

Basic Matter and Energy Relationships Involved in Remote Reconnaissance

Report of Subcommittee I

Photo Interpretation Committee, American Society of Photogrammetry

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ABSTRACT: Earth scientists, space scientists and life scientists frequently have need to detect and identify various objects and conditions in the physical universe solely from information collected by sensors that are remotely situated with respect to the area being investigated. Energy that is either emitted or reflected from the objects of interest is recorded by the sensors, either in photographic form or in a form which can be readily reconstituted into a photo-like image. Empirically it has been found that some parts of the desired information are best obtained when sensing the energy returns in ONE BAND of the electromagnetic spectrum, while other parts are best obtained by sensing in a DIFFERENT BAND.

These considerations lead to a major area of concern to Subcommittee I, dealing as it does, with the basic characteristics of matter and energy in relation to image creation by remote reconnaissance. The time has come when real progress in the acquisition of information by remote reconnaissance must be sought through fundamental research solidly founded on the basic sciences.

This paper first considers certain basic characteristics of the electromagnetic spectrum that are of importance in the remote sensing process. It then considers various electromagnetic sources (including the sun) that can be used in remote reconnaissance, and what happens to the energy from these sources as it encounters various media during the remote sensing process. Specific examples serve to illustrate that absorption, emission, scattering and reflection of electromagnetic energy by any particular kind of matter are selective with regard to wavelength, and are specific for each particular kind of matter, depending upon its atomic and molecular structure. Additional effects exerted by larger aggregations of matter such as crystals, plant tissues and even by large masses of rock, soil or vegetation also are considered. The paper concludes with a consideration of the manner in which accurate but highly complex data which summarize basic matter and energy relationships can be profitably analyzed by an electronic computer, permitting remarkably accurate predictions to be made of the type of imagery obtainable with various remote sensing devices under various environmental conditions.

INTRODUCTION

IN THE field of remote reconnaissance we have gone about as far as we can with empiricism. It no longer suffices merely to identify the more obvious objects and conditions

by examining an array of images recorded by a variety of remote sensing devices; in obtaining more refined information about the physical universe, we need to think in terms of the basic physical parameters which characterize

every piece of information presented by these images. *The primary objective of this report is to provide the photo interpreter or "image analyst" with an appreciation of the basic interactions between matter and energy that are at play when remote reconnaissance is being performed;* if this objective is realized he will be better able to extract useful information from both conventional and unconventional kinds of imagery. Within the space limitations of this report only a skeletal presentation will be possible. The presentation will have served its major purpose, however, if it succeeds in motivating the reader to think more deeply in terms of these basic physical parameters.

BASIC CHARACTERISTICS OF THE ELECTROMAGNETIC SPECTRUM

Anyone who has observed ocean waves surely has been impressed by their ability to transmit energy from one part of the ocean to another. He also will have developed the correct concepts of (1) *wavelength*, (the distance from one wave crest to the next); (2) *wave velocity*, (the speed with which the wave crests advance), and (3) *wave frequency*, (the number of wave crests passing a given point in a specified period of time). If he has observed carefully, he will have noted that the wave lengths on one day probably are not the same as on another day, and that, even on a given day, there are not only the primary waves, but various secondary waves also, of different wave lengths. Thus, there is a *spectrum* of wave lengths ranging from quite short ones to very long ones, all of which are simultaneously transmitting energy. Finally, if he has given it the slightest thought, he will have recognized a simple mathematical relationship of the above parameters which he might express in these terms: The wave frequency, f , is directly proportional to the wave velocity, v , and inversely proportional to the wavelength, λ . This relationship can be expressed by the equation:

$$f = \frac{v}{\lambda} \cdot a$$

where a is a constant whose value depends on the units in which the three parameters are expressed.

All of the foregoing concepts are useful in considering characteristics of another spectrum—the *electromagnetic spectrum*—which classifies (according to wave length or frequency) *all energy that moves with the constant velocity of light in an harmonic wave pattern*. ("Harmonic" implies that the waves are

equally and repetitively spaced in time.) It is this spectrum, hereafter referred to as the *e-m spectrum*, with which we are primarily concerned, as we consider the basic matter and energy relationships which we wish to exploit through remote reconnaissance. Figure 1 shows a form of the *e-m spectrum* adapted to remote sensing problems; we will make frequent reference to this diagram in the discussion. It should be noted that the *e-m spectrum excludes* some important fields of remote sensing application. These include:

1. *Force Fields*: The gross electrical, magnetic, and gravitational fields surrounding objects. These fields are fairly static, and non-radiative; there is nothing actually moving through the space between object and sensor.
2. *Charged or uncharged particles*: Beams of electrons, protons, neutrons and larger particles such as the ions in a plasma stream, and the very small subatomic units. These particles move with varying velocity, but always less than that of light.
3. *Sonic and other mechanical vibrations*: Harmonic waves which require a medium for propagation, and whose velocity is a function of that medium.
4. *Dispersed material objects*: Dust, vapor, and migrating ions.

Each of these fields will continue to be exploited for valuable information by active groups of physicists and geophysicists; however this committee will confine its view, for the present, to strictly defined electromagnetic radiation.

The early work of Planck established that there is a minimum energy unit in electromagnetic radiation; i.e. that *the energy is transferred only in discrete units or "quanta"* (also referred to as "photons"). Thus we must consider the radiation both as waves, and as energy pulses, or "particles of energy." This concept leads to the most satisfactory conclusions when we consider interactions between *particulate energy and particulate matter*.

We know that the energy *changes* of photons are due exclusively to interactions with matter; *e-m waves* do not interact among themselves. In empty space electromagnetic radiation (e.g. from the sun) may be propagated without limit, but in most of the real applications, propagation occurs through media (e.g. the atmosphere) and reflects from or dissipates in matter (e.g. objects on the

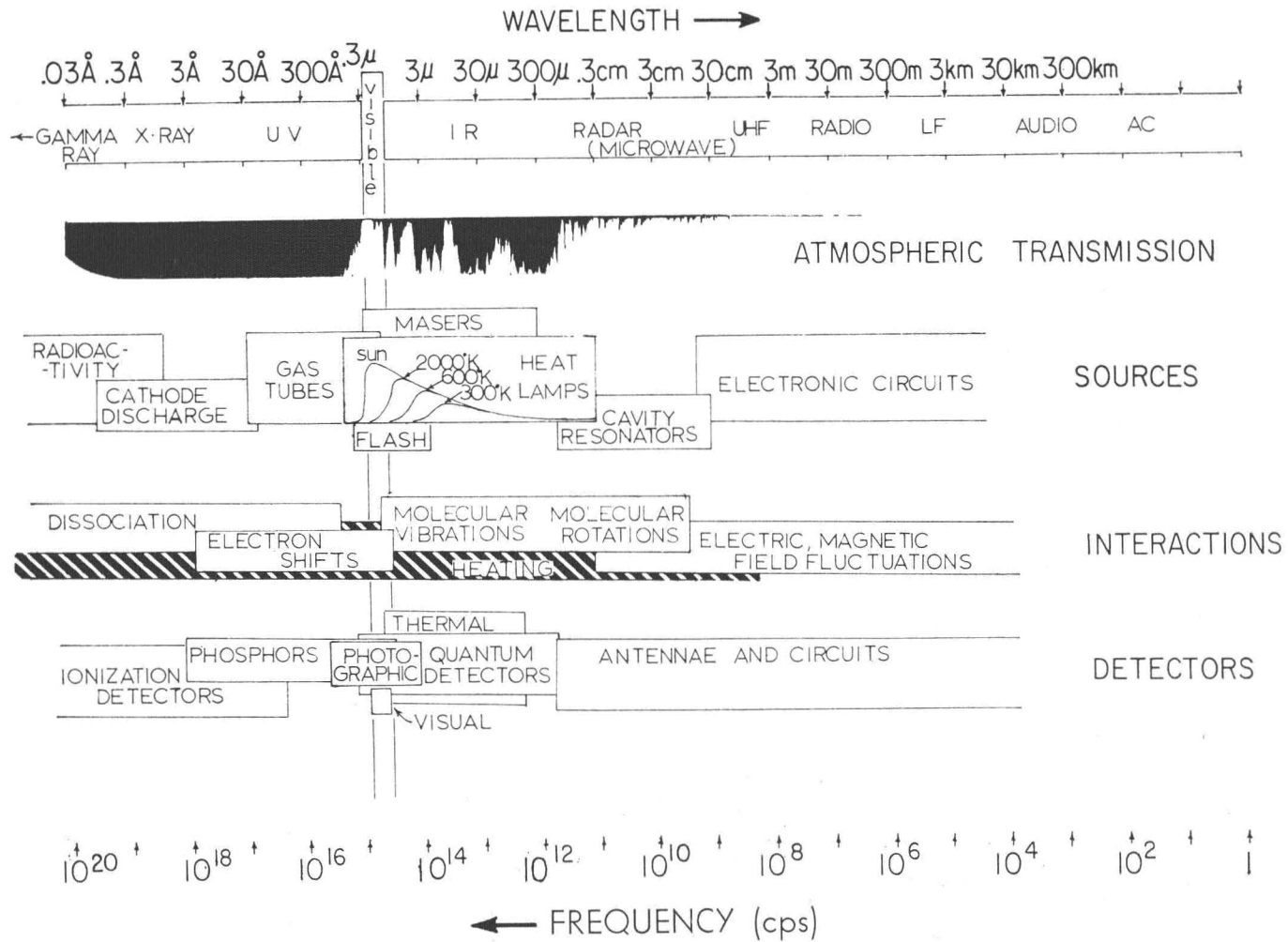


FIG. 1. Characteristics of the electromagnetic spectrum which are of significance in remote reconnaissance. For explanation, see text.

earth's surface) just as ocean waves are propagated through water and are reflected from or dissipated on a rocky shoreline. Furthermore, we know that the essential character of all electromagnetic waves is the same, and that they differ only in *wavelength, frequency, and energy*. The effective differences between, say, visible light and X-rays, then, are only differences in their interactions with matter. The *intensity* of radiation is simply the number of photons per unit time and area.

SEQUENCE OF THE REMOTE SENSING PROCESS

Let us consider a source of *e-m* radiation, either natural or man-made. The source emits radiation, usually with some distribution or spectrum of wavelengths; i.e., a distribution of photon intensities which varies with wavelength. Some sources, such as the sun, emit a continuum; that is, a continuous distribution of *all wavelengths* over a sizeable interval of the spectrum, with a smoothly varying *intensity* distribution as well. Other sources, such as the sodium vapor lamp commonly used to illuminate highway bridges at night, emit either single wavelength "lines," or "bands." The latter are found, under high resolution, to be composed of a number of lines very closely spaced with regard to wavelength.

In either case, an arbitrary bundle of radiation tends to be propagated along straight rays through a medium; i.e. through space containing matter, usually heterogeneous. Some of the energy contained in the bundle may be lost through interactions, while the rest continues on toward the target. The medium with which we are most commonly concerned in remote reconnaissance is the atmosphere—a complex gas mixture. In attempting aerial reconnaissance of *underwater* features, however, we may be concerned with at least two media, air and water. In fact the term "medium" in the sense here used, can refer to *any* collection of matter which is largely transparent to the particular wavelengths of the energy source for which we wish to accomplish remote sensing. For example, some very sturdy metals are nearly transparent to infrared radiation at specific wavelengths, whereas certain gases at that same wavelength are, to the radiation, very "solid" matter, not at all transparent. Similarly the atmosphere has well defined "windows," such as the 8 to 14 micron infrared band, alternating with wavelength bands in which the atmosphere is opaque and therefore transmits little or no electromagnetic energy (see Figure

1). The interactions between radiation and matter in both medium and target are of the same types; it follows that the distinction between medium and target is arbitrary. If the ground is the target, atmospheric effects are detrimental to sensing, but if the atmosphere itself is the target—as is sometimes the case—these same atmospheric effects are the essential ones in the remote sensing process.

All matter is made up of a collection of particles held together by finite forces. These particles are the fundamental building units of atoms and molecules, dominated (in bulk) by the electron clouds surrounding atomic nuclei. The electrons are in constant rapid motion, generally harmonic, and they have a definite distribution in space and time around certain equilibrium or mean positions; i.e. they have definite frequencies of vibration, rotation, precession, etc., on both atomic and molecular scales. Hence the electron structures of the atoms or molecules of which a given kind of matter is composed are different from those of the atoms or molecules comprising some *other* kind of matter.

It is essential here to understand that the high frequencies and minute energies associated with the individual electrons are roughly the same as those associated with the individual photons in electromagnetic waves from the middle sector of the *e-m* spectrum; i.e. the ultraviolet, visible, and infrared. As we move toward the very short wavelength, high frequency end of the spectrum (see Figure 1), the energy of a 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 (radio) end, photon energies are low, and wavelengths are large compared to atomic distances, so that no permanent structural adjustments occur.

The *basic energy equation* in photon study is

$$E_p = hf = hc/\lambda$$

Where

- E_p = the energy of any photon, regardless of the amplitude of its wave motion
- f = the frequency of the wave motion, in cycles per second
- c = the velocity of wave motion (3×10^8 meters per second for all *e-m* waves in vacuo)*

* More commonly expressed as 186,000 miles per second, when speaking of the velocity of light in vacuo.

λ = the wavelength in meters (1 meter = $10^6 \mu = 10^{10} \text{ \AA}$)

h = Planck's constant (6.62×10^{-34} joule-sec)

(It should be noted here that a photon has no rest mass, but acquires mass through motion according to the Einstein equation $E = mc^2$. The mass is given by $m_p = hf/c^2$.)

When a photon of any specific energy strikes the boundary of solid matter, a number of interactions are possible. Mass and energy are conserved according to basic physical principles, and the energy can either be:

1. *absorbed*, giving up its energy largely into heating the matter,
2. *emitted*, or more commonly re-emitted by the matter as a function of temperature and structure, at the same or different wavelength,
3. *scattered*, that is, deflected to one side and lost ultimately to absorption or further scatter, or
4. *reflected*, that is, returned unchanged to the medium.

The foregoing leads us to one of the most important points to be made in this paper:

Absorption, emission, scattering and reflection of electromagnetic energy by any particular kind of matter are selective with regard to wavelength, and are specific for that particular kind of matter, depending primarily upon its atomic and molecular structure.

In view of this fact, we can in principle identify the material constituting a target (e.g. an object on the surface of the earth) from a wavelength plot, or from a spectral series of remote reconnaissance photographs, or from any other record which is sufficiently detailed to show its spectral absorption, reflectance, emission and/or scattering properties. In the field of remote sensing this possibility often is exploited by a process known as "multiband spectral reconnaissance" (Colwell, 1961). There are complications to the process, however; in a real environment there is never a perfect absorption-reflection interaction. Scatter is a large term, for example, in the transmission through the medium, in the material itself, and in the transmission back to the detector. Furthermore the amount of scatter is a function of wavelength.

Determining the spectral composition of emitted radiation also is a problem to the observer because, added to the signal that is emitted by the target, there is some radiation

contributed by the propagating medium, itself, at various points along the path. This latter energy also is a function not only of wavelength, but of temperature and atomic-molecular structure of the medium. Since there is no way to distinguish between individual photons having the same energy, the true reflected signal may become submerged in radiation from other sources.

Finally, we must consider the fact that the intensity of radiation falling on the detector is a function of the inverse square of the distance along the path, from energy source to target to detector. From the standpoint of remote reconnaissance this imposes the requirement for either strong sources, short distances, sensitive detectors, or some compromise that will give a favorable combination of these three factors.

Despite this array of complications, we should take heart in the fact that many practical remote sensing systems exist. We should therefore feel encouraged to attempt a systematic study of the factors mentioned in the foregoing discussion.

The material which follows is highly condensed and is not to be taken as a rigorous treatment. Simple physical analogies will be used to circumvent extremely complex treatments, but these liberties will be justified if the discussion is kept moving.

If, by reading this less-than-rigorous discourse, the photo interpreter will acquire increased appreciation of the importance of these concepts and obtain some practical understanding of them, progress will have been made in the right direction. He may even be motivated to delve into the more thorough treatises relating to this subject, which he never would have considered studying without first acquiring an appreciation of the importance to him of such matters. The brief bibliography has been laid out with this in mind; we have cited references such as Van Vlack (1950), Moore (1955) and Kittel (1956) for readability as much as for content.

CHARACTERISTICS OF ELECTROMAGNETIC ENERGY SOURCES

All matter at temperatures above absolute zero (0°K.) radiates electromagnetic energy, so that all matter is, in a sense, a "source." We will discuss several energy radiators which are specific for desired regions, but it is essential that we appreciate the underlying principle. While it may be possible to photograph a raging forest fire or the flow of lava without benefit of some external illuminant, most of the objects with which photo interpreters are

concerned must be illuminated, as a practical matter, either by the sun or by an artificial source.

Matter, as we have seen, consists of particles in harmonic motion, and the energy of this motion is comparable in scale to the energy of radiant photons. When any collection of matter (i.e., any object) 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 incident energy is absorbed, and reemitted, the object is said to be a "blackbody radiator." Some objects are close approximations to blackbodies, while others are "graybodies," which do not absorb all incident radiation.

