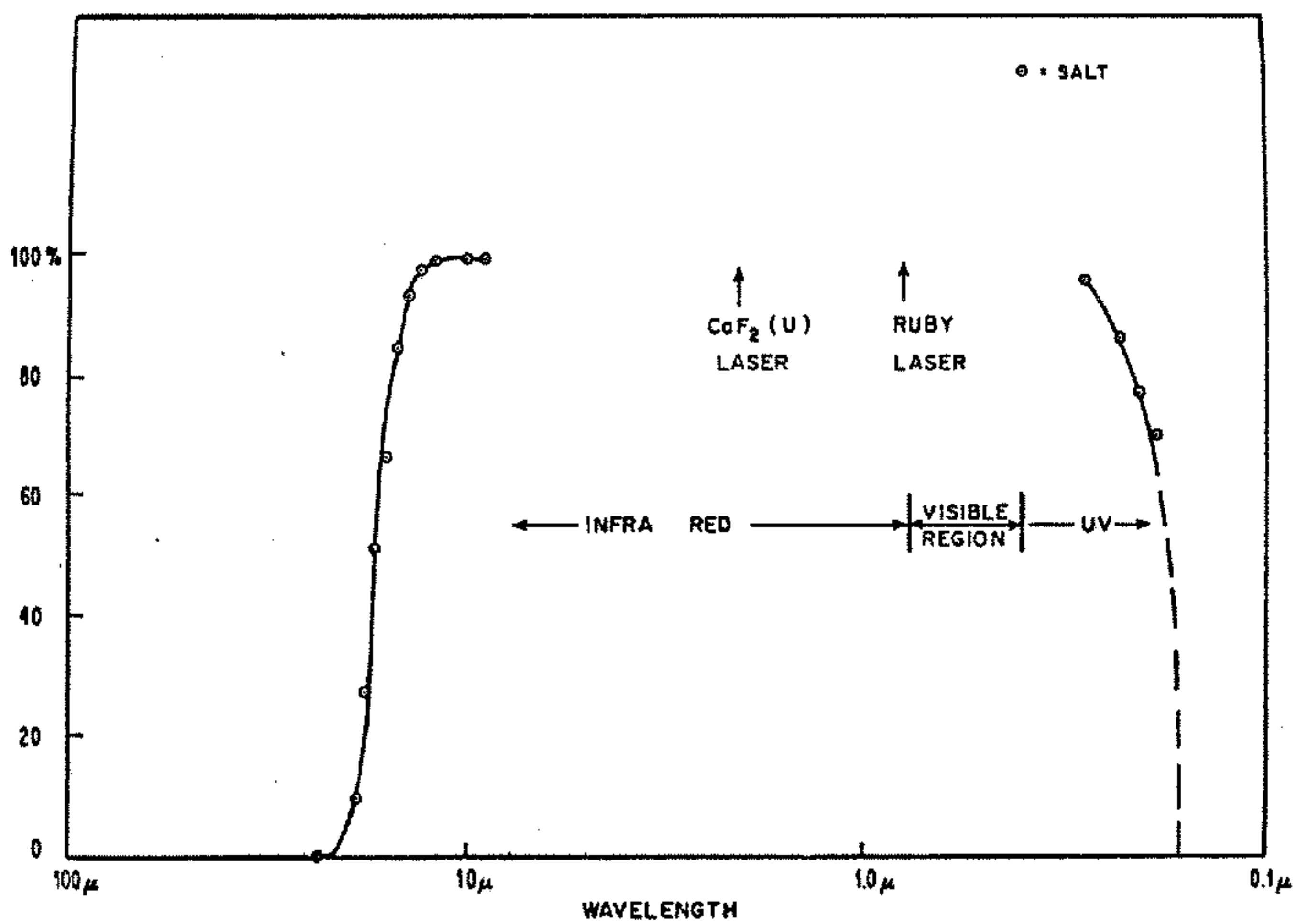

Figure 2. Transparency of Salt References: (1) Smithsonian Phys. Tables Page 536 and Page 545.

