Photonics-Enabled Technologies

Spectroscopy and Remote Sensing

NSF OP-TEC*

Optics and Photonics Series

Spectroscopy and Remote Sensing

Photonics-Enabled Technologies

OPTICS AND PHOTONICS SERIES

**OP-TEC: The National Center of Optics
and Photonics Education**

An NSF ATE Project

National Center for Optics and Photonics Education

PREFACE

This module is one of three pertaining to the role of optics and lasers in spectroscopy. OP-TEC treats spectroscopy as a *photonics-enabled* technology. The current OP-TEC series on photonics-enabled technologies comprises modules in the areas of manufacturing, biomedicine, forensic science and homeland security, optoelectronics, and environmental monitoring, as listed below. (This list will expand as the OP-TEC series grows. For the most up-to-date list of modules, visit http://www.op-tec.org.)

Manufacturing

Laser Welding and Surface Treatment

Laser Material Removal: Drilling, Cutting, and Marking

Lasers in Testing and Measurement: Alignment Profiling and Position Sensing

Lasers in Testing and Measurement: Interferometric Methods and Nondestructive Testing

Environmental Monitoring

Basics of Spectroscopy

Spectroscopy and Remote Sensing

Spectroscopy and Pollution Monitoring

Biomedicine

Lasers in Medicine and Surgery

Therapeutic Applications of Lasers

Diagnostic Applications of Lasers

Forensic Science and Homeland Security

Lasers in Forensic Science and Homeland Security

Infrared Systems for Homeland Security

Imaging System Performance for Homeland Security Applications

Optoelectronics

Photonics in Nanotechnology

The modules pertaining to each technology can be used collectively as a unit or separately as stand-alone items, as long as prerequisites have been met.

For students who may need assistance with or review of relevant mathematics concepts, a review and study guide entitled *Mathematics for Photonics Education* (available from CORD) is highly recommended.

The original manuscript of this module, *Spectroscopy and Remote Sensing,* was prepared by Dr. Leno Pedrotti (CORD). Formatting and artwork were provided by Mark Whitney and Kathy Kral (CORD).

CONTENTS

Spectroscopy and Remote Sensing

INTRODUCTION

This module is part of a series of three modules that deal with *spectroscopy*. The three taken together cover the basic ideas of what spectroscopy is and what it does (*Basics of Spectroscopy*), how spectroscopy is involved in the important domain of *remote sensing* (*Spectroscopy and Remote Sensing*), and the equally important world of *pollution monitoring* (*Spectroscopy and Pollution Monitoring*).

In this module you will learn how the science of spectroscopy is used to determine various details of the Earth's surface. This is done by analyzing the forms of energy that are both reflected and emitted by the different regions of the Earth's crust, e.g., lakes, oceans, forests, vegetation, marshes, deserts, and mountains. This analysis is carried out remotely for the most part, from positions and platforms above the Earth, using mostly aircraft and satellites.

Before looking more closely at remote sensing, this module will introduce the reader to three main instruments that are used in spectroscopy to detect and identify different parts of the electromagnetic spectrum. These are the *prism* spectrometer, the *grating* spectrometer, and the *spectrophotometer*. In addition, we describe the operation of a *mass* spectrometer.

Photonics technicians with a basic knowledge of lasers and optics are strategically positioned to carry out measurements in spectroscopy that yield vital information concerning the Earth's environment and ecological status.

PREREQUISITES

The student should be familiar with the following before attempting to complete this module.

1. High school mathematics through intermediate algebra and the basics of trigonometry

2. CORD's Optics and Photonics Series Course 1, *Fundamentals of Light and Lasers*

3. CORD's Optics and Photonics Series Course 2, *Elements of Photonics*

> Module 2-1: *Operational Characteristics of Lasers*
> Module 2-2: *Specific Laser Types*
> Module 2-3: *Optical Detectors and Human Vision*
> Module 2-5: *Photonic Devices for Imaging, Storage, and Display*

4. It is highly recommended that the module *Basics of Spectroscopy* be perused before studying this module.

OBJECTIVES

When you have finished this module you will be able to:

- Define *remote sensing* and *spectroscopy* and tell how they are related.

- Describe three instruments used to analyze spectra.

- Describe an instrument used to determine atomic mass.

- Identify three general types of spectroscopy.

- Identify the five wavelength regions of common use in remote sensing.

- Calculate the *dispersion* and *chromatic resolving power* for a prism.

- Draw a diagram of a grating spectrometer.

- Calculate the *linear dispersion* $\frac{\Delta \ell}{\Delta \lambda}$ for a prism spectrometer.

- Draw a schematic diagram for a spectrophotometer.

- Describe the six main parts of a complete remote sensing process.

- Describe what is meant by *atmospheric windows* and how sensors are chosen to match them.

- Describe how remote sensing from foliage, water, and heated buildings, for example, is carried out.

- Distinguish between active and passive sensors.

- Identify four platforms generally used in remote sensing.

- Calculate the *resolution cell* for a sensor given its *altitude* and *instantaneous field of view* (IFOV).

- Distinguish between weather satellites and Earth-surface satellites.

- Describe characteristics of a GOES weather satellite.

- Describe characteristics of a LANDSAT satellite.

- Describe how a spectrophotometer is used to determine absorption/transmission through a substance.

- Use the Beer-Lambert law to relate transmission and absorption for a medium.

SCENARIO

Chris Colton is excited! After working as a technician in the field of optics and photonics for two years, Chris has been accepted by a nearby university to continue work in remote sensing. One of the labs at the university is conducting research on the use of laser-induced fluorescence to probe the temperature and winds of the *mesopause,* an atmospheric region about 90 kilometers above the Earth's surface. Chris is well qualified for his new situation because he studied spectroscopy and remote sensing at the local two-year technical institute, where he learned how laser energy is used to cause substances to fluoresce and emit light signals that help to identify them. In the research that he is soon to become involved in, laser energy near 589 nanometers is being beamed up at sodium (Na) atoms in the mesopause region, enabling researchers to use the science of LIDAR, Doppler broadening, and Doppler shift to obtain important information about temperature and wind speeds. Chris knows that he has much to learn about LIDAR and Doppler effects, but he is confident that he can build on what he has already learned about lasers and spectroscopy as a photonics tech. And what could be more challenging than extracting information—through remote sensing—from a part of the atmosphere some 100 kilometers away? Even better, Chris knows that the information he will help to obtain will give us a better understanding of the energy dynamics between the sun and the Earth—and help to control global warming. Chris can't wait to get started.

BASIC CONCEPTS

Introduction

Spectroscopy can be defined simply as the study of matter and its properties via an analysis of the radiant energy, sound, and particles that are absorbed, emitted, or scattered by the target substance. While spectroscopy began as a study of the interaction of visible light and matter, it has now been extended well beyond visible light to include much of the electromagnetic spectrum, from short-wavelength X rays to long-wavelength microwaves.

Three general types of spectroscopy

The three general types of spectroscopy—as described in the module titled *Basics of Spectroscopy*—are absorption spectroscopy, emission spectroscopy, and scattering spectroscopy.

In *atomic absorption spectroscopy,* the target substance is atomized (vaporized) and then radiant energy of a particular wavelength is passed through the vapor. After a suitable calibration of the spectroscopic instruments, the amount of absorption can be traced to the particular concentration of atoms or ions in the vapor, thereby allowing identification of the elemental substances present in the sample. Such a method is used, for example, to measure concentrations of sodium, potassium, and calcium ions in the blood.

Figure 1 shows how absorption lines are seen in the solar spectrum of the sun. The hot sun sends intense UV, IR, and white light through gases surrounding the sun. Specific chemical elements in the gas cloud absorb certain wavelengths of the sun's light and show up in the white light spectrum at the detector as dark lines. A sample of such a spectrum, from 6100 to 6900 angstroms, is shown as part of Figure 1. In this spectral segment, the dark lines indicate the presence of the elements hydrogen (H_2), iron (FE), and argon (A).
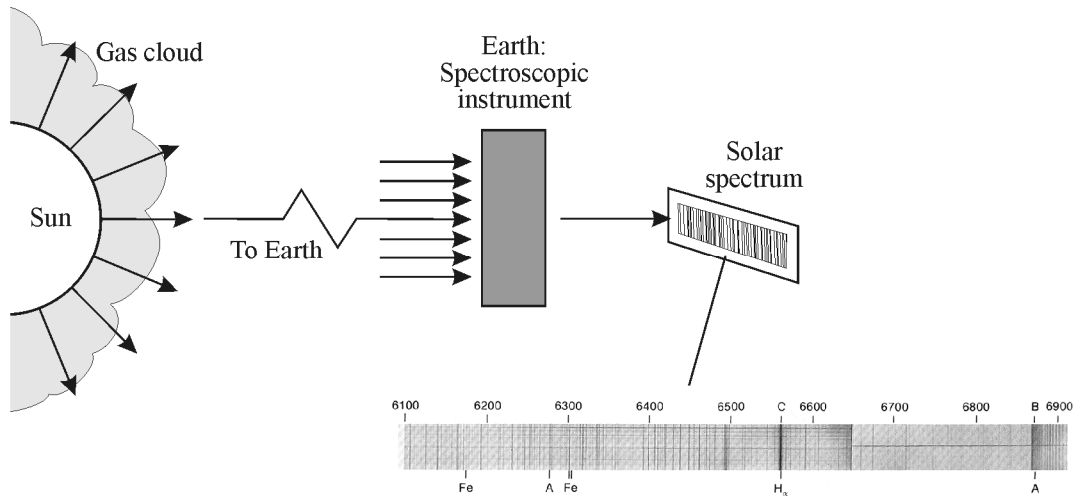
Figure 1 *Formation of solar spectrum with sample spectral segment from 6100 to 6900 angstroms*

In *emission spectroscopy* (Figure 2), the atoms/molecules in the target sample absorb some of the incident radiation energy, move to higher energy levels, and then give up the absorbed energy as emission of different wavelengths. The emitted energy is typical of the atoms/molecules in the target sample and serves to reveal the type and amount of the emitting substance, thereby disclosing an *identifying fingerprint*.

Figure 2 *Energized gases emit light characteristics of their energy level structure*

Unlike absorption and emission spectroscopy, *scattering or reflection spectroscopy* (Figure 3) identifies properties of the radiated target via the analysis of energy scattered by the target. The scattering process, much faster than either the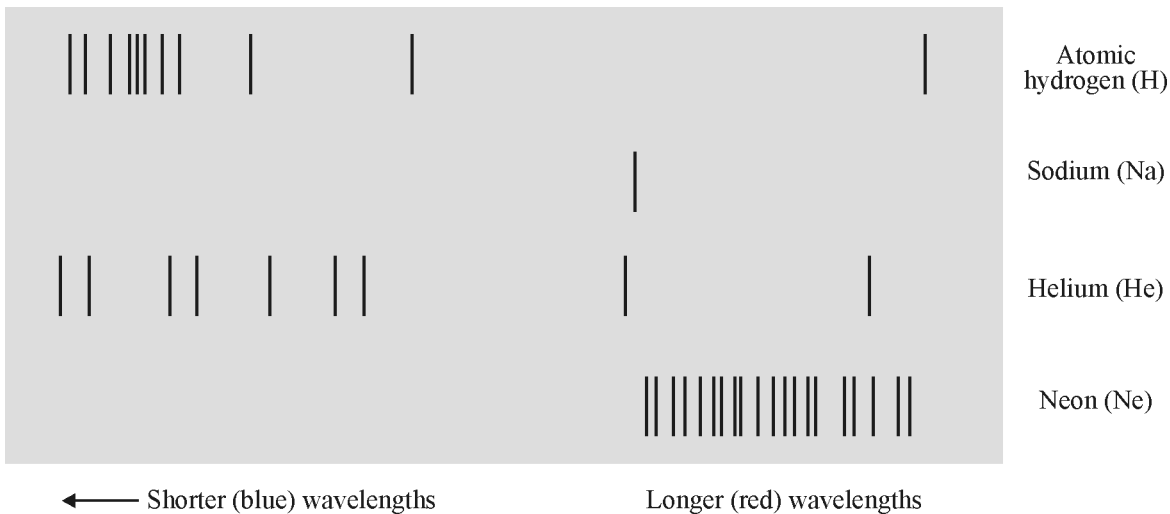 absorption or emission process, can be studied as a function of the wavelength/frequency and polarization of the incident electromagnetic radiation. Clearly, scattering spectroscopy would be of considerable interest in studying the nature of swamps, forests, and vegetation, which constantly scatter sunlight back into the atmosphere.
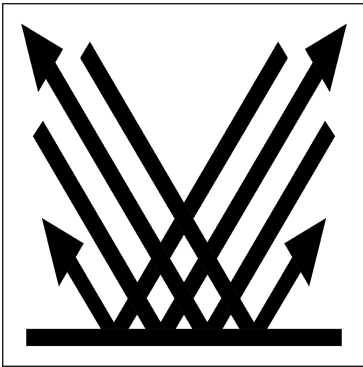
Figure 3 *Scattering or reflection spectroscopy*

Specific types of spectroscopy

Depending on the incident radiation used to illuminate the target, and on the wavelength regions in which the targets emit electromagnetic radiation, different types of spectroscopy are used and are described as follows:

- Spark or arc spectroscopy
- Visible spectroscopy
- Fluorescence spectroscopy
- Flame spectroscopy
- Ultraviolet spectroscopy
- Infrared spectroscopy
- X-ray spectroscopy
- Thermal radiation spectroscopy

Detecting and analyzing spectroscopic outputs

The goal of all spectroscopic systems is to receive and analyze the radiation absorbed, emitted, or scattered by the target (gas, liquid, or solid). This detection and analysis is accomplished with instruments involving prisms, gratings, spectrophotometers, and, in some cases, mass spectrometers. The characteristics of prisms, gratings, and spectrophomoters will be described briefly, along with the principle of operation of a mass spectrometer.

