PHENOMENA AND PROPERTIES OF GEOLOGIC MATERIALS
AFFECTING MICROWAVES - A REVIEW

by
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Approved:  

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Principal Investigator

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70-9 "Remote Sensing in Exploration for Mineral Deposits" (by R.J.P. Lyon and Keenan Lee) to be published in Economic Geology.
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ABSTRACT

A literature search made on microwave remote sensing included material on electromagnetic theory, parameters affecting passive microwave systems, and properties of natural occurring materials. Some results and conclusions reached were: (a) Data on electric and thermal properties of materials are lacking in quality and quantity; (b) systematic analyses are needed of parameters in the microwave portion of the spectrum under conditions that would make the data useful for remote sensing purposes; (c) the complex compositional, structural, and temporally-dependent make-up of the natural environment suggests that even a fundamentally sound knowledge of elemental interactions with electromagnetic radiation is probably insufficient to completely solve real world problems; and (d) while modeling techniques may be very helpful in gaining information on relatively simple relationships, the empirical approach of making parametric measurements under carefully selected field conditions may provide better insight into the causes of the integrated responses recorded by passive microwave systems.
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LIST OF SYMBOLS

\( \alpha \)  absorptance

\( \alpha \)  thermal diffusivity

\( B(f, T) \)  specific intensity (watts-m\(^{-2}\)-steradian\(^{-1}\)-Hertz\(^{-1}\))

\( c \)  speed of EMR in free space

\( c_s \)  specific heat

\( ^\circ C \)  degrees Centigrade

\( \text{cal} \)  calorie

\( \text{dB} \)  decibel

\( \frac{dT}{dx} \)  temperature gradient

\( E \)  energy

\( E(f) df \)  energy radiated, per unit wavelength, per unit volume of the radiator

\( \text{EM} \)  electromagnetic

\( \text{EMR} \)  electromagnetic radiation

\( \varepsilon \)  emittance

\( \varepsilon \)  dielectric coefficient

\( \varepsilon_a \)  atmospheric emittance

\( \varepsilon_g \)  material emittance

\( \varepsilon_r \)  relative complex dielectric coefficient

\( \varepsilon' \)  real part of \( \varepsilon_r \) (\( \varepsilon \) of a material)

\( \varepsilon'' \)  imaginary part of \( \varepsilon_r \) (loss factor)

\( f \)  frequency

\( \text{GHz} \)  GigaHertz (\( 10^9 \) Hertz)
\( h \) Planck's constant \((6.62 \times 10^{-34} \text{ joule-sec})\)

\( H \) horizontal polarization

\( i \) \(\sqrt{-1}\)

\( IR \) infrared

\( k \) Boltzmann constant \((1.38 \times 10^{-23} \text{ joule/degree})\)

\( k \) thermal conductivity

\( kT \) "ideal" total energy of an oscillating atom or molecule

\( ^\circ K \) degrees Kelvin

\( \lambda \) wavelength

\( m \) mass

\( m_p \) mass of photon in motion

\( MW \) microwave

\( n \) refractive index

\( P \) power

\( P_a \) atomic polarization

\( P_e \) electronic polarization

\( P_o \) orientation, or molecular, polarization

\( q \) rate of heat flow across a unit area

\( q \) rate of heat flow per unit volume

\( Q_p \) energy unit or photon

\( \rho \) reflectance

\( \rho \) density

\( \rho_g \) surface reflectance

\( T \) absolute temperature (degrees Kelvin)

\( T_a \) actual temperature of a clear atmosphere
\( T_B \)   apparent brightness temperature
\( T_g \)   thermometric ground temperature
\( T_s \)   sky temperature
\( \tan \delta \)  loss tangent \((\varepsilon''/\varepsilon')\)
\( \Theta \)   angle of incidence
UV    ultraviolet
V     vertical polarization
w     watts
z     relief of a surface
I. INTRODUCTION

A search of the available literature was made to gain familiarity with the principles and problems of remote sensing in the microwave portion of the electromagnetic spectrum. The first section of this paper contains a brief review of electromagnetic theory. -The second section describes the phenomena and parameters relevant to making measurements with passive microwave systems in general. Although more could have been covered in this section, those factors highly influenced by equipment modes and operation more appropriately belong in a discussion of specific instrument capabilities and deployment.

Emphasis is placed on section three in which the interaction of electrical, thermal and physical properties of natural occurring materials with electromagnetic radiation at microwave frequencies were investigated. Although basic interactions are functions of atomic-molecular characteristics of matter, the scale of parameters affecting passive microwave detectors range from subcrystalline particles to gross topographic features; and the domain from which the sensors receive signal inputs ranges from space-derived solar radiation through the atmosphere and into the shallow subsurface of the earth's crust. The fourth section discusses some conclusions reached as a result of this literature research.
II. ELECTROMAGNETIC THEORY

Electromagnetic radiation (EMR) is energy, in wave and particulate form, produced by the oscillations of various kinds and combinations of charged particles.

EMR is propagated as waves, and the essential character of all EM waves is the same. They vary only in wavelength, frequency and energy. Wavelength (\( \lambda \)) and frequency (\( f \)) are related as shown by the equation:

\[
\lambda = \frac{c}{f}.
\]

where \( c \) is the speed of EMR in free space

\( (c = 3 \times 10^8 \text{ m/sec}) \)

The frequency and intensity of the EMR depends primarily on the temperature of the body. If a body is in thermal equilibrium with its surroundings, it receives (or absorbs) radiated energy in some amount, and radiates (or emits) an equal amount. If all the incident energy is absorbed and reemitted, the object is said to be a "blackbody radiator". Others which do not absorb (and hence reemit) all incident radiation are called "graybodies" (Colwell, et al., 1963).

The Stefan-Boltzmann law states that the total energy radiated from a blackbody per unit area, per unit time, is proportional to the fourth power of the absolute temperature, or

\[
E_{\text{total}} = 5.67 \times 10^{-8} T^4. \quad (E \text{ in watts per } m^2)
\]
According to Planck's distribution law, radiation from a blackbody will be distributed according to frequency as follows:

\[ E(f) \, df = \frac{8\pi \hbar^3}{c^3} x \frac{df}{(e^{\frac{\hbar f}{kT}} - 1)} \]  \hspace{1cm} (3)

where \( E(f) \, df \) = number of oscillations, over an incremental frequency band, \( df \), times the average energy per oscillation (or = the energy radiated, per unit wavelength, per unit volume of the radiator).

\( \hbar \) = Planck's constant: \( 6.62 \times 10^{-34} \) joule-sec.

\( kT \) is the "ideal" total energy of an oscillating atom or molecule: \( k = \) Boltzmann constant: \( (1.38 \times 10^{-23} \) joule per degree) and \( T = \) absolute temperature (°K)

EMR is also considered a discrete "quanta" of energy, or "photons".