Planck proposed that energy is acquired and emitted by the radiator only in small, variable energy units which we define as quanta or photons. This concept led to a general rule known as Planck's distribution law, which predicts that radiation from a blackbody will be distributed according to wavelength in a very specific way. A conventional form of the statement is

$$E_{(f)}df = \frac{8\pi hf^3}{c^3} \cdot \frac{df}{(e^{hf/kT} - 1)}$$

where $E_{(f)}df$ is the number of oscillations, over an incremental frequency band, df , times the average energy per oscillation; more simply, it is the energy radiated, per unit of wavelength, per unit volume of the radiator.

kT is the "ideal"* total energy of an oscillating atom or molecule; k , the Boltzmann constant, is often defined as the gas constant per molecule, and has the value

$$k = 1.38 \times 10^{-23} \text{ joule per degree.}$$

T is the absolute temperature ($^{\circ}\text{K}$).

From this law two additional useful concepts are derived. *Wien's displacement law* gives the *wavelength*, λ , for which radiation emittance is maximum as:

$$\lambda_{\max} = \frac{2.897 \times 10^3}{T}$$

where λ is in microns, μ .

The *Stefan-Boltzmann law* states that the total energy radiated from a blackbody per unit area, per unit time, is proportional to the

* The term "ideal," as used here, refers to the sum of potential and kinetic energy, per degree of freedom in the absence of perturbing factors. Hence, the term does not allow for forces or energies arising from internal atomic structure.

fourth power of absolute temperature

$$E_{\text{tot}} = 5.67 \times 10^{-8} T^4 \text{ (where } E \text{ is in watts per meter}^2\text{)}$$

The radiant spectrum of a thermal source will be a skew curve falling off sharply on the high frequency (short wavelength) side, and will have an intensity peak which shifts toward higher frequencies as the temperature rises.

The sun, being at very high temperature, radiates enormous amounts of energy all across the ultraviolet (*UV*), visible (*V*), and infrared (*IR*) bands (see Figures 1 and 2) and

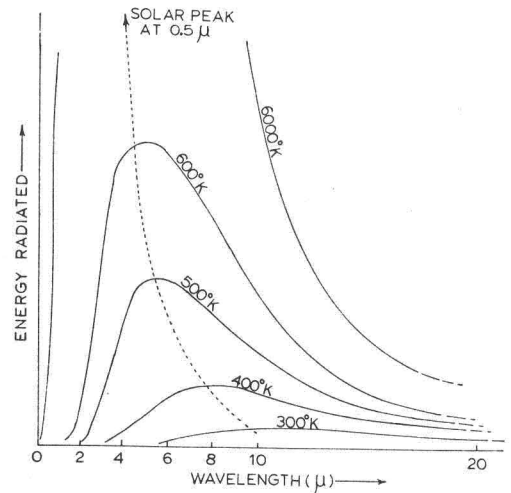


FIG. 2. Blackbody radiation curves.

has a sharp power peak at about 0.5μ wavelength; thus it is an excellent source for illuminating the surface of the earth when we wish to accomplish remote reconnaissance of the earth by use of *reflected* light in the *V* (0.4 to 0.75μ) range, as when using conventional panchromatic film.

The earth, primarily because of its having absorbed energy from the sun, has an average temperature of 300°K ., and consequently a radiant power peak at about 9.6μ . (See Figures 1 and 2.) Its distribution curve is low and broad compared to that of the sun, however; for this reason, when we wish to accomplish remote reconnaissance of the earth by the use of *emitted* energy, we have available a broad band extending from about 5 to 25μ in the middle infrared or "heat mapping" part of the *e-m* spectrum.

Since there exist good atmospheric "windows" for both the *V* and *IR*, (See Figure 1) remote reconnaissance of the earth's surface by both *reflected* and *emitted* energy is possible.

Any object, such as the filament of a lamp, may be raised to a specific temperature, at which it will radiate "light" with a specific peak wavelength (for the light to be visible, T must approach 600°C ., i.e., 873°K .). The energy it *absorbs* may come from internal electrical or chemical action, or from another radiant source at a distance, and the energy it *radiates* is distributed according to wavelength as a function of its temperature alone, in theory. The limitation on a purely thermal source of "light" (on the high frequency, short wavelength side) is simply the maximum temperature obtainable in the radiator before it physically dissociates. For ordinary filament materials the peak of the power curve falls in the range "white hot"; i.e., in the V and UV . For chemically reacting systems such as the acetylene flame, there is a slight shift of the peak toward the UV side, but not very far in terms of the whole spectral range.

Toward the longer wavelength (IR) side of the spectrum there is no sharp limit on the practical cutoff for a thermal source in remote sensing. Rather this is established by comparing the temperature of the object to be resolved with the temperature of the background, in any thermal range down to the extremely "cold" background of space. Recent advances in detector design make it possible in some cases to discriminate within a few tenths of a degree between objects within the earth's temperature range (275°K . to 325°K .), corresponding to the 5 to 25 μ band of the $e-m$ spectrum. Beyond this point, there are more efficient radiation sources available of a nonthermal character. For radiofrequency (RF) waves there is the familiar oscillating dipole source, and for the radar-microwave region, some specialized tube and resonant cavity sources, which will not be discussed further in this report.

It is possible to obtain fairly narrow band widths of UV radiation from vapors or gases by putting them in a tube at low pressure and "exciting" some of the atoms to emit radiation. An electric field is generally required, which causes a stream of electrons to pass through the gas, colliding with some of the atoms. These collisions are "inelastic"; i.e., some of the energy of the electron beam is absorbed by the atoms and re-emitted as photons in the UV and visible parts of the spectrum. The wavelengths of radiation from these gas tubes are specific for any atomic species, but are invariably complex with regard to their "fine" structure. However, many

closely spaced spectral lines may give a visual impression of one dominant color, as in the yellow sodium vapor lamp or blue mercury vapor lamp.

Such sources are useful for obtaining radiation in the UV region, being practically unlimited in the range which they may be made to cover. When a nearly complete vacuum is attained and the potential is increased to some hundred thousand volts, X-radiation is emitted from the cathode, partly as a continuum and partly as band spectra, representative of electron shifts within the cathode atoms.

The UV , V , and IR -microwave regions are in a sense the regions where energy truly *interacts* with matter, neither violently disrupting it, as in the short wavelength region (X-rays, gamma rays, and cosmic rays), nor interacting with it only feebly and transiently, as in the long wavelength region (radar and radio waves).

Until recently UV - V - IR energy sources were practically limited to thermal sources and, in terms of money spent on remote sensing, activity was concentrated in the visible and other photographic regions. Ultraviolet sensing was and is essentially a laboratory or short-range tool for the earth scientist, because UV radiation propagates poorly through air; but military requirements for heat (IR) sensors have led to some very basic investigations of IR in general, and recent detector development has made the region "accessible." In almost all cases, this sensing has been based on some kind of thermal source.

In the last five years an additional energy source with unique characteristics has appeared. It is referred to as the *maser* (microwave amplification by stimulated emission of radiation). When "light" is substituted for "microwave" such a source is termed a *laser*.

Maser and laser devices function as nearly monochromatic (i.e., single "color," or single frequency) radiation sources, amplifiers, or oscillators for a rapidly growing number of very specific wavelengths in the V through IR to microwave region. True monochromatic radiation is unattainable, but masers come fairly close to it, and have considerable potential as sources of identifiable or "coded" radiation in an environment containing a lot of "hash" or unidentifiable radiation. These will be discussed in more detail later, using the molecular model.

In summary, the sun is such a rich source of electromagnetic energy that most remote reconnaissance currently is being accomplished with "passive" systems, i.e., those which rely on solar energy, rather than supplying, of themselves, the radiant energy for sensing. Thus, for example, in the visible and near-infrared regions, solar energy that has been *reflected* from objects is exploited in the remote sensing of those objects, while in infrared regions of longer wavelength, solar energy that has been absorbed by and then *emitted* from these objects is exploited. When "active" sensing systems (i.e. those using artificial energy sources) must be employed, there are practical methods of obtaining electromagnetic radiation of almost any desired wavelength. For example, X-radiation can be obtained from high-voltage cathodes; radar and microwave radiation from specialized tubes and resonating cavity sources; radio frequency radiation from oscillating dipole sources; and radiation for most of the other parts of the spectrum from masers, filaments and gas lamps. It often is advantageous to filter out all but one or two broad bands in remote reconnaissance to exploit unique energy signatures that occur within those bands for the various objects and conditions that are to be identified. The narrower the filtering, however, the less the energy available for remote sensing; really efficient filtering can be self-defeating.

THE PROPAGATION OF ELECTROMAGNETIC ENERGY THROUGH THE ATMOSPHERE AND OTHER MEDIA

We have mentioned that *e-m* radiation travels through empty space without the slightest modification; the sensing of celestial radiation sources such as stars offers dramatic support for this view. (Actually interstellar space is not completely empty, but is so nearly empty that practically no effects attributable to media appear.)

In terrestrial media, such as air and water, we are concerned with very strong effects, which are highly selective with regard to wavelength. Let us therefore consider what is known about these effects, first in relation to remote reconnaissance of objects above the waterline, where only atmospheric effects are of concern to us; then for underwater objects where we are concerned with the propagation of electromagnetic energy through two media, atmosphere and water.

Middleton (1950), in dealing with the attenuation by scattering of electromagnetic

energy in the atmosphere, has provided an excellent summary of our present state of knowledge on this subject. He emphasizes that the atmosphere often contains much in addition to the gas molecules for which Rayleigh's law (see later sections of this paper) applies; haze, fog, rain, snow, and smoke also are frequently present. The effect of these aerosols on light is complicated, because their particles vary in a range of sizes from, say, 10^{-6} to 10^{-1} cm.; this size range includes the wavelengths of radiation used by the photographer. The theory of the scattering of light by small spheres in the lower part of this range of sizes was dealt with quite adequately in the classic paper by Mie in 1908. A great deal of work has been done on this problem by other workers, with the general result that Mie's theory has been abundantly confirmed.

One of the most interesting results of Mie's theory is that a particle has an "effective radius" which is in general not the same as its actual physical radius.

The ratio, k , of the effective area of a small droplet of water to its actual area is shown in Figure 3, from Houghton and Chalker (1949), in which the abscissa is in units of $2\pi r/\lambda$, where r is the radius of the droplet and λ the wavelength of the light. The curve approaches $K=2$ for large values of the radius, a fact which seems rather surprising but can be explained quite adequately by considerations of diffraction phenomena in the terms of classical electromagnetic theory. The complexity of the curve is of interest and explains certain anomalous scattering effects noted in earlier times by various authors. In visible light the Mie theory can reasonably be used for droplets of radius not greater than a few

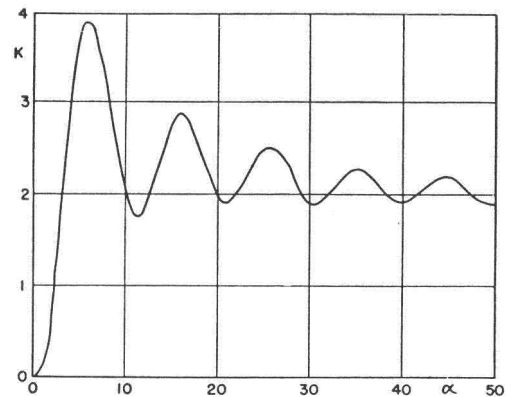


FIG. 3. Ratio of the effective area of a small droplet of water to its actual area. (After Houghton and Chalker, 1949.)

microns. For the larger drops of fog and cloud, geometrical theories, which have been given by Wiener (1907, 1910), Bricard (1943) and others, can be used more easily and provide satisfactory results.

Figure 4 shows how these methods can be used to calculate the extinction coefficient of droplets of various sizes throughout the ultra-violet, visible and near-infrared spectra. It will be seen that while for very small particles the extinction in blue light is much greater than in red, this is not true for larger particles. In fact it will be noted that for very large particles, there is practically no change in the extinction coefficient as we pass from one end of the visible spectrum to the other.

The question which is most often asked workers in atmospheric optics concerns the possibility of signalling through fog or seeing through it or photographing through it by means of infrared light. If the inquirer is really referring to fog, which consists of comparatively large particles of water, the answer must be in the negative, unless he is prepared to use radiation of several microns in wavelength. The inquirer is always left with the problem of producing such radiation in sufficient quantity; this is a field of potential maser applicability.

If on the other hand he is concerned with haze, then the answer is more encouraging. Particles in haze are inclined to be less than a micron in radius, probably on the average 3 or 4 tenths of a micron, and it will be seen from Figure 4 that there is a good deal of change in the extinction coefficient as we go across the visible spectrum and near-infrared, so that a considerable increase in range might be expected. Table 1, taken from some early work by Middleton (1935) suggests what we might obtain if we photographed with radiation of wavelength 1 micron, and it will immediately

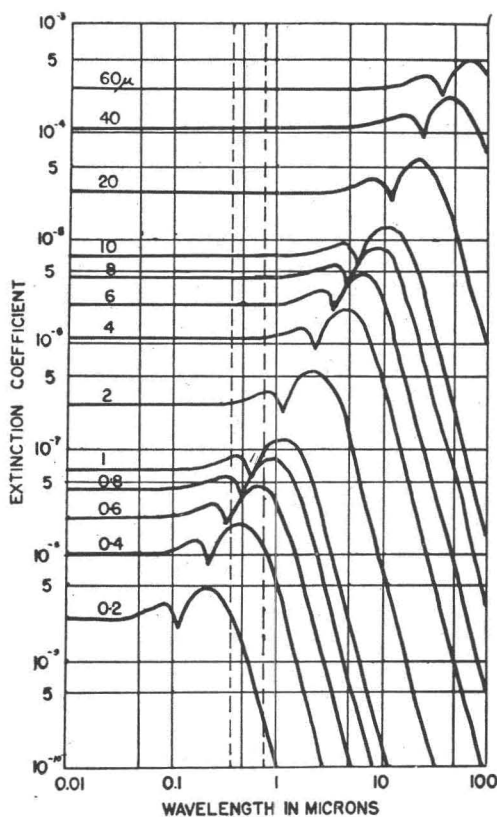


FIG. 4. Extinction coefficient in (cm.⁻¹) as a function of wavelength for a density of one particle per cm³. of atmosphere. The numbers of the curves refer to the radii of the particles in microns. The visible spectrum lies approximately between the two vertical broken lines. (Adapted from Bricard, 1943)

appear that the improvement in range by going to a longer wavelength is greatest when the visual range is already greatest. In actual fog, infrared emulsions give practically no help, but with haze they offer appreciable improvement.

TABLE 1
EXTINCTION COEFFICIENTS AND VISUAL RANGES FOR GREEN LIGHT AND FOR 1.0 MICRON RADIATION. (FROM MIDDLETON, 1950)

Extinction Coefficients (σ)		Visual range for green	"Visual range" for 1.0 μ	Ratio
For Green Light	For 1.0 μ radiation			
0.0136	0.00103	288 km.	3,800 km.	13.6
0.0298	0.00782	131	500	3.82
0.0440	0.0154	89	254	2.86
0.129	0.0541	30.4	72.4	2.38
0.298	0.160	13.1	24.5	1.87
0.461	0.275	8.5	14.2	1.67

As distinguished from the aerial photography of inland objects, where the quality of the obtained image is affected solely by the presence of the *air column* between the object to be photographed and the lens of the aerial camera, the aerial photography of underwater objects requires additionally the consideration of the *water column* above the photographed object. Both water and air are turbid media, and therefore the light flux creating the brightness of the photographed object—in the given case, an underwater object—undergoes quite a number of quantitative and qualitative changes. These changes and their causes have to be known by the researcher in the given field so that, even if it is not possible to restrict or eliminate them, the selection of the optimal technical conditions and means of photographing will be ensured.

When taking aerial photography of underwater objects the image range of the photographs depends chiefly on the ratio of the brightnesses of individual objects, and their brightnesses in turn will vary, depending on the water and air layers. These two turbid media selectively absorb and scatter solar light, so that as a result the spectral composition and intensity of the reflected light vary drastically.

Optical phenomena in the *atmosphere*, as previously indicated, are principally accompanied by the scattering of light in the range of blue-violet rays, i.e., in the shortwave part of the visible spectrum, by the air molecules themselves insofar as the dimensions of the latter do not exceed the length of the light wave. *Water*, however, displays completely different optical properties. According to a recent study by Russian scientists, as reported by the *American Society of Photogrammetry* (1960), the maximum absorption of light in optically pure water containing no secondary inclusions occurs in the infrared range, and the minimum, in the blue-violet range. For clear sea-water the absorption maximum also occurs in the infrared range, but the minimum shifts to the green range (460 to 540 millimicrons). For river water, which as a rule is more turbid than sea water, the absorption maximum lies in the blue-violet range of the spectrum, while the absorption minimum shifts in the longwave direction and corresponds approximately to the yellow-orange sector (576 to 609 millimicrons). These optical properties of water are illustrated by Bashkirtsevaya (Moore, 1947). This change of the spectral composition of the light reflected from an underwater

object should be taken into account when selecting the photo-sensitive material and light filters for remote reconnaissance of underwater objects.

The factors affecting the brightness of an underwater object are as follows:

- (1) The atmospheric haze—the layer of atmosphere between the lens of the aerial camera and the surface of water.
- (2) The water surface, which, mirror-like, reflects the sky.
- (3) The water layer above the photographed object.
- (4) The underwater object.

Let us consider separately the influence of each of these factors.

