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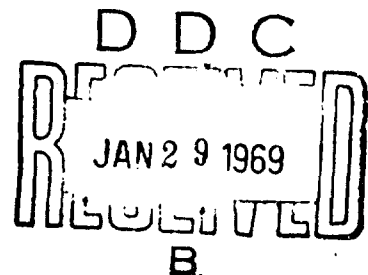


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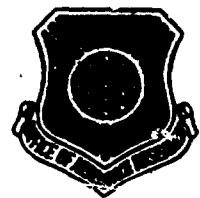
L. G. HANSCOM FIELD, BEDFORD, MASSACHUSETTS

**Ultraviolet Radiation and
the Terrestrial Surface**

J.F. CRONIN
T.P. ROONEY
R.S. WILLIAMS, JR.
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OFFICE OF AEROSPACE RESEARCH
United States Air Force



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TERRESTRIAL SCIENCES LABORATORY PROJECT 7628

AIR FORCE CAMBRIDGE RESEARCH LABORATORIES

L. G. HANSCOM FIELD, BEDFORD, MASSACHUSETTS

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Abstract

Although variations in the intensity of solar ultraviolet irradiation of the Earth's surface may provide significant opportunities for observation in the ultraviolet spectrum, research in the ultraviolet region has been neglected by terrestrial scientists. The spectral properties of vegetation and soils and of undisturbed weathered natural surfaces of rocks and sediments, in situ, are unknown. Limited spectrophotometric data obtained in the laboratory, but of samples removed from their environment, indicate that there may be less distinctive spectral character in the ultraviolet than at the longer wavelengths. Spectral reconnaissance studies in the near-ultraviolet region are therefore warranted.

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Ultraviolet Radiation and the Terrestrial Surface

I. INTRODUCTION

In 1801, the year after Sir William Herschel discovered that the solar spectrum extended beyond human vision ($>7000 \text{ \AA}$), J. W. Ritter found the ultraviolet region when he observed that silver chloride blackened more rapidly beyond the violet end of the spectrum ($<4000 \text{ \AA}$) than it did in the visible region. In subsequent years, it was observed that energy in the ultraviolet, visible, and infrared, regions differed only in frequency; that all three regions were in the electromagnetic spectrum; and that there were no sharp boundaries between contiguous spectral regions. By the early part of the twentieth century, Lyman had extended the spectrum to $500 \text{ \AA}$ after it had become known that quartz, fluorite, and other substances allowed ultraviolet radiation to be observed at shorter and shorter wavelengths.

The ultraviolet frequencies have since been used for research in such diverse fields as astronomy, medicine, biology, atmospheric physics, and aerial reconnaissance. To the ~~terrestrial~~ scientist the more significant investigations have been those in the areas of (a) the luminescence of organic and inorganic materials, (b) the atmospheric ozone, and (c) the spectral and photographic studies of Mars and the Moon by astronomers and physicists during this century. It was not until after World War II that any thought was given to looking back at Earth at bandwidths other than those of the so-called photographic spectrum. Since that time, however,

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much interest has been generated in the development of 'remote sensing' techniques at all wavelengths of the electromagnetic spectrum.

The impetus toward a coordinated program of nonmilitary sensor research of terrestrial surfaces originated in 1964 in the offices of P. C. Badgley at NASA Headquarters in Washington, D. C. when Badgley, with W. A. Fischer of the U. S. Geological Survey, R. J. P. Lyon of Stanford Research Institute, J. F. Cronin of Air Force Cambridge Research Laboratories, and a few other terrestrial scientists set out to establish a set of techniques suitable for the exploration of lunar and planetary bodies (including Earth) from orbiting spacecraft. The entire electromagnetic spectrum was to be scanned for regions proved or potentially useful to scientists seeking to extend their knowledge of the solar system. This program has to date elicited only one or two sustained efforts of nonmilitary research in the ultraviolet spectrum.

Although the ephemeral variations in the composition, physical properties, and distribution of the Earth's atmosphere have been intensely studied by atmospheric physicists for several decades, it is only since manned orbitors were launched by NASA that the spectral character of the Earth's surface has provoked much curiosity. Indeed, it is now becoming apparent how very little is actually known of the reflection, absorption, polarization, and emission properties of the Earth's vegetative, rock, and sedimentary cover. Environmental spectral data during the diurnal and annual cycles are particularly sparse.

Among the conventional subdivisions of the electromagnetic spectrum—gamma ray, x ray, ultraviolet, visible infrared, microwave, radio and audio—perhaps the least explored and least utilized is the ultraviolet. This is so, in spite of the fact that the ultraviolet region is contiguous to man's visual limits—and the region where silver halides of photographic emulsions are most light-sensitive.

This paper defines the need for a study of the properties of terrestrial surfaces in the ultraviolet spectrum. The significant parameters of the atmosphere and of the terrestrial surface are defined. Potential research and military applications are suggested. It is our intent to undertake a more detailed scientific examination of the terrestrial surface potentials described and to periodically report our results.

2. ULTRAVIOLET RADIATION

Ultraviolet radiation is characteristically defined as that part of the electromagnetic spectrum from $4000 \text{ \AA}$ to $100 \text{ \AA}$, or, between the visible region and the x-ray region. The ultraviolet spectrum may be divided into the near ($4000 \text{ \AA}$ to $3000 \text{ \AA}$), far ($3000 \text{ \AA}$ to $2000 \text{ \AA}$), and extreme ($2000 \text{ \AA}$ to $100 \text{ \AA}$) ultraviolet. The primary source of energy at these wavelengths is the sun.

The total solar irradiance of Earth is essentially constant, although there is a seasonal variation of -3.27 percent at aphelion and +3.42 percent at perihelion. In the far ultraviolet, solar flares cause relatively large fluctuations in intensity, but these are of little consequence at the Earth's surface since the atmosphere absorbs solar energy at wavelengths shorter than 2900 Å.

Solar irradiance within the Earth's atmosphere is, to some extent, a function of the integrated density of the atmosphere in the path of the solar beam. Solar ultraviolet intensity depends on such factors as elevation above sea level, latitude, time of day, and time of year.

The intensity of solar ultraviolet radiation within the Earth's atmosphere or at sea level is not simply a function of the air mass through which the solar energy has traversed, but also of the turbidity, optical properties, chemical composition, component distribution, and especially of the amount of total ozone. Measurements of the ultraviolet flux, after the incoming solar radiation has passed through the atmosphere and been reflected from a surface, depend on the optical thickness of the atmosphere, the zenith angle of the sun, the zenith angle and azimuth of the direction of observation, and the spectral reflection, emission, and polarization of the terrestrial surface.

The physical processes that effect changes in ultraviolet radiation are primarily scattering and absorption by the atmosphere. Scattering is the angular redistribution of radiation incident upon the atmosphere. It is of two types: Rayleigh, or molecular, scattering; and Mie, or aerosol, scattering. The Rayleigh molecular law of scattering may be written as:

$$\beta_{\phi\lambda} = \frac{2\pi^2}{N\lambda^4} (\mu_\lambda - 1)^2 (1 + \cos^2\phi),$$

where $\beta_{\phi\lambda}$ is the Rayleigh scattering coefficient at angle ϕ and wavelength λ ; N is the number of scatterers per unit volume, and μ_λ is the wavelength-dependent index of refraction of the scatterers. A popular description of Rayleigh scattering is that it is inversely proportional to the fourth power of the wavelength.

For the larger Mie particles, the intensity of the scattered light is a complicated function of λ , μ , ϕ , and the radius of the scatterers. Field measurements seldom agree with classical theory largely because of the variable concentrations of aerosols in the atmosphere.

All of the major atmospheric gases—nitrogen, oxygen, water vapor, carbon dioxide, and ozone—and some of the minor constituents—such as nitrous oxide, methane, and carbon monoxide—demonstrate various degrees of absorption. The most important of these is ozone since it is the ozone in the Earth's atmosphere that effectively terminates solar irradiation of the Earth's surface below 2900 Å.

3. OZONE

The first to note the important relationship between the ultraviolet region and the atmosphere was Cornu (1879), who suggested that the abrupt termination of the solar spectrum in the ultraviolet at ground level was due to absorption in the atmosphere. Hartley (1880), delineating what are now termed the Hartley absorption bands, suggested that ozone was responsible for this absorption in the ultraviolet. Several decades later, Fabry and Buisson (1913, 1921) proved the existence of ozone in the atmosphere when they discovered that the absorption pattern of sunlight in the ultraviolet matched their earlier laboratory measurements of the absorption spectrum of ozone. With G. M. B. Dobson's (1931) development of the ozone spectrophotometer, a worldwide network of stations was eventually established to provide continuous daily measurements of ozone.

3.1 Absorption by Ozone

There are three principal absorption bands in the ozone spectrum: the Hartley bands in the far ultraviolet, the Huggins bands in the near ultraviolet, and the Chappuis bands in the visible region (Figures 1, 2, 3). The Hartley bands, which are centered at $2553 \text{ \AA}$ and dominate the ozone spectrum with a very strong continuum, generally block out all radiation shorter than $3000 \text{ \AA}$. The Huggins bands overlap, but are weaker than, the Hartley region, and extend to $3400 \text{ \AA}$. Between $3400 \text{ \AA}$ and $4500 \text{ \AA}$ there exists a relatively transparent window. In the region from $4500 \text{ \AA}$ to $7500 \text{ \AA}$ there are the Chappuis bands, the weakest bands of the ozone spectrum, with a peak absorption of about 7 percent for solar radiation traversing two air masses. Although the Chappuis absorption is small, its optical effect at twilight is significant.

Since absorption of ultraviolet radiation by ozone is an exponential function of the quantity of ozone along the path length of irradiation (Bouguer's law), relatively small variations of total ozone in wavelength regions of strong absorption may cause large changes in ultraviolet intensity. At the earth's surface, variations in solar ultraviolet radiation, which are related to variations in total ozone, are small. Seasonal changes in total ozone increase poleward and are about ± 35 percent in the middle and high latitudes. The standard deviation of total ozone about the seasonal mean is approximately 10 to 15 percent at all latitudes; the standard deviation of total ozone about the monthly mean is less than 15 percent for all latitudes (Hering and Borden, 1967).

