## CHAPTER THREE

# Photographic Sensors

## 3.1. Introduction

The word *photography* was coined in France in the mid-1800s, when it was fashionable to use Greek and Latin words to name new scientific discoveries. The word *photography* means "to write with light"—a literal description of what the newly invented camera could do. Today our meaning is often expanded to include radiation just outside the visible spectrum, in the ultraviolet and near infrared regions.

Although the status of photography is challenged by continuing innovations in digital imaging technology, photography remains the most practical, inexpensive, and widely used means of remote sensing. Further, the basic optical principals used for photography are also employed in optical systems of nonphotographic sensors, and we often use photographic film to record images generated by nonphotographic sensors. Therefore, knowledge of photography forms a central core for understanding the field of remote sensing.

The formation of images by refraction of light is a surprisingly old practice. In antiquity, Greek and Arab scholars knew that images could be formed as light passed through a pinhole opening in a dark enclosure. Refraction of light at the tiny opening bends light rays to form an inverted image in a manner analogous to the effect of a simple lens. In medieval Europe, a device known as the *camera obscura* ("dark chamber") employed this principle to project an image onto a screen as an aid for artists, who could then trace the outline of the image as the foundation for more elaborate drawings or paintings. During the Renaissance, the addition of a simple convex lens improved the camera obscura, although there was still no convenient means of recording the image formed on the screen. Later, with the development of photographic emulsions (described below) as a means of making a detailed record of the image, the *camera obscura* began its evolution toward the everyday cameras that we know today, which in turn are models for the more complex cameras used for aerial survey.

Despite the current availability of more sophisticated imaging systems, aerial photography still remains the most accessible and versatile form of remote sensing imagery. Routine use of aerial photography has incalculable value throughout the world as a major source of information concerning the landscape and as the primary means of producing modern topographic maps. Its economic contributions to surveying of the earth and effective planning are considerable, and it is clear that aerial photography will remain as a primary source of remote sensing imagery for many years to come.

## 3.2. The Aerial Camera

In their most basic elements, aerial cameras are similar to the simple handheld cameras we all have used. Both share the four main components of all cameras: (1) a lens to focus light on the film, (2) a light-sensitive film to record the image, (3) a shutter that controls entry of light into the camera, and (4) the camera body, a light-tight enclosure that holds the film, lens, and shutter in their correct positions.

In addition, aerial cameras include three other elements not usually encountered in our personal experiences with photography: the film magazine, the drive mechanism, and the lens cone (Figure 3.1).

### *The Lens*

The *lens* gathers reflected light and focuses it on the film. In its simplest form, a lens is a glass disk carefully ground into a shape with nonparallel curved surfaces (Figure 3.2). The change in optical densities as light rays pass from the atmosphere to the lens and back to the atmosphere causes refraction of light rays; the sizes, shapes, arrangements, and compositions of lenses are carefully designed to control this bending of light rays to maintain color balance and to minimize optical distortions. Optical characteristics of lenses are determined largely by the refractive index of the glass (Chapter 2), and the degree of curvature present in the lens surface. The quality of a lens is determined by the quality of its glass, the precision with which that glass is shaped, and the accuracy with which it is positioned within a camera. Imperfections in lens shape contribute to *spherical aberration,* a source of error that distorts images and causes loss of image clarity. For modern aerial photography, spherical aberration is usually not a severe problem because most modern aerial cameras use lenses of very high quality.

Figure 3.2 shows the simplest of all lenses: a simple positive lens. Such a lens is formed from a glass disk with equal curvature on both sides; light rays are refracted at both edges to form an