The dependence of remote sensing on spectroscopy

To accomplish the analysis and description of the ever-changing crust of the Earth, spectroscopic systems are positioned remotely from their targets—on aircraft, satellites, spacecraft, ships, and, in some cases, near-to-ground platforms.

The important point to keep in mind is that in a broad sense, remote sensing is just that, sensing/measuring information received from a target object *remotely*, from a distance. And in most cases "remote sensing" in our discussions will be limited to terrestrial phenomena and weather observations.

Thus, remote sensing, which by definition does not take place "in contact" with the object or target, is sometimes described as "trying to determine the type of animal from its footprints." For example, we acknowledge that it may be difficult to measure temperatures in the upper atmosphere, so we measure instead the spectral emissions from a certain chemical element, such as CO_2, in that vicinity. Then, using the laws of thermodynamics, we can relate the frequencies of the spectral emissions of the CO_2 molecules—as measured by a spectroscopic system—to the temperatures in that region of the atmosphere and achieve our goal indirectly.

An Overview of Common Spectroscopic Instruments

In this section we begin with a general description of the parameters that characterize the capability of a spectrometer and then describe in more detail the operations of a prism spectrometer, a grating spectrometer, a spectrophotometer, and a mass spectrometer.

Defining parameters for spectrometer capabilities

In general, three parameters can be used to describe the capabilities of a spectrometer:

- Spectral range
- Spectral bandwidth
- Signal-to-noise ratio

Spectral range refers to the width of the wavelength band or region over which the spectrometer can access and analyze incoming data. In remote sensing, the spectral ranges that are in common use are these:

- Ultraviolet (UV) – 0.001 μm to 0.40 μm
- Visible (VIS) – 0.40 μm to 0.7 μm
- Near infrared (NIR) – 0.7 μm to 3.0 μm
- Mid infrared (MIR) – 3.0 μm to 30 μm
- Far infrared (FIR) – 30 μm to 1 mm

For example, thermally emitted energy from the Earth lies in the MIR range, so that spectrometers used to examine thermal energy from "hot" spots on the earth would have to be active in the 3 μm to 30 μm range.

Spectral bandwidth refers to the width of an individual spectral band—a wavelength or frequency-width—that can be distinguished from adjacent wavelength or frequency bands. For example, if a spectrometer can distinguish between bandwidths of 0.1 μm in the MIR spectral region (3 μm–30 μm), as compared to a spectrometer with a bandwidth of 10 μm, it is clear that the spectrometer with the narrower bandwidth can more accurately differentiate between wavelength information contained in the incoming signal, thereby improving the instrument's resolution.

The signal-to-noise (S/N) ratio of the spectrometer is just that—a comparison of the strength of the incoming signal to the strength of the background optical-electronic "noise." Noise is a signal generated from sources other than the one being studied. An effective spectrometer must distinguish between the signal from noise and the desired signal from the source of interest. The S/N ratio is a parameter that indicates how well a spectrometer is distinguishing between the two signals. The S/N ratio depends on the strength of the signal being detected, the sensitivity of the detector, and the spectral bandwidth of the spectrometer. For example, if a spectrometer is "looking" at only a few strong spectral peaks, an S/N ratio of 5 or so may be sufficient to distinguish between signal and noise. On the other hand, for complex signals with relatively weak peaks, all crowded together, a higher S/N ratio of 10 may be required. Figure 4 shows the effects of different S/N ratios in the process of separating signal from noise. For (a) where S/N ≥ 10, all signal strengths are above the noise level and are detectable. In (b) for S/N ≃ 1, the signal is not strong enough to be separated from the noise. In (c), for S/N < 1, the signal strength is too low or the noise level is too high, and details of the signal will not be picked up by the detector.
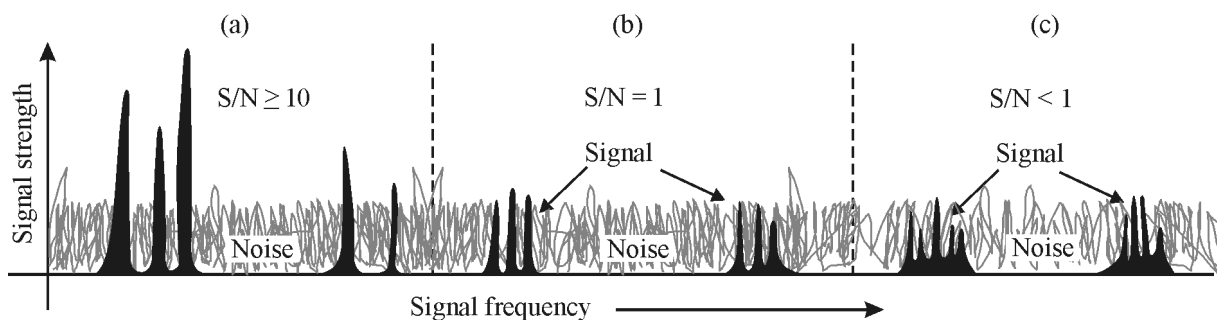

Figure 4 *Comparison of signal strength and noise strength for S/N ratios of ≥ 10, 1, and < 1*

Spectrometers used in remote sensing, with the parameters described above, are found in laboratories, near the ground, in aircraft, and on satellites. The operating parameters of spectrometers used in remote sensing will depend on the detailed nature of the target to be examined (vegetation versus lakes, for example), the size of the field-of-view of the target, the distance from spectrometer to target, and the nature of the intervening "atmosphere" between the target and spectrometer.

Prism spectrometers

An instrument that uses a *prism* to disperse or separate light into its basic components (wavelengths) is called a prism spectrometer. Its essential elements are shown in Figure 5. Light from a light source to be analyzed is focused onto a narrow slit S. It is then collimated (made parallel) by lens L_1 and refracted by prism $P,$ which typically rests on an indexed rotatable

platform. Rays of light corresponding to each wavelength emerge mutually parallel after refraction by the prism and are viewed with a telescope T focused for distant vision.
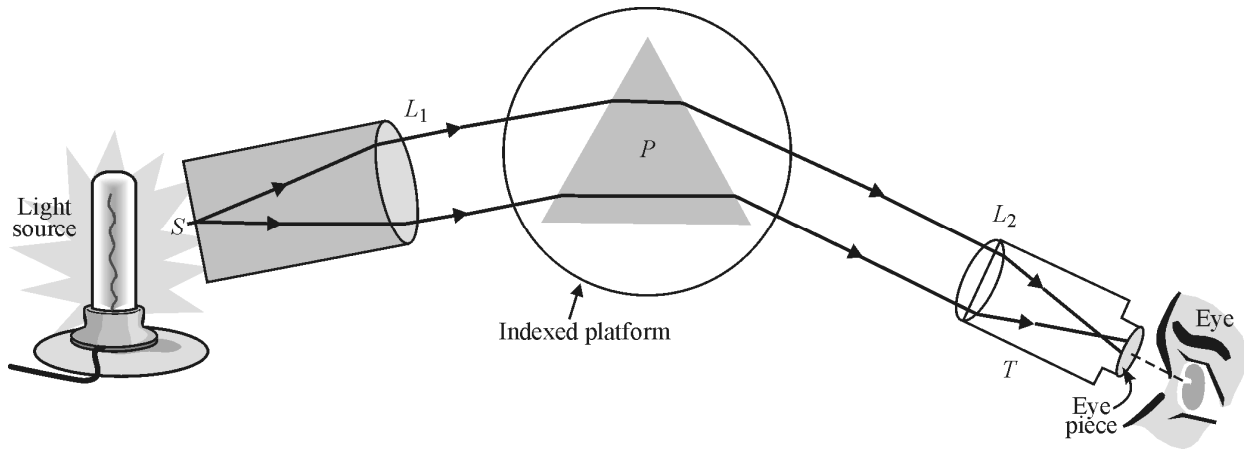
Figure 5 *Essentials of a prism spectrometer*

As the telescope is rotated around the indexed prism table, a focused image of the slit is seen through the telescope for each distinct wavelength—at its corresponding angular deviation. The dispersion and deviation of a light beam incident on a prism are pictured in Figure 6.

(a) Typical dispersion curve for refractive index n versus wavelength λ

(b) Color separation of white light by a prism

(c) A case of large deviation δ and small dispersion D

(d) A case of small deviation δ and large dispersion D

Figure 6 *Examples of dispersion n versus λ, color separations, and different deviations and dispersions*

In Figure 6a we see a sketch of a typical dispersion curve, that is, the variation of the index of refraction n as a function of wavelength λ. We see that n is larger for shorter wavelengths. Since a prism bends the direction of a light ray more if its corresponding refractive index is higher, the

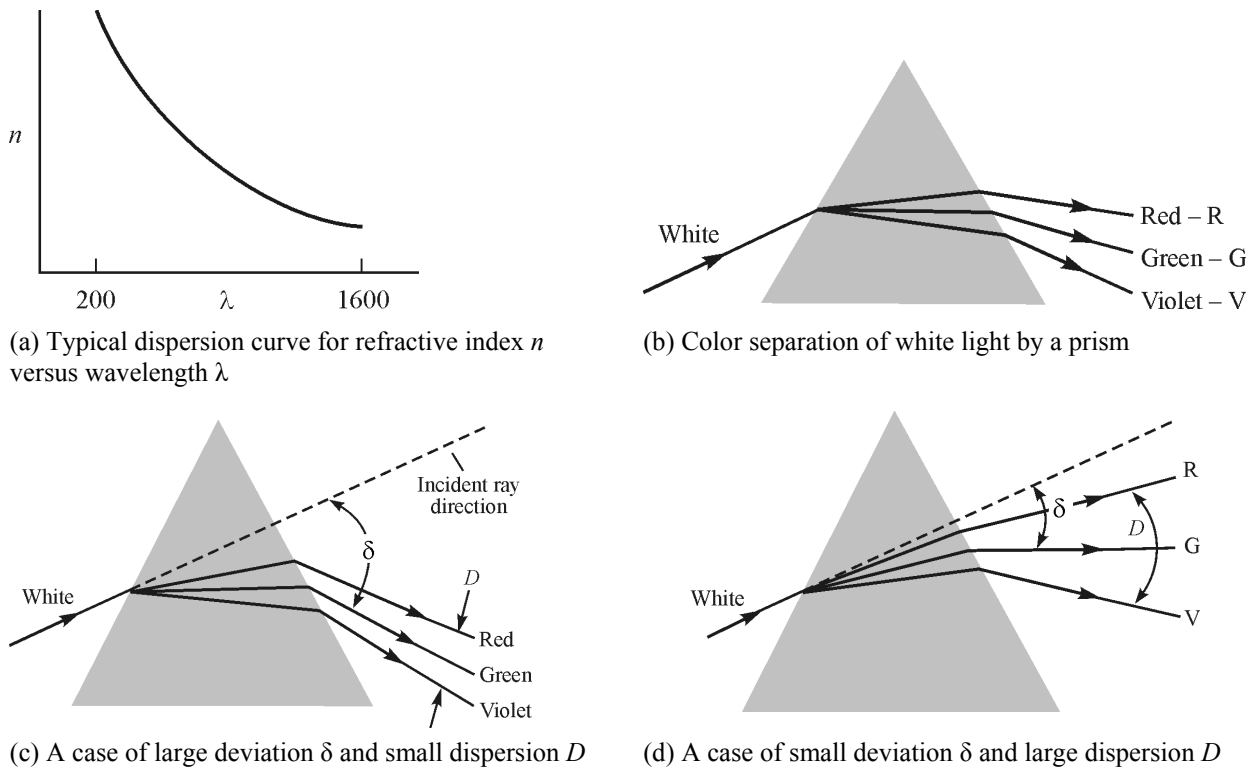different colors are bent by different amounts as shown in Figure 6b, with violet light bent more than red light. The steeper the slope of the dispersion curve shown in Figure 6a for a given prism, the greater will be the dispersion (separation of adjacent wavelengths).

