Chapter 2
Principles of Remote Sensing

2.1 Beyond Human Sensors and Controlled Environments

Instruments available today, whether in the laboratory, in situ (observing instrument close to target in a natural, remote location), or remote in every way (observing instrument distant from target in natural, remote location), are elaborate and sophisticated extensions of the most ancient and venerable remote sensing devices: binocular human vision. The eyes, probably the most sensitive organs, can sense only a small portion of the electromagnetic spectrum—the visual—but the brain can then interpret this information in many ways: as brightness or color, yielding compositional information, and as shape, orientation, or perspective, yielding morphological or structural information. The ears act in similar fashion, providing information that can be interpreted in terms of sonic frequency spectrum and direction of a source.

Can human-made instruments now act as eyes and ears for the entire electromagnetic spectrum with equal ease in any setting? The use of such instruments in the laboratory is less challenging, because a controlled experiment can be conducted. Every aspect of the environment that could have an impact on the experiment is monitored and, to a great extent, controlled, including the preparation of the target, the viewing geometry, and indoor atmospheric conditions. With actual samples at hand and the control of one variable at a time possible, calibration, documenting instrument response as a function of energy under given conditions, is thus a relatively straightforward process.

What happens when the instrument is operating in an environment where conditions cannot be controlled? Before an instrument is sent to a remote setting, the anticipated environmental and target conditions are modeled as an important part of instrument design. The instrument is subjected to preflight calibration in the laboratory. While in flight, the changing source and surrounding environmental conditions, and viewing conditions are constantly monitored to provide important ancillary data that will be used later to normalize data, and periodic in-flight calibration is performed with sources of known composition. These practices help to provide accurate (absolute calibration) and precise (repeatable measurements) data and to minimize error bars. Before, during, or after the time data is being collected, representative field sites and samples should be investigated to provide a basis for measurement accuracy and interpretation in more than a relative varia-
tion sense. When ground truth is available ahead of time, well-constrained models can be developed to provide a good basis for instrument hardware and data management plan design. When ground truth is not available through direct sampling and site analysis, investigators can be clever at developing alternatives. For example, to prepare for the Near Earth Asteroid Rendezvous mission to 433 Eros, models were created using meteorites of related compositional classes as samples for that observational Class S asteroid.

Remote sensing observations with or without extensive ground truth can provide reconnaissance, indicating representative or anomalous areas with characteristic signatures for in depth study. Geologists first learned to use remote photographs to construct geological unit maps, a practice that became known as photogeology (Compton 1985), a critical step for map making. Even today, visual imaging provides the framework for our understanding of an object at a distance. Samples of local rocks and soils are collected and field studies of the geological setting are completed and presumed to originate from processes with a wider distribution. This work establishes relationships between units in terms of age, stratigraphy, in the field. Remote data again provide the means for extending the inherently limited coverage of individual site ground truth to allow the generation of hypotheses of global processes that formed them. The ability to model, measure, and interpret measurements for the entire spectrum has revolutionized our ability to observe and understand natural processes (e.g., Sabins 1996, Elachi and van Zyl 2006, Siegal and Gillespie 1980, Short 2007, Lillesand et al. 2003). Interactions between energy and matter occurring at a sub-microscopic level generate information that allows mapping of kilometer scale features and interpretation on a global scale.

2.2 The Electromagnetic Spectrum

The electromagnetic spectrum, generally referred to as light, could be defined as the entire range of energies that can be produced as a result of all types of interactions between matter and energy in the form of electromagnetic waves. Energy level, position or region within the spectrum can be expressed in electron volts (eV), wavelength (e.g., cm, μ), or frequency (Hz). Energy exists in a number of forms, depending on the nature of interactions within matter, each with associated spectral regions, ranging, at progressively lower frequencies, from nuclear (subatomic particle), to chemical (atom or ion), to thermal or mechanical (molecule or larger particle). Energy is emitted whenever a particle with mass, whether electron, ion, or molecule, is accelerated. At an atomic level, electrons can be accelerated briefly to a higher atomic energy level and then returned to a lower energy state releasing an energy characteristic of that transition. At a molecular level, emission occurs when atoms are accelerated into higher vibrational states. At any given time, the number of particles in a higher energy state is small.
Remote sensing involves detection of electromagnetic radiation, and, typically, the transfer of energy from matter through free space. Within matter, energy may be transferred in a number of ways. Conduction involves collisions of molecular or atomic particles in motion, possessing kinetic energy, with other such particles. If energy is transferred, these collisions are called inelastic, if not transferred, elastic. Particles also possess potential energy, which depends on their physical position, chemical or nuclear reactivity, relative to other particles. This potential can be converted to kinetic energy, or motion, as well as chemical or thermal energy. Convection involves the physical movement of particles with kinetic energy, as in fluid flow. Such effects of radiation on matter are the technological bases of remote sensing detectors.