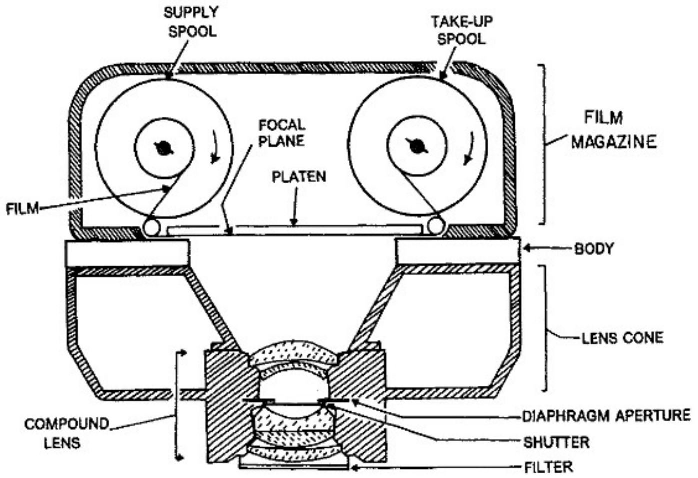


**FIGURE 3.1.** Schematic diagram of an aerial camera, cross-sectional view. Labeled items are discussed in text.

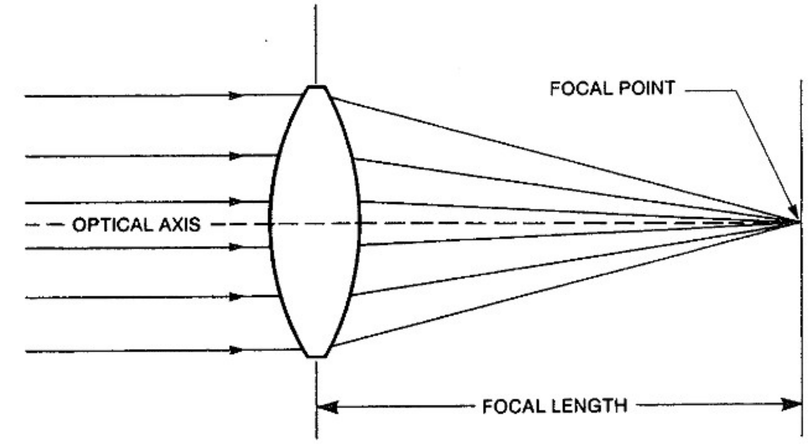


**FIGURE 3.2.** Simple lens.

image. Most aerial cameras use *compound lenses,* formed from many separate lenses of varied sizes, shapes, and properties. These many components are designed to correct for the errors that may be present in any single component, so the whole unit is much more accurate than any single element. For present purposes, consideration of a simple lens will be sufficient to define the most important features of lenses, even though a simple lens differs from those actually used in modern aerial cameras.

The *optical axis* joins the centers of curvature of the two sides of the lens. Although refraction occurs throughout a lens, a plane passing through the center of the lens, known as the *image principal plane,* is considered to be the center of refraction within the lens (Figure 3.3). The image principal plane intersects the optical axis at the *nodal point.*