OTHER FACTORS IN COMPARING VHF RADAR AND LASER RADAR

Preciseness of measurement. The basic radar equation which will hold for either VHF or laser radar (including attenuation by the transmission medium) is:

$$S/N = 10 \log \frac{P_o G^2 \lambda^2 \sigma}{(4\pi)^3 R^4 P_N} \; e^{\frac{-4\pi R \tan \delta}{\lambda} \sqrt{(\epsilon'/\epsilon_o)(\mu'/\mu_o)}} \quad (5)$$

where:

S/N	is the signal-to-noise ratio in decibels
P_o	is the peak power output in watts
P_N	is the noise power of the receiver in watts
G	is the antenna gain
σ	is the backscattering of the target in meters squared
R	is the radar range in meters
λ	is the wavelength in meters
$\tan \delta$	is the loss tangent of the transmitting material (salt, in this case)

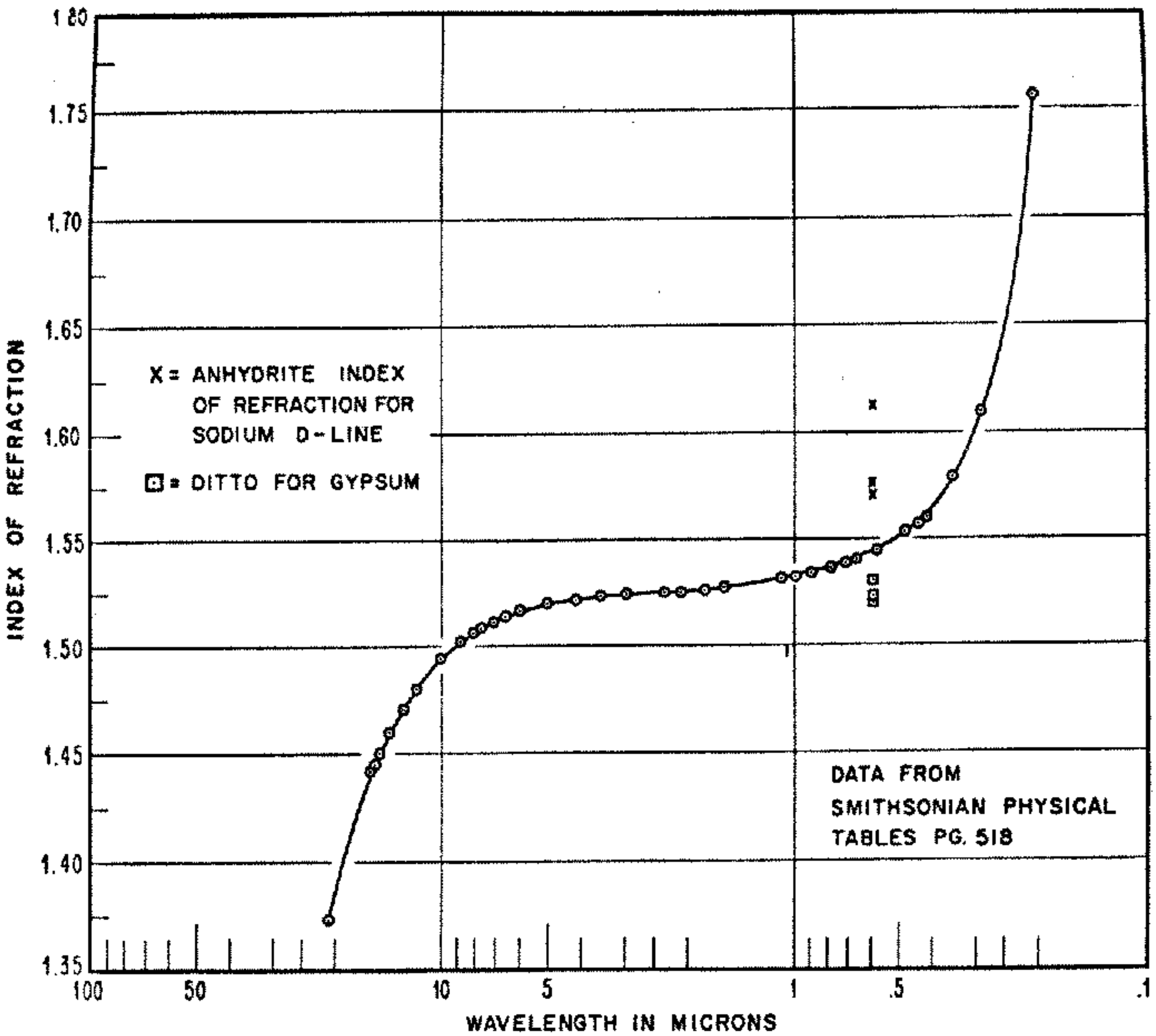

Figure 3. Index of Refraction of Salt.