The electromagnetic spectrum is illustrated in Figure 2.1. The division of the spectrum into distinctive regions mentioned above is based on the distinctive energy production mechanisms, detection methods, and analysis techniques associated with each region. Overlap occurs on the edges of regions where the operational mechanism depends on the nature of the target.

1) the highest energy Ray Region of gamma-rays, X-rays, and high energy Ultra-violet (XUV) involving nuclear or inner electron interactions
2) the Circumvisible Region of soft UV (SUV), visible, near IR (NIR) involving outer electron interactions,
3) the Infrared Region of mid- to far IR (MIR and FIR) involving inter-atomic or molecular interactions,
4) the Longwave Region of thermal, microwave, and radio involving intermolecular interactions, and
5) the lowest energy and frequency Acoustic Region of sound and seismic waves coupling to electromagnetic fields to provide information on the internal structure of liquids or solids.

2.3 The Nature of Electromagnetic Radiation

Light has been observed to have the characteristics of both waves and particles, and in the discussion here will be evaluated in terms of both Maxwell’s wave theory and quantum theory (Feinberg 1973). The first recorded observations led scientists, including Newton, Huygens, and Young, to observe that light behaved in a manner analogous to water or sound waves.

1) Light traveled in a straight line.
Figure 2.1 Remote Sensing thumbnail sketch.
2) It could be reflected or refracted (change its direction) when encountering denser matter.

3) Finally, waves coming from a variety of directions were diffracted (Figure 2.2), spread to form a diffuse source, when passing through a narrow opening.

Young’s double slit experiment (Figure 2.2) involved light that was not typical polychromatic (incoherent), but monochromatic (coherent). Light from a diffuse, or multi-directional, source was passed through each pinhole and diffracted, as described above. A plate beyond the pinhole showed a pattern of light and dark areas. When light from the split beams recombined, constructive interference occurred for waves in phase (at the same frequency and position in the sine function), increasing their intensity. Destructive interference occurred for waves out of phase (at the same frequency but offset by 180 degrees in the sine function), decreasing their intensity. Thus, the interference pattern observed on the plate was generated. Incoherent light would allow constructive and destructive interference to occur at random, and not generate the discrete patterns.

Although earlier observations supported a wave model for light, Maxwell observed rapid variations in the field associated with light and interpreted the cause as oscillating particles. Furthermore, light interacting with matter can be seen to generate photons, particles with discrete energies resulting from discrete or quantum transitions in energy state characteristic of the matter, as predicted by quantum model described below. The wave and particle properties of light are related through the property of frequency. Waves have a characteristic frequency, and corresponding photons (energy pulses or quanta), have characteristic duration associated with that frequency. Shorter wavelengths are the equivalent of shorter pulses and greater frequency, longer wavelengths of longer pulses and lower frequency. Young’s double slit experiment can perhaps be best understood in terms of the wave model.

The quantum model can be utilized to explain discrete absorption and emission phenomena associated with a range of observed phenomena, including the discrete energy state transitions and spectral features characteristic of elements and compounds. Particles with mass (electrons, protons, neutrons) as well as energy (photons) have discrete or quantized states. The discrete transitions of electrons from one energy state to another are shown schematically as quantum events on the transition level diagram in Figure 2.3.

Electrons can only occupy specific quantized orbits, specifiable in terms of four quantum numbers: n, principle quantum number, or shell; L, angular momentum quantum number, characterizing the increasingly larger and more complex shape of an orbital as a function of energy; m, magnetic quantum number; and s, the spin quantum number. In the circumvisible region, electronic energy levels for polyatomic atoms can be described by L= S, P, D, F (the equivalent of 0, 1, 2, 3) and multiplicity defined by 2s+1 where s is the spin with a value of ½. Thus, 2s+1 could have values of 1 (singlet), 2 (doublet), 3 (triplet), 4 (quadruplet, or
Visible energy transitions occur due to transitions by the relatively unshielded outer electrons in partially filled 3(shell)d–orbitals. Partially filled 4f orbitals in rare earth metals are too shielded to exhibit such transitions. In the X-ray region, characteristic transitions occur in the innermost electrons of the 1s orbitals.