In Figures 6c and 6d, we compare the total bending of the incident ray measured from the straight-through direction (dashed line), which we call *deviation*—with the separation (dispersion) of component wavelengths. The comparison is made using three widely separated wavelengths—seen as red, green, and violet colors—to indicate dispersion D and deviation δ.

When the instrument is used for visual observations alone (no measuring of angular deviations), it is called a *spectroscope*. If means are provided for recording the angularly deviated spectrum components, for example, with a photographic film positioned in the focal plane of the telescope objective L_2, the instrument is called a *spectrograph*.

To extend the usefulness of the prism into UV and NIR regions, prisms made from quartz and fluorite are used for UV light, and prisms made of salt and sapphire are used for NIR light. It should be clear that the function of a prism is to separate (disperse) different wavelength components as widely as possible. This will happen, of course, if the difference in refractive indices (Δn) is *large* for two wavelengths λ_1 and λ_2 whose wavelength difference ($\Delta\lambda$) is *small*. Thus the dispersion D is defined to be the ratio $\Delta n/\Delta\lambda$.

$$D = \frac{\Delta n}{\Delta\lambda} \qquad\qquad (1)$$

where D is the dispersion,
Δn is the difference in refractive indexes, and
$\Delta\lambda$ is the corresponding difference in wavelengths.

A closely related parameter in the optical capabilities of a prism spectrometer is called the *chromatic resolving power, R*. It is given by

$$R = b\frac{\Delta n}{\Delta\lambda} \qquad\qquad (2)$$

where b = length of the prism base,
$\frac{\Delta n}{\Delta\lambda}$ = dispersion, and
R = chromatic resolving power.

The chromatic resolving power R can be expressed also as

$$R = \frac{\lambda}{(\Delta\lambda)_{min}} \qquad\qquad (3)$$

where $(\Delta\lambda)_{min}$ is the minimum wavelength difference that the prism can resolve, that is, distinguish clearly between closely spaced wavelengths λ_1 and λ_2, and where λ is the wavelength of the radiation incident on the prism.

Example 1

Jocelyn is a photonics tech working with a prism spectrometer whose prism is made of flint glass. Her supervisor has asked her to calculate the dispersion, the chromatic resolving power, and the minimum resolvable wavelength difference for this particular prism for a wavelength around 530 nm.

Solution

Jocelyn measures the prism base b to be 5 cm (5×10^7 nm) and from appropriate tables for flint glass, she finds that $n = 1.7328$ at $\lambda = 486.1$ nm and $n = 1.7205$ at $\lambda = 589.2$ nm. She sees that the operating wavelength of 530 nm is about halfway between the two endpoint wavelengths in the table she is using.

From Equation 1 she finds the dispersion D to be

$$D = \frac{\Delta n}{\Delta \lambda} = \frac{1.7328 - 1.7205}{486.1 - 589.2} = \frac{0.0123}{-103.1 \text{ nm}} - 1.19 \times 10^{-4} \text{ per nm.}$$

From Equation 2, she finds the resolving power R to be

$$R = b\left(\frac{\Delta n}{\Delta \lambda}\right) = (5 \times 10^7 \text{ nm})\left(\frac{1.19 \times 10^{-4}}{\text{nm}}\right) = 5950.$$

From Equation 3 she finds $(\Delta \lambda)_{min}$ around $\lambda = 530$ nm to be

$$(\Delta \lambda)_{min} = \frac{\lambda}{R} = \frac{530 \text{ nm}}{5950} = 0.09 \text{ nm, about 1/10 of a nm, the minimum wavelength difference the}$$

prism can resolve around $\lambda = 530$ nm.

Jocelyn notices from Equations 2 and 3 that if she were to use a flint prism with a base of 10 cm, the resolving power would be doubled and the value for $(\Delta \lambda)_{min}$ would reduce to 1/20 of a nm. But that might make the flint prism too large and bulky.

Grating spectrometers

The diffraction grating, which serves as the heart of a grating spectrometer, is a simple and most useful optical device. The grating consists of a grid of fine parallel lines, uniformly spaced on a polished reflecting or transmitting surface. The lines generally are ruled with a fine diamond point and generally number several thousands of lines per centimeter. The reflection or transmission of light, by the uniformly separated portions of the surface, causes *diffraction* and *interference* effects, as discussed in Module 1-5, *Basic Physical Optics,* in Course 1, *Fundamentals of Light and Lasers*. These effects lead to the formation of a spectrum characteristic of a given light source.

The essential makeup of a grating spectrometer is shown in Figure 7. The similarity between this arrangement and that of the prism spectrometer shown earlier in Figure 5 is readily apparent.
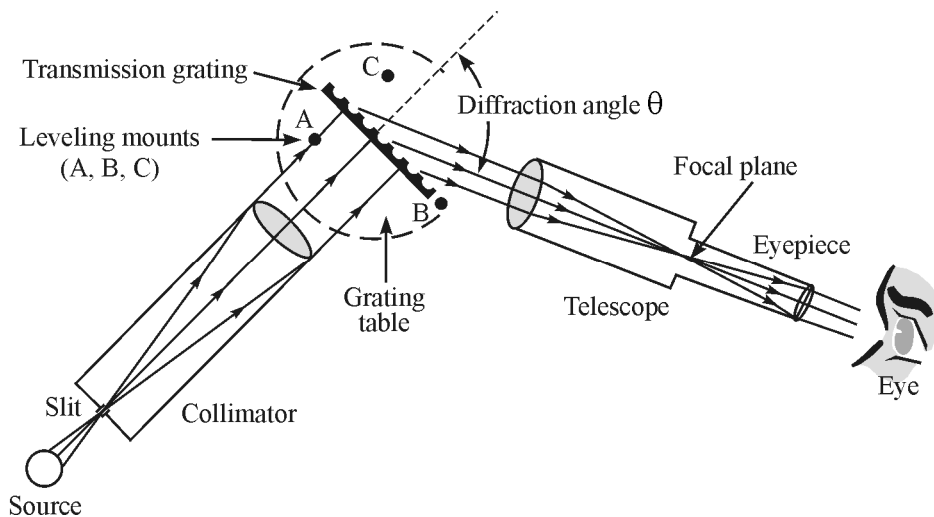
Figure 7 *Essentials of a grating spectrometer*

The collimator directs parallel light onto the grating. The grating, in turn, serving as the dispersing element, separates the bundles of parallel light of different wavelengths and directs them into the telescope. The observer adjusts the telescope for proper focus and views the characteristic line spectra or band spectra of the source in the focal plane of the telescope.

The diffraction angle θ shown in Figure 7 is unique for each wavelength of light in the light source. As described in Module 1-5, *Basic Physical Optics*, the wavelength of light λ, the diffracting angle θ, the grating constant *d,* and the diffraction order *m* are all related in the grating equation.

$$m\lambda = d(\sin i + \sin \theta) \qquad (4)$$

where *i* is the angle of incidence of light measured with respect to the normal of the grating surface and *d* is the grating spacing. For example, if there are 3000 lines/cm ruled on the grating surface, $d = \dfrac{1 \text{ cm}}{3000} = 3.33 \times 10^{-4}$ cm = distance between centers of the ruled lines.

The collimated beam illustrated in Figure 7 is perpendicular to the plane of the grating so that for this orientation angle *i* is zero and sin *i* is zero. Thus, for light normally incident on the grating, the grating equation reduces simply to Equation 5.

$$m\lambda = d \sin \theta \qquad (5)$$

where *m* = 0, ±1, ±2, . . . refers to the different orders of diffraction. The essential geometry relating λ, θ, and *d* for order *m* is illustrated in Figure 8.
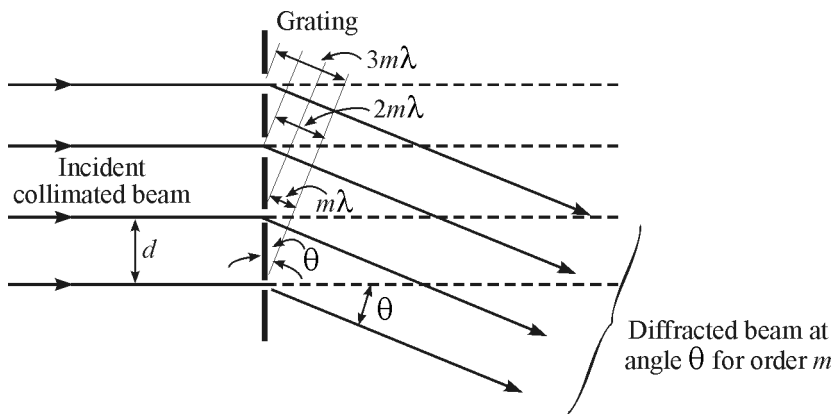
Figure 8 *Diffraction for order m at angle θ at normal incidence*

Thus, for a given order other than the zeroth order) ($m = 0$), the incident light is diffracted (bent) at an angle θ, given from Equation 5 by sin θ = ($m\lambda$)/d. Since d is the grating constant and m is a constant for a given diffraction order, the angle θ changes with wavelength. For each order ($m = 1, 2, 3$, etc.), the different wavelengths are separated out and observed as a distinct spectrum. However, since spectral lines in adjoining orders *may overlap,* one must be careful in interpreting the spectral lines observed in the focal plane of the telescope. For example, a red line of *700-nanometer wavelength in third order* is diffracted through the same angle as the green line of *525-nanometer wavelength in fourth order* since sin θ = 3(700)/d = 4(525)/d is identical for each wavelength. For visible light, there is no overlapping of the first and second orders since, with $\lambda_1 = 720$ nm and $\lambda_2 = 400$ nm, the red end of the first order ($m = 1$) falls just short of the violet portion of the second order ($m = 2$). When photographic observations are made, however, these orders may extend down to 200 nm in the ultraviolet, and then the first two orders would overlap.

One can avoid this complication through the use of suitable color filters to absorb the wavelengths from the incident light that would overlap in the region under examination. For example, a cutoff filter that transmits only wavelengths longer than 600 nm might be used to block the shorter wavelengths at order $m = 2$ or higher from disturbing the observations in the wavelength region near 700 nm. In any case, a little common sense and attention to color, where orders do overlap, will help in avoiding incorrect identification of wavelengths in unknown spectra.

Example 2

Sean is using a grating spectrometer to analyze the spectral light from an emission spectrum put out by a glowing gas. The emitted light is incident on the grating surface along the grating normal ($i = 0°$), and the spectral line Sean is looking for diffracts at an angle of 23° in first order ($m = 1$). The grating constant for Sean's grating is $d = 1.25 \times 10^{-4}$ cm. What is the wavelength of the diffracted light and what is the color of the spectral line?

Solution

Using Equation 5 and rearranging terms to isolate λ, Sean finds that

$$\lambda = \frac{d \sin \theta}{m} = \frac{(1.25 \times 10^{-4} \text{ cm})(\sin 23°)}{1}$$

$$\lambda = 0.488 \times 10^{-4} \text{ cm} = 0.488 \times 10^{-6} \text{ cm}$$

So the spectral line has a wavelength of 0.488 μm or 488 nm. Such a wavelength places the line at the blue-green end of the visible spectrum.

Linear dispersion—The linear dispersion $\frac{\Delta \ell}{\Delta \lambda}$ is a useful parameter that describes the ability of the grating spectrometer to separate spectral lines. For example, a grating spectrometer whose linear dispersion is 0.25 mm/Å is obviously superior to one whose linear dispersion is 0.06 mm/Å in the same region, since a linear dispersion of 0.25 nm/Å separates lines nearly four times as much as a linear dispersion of 0.06 nm/Å. (Recall that Å stands for "Angstrom," a measure of wavelength where $1 \text{ Å} = 10^{-10}$ m $= 0.1$ nm.)