ϵ'/ϵ_0	is the real part of the complex permittivity of salt
μ'/μ_0	is the real part of the complex permeability of salt (assumed to be equal to 1 because of the lack of ferro- or paramagnetic substances within the salt mass).

It is the signal to noise ratio for a particular reflection at range R, for a target of radar cross-section σ, that determines whether the target discontinuity in the salt is seen or not. Looking at each individual parameter one can see how the two systems compare. First note that the parameters on the right side of the equation can be divided into two groups, precise and imprecise parameters. The imprecise parameters are those to which a precise value is difficult to assign. The precise parameters, those which one can measure easily, are:

P_o = power output
G = antenna gain
λ = wavelength
P_N = receiver noise power

The imprecise ones are:

σ = radar scattering cross section of the target
$\tan \delta$ = loss tangent of salt

Note the omission of the real part of the relative electric permittivity ϵ'/ϵ_0 (which for salt = 5.90) and the similar real part of relative magnetic permeability μ'/μ_0 of salt which is = 1. According to the Soviet literature, Karlov et al. (1970) electrical breakdown of NaCl occurs at a radiation density of $\approx 2 \times 10^9$ W/cm² corresponding to a field intensity of 1.5×10^6 V/cm. Consequently, an effective laser radar must not exceed this value.

Precise parameters. Next the precise parameters are compared for VHF and laser radars. Whereas VHF might have 10^4 watts of peak power, or possibly 10^5 if extended, the peak power of lasers are for example

750×10^6 W	for a Korad K-2Q ruby laser
50×10^9 W	for a Cogenel VK-640 Neodymium Doped Glass laser

A nine path neodymium laser by the Russian scientist Dr. Basov produces 300×10^9 watts or 0.3 TW. (Solon, 1972).

Using the Cogenel laser for comparison it is clear that the laser radar has a peak power output advantage of

$$\frac{10^{10}}{10^5} = 10^5 \text{ over the VHF radar.} \qquad (6)$$

Thus the laser radar has a relative advantage of 100,000 over the VHF radar.

Antenna gain. It is known from optics that the Fraunhofer diffraction pattern for a slit of width a, has the general expression for minima given by:

$$\sin \theta = k\frac{\lambda}{a} \ (k = 1,2,3) \qquad (7)$$

Taking the first minimum (k = 1) and making the usual assumption that $\sin \theta = \theta$ for small angles, the beamwidth for the diffraction-limited source is:

$$\theta = \frac{\lambda}{a} \qquad (8)$$

Note the similarity of this optics equation to the beamwidth for a parabolic microwave dish (Silver, 1949) of diameter D, which is given by 1.2 λ/D. Assuming a 1 cm diameter rod and a wavelength of 1 micrometer the beam angle is:

$$\theta = 10^{-4} \text{ radians} \qquad (9)$$

In practice, however, one can only obtain a beamwidth ten times that of the theoretical 10^{-4} radians. Thus take 1 milliradian to be the beam angle or a beamwidth of .06° for the laser radar in the horizontal and vertical direction. The beamwidth of the 2-bay stacked array VHF radar is ± 20° in the horizontal plane and ± 30° in the vertical plane. Multiplying these relative factors together, and because the peak radiated power is more concentrated in both azimuth and elevation directions, one obtains the formula:

$$G_t = \frac{2400}{(.06)^2} = 6.6 \times 10^5 \qquad (10)$$

i.e., a laser radar *transmitting* antenna gain advantage of 6.6×10^5. This expression compares only the transmitting antennas of the VHF and laser radar. For the VHF radar, there are two antennas (transmitting and receiving) which are the same but not identical. No duplexer is used and each antenna is a 2-bay, vertically stacked, horizontally-polarized array. The laser radar receiver could very well have a collector mirror of ten times the laser transmitter dielectric rod size. A laser receiver using a mirror 10 cm in diameter is common. The laser receiver gain G_r advantage is now 6.6×10^6, ten times that calculated for the transmitter. The total laser radar antenna gain advantage is the product G_tG_r or

$$6.6 \times 10^5 (6.6 \times 10^6) = 4.35 \times 10^{12} \qquad (11)$$

So far the laser has advantages in both peak power output and antenna gain.