The relationship between EMR in wave form and as quanta is

\[ Q_p = hf = \frac{hc}{\lambda} \]  \hspace{1cm} (4)

where \( Q_p \) is the energy unit, or photon.

The intensity of radiation is simply the number of photons per unit time and area. A photon has no rest mass, but acquires mass through motion according to the Einstein equation \( E = mc^2 \). The mass is given by \( m_p = \frac{hf}{c^2} \).

In the middle region of the EM spectrum (UV, Visible, IR) the frequency and minute energies associated with the individual photons are roughly the same as those associated with individual electrons in the atoms.
and/or molecules making up a given kind of matter. Toward the very high frequency end (gamma-ray) of the spectrum, the energy of the photon increases beyond the binding energies of molecules or even atoms, and individual collisions with such photons result in dissociation or violent disruption of matter. Toward the low frequency end (radio), photon energies are low, and wavelengths are large compared to atomic distances, so that no permanent structural adjustments occur.

When a photon of any specific energy strikes the boundary of solid matter, a number of interactions are possible. The energy can be reflected and/or scattered, absorbed and/or emitted, or transmitted; or any combination thereof.

EMR incident on a plane interface between two media is reflected according to well-known laws: The reflected field depends upon the wavelength, the angle of incidence and the electrical properties of the two adjoining media. When the interface deviates from a plane, the incident wave will either be specularly reflected or diffusely scattered depending upon whether the surface is smooth or rough. A smooth surface will reflect the incident wave specularly in a single direction whereas a rough surface will scatter it into various directions, though certain directions may receive more energy than other. Thusly defined, the same surface may be rough for some wavelengths and smooth for others; or for the same wavelength it may be either rough or smooth for different angles of
incidence. Reflection and scatter can occur together, in any combination.

The transition from specular reflection to diffuse scatter, or when a smooth surface becomes rough, can be qualitatively expressed by the relation known as the Raleigh criterion, namely that a surface is considered smooth for \( z < \frac{\lambda}{8} \sin \theta \), where \( z \) is the height of the surface irregularities, \( \lambda \) is the wavelength, and \( \Theta \) is the angle of incidence. This relation is set arbitrarily half-way between rays in phase (\( \Delta \phi = 0 \)) and rays in phase opposition (\( \Delta \phi = \pi \)), i.e., \( \Delta \phi = \pi/2 \); where \( \Delta \phi \) is the phase difference. Other values of \( \Delta \phi \), such as \( \pi/4 \) and \( \pi/8 \) have been suggested as more realistic, thus replacing the factor 8 in the Raleigh criterion by 16 or 32; however, there seems to be little point in assessing an exact dividing line, which must in essence be more or less conventional (Beckmann and Spizzichino, 1963).

In both specular reflection and diffuse scatter, especially the latter, polarization characteristics of EMR frequently are changed depending upon the nature of the surface. Land surfaces of different composition produce different amounts of scatter at various angles of incidence; and the scatter is likewise different for different wavelengths. Also, scatter occurs in the transmission through the propagating medium, in the material itself, and in the transmission back to the detector.
Absorption occurs when energy of the same frequency as the resonant frequency of an atom or a molecule is absorbed, producing an excited state. The energy is largely converted into heat and is subsequently reemitted, which may be at a different wavelength.

The total emitted radiation received at the detector consists of the signal emitted by the target material plus some radiation contributed by the propagating medium at various points along the path. This latter energy also is a function of wave length and of temperature and atomic-molecular structure of the medium. There is no way to distinguish between individual photons having the same energy, so it is possible that the emitted signal may become engulfed in radiation from other (unwanted) sources.

Emissivity is an intrinsic property of a material, depending primarily upon its chemical composition and physical state. It can be measured for a material sufficiently thick to be opaque and having a specular surface. Emittance is the ratio of the rate of radiant energy emitted from a body to the corresponding rate of emission from a blackbody at the same temperature. It is the usual measurement of a particular body. In the remote sensing literature the term 'emissivity' has been used in both senses defined above for emissivity and emittance. In this paper the distinction implied by the suffixes: -ity (denoting state, quality, or degree), and -ance (act or fact of doing what the verbal root denotes); shall be made.
Transmittance is the ratio of the energy transmitted through a body to that incident upon it.

To briefly summarize then, the interaction of EMR with matter can result in reflection, scatter, absorption, emission or transmission --- or some combination thereof; and is dependent upon the wavelength and the nature of the matter. During these interactions certain changes can take place, such as polarization of the wave form, conversion to heat energy and change of wavelength.
III. MICROWAVE PRINCIPLES AND PARAMETERS AFFECTING PASSIVE MICROWAVE SYSTEMS

The microwave (MW) region may be broadly defined as that frequency range between approximately $10^9$ and $10^{12}$ Hertz (cps), corresponding to free-space wavelengths of the order of a few tens of centimeters to a few tenths of a millimeter (Atwater, 1962). Somewhat shorter regions have been designated in the literature (e.g. Colwell et al., 1963, Reeves ed., 1968), probably reflecting operational considerations. Because the EM spectrum is a continuum, there are no definitive boundaries, rather the various regions have been roughly categorized with respect to the nature of their interactions with matter and the types of instruments capable of detecting their signals. Figure 1 shows the MW region as broadly defined, however, subsequent data and discussions will generally deal with more limited portions of the region where research has been concentrated.

For the MW region and at terrestrial temperatures (Hodgin, 1964), where $hf << kT$, Planck's radiation formula can be replaced by the Rayleigh-Jeans approximation which is accurate to about one percent:

$$ B(f,T) = \frac{2kT}{\lambda^2} . $$

(5)

where $B(f,T)$ is the specific intensity (watts-m$^{-2}$-steradian$^{-1}$-Hertz$^{-1}$)
Figure 1. Microwave Region of the Electromagnetic Spectrum
This gives the transposition between the infrared region where the fourth (or higher) power law of temperature (Wien equation) is in effect and the MW region where the first power of temperature is in effect (Vivian, 1962).

Assuming thermal equilibrium, emissive power equals absorptive power according to Kirchhoff's Law and the incoming energy must equal the outgoing energy. Thus the components resulting from the interaction of EM energy upon a surface can be expressed in terms of power, \( P \), in normalized form as

\[
\frac{P_{\text{reflected}}}{P_{\text{incident}}} + \frac{P_{\text{emitted}}}{P_{\text{incident}}} + \frac{P_{\text{transmitted}}}{P_{\text{incident}}} = 1 \quad (6)
\]

and \( \rho + \varepsilon + \tau = 1 \), where

\( \rho \) is the reflected component,
\( \varepsilon \) is the emitted component, and
\( \tau \) is the transmitted component.