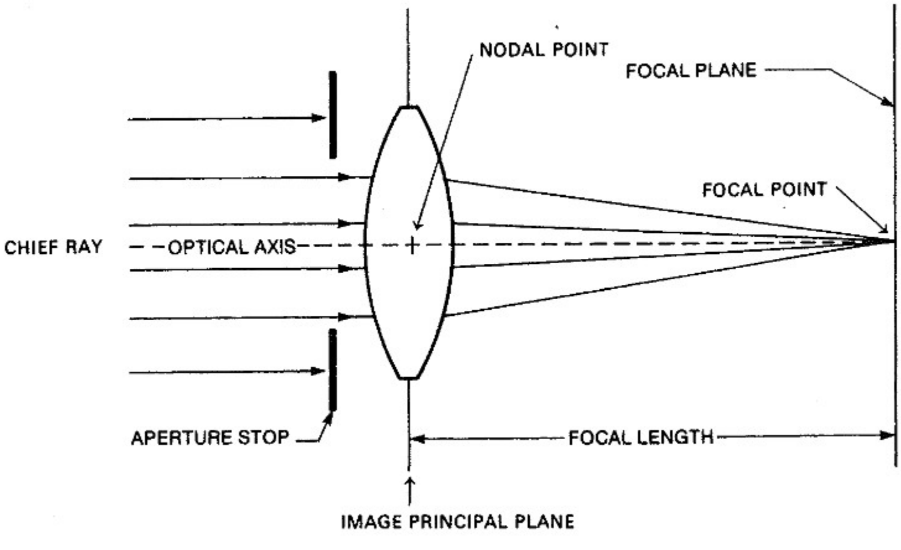


**FIGURE 3.3.** Cross-sectional view of an image formed by a simple lens.

Parallel light rays reflected from an object at a great distance (at an "infinite" distance) pass through the lens and are brought to focus at the principal *focal point,* the point at which the lens forms an image of the distant object. The chief ray passes through the nodal point without changing direction; all other rays are bent by the lens. A plane passing through the focal point parallel to the image principal plane is known as the *focal plane.* For handheld cameras, the distance from the lens to the object is important because the image is brought into focus at distances that increase as the object is positioned closer to the lens. For such cameras, it is important to use lenses that can be adjusted to bring each object to a correct focus as the distance from the camera to the object changes. For aerial cameras, the scene to be photographed is always at such large distances that the focus can be fixed at infinity, with no need to change the focus of the lens.

For a simple positive lens, the focal length is defined as the distance from the center of the lens to the focal point, usually measured in inches or millimeters. (For a compound lens, the definition is more complex.) For a given lens, the focal length is not identical for all wavelengths. Blue light is brought to a focal point at a shorter distance than are red or infrared wavelengths (Figure 3.4). This effect is the source of *chromatic aberration.* Unless corrected by lens design, chromatic aberration would cause the individual colors of an image to be out of focus in the photograph. Chromatic aberration is corrected in high-quality aerial cameras to assure that the radiation used to form the image is brought to a common focal point.

The field of view of a lens can be controlled by a *field stop,* a mask positioned just in front of the focal plane. An *aperture stop* is usually positioned near the center of a compound lens; it consists of a mask with a circular opening of adjustable diameter (Figure 3.5). An aperture stop can control the intensity of light at the focal plane, but does not influence the field of view or the size of the image. Manipulation of the aperture stop controls only the brightness of the image without changing its size. Usually aperture size is measured as the diameter of the adjustable opening that admits light to the camera.

*Relative aperture* is defined as

$$f = \text{Focal length / aperture size} \qquad \text{(Eq. 3.1)}$$

where focal length and aperture are measured in the same units of length, and $f$ is the *f number,* the relative aperture. A large $f$ number means that the aperture opening is small relative to focal length; a small $f$ number means that the opening is large relative to focal length.

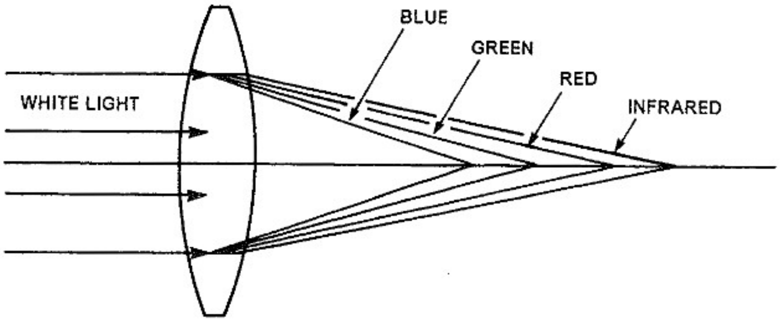


**FIGURE 3.4.** Chromatic aberration. Energy of differing wavelengths is brought to a focus at varying distances from the lens. More complex lenses are corrected to bring all wavelengths to a common focal point.

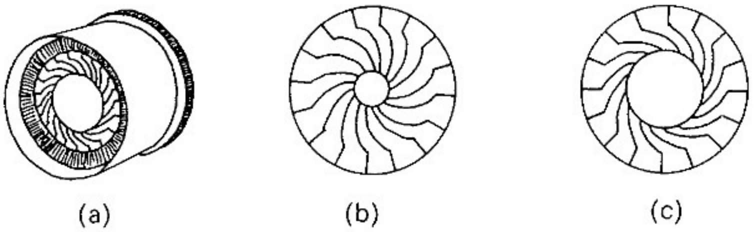


**FIGURE 3.5.** Diaphragm aperture stop. (*a*) Perspective view. (*b*) Narrow aperture. (*c*) Wide aperture.

Why use *f* numbers rather than direct measurements of aperture? One reason is that standardization of aperture with respect to focal length permits specification of aperture sizes using a value that is independent of camera size. Specification of an aperture as "23 mm" has no practical meaning unless we also know the size (focal length) of the camera. Specification of an aperture as "*f* 4" has meaning for cameras of all sizes; we know that it is one-fourth of the focal length for any size camera.