From $3000 \text{ \AA}$ to $3700 \text{ \AA}$ the standard deviation of solar UV at the earth's surface, owing to fluctuations in ozone, is approximately 5 percent day to day, and 10 percent seasonally (W. S. Hering, private communication). Relative

changes in intensity due to changes in ozone are somewhat larger at noon and somewhat smaller near sunset, owing to the increase in optical depth with increasing solar zenith angle.

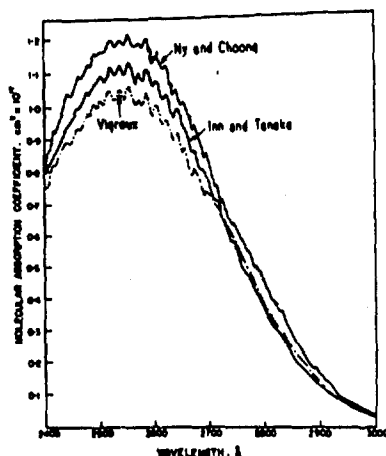


Figure 1. Molecular Absorption Coefficients in the Hartley Bands of Ozone, at 18°C

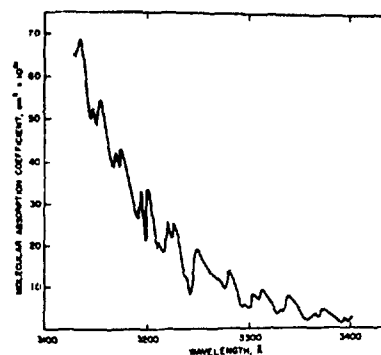


Figure 2. Molecular Absorption Coefficients in the Huggins Bands of Ozone, at 18°C

Figures 1 to 3:
Comparison of Molecular Absorption
Coefficients in Ozone at 18°C
(Goody, 1964)

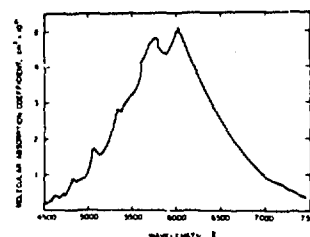


Figure 3. Molecular Absorption Coefficients in the Chappuis Bands of Ozone, at 18°C

3.2 Total Ozone

Ozone is formed primarily by photodissociation of molecular oxygen and subsequent recombination of atomic and molecular oxygen. The primary source region is near 30 km. Total ozone and changes in total ozone are least at the equator, but both increase with increasing latitude. In the northern hemisphere the amount of total ozone varies with latitude and season; it is greatest in the spring and least in the fall. In addition, there are daily or short-period variations in total ozone that are the result of vertical or horizontal air motions.

Numerous studies (Johnson, 1954; Craig, 1965; and others) have shown that there is a definite relationship between total ozone and the cyclonic-anticyclonic circulation of the lower stratosphere and the troposphere. In the trailing area of a cyclonic trough, ozone both subsides and increases because of horizontal

advection from the polar regions and the effect of the vertical motions that have been described by Reed (1950) and Normand (1951). Conversely, in the leading area of the trough, or the region of the anticyclonic circulation, ozone is observed to ascend and decrease.

3.3 Ozone Distribution

F. W. Paul Götz (1931; 1934) discovered that with the decrease in the zenith angle of the sun shortly after culmination, the decrease in intensity at the ultraviolet wavelengths is more rapid than at the longer wavelengths; when the sun is low the reverse is true, the decrease in intensity at the shorter wavelengths being slower than at the longer ones. G. M. B. Dobson confirmed this in 1930 when he found that the ratio of ultraviolet to longer wavelengths does increase at first as the sun rises, then becomes constant, and eventually shows the normal decrease expected with the increasing height of the sun.

Götz developed the so-called 'umkehr' method, which depends on a simple measurement of the ratio of the intensity of two ultraviolet wavelengths in the Hartley ozone band. (See Figure 4.) It gives an accurate measure of the average height of the ozone, but only a general estimate of its vertical distribution. The umkehr method is used only on clear days, and normally when the zenith angle of the sun is between 90° and 60° .

The development in 1960 of the bubbler type of electrochemical (wet chemical) ozonesonde by Brewer, and the chemiluminescent (dry chemical) ozonesonde by Regener (1960, 1964) has considerably increased our ability to measure vertical ozone distribution. The chemical ozonesondes can be used at any time of the day or night since they do not need solar radiation to be activated. They also determine the variation of ozone with height in greater detail than was possible with earlier methods.

The seasonal and latitudinal variations of ozone in a vertical direction through the atmosphere have been quantitatively described by Paetzold (1963), who defined the ozone profile for the polar and equatorial latitudes as follows:

Equatorial Ozone Profile:

- a) Only 10 percent of the ozone is between ground level and 18 to 20 km.
- b) The increase of ozone density does not begin at the tropopause, but at 1 to 3 km above it.
- c) The profile of ozone density in the atmosphere has a single sharp maximum at about 26 to 28 km.
- d) There are little, if any, seasonal variations.

Polar Ozone Profile:

- a) 60 percent of the ozone is below 20 km in the spring; only 20 percent is below 20 km in the fall.

- b) The increase of ozone begins immediately above the tropopause.
- c) There is a marked seasonal variation in the total amount of ozone below 20 km. It is greatest in the spring and least in the fall.

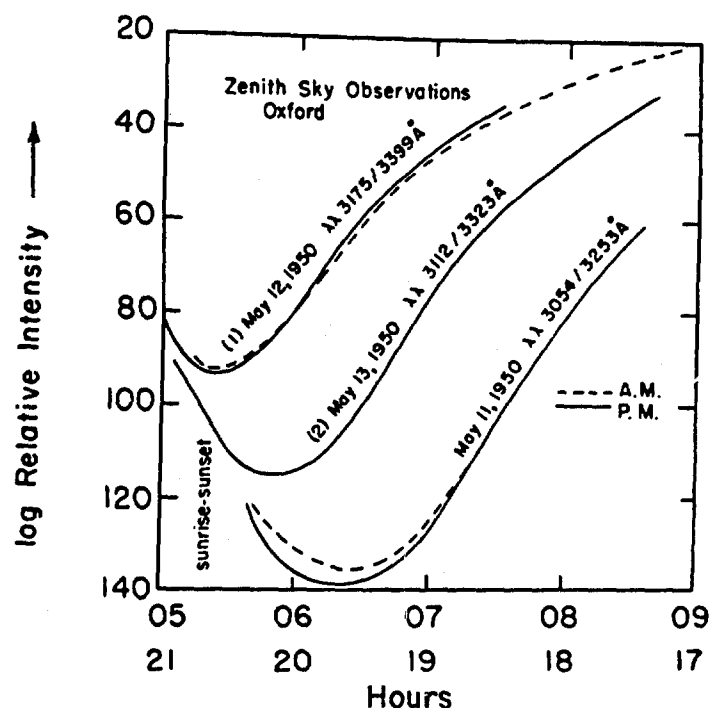


Figure 4. Measurements of Zenith Skylight Near Sunrise and Sunset (Johnson, 1954)

4. TERRESTRIAL SURFACES

Although visual and photographic contrast definition or contrast attenuation is most significant, ~~determinations~~ of the photometric properties or optical properties of the features or objects whose contrast is significant are too often neglected. A few casual measurements of some of the properties of paint, concrete, grass, or glass have been reported. The background is usually described as some kind of 'formation,' or as a clump of vegetation, with no indication of the optical properties. Many studies of polarization and reflectance are greatly diminished in value when the material is described simply as a desert sand or a white soil. Measurements, for instance, of such important parameters as the composition, size, shape, and orientation of the grains composing the sediment or soil, or of the microrelief of

the surface, are utterly lacking. Most investigators seem to be unaware of the complexity of an apparently uniform terrestrial surface.

Organic matter, a major constituent of soils, is intimately mixed with the water, air, and mineralogic materials of soils. Rock surfaces and the regolith also support a variety of life forms, primarily bacteria and actinomycetales, and various algae, fungi, and lichens. Again, many investigators appear to be unaware of the ubiquity of such microorganisms. For instance, no research has been directed toward the study of the optical properties of the natural, undisturbed, weathered surfaces of rocks and sediments and their organic surface materials. Further, although 75 percent of the Earth's surface is composed of soil, unconsolidated sediments, or sedimentary rock, studies in situ of the reflection, absorption, polarization, and emission properties of such lithologic materials are almost unknown.

4.1 Rocks and Minerals

In the visible and infrared regions the laboratory spectrophotometric characteristics of rocks and minerals are well known but in the ultraviolet, such information is scanty. Two recent reports (Greenman et al, 1967; Thorpe et al, 1966) are the first to provide data in the far-ultraviolet region ($2000 \text{ \AA}$ to $3000 \text{ \AA}$). As for the near-ultraviolet region ($3000 \text{ \AA}$ to $4000 \text{ \AA}$), little data is available. To fill the need, two of the writers of this report are obtaining spectra in the near-ultraviolet region of a considerable number of rocks, minerals, and sediments.

In the near-ultraviolet and the shorter-wavelength regions of the visible spectrum, the carbonates, phosphates, and evaporites are usually more reflective than other lithologic materials. Acidic rocks such as granite and rhyolite show little reflectance in the ultraviolet but considerable reflection in the visible; basic rocks such as basalt show little reflection in either the ultraviolet or visible (Figures 5).

Hemphill (1968) has shown that at $2500 \text{ \AA}$ in the ultraviolet, limestone is $2\frac{1}{2}$ times more reflective than granite and 10 times more reflective than rhyolite.

Greenman (1967) has measured the reflectance in the ultraviolet from $2000 \text{ \AA}$ to $3000 \text{ \AA}$ of the silicate rocks, granite, gabbro, and serpentine, both solid and granular (Figure 6). Reflectance declined gradually from the longer to the shorter wavelengths. No differences attributable to composition were discovered. Spectroscopy of a higher resolution than normally used is suggested by the authors if further investigation is warranted.