Equation 2.1 establishes the relationship between the transition from one energy state to another \((E_1 - E_2)\), the empirically demonstrated quantized energy release \((nh)\), frequency \((\nu = c/\lambda)\), and wavelength \((\lambda)\) (where \(c\) is the speed of light). \[ E_1 - E_2 = nh\nu \] (2.1)

Planck’s constant, \(h\) \((6.626 \times 10^{-34} \text{ joule-second})\), sets the size of quanta, relating the energy in a photon to its wave frequency. Wave number, \(k\), can also establishes the formal relationship between frequency and wavelength (Equations 2.2 and 2.3):

\[ k = \frac{1}{\lambda} \] (2.2)

\[ c = \nu/k \] (2.3)

Equation 2.3 is the dispersion relation involving the phase velocity of light in free space. Mass (for particles at rest) \(m\), momentum, \(p\), and energy, \(E\), are related as in Equations 2.4 and 2.5:

\[ E^2 = (pc)^2 + (mc^2)^2 \] (2.4)

\[ E = pc \] (2.5)
Equation 2.4 reduces to Equation 2.5 for massless particles like photons. The rest-mass energies are so small for photons, that energy is completely transferred in interactions with matter particles, with the properties of re-emitted photons or other particles depending on the details of the interaction. Overall, energy and momentum are conserved. The speed of light is independent of energy (Equation 2.3) and the momentum of a photon, $p$, is equivalent to $hν/c$.

Transfer of a single photon of energy to an electron has relatively little effect on the emission spectrum. However, the transfer of energy as a result of many such interactions can generate an equilibrium emission, or black-body, spectrum, with a shape that depends on the amount of heat released, or temperature achieved, by the body. This continuous emission spectrum is known as black body because the energy would be totally absorbed and potentially re-emitted, but not reflected, in a perfectly black body. The greater the number of collisions, the greater the emitted energy and the greater the frequency of the peak energy emitted, up to the point where there is a balance in energy transfer between light and matter. Planck experimentally demonstrated that the observed spectrum resulted from discrete electromagnetic energy levels, with a scale constant, $h$, with a value given above (See Figure 2.5). Black body radiation can be calculated as indicated in Equations 2.6 (Planck’s Principle) and 2.7 (Elachi and van Zyl 2006), where spectral emittance ($S$) is a function of wavelength and temperature ($T$) in Kelvin, where $k$ is the Boltzmann constant, $h$ is Planck’s constant, $σ$ is the Stefan-Boltzmann constant, and $c$ is the speed of light:

$$S(λ,T) = \frac{(2π h c^2)}{[λ^5 \left( e^{\frac{hc}{λkT}} - 1 \right)]}$$  

(2.6)

$$S = σT^4$$  

(2.7)
Electric and magnetic forces themselves can be thought of in a similar quantized fashion, with interactions that occur between charged particles resulting in the exchange of current in the form of virtual photons. The energy value of individual photons is, again, relatively small; thus, quantized fluctuations in the field strength resulting from photon exchange are small compared to the average field value. Classical force field behavior best explains observed phenomena, where macroscopic fronts with electromagnetic or mechanical properties are generated.

2.4 Optics

Maxwell’s wave model can be used to deal with energy propagation and its associated continuous probabilistic properties such as polarization, coherence and phase, and macroscopic phenomena such as scattering, reflection, and refraction. The wave model is most useful where continuous optical phenomena are observed. Equation 2.8 (Elachi and van Zyl 2006) expresses the relationship between energy and wave amplitude ($A$), phase ($\phi$), wavelength ($\lambda$), frequency ($\nu$), and permittivity of the medium ($\varepsilon$) for the wave model:

$$E = A e^{-[(2\pi/\lambda)/(\lambda t + \phi)]}$$

(2.8)

Waves, as illustrated in Figure 2.6, have a variety of properties. Electromagnetic waves propagate away from a source with a speed that depends on the medium of propagation. Then waves interact with matter in a manner that depends on their wavelength and the properties of the medium. When waves encounter a medium that is relatively transparent to light of that wavelength, the interaction depends on the density difference between the two media. Waves may be refracted or bent due to differences in density and resulting speed, or, in the case of X-rays,
diffracted at angles characteristic of the crystalline structure. When the second medium is relatively opaque to light of that wavelength, waves may be reflected from a surface smooth or diffusely scattered from a surface rough on the scale of the wavelength.

Waves consist of E (electric) and H (magnetic) field components orthogonal to one another and the direction of propagation. Waves with E and H components oriented in fixed planes along the direction of propagation and polarization are called linearly polarized, horizontally polarized if E is oriented left/right relative to the observer, and vertically polarized of E is oriented up/down relative to the observer. What if the planes vary in position along the direction of propagation? Waves with the same frequency, amplitude, and direction of propagation, but with directions of polarization varying from vertical to horizontal are elliptically polarized in the general case. They are circularly polarized in the special elliptical polarization case where the planes of polarization are always at ninety degrees from one another. Shifts in polarization of waves coming from or being transmitted through a target can be used to characterize the target.

Waves also have characteristic wavelength (λ) or frequency (ν) and amplitude (A). Wave sets with integral (multiplicative factor) frequencies can be in phase, and constructively interfere to amplify the signal. Those with different non-integral frequencies are out of phase and destructively interfere, producing irregular waves with overall lower amplitudes. Waves with the same frequency and phase are coherent. Variation in frequency produces incoherence, or out-of-phaseness. Coherency is expressed as the degree to which two waves have phases varying systematically over a narrow range.