(1) The *atmospheric layer* between the water surface and the lens of the aerial camera is a turbid medium whose scattering particles are commensurate with the length of light waves. Such turbid media are characterized by Rayleigh scattering of light. Generally speaking, within the visible spectrum, the scattering is inversely proportional to the fourth power of the wavelength of the light. Thus the brightness of the air haze is created by the scattered light of the shortwave sector of the spectrum, which corresponds to blue-violet rays. Inasmuch as in natural waters these rays do not participate in creating the image of the underwater object, the brightness of the air haze should be excluded, which is in fact done in aerial photography by applying yellow, orange or red compensating color filters.

(2) The reflecting power of the *water surface* depends chiefly on its light intensity which, in turn, depends on the height of the sun above the horizon, cloudiness, and height of the waves.

The light intensity from the water surface increases as the sky becomes cloudy. This is because clouds play the role of a screen reflecting light back onto the water surface, and inasmuch as the clouds themselves scatter light, the light thus reflected will also be scattered light.

The relationship between the depth of penetration of solar rays into water and the height of the sun above the horizon is expressed by the formula

$$I_1 = I_0 \cdot \left[1 + \frac{\cos^2(\phi + \psi)}{\cos^2(\phi - \psi)} \right] \cdot \left[\frac{\sin^2(\phi - \psi)}{2 \sin^2(\phi + \psi)} \right],$$

where I_1 is reflected light; I_0 is incident light; ϕ is angle of incidence of solar rays; and ψ is angle of refraction of solar rays.

From the above formula it is clear that a decrease in the height of the sun above the horizon entails an increase in light reflection, while at a normal angle of incidence reflection is absent. In the presence of waves on the water surface, reflection will be greater, because then even when the sun is at heights near to its zenith it is always possible that a surface is present which will not be normal relative to the solar rays. During aerial photographic surveying of underwater objects it is desirable that a major part of the solar rays incident on the water surface penetrate deep into the water; a high sun angle and a calm surface favor this penetration.

(3) The *water layer* above the photographed object constitutes, like the overlying atmospheric layer, a turbid medium but one with different optical properties, because the dimensions of the particles present in the suspended state in water are not commensurate with the length of the light wave.

A detailed study of the question of the particles incommensurate with the length of the light wave was made by V. V. Shuleykin (1933), who demonstrated that, at an increase in the size of scattering particles, the $K = 1/\lambda^4$ law loses its validity; scattering loses its selective-spectral character and, for quite large particles, becomes practically identical for all segments of the visible spectrum.

(4) Light reflected from the *sea floor* is diffuse in nature; moreover it is always reduced owing to the moisture of the floor, and it depends on the color and structure of the floor. Observations of sand samples have shown that the reflection coefficient varies approximately three-fold, decreasing for a wetted object.

A quantitative consideration and thereby also a rigorous restriction of the effects of the above factors is not feasible in practice, and therefore, the process of photographing involves attempts at minimizing—through the proper selection of photographic films, filters, and atmospheric conditions—the effects of deleterious factors such as brightness of the atmospheric haze, and brightness of the water layer above the object.

The brightness and image contrast range of an underwater object greatly affect the possibility of obtaining an image of that object; therefore, in selecting the conditions and means of photography, an attempt is made to reduce the detrimental brightnesses, while choosing favorable conditions for the light flux emanating from the underwater object.

TABLE 2
RELATION BETWEEN STATE OF ATMOSPHERE (INTENSITY OF HAZE) AND HORIZONTAL VISIBILITY. (FROM MIDDLETON, 1950)

<i>Nature of Haze</i>	<i>Visibility Range in Kilometers</i>
Haze Absent or Barely Noticeable	115
Light Haze	55
Normal Haze	25
Strong Haze	15
Mist-like Haze	7
Fog-like Haze	2-3

In the aerial surveying of underwater objects it is desirable to photograph them at times when the transparency of the atmosphere is greatest. Table 2 indicates the relationship between intensity of the atmospheric haze and horizontal visibility.

Usually it is possible, under conditions which are otherwise favorable, to obtain satisfactory aerial photographic images of underwater objects in the first three cases, i.e., in cases of:

- (a) Absent or barely noticeable haze.
- (b) Light haze.
- (c) Normal haze.

On the basis of the foregoing analysis it is possible to compile Table 3 for the selection of color filter and film as depending on the degree of transparency of water and air.

To summarize, in real terrestrial media such as air and water, we are concerned with very strong energy-scattering effects, which are highly selective with regard to wavelength.

The sections immediately following will describe the underlying processes in the terminology of quantum theory; it seems appropriate here to mention, however, that in the practical engineering calculations for remote sensing applications, there are other treatments which facilitate the computations. In general, the effects which diminish the intensity or purity of a propagating signal are best handled *quantitatively* by what we have referred to as "classical theory."

If there seems to be a conflict between the quantum concept and the classical theory of electromagnetic radiation, it is not surprising. The classical treatment considers *e-m* waves

TABLE 3
RECOMMENDED COMBINATION OF AERIAL FILM AND COLOR FILTER FOR WATERS WITH DIFFERING DEGREES OF TRANSPARENCY

Observed Depth of Disappearance of White Disk, in Meters	Recommended Film	Recommended Color Filter, Transmission in Millimicrons	Remarks
15 and deeper	RF Type, Orthochromatic, With Supplementary Sensitization in the Green Ray Zone	Yellow, From 520 On	Sea Water, Use of Panchromatic Film Would Yield Less Contrasting Photograph
15 to 8	RF Type	Yellow, From 520 On	Sea Water
8 to 4	Panchromatic	Orange from 576 On and Yellow From 520 On	Transparent River Water
4 to 2	Panchromatic	Deep-Yellow Light-Orange	Transparent River Water
2 to 1.5	Panchromatic	Light-Orange Orange, Dense	Turbid River Water
1.5 and less	Panchromatic	Dark-Orange and Red	Very Turbid River Water

as continuous, additive, and of variable amplitude or height; the intensity of radiation is treated as a function of wave amplitude. This method is convenient, and perfectly valid for most macroscopic application. It fails only when one begins to deal with the smaller units of matter, and the precise description of matter and energy interactions. Yet these are the primary topics on which our Subcommittee has been asked to report.

We will retain one fundamental principle of classical theory in our discussion, the idea that each wave has associated with it a constantly changing electrical (E) field and a constantly changing magnetic (H) field. (The term "field" means roughly the existence of energy in space.)

Figure 5 shows an idealized electromagnetic plane wave. The fields of the force lines (vec-

tors) E and H are related by Maxwell's Equations, which describe the position, intensity and time rate of change of all the energy "fluxes" or currents.

We are concerned now with the *qualitative* aspects of *e-m* radiation and its interactions with matter. It would be inappropriate to develop the bases for *quantitative* calculations in the terminology of classical theory. We will make the point that quantitative propagation studies are important, and that another treatment different from, but not irreconcilable with the quantum treatment exists.

INTERACTIONS BETWEEN ELECTROMAGNETIC ENERGY AND THE TARGET MATTER

1. ATOMIC INTERACTIONS

We have mentioned that a *photon* can only change its energy (i.e., frequency or color) by

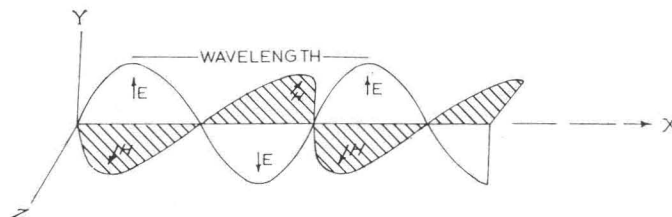


FIG. 5. An idealized electromagnetic wave. The wave propagates in the X direction. The E vector is constrained to move in the XY plane, and the H vector in the XZ plane. Individual photons may move in some other undefined plane, but with the same wavelength.

interaction with matter. We will find that *matter*, in its basic units, can only change its energy across certain "allowed" intervals, and that these are fundamentally linked with energy changes in photons. Furthermore, we will find that the wave motions and electromagnetic fields of photons are matched by wave motions and fields of the smallest particles which make up atoms and molecules. Atomic and chemical physics begin at this point.

There are several languages employed in discussing atomic and molecular models; we cannot directly observe an atom, or any but the largest molecules, so we have developed various concepts which give an adequate description of the particular effects in which we are interested.

The chemical approach is based on atoms and *larger* units, while the physical approach, generally speaking, deals with the smallest indivisible particles, arranged in definite configurations or models (i.e., atoms and *smaller* units). Besides these mechanical or geometric models, there are purely mathematical models in which all geometric significance disappears.

We will begin with a physical, geometric model because it is easiest to understand and because it adequately explains many of the phenomena of remote sensing. "Truth" and "validity" are now very subjective terms; we believe in whatever works out best. Furthermore, our model will be tailored to the *UV-IR* spectral region; many of the effects here present are either missing or insignificant in other spectral regions, where new effects appear.

An atom consists of a nucleus and, surrounding it in space, orbiting electrons which build up in "shells" or "levels." Atoms of different elements, and in different chemical states, vary in the number and configuration of shells and in the number of electrons within each shell. Electrons and the protons of the nucleus have motion, mass, and electrical charge, and it is the balance of familiar forces, both mechanical and electrostatic, which holds matter together.

When a single electron for some reason changes position within an orbital shell, or jumps from one shell to another, the total energy content of the atom changes. This energy change is reasonably specific for each type of electron shift, and for each type of atom, and it is fundamental that for *each energy change there may be a photon absorbed or*

emitted, with energy equal to the energy change in the atom as a whole. We know that the energy of a photon, E_p , determines its frequency through the relation

$$E_p = hf$$

and that

$$\lambda = \frac{c}{f}$$

where

λ = wavelength,

f = frequency,

c = velocity of light, and

h = Planck's constant.

Then the whole basis for determining the energy associated with various electron energy levels stems from the simple relationship

$$f = \frac{\lambda E}{h} = \frac{1}{h}(E_{n1} - E_{n2})$$

where E_{n1} and E_{n2} are the energies of an electron in two states or levels, $n1$ and $n2$, and f is the frequency of the photon absorbed or emitted.

Because the frequency is specified, there is a specific wavelength or "color" associated with every photon emitted or absorbed by electronic shifts. The physical manifestation of electron shifts is the heating or cooling of an atom; while being heated, the atom absorbs photons and gains in energy, and while cooling it releases photons and liberates energy.

We say that the energy change is "reasonably" specific, because there is an "uncertainty" arising from the fact that the electron shift occurs over a very brief time interval. Because electrons move in undulating wave patterns superimposed on the gross orbital pattern (Figure 6) one cannot be sure at any given instant of the exact position of the electron with relation to other electrons in the atom, or with relation to the nucleus. Hence, there is uncertainty at any given instant regarding the angular momentum of the electron, and this leads to uncertainty in its energy in either state or level at the instant of shifting. The wavelengths of the photons associated with each class of shift are thus not monochromatic but have a certain narrow "spread" of possible values. Other factors tend to increase this spread, such as the effect of nearby atoms in the system or the motion of the atoms relative to the observer; these are termed "broadening effects."

Electrons are pictured as being held in orbit by electrostatic "potential energy barriers,"

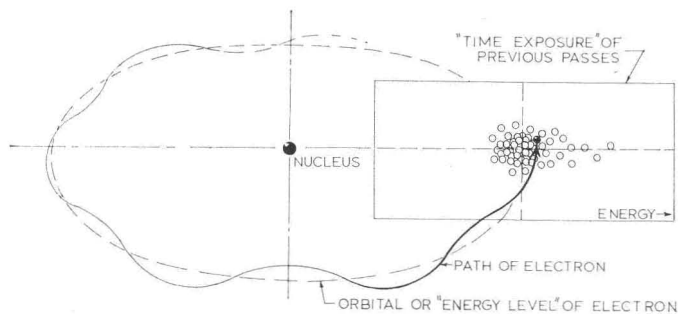


FIG. 6. The possible motion of an electron. In this case the orbit about the nucleus is circular. The angular motion of the electron is constantly varying in time and space.

walls of potential energy, U , which, in Newtonian mechanics, would have to be surmounted by kinetic energy $E > U$ for an electron to escape. As a matter of fact, there is another treatment of mechanics called "quantum mechanics," which predicts that as long as these walls are not infinite, some electrons will escape to other orbits according to *calculable probability* for any set of external conditions. (An example of an infinite potential wall is that between the nucleus and an approaching electron.) The analogy of "tunneling" has been used, although the proper explanation lies in the solution of the mathematical equations which describe the energy distribution in an atom.

Energy distribution in an atom is fundamentally a question of the relative position of all the particles at any instant; because all the particles are in constant rapid motion, we must "freeze" this motion to study it. In general, then, we will be trying to locate electrons in the 3-dimensional space around a nucleus. Unlike the precise solutions obtained in celestial (essentially Newtonian) mechanics, we can only get a solution in terms of *probability* that an electron is in a certain position, and that it is likely to make a certain shift. For many purposes this is adequate, since we are dealing with very large populations, and hence are ultimately interested only in mean values.

The fundamental equation relating the dual wave and particle concepts of quantum mechanics is the Schrödinger equation, which for the one dimensional case of a particle moving on a line, i.e., in the x -direction, is

$$\frac{d^2\psi}{dx^2} + \frac{8\pi^2m}{h^2} \cdot (E - U)\psi = 0$$

The new terms introduced are

m , the particle mass, and

ψ , the wave function, characteristic func-

tion or "eigenfunction" which will allow solutions for the differential equation. (This is defined by $\psi(x) = \sin 2\pi ft = \phi$, the displacement.) Only certain wave functions or wave forms will satisfy the equation, and knowing ψ we can describe the wave motion exactly.

The possible solutions to the Schrödinger equation give the *number of nodes* in various standing wave configurations, and this will turn out to have great importance.

If we call the "particle" an electron, and put a three-dimensional environment in place of one that is only one-dimensional, then

$$\nabla^2\psi + \frac{8\pi^2m}{h^2} \cdot (E - U)\psi = 0$$

and m becomes the mass of the electron. Furthermore, ψ becomes the amplitude of an electron wave, and *the probability of finding an electron in any incremental region can be derived*. (∇^2 is an operator or shorthand notation allowing for a three-dimensional situation.)

Thus we obtain a number of "allowed" solutions to the *probable* energy distributions in space around the nucleus for various boundary conditions. For the simple hydrogen atom we can calculate a "radial distribution function" which describes the probability of finding an electron in a spherical shell with finite thickness at any distance from the nucleus, and thus the energy associated with that orbit.

The original (Bohr) model of atomic structure, with hard little electrons circling the nucleus on precisely defined "rails," has given way to a nucleus surrounded by rather fuzzy-edged "clouds" of electrons, each cloud having, however, a definite size and shape. The individual electron positions in such a cloud are of maximum density in the region of the

old "rails" (see Figure 6). When an electron shifts within or between shells a photon may be emitted or absorbed. The energy of the photon corresponds exactly to the energy gap between the original and final levels. Since these levels are not precisely fixed for all instants of time, a specific class of electron shift within a large collection of atoms will absorb or emit any photons with "colors" varying *slightly* from some mean color. This is by definition a spectral line.

For atoms more complex than hydrogen it is not always possible to solve for a complete radial distribution function, and the calculations are in any case quite involved. In practice, however, the electrons whose shifts are responsible for spectral lines are usually outer shell or "valence" electrons, and if we can characterize their motion alone, we have a powerful tool for predicting and identifying wavelengths associated with characteristic electron shifts. Hence we can predict what combination of sensor and filter to use when attempting to identify certain kinds of matter, from their atomic spectra, by means of remote reconnaissance.

It turns out that four simple parameters will adequately describe the position in space and time of any bound electron, and that each of the four has a reasonable physical significance. Furthermore, they arise naturally as "allowed" values in the basic quantum-mechanical equations, such as the Schrödinger equation. They have been named n , l , m , and s , and are referred to as the "quantum numbers."

n is the "shell" or "principal" quantum number, and it must be noted that shells are not always spherically symmetrical about the nucleus, or even spherical at all. In a large complex atom the position of each electron at any instant of time is determined by the electrostatic forces, and hence by the positions, of all other electrons and of the nucleus itself. Since the circle is a special case of the ellipse, let us consider for the moment that the shells are ellipsoids and that the nucleus occupies one focus.

Then n and l can be considered as characterizing (but not equaling) the major and minor axes of an ellipse, and l will be called the "azimuthal" quantum number, or the angular momentum of the electron.

At this point we will tie in the "allowed" or eigenvalues used in the Schrödinger equation, and a little basic mechanics.

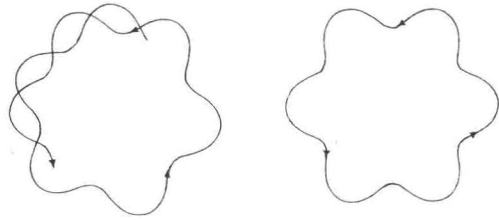


FIG. 7. Unstable and stable electron orbitals. The configuration on the left is inherently unstable. On the right is a stable standing wave configuration with twelve nodes.