Since no MW energy is transmitted through the earth, \( \tau \) is considered zero, and the resulting expression becomes \( \rho = 1 - \varepsilon \).

Only the emitted and reflected radiation need to be considered. These two components can be expressed as apparent brightness temperature, \( T_B \), which written in simple form is: \( T_B = \varepsilon T_g + \rho T_s \); where

\( T_B \) is measured in degrees Kelvin
\( \varepsilon \) = emittance of the target material
\( T = \text{thermometric ground temperature} \)
\( \rho = \text{surface reflectance} \)
\( T_s = \text{sky brightness temperature} \)

A slightly expanded version of the above equation to include the atmospheric contribution, can be expressed as

\[
T_B = \rho T_g + \varepsilon T_g + \varepsilon_a T_a + \rho \varepsilon T_a
\]

where

\( T_a = \text{thermometric atmospheric temperature} \)
\( \rho_g = \text{surface reflectance} \)
\( \varepsilon_g = \text{surface emittance} \)
\( \varepsilon_a = \text{atmospheric emittance} \)

Figure 2 shows these sources of measured energy.

The apparent brightness temperature is also dependent on the angle of incidence, \( \theta \). The microwave sky temperature is shown as a function of the angle of incidence in Figure 3 for zenith sky temperatures of 40 ° and 30 ° K. The sky temperature increases with increasing angle from the zenith because of the increased atmospheric path. Energy is absorbed and radiated by the atmosphere.

In Figure 4 the relative response of horizontally- and vertically-polarized components with respect to viewing angle are shown for the microwave sky temperatures of Figure 3. The vertical component shows a Brewster angle effect which is maximum at a viewing angle of about 65°.
Figure 2. Sources of Measured Energy for Passive Microwave System
Figure 3. Theoretical Radiometric Sky Temperature
(no polarization) (Kennedy and Edgerton, 1967)

Figure 4. Theoretical Microwave Temperature vs. Viewing Angle
(Kennedy and Edgerton, 1967)
At this point the reflectivity is zero and emissivity is one. Therefore, the radiometric temperature is identical to the thermometric temperature. The horizontal component drops in radiometric temperature with increasing observation angle and maximum separation of vertical and horizontal components occurs in the region slightly beyond the Brewster point. This radiometric temperature difference can often be useful in determining the physical properties of materials. Also note that the horizontal component values for the respective zenith sky temperatures diverge almost immediately as the viewing angle increases; however, the vertical component values do not diverge until after the Brewster point.

At MW wavelengths, the differences between the radiometric temperatures of various terrain surfaces are primarily the result of differences in their emittances. The radiometric temperature observed for terrain bodies is also a function of the atmospheric absorption. At MW frequencies, this contribution can be large at high frequencies, and if operating at absorption bands (e.g., H₂O and O₂).

Gross thermometric temperature differences which have been measured for different types of terrain are illustrated in Figure 5 (Conway, et al., 196?). It is apparent from this that absolute MW apparent temperature measurements will change as a result of seasonal and diurnal effects. The absolute thermometer temperature will be a function of solar heating, thermal diffusivity, radiation and local cooling.

The differences in apparent temperatures between various materials and dependence on incidence angle is illustrated in Figure 6. These curves will change if the frequency is changed markedly (however, no frequency information was given with the figure).
Figure 5. Typical Gross Thermometric Temperature Differences for Various Terrain Types (Conway, et al., 1962)
Figure 6. Measured Radiometric Temperature ($T_M$) vs. Viewing Angle (horizontal polarization) (Conway, et al., 1962)
In the MW region very few natural materials have emittances that are close to one. The majority are distributed over the range of 0.6 to 0.9; however, vegetation, such as high grass, often approaches an emissivity of unity and thus can be used for calibration purposes (Vivian, 1962). Certain materials exhibit considerable changes of emittance with changes of frequency over the MW region. Water, for example, ranges from a low of about 0.05 at the low MW frequencies (20 cm) to a value of approximately 0.3 at the 70 GHz (0.4 cm) region. Water reaches an emittance of approximately one in the far IR region; so this transition occurs somewhere between 70 GHz and the far IR (Conway and Sakamoto, 1964).

Factors controlling MW emittance of a surface are:

- Wavelength (or frequency)
- Polarization
- The angle of incidence at which the surface is observed
- The complex dielectric constant* of the material comprising the surface. If the body consists of several layers of different materials, then the surface emittance can depend on subsurface as well as surface layers.
- The surface roughness of the surface layer
- Subsurface interface effects.

---

*This so called "constant\" is discussed at some length in the next section on properties of natural occurring materials. Actually it is not a constant, but varies to some degree as a function of temperature and frequency; and so will be referred to as dielectric coefficient.
Thus, the emittance and reflectance of terrain constituents and the resulting apparent temperature are functions of wavelength, polarization, incidence angle, thermometric temperature, surface roughness, subsurface structure and complex dielectric coefficient of the material. These in turn are either properties of, or affected by certain properties of, the natural occurring materials.
IV. PROPERTIES OF NATURALLY OCCURRING MATTER AND PHENOMENA AFFECTING EMR AND PASSIVE MICROWAVE MEASUREMENTS

A. SOLAR ENERGY

The input of solar energy to the earth is essentially a solid geometrical problem. The solar radiation incident upon the earth's atmosphere is partially absorbed and partially reflected or scattered by the atmosphere and the earth's surface. The portion scattered and reflected back into space is generally referred to as albedo. The global yearly average albedo is about 35% based upon work by Fritz. Houghton calculated about 34% and Beuer and Phillips got 42% which is too high. The relation of incident solar and albedo radiances by latitude as determined by Houghton can be seen on Figure 7 (Johnson, 1965).

All of the values except those for solar radiation are apt to be highly variable. For example, water which covers most of the earth's surface, absorbs over 90% of the incident solar radiation when solar-altitude angle is above 25°. This absorption would lead to an extremely low albedo when the sky is very clear, whereas in the presence of extensive cloudiness about half of the incident solar radiation may be reflected, representing a change by a factor of five or more from the extreme of no cloudiness. Similarly, in the case of the outgoing radiation from the earth and atmosphere, one can imagine the extremes of dry and cloudless conditions and of extensive high-level cloudiness. In the former case there will be appreciable radiation from the earth's
Annual-average values of the albedo radiation and of the long wavelength radiation emitted by the earth and atmosphere, shown as functions of latitude. Also shown is the annual-average flux of solar energy incident upon the atmosphere.

Data from Houghton.