**Figure 2.5** Black body radiation curves with illustrating shift in peak radiation to shorter wavelength as a function of temperature (Courtesy of NASA).
Figure 2.6 Propagation, polarization, and interference phenomena of light as waves.
2.5 Radiation Measurement

Remote sensing measurements have characterized the energy signatures of targets in progressively more sophisticated ways. In the most primitive sense, the integrated intensity of energies being generated in a broad spectral region, the target’s albedo in that region, can be measured with a sensor incapable of spectrally or spatially resolving the signal for the target. This was how the earliest measurements of very remote objects, the stars, were recorded, as determinations of the visual magnitude of point sources. As more sensitive detectors capable of resolving discrete spectral features have been developed, spectrometers have obtained measurements with progressively finer spectral resolution. Improvements in collimation techniques as well have allowed spectrometer measurements to be taken with either shorter integration times or smaller fields of view and thus effectively finer spatial resolution. Meanwhile, imaging devices with progressively improved spatial resolution have been developed. In the circumvisible part of the spectrum, and gradually in other spectral regions as well, imaging spectrometers allow spectrally and spatially resolved intensity measurements. The measurement of characteristic energies requires that the processes have sufficient intensity and sensors have adequate spectral resolution and sensitivity.

Characteristic spectral features, lines or bands, can be modeled and considered quantitatively. The magnitude of features is calculated by integrating the radiant flux (in watts), I or dQ/dt, over the width of the band or line, d\(\lambda\). \(\textit{Equation 2.9}\) (Elachi and van Zyl 2006):

\[
I(\lambda_1 \text{ to } \lambda_2) = \int_{\lambda_1}^{\lambda_2} I(\lambda) \, d\lambda
\]  

(2.9)

The radiant flux density (watts/m\(^2\)) (irradiance for the incident flux (E), and emittance for the departing flux (M)) is the radiant flux (\(\Phi\)) intercepted per unit area (A); the radiant intensity (W/sr) is the radiant flux per unit solid angle (\(\Omega\)) for a remote point source; and the radiance (L) (watts/m\(^2\)sr) is the radiant intensity for an extended source or surface per unit area \(\textit{Equations 2.10 to 2.12}\):

\[
E \text{ or } M = d\Phi/dA
\]  

(2.10)

\[
I = d\Phi/d\Omega
\]  

(2.11)

\[
L = (dI/dA) \cos(\Omega)
\]  

(2.12)

If the radiance doesn’t change as a function of direction, the surface, essentially a featureless body, is called Lambertian.

Generically, the radiant flux (dQ/dt) or intensity (I) of a particular spectral feature (n) is calculated for detector response (R), and probability factors for target interaction (P), as a function of source intensity (J), distance (D) and target ab-
sorption characteristics ($\mu$) integrated over wavelength or energy, for the fractional solid angle surface coverage ($d\Omega/4\pi$) resulting from collimation, for components 1 through i with abundances ($C_i$) (Equation 2.13):

$$I_n(E) = P_n R_n \left\{ \frac{J(\lambda)}{D^2} \sum (\mu_i(\lambda) C_i) \right\} (d\Omega/4\pi) \quad (2.13)$$

### 2.6 Interactions as a Function of State

Matter exists in the gas, liquid, solid, or plasma (highly energetic ionized gas) state. Except in astrophysically extreme environments, the higher energy interactions are largely independent of state. Other interactions involving atomic and molecular interactions are influenced by the state, and the degrees of freedom and frequency of characteristic interactions of constituent atoms or molecules. Gas molecules exhibit many transitions throughout the electromagnetic spectrum, electronic as well as translational, rotational, and vibrational states and the associated spectral features are well-defined, narrow lines. Spectral features associated with liquids and solids are broader, less well defined bands because of the proximity and influence of surrounding constituents. Molecules in liquid form have fewer degrees of freedom, but important bonding group transitions ($H^+, OH^-$ for water) detectable in the infrared as well. Energy interactions associated with solids, in typical geological applications consisting of crystal lattices, result from macroscopic (physical nature of the surface) and molecular (compositional involving outer bonding electron) level behavior. Scatter may occur with any state. The nature of the scatter, as described below, depends on relative sizes of the particle and the wavelength.

The population density, $N$, of a population at a particular energy level is defined by Boltzmann’s Principle (Equation 2.14) when the population is in thermal equilibrium:

$$N \sim e^{-E/kT} \quad (2.14)$$

$E$ is the energy level, $k$ is Boltzmann’s constant, and $T$ the absolute temperature. A temperature of absolute zero means that all systems, e.g., electrons in atomic orbitals, will be in the lowest energy level, or ground state.