The Bohr model of the atom was based on the idea that mechanically stable orbits occur where the angular momentum of an electron is equal to some multiple of a basic geometric unit. The condition for a circular orbit was

$$mvr = n \frac{h}{2\pi}$$

where v was the velocity of the electron, and r , the radius of the orbit. n was any integer. $h/2\pi$ was a constant term which defined the model for certain "quantized" values only, and is still the unit or dimension of quantum numbers. Now if we further define $(n-1)$ as the number of nodes in the electron's standing wave, and employ the Broglie condition for a stable orbit, that

$$2\pi r = n\lambda, \quad \text{where } \lambda = \frac{h}{mv},$$

then we have expressed, in the two relations, the condition for a stable orbit in terms of geometry, wavelength of the electron wave, and the quantized nature of the energy involved. Figure 7 shows the ideal case of a stable orbit.

This treatment can be extended to more complex configurations. The azimuthal quantum number l for example, characterizes an ellipse when $(l+1)/n$ is the ratio of the major to minor axes. But it turns out that the quantum numbers arise naturally from consideration of the wave mechanical (Schrödinger) function alone when proper boundary conditions are employed, so that we can obtain solutions in terms of *energy states or levels* for any combination of n , l , m and s , *without reference to a geometrical analysis*. This is of fundamental importance.

To complete the description, we will call m the magnetic quantum number and define it as the component of angular momentum along the direction of an external field; the application of an external field, either mag-

netic or electric, causes the fields associated with the electron wave to take up specific orientations, so that in a sense we "freeze" the orbits in a three-dimensional coordinate system. The component of angular momentum in the field direction is "quantized" in units of $h/2\pi$, even when the field is vanishingly small, and m is its value.

The term s is defined as the "spin" quantum number, with only two possible values. If an electron is considered to be spinning on its axis, it has an angular momentum component of $\pm \frac{1}{2} h/2\pi$ in any given direction. This concept was developed to account for the observed fine splitting of spectral lines into "doublets" or closely spaced pairs.

Here we arrive at a very important general concept: *by varying the four quantum numbers to obtain solutions of the wave functions, ψ , we can obtain from our basic equation the energy associated with an electron in any configuration, even though in complex atoms we have lost the geometrical significance of this configuration.* Instead of speaking of *orbits*, we now speak of *energy levels*, and we can predict a great deal of useful information about energy changes, and hence photon effects, when electrons shift within an atom. We can, for example, predict the wavelengths at which photons will be emitted from various kinds of matter; hence we can predict the spectral zone in which such matter is best detected by remote reconnaissance. *The value of this statistical-mathematical model in relation to the matter-energy interactions which are of significance in remote reconnaissance can hardly be overemphasized.*

That the model is valid cannot be proven for all cases, but so far it has not been disproven; also it has explained many observed phenomena in energy-matter interactions; the basic concept is contained in the Pauli Exclusion Principle, which states in part that in an atom, no two electrons can have the same four quantum numbers n , l , m and s .

The periodic table of the elements shows how the gross structure of atoms is built up in an orderly way—(so many electrons in each shell, balanced in charge by the nucleus); the quantum-mechanical model shows how individual electrons may exist in different energy levels within shells.

In practice, we use a shorthand method for labelling individual electrons, according to their location in the atom. Obviously four parameters are required; in decreasing order of the energy involved, these are:

- (1) *shell number*: K, L, M, N, O, P , or Q shell, as $n = 1, 2, 3, 4, 5, 6$, or 7 .
- (2) *energy levels within shells*: s, p, d, f, g , or h level, as $l = 0, 1, 2, 3, 4$, or 5 ; l can generally have values up to $n - 1$.
- (3) *magnetic quantum number*: m can have values from $-l$ through 0 to $+l$ so that there is a possible electron *position* for each value of m ; this is in turn controlled by the value of l , which depends ultimately on the value of n .
- (4) *spin number*: for every electron *position*, two *states* are possible, as s assumes values of $+\frac{1}{2}$ or $-\frac{1}{2}$ (i.e., two electrons with opposed spins for each position).

Using these rules, it turns out that the inner (K) shell can have only two (s) electrons; l must equal 0 . The L shell can have eight electrons; (two s electrons, where $l = 0$; and six p electrons with l taking the values $-1, 0$ and $+1$). Similarly, the M shell may have up to 18 electrons, the N shell 32, and so on. (For shells beyond N , structural complexities arise; the general result is that fewer states exist than theory predicts.)

When these possible states of an electron are computed for an entire atom, and certain side conditions ("selection rules") are imposed, a very definite number of electron transitions become *possible*, as individual electrons move from one energy level to another. For each particular shift, the change in energy is fixed, thus fixing the wavelength of the photon absorbed or emitted; each possible wavelength defines a spectral line, characteristic of the atomic species, which is potentially exploitable in remote reconnaissance through proper choice of film and filter to obtain atomic "tone signatures."

In the process of performing emission spectroscopy, which is one of the most sensitive techniques for sensing the composition of materials, a collection of atoms is heated; that is, the atoms absorb energy by raising the energy levels of their outer-shell electrons. The process is one of continuous electron shifts if the temperature is high and constant; for each electron that shifts up in energy, another shifts down with the emission of a photon in the UV or V range. In practice the temperature is maintained at a level such that emission is greater than absorption. These photons are beamed through a prism and dispersed according to wavelength onto a calibrated scale, and the presence of any element is detected by the presence of its char-

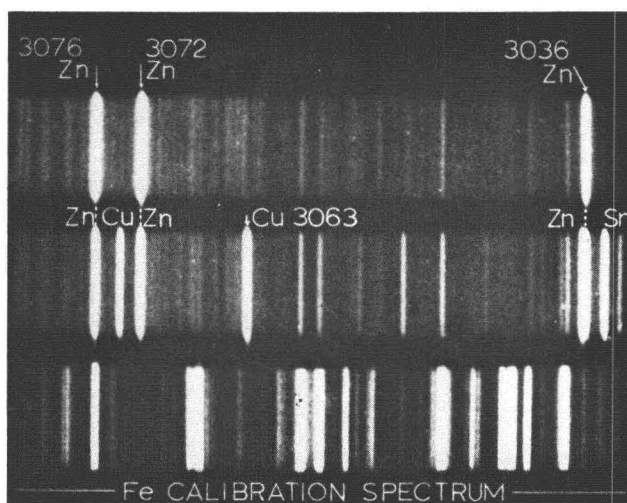


FIG. 8. Typical Emission Spectra. The upper spectrum shows some of the strong Zn lines which permit identification of even trace amounts of this element. In the second spectrum, Zn and Cu lines predominate, but there is also a Sn line, suggesting that the material analyzed is an alloy of these metals. The lower spectrum of fairly pure Fe, is used for calibration of wavelengths. The numbers refer to the wavelength in Angstrom units; ($1\text{\AA} = 10^{-10}$ meter). This photograph is enlarged from a section of 35 mm. film measuring 0.30×0.22 in., and represents three successive exposures through a narrow slit in a mask.

acteristic spectral lines (see Figure 8). Essentially the same thing may be done in absorption; electrons gaining in energy will select out the same specific spectral lines from a light beam which is a continuum. At room temperature the number of high energy or "excited" electrons is small, and furthermore much of the spectral information is in the *UV*. This somewhat limits the process as a long-range sensing method, if we are interested only in remote reconnaissance of the earth, because of *UV*-scattering by the Earth's atmosphere. The basic ideas we have developed are fully applicable however, to remote sensing of the Moon, from an orbiting reconnaissance satellite, since there would be no atmospheric scattering with which to contend.

Thus on the one hand it may be of great value for a photo interpreter or "image analyst" to know in which spectral region the energy emanating from a given kind of material is uniquely high as evidenced by its light tone on a positive print; and on the other hand it may also be of great value for him to know in which spectral region the energy emanating from a given kind of material is uniquely *low*, as evidenced by its *dark* tone on a positive print. Emission and absorption spectra facilitate selection of the spectral zones where energy emanations will be high or low.

Atomic spectra fall in the *UV* and *V* ranges because the energy changes between levels *in one shell* are of the magnitude which produces photons in these ranges. If, however, we can somehow knock out an electron from an *inner* shell, an *outer* shell electron will jump in to fill the gap, emitting a photon. Because the energy change will be large, this photon will have a short wavelength, representative of the X-ray region. This is the basis for X-ray spectroscopy, another short-range sensing method for atomic information.

Going toward the other end of the *e-m* spectrum, we see intuitively that to obtain spectral lines in the *IR*-microwave bands, we will have to find smaller energy changes and hence longer photon wavelengths; these prove to be *molecular* in nature.

It should be noted that the light or dark tone registered on a photographic print may be due to the combined effects of many fundamental interactions, including but not limited to the atomic interactions that have just been described.

2. MOLECULAR INTERACTIONS

Since purely *atomic* electron shifts yield radiation which is mainly of short wavelengths, such shifts cannot be sensed in most of the visible spectrum, nor at longer wavelengths. Yet most matter does have characteristic spectra for the transmission, emission,

reflection, and absorption of radiant energy, even in the visible, infrared and radar wavelengths. Many of these phenomena arise from energy changes in *molecules*, and the field of molecular spectroscopy is one with potentially good remote sensing applications.

Molecules, like atoms, have definite energy states, and energy changes involve absorption or emission of photons, following the same basic relationship as in the atomic model; i.e.,

$$f = \frac{\Delta E}{h}$$

Photon effects in molecules arise not only from (1) electron shifts in the bonding of atoms, but also from (2) energy changes in the vibrations of atoms within the molecule, and (3) changes in rotational energy of the molecule as a whole. Because of their fundamental importance in relation to remote reconnaissance, factors under each of these three categories will now be discussed.

Bonding. In order to understand energy changes in molecules we must have some idea of molecular structure, realizing that atoms are held together (i.e., "bonded") in several quite different ways to form molecules. The various bonds may be described as either "polar" or "non-polar," but more commonly are a mixture of the two. Polar bonding occurs when the bonding force between atoms comes only from the attraction of opposed permanent electrical charges, while non-polar bonding includes bonds set up by the continuous motion or interchange of electrons from one atom to another and back again. The accepted classification includes:

Ionic bonds: purely polar bonding as described above.

Covalent bonds: purely non-polar; the mechanism is the sharing of two electrons between two atoms, in such a way that the electron pair contributes to a quantum-mechanically stable configuration in both atoms simultaneously, the general case of stable configuration is an octet, eight electrons in the outermost shell of the atom. Modifications with one or three electrons being shared are known.

Metallic bonds: in metals the atoms are closely and symmetrically packed, so that each atom is roughly at the same distance from a large number of "nearest neighbors," generally twelve. No one atom can contribute twelve electrons to form covalent pairs with each neighbor, but it contributes as many

electrons as it can, and these "jump" very rapidly from one atom to the next, so that at any *instant* a bonding electron may be found in the outer structural shells of two atoms. Over any *very small time interval*, however, it will be found in the structures of twelve atoms. Thus there is an electron cloud *between* the atoms, just as there is a cloud for each internal shell *within* the atom itself.

Van der Wall bonds: these are fairly weak forces of an electrostatic nature acting on atoms or molecules which are free to move, as in gases, and which result mainly from the transient attraction between electrons in one atom and electrical fields in another. They contribute less to molecular spectra than do the other types.

It has been established that most metals and molecular substances show a mixture of ionic and covalent, or covalent and metallic bonding. Remembering that we defined ψ , the wave function, as describing a certain geometric configuration of an electron in an atom, we may often do the same thing for electrons in molecules, using the same quantum-mechanical treatment. If we call ψ_1 a bonding electron wave in, say, the ionic bond and ψ_2 an electron wave in the covalent bond, we may consider a "mixed" bond as being a very rapid changing or "resonance" between ψ_1 and ψ_2 . Resonance bonding occurs between many configurations in molecules; a general requirement for resonance between two structures is that they have the same number of unpaired or "available" electrons. When resonance bonding occurs, a definite *extra* amount of energy is involved which contributes to the strength of the bond, and the rapid small changes in this energy may contribute to molecular spectra, through the previously-mentioned relationship, $f = \Delta E/h$.

Synthetic organic dyes, for example, generally consist of complex molecules which have more than one possible bond configuration, and which can be tailored to a desired color by varying the size of the molecule so that it will absorb and emit the desired wavelengths; in larger molecules the uncertainty principle leads to smaller ΔE 's between electronic energy levels, so that correspondingly longer wavelengths of light are absorbed and emitted. The resonance ΔE 's of dyes, by definition, define photons in the visible range.

The same mechanism operates, of course, for many natural organic molecules, such as the dyes found in plants and animals. Reso-

nance effects are at least partly responsible for the color of living organisms; hence in the last analysis the basic matter and energy relationships involved in resonance effects may determine the photographic tones or colors of many of the images recorded by remote reconnaissance.

The green color of leaves was originally ascribed to the complex substance chlorophyll; recent investigations suggest that this is only partly correct, and that other related substances are involved. However the chlorophyll molecule does have the capacity to capture photons. By direct absorption of energy (mainly photons in the blue and red regions), some electrons move up to excited levels, and these can be either donated immediately to chemical reactions, or used to create conditions in other materials which subsequently favor chemical reaction. With much of the blue and red light absorbed, green light is reflected back to the observer. Consequently the leaves appear green, and photograph green on aerial color photographs, or in predictable shades of gray when photographed with panchromatic film in conjunction with various filters. The appearance of leaves on near-infrared photography is attributed to a quite different phenomenon, however, as will be explained presently.

In natural *inorganic* materials, color arises in several ways, and resonance bonding is not the most important of these. One explanation is found by considering the bonding electrons in molecules to be subject to the same minimum "allowed energy levels" as in atoms. The amount of energy involved in even a partial covalent bond is generally more than the energy required to produce photons in the visible spectrum, so that most partially covalent-bonded molecules, including the *stable* minerals, have no dominant hue (color) in the visible spectrum. Their unique spectral returns, arising from the displacement of bonding electrons, tend to fall in the *UV*. If, however, one of these bonding electrons is "loosely held," that is, if a fairly small change in energy is likely to *break* the bond and release photons, the compound is likely to be visibly colored. For the same reasons, this colored compound will be chemically active, i.e., relatively unstable. The first case (uncolored) is generally true for the stable minerals (compounds) seen in nature, and in durable mineral materials such as concrete. The more reactive compounds, often those with a lesser amount of covalent bonding, such as copper salts, are more likely to be colored.

To generalize, resonance bonding in organic matter, and weak chemical bonding in inorganic matter account for several of the visible color effects in familiar materials. Our discussion is not limited to this spectral range, however. Since the spectra of molecules and their origins are so varied, it will be convenient to discuss what we actually see or photograph all across the *UV*, *V*, *IR*, and microwave regions of the spectrum, and to relate this to what is known about molecular structure.

a. *Origin of Molecular Spectra*

In addition to energy levels determined by the shift of electrons (in either the inner structure of the atoms, or the outer shells involved in molecular bonding) molecules have quantized energy levels associated with vibrations of the atoms relative to each other, and with rotations of the molecule as a whole. Electron shifts require the largest ΔE 's, so that the associated spectral lines fall in the *UV* and *V*. Vibrational energy changes are intermediate in magnitude; the spectral lines are found in the near- and middle-*IR*. Rotational spectra are characteristic of the far-*IR* and microwave regions.

In dealing with *electron shifts*, there is no completely satisfactory treatment which will invariably predict the corresponding line or band spectra. The motion of the electrons is complex, and the number of possible excited states is large. Furthermore, many molecules can dissociate into ions by the absorption of sufficiently large amounts of energy; when this occurs, the requirement of definite energy levels for excited states is lost. Photons of all energies just above a threshold value can be absorbed; part of the energy (a definite amount) goes into dissociation of the molecule, and the rest (an indefinite amount) is taken up by the ions as kinetic energy (energy of motion). This absorption of all photon energies across some interval produces a "continuous absorption band," as contrasted with the line spectra (Figure 8) of electron shifts between fixed energy levels. Thus the *UV electronic* spectra of molecules are often built up of:

- (1) spectral lines, with many possible wavelengths and a very complex distribution of intensities, and
- (2) continuous absorption bands, which may join or overlap the line spectra.

It often happens that the atoms or ions liberated by dissociation are themselves in an excited state at the instant of separation, and

thus have the ability to emit additional photons of various wavelengths, which may further complicate the strictly molecular spectrum.

It should be noted that both resonance bonding and weak chemical bonding, as previously described, are electronic effects; the actual mechanisms are to be found in the shift of electrons between energy levels that are so spaced as to give absorption or emission in the visible region.

Vibrational molecular spectra, characteristic of the near IR (to about 25μ), arise from quantized energy changes in the harmonic motion of mass centers within molecules. In the simplest case, two atomic nuclei of a linear dumb-bell-shaped molecule move toward and away from each other, as if connected by a spring. The stiffness of the spring implies the strength of the bond; stretching it beyond its elastic limit corresponds to dissociation of the molecule. The vibrational spectra of many compounds consist of lines which are closely and nearly harmonically spaced—as the vibrational energy increases, the spectral lines become more intense, but at the same time lose their ideal harmonicity; i.e., dissociation is approaching, upon which all harmonicity will disappear. Thus the characteristic vibration spectrum of a compound depends a good deal on its physical state—in particular its temperature.

Bonds not only stretch, but bend as well. This becomes important as a source of molecular spectral lines in polyatomic molecules, including many natural organic substances. Changes in energy (ΔE 's) produced by bending are smaller than those produced by stretching, and the spectra fall in the middle IR.