The standard sequence of apertures is: *f* 1, *f* 1.4, *f* 2, *f* 2.8, *f* 4, *f* 5.6, *f* 8, *f* 11, *f* 16, *f* 22, *f* 32, *f* 64, . . . This sequence is designed to change the amount of light by a factor of two as the *f*-stop is changed by one position. For example, a change from *f* 2 to *f* 2.8 halves the amount of light entering the camera; a change from *f* 11 to *f* 8 doubles the amount of light. A given lens, of course, is capable of using only a portion of the range of apertures mentioned above.

Lenses for aerial cameras typically have rather wide fields of view. As a result, light reaching the focal plane from the edges of the field of view is typically dimmer than light reflected from object positioned near the center of the field of view. This effect creates a dark rim around the center of the aerial photograph—an effect known as *vignetting.* It is possible to employ an *antivignetting filter,* darker at the center and clearer at the periphery, which can be partially effective in evening brightnesses across the photograph.

### *The Shutter*

The *shutter* controls the length of time that the film is exposed to light. The simplest shutters are often metal blades positioned between elements of the lens, forming "intralens," or "between-the-lens," shutters. An alternative form of shutter is the focal plane shutter, consisting of a metal or fabric curtain positioned just in front of the film, near the focal plane. The curtain is constructed with a number of slits; the choice of shutter speed by the operator selects the opening that produces the desired exposure. Although some aerial cameras use focal plane shutters, the between-the-lens shutter is preferred for most aerial cameras. The between-the-lens shutter subjects the entire negative to illumination simultaneously, and presents a clearly defined perspective that permits use of the image negative as the basis for precise measurements.

### *The Film Magazine*

The *film magazine* (Figure 3.1) is a light-tight container that holds the supply of film. The magazine usually includes a supply spool, holding perhaps several hundred feet of unexposed aerial film, and a take-up spool to accept exposed film.

### *The Lens Cone*

The *lens cone* (Figure 3.1) supports the lens and filters and holds them in their correct positions in relation to the film. The lens cone is usually detachable, to permit use of different lenses with the same camera body. The camera manufacturer carefully aligns the lens with the other components of the camera to assure geometric accuracy of photographs. Common focal lengths for typical aerial cameras are 150 mm (about 6 in.), 300 mm (about 12 in.), and 450 mm (about 18 in.). Slater (1975) lists characteristics (including focal lengths and apertures) for a number of specific models of aerial cameras.

### *The Drive Mechanism*

The *drive mechanism* advances the film after each exposure, using electric motors activated in coordination with the shutter and the motion of the plane. At the time of exposure, it is important that the film lie flat in the camera's focal plane. This function is performed by the *platen,* which for simple handheld cameras is a small, spring-mounted, metal plate positioned to hold the film flat at the instant of exposure. Because of the difficulty of holding large sheets of film flat, aerial cameras use special platens. A *vacuum platen* consists of a flat plate positioned at the focal plane; a vacuum pump draws air through small holes in the plate to hold the film flat and stationary during exposure. The vacuum sucks the film flat against the platen to prevent bending of the film or formation of bubbles of air as the film is positioned in the focal plane. The vacuum is released after exposure to allow the film to advance for the next exposure, then is applied again as the next frame is ready for exposure.

High-quality aerial cameras usually include a capability known as *image motion compensation* (or *forward motion compensation*), achieved by a mechanism that moves the film platen (or other components of the camera's optical system) during exposure at a speed and in a direction that compensates for the apparent motion of the image in the focal plane. As outlined in Section 3.4, high-resolution aerial films will have slower film speeds (i.e., will be less sensitive to light), so they will require slower shutter speeds, thus subjecting the image to blur when the aircraft is operated at relatively low altitudes. Image motion compensation permits the photographer to use a slower speed film than otherwise would be practical, and therefore to acquire higher spatial resolution images at lower altitudes (where image motion is fastest) or at lower light levels than would otherwise be feasible.