It should be noted that neither Hemphill's nor Greenman's studies were of weathered or naturally occurring lithologic surfaces.

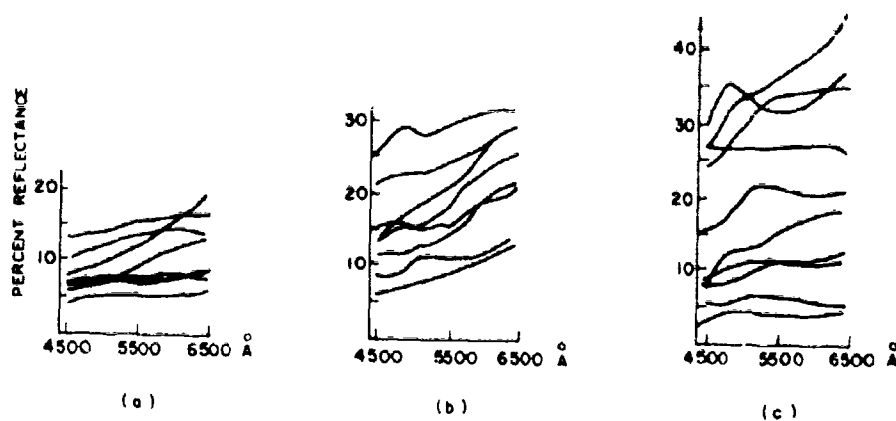


Figure 5. Spectral Reflectance of the Principal Rock Types: (a) Basic Igneous, (b) Acidic Igneous, (c) Sedimentary (after V. V. Sharonov, 1956)

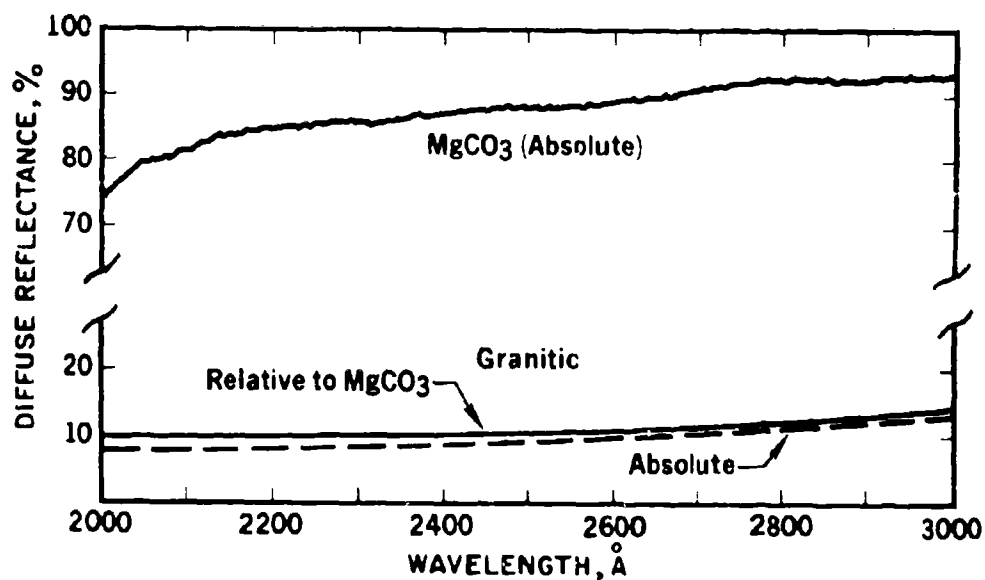


Figure 6. Diffuse Reflectance of Solid Granitic Sample and of MgCO_3 Standard (Greenman et al, 1967)

4.2 AFCRL Studies

Experiments at AFCRL have been conducted to provide a basis for more extended interpretations of ultraviolet reflectance from geologic materials. Only freshly exposed surfaces have been measured to date but studies of weathered surfaces are scheduled. The influence of composition and grain size on spectral reflectance has been assessed for a few common rocks and minerals. Spectra were obtained from 2400 Å in the far-ultraviolet to 1.8 μ in the infrared region. Measurements were made on a Cary model No. 14 spectrophotometer equipped with a model No. 1411 diffuse reflectance accessory.

The Cary No. 14 is a ratio-recording double-beam instrument using two monochromators, a fused-silica foreprism and a 600 line/mm echelette grating. The spectral bandwidth is not constant since the width of the monochromator slits is varied automatically in order to maintain constant energy in the reference beam.

A ring collector is used to measure the diffuse reflectance. The sample is illuminated at normal incidence by monochromatic light. A phototube, mounted at the top of the ring collector, alternately receives reflected radiation from the annular mirror viewing the sample at $45^\circ \pm 7^\circ$ and from the reference beam. A screen allows the reference beam to be standardized to a reference sample. The reference for all measurements is a freshly prepared MgCO_3 surface.

The ring collector makes it possible to measure diffuse reflectance of horizontally mounted powdered samples, a considerable advantage over methods that require the samples to be mounted vertically. Vertically mounted powders, unless they are very finely divided, have to be covered. Reflection losses of samples covered by glass are 10 to 15 percent between 4000 Å and 7000 Å. In addition, below 3500 Å the glass begins to absorb strongly, although this might be avoided by the use of an optical fused-silica cover. (See Table 1.)

Table 1. Wavelength Range, Light Sources, and Detectors

Wavelength Range (Å)	Source	Detector
2400-3500 Å	Nester H ₂ lamp	Dumont 7664*
3200-7000 Å	Quartz halogen tungsten lamp†	Dumont 7664
7000 Å - 1.8 μ	Quartz halogen tungsten lamp†	Dumont Pbs

*s-13 response, fused-silica window

†Operated at 70 V

The reflectance of coarse powders may be affected by the packing arrangement of the grains. Reflectance curves for compacted and uncompact samples of quartz grains with diameters of 420μ to 500μ and $<53\mu$ are given in Figure 7. The compacted samples of larger grain size show 2 to 5 percent higher reflectance throughout the $3000\text{ \AA}$ to $7000\text{ \AA}$ range, with more pronounced differences at the longer wavelengths. The upper curves of Figure 7 show that packing has little influence on the reflectance of $<53\mu$ powders.

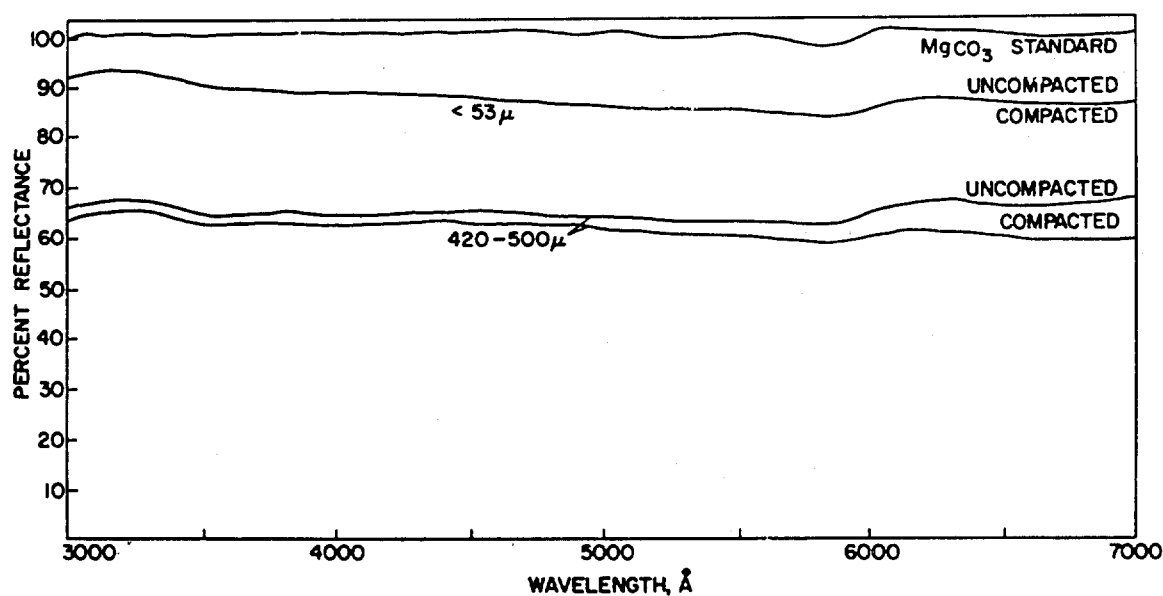


Figure 7. Compaction Effects on the Spectral Reflectance of Powdered Quartz

Based on these results, a standard loading technique for powders was developed. The sample holders were filled to above the top of the sample holder, a straight edge was drawn across the holder to level the powder to the top of the holder, a small additional amount of powder was added, and a 500-gm weight was then placed on top of the powder and rotated until the powder surface was smooth and level. This procedure gave highly reproducible results.

Particle shape or preferred orientation may also bear importantly on the reflectance response of natural materials. Some common minerals such as clays have a flaky habit and thus, in water they tend to settle out parallel to their prominent cleavage.

One experiment was conducted to measure differences in reflectance as a function of grain shape (Figure 8). The National Crushed Rock Institute prepared several samples of crushed rock, carefully graded with respect to size and shape.* Three reflectance runs were made of rounded aggregate and three of angular grains. Both samples had grain diameters of 590μ to 1190μ . The rounded samples were more reflective by 2 to 9 percent, the greatest difference being in the ultraviolet region.