By cataloging and analyzing IR spectra, it is possible to identify, in unknown substances, many specific bonds between common atoms, and hence to describe the molecular structure of the material. Conversely, it is possible to predict the IR spectra, at least in general terms, of many compounds and materials and thus to predict the optimum combination of sensor and filter to use in the remote reconnaissance of such compounds and materials. As in the case of the electronic spectra, both lines and bands appear, but the bands, under high resolution, always turn out to be non-continuous, that is, made up of many closely spaced lines.

Rotational molecular spectra are found in the far IR and microwave regions, and have been extensively investigated for many gaseous substances. For a molecule to show rotational effects it must:

- (1) have a permanent electric dipole moment, that is, a finite separation of permanent opposed electrical charges, and
- (2) be free to rotate, that is, it must not be locked into a crystalline structure.

Gases and vapors of many substances meet these requirements, and can be "sensed" or detected in the atmospheres of even distant planets. The spectra consist of very closely packed lines, regularly spaced, and because of their long wavelength, they can be resolved in great detail. Many of the fundamental assumptions about extraterrestrial environments are based on analysis of rotational molecular spectra, through truly "remote" reconnaissance.

"Rotational-vibrational" spectra, showing the combined effects of both mechanisms, are known for many molecular gases, including water vapor. Figure 9 shows a combination of spectral effects in a hypothetical molecular spectrum.

b. *Fluorescence and Phosphorescence*

Up to this point, we have specified that when electrons in atoms or molecules move up to excited orbitals they absorb photons of fairly specific energy. It was tacitly assumed that the reverse process, emission of a single photon equal in energy to the exciting photon, was the normal subsequent course of events. However, many substances have intermediate energy levels between the two levels involved in photon *absorption*, and under some conditions, the energy of the atom or molecule as a whole returns to its original level through a *series* of steps, each accompanied by emission of a photon of different wavelength; this is fluorescence. The special conditions are the "selection rules" for electronic transitions, which we touched on previously. Like so many of the rules or laws of quantum mechanics, these are probability statements; when the probability of something happening approaches 1, the rule approaches complete validity.

For the phenomenon of fluorescence to occur, we must have an electron in an excited state; this happens through photon absorption in the normal manner. Then if the selection rules dictate that the return to "ground

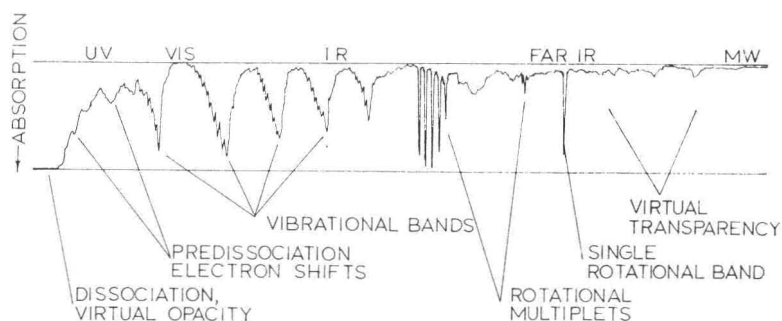


FIG. 9. Spectral characteristics in relation to *molecular* structure. For explanation of the various portions of this hypothetical curve, see text.

state" (lowest potential energy state), can be accomplished by steps, with a reasonable probability, such a stepwise descent *will* occur; fluorescence results.

It should be fairly obvious by now that the energy of any photon from a single step in the return to ground state will be less than the energy of the exciting photon; i.e., its wavelength will be greater. This concept is formalized as Stokes' law.

The practical effect of fluorescence is that matter may absorb energy at one wavelength and radiate it at another; consequently, in real systems there is often a multiplicity of spectral lines in the fluorescent radiation.

The "black light" of common application in short-range remote sensing is based on these principles; *UV* radiation is emitted from a gas tube and excites fairly high electronic states in the target. As decay to ground state occurs, visible fluorescent radiation, often with very characteristic color, is radiated from the target to the observer. Certain kinds of valuable mineral deposits which may be directly exposed to the aerial view exhibit strong and unique fluorescent properties. There is a possibility that these properties could be exploited in remote reconnaissance to discern such deposits, particularly if reconnaissance were to be made at low altitude, at twilight, by a vehicle containing not only the appropriate sensor but also a strong source (i.e., an "illuminant") of radiant energy.

The time lapse between excitation and fluorescence is often quite short, on the order of 10^{-8} second, so that it appears to be instantaneous. Yet we know that some materials continue to glow for long periods after excita-

tion. The explanation lies in the fact that certain electronic levels are "metastable"; an electron descending from a higher state enters the metastable level and is "trapped" there, because the probability of further descent is either small or nil. If the probability is small, the material continues to glow with radiation intensity falling off exponentially, but in the case of zero probability of further decay, some new excitation by photons is necessary to put the electron back in a level where decay can begin again by a different path. This dual process is defined as phosphorescence. The interplay of probable courses of action, and variations in the exciting spectrum itself, lead to very complex results in terms of the ultimate spectral distribution of photons, but the field has many practical applications. For example, phosphors, (substances which fluoresce or phosphoresce), are the wavelength-conversion materials used in cathode ray tubes and other imaging tubes employed in radar reconnaissance and thermal infrared reconnaissance.

c. Scattering

A number of mechanisms exist for the ray deflection and wavelength modification of radiation beams. Scatter is a general term for these effects, although they arise in very different ways, and are operative in different spectral regions. Some of the observed results (Mie scattering) have been covered in a previous section.

One of the other principal scattering effects in the *UV-V-IR* region (also mentioned previously) is called *Rayleigh scattering*; it occurs in all materials and media, but with variable intensity. The statement of the law depends on the material under consideration; the net result is that the amount of scattering is inversely proportional to the fourth power of

the wavelength, for particles of a specified size range. In other words, any collection of particles within this size range will scatter short wavelength radiation much more than long wave radiation. For the visible region, blue light is scattered more than red light; we see the daytime sky as being blue because the atmosphere reradiates (scatters) more blue light than red light. In the absence of an atmosphere, the sun would appear as a brilliant sphere against a black background, as indeed it does to the earth-orbiting astronaut.

Actually, much of what we see and record photographically as "daylight" is secondary (scattered) radiation from the atmosphere, and its spectral composition is a function of many variables, including time of day. Early or late in the day, Rayleigh scattering occurs over a longer atmospheric path than at noon, and much of the blue light is scattered out of the sun-to-observer beam. That light which reaches the observer is effectively shifted toward the red direction. This phenomenon explains the red glow of the horizon sky commonly seen at sunrise or sunset.

The size of the scattering particles is of vital importance; atoms and molecules in the atmosphere scatter *UV* radiation, dust (particle diameter around 0.25μ) scatters visible light, and fog (particle diameter around 4μ) scatters near-*IR* radiation. For longer wavelengths the macroscopic texture of the material surface is important (Feder, 1960).

An insight into the scattering mechanism is gained from considering the electrical field, E , of the incoming light wave. When this field interacts with the electrostatic binding forces of the matter, a nearly instantaneous separation of opposed charges occurs (creating an electric dipole), and the magnitude of this separation is proportional to the field, E . This causes a new ray to originate from the particle, in some new direction. A detailed discussion of the subsequent events is beyond the scope of this paper, but straightforward calculations show two results of importance:

- (1) the scattered radiation is coherent with the incoming radiation; that is, the reradiated wave of photons is "in step" or in phase with the incoming wave, and
- (2) for a system such as the sun-atmosphere-earth system, the scattered radiation is partially polarized; that is, the waves have a preferred plane of vibration.

Rayleigh scattering does not change the energy (color) of individual photons, nor does it erase any spectral signal contained in the incoming beam. What it does is to alter the direction of photon paths, selectively, according to wavelength. A small amount of scatter is tolerable in many remote sensing applications, while large or total scatter prevents the recording of information. Because of the lesser scattering of long wavelengths, remote sensing utilizing *IR*-microwave bands is inherently better than that using the *UV*- or *V*-bands, as long as there is equivalent information available in the spectral region utilized.

Another type of scattering is called *Raman scattering* or the *Raman effect*. In the case of Rayleigh scatter we imply that an incoming photon interacts elastically with a particle, e.g., a molecule; there is no change in the energy of the scattered photon. In some cases, however, the photon impinging may give up some of its energy to a molecule in the vibrational or rotational manner, that is, by raising the molecule to a higher vibrational or rotational energy state. Conversely, it may gain some additional energy if the target molecule was in a higher state at the moment of collision. As the photon is scattered (through the Rayleigh mechanism) its energy is altered slightly, by an amount equal to the ΔE of the molecule. Thus the incoming beam is not only scattered, but has taken on the "signature" of the scattering molecule; it is compositionally coded.

Raman scatter is usually small compared to Rayleigh scatter; its importance lies in the fact that it may give molecular information in cases where none is readily available from normal *IR* molecular spectroscopy. Furthermore, Raman spectra commonly fall in the *UV* and *V* regions, and may be the only molecular information available in those regions for some materials. Rayleigh and Raman scattering form a continuous transition, with the Raman factor being a small and variable part of the total scatter.

There are other scattering effects, generally of small magnitude, whose description tends to be difficult. One general characteristic of a scattering mechanism as compared to an absorption or fluorescent mechanism is that the scattered radiation is coherent with that coming into the system. In the radar region, scattering and the dissipation of energy are intimately tied in with the electrical conductivity-impedance characteristics of the target; this field requires separate treatment.

Reducing the Effects of Media. Early in this discussion we specified that the definitions of "target" and "medium" were made on pragmatic principles. The meteorologist sensing upper atmosphere composition and temperature would feel rather differently about atmospheric transmission than would a photo interpreter or a heat mapper (Fischbach, 1963). Whether in target or medium, the energy-matter interactions are the same. We have covered the main physical effects in previous sections, so this discussion will be devoted to principles of application.

By understanding thoroughly the origin and spectral distribution of the information we seek, we will almost always be able to make some reasonable compromise between the ideal band for sensing and the ideal band for transmission of the coded signal through the medium.

Secondly, we must realize that the effects of a medium are a function of path length. These effects are not always linear, however. For example, in the atmosphere, most of the gas molecules are concentrated in the extreme lower layers, but most of the ozone is at high levels; ozone absorption is seldom a problem near the earth's surface.

Finally, by careful selection of the strongest and most characteristic signal or combination of signals, based on scientifically sound theory, we may be able to gather information in spite of the detrimental effects of the medium. Forest fires are difficult to pinpoint through a heavy pall of hot smoke, in both the visible and *IR*, but they can be located with great precision by near-*IR* mapping of the thermal emission intensity peaks (Hirsch, 1963); the signal overpowers the medium.

With some idea of what the medium is going to be—how thick, containing what impurities, etc.—and with a detailed knowledge of the spectral response of the target, one is ready to lay down specifications for the detector, and, in an active system,* for the source also. Fortunately, this is the area which yields most readily to a determined attack; if the detector or source one needs does not exist, it probably will be developed soon.

Most remote sensing is done in or through the atmosphere, which is composed of nitrogen, oxygen, argon and other inert gases,

* One in which an artificial source of the energy to be sensed is employed.

water (in all its physical states), CO_2 , CO , N_2O , O_3 , and a host of other materials. The composition of the atmosphere in terms of most of the molecular gases is reasonably fixed; water is the principal variable. Numerous experimental and theoretical determinations of atmospheric transmittance have been made, which cover absorption and scattering at all wavelengths, for individual materials, and for all materials taken together. This, therefore, is yet another example of the value of our considering basic matter and energy characteristics in relation to remote reconnaissance. For when these data are combined with actual atmospheric spectra measured under conditions similar to those encountered in one's real problem, many otherwise inexplicable deviations from ideality are cleared up immediately. Certainly no one should attempt a remote sensing application without fairly complete knowledge of the media effects at hand; the cost in time and money to obtain this information is usually minimal.

The principal absorption bands of the atmosphere are shown in Figure 1; their general description is given in Table 4.

The intensity and width of all bands and continua are variable according to changing conditions and compositions in the atmosphere; detailed spectra should be consulted (Taylor and Yates, 1957; Yates and Taylor, 1960).

Energy Interactions Within Crystals, Cells, Tissues and the Larger Aggregates of Matter. Molecules are formed by aggregates of atoms, combined in a definite structural arrangement. Mineral crystals, and the walls and other components of plant and animal cells are formed by aggregates of molecules. Cells, in turn, are combined by definite structural arrangement into tissues, tissues into organisms, organisms into groups or colonies, and groups or colonies into entire plant and animal communities, while crystals aggregate to form rocks, soils, metals, and construction materials. Consequently, in the remote reconnaissance of a forested area, for example, *the signatures which are recorded by a given sensor represent the combined effects of the energy spectra attributable to these successively ordered aggregations of matter*, ranging from the various configurations of electrons in the cloud surrounding an atomic nucleus, to the aggregations of timber stands, grass stands and other plant cover (each with its own species composition) which comprise the major vegetation types that characterize a continent.

TABLE 4
ABSORPTION BANDS OF THE ATMOSPHERE

<i>Wavelength Region</i>	<i>Kind and Degree of Absorption</i>
<i>X-ray</i> 0.003 to 0.03 μ :	complete absorption because of (a) short wavelength in relation to size of atmospheric particles, and (b) very high photon energy with consequent high probability of interaction with atmospheric matter.
<i>UV</i> 0.03 to 0.13 μ :	N ₂ and O ₂ electronic bands and associated continua; almost complete absorption
0.13 to 0.22 μ :	O ₂ electronic bands; almost complete absorption
0.22 to 0.30 μ :	O ₃ electronic bands; strong absorption
0.30 to 0.40 μ :	No specific absorption bands, but Rayleigh scattering is very troublesome
<i>V and Photographic IR</i> 0.40 to 1.0 μ :	few absorption bands except for water band at 0.9 μ ; good transmission
<i>Near IR</i> 1.0 to 20 μ :	many rotational-vibrational bands, throughout the region, of H ₂ O and CO ₂ ; electronic O ₂ at 1.06 and 1.27 μ , rotational H ₂ O bands in 15 to 24 μ region. (the best window is the 8 to 14 μ band)
<i>Far IR</i> 24 to 1000 μ :	many rotational lines, principally H ₂ O; strong absorption
<i>Microwave</i> 1 mm. to 10 cm.:	widely spaced pure rotational lines, many clear windows
<i>Radiofrequencies</i> 10 cm. (t):	almost complete transmission

a. Crystals

An interesting example of a spectral zone in which basic matter and energy relationships involved in remote reconnaissance are being investigated is part of the middle *IR*—the 10 to 25 μ band. Radiation in this range corresponds to the heat radiation peaks of blackbodies between normal earth temperatures (about 300°K.) and 116°K., as calculated by the Wien displacement law. This is a fair approximation of the lunar temperature range.

Two of the most vital problems in lunar exploration are:

- (1) the lunar composition, as an indicator of origin, and
- (2) the possibility of finding water as a component of lunar minerals. The practical extraction of water on the Moon would greatly simplify the payload requirements in putting a life system there.

Recent studies (Lyon 1962) suggest that rocks and minerals may have very characteristic absorption, reflection, and emission spectra in this range, arising largely from energy changes in "lattice vibrations," the vibrations of atoms which are locked in the crystal structure. We previously defined this type of molecular spectrum as *vibrational*; because minerals have such a wide range of

crystal structures, their spectra are particularly rich and diagnostic. Other spectral lines may be due to *bending* of molecular links, and to molecular *bonding* itself.

Sensing for composition of the lunar surface using this spectral zone appears to be feasible; the *IR* spectra of common rock-forming minerals can be correlated with fair accuracy, and the mixtures of minerals which define ordinary rocks can be classified. Some typical reflection spectra are shown in Figure 10.

The water problem is complicated by the fact that water becomes a rock component in several different ways, but the effects of water upon the spectral return also seem to be diagnostic.

By determining the net spectral return across a reasonably narrow bandwidth, and comparing this with an internal standard, fairly simple instruments will be able to measure the intensity of the most characteristic spectral bands of many rocks and minerals occurring on the Moon, and to put this information into a form suitable for telemetry. Practical devices of light weight, for incorporation in surface-roving robots, are within existing engineering capabilities.

By going one step further, and obtaining

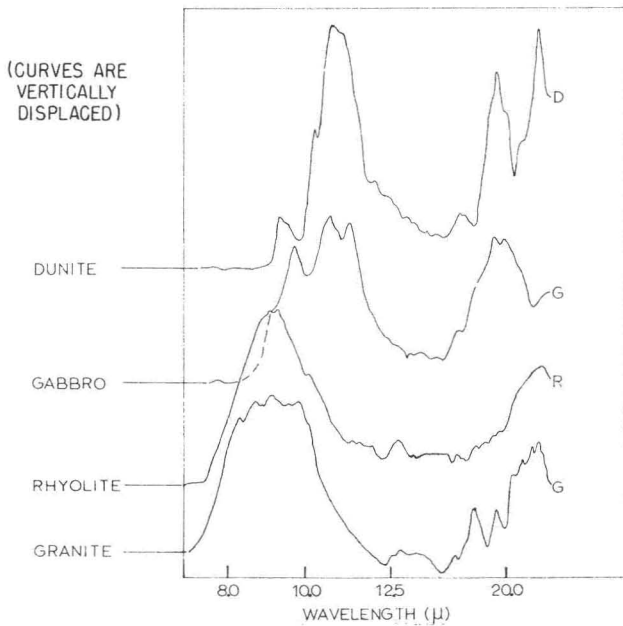


FIG. 10. Spectral characteristics of some common rocks. The curves have been vertically displaced to facilitate comparisons of peaks and valleys. (After Lyon, 1962.)

complete spectral scans of the surface material, such as in Figure 10, it should be possible to classify the rocks, identify the most important constituent minerals, determine the degree of crystallinity, and note the amount and state of water present.

b. Plant Material

Most of the earth's land surface is obscured by vegetation. From the standpoint of remote reconnaissance, therefore, it is important to know something of the spectral characteristics of plant material.