Figure 7. Incident-Solar and Earth Radiation vs. Latitude (Johnson, 1965)
surface at temperatures as high as $+30^\circ$ C, while in the latter the source of the radiation may have a temperature as low as $-55^\circ$ C (Johnson, 1965). Although the overall values by Bauer & Phillips are too high, they have tabulated data showing seasonal trends of the long-wavelength radiation which is probably valid in a relative sense.

B. ATMOSPHERE

Transmission of microwaves through the atmosphere is much higher than for IR. It generally increases with increasing wavelength, however, there are some narrow, fairly steep-peaked sections of relatively significant attenuation due to water vapor and oxygen which are diagrammed in Figure 8. Windows between these peaks occur at approximately 300-250 GHz (approx. 0.1 cm), 130 GHz (0.2 cm) and 33 GHz (0.9 cm). From about 13 GHz (1.8 cm) to the low-frequency end of the MW region (about 1 GHz), transmission is very good.

Although very fine solid and liquid particles in the form of haze and clouds are fairly transparent to MW radiation (especially at the longer wavelengths) rainfall has an attenuating effect which increases with decreasing wavelength due to scattering, self-emission, and attenuation. Attenuation vs. wavelength for various rates of rainfall is shown in Figure 9. At wavelengths shorter than about 0.1 cm, other absorption bands caused by CO$_2$, N$_2$, dust, fog, etc. make remote sensing of terrain most difficult.
Figure 8. Atmospheric Attenuation of Microwaves Due to Water Vapor and Oxygen (Reeves ed., 1968)
Figure 9. Attenuation vs. Rainfall Rate (rain at 20°C) (Hunter, 1964)
C. PROPERTIES OF MATERIALS

The electrical properties of the materials determine to a large extent the character and relative amounts of reflection and absorption. Most non-metallic earth materials are dielectrics (i.e. "insulators"). An ideal dielectric is a medium in which a moderate electric field once established may be maintained without loss of energy. Actual dielectrics may be slightly conducting and the line of demarcation between dielectrics and conductors is not sharp.

The dielectric constant of a material may be defined as the ratio of the capacitance of a condenser filled with the material to the capacitance of the condenser when a vacuum exists between its plates. However, this property is not really a constant because its value can change as a function of temperature and frequency, so in this paper it is referred to as the dielectric coefficient.

For a dielectric material the movement of charges is limited by various structural restoring forces, so that the application of an electric field to such a material produces only limited movement of these charges about points of equilibrium. The net result of this is that centers of gravity of positive and negative charges in the structure no longer coincide, i.e., the material will behave as an electric dipole. The material is then said to be polarized.

There are various types of charge movements that contribute to the total polarization, $P$. These are $P_e$ (electronic), $P_a$ (atomic) and $P_o$ (orientation or molecular). The $P_e$ associated relaxation time is
very short (about $10^{-15}$ sec) and is similar to optical polarization. So for material exhibiting only $P_e$, the dielectric coefficient ($\varepsilon$) can be directly related to the refractive index ($n$) of the material by $\varepsilon \approx n^2$. And because the refractive index of a material depends both on the temperature of measurement and on the frequency of the wavelength used, $\varepsilon$ must also depend on the frequency of the EMR.

The $P_a$ associated relaxation time is slower (about $10^{-13}$ sec) and sometimes is referred to as IR polarization.

$P_o$ is the result only of movement of dipoles in the field itself. Because of forces restricting molecular movements the relaxation times may be very long and indeed in some cases the hindrance forces may be such as to inhibit orientation completely below a certain temperature. Thus $P_o$ is temperature dependent.

The nature of EMR interactions with soil, rock, water, vegetation, etc. depends on frequency, intensity and polarization of the EMR, and on properties of the solid or liquid with which the EMR is interacting. There are two general interactions: reflection of EMR, and absorption or penetration of EMR. Reflection may be nearly total or partial; and if partial, all or most of the same frequencies may be absorbed, or a portion of all or most frequencies may be absorbed and the remaining reflected. EMR that penetrates into solid or liquid material may be reflected from boundaries between layers of different properties or may be dissipated in the form of heat or a combination of these. EMR that goes to produce heat is, theoretically, re-
radiated, but the reradiation may be at a different wavelength, may be so small as to be detected with great difficulty, or may occur later. The interaction between EMR and the solid and liquid earth materials of the lithosphere and hydrosphere is complex and imperfectly known (Reeves ed., 1968).

Even though materials are fairly good dielectrics, most have a certain amount of energy loss by conductivity. (Those that have significant loss due to conductivity are sometimes called "lossy" dielectrics.) Consequently the dielectric coefficient, $\varepsilon$, is usually expressed by two terms, $\varepsilon'$ and $\varepsilon''$, and is then called the complex dielectric coefficient. The first term $\varepsilon'$, is the dielectric coefficient for the material and the second term, $\varepsilon''$, is the loss factor. The ratio $\varepsilon''/\varepsilon'$ is a direct measure of the ratio of the conduction and displacement currents, and is referred to as the loss tangent (tan $\delta$). For many solid materials, $\varepsilon'$ remains relatively constant over a wide range of frequencies, especially in the MW portion of the EM spectrum. The variation of tan $\delta$ with frequency usually is much greater. $\varepsilon$ is sometimes referred to as the relative dielectric coefficient ($\varepsilon_r$); and when complex, $\varepsilon'$ as the real part and $\varepsilon''$ as the imaginary part of the relative complex dielectric coefficient. The equation for $\varepsilon_r$ appears in the literature in a variety of notations, however, it basically has the form:

$$\varepsilon_r = \varepsilon' - i \varepsilon''.$$ (8)
The higher the value of tan $\delta$, the greater the attenuation of EMR that penetrates a dielectric material. Tan $\delta$ generally increases with frequency, so the lower frequencies generally have greater penetration.

Considering the important role that the dielectric coefficient plays in determining the emitted and reflected radiation obtained from natural materials, the data on this property is very poor indeed.

Kennedy (1967) has reported that insufficient measurements have been made at many frequencies of interest, that in many cases the data are unreliable, and that techniques developed for measuring the dielectric coefficient in the lower frequency regions, such as MW, are not very practical. Many times misleading information is developed because the sample being examined is so small as to be non-representative of a natural occurring mass.