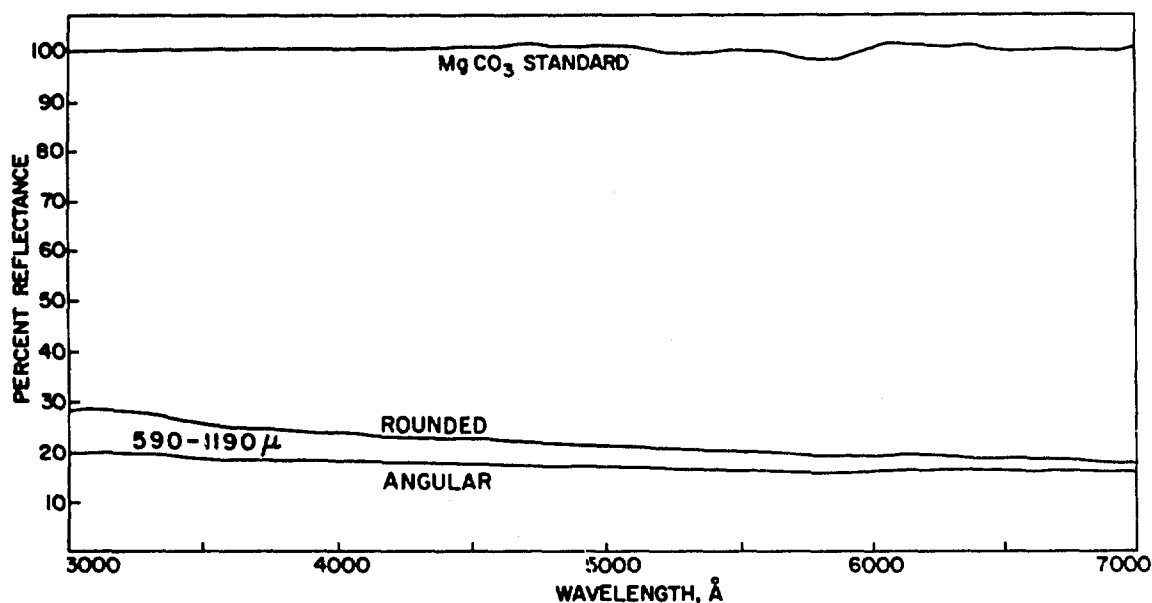


Figure 8. Influence of Particle Shape on Reflectance (The upper curve represents the average of three tests of rounded particles whose grain diameters are from 590μ to 1190μ . The lower curve represents the average of three tests of angular particles whose grain diameters are from 590μ to 1190μ .)

Figures 9 through 18 show the reflectance spectra of granite, rhyolite, obsidian, basalt, and peridotite, of the three iron oxides limonite, goethite, and hematite, and of quartz and calcite; the grain sizes are $<37\mu$ to 500μ . Several features are evident from examination of these spectra.

*Furnished by Prof. H. F. Winterkorn, Princeton University

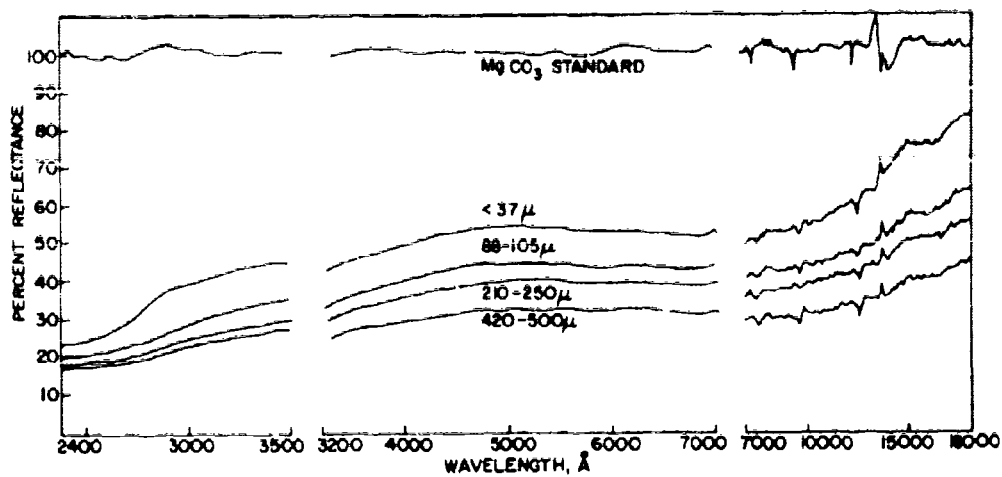


Figure 9. Spectral Reflectance of Alkali Granite

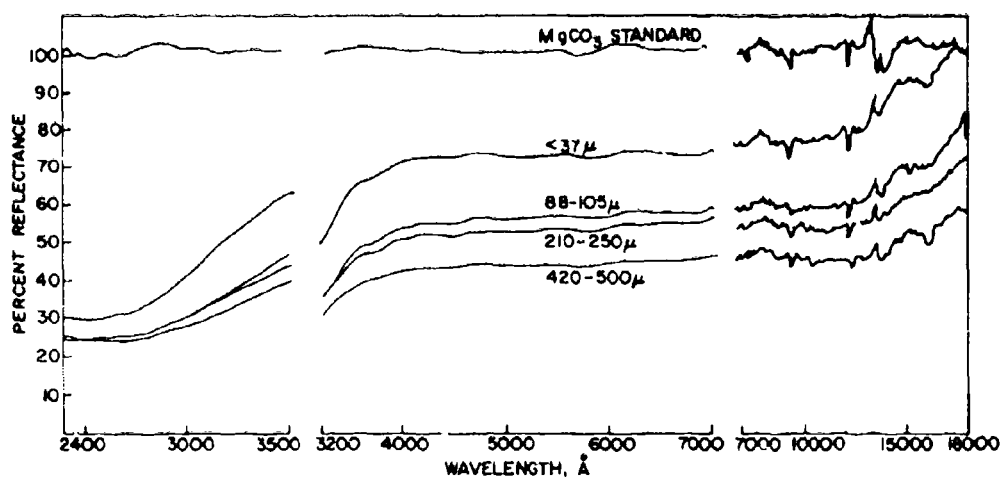


Figure 10. Spectral Reflectance of Rhyolite

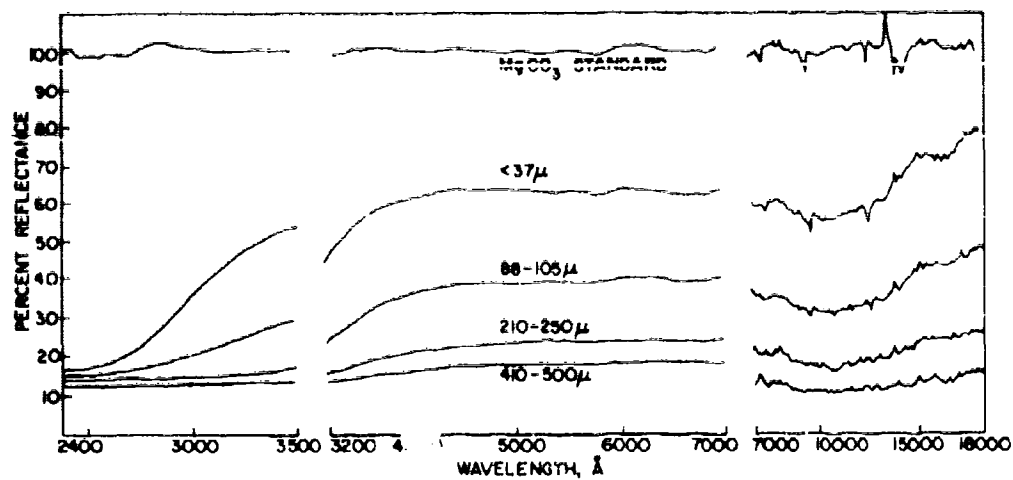


Figure 11. Spectral Reflectance of Obsidian

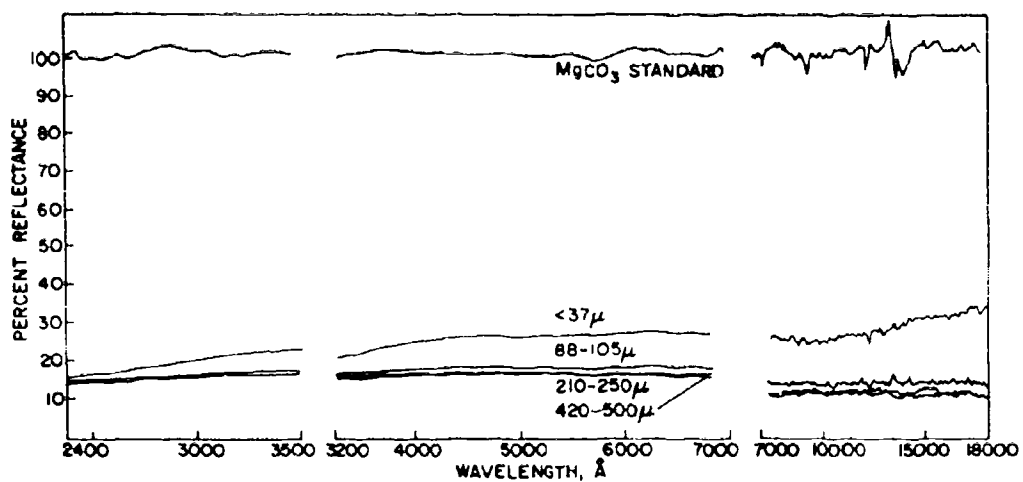


Figure 12. Spectral Reflectance of Basalt

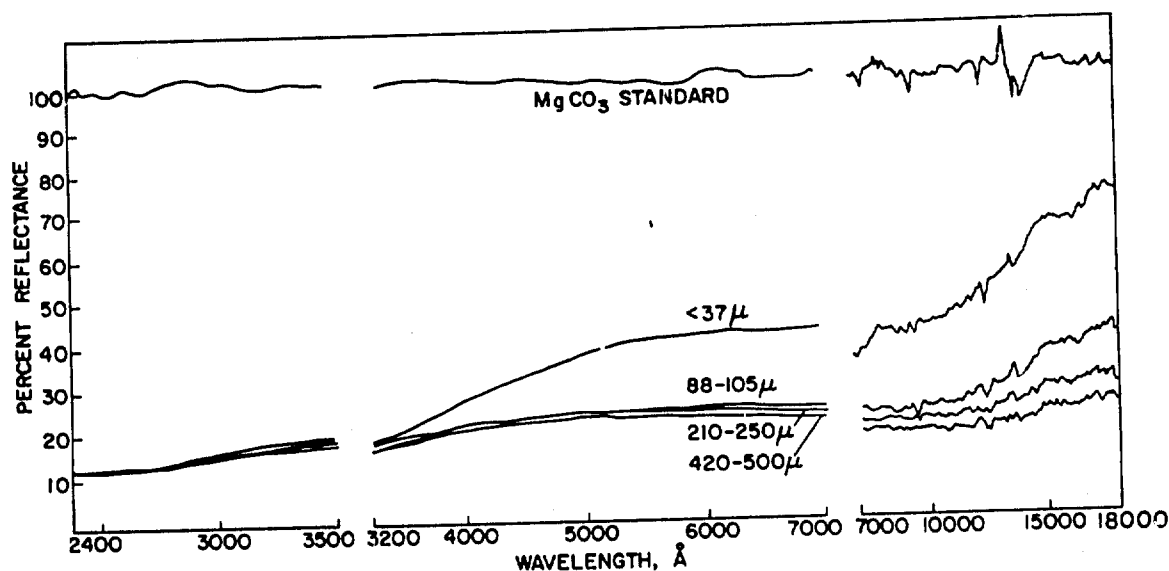


Figure 13. Spectral Reflectance of Peridotite

The most salient features are:

1. No distinctive peaks are present in the wavelength range $2400 \text{ \AA}$ to 1.8μ .
2. The reflectance intensity falls off from the near infrared to the ultraviolet. In the ultraviolet the reflectance level is generally from 15 to 30 percent, and the curves for various grain sizes tend to converge in this region. There is little difference in reflectance of light or dark rocks.

3. The reflectance level, especially at longer wavelengths, depends distinctly on grain size; the finer the grain size, the greater the reflectance.

4. The spectra of the three iron oxides (limonite, goethite, and hematite, Figures 14 to 16) follow the same trends as noted for the rocks.

5. The spectral features of two transparent minerals, (quartz and calcite, Figures 17 to 18) depart somewhat from those of the rocks and iron oxides. The major difference is that the reflectance level is high and remains high throughout the range $2400 \text{ \AA}$ to 1.8μ . The dropoff in the ultraviolet is slight, except perhaps for the coarsest grain size.

4.3 Vegetation, Soils, and Sediments

The current resurgence of interest in multispectral studies in the fields of forestry and agriculture is undoubtedly due to R. N. Colwell of the Department of Forestry of the University of California. Other investigation centers following his lead include the U.S. Department of Agriculture, the National Bureau of Standards, Purdue University, and the Willow Run Laboratories of the Institute of Science and Technology of the University of Michigan.