Usually it is the *leaves* of a plant, rather than its stems, roots, flowers or fruits, which are exposed to the aerial view. Consequently, our attention here is devoted primarily to the spectral characteristics of *foliage* in relation to remote reconnaissance. Within the visible and near-infrared portions of the *e-m* spectrum, healthy foliage typically interacts with radiant energy as follows: Reflection or emission from the leaf's cuticle and epidermis is relatively minor and ordinarily need not be considered; most of the light from the blue and red ends of the visible spectrum is absorbed by chlorophyll, while green light is largely reflected by it, thus accounting for the green appearance of the leaves. Energy from the near-infrared part of the spectrum is little affected by the chlorophyll, but is greatly affected by the gross structure of the spongy

mesophyll tissues deep within the leaf. Just as snow and foam appear white because, with their spongy structure, they are good reflectors of energy, so the spongy mesophyll is also a good reflector. In fact this tissue appears very white when the overlying portions of the leaf are dissected so as to expose it; but so long as the overlying tissues remain in place, the radiant energy which penetrates to the mesophyll and thereupon is reflected from it is of far greater intensity in the near-infrared than in the visible part of the spectrum.

As applied to hardwood and coniferous foliage the foregoing information is summarized diagrammatically in Figure 11. The peak reflectance in the green and the low reflectance in the blue and red ends of the visible spectrum are primarily attributable to the interactions of light with chlorophyll. The peak reflectance in the near infrared is primarily attributable to interactions of infrared radiant energy with the spongy mesophyll. The higher infrared reflectance from broad-leaved plants is attributed to the fuller development of spongy mesophyll in them than in needle leaved plants. The healthy conifer and hardwood trees shown in Figure 12 show tone values which have been predicted from Figure 11.

So long as the plant remains healthy, there is an adequate flow of water to the spongy

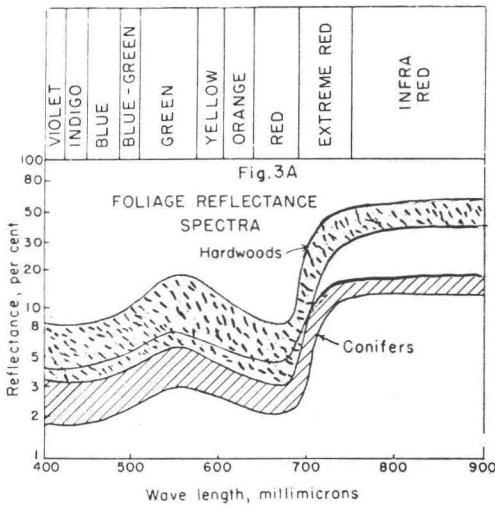


FIG. 11. Light reflectance as a function of wavelength for the foliage of representative hardwood and coniferous trees. The wide separation between these light reflectance curves in the near-infrared range (720 to 900 millimicrons) assures a consistent tonal separation between them on photography taken in that range as shown in Fig. 12.

mesophyll to replace the moisture that is being lost from it through transpiration; hence the cells in this tissue remain turgid and distended, much like a mass of inflated balloons, with air spaces in between them; i.e., the mesophyll tissue remains spongy and highly reflective of the near-infrared energy that strikes it. (See top half of Figure 13.) But once the plant starts to lose its vigor (e.g. because of damage to its roots and a consequent impairment of its ability to *absorb* water, or because of damage to the vascular tissues of either its roots, stems or leaves, and a consequent impairment of its ability to *translocate* water), the spongy mesophyll soon collapses. As a result there may be a great loss in the reflectance of near-infrared energy from the leaves very soon after the damaging agent has struck (Colwell, 1956), as diagrammed in the bottom half of Figure 13. Apparently this change occurs long before there is a detectable change in foliage reflectance within the visible part of the spectrum, and before a change has occurred in the quantity or quality of chlorophyll in the palisade parenchyma cells.

From the foregoing it is apparent why, on positive prints made from infrared photography, plants which are just beginning to become unhealthy consistently appear darker in tone than plants of the same species which

are healthy. (See Figure 14.) On panchromatic photography taken at the same date, however, little or no tone difference between the healthy and unhealthy plants can be distinguished, regardless of the filter used in conjunction with this film. As a corollary, neither can we see a difference in tone or color between healthy and unhealthy plants. This leads to the rather startling conclusion, already borne out by numerous tests, that a loss of vigor in many plants can be seen more readily on infrared photography taken from an altitude of two miles or more above the earth's surface than by the expert on the ground as he walks through the fields, relying on differences in reflectance in the visible spectrum. Herein also lies the probable explanation for the success of an infrared-sensitive color film, known as "camouflage detection film," in detecting objects hidden beneath freshly-cut branches, even before such objects can be detected by the naked eye or by conventional panchromatic or color films.

Eventually a general loss in plant vigor results in the inability of a plant to manufacture chlorophyll at a sufficient rate to replace that which is constantly being decomposed in the leaves. When this happens, other leaf pigments which are for the most part yellow or red, become "unmasked," with the result that the unhealthy foliage turns yellow, brown or red, and photographs in distinctive tones and colors on panchromatic and color films, respectively. In Figure 13 the curve labelled "longer after disease strikes" is representative of the reflectance of foliage at this state, and the aerial photographic tones of Figure 15 are consistent with these reflectance values.

MATTER AND ENERGY INTERACTIONS IN MASERS AND LASERS

In previous sections we have developed an atomic-molecular model which will serve as the starting point for this discussion.

In the treatment of energy levels, from ground state up through the various levels permitted by quantum-mechanical rules, we implied that at ordinary temperatures, most atoms and molecules are in the lower energy states. In other words, the largest number of atoms are in some ground state E_1 ; the next higher energy level E_2 has a smaller "population" than E_1 , but larger than E_3 , and so on. This energy distribution is given in general by the Fermi-Dirac law:

$$f(E) = \frac{B}{e^{(E-E_f)/kT} + 1}$$

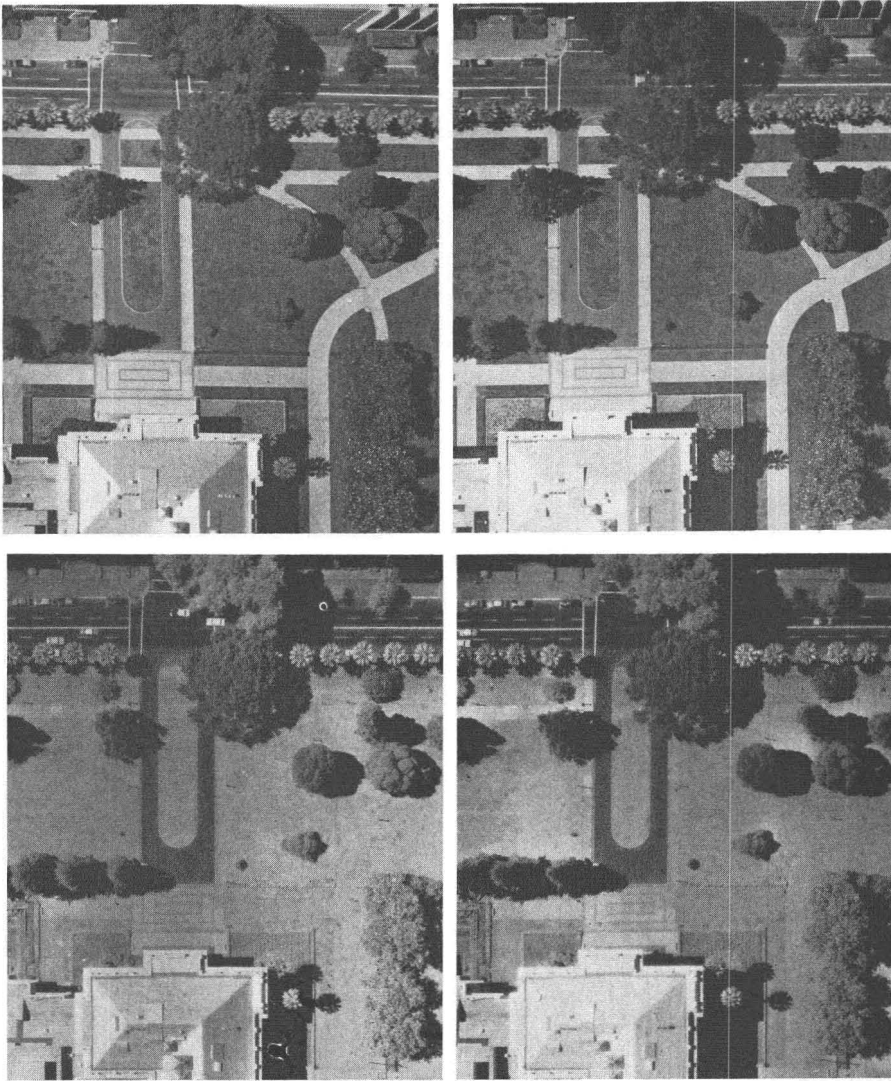


FIG. 12. Panchromatic (top) and infrared stereograms of an area in which both hardwood and coniferous trees (as well as palm trees) are present. On the infrared stereogram the light-toned hardwoods contrast sharply with the dark-toned conifers (note, for example the top center of the stereogram), but not so on the panchromatic stereogram. Such results were accurately predicted from the light reflectance curves of Fig. 11. For additional examples, showing accurate prediction of tones for asphalt, cement, grass and soil on these two stereograms see page 50 of *MANUAL OF PHOTO INTERPRETATION* (Amer. Soc. Photogrammetry, 1960).

where

$f(E)$ = the probability that any given energy state is occupied by an electron

B = a constant

E = the energy of the given state

E_f = the Fermi energy, which is a constant value for the atomic species; it is the cutoff point in an atom at absolute zero temperature, below which all

energy levels are filled by electrons and above which all energy levels are vacant

k = the Boltzmann constant, 1.38×10^{-23} joule per degree

T = the temperature in $^{\circ}\text{K}$.

The result of this condition is that at very low temperatures almost all electrons are in the lowest possible energy level, but at higher

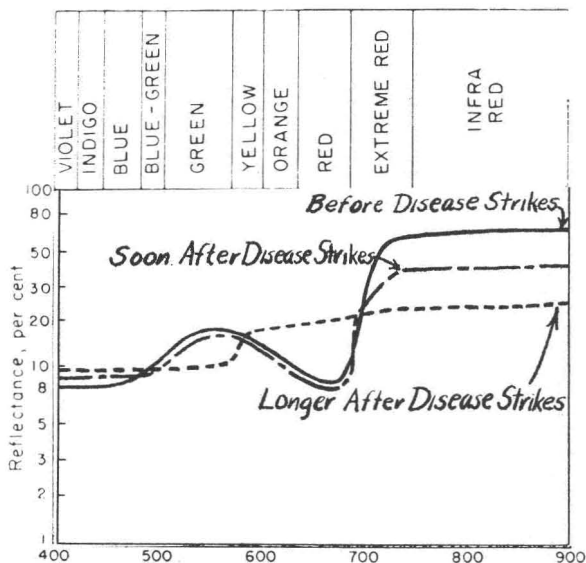
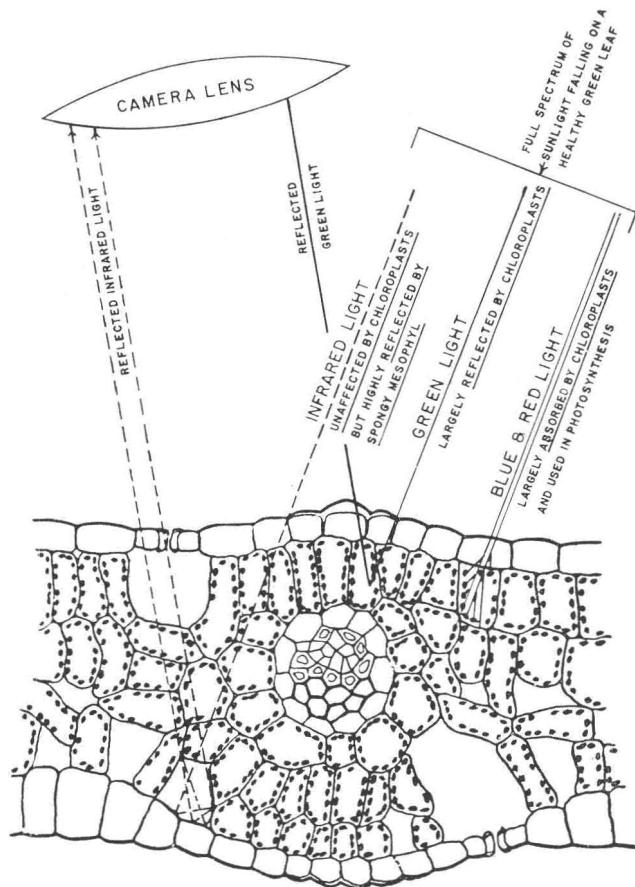


FIG. 13. *Top*: Schematic drawing in which the highly infrared-reflective tissue of the lower half of a leaf is shown in its normal, healthy state. When the plant loses its vigor, this tissue may collapse long before the leaf's green color begins to fade. Hence the disease may be detectable much sooner on infrared than on panchromatic photography. *Bottom*: Successive changes in the light reflectance from leaves, associated with a loss of plant vigor, are diagrammed here. (x axis is in millimicrons.) Not all species of plants respond in this manner, but a great many do. For further explanation, see text and Colwell (1956).

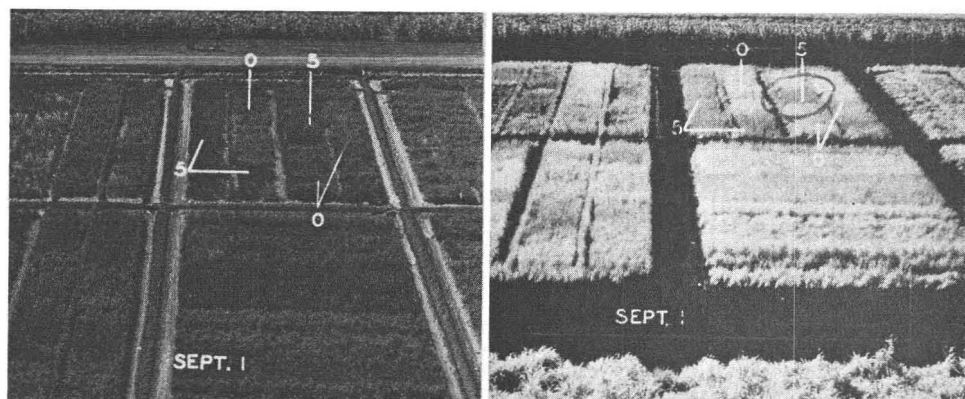


FIG. 14. Oats plants in the earliest stages of vigor loss. Compare with Figure 13.

temperatures there is a range of energies centering around E_f in which electrons may be found in either a slightly lower or slightly higher level. As the temperature goes up, the range broadens, creating more and more possibilities for electrons to shift within greater and greater limits, thus giving more spectral information when photon emission occurs.

The idea that more electrons will exist in the lower states, and that the distribution tails off toward high energies still holds, but the possibility of shifts between levels increases with temperature. This is a spontaneous process, and there is no way of knowing *exactly* when a photon will be emitted. Thus the radiation from the system is incoherent; i.e., the individual waves are out of phase, or "out of step" with each other.

Besides spontaneous transition, there is another process called *induced transition*. If an atom is already in an excited state (through photon absorption acting on a system with Fermi-Dirac distribution) and is struck by a photon of the proper energy, it will emit a second photon which is precisely in step (coherent) with the first; where there was one photon there are now two. This defines "stimulated emission." The energy of the stimulating photon must correspond, within certain limits, with the energy between the excited state and ground state, and the remarkable result is that *the stimulating photon has been amplified by the creation of a second, coherent photon with the same energy (color)*. This is the basic process in maser operation.

In a maser device, some energy must be expended in raising more than the Fermi-Dirac number of electrons to the desired energy level; i.e., in obtaining population

inversion—this is called "pumping" energy. It can come from many conventional sources, such as gas tubes, electron bombardment, or, in the new devices, a very ordinary electric current. Then a source of photons is required to start the process, and this radiation must provide photons of the precise energy required for the transition between the higher level and a ground or intermediate level, whichever transition is more likely. The number of stimulating photons may be very small, possibly as few as 8 or 10—this could be provided by a very weak signal at a distance, or by internal fluorescence. The fact that the higher level population is larger than it would be under equilibrium conditions means that many more photons are emitted than absorbed.

Amplification begins, and the device (consisting of a tube or bar with parallel reflecting ends) causes the cascading photon beam to pass back and forth through the maser medium a large number of times, amplifying the signal continuously on each pass. Because the energy and coherence of the photons are controlled so precisely by the "atomic resonator," there is practically no distortion of the signal.