The G. S. A. Handbook of Physical Constants (Clark ed., 1966) has three tables containing dielectric coefficient data on minerals, rocks and soil. One table lists the values under two categories: radio frequencies and optical frequencies (the former of which covers a very wide range); and for some minerals it lists values along crystal axes, and for two of the sedimentary rock types lists values for different moisture content. The second table lists the values as a function of frequency ranging from 100 Hz to 10 MHz. The third table is titled "Low-Frequency Dielectric Constants", with no mention of what range "low frequency" encompasses.
There is no point in perpetuating data whose reliability is in question, so none of the above-mentioned tables will be reproduced here. Rather, some general statements will be made on the subject, followed by a table of $\varepsilon_r$ and $\tan \delta$ as a function of frequency that was prepared from several sources by Peake, 1967 (Table 1).
<table>
<thead>
<tr>
<th>FREQ. (GHz)</th>
<th>$\varepsilon_r$</th>
<th>TAN $\delta$</th>
<th>DENSITY</th>
<th>MATERIAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>35</td>
<td>2.3</td>
<td>.08</td>
<td></td>
<td>Red granite</td>
</tr>
<tr>
<td>35</td>
<td>2.4</td>
<td>.06</td>
<td></td>
<td>White granite, crushed</td>
</tr>
<tr>
<td>35</td>
<td>1.7</td>
<td>.012</td>
<td></td>
<td>White pumice, crushed</td>
</tr>
<tr>
<td>35</td>
<td>1.6</td>
<td>.02</td>
<td></td>
<td>Black pumice, crushed</td>
</tr>
<tr>
<td>14</td>
<td>4.6</td>
<td>.006</td>
<td>1.81</td>
<td>Halite</td>
</tr>
<tr>
<td>14</td>
<td>3.8</td>
<td>.012</td>
<td>1.56</td>
<td>Halite</td>
</tr>
<tr>
<td>14</td>
<td>3.3</td>
<td>.009</td>
<td>1.42</td>
<td>Halite</td>
</tr>
<tr>
<td>14</td>
<td>2.9</td>
<td>.011</td>
<td>1.63</td>
<td>Desert sand</td>
</tr>
<tr>
<td>14</td>
<td>8.2-8.6</td>
<td>.004-.02</td>
<td>2.65</td>
<td>Limestone</td>
</tr>
<tr>
<td>14</td>
<td>4.7-6.0</td>
<td>.01-1</td>
<td>2.35</td>
<td>Asphalt</td>
</tr>
<tr>
<td>14</td>
<td>4.5-52.</td>
<td>.02-.06</td>
<td>2.10</td>
<td>Concrete</td>
</tr>
<tr>
<td>~10</td>
<td>4</td>
<td>.1</td>
<td></td>
<td>Limonite, coarse</td>
</tr>
<tr>
<td>~10</td>
<td>4</td>
<td>.01</td>
<td></td>
<td>Limonite, fine</td>
</tr>
<tr>
<td>10</td>
<td>4.8</td>
<td>.005</td>
<td>2.45</td>
<td>Basalt, vesicular</td>
</tr>
<tr>
<td>10</td>
<td>4.4</td>
<td>.013</td>
<td>2.63</td>
<td>Biotite granite</td>
</tr>
<tr>
<td>10</td>
<td>5.1</td>
<td>.081</td>
<td>2.35</td>
<td>Obsidian</td>
</tr>
<tr>
<td>10</td>
<td>4.8</td>
<td>.009</td>
<td>2.74</td>
<td>Olivine basalt</td>
</tr>
<tr>
<td>10</td>
<td>5.4</td>
<td>.086</td>
<td>2.68</td>
<td>Serpentine</td>
</tr>
<tr>
<td>10</td>
<td>5.0</td>
<td>.027</td>
<td>1.62</td>
<td>Volcanic ash</td>
</tr>
<tr>
<td>10</td>
<td>4.7</td>
<td>.017</td>
<td>2.27</td>
<td>Altered tuff</td>
</tr>
<tr>
<td>10</td>
<td>5.5</td>
<td>.016</td>
<td>2.03</td>
<td>Tuff</td>
</tr>
<tr>
<td>10</td>
<td>4.7</td>
<td>.01</td>
<td>2.3</td>
<td>Hornblende</td>
</tr>
<tr>
<td>10</td>
<td>3.0</td>
<td>.012</td>
<td>0.78</td>
<td>Mono pumice</td>
</tr>
<tr>
<td>8.5</td>
<td>3.3</td>
<td>.0055</td>
<td>1.11</td>
<td>Magnesite, hard packed</td>
</tr>
<tr>
<td>8.5</td>
<td>2.45</td>
<td>.002</td>
<td>1.22</td>
<td>Quartz, powder</td>
</tr>
<tr>
<td>1.0</td>
<td>35</td>
<td>.175</td>
<td>3.01</td>
<td>Chondritic meteorite</td>
</tr>
<tr>
<td>&gt; 0.1</td>
<td>10</td>
<td>.02</td>
<td></td>
<td>Basalt, oven dry</td>
</tr>
<tr>
<td>&gt; 0.1</td>
<td>10</td>
<td>.08</td>
<td></td>
<td>Basalt, 0.36% water</td>
</tr>
<tr>
<td>&gt; 0.1</td>
<td>7-9</td>
<td>.10</td>
<td></td>
<td>Granite</td>
</tr>
<tr>
<td>&gt; 0.1</td>
<td>8.4</td>
<td>.066-.018</td>
<td>2.65</td>
<td>Limestone</td>
</tr>
<tr>
<td>&gt; 0.1</td>
<td>5.5</td>
<td>.001</td>
<td></td>
<td>Rhyolite</td>
</tr>
<tr>
<td>3</td>
<td>81</td>
<td>.38</td>
<td></td>
<td>Potato, 80% water</td>
</tr>
</tbody>
</table>

**TABLE 1.** Relative Dielectric Coefficient and TAN $\delta$ vs. Frequency (Peake, 1967)
All dielectric materials have a coefficient greater than one. Normal solid insulators have values in the range 2 to 10; dipole liquids (water) in the range 20 to 80. The dielectric coefficient of water is frequency dependent in the upper MW bands, therefore earth materials that have significant amounts of water will have dielectric coefficients that are not only dependent on the material but also on the moisture content. Water is one of the relatively few materials for which dielectric coefficients and loss tangents are available at MW frequencies (Conway & Sakamoto, 1964). Besides moisture content and composition, the electrical properties ($\varepsilon'$ & $\varepsilon''$) are affected by density and homogeneity of the material.

At the Brewster angle the vertical reflection coefficient becomes zero for a homogeneous material, i.e., the emissivity becomes equal to unity. This gives a peak in the MW temperature. Thus, by locating the peak, an estimate of the dielectric coefficient can be made. For "lossy" dielectrics the emissivity does not become unity, but it will still show a peak. The peak still can be used to predict the magnitude of the dielectric coefficient (Conway & Sakamoto, 1964).

When EMR is perpendicularly incident on a perfect dielectric, the amount of energy transmitted through the dielectric material is not diminished; however, the velocity at which the EMR travels through the material is less than that in free space. As the angle of incidence departs from the normal, part of the EMR is reflected and
part transmitted into (and through) the dielectric. Under certain conditions, when a critical angle is reached, there will be total reflection. At another critical angle, the Brewster angle, there will be total refraction.