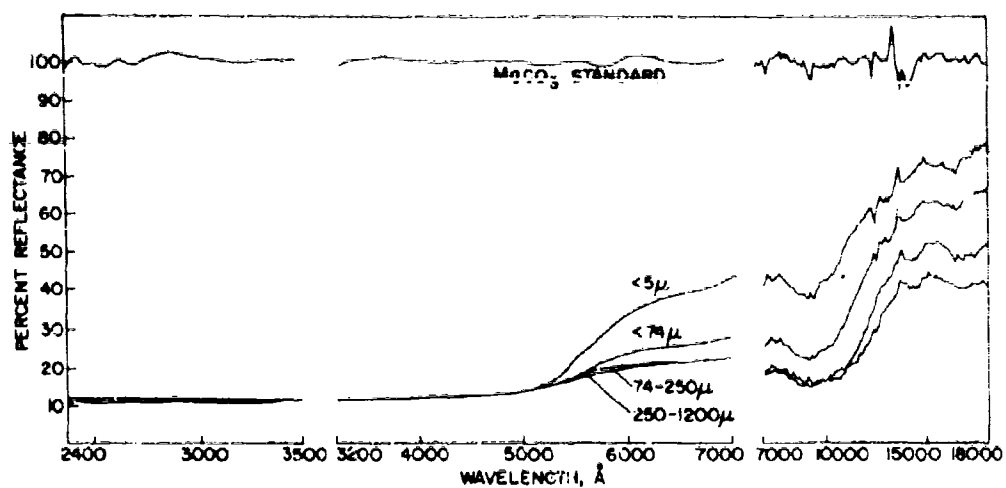


Figure 14. Spectral Reflectance of Limonite

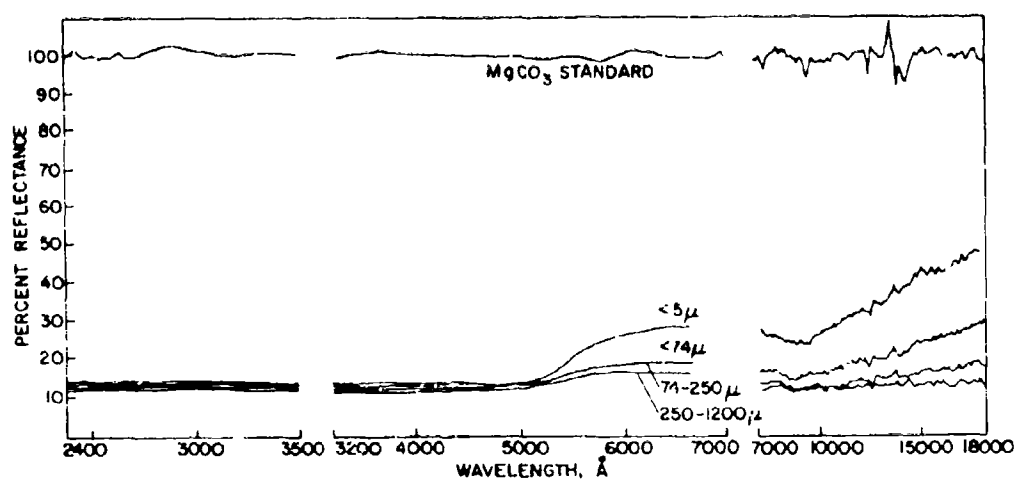


Figure 15. Spectral Reflectance of Goethite

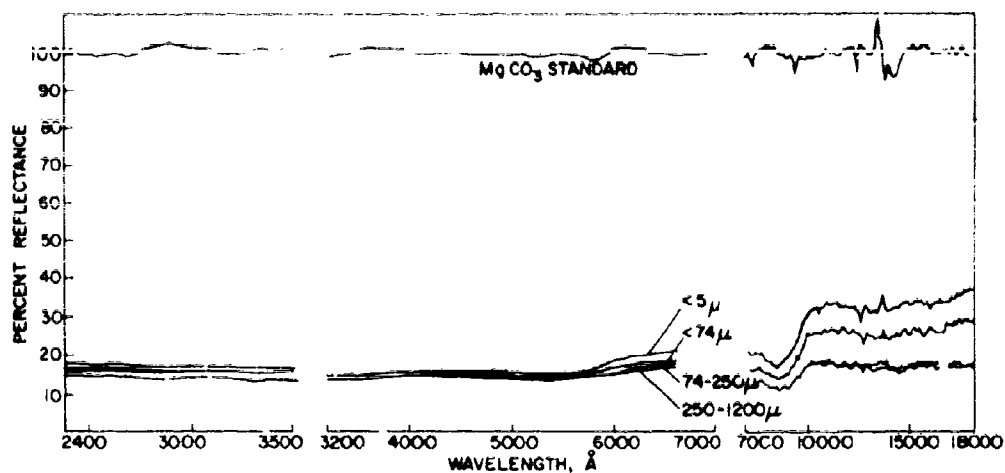


Figure 16. Spectral Reflectance of Hematite

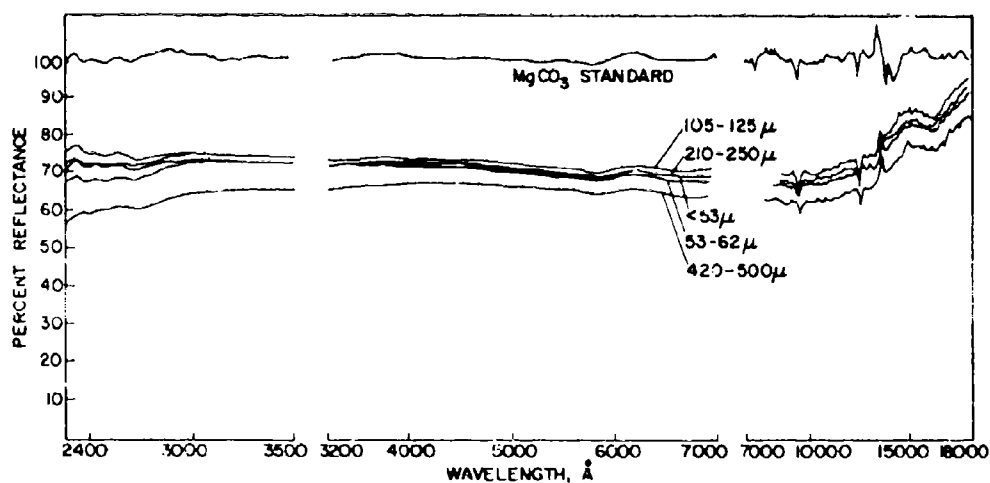


Figure 17. Spectral Reflectance of Quartz

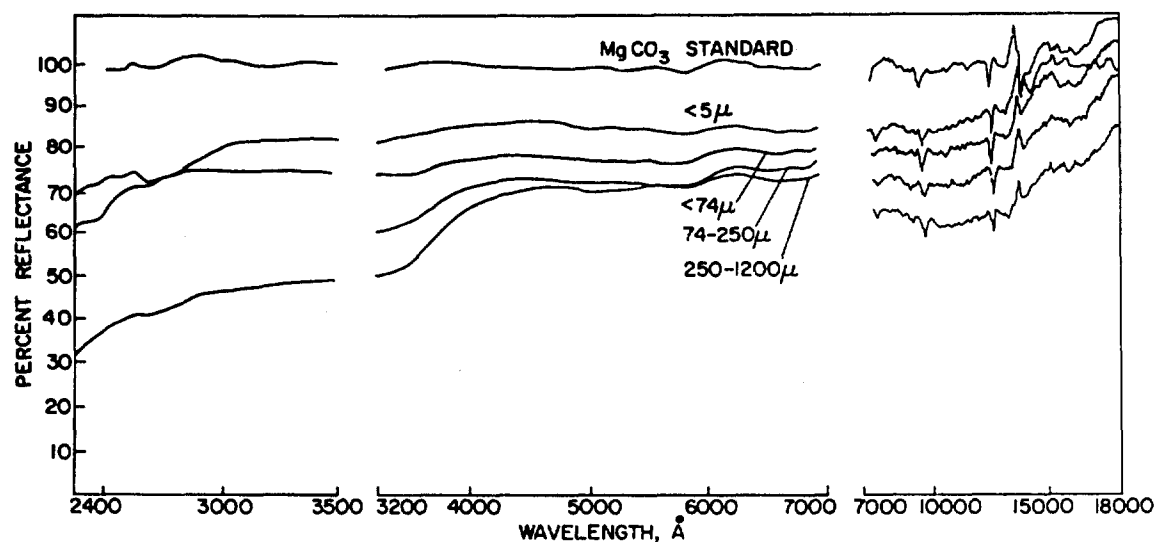


Figure 18. Spectral Reflectance of Calcite

Support to Purdue and Michigan was provided in 1963 by the U. S. Army Electronics Command and in 1964 by the National Aeronautics and Space Administration. As Polcyn (1967) reported, the early work at Michigan and Purdue confirmed the differences between crops. Many of these differences had been pointed out earlier by Colwell (1956, 1961, 1963) in his many papers. Polcyn and his coworkers also observed that tonal differences in selected bands for certain crops depended on sun and view-angle geometry, state of maturity (which is in turn a factor of soil and moisture), herbicide treatments, irrigation, row direction, and wind damage.

One of their more interesting observations was the effect of scan angle and scan direction at the bandwidth 0.502 to 0.524 μ (Figure 19). It was found that the scan-angle dependence at this bandwidth was quite different from that at other bandwidths. For instance, it was as much as +60 percent of the nadir (0°) value of the bandwidth from 0.58 to 0.62 μ , but only +5 to +10 percent of the infrared channels 0.72 to 0.8 μ and 0.80 to 1.0 μ .

Michigan and Purdue concluded that calibrated, simultaneous, multispectral sensing does indeed provide a basis for automatic recognition, and recommended a broadband multichannel instrument, from the ultraviolet to the infrared. Their work, which had been confined to the visible and infrared regions, had not included the ultraviolet and therefore has not contributed to the little information that was heretofore available on the ultraviolet spectrum.

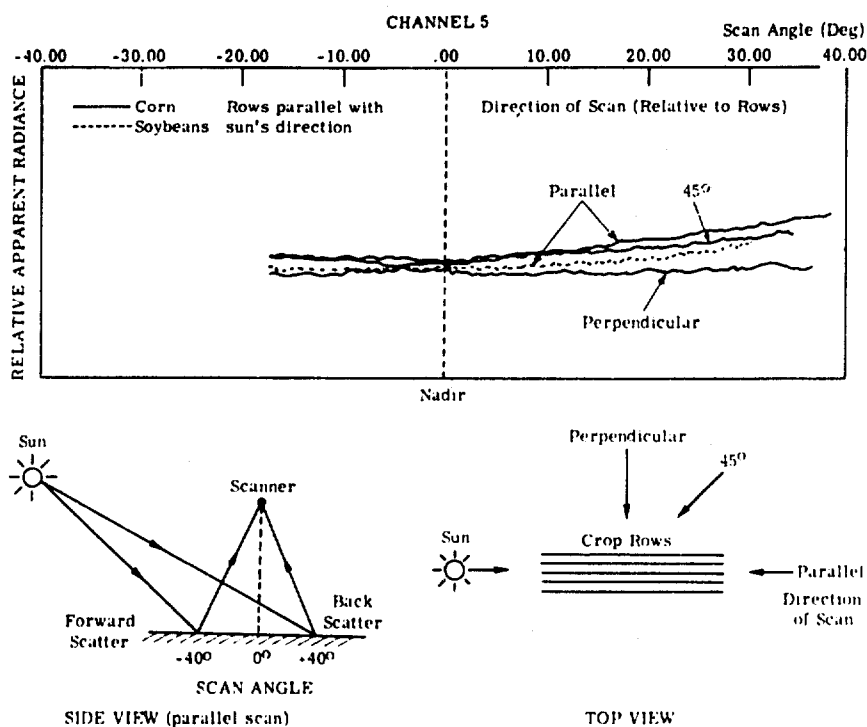


Figure 19. Effects of Scan Angle and Scan Direction on Crop Rows (Polcyn, 1967)

Spectral properties of leafy materials are strongly dependent on the characteristics of the cellulose in the cell walls, of water and solutes within the cells, of intercellular air spaces, and of pigments within the chloroplasts. The usual pigments, in order of abundance, are chlorophylls, xanthophylls, and carotenes. Absorption spectra of plant pigments and water (Figure 20), measured by Gates et al (1965), indicate that all the predominant pigments absorb strongly in the vicinity of $4450 \text{ \AA}$. Chlorophyll a and chlorophyll b, which are most frequent in the higher plants, also absorb significantly at $6450 \text{ \AA}$. In the visible range, plants lacking chlorophyll show markedly less absorption than other plants.

Spectral absorption by chlorophyll converts absorbed energy into heat or fluorescence. The principal representatives of plant life known to be luminous are certain bacteria and fungi; ~~their~~ emission of light is continuous and independent of any stimulus. The Japanese, who have been particularly interested in the study of luminous plants and animals, grew luminous bacteria for use during blackouts in World War II.

In the tropics there are many species of luminescent fungi that appear to multiply exuberantly during the rainy season. Spectral data, of luminescent fungi and bacteria, together with pertinent environmental information, are not known to the writers; information on bacterial luminescence versus pH, temperature, and salinity of environment, is available.

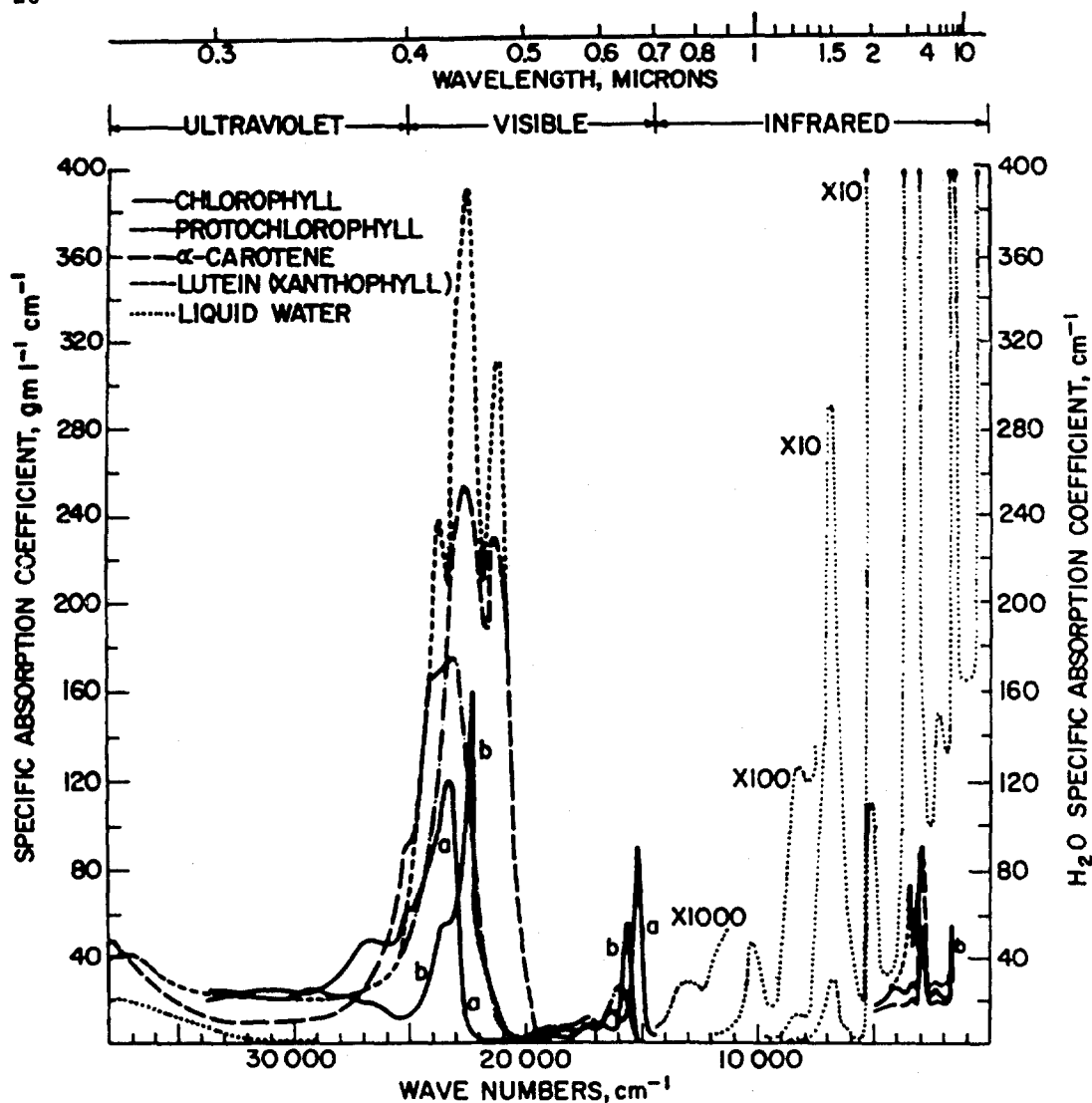


Figure 20. Absorption Spectra of Plant Pigments and Water (Gates et al, 1965)

Plants possessing protochlorophyll and chlorophyll a and b may demonstrate a shift in spectral properties during growth. The red protochlorophyll reflectance band may shift to shorter wavelengths; and the development of chlorophyll at a later stage may be accompanied by a recurrent shift to shorter wavelengths. With further growth, however, the reflectance peak in the green diminishes and that at infrared wavelengths increases.