If one of the reflecting ends of the tube has perhaps 1 to 5% *transmission*, a small part of the now intense beam may be drawn off for useful purposes. The possible applications of this coherent, nearly monochromatic radiation are almost limitless. In remote sensing, only the barest beginning has been made.

For example, we have seen that most materials which we would like to identify from a distance have very characteristic spectra, consisting of lines, bands, and/or continua. When illuminated by a broad band source such as the sun, they select out some wave-

lengths, and reflect others. The energy radiated at the *surface* of the sun is about 7,000 watts/cm.², and of course is much less than that on reaching the earth's surface. Furthermore, the energy over any very narrow wavelength band is minute. The spectral signatures excited by solar radiation are almost always submerged in "noise"—the background of other radiation from many sources. While the solar radiation could be concentrated by focusing (as in a solar furnace) to a high degree, no device could produce a concentration greater than that of the source—7KW/cm.² over the entire blackbody radiation spectrum.

Maser beams, on the other hand, are intrinsically concentrated in bandwidths which are on the order of $10^{-6} \mu$ or less. The energy radiated by some existing maser devices, *per unit bandwidth*, rises to something more than 10^9 times that of the solar surface. It is here suggested that this power should be sufficient, even at aircraft flight altitudes, to excite spectral response in some earth materials. A simple active system would be comprised of a maser source and a sensitive detector, both carefully designed to excite and to sense spectral response for very specific materials, such as fluorescent minerals. The source maser would emit a pulsed beam of the exciting frequency, and the detector maser would record any properly time-distributed "reflected" (i.e., re-emitted) radiation from the illuminated area on the ground. A scanned and imaged plot of signal intensity would thus form a map of the concentration of one substance only, but this alone would provide geological information of great utility in several applications (Brewer 1963).

Such a system would utilize directly the best maser characteristics, such as narrow but

finite bandspread, extreme parallelism of the output beam (divergence about 0.5 degree or less originally, with almost ideal characteristics for focusing by ordinary lenses), high power output in pulsed devices, and modest size and power requirements.

Other devices using the maser principle of stimulated emission are in early stages of development. Some will have possible applications in the *direct* amplification and transmission of *complete images*, which of course will revolutionize telecommunications and some forms of remote sensing.

BASIC MATTER AND ENERGY RELATIONSHIPS IN THE PHOTOGRAPHIC PROCESS

Within the frame of reference of this report, the actual photographic process itself entails important matter and energy relationships which we should seek to understand clearly. Specifically, in the photographic process, an energy-sensitized material records, for those photons having energies within the range for which the material is sensitized, the total number of such photons falling on each unit area of the sensitized material during the exposure period.

As stated by Tarkington (1959), "sensitivity," that is the evidence of detectable change after exposure to radiant energy, is a phenomenon of many materials in nature. In fact, it appears that there are many more substances affected in some way by radiant energy than those which are not—for instance, human skin is rather "sensitive." However, of this large number in existence, only a few have proved to have utility for the purpose of recording images or data. Since time in most human endeavor is important for one reason or another, the outstanding char-

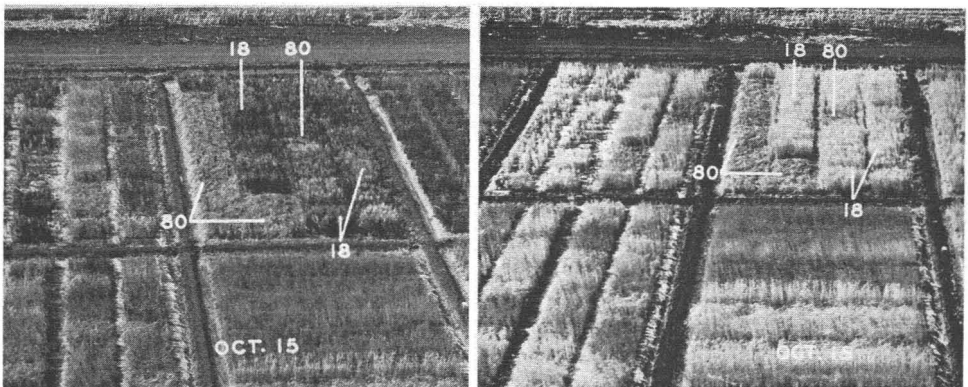


FIG. 15. Oats plants in more advanced stages of vigor loss. Compare with Figures 13 and 14.

acteristic desirable in a sensitive material is that it possess high sensitivity so that the time required to obtain a record is reduced to the point where it is of little, if any, consequence in the intended application. At the same time, it should be emphasized that the quality of the image produced is a necessary implication of the sensitivity characteristic, since to have utility, the image produced must be interpretable by mental processes, or by mechanisms, in some manner related to the subject which has been recorded.

Tarkington (1959) further points out that the first event in recording information by the photographic process is the absorption of photons, which changes the characteristics of affected silver halide crystals, producing in them what is called the "latent image." This is a unique phenomenon and it is the solid-state characteristics of the minute silver halide crystals that provide the explanation.

Latent-image formation in the silver halide crystal takes place in three distinct steps. The first step is a change in the energy level of an electron in the crystal. According to the laws of quantum mechanics, an electron in a silver halide crystal, from absorption of a photon by the crystal, can have its energy state raised from a lower energy band of the crystal—which is completely filled with electrons—to an upper empty band, commonly referred to as the "conduction band." An electron in the conduction band may be viewed as shared by all the silver ions of the lattice and as continually moving about from one silver ion to another. Such an electron behaves in the manner of a free conduction electron of a metal, which, in the presence of an electric field, gives rise to electronic conduction.

The second step depends on the presence of impurities or discontinuities in the crystal lattice of the silver halide crystal. Silver halide crystals incorporated in photographic materials are generally considered to have one or more colloidal silver metal or silver sulfide specks (or some other type of "foreign" material) within the crystal lattice or on the surface. The energy levels of the filled conduction band of silver metal and silver sulfide lie just below, or slightly overlap, the energy levels of the free conduction band in silver bromide. Under these conditions, the electron passing from the silver bromide to the speck will drop to a lower energy state where it can no longer move freely through the crystal. It becomes trapped, giving this speck a negative charge.

The third step results from the ionic conductivity in the silver halide crystal due to motion of some silver ions (a very small fraction of all the ions) which have escaped from their normal positions in the crystal. Since these ions are positively charged, they are attracted by the electrostatic field formed by the electron trapped on the speck and migrate to that point.

Therefore, the formation of the latent image, as the physical evidence of the absorption of photons is called in photography, takes place when a photon excites an electron in the crystal sufficiently to place it in the conduction band. It can move freely now through the crystal until it falls through a potential into the trap formed by a silver particle, or other "foreign" material, which becomes charged negatively. The speck then attracts a positively charged silver ion to the site, thus forming an atom of silver metal. This process is repeated and the original colloidal silver speck grows in size with each photon of radiant energy absorbed.

The second major event in recording information by the photographic process is the selective reaction of certain chemical reducing agents in providing electrons to those crystals of silver halide having in excess of a certain number of silver atoms at the speck, and the fact that those having less than this minimum number have a much lower rate of acceptance of electrons from this source. Once the silver halide crystal begins to accept electrons from the developer, the reaction proceeds until all the silver halide of the crystal is reduced to metallic silver. (See Figure 16.) Since the number of grains having a latent image in an area of the material is greater the higher the intensity of light incident on that area, the result is an image-wise production of metallic silver.

One important fact of this event is that the reduction of a whole silver halide crystal that has absorbed a few photons of light to silver represents "amplification." In an electronic circuit, an electron produced by photon absorption in the sensitive surface of a phototube triggers the controlled flow of many more electrons from a source of electrical potential. The amplifier in the photographic material uses a chemical source of electrons, the amplification being controlled by the number of photons needed to produce a latent image and the limit of amplification being imposed by the size of the crystal. With some crystals, the number of photons required to produce a

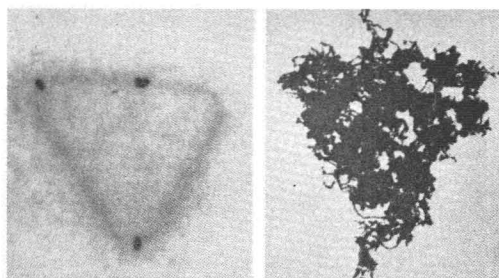


FIG. 16. Two important steps in the creation of a photographic image. *Left*: An electron micrograph showing the sites of photolytically produced silver on a crystal of silver halide. The latent image nuclei are so small that the electron microscope has been unable to resolve them; hence these latent image centers were "amplified" by "arrested development" so that they could be detected. *Right*: A silver halide grain that has been chemically reduced to silver, although not the same crystal as shown on the left. (From Tarkington, 1959.)

latent image is small and the amplification is of the order of a billion times.

A quick review of the energy levels existing in latent-image formation and development will serve to emphasize the uniqueness of the process. First, there must be an empty conduction band in the crystal lattice at the right energy level above the filled band such that a photon can just raise an electron from the lower energy level to the upper. Then the sensitivity speck, silver sulfide, for instance, must be at just the right energy level to trap this free-roaming electron from the conduction band of the crystal but not accept any electrons from the developing agent later. Otherwise, all crystals would develop and no image would result. Some silver ions in the crystal must be mobile and migrate to the electron on the sensitivity speck, the electron being obtainable only from the same crystal and form a silver atom *in situ*. Then this event, plus a few more similar ones, must change the energy level of the sensitivity speck so that it now *will* accept electrons from the developer and so reduce the properly exposed crystal of silver halide to silver. Statistically, it appears that these are a set of unique phenomena. For instance, there is good evidence that a "latent image" is formed in thallos bromide by the same general mechanism as just discussed for the silver halides. However, there is no known way to develop it directly; the thallos bromide can be converted to silver bromide, after exposure, and in this indirect way used as a photographic process. Mercury halides also will form a latent image which can be chemically

developed, but the efficiency of latent-image formation is comparatively very low.

While it is remarkable that these exact energy levels and energy-level differences in the silver halide crystals match those of certain chemical reducing agents, the technological techniques that apply these phenomena to provide a practical, convenient method of recording radiant energy are no less remarkable. The silver halide crystals—photoconductors like lead sulfide, indium antimonide, etc., based essentially on the same general phenomenon as transistors—must be (1) made by the millions in a suitable matrix; (2) modified by physical and chemical operations to provide specified characteristics, and (3) coated in a layer sometimes 0.0001 inch thick, up to 50 inches wide and several miles long (the thinness controlled to 0.000003 inch for this vast area). This is done in order to provide a radiant-energy recording system that (1) yields to a specified level and type of radiant energy the same results in any square millimeter of its matrix or of the matrix of a similar material made a year hence and (2) possesses the sensitivity, image quality and response to intensity variation required for the intended applications. As Tarkington (1959) points out, it is no wonder that photography could not have been predicted from a consideration of the scientific principles involved—it had to be "discovered" or "invented."

STATISTICAL ANALYSES IN RELATION TO BASIC MATTER AND ENERGY RELATIONSHIPS

To date, our studies concerning the spectral characteristics of various objects and conditions for which we wish to accomplish remote sensing have shown that (1) the *average* values of the characteristics vary with wavelength, (2) the *variability* surrounding an average value may be far greater in one part of the spectrum than in another, and (3) part of the variability is attributable to differences in environmental conditions, while the remaining portion, in the language of the statistician is "random variation." This random variation places the outcome of our remote reconnaissance missions at the mercy of statistical probability functions. The nature of the functions depends on the distribution of values around the parametric means. Therefore, even though we can make theoretical predictions concerning the photographic tone, for example, that will be obtained with a remotely-situated sensor under "average conditions," the variation surrounding the average

results must be dealt with. The most effective way to minimize the effect of random variation is through wise planning of data collection and the use of statistically valid analytical procedures.

Let us briefly consider a recently conducted experiment* to illustrate the benefits that can be obtained from a statistical model applied to a remote reconnaissance problem. The experiment was aimed toward optimizing the photographic tone contrast between two or more kinds of objects appearing on aerial photographs taken under varying environmental conditions with specified film-filter combinations. The statistical "model" was designed to determine in which portions of the electromagnetic spectrum (between 260 and 2,000 millimicrons) the maximum reflectance differences occur which are *significant* at specified levels of statistical probability. The mean reflectance differences between pairs of subjects were to be integrated with selected film sensitivity and filter transmission data, by 10 millimicron increments. These combinations would result in the computation of a theoretical tone contrast between the two subjects that each film-filter combination would "see" in a given environmental situation.

After the experiment was designed, reflectance data were collected in the field with a portable spectrometer in several environmental situations and time periods. The data were then fed into an IBM 7090 computer which was programmed to compute, for each environmental situation, the mean reflectance difference, the variance of the mean difference, and the significance of the difference for each ten millimicron wavelength interval. The resulting data were analytically integrated with film sensitivity and filter transmission data to predict which combination would theoretically be optimum for both contrast level and reliability. The results showed that there was such a large variation surrounding the mean reflectance difference between subjects that it would have been impossible, merely from visual inspection of the reflectance data, to select the optimum spectral regions for use in remote reconnaissance.

* This experiment was conducted on the Davis Campus of the University of California under the auspices of the Mine Detection Branch, U. S. Army Corps of Engineers, Fort Belvoir, Virginia. The study was performed by personnel of Airview Specialists Corporation, Pleasant Hill, California with the cooperation of the Pacific Southwest Forest and Range Experiment Station of the U. S. Forest Service.

Spectral variations were found to be much greater in some wavelengths than in others. Consequently, *consistent* reflectance differences (tone contrasts) were available only in relatively narrow wavelength intervals when two vegetation types, for example, were compared over a series of similar, though not identical, environmental conditions and time periods. Therefore, the truly optimum film-filter combination proved to be the one that would exploit only that part of the spectrum which, "had the greatest area between the lower confidence bound surrounding the sample mean difference and the point of zero contrast" (Langley, 1962).

Even though the tone contrast theoretically obtainable between two subjects was identical in two or more parts of the spectrum, the degree of certainty of obtaining this difference by remote reconnaissance was often radically different. The most consistent results proved to be obtainable from the narrowest, and statistically most reliable, spectral band which could be used to obtain a satisfactory exposure.

The results of the study were, indeed, used effectively to specify those film-filter combinations on which the maximum tone contrast between the subjects would appear most consistently, in as many environmental situations as possible. Correlation coefficients as high as 0.96 were obtained between the theoretical contrast predictions and the actual tone contrasts obtained on aerial photographs.

Nearly half a million computations had to be made in order to arrive at these predictions. Yet, on the electronic computer, once the spectral data had been properly programmed, these predictions were made in approximately three minutes and at a cost of less than twenty-five dollars. This procedure permitted selection of spectral zones for optimum tone contrast far more reliably than would have been possible without the intelligent use of computer techniques.

The following examples, taken from the experiment just described, illustrate how an analytical procedure can be used to optimize the tone contrast, between two or more objects, on reconnaissance photographs.

Spectrophotometric traces were collected on a series of 4'x8' color panels. Several traces were taken on each panel. The resulting reflectance data were punched into IBM cards and fed to the computer. Selected portions of the output sheets pertaining to color contrasts that might be obtained between one

of the red panels and one of the green ones used in the experiment are illustrated in Tables 5 and 6. The figures shown are the actual data obtained with the aid of a spectrophotometer. First, the spectral analysis listed in tabular form (Table 5) was made.

As used in Table 5, the "mean reflectance" for a given wavelength band is the arithmetic mean of all reflectance measurements obtained in that band for the object in question. The "normalized reflectance difference" is the value obtained by subtracting, in this case, the reflectance value of the blue panel from that obtained from the light green panel, and then dividing this difference by the reflectance value of the blue panel. Since we are interested in maximizing tone contrast between two adjacent objects, the data are collected as paired observations and the normalized reflectance difference is treated as a single variable, Y . The standard deviation of the mean difference is the square root of the variance of the mean. T is "student's t ," the mean normal reflectance difference divided by its standard deviation. T is compared with the standard t table when testing the null hypothesis that no significant difference exists between the objects. If T exceeds t_α from the

standard t table, the hypothesis is rejected and it is assumed that a significant reflectance difference does exist between the two objects in the wavelength interval tested.

It should be noted that the computer carries many more significant digits within the machine than are shown on the output format. Therefore, the calculation of T from the listed mean difference and standard deviation will not always exactly check with the tabled values of T , due to rounding errors.

One can quickly find the most useful wavelength intervals by scanning this tabulation sheet. For instance, as shown in Table 5 there is a reversal in reflectance difference from plus to minus in the 430-460 millimicron range. Furthermore, the most significant differences within this range are in the 440 and 450 millimicron bands. If a photograph were taken of the blue and green color panels, exposing only for the 440 and 450 $m\mu$ bands, the blue panel should appear lighter in tone than the light green panel on a positive print. The opposite contrast should result throughout the remainder of the spectrum to 2 microns. Within the range of photographic film sensitivity, the most significant normal reflectance difference occurs at 840 millimicrons as shown on the

TABLE 5

EXTRACT OF TABULAR DATA FOR THE IBM 7090 COMPUTER, AS PROGRAMMED FOR SPECTRAL ANALYSIS

<i>Wave length (millimicrons)</i>	<i>Mean Reflect. (%) Blue:Green</i>		<i>Normalized Reflectance Difference</i>	<i>Standard Deviation of the Mean Difference</i>	<i>T</i>
..					
..					
410	23	25	0.06	0.09	0.7804
420	26	26	0.00	0.11	0.2212
430	28	27	-0.06	0.10	0.3614
440	31	27	-0.12	0.10	0.9408
450	32	28	-0.12	0.10	0.9548
460	32	30	-0.07	0.14	0.2839
470	33	36	0.10	0.14	0.9047
..					
..					
..					
810	17	43	1.50	0.31	4.9719
820	18	48	1.74	0.25	7.0204
830	18	55	1.98	0.20	9.9570
840	19	60	2.21	0.07	33.4522
850	19	65	2.34	0.13	17.6681
860	20	68	2.40	0.08	28.7589
870	21	70	2.40	0.13	19.2603
880	21	73	2.41	0.09	27.0829
890	22	74	2.36	0.16	14.7302
900	23	75	2.32	0.11	20.8538
..					
..					