The equation for linear dispersion $\frac{\Delta \ell}{\Delta \lambda}$ is given by Equation 6.

$$\frac{\Delta \ell}{\Delta \lambda} = \frac{mf}{d \cos \theta} \tag{6}$$

where m = order number,
f = focal length of the objective lens in the telescope,
d = grating constant, and
θ = diffracting angle for the corresponding wavelengths.

Since linear dispersion does depend on the diffraction angle θ, one cannot quote a value for the linear dispersion of a spectrometer that is valid at all wavelengths. However, one still can compare different spectrometers by calculating $\frac{\Delta \ell}{\Delta \lambda}$ in the middle of the visible spectrum (say, 550 nm in the first order) for each spectrometer.

The resolving power of a grating spectrometer—just as the chromatic resolving power for a prism spectrometer—is obtained from the basic definition of $\frac{\lambda}{\Delta \lambda}$. It can be shown that for a grating spectrometer, the resolving power RP is given by Equation 7.

$$RP = \frac{\lambda}{\Delta \lambda} = mN \tag{7}$$

where N = total number of ruled lines on the grating and
m = the order in which the diffracted light is being observed.

Thus, for a grating that contains 10,000 lines, the resolving power in *second* order is $2 \times 10,000$, or 20,000. This means that at 500 nm, the grating used in second order theoretically can resolve spectral lines differing in wavelength by $\Delta \lambda = 500$ nm/20,000, or 0.025 nm. Used in first order, the resolving power would be cut in half (i.e., 10,000). In this case, the grating could separate spectral lines differing in wavelength by ~0.05 nm.

Example 3

Camryn is working in a photonics laboratory that is comparing the resolving power of different grating spectrometers. One particular grating spectrometer she is investigating has a grating with 500 lines/mm and the spectrometer telescope has a focal length of 25 cm. Her supervisor wants to know if this instrument can give a linear dispersion of 5×10^{-2} mm/Å. in third order at diffracting angles around 67°.

Solution

Camryn makes use of Equation 6 with $m = 3$, $\theta = 67°$, $d = \dfrac{1}{500}$ mm = 0.002 mm = 0.0002 cm,

$$\frac{\Delta\lambda}{\lambda} = \frac{mf}{d\cos\theta} = \frac{3 \times 25 \text{ cm}}{(2 \times 10^{-4} \text{ cm})(\cos 67°)}$$

$$\frac{\Delta\lambda}{\lambda} = \frac{75 \text{ cm}}{7.8 \times 10^{-5} \text{ cm}} = 9.6 \times 10^5 \text{ cm/cm}$$

To convert this value from cm/cm to mm/Å we change as follows:

$$9.6 \times 10^5 \frac{\cancel{cm}}{\cancel{cm}} \times \frac{1 \text{ mm}}{0.1 \cancel{cm}} \times \frac{1 \cancel{cm}}{10^8 \text{ Å}} = 9.6 \times 10^5 \times 10 \times 10^{-8} = 9.6 \times 10^{-2} \frac{\text{mm}}{\text{Å}}$$

Camryn sees that the linear dispersion of 9.6×10^{-2} mm/Å is above the "target" of 5×10^{-2} mm/Å, so this particular grating spectrometer would "meet specs."

Types of gratings—Before leaving this section on grating spectrometers, we might say a few words about the different types of gratings we find in grating spectrometers.

A *transmission grating* is distinct from a *reflection grating*. In the former, the lines are ruled on glass, the unruled portions acting as the grating slits. In the latter, the reflection grating, the lines are ruled on a polished metal surface and the incident light is reflected from the unruled areas, producing by reflection the same result as that produced by transmission through the transmission grating. Depending on the shape of the ruled surface, one can also distinguish between *plane* and *curved* gratings. Clearly, curved reflection gratings have a focusing capability—depending on the radius of curvature of the surface which will be superimposed on the diffraction effects of the grating itself.

In some instances, one may have occasion to use a so-called *blazed* grating. In a blazed grating, the grooves cut into the surface are given a particular, regular geometrical shape, causing most of the diffracted light energy to be concentrated in a certain direction. When grating grooves are made in the triangular, staircase (echelette) shape as shown in Figure 9, the reflected light is concentrated in one direction or order. To the observer's eye, the
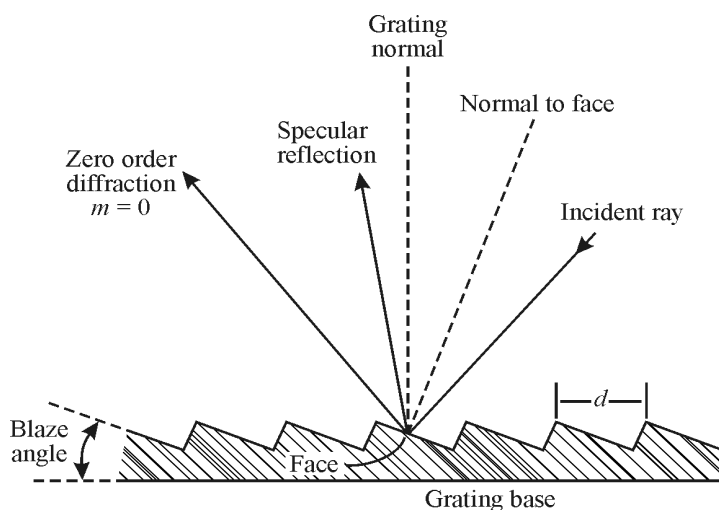

Figure 9 *Profile of blazed reflection grating and angular relationships*

grating appears to light up or "blaze" as it is being rotated into the "blaze" direction, and gives only faint spectral images in any of the other possible orders.

Referring to Figure 9, it may be seen intuitively that the incident light will be diffracted at optimum intensity along the direction labeled "specular reflection." The wavelength that coincides with the intensity peak is known as the *blaze wavelength.* Most modern gratings are of the shaped or blazed variety. Their significance lies in the fact that they shift energy out of the useless zeroth order into one of the useful higher-order spectra.

Spectrophotometer

An instrument that incorporates a prism or grating monochromator to analyze spectra is called a *spectrophotometer*. Shown piecemeal in Figure 10, a spectrophotometer contains the following main parts.

- Monochromator (light source, lens, entrance slit, mirror, lens, rotatable grating, lens, exit slit)

- Two cells or cuvettes to hold the reference material and the sample to be measured—labeled Cell 1 and Cell 2

- Photodetector to convert incident light energy into electrical energy

- Electronic meter to register the output of the photodetector
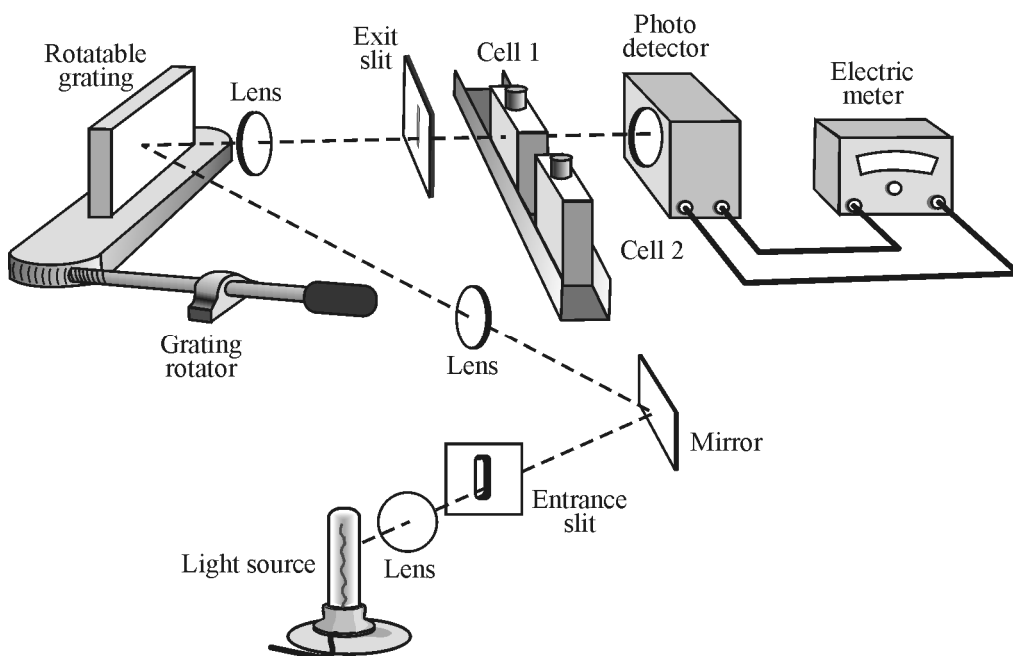
Figure 10 *Schematic diagram of a single-beam spectrophotometer*

Spectrophotometers may be divided into one-beam or two-beam instruments. The band of wavelengths of light passing through either cell depends on the dispersion of the prism or grating and on the widths of the entrance and exit slits. The narrower the slit widths, the smaller the bandwidth that reaches the absorption cells and the greater is the resolution. Quartz prisms

and other special materials can be used to extend the optical range of spectrophotometers. By such techniques, including the use of different light sources, some instruments can cover a total optical range from 200 nm (ultraviolet) to 1000 nm (infrared). A typical spectrophotometer can be a rather compact instrument as shown for the UNICO 1200 Spectrophotometer in Figure 11.

In a one-beam spectrophotometer, the reference cell is first placed in the optical path, then replaced by the sample cell. The magnitude of the electric current from the photodetector is proportional to the intensity of the reference light transmitted through the substances in the cells.

In a typical experiment, a reference cell containing solvent only is first placed between the exit slit of the monochromator and the detector. The gain of the detector amplifier is adjusted so that a full-scale (100%) reading is obtained. Generally, some light incident upon the cell is lost by reflection or by absorption in the glass walls of the reference cell. However, these losses will be the same for the *identical* cell containing the *sample* solution, which is inserted next between the slit and detector. Since the response of the photo detector is directly proportional to the light intensity, the reading now gives the percentage transmission (%*T*) of the sample solution.
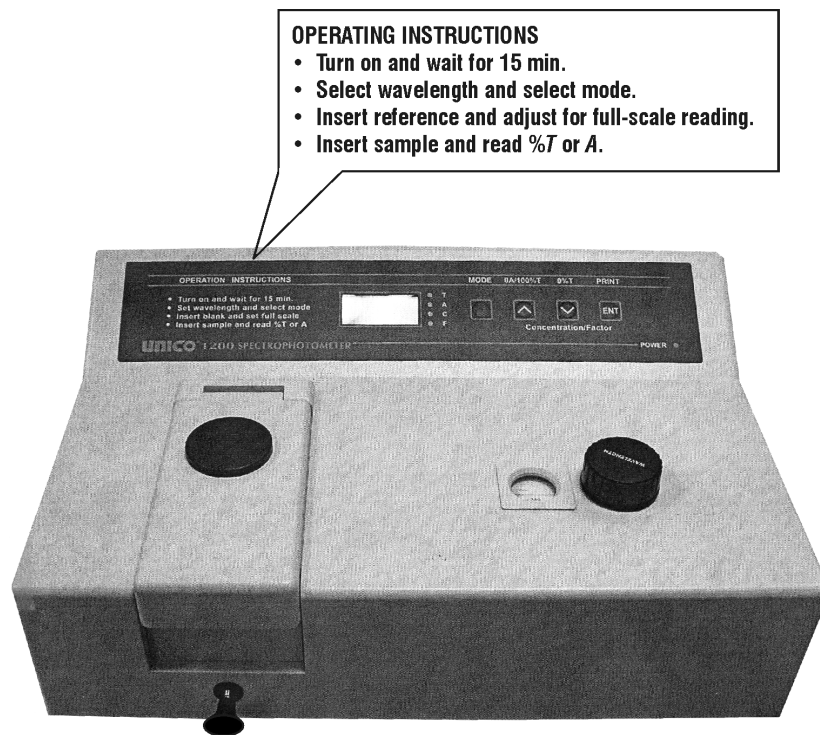

Figure 11 *A compact UNICO 1200 Spectrophotometer*

The transmittance can be measured for each new wavelength by turning the prism or grating so that light of another wavelength passes through the reference cell, adjusting the detector gain to obtain a 100% reading, and then making a reading on the sample cell. By repeating this procedure, the transmittance can be mapped over the UV, visible, and near infrared regions. Recently developed microcomputer-controlled spectrophotometers provide full spectrum analysis in seconds. For example, the Perkin-Elmer Model 1300 series is a microprocessor-controlled infrared spectrophotometer that can be used for industrial quality control, for routine

analytical chemical applications, and in a variety of laboratory teaching environments. We shall have an opportunity to use a spectrophotometer to analyze the transmission of a common dye in the laboratory part of this module. But before leaving this overview of spectra-analyzing instruments, let's take a brief look at a mass spectrometer.