### 2.7 Atmospheric Effects

The Earth, and most of the major planets, have atmospheres. The atmosphereless bodies, including the Moon, Mercury, and the asteroids, have tenuous exospheres. Although these are certainly of interest in terms of their origins, exospheres lack significant interaction between constituents. The presence of an
atmosphere, with gases rather than the vacuum of free space, affects all aspects of the energy transmission process, including the speed, frequency, intensity, direction, and spectral distribution of the energy. Atmospheres scatter, absorb, and refract light as described below, using the Earth as an example.

Radiation is scattered in all directions by atmospheric particles. The type of scatter depends on the relationship between the size of the particle and the wavelength. Scattering is effectively absorption and reemission. Mie scatter is the most common form of scattering and occurs when the diameter of particles is on the scale of the wavelength. The main scattering agents for visible light, where the atmosphere is most transparent and the Sun’s output is greatest, are water vapor and dust particles ranging from just less than a micron to a few microns in size. This type of scattering is responsible for the red of sunset, when the sun is near the horizon and its light is being scattered by particulates near the ground. Rayleigh scattering is inversely proportional to the wavelength to the fourth power and thus is greater at smaller wavelengths. It occurs when the size of the particle, typically a gas molecule, is many times smaller than the wavelength. The color of the sky is thus most affected by the more efficient scatter of the shortest visible wavelength, ranging from the palest blue overhead, where the path of the Sun’s light through the atmosphere is shortest, to progressively deeper blue toward the horizon, as the path grows longer. Selective scattering of sky light into shadows makes them bluish. Nonselective scatter, or scatter occurring equally at all wavelengths, results from interaction between large particles, typically water droplets, with photons of wavelengths considerably smaller than the particles. The white or gray of clouds is a result of this type of scatter. The existence of an atmosphere scatters light, adds brightness, and removes contrast. When no atmosphere exists, no scattering of light into shadows occurs and shadows are completely black.

Atmospheric absorption is the most effective process at most wavelengths, particularly those shorter than visible light as well as some of the longer wavelengths, including most of the infrared (Figure 2.7). When the interaction between a photon with a frequency the same as the resonant frequency of the atom or molecule, the particle absorbs the photon, moves into an excited state, and reemits energy at a longer wavelength (the greenhouse effect). Absorption and scatter result in attenuation of the incoming energy, expressed as an extinction coefficient.

The atmosphere also refracts incoming light (Figure 2.8). As an incoming photon encounters matter of a greater density, its speed and direction change in a manner described by the index of refraction, \( n \), the ratio of the speed of light in a vacuum, \( c \), to the speed of light in the substance \( c_n \). The ratio between the two angles relative to the normal made as a result of the direction change is directly proportional to the density-dependent indices of refraction (Equation 2.15, Snell’s Principle):

\[
\frac{n_1}{n_2} = \frac{\sin(\theta_1)}{\sin(\theta_2)}
\]  

(2.15)
2.1 Close to home: Dealing with an atmosphere. We were proposing to fly an X-ray spectrometer on a mission to Tempel 2, as I recall, and I was asked to model solar induced secondary (fluorescent) X-ray production from the cometary nucleus. Up to that point, I had been doing similar measurements for the atmosphere-less Moon. Suddenly I had to consider attenuation of incoming and outgoing flux by not only gas, primarily water vapor, but also dust particles with abundances correlated with cometary age and solar distance. I had an opportunity to get up close and personal with absorption coefficients, which I did by considering the atmosphere constituents as filters on the detector. I was shocked to find out that such an atmosphere, as tenuous and small as it was, attenuated the signal by more than an order of magnitude. I never was too fond of atmospheres after that.

2.8 Surface Interactions

When electromagnetic energy encounters a solid or liquid interface, or target, with profoundly greater density, scatter (specular or diffuse), absorption, and transmission result, in proportions which depend on the optical properties of the target (absorption coefficient and refractive index), the physical properties of the target (surface roughness on the scale of the wavelength), the angle of incidence (target orientation), and the spectral distribution (intensity as a function of energy). Specular reflection (coherent scatter) or diffuse surface scatter may occur, as
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discussed in the previous chapter. The degree, or coefficient, of reflectivity for horizontally ($R_h$) and vertically ($R_v$) polarized waves is proportional to the incidence and transmission angles, $\theta$ and $\theta_t$, respectively, which are a function of refractive index, $n$ (*Equations 2.16, 2.17, and 2.18*):

$$n = \frac{\sin(\theta)}{\sin(\theta_t)} \quad (2.16)$$

$$|R_h|^2 = \frac{(\sin^2(\theta - \theta_t))/(\sin^2(\theta + \theta_t))}{\tan^2(\theta - \theta_t))/(\tan^2(\theta + \theta_t))} \quad (2.17)$$

$$|R_v|^2 = \frac{(\tan^2(\theta - \theta_t))/(\tan^2(\theta + \theta_t))}{\sin^2(\theta - \theta_t))/(\sin^2(\theta + \theta_t))} \quad (2.18)$$

When the tangent of the incoming angle is equal to the refractive index, otherwise known as the Brewster angle, no reflection occurs for the vertical component. The greater the density and refractive index, the greater the incidence angle where this condition occurs. Near surface normal and parallel incidence angles, the two reflection coefficients approach the same value.