TABLE 6

PORTION OF A TABLE SHOWING NORMALIZED MEAN DIFFERENCES IN LIGHT REFLECTANCE FROM BLUE AND GREEN PANELS, AS A FUNCTION OF WAVELENGTH, AND THE CONFIDENCE BOUNDS FOR THESE MEAN DIFFERENCES AT VARIOUS LEVELS OF PROBABILITY

<i>Wave Length</i>	<i>Pr = .01</i>	<i>.05</i>	<i>.50</i>	<i>Mean-Diff. +</i>	<i>Pr = .50</i>	<i>.05</i>	<i>.01</i>	<i>Standard Deviation</i>
410	.84	-.33	-.01	.06	.13	.45	.96	.091
420	-1.05	-.46	-.09	0.00	.09	.46	1.05	.105
430	-1.06	-.49	-.14	-.06	.02	.37	.94	.100
440	-1.15	-.56	-.20	-.12	-.04	.32	.91	.103
450	-1.11	-.55	-.20	-.12	-.04	.31	.87	.100
460	-1.51	-.69	-.19	-.07	.05	.55	1.37	.144
470	-1.33	-.52	-.02	.10	.22	.72	1.53	.144
..								
..								
..								
810	-1.56	.17	1.25	1.50	1.75	2.83	4.56	.307
820	-.73	.67	1.54	1.74	1.94	2.81	4.21	.248
830	-.02	1.11	1.82	1.98	2.14	2.85	3.98	.201
840	1.55	1.92	2.16	2.21	2.26	2.50	2.87	.066
850	1.02	1.77	2.23	2.34	2.45	2.91	3.66	.133
860	1.57	2.04	2.33	2.40	2.47	2.76	3.23	.083
870	1.15	1.86	2.30	2.40	2.50	2.94	3.65	.125
880	1.53	2.03	2.34	2.41	2.48	2.79	3.29	.089
890	.75	1.66	2.23	2.36	2.49	3.06	3.97	.161
900	1.21	1.84	2.23	2.32	2.41	2.80	3.43	.111

tabulation sheet. However, it appears that the mean reflectance difference reaches a maximum value at 880 millimicrons. This raises the question of which wavelength interval would be best for exploitation. The answer to the question depends on the use to which the results will be put. If the reliability of the difference is of primary importance, with the actual difference value secondary, the 840 millimicron band would theoretically be optimum. If one wishes to exploit that part of the spectrum which yields the maximum difference most of the time, he can combine the mean difference with its standard deviation to generate confidence intervals around the mean at specified levels of probability. A computer program was prepared to perform this task, also, as shown in Table 6.

These results show, for each wavelength band, the confidence intervals generated about the mean reflectance difference between the blue and light green panels, when selecting t_{α} at specified levels of probability. These probability levels are shown under "lower limits" and "upper limits" in Table 6.

If we wish to have the blue panel appear lighter in tone than the green one, on a positive print, we should limit the exposure to the 440 and 450 millimicron bands (see top photo of Figure 17). This is the only part of the spectrum where there is a negative "normal re-

fectance difference" on both sides of the "mean difference." Looking under "upper limits, $Pr = .50$ " we see the value $-.04$ at both 440 and 450 $m\mu$. This means that we have a 75 per cent degree of confidence that the true mean reflectance difference is greater than 4 per cent in a negative direction. (Note: the .5 probability level for a two tailed test is equivalent to the .25 level on a one tailed test.) By taking more spectrophotometric traces, we could increase our level of confidence in the figures. Looking further down the tabulation sheet, we see that the optimum wavelength for obtaining a plus difference between the blue and light green panels is at 860 $m\mu$. We look under "lower limits, $Pr = .01$," and we see that the reflectance difference reaches a maximum value at this point. At this wavelength, we have a 99½ per cent level of confidence that the true normal reflectance difference between the blue and light green panels is greater than 157 per cent. Note that this wavelength lies midway between the wavelength intervals, 840 and 880 $m\mu$, (see bottom photo, Figure 17) which were of interest on the first tabulation.

These results are illustrated graphically in Figure 18.

The lower confidence bound shown in Figure 18 is at the 97½ per cent confidence level using a one-tailed test. The upper bound shown is at the 75 per cent level using a one-

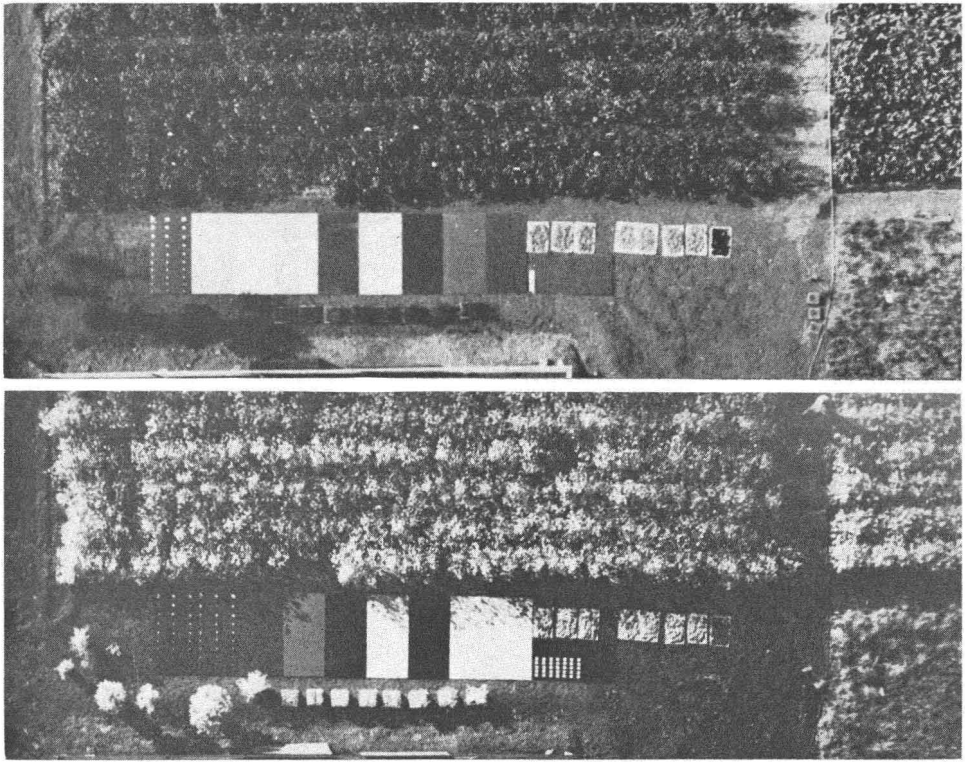


FIG. 17. Vertical photos, taken from atop a 150-foot tower, of a target array which includes variously colored sheets of plywood, each 4 feet wide and 8 feet long. Note that, on the *top* photo, the third panel from the left (which is blue) has a slightly lighter tone than the fourth panel (which is green) and that, on the *bottom* photo, the reverse is true for reasons explained in the text.

tailed test. The cross hatched areas are the spectral regions of significant difference at the stated probability levels.

The foregoing statistical analysis is far better than a mere visual inspection of spectral data would have been for showing which areas of the spectrum should be exploited to obtain maximum tone contrast between the blue and light green color panels. Furthermore, most reflectance environments involving natural objects or vegetation are much more complex. In addition, the problem is compounded due to the variability of film-sensitivity and filter-transmittance across the spectrum. To help overcome these complications a computer routine was developed which would analytically combine the three variables, spectral reflectance, film sensitivity, and filter transmittance. The theoretical resultant combined curves for the blue and light green color panels, exposed on panchromatic film, through a Wratten 12 (minus blue) filter are shown in Figure 19. The difference between the areas under the two curves is normalized to the area under the blue curve to arrive at a predicted tone contrast that would

theoretically register on a particular reflectance-film-filter combination. The computer program was written to produce these predictions and to plot the resultant graph for any number of possible film-filter combinations with a given environment or series of environments. Obviously, if a film-filter combination

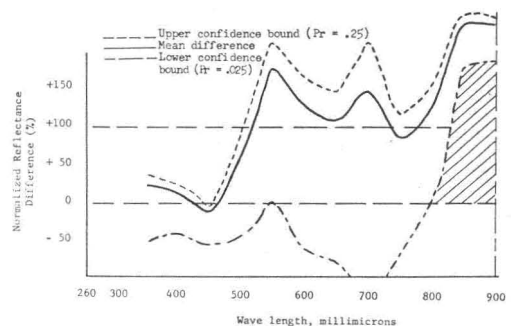


FIG. 18. Curves showing the normalized reflectance difference between blue and green panels as a function of wavelength. From such curves the photographic tone contrasts between objects, as registered with various film-filter combinations, can be predicted with far greater accuracy than would otherwise be possible.

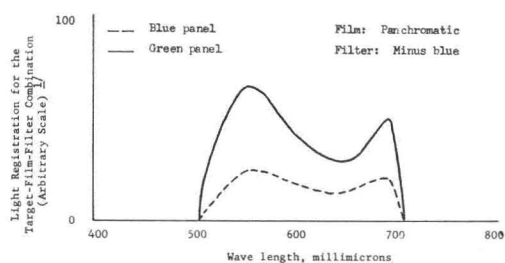


FIG. 19. See text for an explanation of the use of this graph in selecting the spectral zones which will give maximum tone contrasts between blue and green panels.

is not wisely chosen for use on an aerial reconnaissance mission, the combined reflectance-film-filter curves for two objects may cross over and little or no contrast between the images of those objects will appear on the resultant photographs. A well chosen combination, however, will maximize the theoretical contrast. In the example just described, the significance of each contrast prediction was also calculated.

In comparing the aerial photographic tones obtained in actual field tests with those that had been predicted by computer techniques, correlations have ranged from 0.74 to as high as 0.96 (Langley, 1962). Far lower correlations have been obtained when the spectral data have been subjected merely to visual inspection. As refinements are made in the methods for making spectral analyses (including consideration of the color temperature of the illuminant at the instant of photography), it is anticipated that computer techniques will permit even higher correlations to be obtained.

SUMMARY AND CONCLUSIONS

The following is a summary of the major points made in this report.

1. In order for a remote sensing system to operate effectively within any specified wavelength range of the electromagnetic spectrum there must be:

- an *energy source* which will provide photons having the proper energies and hence the proper wavelengths,
- a *collection of matter* (i.e. a target) which will interact with photons in this range,
- an *energy detector* which is sensitive to photons in this range,
- a *propagating medium* (or else a void) between detector and target, which will transmit photons in this range, and
- an *energy filter* which will screen out un-

wanted photons to which the detector is sensitive, while transmitting the wanted ones.

2. The radiant power peak of the *sun* is at a wavelength of about 0.5 microns. It is an excellent energy source when we wish to accomplish remote reconnaissance of the earth by use of *reflected* energy in the *V*, as when using a panchromatic film (0.40 to 0.75 microns), or in the rear infrared (0.75 to 1.2 microns), as when using an infrared-sensitive film. Atmospheric haze effects usually preclude its use in remote reconnaissance of the earth's surface in the *UV* (less than about 0.4 microns).

3. The radiant power peak of the *earth* is at a wavelength of about 9.6 microns. This radiant energy is an excellent source when we wish to accomplish remote reconnaissance of the earth by use of *emitted* energy in the *IR*, as when using a "heat-mapping" sensor in the 8 to 13 micron range.

4. There are practical methods of obtaining electromagnetic radiation of almost any desired wavelength for use in *active* remote reconnaissance systems Specifically:

- X-radiation can be obtained from high-voltage cathodes
- radar and microwave radiation, from specialized tubes and resonating cavity sources
- radio-frequency radiation, from oscillating dipole sources
- radiation for most of the other parts of the spectrum, from masers, filaments and gas lamps.

5. When a photon of any specific energy strikes the boundary of solid matter, a number of interactions are possible; mass and energy are conserved according to basic physical principles; and the energy can either be

- absorbed*, giving up its energy largely into heating the matter,
- emitted*, or more commonly re-emitted by the matter, as a function of temperature and structure, at the same or different wavelength,
- scattered*, that is, deflected to one side and lost ultimately to absorption or further scatter, or
- reflected*, that is, returned unchanged to the medium.

6. The atmosphere is a turbid medium whose scattering particles, for the most part, have diameters commensurate with the length of light waves. Light *scattering* by these par-

ticles is *inversely proportional to the fourth power of the wavelength* of the light, in accordance with Rayleigh's Law.

7. In addition, the atmosphere exhibits distinct *molecular absorption bands* at various points in the electromagnetic spectrum caused by the presence of such molecules as N_2 , O_2 , O_3 , H_2O , CO , and CO_2 . The location and intensity of each of these bands are predictable from a knowledge of the matter and energy relationships for each type of molecule present in the atmosphere.

8. The following properties of water are important in relation to the remote reconnaissance of underwater objects:

- a. In *optically pure water* the maximum absorption is in the infrared range and the minimum in the blue-violet range.
- b. In *clear sea water* the absorption maximum also occurs in the infrared range, but the minimum shifts to the green range (460 to 540 millimicrons).
- c. In *river water*, which as a rule is more turbid than sea water, the absorption maximum lies in the blue-violet range, while the absorption minimum shifts to the yellow-orange sector (576 to 609 millimicrons).
- d. The change in spectral composition of light reflected from an object when it is submerged should be taken into account when selecting the photo-sensitive material and filters for remote reconnaissance of underwater objects.

9. Absorption, emission, scattering and reflection of electromagnetic energy by any particular kind of matter are selective with regard to wavelength, and are specific for that particular kind of matter, depending primarily upon its atomic and molecular structure.

10. The following equations express some of the most basic matter-energy relationships of significance in remote reconnaissance.

$$a. e = mc^2$$

$$b. f = \frac{v}{\lambda} \cdot a$$

$$c. E_p = hf = \frac{hc}{\lambda}$$

$$d. f = \frac{\Delta E}{h}$$

$$e. S = \frac{k}{\lambda^4}$$

11. *Atomic* matter and energy relationships may be summarized as follows:

- a. When an atom *absorbs* the energy of a colliding photon, an electron in the atom's shell may be shifted to an orbital path of higher energy level; in that event the photon ceases to exist.
- b. When an atom *liberates* energy, an electron in the atom's shell may be shifted to an orbital path of lower energy level; in that event a photon is generated where none existed before.
- c. The number of "allowed" electron shifts, and their attendant changes in energy, are absolutely characteristic for each atomic species; consequently each atomic species has unique absorption and emission spectra which can be exploited in remote reconnaissance to provide unique tone signatures.

12. *Molecular* matter and energy relationships may be summarized as follows:

- a. Molecules, like atoms, have definite energy states; energy changes involving the absorption or emission of photons by molecules follow the same basic relationships as in atoms.
- b. Photon effects in molecules may arise from either
 - (1) electron shifts in the *bonding* of atoms of the molecule, producing energy changes in the *UV* and *V*;
 - (2) *vibrations* of atoms within the molecule, producing energy changes in the *near-* and *middle-IR*;
 - (3) changes in the *rotational energy* of the molecule as a whole, producing energy changes in the *IR* and *micro-wave* regions.

13. In the photographic process, latent image formation in the silver halide crystal takes place in the following distinct steps.

- a. The crystal absorbs a photon, which raises the energy state of an electron in the crystal.
- b. This electron passes from the crystal to a silver sulfide "speck" associated with the crystal.
- c. The electron on the "speck" attracts, and unites with, a silver cation, thus forming an atom of metallic silver.

14. The three-step process of latent image formation is repeated as each additional photon is absorbed, thus causing the "speck" to grow. During film development, reducing agents provide many additional electrons to each silver halide crystal that is associated with an activated "speck," thus reducing *all*

the silver halide in the crystal to opaque metallic silver.

The "amplification" in this process (in relation to the number of photons absorbed) may exceed one billion times, in photographic films of high sensitivity.

15. In attempting to select the combination of filter and sensor which will "optimize" the image quality obtainable by remote reconnaissance, we must recognize that there may be significant variability in:

- a. the intensity and spectral composition of the illuminant
- b. the reflectivity and emissivity of the target
- c. the sensitivity of the film or other sensor
- d. the transmissivity of the filter, and
- e. the transmissivity of the atmosphere, water or other medium intervening between target and sensor.

16. Because of spectral variability, statistical analyses of spectral data are far better than mere visual inspection of such data for determining which parts of the *e-m* spectrum will provide the most favorable tone signatures for various objects and conditions.

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