Mass Spectrometer

Whereas prism and grating spectrometers are used to measure the wavelength involved in emission and absorption spectra, and a spectrophotometer measures transmission through light-absorbing substances, a *mass spectrometer* measures *masses of atoms*. Mass spectrometers are used in atomic physics, chemical analysis, geology, and medicine to identify atoms and their concentrations in given substances. A schematic diagram of a mass spectrometer is shown in Figure 12.
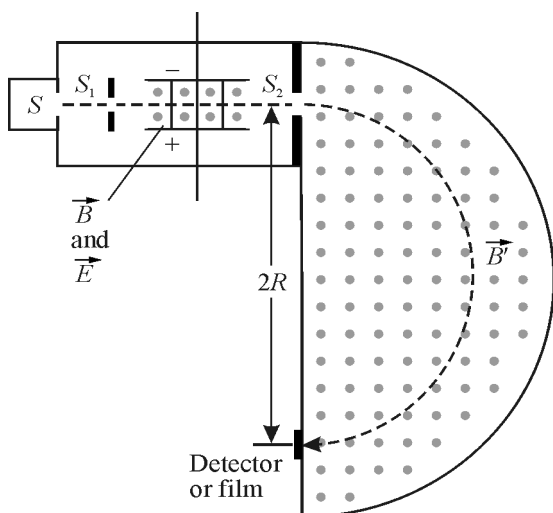

Figure 12 *Mass spectrometer*

Ions are produced by thermal or electrical energy in a source S. The ions pass through slit S_1, and enter a region where there are crossed electric fields (E) and magnetic fields (B). The electric field points vertically up between the two charged plates, from + to −. The magnetic field B points out of the paper as shown by the dots. The ions of speed υ follow a straight-line path between the two plates if the upward electric force (qE) is just balanced by the downward magnetic force ($q\upsilon B$), so that $qE = q\upsilon B$ or $\upsilon = \dfrac{E}{B}$. Thus only those ions with speed $\upsilon = \dfrac{E}{B}$ will pass undeflected, centrally, between the charged plates and emerge through slit S_2. In the region beyond S_2, only a magnetic field B' (out of the paper) exists; its action bends a positive ion in a circular path of radius R. The radius R is determined by marks that the ions leave on a film or detector, as shown. Based on the dynamics of circular movement and Newton's 2nd law of motion, one can show that the mass m of the ion undergoing circular motion is given by Equation 8.

$$m = \frac{qBB'R}{E} \tag{8}$$

where m = mass of the ion,
         q = charge carried by the ion,
         B and B' = strength of the magnetic fields,
         E = strength of the electric field, and
         R = radius of a particular ion's path.

Since all the quantities on the right side of Equation 8 are known or can be measured, the mass of the ion tracing out the circular path of radius R can be determined. Historically the masses of many atoms were measured this way and, in fact, different isotopes were discovered.

Example 4

Ramon has been directed to determine the identity of an unknown element present in a mixture containing carbon-12. Ramon sets up a mass spectrometer and fixes the values of the electric field E and the magnetic fields B and B'. The radius R traveled by the C_{12} ion is 22.4 cm while the path traveled by the unknown ion has a radius 26.2 cm. Ramon knows that C_{12} has a mass of 19.92×10^{-27} kgm. He assumes that the charge q is the same for each ion.

Solution

Ramon uses Equation 8 to set up a ratio of masses for the Carbon-12 (m_c) and the unknown element (m_x). He obtains

$$\frac{m_x}{m_c} = \frac{\dfrac{qBB'R_x}{E}}{\dfrac{qBB'R_c}{E}} = \frac{R_x}{R_c} \text{, since } q, B, B', \text{ and } E \text{ are the same and cancel.}$$

Thus, $m_x = (\dfrac{R_x}{R_c})m_c = (\dfrac{26.2 \text{ cm}}{22.4 \text{ cm}})(19.92 \times 10^{-27} \text{ kgm}) = 23.3 \times 10^{-27}$ kgm.

Using the fact that one atomic mass unit (1 amu) = 1.66×10^{-27} kgm, we have

$$m_x = \frac{23.3 \times 10^{-27} \text{ kgm}}{1.66 \times 10^{-27} \text{ kgm/amu}} = 14.0 \text{ atomic mass units.}$$

Ramon concludes that the unknown element might be an isotope of carbon, such as carbon-14, which has the same charge as carbon-12 but a mass of 14 amu rather than 12 amu.

Remote Sensing

Now that we have developed a basic understanding of how optical instruments can process radiant energy and obtain information regarding wavelength, intensity, and atomic mass, we are ready to examine the world of remote sensing. As we explained, *remote sensing* is nothing more than the science of acquiring information about the Earth's surface without actually being in contact with that surface. In general, remote sensing makes use of optical and electronic instruments to obtain and process energy *reflected, scattered,* or *emitted* by different parts of the Earth's surface. The following sketch outlines the main steps in the general process of remote sensing.

In Figure 13 the following parts of the total process are indicated.

1. The *energy source* provides the radiant energy that falls on the Earth's surface and is absorbed, reemitted, or reflected there. Such an energy source is the sun.

2. The *atmosphere* that the radiant energy must traverse as it passes from the source to the target—and back again to the sensor platform if the platform is a high-flying satellite. The traversing energy will suffer absorption and scattering for each pass through the atmosphere.

3. The *Earth's patch of surface* under study, illuminated by whatever radiation gets through the atmosphere. This surface reflects and/or reemits the incident energy. The reflected/reemitted energy now contains information characteristic of the properties of the Earth's surface (vegetation, desert, mountain, lakes, swamps, etc.).

4. A *platform with sensors* "looking down" from various altitudes—aircraft, satellites, land-based observation posts. The sensors receive the energy reflected or emitted by the Earth's patch of surface under study.

5. A *ground-based receiver* that processes the information sent to it from the sensors on the observation platform

6. A final *station dedicated to interpreting* the information processed by the ground-based receiver and presenting it in visual, digital, or electronic form so as to understand the characteristics of the Earth's surface under study.
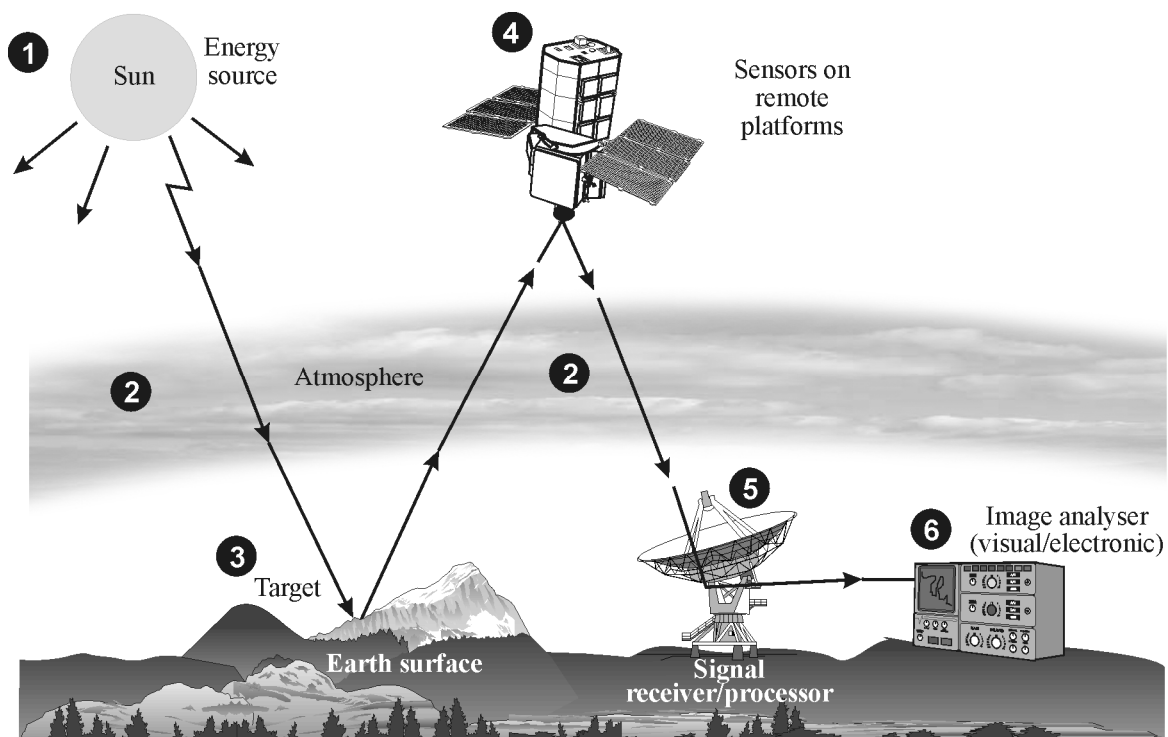

Figure 13 *The remote sensing process*

Useful parts of the EM spectrum for remote sensing

The sun provides electromagnetic energy across a broad spectrum, parts of which are useful for remote sensing. *Ultraviolet radiation*, in the wavelength range from 1 nm to 300 nm, causes rocks and minerals to fluoresce and emit visible light when irradiated. *Visible radiation*, from 400 nm to 700 nm, provides us with the visible colors we see—green for tree leaves, gray-brown for mountain ranges, and bluish-green for lakes. *Infrared radiation*—both reflected (700 nm to 3000 nm) and thermal (3000 nm to 0.1 millimeter) provides useful remote sensing information. The thermal part discloses information about the temperature of the Earth's surface, thereby providing different spectral emissions, for example, for deserts and oceans. *Microwave radiation,* recently of growing importance in remote sensing, can penetrate cloud cover, haze, dust, and even heavy rainfalls. This radiation, in the range 1 cm to 1 m, allows detection of microwave energy under a variety of inclement weather and environmental conditions.

Atmospheric windows

Gases, such as carbon dioxide, absorb electromagnetic energy strongly in different regions of the EM spectrum, so we cannot remotely sense equally across this spectrum. Instead, we must locate and take advantage of *atmospheric windows*. Figure 14 shows energy transmitted for UV, visible, IR, and microwave regions of the EM spectrum, and shows also a plot of energy versus wavelength emitted by the sun and the Earth. One can see, for example, that the atmosphere is a "window" near the visible region (0.4 µm to 0.7µm) and in the microwave region (beyond 1 mm). Note that the visible portion corresponds to both an atmospheric window and the peak energy emitted by the sun. Note also that the heat energy from the Earth matches a window around 10 µm in the thermal part of the spectrum. A close analysis of Figure 14 helps provide us with the EM wavelengths we can use effectively for remote sensing.
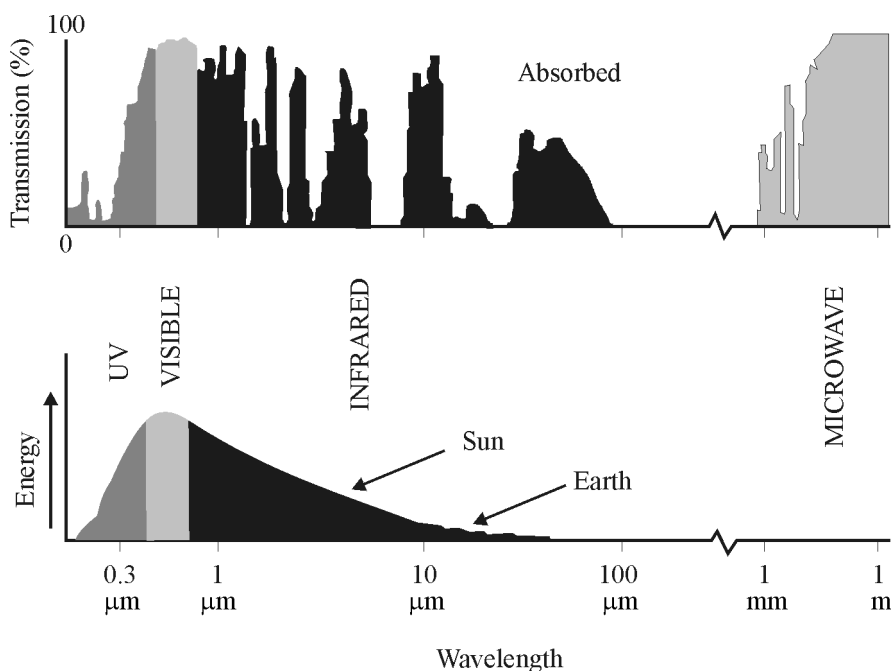

Figure 14 *Atmospheric windows from 0.1µm to 1 m (adapted from Canada Centre for Remote Sensing)*

EM Radiation Interaction
with Several Earth Targets

Once we have located the atmospheric windows and know what radiation impinges on the Earth's surface, we can determine how this radiant energy—visible and infrared—interacts with different parts of the Earth's surface. Generally the reflection of radiant energy from these Earth patches is a mixture of *specular* and *diffuse* reflection.