The degree of penetration is a function of EMR wavelength and certain material properties. It increases with temperature and wavelength. It decreases with increasing tan δ, moisture content and ionization of interstitial fluids. Figure 10 shows skin depth vs. frequency (Peake, 1967). Table 2 shows how penetration is affected by temperature in the case of water, and by moisture content in the case of soil (Feder, 1960) (wavelength unspecified).

Thermal properties of a material are dependent on mineral composition and structure, water content, pressure, temperature and wavelength. The thermal conductivity of a material can be defined by the equation: $k = q / (∂T/∂x)$, where $q =$ the rate of conduction of heat across a unit area of the material perpendicular to the temperature gradient $∂T/∂x$.

The general heat conduction equation in three dimensions assuming constant properties is given by:

$$\frac{∂^2T}{∂x^2} + \frac{∂^2T}{∂y^2} + \frac{∂^2T}{∂z^2} + \frac{q}{k} = \frac{1}{α} (\frac{∂T}{∂t})$$  \hspace{1cm} (9)

where $k$ is the thermal conductivity, $q$ is the rate of heat flow per unit volume, and $α$ is diffusivity. $α = k/ρc$ where $ρ = $ density and $c = $ specific heat.
Figure 10. Skin Depth vs. Frequency for $\varepsilon/\tan \delta$
(Peake, 1967)
<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>CONDITION</th>
<th>TEMP. (°C)</th>
<th>DIELECTRIC COEFF.</th>
<th>LOSS FACTOR</th>
<th>PENETRATION (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fresh water</td>
<td>with conductivity</td>
<td>5</td>
<td>41</td>
<td>.95</td>
<td>.17</td>
</tr>
<tr>
<td>Sea water</td>
<td></td>
<td>15</td>
<td>49</td>
<td>.70</td>
<td>.21</td>
</tr>
<tr>
<td>Sea water</td>
<td></td>
<td>25</td>
<td>55</td>
<td>.54</td>
<td>.25</td>
</tr>
<tr>
<td>Sea water</td>
<td></td>
<td>28</td>
<td>65</td>
<td>.47</td>
<td>.26</td>
</tr>
<tr>
<td>Ice</td>
<td></td>
<td>-12</td>
<td>3.17</td>
<td>.07 x $10^{-2}$</td>
<td>763.</td>
</tr>
<tr>
<td>Soil, sandy</td>
<td>dehydrated</td>
<td>25</td>
<td>2.53</td>
<td>.36</td>
<td>187.</td>
</tr>
<tr>
<td>&quot; &quot;</td>
<td>2.18% moisture</td>
<td>25</td>
<td>2.50</td>
<td>6.5</td>
<td>9.3</td>
</tr>
<tr>
<td>&quot; &quot;</td>
<td>3.88% &quot;</td>
<td>25</td>
<td>4.40</td>
<td>12.0</td>
<td>3.8</td>
</tr>
<tr>
<td>&quot; &quot;</td>
<td>16.8% &quot;</td>
<td>25</td>
<td>20.0</td>
<td>29.0</td>
<td>.74</td>
</tr>
<tr>
<td>Soil, loamy</td>
<td>dehydrated</td>
<td>25</td>
<td>2.44</td>
<td>.14</td>
<td>437.</td>
</tr>
<tr>
<td>&quot; &quot;</td>
<td>2.2% moisture</td>
<td>25</td>
<td>3.50</td>
<td>3.0</td>
<td>17.</td>
</tr>
<tr>
<td>&quot; &quot;</td>
<td>13.77% &quot;</td>
<td>25</td>
<td>13.80</td>
<td>13.80</td>
<td>1.4</td>
</tr>
<tr>
<td>Soil, Ariz.</td>
<td>6.0% &quot;</td>
<td>?</td>
<td>8.1</td>
<td>26.0</td>
<td>1.3</td>
</tr>
<tr>
<td>&quot; &quot;</td>
<td>20.0% &quot;</td>
<td>25</td>
<td>19.0</td>
<td>25.0</td>
<td>.88</td>
</tr>
<tr>
<td>Soil, Texas</td>
<td>nearly dehydrated</td>
<td>25</td>
<td>2.8</td>
<td>.51</td>
<td>112.</td>
</tr>
<tr>
<td>&quot; &quot;</td>
<td>9.1% moisture</td>
<td>25</td>
<td>4.6</td>
<td>.9.2</td>
<td>4.8</td>
</tr>
</tbody>
</table>

**TABLE 2. Relative Penetration for Soil and Water (Feder, 1960)**
The thermal diffusivity is important in transient heat flow problems; in situations involving heat conduction in the steady state, \( \alpha \) disappears from the above equation. A large value of \( \alpha \) indicates the ability of a body to equalize temperature differences occurring within itself. This could combine a small value of \( c \), denoting little heat storage, and a large value of \( k \) indicating a high heat flux for a given temperature gradient. The value of the diffusivity can either be measured directly, or computed from values of \( k, \rho \) and \( c \) which have been experimentally determined. Figure 11 shows the effects of relative thermal diffusivities for various rock types (Reeves ed., 1968).

Thermal conductivity measurements have been made on a wide range of rocks and a various assortment of minerals and individual crystals. The section on thermal conductivity in the Handbook of Physical Constants, however, contains some cautionary words about the tables of data therein: "Even for relatively well-defined substances, measurements by qualified investigators show startling discrepancies; some of them are due to real differences between different samples of what is nominally the same material, but some must be attributed to experimental error" (Clark ed., 1966). Some selected data was taken from two of the tables to demonstrate how the conductivity can vary with respect to various parameters, not for the significance of the actual values. Range in conductivity as a function of rock type at
Figure 11. Effects of Relative Thermal Diffusivities for Six Rock Samples (Reeves ed., 1968)
a given temperature is shown in Figure 12. The effect of temperature on the conductivity of various rock types is presented in Table 3.

A few general conclusions that can be drawn from other tables in the handbook are that wetting (or replacing air in pore space with water) and simple compression of rocks-increases the thermal conductivity in most cases, and conductivity parallel to the optic axes of noncubic crystals is greater than perpendicular to them.

Physical properties of earth materials that affect passive MW measurements include crystal structure and anisotropy; petrography and inhomogeneities of rock masses; subsurface interfaces caused by bedding, lithologic contacts, water tables, and fractures; density and porosity; and surface roughness and topographic slope. To a large degree these have already been covered or implied regarding their contribution to electric and thermal parameters and their interaction with EMR. To what extent some of these properties can affect MW systems will be illustrated in the following figures.