Absorptance, $A$, is the ability of the target to absorb energy as a function of the absorption coefficient, $a$, and the wavelength, $\lambda$, at a depth of $x$, and a relative density or concentration, $C$ of the component of interest, and is inversely proportional to the transmittance, $T$ (*Equation 2.19*):

$$A = -\ln T = a \lambda x C \quad (2.19)$$

The extinction coefficient and the absorption coefficient are directly proportional; thus, reflectivity is directly proportional to absorption, and inversely proportional to transmittance, as illustrated by metallic surfaces.

The total incident radiation is subjected to absorption, transmission, and scatter at the target and the sum of all three. Absorption is maximum at absorption bands characteristic of a substance. Typically for spectra from solid surfaces in the visible and infrared, spectral features in reflectance spectra are due to absorption.
bands. Energy is multiply scattered, with some directed back toward the observer and absorbed.

### 2.9 The Major Spectral Regions

It is not accidental that our major sensory organs, eyes and ears, correspond to energy regions where our atmosphere is non-attenuating, or transparent (Figure 2.7), the visible or sonic regions, respectively. So much data is available in these regions, facilitating the capability for interpreting the nature of the source, that we have stereo sensors to help us to pinpoint the location of the source as well.

As you read this section, and chapters on each spectral region in the book, we encourage you to refer to the periodic table of the elements (Figure 2.9) included here to provide a context for understanding variations in the behavior and properties of target constituents. For example, as the number of neutrons and protons (atomic number) of an element increases, the energy required for inner electron transitions increases, e.g., characteristic X-ray line energies increase. Visible or near visible transitions, or energy bands, are associated with the outer bonding electrons of cationic elements, including metals, in the crystalline matrix. Characteristic IR transitions result from vibrational or rotational modes associated with

![Figure 2.9 The periodic table of elements with trends in energy production mechanisms as a function of periodicity and group.](image-url)
The bonds associated with functional groups or molecules associated with the lightweight anionic elements.

The **Circumvisible Region** extending from about 0.1 to 2.5 microns includes and yet is far more than the visible spectrum we associate with color, as impressive and useful as that is. This region provides information needed to characterize important aspects of a target’s composition, as well as, in the case of a solid surface, its optical properties. Characteristic spectral features result from the absorption of light causing the observed transitions in energy states of individual atom’s outermost, or bonding, electrons (**Figure 2.10**). Atoms in which such energy transitions occur as a result of interactions with a crystal lattice include the so-called alkali, alkali earth, and transition metals. Visible/Near IR (NIR) reflectance measurements (**Figure 2.11**) are dominated by transitions associated with iron bonding in the major minerals, pyroxene and olivine, as a function of Fe/Mg/Ca ratios, and thus yield the relative abundance of those minerals and their cation ratios. In the case of an atmospheric gas species, excitation in the SUV and visible occur at
characteristic energy transitions via activation by an external energy source. Solid surfaces have optical properties that generate useful features and complicate the processing of this data for compositional information. If the sun is directly overhead, the reflection of the entire visible component, or albedo, is an indication of the reflectivity of a mineral, as well as the relative freshness of a deposit, younger deposits and those bearing the more aluminous mineral plagioclase being brighter. Variations in albedo, the equivalent of texture on scales ranging from centimeters to kilometers, can be characteristic of a given rock type or surface deposit. If the illumination angle is oblique, shadows can show the details of structure within an image.

The Ray Region includes soft to hard X-rays, with energies ranging from keVs to more than hundreds of keVs, overlapping with the hard UV (XUV) and gamma-ray regions. Historically, the term gamma-ray indicated nuclear emission, i.e. from radioactive decay, but many now use the term synonymously with hard X-rays beyond a few hundred keVs. Energies fluoresced or reflected from surfaces in this region can be the result of interaction of high energy solar or cosmic rays with the surface to energy-correlated depths ranging from tens of microns to tens of centimeters. Spectral features in this region (Figure 2.12) are the result of energy transitions near the nucleus, either within the nucleus in the case of gamma-rays or among the innermost electrons in the case of X-rays. Energetic electrons are generated by interactions with energetic protons and neutrons, which are often measured as well to provide a source baseline. Features on energy spectra accumulated in this region result from properties intrinsic to the individual atoms themselves, regardless of their surroundings, and thus can provide the only direct information on elemental abundance. Because energies in this region are rapidly attenuated, or

Figure 2.12 Gamma-ray spectrum with characteristic scatter lines associated with common elements indicated taken of 433 Eros surface (Courtesy of NASA).
absorbed, most of these rays never reach the surfaces of planets with atmospheres and thus are most suitable for studying atmosphereless bodies. However, natural radioactive decay processes occurring within the uppermost meter or so of the surface may produce detectable gamma-rays on planets with atmospheres.