Let's take a look at *reflection* from *leaves* and *water*, and *thermal emission* from *city buildings* (adapted from the tutorial *Fundamentals of Remote Sensing* by the Canada Centre for Remote Sensing).

Leaves—A chemical compound in leaves called chlorophyll strongly absorbs radiation in the red (R) and blue (B) wavelengths but reflects green (G) wavelengths (Figure 15). Thus, leaves appear "greenest" in the summer, when chlorophyll content is at its maximum. In autumn, there is less chlorophyll in the leaves, so there is less absorption of red and blue and proportionately more reflection of the red wavelengths, making the leaves appear red or yellow.

The internal structure of healthy leaves acts as excellent diffuse reflectors of near-infrared wavelengths. If our eyes were sensitive to near-infrared, trees would appear extremely bright to us at these wavelengths. In fact, measuring and monitoring the near-IR reflectance is one way that scientists determine how healthy (or unhealthy) vegetation may be.
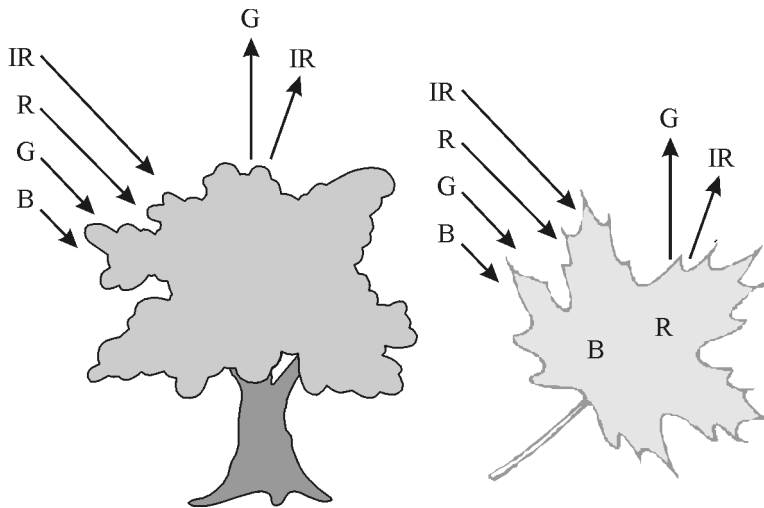

Figure 15 *Reflection from leaves*

Water—Longer wavelength visible and near infrared radiation is absorbed more by water than are shorter visible wavelengths (Figure 16). Thus water looks bright and typically blue or blue-green due to stronger reflectance at these shorter wavelengths, and looks darker if viewed at red or near infrared wavelengths. If there is suspended sediment present in the upper layers of the water body, this will allow better reflectivity and a brighter appearance of the water. The apparent color of the water will show a slight shift to longer wavelengths. Suspended sediment (S) can be easily confused with shallow (but clear) water, since these two phenomena generate similar optical effects. Chlorophyll in algae absorbs more of the blue wavelengths and reflects the green, making the water appear more green in color when algae is present. The topography

of the water surface (rough, smooth, floating materials, etc.) can also lead to complications for water-related interpretation due to potential problems of specular reflection and other influences on color and brightness.
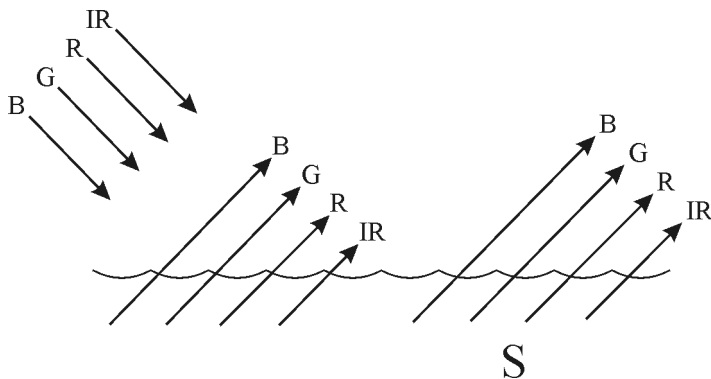

Figure 16 *Reflection from water*

Heated buildings—Detecting and monitoring heat loss from buildings is an excellent application of thermal remote sensing (Figure 17). Heating costs, especially in cold climates, can be high. Thermal imaging in both residential and urban areas allows one to identify the buildings, or parts of buildings, where heat is escaping. If heat loss is significant, those buildings can be targeted for appropriate insulation to reduce costs and energy.
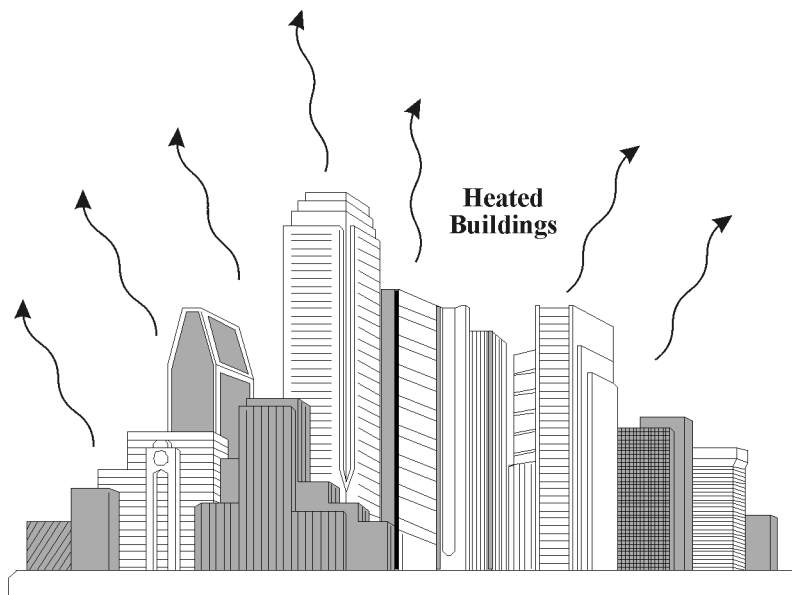
Figure 17 *Heat loss from buildings*

We can see from these examples that, depending on the complex makeup of the target being studied, and the wavelengths of radiation involved, we can observe very different responses to the mechanisms of absorption, transmission, and scattering reflection. By measuring the energy that is reflected (or emitted) by targets on the Earth's surface over a variety of different wavelengths, we can build up a *spectral response* for that object. For example, Figure 18 shows curves depicting the percent reflectance of deciduous trees (e.g., maple, birch) and coniferous

trees (e.g., pine, fir, spruce) as a function of wavelength in the visible and near infrared. Clearly, visible-region photography would not be able to distinguish between the two clusters of trees. However, in the near infrared (0.7 μm–0.9 μm) the reflectance is decidedly greater for deciduous trees than for coniferous trees, and consequently their reflected signals would be distinguishable. Thus, a remote-sensing camera, using black and white infrared film, sensitive around 0.8 μm wavelength, would discriminate well between the different trees.
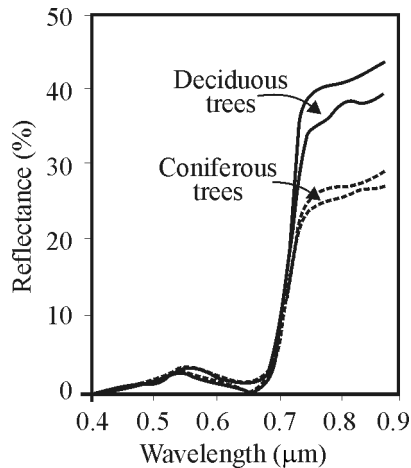

Figure 18 *Discriminating between deciduous and coniferous trees*

Passive and Active Sensing

Remote sensing systems that receive and process reflected energy from sources that emit *discontinuously* are called *passive* systems. Such systems can only "receive" energy when the source is "on." For example, a passive remote sensing system receives reflected energy from the sun only during the *day,* when the sun is shining over a given patch of the Earth's surface. At *night* time, the system is passive—inactive—since there is no reflected sunlight.

By contrast, a remote sensing system that can activate reflection from a given target, such as a radar system used by law enforcement officers, is called an *active* sensing system. Thus, if sensors on board a satellite receive reflected energy that the satellite initially directed onto the target, the system is active. Or, if the system is receiving reflected energy from a warm body, day or night, the system is active.

Since oil slicks and oil spills are environmentally damaging, their detection and clean up are of vital interest to seashore industries. Oil films on the surface of sea water reflect radiant energy in the electromagnetic spectrum from the microwave region of the ultraviolet region, enabling special sensors to detect the thickness and extent of the oil spill. Because oil differs from ocean water in refractive index, coefficient of absorption, and fluorescence, appropriate optical sensors are able to distinguish clearly between oil and water via spectral analyses. Detection of oil spills may include both passive and active sensors.

Photographic Images Versus Digital Images

As we know, photographs taken with cameras provide images generally in the wavelength range from 0.3 μm to 0.9 μm, extending a bit beyond the visible in both the ultraviolet and infrared. The well-known photographic process uses chemical reactions on the surface of light-sensitive film to detect energy variations and record, faithfully, reduced images of the target scenes in view. Such photographs, for example, are used when capturing images of land areas from aircraft. The image resolution and photographic detail depends on the complexity of the target, the wavelength, and the optical camera system.

As shown in Figure 19, a photograph of a harbor scene can be recorded and displayed in *digital* format. This is done by subdividing the photographic image into small, equally shaped square areas, referred to as *picture elements* or *pixels*. These are shown in the large rectangle to the left in Figure 19. Then, the brightness of each segment of the photograph, corresponding to a given pixel, is assigned a number value, proportional to the brightness in the real image. Thus the square to the far right of the top row of numbered squares in Figure 19 is assigned the value 0 since the corresponding bit of image is dark—or black; whereas the second square from the left, in the same row, is assigned the value 238, representing a much brighter part of the true image. In this way it is possible to convert photographic images to digital images and vice-versa. Many sensors that record radiant energy, actually record the bits of contrasting radiant energy electronically, from the beginning of the sensing process, and produce an array of numeric values in digital format. Either photographic or digital means can be used to capture images obtained by remote sensing, since they record the same information.