The important effect of moisture on radiometric temperatures is illustrated in Figure 13 for a playa sediment. The vertical polarization curves in the top diagram indicate that with increasing moisture, the Brewster angle shifts further away from the nadir and has a more pronounced peak. For both the vertical and horizontal polarizations, increasing moisture content substantially lowers the temperatures.

Figure 14 shows how particle size can affect radiometric temperature curves. In the lower diagram where the rock diameter is slightly
<table>
<thead>
<tr>
<th>ROCK TYPE</th>
<th>CONDUCTIVITY (MEASUREMENTS MADE AT ABOUT 20°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(x10⁻³ cal/cm sec °C)</td>
</tr>
<tr>
<td></td>
<td>5</td>
</tr>
<tr>
<td>Granite</td>
<td></td>
</tr>
<tr>
<td>Granodiorite</td>
<td></td>
</tr>
<tr>
<td>Granodiorite</td>
<td></td>
</tr>
<tr>
<td>Lava</td>
<td></td>
</tr>
<tr>
<td>Schist:</td>
<td></td>
</tr>
<tr>
<td>Perpendicular</td>
<td></td>
</tr>
<tr>
<td>Parallel</td>
<td></td>
</tr>
<tr>
<td>Calcareous mica phyllite</td>
<td></td>
</tr>
<tr>
<td>Perpendicular</td>
<td></td>
</tr>
<tr>
<td>Parallel</td>
<td></td>
</tr>
<tr>
<td>Quartzite</td>
<td></td>
</tr>
<tr>
<td>Quartzite</td>
<td></td>
</tr>
<tr>
<td>Limestone</td>
<td></td>
</tr>
<tr>
<td>Dolomite</td>
<td></td>
</tr>
<tr>
<td>Sandstone</td>
<td></td>
</tr>
<tr>
<td>Sandstone</td>
<td></td>
</tr>
<tr>
<td>Carbonaceous shale</td>
<td></td>
</tr>
<tr>
<td>Marl</td>
<td></td>
</tr>
</tbody>
</table>

Figure 12. Thermal Conductivity Ranges for Selected Rock Types (Clark ed., 1966)
## TABLE 3. Temperature vs. Thermal Conductivity for Selected Rock Types (Clark ed., 1966)

<table>
<thead>
<tr>
<th>ROCK TYPE</th>
<th>TEMP. (°C)</th>
<th>CONDUCTIVITY 10^-3 cal/cm sec °C</th>
<th>DENSITY gm/cm^3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Granite</td>
<td>0</td>
<td>5.80</td>
<td>2.64</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>5.60</td>
<td></td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>5.42</td>
<td></td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>5.12</td>
<td></td>
</tr>
<tr>
<td>Granite</td>
<td>0</td>
<td>8.4</td>
<td>2.61</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>7.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>7.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>6.5</td>
<td></td>
</tr>
<tr>
<td>Granite gneiss: Parallel to foliation</td>
<td>0</td>
<td>7.42</td>
<td>2.64</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>6.58</td>
<td></td>
</tr>
<tr>
<td>Perpendicular</td>
<td>0</td>
<td>5.17</td>
<td>4.82</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Limestone (carbonaceous):</td>
<td>0</td>
<td>8.2</td>
<td>2.69</td>
</tr>
<tr>
<td>Parallel to bedding</td>
<td>100</td>
<td>7.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>6.5</td>
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</tr>
<tr>
<td>Perpendicular</td>
<td>0</td>
<td>6.1</td>
<td>2.83</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>5.4</td>
<td></td>
</tr>
<tr>
<td>Dolomite</td>
<td>0</td>
<td>11.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>10.3</td>
<td></td>
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Figure 13. Radiometric Temperatures vs. Moisture Content
(13.4 GHz) (Kennedy and Edgerton, 1967)
Figure 14. Radiometric Temperature Profiles for Varying Rock Size (13.4 GHz) Kennedy and Edgerton, 1967
less than the wavelength, the Brewster angle is readily discernible and the maximum separation between the vertical and horizontal polarizations is considerable. In the middle diagram where the rock diameter is nearly six times greater than the wavelength, the Brewster angle effect is beginning to fade and the separation between vertical and horizontal polarizations is lessening. In the top diagram, where the rock diameter exceeds the wavelength by roughly fifty times, there is no apparent Brewster angle effect and the previously distinctive pattern of the vertical and horizontal polarizations has changed to a narrowly-separated oscillating pair of curves.

An effect of topographic slope from a volcanic cinder cone is demonstrated in Figure 15. The radiometric temperatures at the longer wavelengths indicate that the subsurface temperatures were noticeably warmer on the south side than the north side. This difference is attributable to sun angles, whereby the sun heats the south side of the cinder cone to higher temperatures than the north side during the day. The lack of a similar variation for the short wavelength curve is evidence that the surface cinder material is more sensitive to the surrounding air temperature than to subsurface temperatures (Blinn, et al., 1968).

Figures 16 and 17 compare radiometric temperatures at two different wavelengths for a variety of earth materials ranging from basalt to mud. The temperatures for mud are much lower than those for the other materials, again demonstrating the pronounced effect
Figure 15. Radiometer Responses over Cinder Cone
(Nighttime, baselines-adjusted) (Blinn, et al., 1968)
Figure 16. Comparison of Mean Radiometric Temperatures at 37 GHz, Vertical Polarization (Kennedy, et al., 1966)
Figure 17. Comparison of Mean Radiometric Temperatures at 13.4 GHz, Vertical Polarization (Kennedy, et al., 1966)
of high moisture content. Also, in comparing the mud curves, the
temperatures for the longer wavelength case are noticeably lower.

For the same group of earth materials, Figures 17 and 18 compare radiometric temperatures for vertical and horizontal polarizations at the same wavelength. In the horizontal polarization case the temperature differential between mud and inundated mud is greater than in the vertical polarization case.

Another important effect on radiometric temperature measurements is diurnal fluctuation. Figure 19 illustrates thermister probe temperatures for basalt cinders at varying depths. The diurnal fluctuation decreases in amplitude with increasing depth and shows a time lag that is also dependent upon depth.