## 3.3. Kinds of Aerial Cameras

Most civilian aerial photography has been acquired using *metric cameras* (sometimes called *cartographic cameras*) (Figure 3.1). These are aerial cameras designed to provide high-quality images with a minimum of optical and geometric error. Metric cameras used for professional work have been calibrated at special laboratories operated by the manufacturer or by governmental agencies. During calibration, each camera is used to photograph a target image having features positioned with great accuracy. Then precise measurements are made of focal length, flatness of the focal plane, and other variables. Such precise knowledge of the internal geometry of a camera permits photogrammetrists to make accurate measurements from photographs.

Other kinds of aerial cameras are less frequently used for routine photography, but may have uses for special applications. *Reconnaissance cameras* have been designed chiefly for military use. For such applications, geometric accuracy may be less important than the ability to take photographs at high air speed, at low altitude, or under unfavorable light conditions. As a result, photographs from reconnaissance cameras do not have the geometric accuracy expected from those taken by metric cameras.

*Strip cameras* acquire images by moving film past a fixed slit that serves as a form of shutter (Figure 3.6). The speed of film movement as it passes the slit is coordinated with the speed and altitude of the aircraft to provide proper exposure. The image is a long continuous strip of imagery without the individual frames formed by conventional cameras. Strip cameras are capable of acquiring high-quality images from planes flying at high speed and low altitudes—optical conditions that are so extreme that conventional cameras often cannot provide the fast shutter speeds necessary to acquire sharp images.

*Panoramic cameras* (Figure 3.6) are designed to record a very wide field of view. Usually, a lens with a narrow field of view scans across a wide strip of land, so an image is formed by the side-to-side motion of the lens as the aircraft moves forward. Photographs from panoramic cameras show a long narrow strip of terrain that extends perpendicular to the flight track from horizon to horizon. Because of the forward motion of the aircraft during the side-to-side scan of the lens, panoramic photographs have serious geometric distortions that require correction before they can be used as the basis for measurements. Panoramic aerial photographs are useful because of the large areas they represent, but only the central portions are suitable for detailed interpretation because of the large variations in scale and detail present near the outside edges of the images.

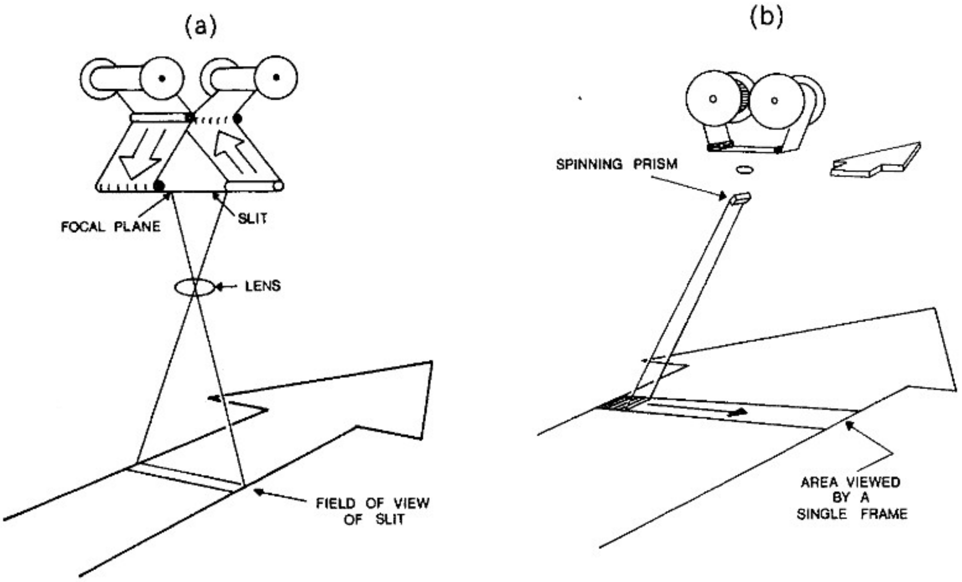


**FIGURE 3.6.** (*a*) Strip camera and (*b*) panoramic camera.

## 3.4. Black-and-White Aerial Films

Today the field of remote sensing encompasses a wide variety of sensors, both photographic and nonphotographic. Yet we have only one practical medium for recording images on paper or film: the photographic emulsion. Therefore, even if we do not use a camera to record an image, we must still use photographic film to prepare film or paper copies of that image. Knowledge of the qualities and limitations of photographic film, therefore, is central to understanding the field of remote sensing.