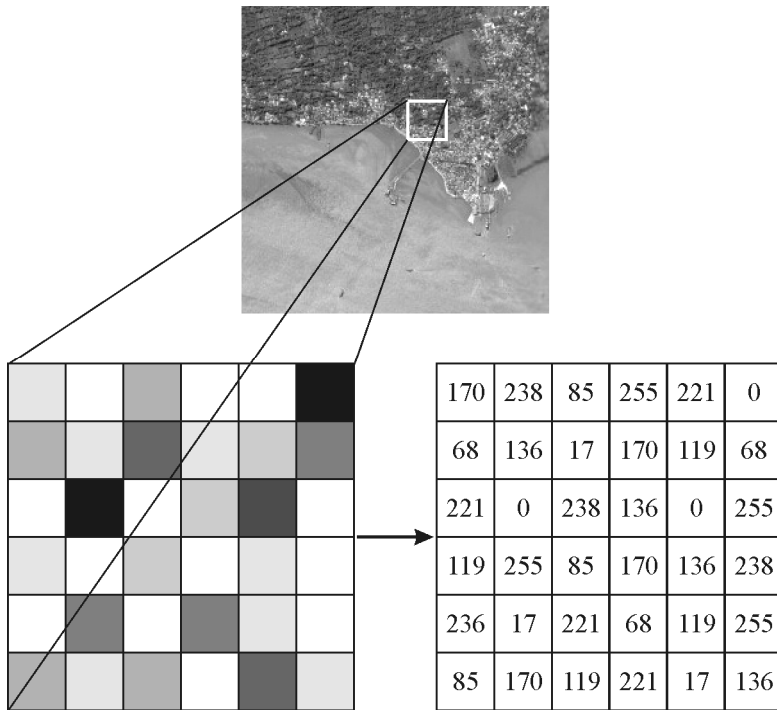| 170	238	85	255	221	0
68	136	17	170	119	68
221	0	238	136	0	255
119	255	85	170	136	238
236	17	221	68	119	255
85	170	119	221	17	136

Figure 19 *From photograph to digital image*
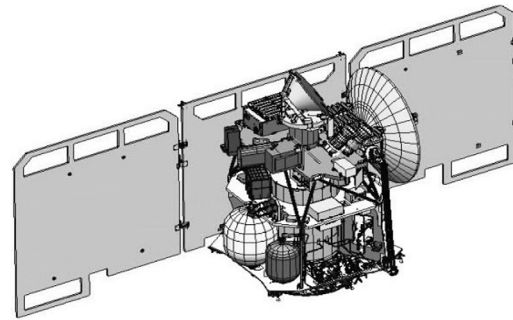
Remote Sensing Platforms

In order for a sensor to receive and process energy that is reflected or emitted from a target surface, the sensor must be situated firmly on a stable platform. This platform may be a satellite or spacecraft beyond the Earth's atmosphere, an aircraft near the Earth's surface, or a ground-based mobile unit. These are depicted in Figure 20.

b. Aircraft platform (Image shows two aircraft used by the National Oceanic and Atmospheric Administration. *Source:* U.S. Department of Commerce)

a. Ground-based platform (*Source:* Canada Centre for Remote Sensing)

c. Satellite platform (Image courtesy NASA/JPL-Caltech)

Figure 20 *Common platforms for remote sensing*

Ground-based sensors are used to record details of the Earth's surface and compare this information with that gathered from aircraft or satellites. The more proximate location of ground-based sensors enables them to better describe the target being imaged by higher-flying platforms. Similarly, aircraft located between ground-based sensors and deep-space sensors are able to collect detail-rich images and, because of their obvious mobility, can cover any portion of the Earth. Satellite platforms, because of their distant space orbits, make it possible to obtain repetitive coverage of the Earth's surface on a continuous schedule. *Geostationary* satellite orbits enable the platform to remain constantly over the *same* Earth surface location since their orbital speed matches the rotational speed of the Earth.

The various swaths of the Earth's surface traced out by satellites revolving around the earth are generally between tens and hundreds of kilometers wide. As the Earth rotates from west to east beneath the satellite, the satellite appears to shift westward and trace out a new swath with each satellite revolution. Thus the Earth's rotation and the satellite's orbital motion, working

together, allow complete coverage of the earth's surface. Of course, achievable high resolution from these altitudes is always a problem: The greater the surface area targeted the less detail that can be captured.

The target patch seen on the Earth's surface depends on the sensor's *instantaneous field of view* (IFOV). Figure 21 shows a sensor on an aircraft platform looking down on the Earth patch from a height H above the Earth, viewing an area A, based on an IFOV of θ angular degrees—the angular size of the cone. Simple geometry tells us that the average width of the patch is given by Equation 9.
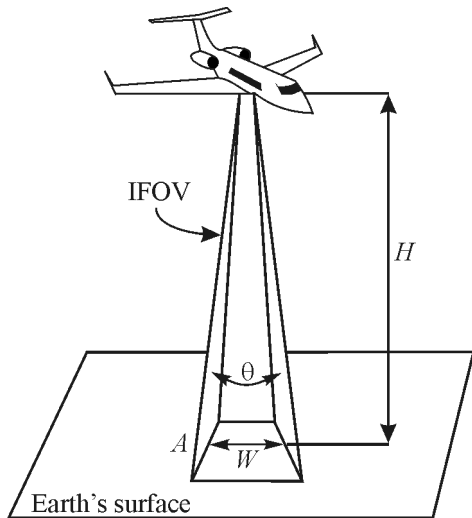
$$W = H\theta \qquad\qquad (9)$$

Figure 21 *Resolution cell*

For example, if H is 5000 feet and the angular size of the cone is 0.012 radians (about 0.69 degrees), then the "width" of the spot A on the ground would be $W = (5000)(0.012) = 60$ feet. This square of side 60 feet—or circle of diameter 60 feet—is referred to as the *resolution cell.*

For a detailed feature on the Earth to be seen, its size has to be equal to or larger than the resolution cell. Thus, a structure 100 ft by 50 ft, located on the shore of a lake would be resolved for an aircraft with cone angle near 0.7° flying at height 5000 feet. A structure 50 ft by 50 ft would not be resolved. To a first approximation, the *pixels* we discussed earlier and the *resolution cell* described here can be considered to be the same.

Example 5

If you are on a remote-sensing mission, flying in an aircraft at 3000 feet, what should the sensor IFOV (cone angle) be (in radians and degrees) if the resolution cell (a circle) has to be of diameter 100 feet?

Solution

Use Equation 9 and rearrange terms to obtain an expression for θ. Thus

$\theta = \dfrac{W}{H}$ where $W = 100$ feet and $H = 3000$ feet

$\theta = \dfrac{100}{3000} = 0.033$ radians

Since one radian equals 57.3 degrees, the IFOV in degrees is $(57.3 \times 0.033) = 1.9°$. Thus the sensors IFOV for these parameters would be 0.033 radians or 1.9°.

Satellite Remote Sensing Systems

There are many satellite systems in operation today, mostly for analyzing weather (meteorology) and Earth surface (terrain). Here we will only describe a few that are typical.

Weather satellites

The GOES System (Geostationary Operational Environmental Satellite) was designed by NASA to support NOAA (the National Oceanic and Atmospheric Administration). The many satellites in the GOES series have been used by weather forecasters for the past 35 years. They are spaced at approximately 70° longitude intervals around the Earth to provide near-global coverage. Two GOES satellites, positioned in geostationary orbits 36,000 km above the equator, together view approximately two-thirds of the Earth's surface. One is above the equator at 75°W longitude and views North and South America and most of the Atlantic Ocean. (See Figure 22.) The other, also above the equator at 135° W longitude, monitors North America and the Pacific Ocean. They are vitally important during hurricane season in tracking storms.
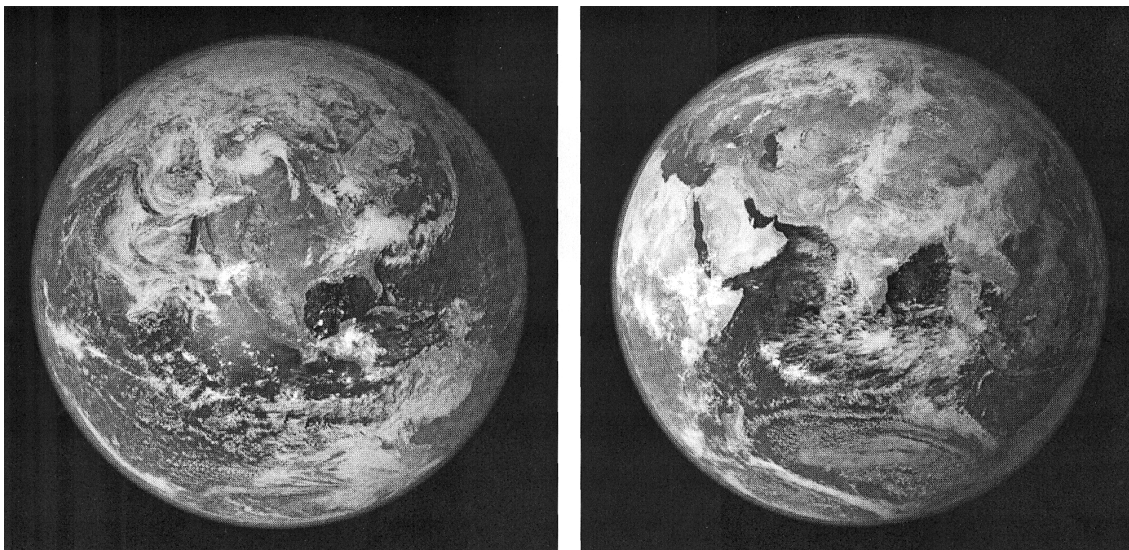

Figure 22 *View of North American, Gulf of Mexico, top of South America, and the Atlantic Ocean. Florida is clearly visible in the left photo about one inch from the right edge, midway up.*

Table 1 provides data on GOES 8, describing the five bands that cover the wavelength range from 0.52 μm (visible green) to the IR window near 10 μm, shown earlier in Figure 14. The table also provides data on the spatial resolution for each band and where each band is found useful in tracking weather.

Table 1. Characteristics of the GOES 8 Weather Satellite
(From Canada Centre for Remote Sensing)

Band	Wavelength Range (μm)	Spatial Resolution	Application
1	0.52 – 0.72 (visible)	1 km	cloud, pollution, and haze detection; severe storm identification
2	3.78 – 4.03 (shortwave IR)	4 km	identification of fog at night; discriminating water clouds and snow or ice clouds during daytime; detecting fires and volcanoes; night time determination of sea surface temperatures
3	6.47 – 7.02 (upper level water vapour)	4 km	estimating regions of mid-level moisture content and advection; tracking mid-level atmospheric motion
4	10.2 – 11.2 (longwave IR)	4 km	identifying cloud-drift winds, severe storms, and heavy rainfall
5	11.5 – 12.5 (IR window sensitive to water vapour)	4 km	identification of low-level moisture; determination of sea surface temperature; detection of airborne dust and volcanic ash

Earth surface satellites

Since the 1960s, special satellites, in addition to the weather satellites described above, have been designed specifically to view and map the Earth's surface. Such a series is the LANDSAT series (see Figure 23), launched by NASA in 1972, transferred to NOAA in 1983, and commercialized in 1985. (LANDSAT stands for "land remote-sensing satellite.") All LANDSAT satellites are placed in near-polar, sun-synchronous orbits at altitudes of 700–900 km. Sensors aboard LANDSAT satellites collect data over a 185 km wide swath, with a full scene specified as a 185 km × 185 km wide swath. Figure 22 shows a picture of a LANDSAT satellite and Table 2 depicts characteristic bands and applications for such a satellite.
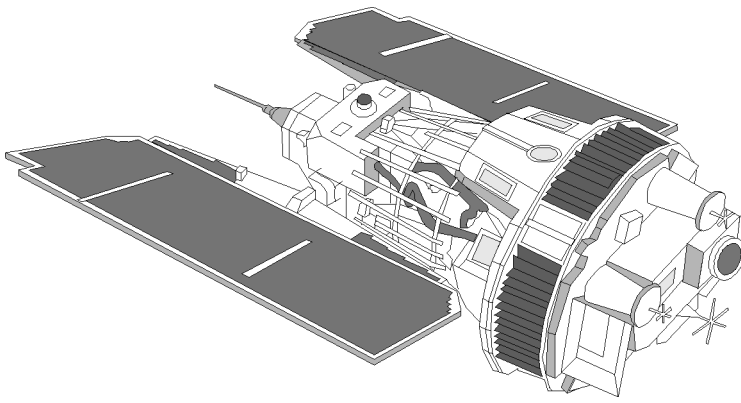
Figure 23 *A typical LANDSAT satellite*

**Table 2. Characteristics of a LANDSAT Satellite
(From Canada Centre for Remote Sensing)**

Channel	Wavelength Range (μm)	Application
TM 1	0.45 – 0.52 (blue)	soil/vegetation discrimination; bathymetry/coastal mapping; cultural/urban feature identification
TM 2	0.52 – 0.60 (green)	green vegetation mapping (measures reflectance peak); cultural/urban feature identification
TM 3	0.63 – 0.69 (red)	vegetated vs. non-vegetated and plant species discrimination (plant chlorophyll absorption); cultural/urban feature identification
TM 4	0.76 – 0.90 (near IR)	identification of plant/vegetation types, health, and biomass content; water body delineation; soil moisture
TM 5	1.55 – 1.75 (short wave IR)	sensitive to moisture in soil and vegetation; discriminating snow and cloud-covered areas
TM 6	10.4 – 12.5 (thermal IR)	vegetation stress and soil moisture discrimination related to thermal radiation; thermal mapping (urban, water)
TM 7	2.08 – 2.35 (short wave IR)	Discrimination of mineral and rock types; sensitive to vegetation moisture content

The weather and LANDSAT satellite systems are just two of many. Other satellite systems with specially dedicated sensors include the MOS (Marine Observation Satellite) and Sea-Viewing system on board the Sea Star spacecraft. There are also other systems that employ such technologies as video, FLIR (forward looking infrared), laser fluorosensor, LIDR, and RADAR. (See reference in the bibliography for the Canada Centre for Remote Sensing.)