Diurnal MW temperatures for a soil and a basalt are represented in Figure 20. The fluctuation is greater for the soil which has a smaller relative dielectric coefficient and thermal diffusivity. The effect of wavelength versus time of day for several different media is discussed in some detail in the next section (see Figures 21 and 22).
Figure 18. Comparison of Mean Radiometric Temperatures at 13.4 GHz, Horizontal Polarization (Kennedy, et al., 1966)
Figure 19. Diurnal Heating-Cooling Curve for Basalt Cinders
(Blinn, et al., 1968)
Figure 20. Apparent Microwave Temperature Fluctuations Showing Time Lag and Amplitude (after Strangway and Holmer, 1966)
V. SUMMARY AND DISCUSSION OF PASSIVE MICROWAVE FIELD EXPERIMENTS

At the beginning of this study it was envisaged that the crux of the problem would be to gain an understanding of the interrelationships between properties of materials and EMR in the MW portion of the spectrum. It soon became evident, however, that although one could get a fairly clear picture on which properties are pertinent to the problem, the state-of-affairs on measurements of these properties for materials of interest is rather discouraging. The data on earth materials, in many cases, is insufficient, inaccurate, presented without all controlling factors being specified, and compiled in a manner not useful for the remote sensing scientist. So, there is a need for systematic analyses of properties with full cognizance and monitoring of all variable elements affecting the property. These analyses should be conducted under conditions that will make the data useful for environmental studies (e.g., at or near atmospheric pressures, and thermal ranges found at or near the surface of the earth).

Assuming that adequate and reliable measurements have been made at the elementary level (i.e., molecules and crystals, or even small lab specimens); is that really sufficient for predicting what will occur when these elementary units are combined as found in nature? Mineral assemblages and distribution within a petrologic body; random vs. ordered orientation of crystals and rock units; variations in density, pore space and particle size; presence of fluids with their chemical and thermal contributions; medium discontinuities such as fractures, faults, unconformities; and temporally-associated phenomena like induced electric and magnetic fields, and chemical
and structural flux; all contribute toward greatly complicating the resultant material properties' response to EMR. Attempting to model this type of problem certainly appears to be a formidable task, and the prospect of success may be questionable. Furthermore, considering that remote sensing systems integrate over some given area, the ultimate signal will be determined by a statistical response of an assemblage of material, not by the nature of the individual crystal.

An alternative is to consider approaching the problem from the other direction. Namely finding a suitable area for making field measurements and empirically trying to unravel the contributing factors. By suitable area is meant relatively simple area, so that the number of variables is reduced and the remainder can be handled with some degree of confidence regarding resolvability.

This latter approach can be well illustrated by the multifrequency MW sensing of a volcanic province near Mt. Lassen, California by JPL and the University of Nevada (Blinn et al., 1968). The radiometric temperature data shown diagrammatically on Figures 21 and 22 from their report were essentially evaluated as discussed below.

The average measured values of antenna temperatures over water, lava, and unaltered cinder of Flight 6 (night-time) are on Figure 21. In the IR, the warmest unit is water, then lava, and cinder is the coolest. The highest frequency MW (34 GHz) is coolest over water, warmest over lava and intermediate over cinder. The lowest frequency MW (9.3 GHz) is coolest over water, intermediate over lava, and warmest over cinder. An intermediate MW frequency (15.8 GHz) showed no contrast between lava and cinder.
Figure 21. Nighttime Radiometer Responses over Water, Lava and Cinder (Blinn, et al., 1968)

Figure 22. Daytime Radiometer Responses over Water, Lava and Cinder (Blinn, et al., 1968)
The values from Flight 5 (daytime) are shown in Figure 22. The IR is coolest over water, intermediate over lava, and warmest over cinder. The 34 GHz (0.9 cm) MW is coolest over water, warmest over lava, and intermediate over cinder. The 15.8 GHz (1.9 cm) and 9.3 GHz (3.2 cm) show even cooler values over water, and warmest over lava, with the lava-cinder contrast being greater than for the 34 GHz.

Several factors that could contribute to the signal differences between the lava and unaltered cinder are chemical composition, moisture content, surface characteristics, MW penetration depth and thermal properties.

Chemical composition was ruled out because it was essentially the same for the two materials. Moisture (very low in both, about 2 to 3%), which lowers brightness temperature and decreases penetration, was ruled out because consistently cooler temperatures at all frequencies were not shown over either of the materials. Surface roughness, which affects cooling rates and hence MW brightness temperature, was ruled out for the same reason. If all other factors are equal, a penetration depth difference would occur between basalt and cinder with the 9.3 GHz, but no difference at the surface (IR and 34 GHz). However, this is not so according to the data; thus while penetration depth could be a contributing factor, it was not deemed a controlling factor.

The investigators concluded that the controlling factor appears to be the thermal properties of the material. The better thermal conductor of the two materials will show a warmer surface temperature and a cooler temperature at depth at night. And there will be an isothermal depth at
which the temperature of both is equal. Although the first four factors may contribute to the signal (especially penetration depth), the explanation that the cinder, because of its porosity, is not as good a thermal conductor as the basalt, seemed to best fit the observed data. The daytime flight results support this conclusion.

Another passive MW field experiment was conducted over a buried karst area in northern California near Cool by Aerojet General (Kennedy, 1968). In this case the objective was to try to detect subsurface solution voids. Here the field conditions were more complex than in the volcanic area previously discussed. There was a soil cover of about 12 feet minimum which contained roughly 26% moisture content because considerable rain fell in the two weeks prior to when the measurements were taken. The soil was very heterogeneous, consisting of a wide range of particle sizes from silt to cobbles. In addition, the ground surface was covered by a mat of three-inch tall, dense grass.

Using radiometers operating at 13.5 GHz (2.2 cm), 37 GHz (0.8 cm) and 94 GHz (0.3 cm), Kennedy reported that a one-to-one correlation of cool anomalies to voids was obtained with the lowest frequency unit, a nearly one-to-one with the 37 GHz and no correlation with the 94 GHz. Several possible combinations of void-associated phenomena were suggested to explain the anomalies, but a plausible solution was not offered at the time of the report. Subsequently Richer (1970) challenged the validity of the correlations, based on some depth-of-penetration calculations at 35 GHz (0.9 cm) for a loam soil.
More recently another field experiment conducted over a known solution cavity in limestone by Aerojet General resulted in a radiometric anomaly. The anomaly is believed to be caused by secondary phenomena, i.e., moisture concentration in sinkholes typically associated with cavities in karst areas; and not by primary phenomena, i.e., direct penetration of microwave radiation from the cavity itself (Edgerton, personal communication, 1970).

The results and experiences of the Lassen and Cool area field studies indicate the importance of having favorable field conditions for testing the capabilities of microwave radiometers in the natural environment. Ideally, the test site should contain a minimum of non-target variable parameters contributing to the signal received at the antenna. Consider the case of a geologic experiment where depth of penetration is important, for example. One would seek to select an area essentially devoid of vegetation, with no soil cover, and consisting of a relatively homogeneous rock having very low moisture content. A fairly recent pahoehoe lava flow situated in a semi-arid to arid climate would generally satisfy these conditions. To maximize penetration depth, long wavelength radiometers are needed. A 21 cm (1.4 GHz) radiometer is now available for field measurements. Thus, site selection, as well as hardware requirements, must be carefully tailored to the objective(s) of the field experiment.