The **Infrared Region** includes energies ranging from about 3 to 20 microns, sometimes known as the mid IR (MIR) to far IR (FIR). The mechanism of energy production here results from the interactions between and among atoms on the molecular level. These interactions result naturally from the absorption and transmittance of ambient solar infrared energy or can be induced by an active source such as an IR laser. The interactions can be thought of as a stretching of bonds at characteristic frequencies in vibrational (varying distance), rotational (varying orientation), and translational (varying overall position) modes (Figure 2.13). In this region, the modes involving functional groups, such as sulfates, carbonates, or nitrates, have characteristic frequencies. Compounds such as silicate minerals produce spectra with features generated from stretching of Si-O and Al-O bonds. Resulting features are too complex to associate with individual bonds but nevertheless acting as fingerprints for the presence of that particular rock type (Figure 2.14). The longer wavelengths are not readily attenuated by an atmosphere but are attenuated on the ground by solid objects on the scale of the wavelength.

The **Longwave Region** consists of thermal Infrared, Microwave, and Radio energies ranging from tens of microns to meters. At the low energy end of the spectrum, in the microwave and radio regions, the energy spectrum is generated from the acceleration of free electrons through inelastic collisions and from fluctuations in the electric and magnetic fields of molecules. Thus, the longer wavelength, lower energies generated here are the result of even larger scale processes, yielding information on the character of a surface on roughly the scale of the

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**Figure 2.13** IR Vibrational, rotational, and translational energy transitions.
wavelengths, from individual particles to rocks to local facets of the terrain. Topography can be derived from using active generators of microwave, radio (masers or radar), as well as infrared or visible energies (lasers) in *ranging* (timed pulses roundtrip time) mode. The energy production mechanism involves absorption and reemission, or specular and diffuse scatter by individual particles, influenced by the dielectric properties, including the ability to create an oscillating dipole in response to an incoming wave, and by the packing density of the particles.

Thermal IR measurements are useful in characterizing the particle size distribution of a surface. For example, characteristically, the presence of higher thermal inertia components, such as rocks, results in greater absorption and longer-lived reemission when the thermal source is removed (Figure 2.15). Radars are useful in determining the character of a regolith for a broad range of component sizes, from fresh, rough components about ten times smaller than the scale of the

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**Figure 2.14** MIR Fingerprint of olivine samples (Courtesy of USGS).

**Figure 2.15** Comparison of lunar nearside images of visible albedo (left) showing bright younger finely comminuted ejecta and thermal emission (right) map showing relatively young areas with high thermal inertia ejecta or underlying (volcanic) rock close to the surface (Courtesy of NASA).
wavelength to rocky facets about ten times larger than the wavelength. This is accomplished by using polarized (detection at opposite polarization of transmission anticipated for direct specular reflection off facets) and depolarized (detection at same polarization of transmission anticipated for diffuse scattering from smaller particles) radars. When thermal and radar measurements of an area of minimal vegetation are combined, the abundance of components ranging from soil particle to boulder size, and the relative freshness or degradation of a basalt flow or an impact crater, can be determined.

At the lowest energy end of the spectrum are the Fields or Acoustic Regions, which consists of signals generated passively by electromagnetic or gravitational field interactions in any medium as well as actively by low frequency waves in atmosphere, liquid, or solid. Gravitational interactions between bodies can be measured by observing the deflection or perturbation caused by one body’s interaction with another. Gravity varies as a result of the non-uniform mass distribution in surface and underlying structures (Figure 2.16).

Typically, gravity is measured by tracking the perturbations to the calculated orbital motions of a spacecraft with a radio transmitter (i.e. radio science). Electrical and magnetic fields along the spacecraft’s trajectory are measured by electrometers or magnetometers. Particle analyzers capable of determining the abundances and directions of particles traveling through these fields are used to characterize them. When in contact with sound-bearing media, acoustic instruments can use sound generators to interact with the target or surrounding material. Depending on the properties and structure of the surrounding material, waves tra-
vel at different speeds and are refracted at boundaries between different materials. Refracted waves are detected by acoustically sensitive recorders of either seismic or sonic (sonar) devices (Figure 2.16). Thus solid objects in water and partially molten layers below the crust can be detected.