In the late 1700s and early 1800s a number of amateur scientists experimented with light-sensitive (*photosensitive*) chemicals. For example, silver nitrate ($AgNO_3$), familiar to high school chemistry students, darkens when exposed to sunlight; therefore, a glass or metal plate coated with silver nitrate formed the basis for recording a crude image. Those areas on the plate where the light is brightest became dark; those where the light is dim remained light in tone.

Joseph Nicephone Niepce (1765–1833), a French chemist, is one of the many who experimented with such chemicals. He is often assigned credit for devising the first negative image (1826). Niepce worked with Louis Daguerre (1789–1851), a French scientist and artist, to design a silver-coated metal plate treated with iodine vapor. Their invention was the first practical means of recording projected images. Their experiments were conducted over many years; by tradition, the year that Daguerre ceded rights to their invention to the French Academy of Sciences (1839) is given as the birthdate of photography.

*Daguerrotypes,* an early name for photographic images made using Daguerre's method, were used for many years, with many modifications. Many features of early photography differ greatly from modern equipment and practice, and were clearly impractical for routine aerial photography. In the 1800s equipment was large, heavy, and cumbersome. Exposure times were long, cameras required bright light, and images were recorded on metal or glass plates, which were heavy, fragile, and awkward. Nonetheless, many aerial photographs were taken in the early days of photography, mainly by using balloons or large kites as a means of elevating the camera. Of course, such photographs were primarily curiosities rather than scientific tools because of the difficulty of controlling the orientation of the camera. Furthermore, each photographer tended to have tailor-made equipment; photographers often prepared their own chemicals and used individually formulated emulsions. The lack of standardization of equipment, materials, and practice meant that even the fundamentals of photographic practice were as much an art as a science.

The more compact photographic equipment required for modern aerial photography was made possible by developments started by George Eastman (1854–1932), who invented roll film and improved and standardized methods of photographic processing. His invention of the Kodak camera in 1888, and formation of the Eastman Kodak Company in 1892, popularized the practice of photography by mass production of standardized photographic products. Widening the scope of photography greatly increased the number of people knowledgeable about photography, standardized photographic practice, and decreased the cost of photographic materials. In brief, his work created the environment in which modern aerial survey could develop and grow into its present form.

Initially, photographic films were sensitive primarily to portions of the visible spectrum, and could portray only those brightnesses in a single broad region of the spectrum. In contrast, modern photographic films can be designed to be sensitive to nonvisible portions of the spectrum, and can represent reflectances in much more specific spectral regions. Therefore, the photographer has a choice of films that can extend his or her reach beyond the visible spectrum.

### *Major Components*

Aerial films have essentially the same structure as photographic films used in handheld cameras. The film *base,* or *support,* is usually a thin (40 to 100 μm), flexible, transparent material that holds a light-sensitive coating. In the early days of photography, the support was often formed from metal or glass plates, but today such materials are inconvenient for everyday use. Modern films have bases of polyester film. These materials are useful because they can be fabricated into thin, lightweight, flexible strips that are strong enough to withstand the forceful motions of winding and unwinding as film is moved within the camera.

The base must be able to resist changes in size caused by variation in temperature and humidity. Photogrammetrists measure distances on images so precisely that even small differences in image size due to shrinking or expanding of the base can introduce significant errors. Therefore, glass plates are still used for images that are to be used with some photogrammetric instruments because they are insensitive to variations in temperature and humidity.

The base is coated with a light-sensitive coating, the *photographic emulsion* (Figure 3.7). Photosensitive coatings used in the early stages of photography were formed from silver nitrate (metallic silver dissolved in nitric acid). When a surface coated with silver nitrate is exposed to light, the silver nitrate darkens as the action of light changes it to metallic silver. The darkening effect increases as the light becomes more intense or as the length of exposure is increased. This effect provided a crude means of recording the image of a scene, but a number of practical problems (including the long exposures required to darken the coating) provided incentives to develop improved photosensitive coatings.