LABORATORY

The heart of this laboratory involves the use of a spectrophotometer, such as a *Welch Chem-Anal System* or a *Unico 1200*. Depending on the spectrophotometer available in your laboratory, you should locate the operating manual and read it in order to understand how to use the instrument.

In the laboratory we outline here, we refer to a Welch Chem-Anal spectrophotometer. However, the procedure is sufficiently general to apply to any spectrophotometer.

Equipment

- Welch-Chem-Anal System (See *Welch Chem-Anal Manual* prepared by J. Zimmerman and E. Halnisch for Sargent-Welch Scientific Co.), or equivalent, such as a UNICO 1200

- Methanol (1 liter)

- Rhodamine 6G dye

- Glass cuvettes (1-cm transverse path length)

Procedure

Regardless of the spectrophotometer to be used, the essential components—whether separately spread out or neatly contained as in the UNICO 1200 (Figure 11)—are as shown in the schematic drawn below, Figure L1.
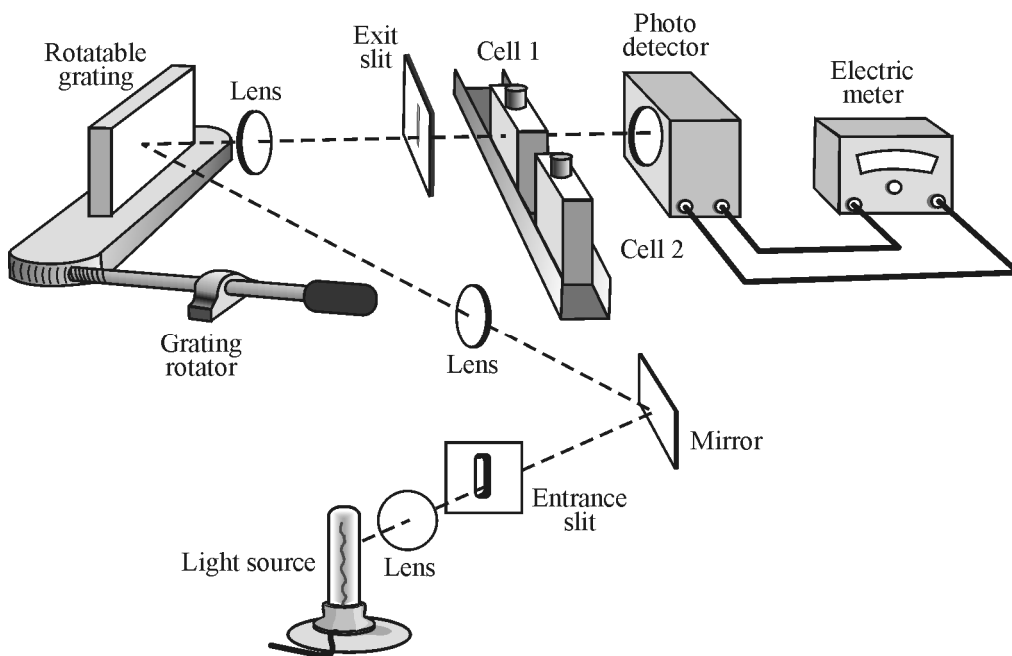

Figure L1 *Essential elements of a spectrophotometer*

The experimental arrangement is that shown in Figure L1. The monochromator (made up of entrance slit, mirror, grating, lenses, and exit slit), the sample compartment, and detector with associated electronic meter are assembled on a level optical base or are self-contained in a spectrophotometer unit.

As a quick overview of the procedure we will follow in this lab, read the following carefully.

The monochromator is set to pass a particular wavelength. The light path to the detector is blocked and the *meter* is set at 0.0 transmission with the zero adjust knob. An absorption cell containing the solvent (methanol) that was used in making the dye solution is placed in the light path. It is the *reference* sample. The detector amplifier gain is adjusted with the reference control so that the meter reads 100% transmission. A second absorption cell, the *dye sample* cell, identical to the first but containing the dye solution, is placed in the beam path and the % transmission recorded. Since the 100% transmission point was set with cell plus solvent in the beam path, the measured % transmission of the second cell represents the transmission of the dye alone. That is, the effects of reflection, absorption, and scattering at the cell walls and in the solvent have been effectively eliminated. Thus, the fraction T of the light transmitted (called the *transmittance*) is given by the usual ratio I_T/I_0, where I_T is the intensity of the transmitted beam and I_0 is the intensity of the incident beam.

With the overall procedure now in mind, you may begin the preparatory part of the lab.

1. The light source is mounted and aligned so as to provide maximum light through the monochromator, from entrance slit to exit slit. To check for maximum throughput, first turn on the photodetector and light source and allow them to warm up for 15 minutes. Then move the monochromator, sample compartment, and detector by appropriately small amounts to achieve a maximum reading on the meter. Then follow the steps below.

2. Open the sample compartment. Inside you will observe a multi-position rotary cuvette holder that is used to reproducibly position the cuvettes (absorption cells) in the beam path between the monochromtor exit slit and the detector. Each of the cuvettes can be rotated into the beam path using the knob on top of the sample compartment. The reproducibility of the positions is ensured by the use of a "detent" grove at each position. Note that if the knob is turned to the zero position, the light from the monochromator is blocked. This position is used to set the meter reading at 0.0% transmission.

3. Prepare a 10^{-4} moles/liter solution of Rhodamine 6G dye in one liter of methanol. The molecular weight of the dye is 449 g. Thus, to achieve the proper solution, dissolve $10^{-4} \times$ one molecular weight of dye in one liter of methanol solution. That means since $(10^{-4} \times 449$ g$) = 0.0449$ g or 44.9 mg, you add about 45 mg of the dye to the one liter of methanol to prepare the solution. Clean two cuvettes. CAUTION: Improper cleaning of the cuvettes (refer to the manual) or improper handling of the cuvette walls will introduce considerable error in your transmission measurements. Clean cells carefully; never use a cell with fingerprints or spilled solution on the outside. Place the rhodamine 6G solution in one cell and methanol in the other. Place the two cells into the rotary cell holder in the sample compartment. The cell containing methanol alone is the reference.

You are now ready to take your data. Proceed as follows:

a. Set the wavelength on the monochromator at 400 nm.

b. Block light path (zero position on sample compartment knob), and set 0.0% transmission with zero adjust.

c. Place reference sample (methanol) cuvette in light path and set 100.0% transmission with reference control, as read by the detector/meter combination.

d. Move the dye sample cuvette into the light path and record the transmission on the meter as %T and the absorbance as A. (Note that the meter contains **two** scales, a linear scale for %T and a logarithmic scale for absorbance A.

e. Repeat Steps a and d at wavelength intervals of 20 nm between 400 nm and 650 nm.

Note that the transmission T and absorbance A are related by Equation 10, the Lambert-Beer law.

$$\log_{10} \frac{1}{T} = A \qquad (10)$$

where T = % transmission or $\dfrac{I_{incident}}{I_{transmitted}}$, where I is beam intensity and

A is the absorbance.

For example, if the absorbance of a certain dye is found to be $A = 0.42$, the transmission T through the absorption medium is:

$$\log_{10} \frac{1}{T} = 0.42$$

$$\frac{1}{T} = 10^{0.42} = 2.63$$

$$T = \frac{1}{2.63} = 0.38 = 38\%$$

So the % transmission is 38%.

4. Plot two curves from this data, one representing the %T as a function of wavelength, the other representing the absorbance A as a function of wavelength. These two curves can be plotted on the same sheet of graph paper using two different scales on the ordinate axis.

The *molar absorptivity a,* in liters/mole-cm, is related to the *absorbance A* by Equation 11.

$$a = \frac{A}{bc} \qquad (11)$$

where a is the molar absorptivity in liters/mole-cm,
b is the cell thickness (transverse width of absorbing medium) in cm, and
c is the molar concentration, in moles/liter, of absorbing solution.

Since A can be obtained from Equation 10 with T measured, b is the known inner diameter of the identical cuvettes, and c is the molar concentration (10^{-4} moles/liter in this case), one can calculate the molar absorptivity a.

5. Using Equation 11, determine the molar absorptivity at each wavelength. Plot molar absorptivity as a function of wavelength. This is a particularly useful curve since molar

absorptivity depends on the molecular structure of the dye but is independent of cell thickness and solution concentration.

6. In order to test the Lambert-Beer law, prepare a 0.5×10^{-4} molar solution of rhodamine 6G in one liter of methanol. This means adding 22.45 mg of the dye to a liter of the methanol. Measure the absorbance of this solution at several different wavelengths such as 480 nm, 520 nm, and 560 nm. Compare these values with those obtained from the 10^{-4} molar solution. Do your results agree with those predicted by Equation 10?

(Since you have now prepared the dye with a molar concentration of 0.5×10^{-4}—one half of the dye concentration used in Step 2—what would you expect the absorbance A to do, increase or decrease?)

Note: $a = \dfrac{A}{bc} \rightarrow abc = A$ (If a decreases, so does A.)

PROBLEM EXERCISES

1. What are the five electromagnetic wavelength regions generally defined in remote sensing?

2. A crown glass prism has a base of 6 cm. From dispersion tables of index of refraction n versus wavelength λ, one finds that $n = 1.5230$ at $\lambda = 589.2$ nanometers and that $n = 1.5205$ at $\lambda = 656.3$ nanometers. For use of this prism in a midrange near 625 nanometers, determine (a) the prism dispersion D, (b) the chromatic resolving power R, and (c) the minimum resolvable wavelength $(\Delta\lambda)_{min}$.

3. You are given a transmission grating marked "9000 lines/cm." At what angle θ does a normally incident HeNe laser of wavelength 632.8 nm diffract in first order?

4. Determine the linear dispersion $\dfrac{\Delta\ell}{\Delta\lambda}$ for a grating spectrometer whose grating is lined at 5000 lines/cm and whose spectrometer telescope has a focal length 30 cm. Do this for second order, near a diffracting angle of 60°. Give your final answer for $\dfrac{\Delta\ell}{\Delta\lambda}$ in millimeters per angstrom (mm/A°).

5. In a mass spectrometer measurement designed to determine the mass of an unknown ion, one finds that the radius of curvature of a known (reference) ion is 24.6 cm while that of an unknown ion is 28.8 cm. If the measurements for each were taken with the identical electric field E and identical magnetic fields B and B', and if the charge on each ion is the same, what is the mass of the unknown ion if the mass of the known ion is near 20×10^{-27} kgm?

6. Identify the six main parts in the remote sensing process from the radiant energy source to the analysis of the emitted or reflected energy from the Earth's surface.

7. Determine the wavelength regions in the range from 0.3×10^{-6} m to 1.0 m (see Figure 14) where there exists atmospheric windows with a transmission of 50% or greater.

8. You are a member of a remote-sensing team flying at an altitude of 3500 feet over a heavily forested area of deciduous and coniferous trees. Your sensor has an IFOV of

about 0.75° and detects sunlight reflected from a circular patch of the forest area. What is the diameter of the circular patch?

9. A GOES-8 satellite is used to detect cloud formation, haze, and severe storms. What wavelength range and spatial resolution would work for this sensing task?

10. A LANDSAT series satellite is to be used to study and identify plant and vegetation types, health and biomass content, water body delineation, and soil moisture. What wavelength range of the LANDSAT satellite would be appropriate for this task? Is this an example of active or passive sensing—or both?

11. A spectrophotometer indicates that the % transmission T of a light source at $\lambda = 555$ nm is 45%. What is the absorbance A of light through a one-cm cell of the absorbing liquid? (Use the Lambert-Beer law.)

12. The defining equation for *molar absorptivity a,* a constant for any given liquid substance, is $a = \dfrac{A}{bc}$, where A = absorbance, b = distance through absorption medium, and c = molar concentration. What is the molar absorptivity for a solution of molar concentration 0.5×10^{-4}, absorption length of 1 cm, and absorbance A of 0.42?

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