As is true of vegetation, soils also readily absorb energy in the ultraviolet and reflect and scatter it at longer wavelengths. Baumgartner (1953) found that the larger the grain size of soils, the deeper the radiation penetrates the soil. In the coarsest soils, significant amounts of radiation reach depths of 5 mm or more.

Earlier, Sauberer (1951) had observed that at a depth of 1.8 mm in wet sand, solar energy at $6600 \text{ \AA}$ is 100 times that at $4250 \text{ \AA}$.

4.4 Water, Snow, and Ice

The transmission of incident solar energy by both salt waters and fresh waters is strongly wavelength-dependent. Further, the transmission properties of coastal waters and inland waters vary greatly with turbidity and the plankton content of the water. For example, the wavelength of maximum penetration shifts from the blue in clear water to the red in muddy water. In a study of the penetration of solar and sky ultraviolet radiation in the Mediterranean Sea, Lenoble (1956) observed that at $4000 \text{ \AA}$, the amount of energy at a depth of 30m is only 10 percent that at the sea surface. At $3200 \text{ \AA}$, the 10 percent depth is 10 m.

For snow and ice, ultraviolet penetration is greatest between 0.4 and 0.5μ , decreasing toward the shorter and longer wavelengths. The transmissivity of snow decreases with increasing water content. At a depth of 10cm it may vary from 2 percent to 20 percent. Glacier ice of the same thickness may transmit as much solar radiation as pure water.

The subject of water penetration is further discussed in Sec. 5. 1.

5. SPECTROPHOTOGRAPHY

Spectral photography originated with astronomers' photographic studies of the Moon and Mars during the early part of this century. In photographs taken in the UV at $3230 \text{ \AA}$ nearly 60 years ago, R.W. Wood (1910) noted an anomalous area on the Moon, the so-called 'Wood's Spot,' near the crater Aristarchus. In 1929, W.H. Wright of Lick Observatory published his lunar photography at six bandwidths, one of which was centered at $3600 \text{ \AA}$.

Wood (1911) had also shown some curiosity about the use of filter techniques in terrestrial photography and was probably the first to note the greater reflectance of trees in the IR than at conventional wavelengths. Angerer (1930) also published some early examples of UV and IR photography of landscapes.

The first aerial spectrophotography of Earth may have been made in the middle 1930s by the Russian, E. L. Krinov (1947) and his associates. The first to have obtained spectrophotometry of the natural surfaces of vegetation and rocks, these workers are known to have also photographed features in the same bandwidths as those used in their photometry. So far as we know, however, they did not publish their photography.

In 1960, the American Society of Photogrammetry, under the editorship of R. N. Colwell, published a Manual of Photographic Interpretation that was at that

time an excellent summary of developments in nonmilitary photo interpretation. This volume contained some of the first spectrophotographs taken from aircraft. By 1964, with the support of many representatives of the scientific community, the National Aeronautics and Space Administration had launched an intensive exploration of potential photographic and sensor techniques.

Discrete bandwidths in spectrophotography can be achieved by proper selection of film emulsion and sensitivity and appropriate filters. All terrestrial materials such as bedrock, sediments, soils, vegetation, and other organic matter have rather specific spectral reflection, absorption, emission, and polarization characteristics. Spectrophotography, with other sensor techniques, may therefore bring about more rapid and positive identification of terrestrial features from airborne sensor platforms.

Many factors are significant in in situ measurement of the spectral characteristics of terrestrial material. Among these are the amount and distribution of water vapor, carbon dioxide, ozone, and aerosols in the atmosphere, the angle of solar illumination, the kind and amount of cloud cover, the microrelief of the surface, the micrometeorology at the site, and the amount and kinds of microorganisms that are supported on the weathered surfaces of rocks and sediments. Such information is not always obtainable in spectrophotographic and spectrophotometric studies. In making every effort to acquire as much of this kind of data as possible, it is particularly important to make such measurements at the same time as the aircraft and satellites, with their sensors, are overhead.

A related subject of interest is the application of spectrophotographic techniques to submerged coastal areas and inland bodies of water. (There are rather obvious military implications as well as simply scientific interest in such an application.)

5.1 Water Penetration

Aerial spectrophotography in the green, blue, and near-UV regions of the electromagnetic spectrum has important applications to marine geologists, hydrologists, cartographers, and other scientists and engineers interested in features covered by water, whether fresh, brackish, or salt. Duntley (1963, 1967) and other optical physicists have devoted considerable effort to the study of visible-light transmission properties of an aqueous medium. But it is only recently that geologists and other earth scientists have tried to apply the results of such research to mapping reefoid, shoal, lacustrine, swamp, lagoonal, and other such environments. Reports of research by Cronin (1967) off Scripps Beach, Calif.; by Vary (1967) along the Florida Keys; and by Williams (1968) in Cayo Icacos, Puerto Rico, have discussed the use of aerial spectrophotography for the study of coastal processes and features.

Conventional aerial photography is selectively filtered so that only 70 percent of the visible spectrum, and less than 30 percent of the photographic spectrum, is used, due to the emulsion characteristics of the Plus-X aerographic film that is commonly used in conjunction with a Wratten No. 12 haze filter. This film and filter combination limits the information recorded to wavelengths between about 5000 Å and 7000 Å. Experience has dictated this choice since aerial photography in the 5000 Å to 7000 Å band is generally superior for photogrammetric purposes (topographic mapmaking, in particular) because of maximum tonal contrast and clarity of the photographic image under most terrain and visibility conditions. It should be realized that such a choice is not necessarily ideal for all applications. It would, for example, be unsuitable for water penetration.

With conventional aerial photography, features in only a few fathoms of water can be photographed, usually under a relatively smooth sea state. Cronin (1967, p. 22) has discussed the application of aerial spectrophotography in the 5000 Å to 5400 Å wavelength region at Scripps Beach, La Jolla, Calif., and at Mono Lake. At the former site the structure of a rip current is well defined at these wavelengths; at the latter site, bottom configuration is recorded with maximum detail.

In the Cayo Icacos area of Puerto Rico, Williams (1968) found that the wavelength region from 4500 Å to 5500 Å had the best water penetration, between 5500 Å and 7000 Å there was a decrease in water penetration, and above 7000 Å there was no penetration. The bottom sediment in this reefoid area is calcite sand.

Similar research was conducted off the Florida Keys by the U.S. Naval Oceanographic Office (Vary, 1967) in cooperation with several other Federal agencies, including the AFCRL Terrestrial Sciences Laboratory. Vary's preliminary report suggested the use of films and filters that would most likely yield the best water penetration in the 5200 Å to 6000 Å range. Vary also found that color infrared film had excellent water penetration capabilities, an unexpected finding.

Figure 21 is a composite of 9 aerial spectrophotographs of the Middle Sambo Reef, Florida Keys area. Band 3 (4400 Å to 5250 Å) appears to have the best water penetration, although Band 5 (5500 Å to 6250 Å) has the best contrast. It appears that optimum water penetration in tropical seas having carbonate bottom sediments is between 4500 Å and 5500 Å. The type of bottom sediment may affect light penetration and reflectance in water penetration experiments with aerial photography.

Duntley (1967) has published curves of light attenuation in distilled water, coastal marine water, and estuarine marine water in the range 3000 Å to 7000 Å. According to these curves, maximum transparency is in the blue-green region of the electromagnetic spectrum.

From 7000 Å to 8780 Å (Bands 7, 8, and 9 in Figure 21) water becomes opaque and thus appears black in aerial spectrophotographs limited to these wavelengths.

Note also the fall-off in water penetration between $6150\text{ \AA}$ and $6900\text{ \AA}$ in Band 6. For the cartographer mapping such areas as swamps and estuaries, lakes, and coasts, the water-land boundary is often difficult to delineate. When aerial spectrophotography in the $7000\text{ \AA}$ to $9000\text{ \AA}$ region is used, there is no difficulty in determining the water-land boundary.



Figure 21. Spectrophotography of the Middle Sambo Reef, Florida Keys

6. INSTRUMENTATION

Photographic or scanning imagery in the ultraviolet region of the spectrum is generally collected on ultraviolet-sensitive film used in (1) conventional cameras with ultraviolet-transmitting narrowband filters, or in (2) specially designed high-resolution ultraviolet cameras; and with (3) optomechanical scanners using photomultiplier tube detectors.

The most efficient narrowband UV photography to date (Mangold, 1966), covering the 3000 Å to 4000 Å spectral range, was accomplished by means of a set of Fabry-Perot thin-film evaporated filters. The camera used was a standard Graflex fitted with an achromat lens of lithium fluoride and quartz. Several varieties of commercial UV film (Tri-X, Kodak 103-0, 1-N, and SO-243) can be used.

Ultraviolet cameras have been commercially developed and used for some time. One such camera, which has been successfully used in a wide variety of UV photographic applications under both natural sunlight and artificial illumination, has an optical system whose f/1.5 lens of 6-in. focal length is capable of resolving 100 lines/mm at the focal plane, with maximum transmission and minimum internal scatter. It accommodates a variety of recording media, in both sheet and roll-film magazines, and uses the same filters as described above to provide a narrowband input to the film. Further details of the development and test program are given by Perkin-Elmer Corp. (1965), who have announced advances in development of an airborne UV camera system incorporating rapid framing and a wider shutter capability.

The proven ability of airborne imaging infrared radiometers (generally called infrared scanners) to generate high-quality imagery of terrain surfaces has led to their use in the ultraviolet region. Modification is readily made by incorporating an ultraviolet-sensitive photomultiplier detector that has an S-11 photocathode and using filters that limit the spectral response to wavelengths shorter than 4000 Å. Such a system has been successfully used by the U.S. Geological Survey (Hemphill, 1966) to generate high-quality UV imagery of geologic features from altitudes as high as 15000 ft. For imaging features in terms of their own individual ultraviolet reflectance, rather than achieving integrated total reflectance from adjacent scan lines, the system must be operated without automatic gain control.