Modern emulsions consist of extremely small crystals of silver halide (typically, silver bromide [95%] and silver iodide [5%]) suspended in a gelatin matrix (possibly 5 μm thick). These crystals form the light-sensitive portion of modern films, just as silver nitrate was the light-sensitive agent in the early days of photography. Although the gelatin that holds the grains is ostensibly a mundane substance, it possesses several important characteristics. Silver halide crystals are insoluble and have other physical characteristics that prevent them from adhering directly to the base. Gelatin holds the crystals in suspension, permitting the manufacturer to spread them evenly on the base. Furthermore, gelatin is transparent, porous (to allow photographic chemicals to contact the crystals), and absorbs halogen gases released when light strikes the emulsion.

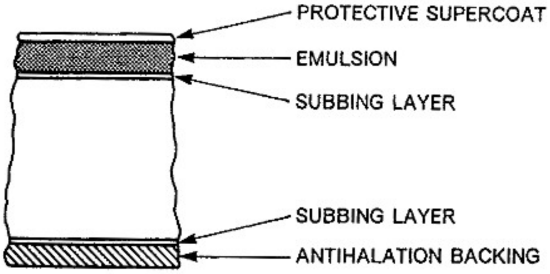


**FIGURE 3.7.** Schematic cross-sectional view of black-and-white photographic film.

Physical characteristics of the silver halide crystals assume some importance. They are extremely small, irregular in shape, with many sharp edges—shapes that favor interception of photons that pass into the emulsion. The finer the size of the grains, the finer the detail that can be recorded. Coarser grains can record less detail, but produce a film with greater sensitivity to light. Thus the spatial resolution of a film is inversely related to its speed; as we increase the size of crystals to improve the film's sensitivity to light, the finest level of detail that the emulsion can record becomes coarser. Alternatively, if we design a film with very fine grains to record fine detail, the emulsion exhibits decreased sensitivity—we must have brighter light or use longer exposures.

Recent research by the Eastman Kodak Company has produced film emulsions with grains that are flat in shape. These new grains have essentially the same volume as those in older emulsions, but their surface area is greatly increased. The flat grains, oriented parallel to the film surface, expose large surface areas to the light, thereby increasing the speed of the film without decreasing the resolution of the film. At present that type of film has been developed and marketed for popular photography (color prints only) rather than for aerial survey.

The film emulsion is coated with a thin layer of clear gelatin—the *protective supercoat*—designed to shield the emulsion from scratches during handling. Despite the presence of the supercoat, the emulsion is still vulnerable to damage from dust and from moisture and oil from handling with bare hands. As a result, analysts and interpreters should always wear cotton gloves when handling film or should protect film with transparent plastic sleeves.

Below the emulsion is a *subbing layer,* designed to ensure that the emulsion adheres to the base. On the reverse side of the base is an *antihalation* backing. This backing absorbs light that passes through the emulsion and the base, to prevent reflection back to the emulsion. In the absence of such a backing, the images of bright objects will be surrounded by halos caused by these reflections. The backing also acts as an anticurl agent, to counteract the curling effect of the emulsion that coats the upper side of the film.

When the shutter opens, it allows light to enter and strike the emulsion. The silver halide crystals are so small that even a small area of the film contains many thousands of crystals. When light strikes a crystal, it changes a very small portion of the crystal (perhaps only a single molecule) to metallic silver. The more intense the light striking a portion of the film, the greater the number of crystals affected. Thus the pattern of crystals influenced by light forms a record of patterns of light reflected from the scene. If it were possible to examine the exposed film without again subjecting it to the effects of light, it would appear no different than before exposure because of the extremely subtle effect of light upon the emulsion. At this point the image is recorded only as a *latent image;* processing is required to reveal this image.