Wavelength. Note from Equation (5) that λ appears in the equation twice: once in the exponent and once (squared) in the numerator. Considering the numerator first, one sees that the VHF radar has an advantage over a neodymium or a CaF_2 glass laser radar at 10,600 Å (or 1.06 micrometers):

$$\left[\frac{\lambda_{VHF}}{\lambda_{laser}}\right]^2 = \left[\frac{68.18}{1.06 \times 10^{-4}}\right]^2 = 4.13 \times 10^{11} \qquad (12)$$

So here the VHF radar has a distinct advantage.

Receiver noise. The VHF radar receiver has a sensitivity of 10^{-12} watts. In addition, use of advanced techniques such as the boxcar integrator, cross or auto-correlation schemes might improve by factors of possibly two orders of magnitude. Advanced techniques (Alfano and Ockman, 1968) are also available for detecting low light levels ($\approx 10^{-17}$W). One may consider the receiver noise in both VHF and laser radar systems to be approximately equal.

The relative advantages of both radars for the precise parameters are summarized in Table I, where it is seen that the laser radar has an advantage of about one million to one over the VHF radar in terms of power output, transmitted gain, and other factors.

TABLE I

Parameter Considered	Relative Advantage for Laser Radar	VHF Radar
Power Output, P_O	10^5	——
Transmitter Gain, G_t	6.6×10^5	——
Receiver Gain, G_r	6.6×10^6	——
Wavelength	——	4.13×10^{11}
Receiver Noise Level	none	none
Total	4.35×10^{17}	4.13×10^{11}
Net Advantage	10^6	

Imprecise parameters

The radar cross section. Referred to in the literature as RCS or σ, the *r*adar (backscattering) *c*ross *s*ection is a highly variable parameter which cannot be handled mathematically. σ is impossible to compute theoretically and laboratories at Hughes Aircraft and Ohio State have been established to measure this parameter for various targets at various aspect angles and various frequencies and polarizations. Much work by the MIT Radiation Laboratory during World War II and by the Naval Research Laboratory after the war revealed amazingly complex, three dimensional patterns for σ for a given wavelength and polarization. Small changes in aspect angle (the direction of looking at the target) affected the received radar signal by 20 dB or more. This is caused by interference in the phase of the signals reflected from different areas of the complex shaped target.

Any infrared target is very likely to be a complex shaped interface which is rough (particularly where λ = 1.06×10^{-4} cm). Unfortunately there are no retroreflectors (the optical equivalent of radar corner reflectors) placed on the target of interest in salt, similar to those the Apollo moon landers left on the moon to aid ranging to the moon from earth with laser radars. With the paucity of information that exists about the target σ, either in the VHF region or in the IR region, it is not possible to determine which radar has the advantage with regard to the radar cross section. Accordingly, they are considered equal.

Tan δ. The loss tangent of salt for VHF, or the absorption coefficient k in the infrared, has been considered. Remember that values of k of about 1/4 the value of tan δ's for salt should give about equal radar performance. The one Palagana dome IR measurement cited may have been made on a very low loss salt sample or just a moderate loss sample. Nevertheless, this measurement appears to be comparable to attenuations measured in salt by us at VHF radar frequencies. Therefore, although the performance of either radar is highly dependent on tan δ or its equivalent k [because of its position in the exponent of equation (5)], on the basis of present knowledge the radars are comparable for this parameter.

SUMMARY

Insofar as one can presently determine the imprecise parameters are about equal, i.e. there is no advantage for either laser or VHF radar. Considering the precise parameters and attenuation in salt, the laser radar has a clear advantage of 10^6 i.e., in signal to noise ratio, its performance should be 60 dB better than the VHF radar which has been so successful thus far. While this sounds like a powerful incentive to develop a laser radar to probe salt for discontinuities, the deciding factor will probably be the amount of infrared scattering one obtains in trying to transmit a narrow infrared beam into salt. Such scattering of laser light in salt may well prove to be analogous to the headlight beam scatter while driving a car in the fog where the water molecules scatter the light and one sees very little.

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