A similar conversion kit is being incorporated into the AFCRL airborne infrared scanner for future use. This scanner has a 70° field of view and resolution of 2 mrad, typical of present-day scanners. Further description of the scanning system is contained in Fisher (1965). For airborne ultraviolet photography, it should be remembered that the normal glass windows covering aircraft camera

wells do not transmit ultraviolet. Fused silica or quartz windows must therefore be installed. A UV-transmitting fused silica lens is being incorporated by AFCRL in its multiband 9-lens camera.

Radiometers or spectrophotometers can readily be adapted to measure reflectance in the ultraviolet as well as in the visible or infrared regions of the spectrum. A 'triradiometer' recently developed for AFCRL (Cronin, et al, 1968) has a spectral range from 2600 Å to 11300 Å in 30 bands, consecutively sampling sun, sky, and target radiance. At each spectral setting, a detector views the radiation from a collector mirror directed into a reflectance sphere. Two detectors are used interchangeably to cover the entire spectral range. The radiometer fields of view are controlled from 1.6° to 0.1°. The amplified current outputs from the detectors are recorded on a paper chart and the entire system is selfpowered for field operation.

Hemphill and Carnahan (1965) of the USGS have demonstrated that in the field, such materials as talc and dolomite, when stimulated by an ultraviolet transmitter, may be imaged at a distance of several hundred feet by an image dissector sensitive to visible light. Their transmitter consisted of a cathode ray tube, a UV phosphor, and a sequentially illuminating raster scan.

A technique demonstrated by the USGS to be of potential value at night is to use a pulsed nitrogen gas laser, emitting at 3317 Å, to stimulate luminescence of various rocks and minerals. On the basis of the luminescence decay time, it is possible to discriminate between granites of differing mineralogic composition and also between various feldspars. The sodic varieties of feldspars appear to have the longest decay times, longer than those of calcic feldspars.

The most promising USGS technique, termed by Hemphill (1968) a 'Fraunhofer line-depth' method, uses the sun as the ultraviolet source. The technique is one of observing the ratio between the central intensity of a selected Fraunhofer line and the continuum as reflected from a terrestrial material, and comparing it directly with the same ratio in the solar spectrum. When the terrestrial ratio exceeds that of the solar conjugate the material is deemed luminescent. The prototype instrument designed for aircraft use will have sufficient sensitivity to detect rhodamine dye in concentrations of 20 ppb or less. It will be operational at the calcium Fraunhofer line at 3868 Å in the UV, where a variety of substances such as oil, detergents, phosphates, and other minerals are luminescent.

7. THE EFFECTS OF OZONE AND ULTRAVIOLET RADIATION ON VISION

Lagerwerff, Kane, and Thornberg (1961) conducted research to determine what effects prolonged exposure to ozone had on several human visual parameters.

Twenty-eight subjects were exposed to a variety of ozone concentrations for two different periods of time. Each exposure was preceded and followed by vision tests.

Photopic visual acuity, stereopsis, vertical phoria, and color vision were not affected at all or, in the case of a few subjects, very slightly. There were significant changes in lateral phoria determinations, however. The range of changes in the prism convergence tests was extremely wide; of a total of 143 pairs of tests, only 9 pairs were identical.

One surprising result was that although there was no apparent change in the normal photopic visual acuity, 25 of the 28 subjects noticed an increase in peripheral vision. Two had a decrease. No explanation was provided.

Scotopic vision was also determined and all subjects indicated deterioration ranging from $\frac{1}{4}$ through $4\frac{1}{2}$ brightness units.

To test whether deleterious effects from exposure to ultraviolet radiation could be demonstrated in human vision, Ludvigh and Kinsey (1964) exposed a group of subjects to radiation from a 1000-W mercury vapor arc from which most of the visible rays and all of the ultraviolet radiation shorter than $3200\text{ \AA}$ had been filtered out. Fixation was for 5 min at a distance of 30 cm. The difference in foveal sensitivity to light and the critical fusion frequency of both eyes of each subject had previously been determined. Results showed no difference between measurements of both eyes of the normal subjects or between measurements of any one eye before and after irradiation. It can therefore be assumed that ultraviolet radiation in the near ultraviolet at wavelengths longer than $3200\text{ \AA}$ are not harmful to these two important functions of the human eye.

On the contrary, infrared radiation can penetrate the cornea and cause considerable damage, such as cataracts.

8. MILITARY FEASIBILITY

It has long been known that seeing into shadowed areas, seeing at twilight hours, and seeing during early morning hours can be far better at near-ultraviolet wavelengths than at conventional or near-infrared wavelengths. Yet those to whom seeing is all important—forward air controllers, artillery spotters, patrols, points, sniper teams, pilots with certain types of low-level missions—are either unequipped for or unaware of the opportunities for enhancing their vision in the ultraviolet region. At the shorter ultraviolet wavelengths, changes in latitude, altitude, atmospheric conditions, sun elevation, ozone distribution, and total ozone can all contribute to improve contrast definition, sensing, and seeing. Circumstances that favor the use of ultraviolet techniques may exist

ground to ground, ground to air, or air to air. The parameters of importance are different in each instance.

Techniques useful in the ultraviolet or near-ultraviolet region would obviously include the camera as the sensor. A recent study for the Air Force Avionics Laboratory at Wright-Patterson AFB was performed by the Perkin-Elmer Corp. (1965) using (a) various films that had high spectral sensitivities in the ultraviolet, (b) a contiguous series of filters, 80 Å to 105 Å wide, and (c) an ultraviolet camera developed by Perkin-Elmer Corp. Three varieties of targets were photographed: (1) a collection of materials used in mechanical devices and structures; (2) a variety of leaves of typical American trees, and of grass, sand, granite, limestone, shale, and concrete and macadam paving; and (3) a variety of landscape features in a typical suburban area. Certain generalizations were made. These included (a) metals having a machined or raw finish will reflect specularly in the ultraviolet, (b) plastic materials can be identified by their absorption and opaque bandwidths, (c) brown dyes and paint appear darker than black finishes, (d) black finishes appear to be lighter in the ultraviolet than at other wavelengths, (e) some camouflage paints appear to be effective in the ultraviolet, (f) houses and macadam roads are readily discernible.

Although this study indicates that some camouflage paints do produce reduced contrasts in the ultraviolet, it is noted that most attempts to camouflage against aerial reconnaissance are made with a view to reducing contrast between objects in the visible or infrared regions. In such instances, detection might best be achieved through ultraviolet photography.

Horn and Hubbard (1967) explored the potential of night aerial ultraviolet photographic reconnaissance with artificial illumination. They consider the method generally unsatisfactory because its operational altitude and range are extremely limited by atmospheric backscatter, it yields a generally reduced contrast, and the reflectance of most objects in the ultraviolet is relatively low. Even if marginal results were acceptable, weather would be severely restrictive. Under ideal conditions and illumination configurations, ultraviolet photographic reconnaissance might be useful up to an altitude or slant range of 5000 ft. It would be best, however, at 200 to 1000 ft, and at such low altitudes it could indeed be valuable for specific kinds of targets.

At present, because of poor lens transmission in the ultraviolet part of the spectrum, it is doubtful that any DoD operational camera systems can be used to obtain ultraviolet photography.

The Hartley absorption band from 2300 Å to 2900 Å, with peak absorption at 2535 Å, may be useful in aerospace surveillance. For example, a vehicle orbiting above the ozonosphere and viewing the sunlit side of the Earth at the Hartley bandwidths observes little or no evidence of meteorological or terrestrial features.

Other than the nacreous clouds, most clouds are below the ozone layers and would provide a dark background against which satellites, missiles, and missile plumes might be readily detectable.

An ultraviolet sensor system would give the combat airman or foot soldier the means of enhancing his vision during periods of low light levels or under conditions of 'poor' lighting. Such periods are twilight and sunrise, and other periods when the relative intensity of ultraviolet radiation is greater than the norm. Other applications are in those regions of environment and climatology where ultraviolet radiation is relatively significant. For example, in mountains, tropics, or under dense forest canopy, there may be many occasions when the contrast or definition of certain features and objects is greater in the near-ultraviolet and ultraviolet than in any other portion of the visible or photographic spectrum.

A great variety of systems have been designed to increase the soldier's ability to view, sense, or reconnoiter during the hours of peak solar radiation and during the hours of maximum darkness. The other one-sixth to one-third of the day*—during the hours immediately before and after sunrise and sunset—most systems are of little value, or, at best, are not of optimum value. At these very times the ratio of ultraviolet to visible and the ratio of ultraviolet to infrared are at their maximum: direct solar radiation is at a minimum and radiation from the sky or from clouds is at a maximum.

It may be that the simultaneous use of discrete ultraviolet and infrared channels would constitute the optimum system.

It is obvious that a considerable number of factors might have to be evaluated to determine when and where ultraviolet sensors would be of value to military forces. It is equally obvious that the following six factors are of prime importance: altitude, latitude, and solar angle, and the optical characteristics of target, background, and atmosphere. Scientists with the appropriate interdisciplinary backgrounds should be called upon to indicate the situations most suitable for the military use of ultraviolet sensing techniques.

*middle latitude regions

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13. ABSTRACT Although variations in the intensity of solar ultraviolet irradiation of the Earth's surface may provide significant opportunities for observation in the ultraviolet spectrum, research in the ultraviolet region has been neglected by terrestrial scientists. The spectral properties of vegetation and soils and of undisturbed weathered natural surfaces of rocks and sediments, in situ, are unknown. Limited spectrophotometric data obtained in the laboratory, but of samples removed from their environment, indicate that there may be less distinctive spectral character in the ultraviolet than at the longer wavelengths. Spectral reconnaissance studies in the near-ultraviolet region are therefore warranted.		

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