2.10 Interpretation of Remote Sensing Data

A given object’s capability of being characterized or even observed at all depends on its characteristic output spectrum, or intensity as a function of wavelength or frequency, and that varies both between regions, because different properties stimulate different energy production processes, and within regions, because its characteristic energy transitions occur at specific wavelengths. Spectral feature patterns act as signatures for specific compositional and physical components. Measurements made in one energy region can constrain those made in another. For example, XRS derived elemental abundances of Fe and Mg could constrain Fe/Mg ratios of Fe-bearing mineral pyroxene identified in Near IR measurements, and provide basis for understanding the partitioning of major elements between minerals, and thus rock types (Clark and McFadden, 2000). Combining data in this way is known as data fusion. A plethora of data types from multiple missions to major targets have already been analyzed and interpreted. Many times interpretations are still poorly constrained because data fusion has not been systematically performed. The unresolved issues require that data fusion be routinely performed now on existing or future datasets. NASA is attempting to address this issue by the creation of participating scientist programs for active flight projects. These investigators are not assigned to specific instrument teams but brought on board to perform cross-correlations of mission data to enhance our ability to study and advance the understanding of the target in a broader context.

2.2 Close to home: The big remote sensing testbed in the sky. Thanks to the Scientific Instrument Module on the Apollo service module, the Moon became a remote sensing testbed early on. Many instrument types that had previously been seen only in laboratories were flown in orbit for the first time, including the X-ray and gamma-ray spectrometers, laser altimeter, and Thermal Infrared detector. Relatively little ground truth was available from the Moon, a handful of small sites sampled and geologically characterized by the astronauts. Those working with the high energy spectrometer measurements, which provided elemental abundance maps, made extensive efforts to establish credibility by calibrating the data with landing sites, and thus being able to establish the distribution of major terranes and rock types for the whole Moon. In addition, the first ever planetary database was created, placing these data with very different fields of view and resolution and format into a common digital array format, in order to encourage data fusion, the combining of geologically related data in a way that enhanced the interpretation process. An unsupervised cluster analysis for the geochemical datasets
revealed that the average Ti and Fe content of the basalts that flooded each basin varied systematically as a function of age indicating that basalt source pools differentiated (separated) from the main source region at the time of basin formation. This interpretation was not taken seriously at the time, but is gaining popularity today.

2.11 Summary

The electromagnetic spectrum could be defined as the entire range of known energies for electromagnetic waves produced as a result of all of interactions between matter and energy. Both wave and particle (quantum) based models have been developed to explain this process. Which model best explains the resulting signal generated by a target depends on the nature of the interaction, which in turn depends on the energy region and the state of matter. The quantum model best describes discrete events inside atoms or molecules at higher energies, the wave model the apparently more continuous media interactions such as reflection and refraction at surfaces, and the force field model the lowest frequency gravitational and magnetic variations. Energy and matter both exhibit quantized behavior. Characteristic spectral features, lines or bands, can be modeled and considered quantitatively.

An atmosphere attenuates incoming energy through scattering, selective (Rayleigh or Mie) for particles comparable or smaller in size and nonselective scattering for particles larger than the wavelength. Energy interactions with liquids and solids involve characteristic interactions with constituents through absorption, transmittance, and reflection. In the case of solids, surface interactions depending on the roughness on the scale of the wavelength, involve specular or coherent scatter and diffuse scatter. The degrees of freedom and distance between constituents in gases translate into a greater number of narrow (characteristic line) features across the entire spectrum. Features in liquids and solids are broader (bands) and fewer. Energy output from a target, point source or extended surface, is calculated on the basis of radiant flux or flux density per unit solid angle, area covered, or both. The division of the spectrum into distinctive regions is based on the distinctive energy production mechanisms, detection methods, and analysis techniques associated with each region: 1) the highest energy Ray Region of gamma-rays, X-rays, and high energy Ultraviolet (XUV), 2) the Circumvisible Region of soft UV (SUV), visible, near IR (NIR), 3) the Infrared Region (transitional between the Circumvisible and Longwave Regions) of mid- to far IR (MIR and FIR), 4) the Longwave Region of thermal, microwave, and radio, and 5) the lowest energy Acoustic Region of sound and seismic waves, through their coupling to electromagnetic fields, providing information on internal structure. Spectral features act as signatures for specific compositional and physical components. Measurements made in one energy region can and should be used to constrain those made in oth-
ers to provide a more complete model of a natural setting in a process known as data fusion.

### 2.12 Some Questions for Discussion

1. When is it appropriate to use the quantum model to explain remote observations? The Maxwell wave model? The force field model?

2. Compare quantum phenomena in energy and matter.

3. Describe interactions between incoming photons and an atmosphere. Consider scattering and other phenomena. Give illustrations for each.

4. Compare and contrast photonic interactions with solids, liquids, gases, and plasma.

### References