*Development* is the process of bathing the exposed film in an alkaline chemical, the *developer,* that reduces the silver halide grains that have been exposed to light (Figure 3.8). Crystals in the latent image that were altered minimally are now completely changed to metallic silver in a process that in effect amplifies the pattern recorded by the latent image. In the latent image only a tiny portion of each grain has been altered by the effect of light; after development, each grain exposed to light is changed entirely to metallic silver. The developer acts most rapidly on those grains that have been exposed to light, so those areas that were exposed to the most intense light have the greatest density of metallic silver in the final image. Application of an acidic *stop bath* allows exact control of the time the film is in contact with the developer by counteracting the chemical effect of the alkaline developer. Next a *fixer* is applied to dissolve, then remove, unex-

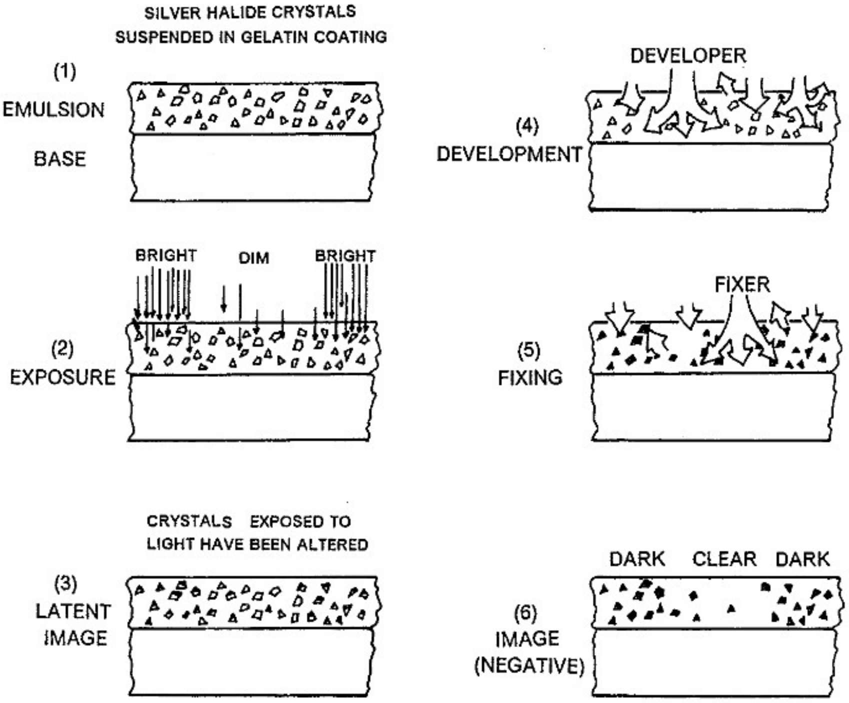


**FIGURE 3.8.** Schematic representation of processing of black-and-white photographic film. (1) Basic structure of the film as seen in cross section; photosensitive chemicals are suspended in a gelatin coating on the film base. (2) During exposure, light strikes the emulsion at varied intensities, depending upon the brightness levels in the scene. (3) Light creates a chemical reaction in the photosensitive chemicals that changes only a few molecules of each grain, creating the latent image. (4) During development, the emulsion is bathed in an alkaline chemical that changes to metallic silver all grains modified in step (3); not shown here is the addition of an acidic chemical, the stop bath, that stops the action of the developer. (5) During fixing, unexposed grains are removed from the emulsion, leaving only those that had been exposed to light in (2). (6) The final image is a negative; those areas exposed to the most intense light in (2) are darkest; those exposed to dim light are clear.

posed silver halide grains. If the fixer were not used, these unexposed grains would darken when the film was next exposed to daylight.

After development and fixing, the resulting image is a negative representation of the scene, because those areas that were brightest in the scene are represented by the greatest concentrations of metallic silver, which appears dark on the processed image (Figure 3.9). Thus, in the negative, brightnesses are reversed from their original values in the scene.

*Film speed* is a measure of the sensitivity of an emulsion to light. A fast film requires relatively low intensity of light for proper exposure; a slow film requires more light, meaning that the aperture must be opened wider or that a longer exposure time must be used. As mentioned previously, film speed is directly related to grain size, and is inversely related to the ability of the film to record fine detail. Amateur photographers are familiar with the Deutsches Institut für Normung (DIN) and American Standards Association (ASA) ratings for assessing the speeds of films for handheld cameras. The analogous scales for aerial films include the aerial film speed (AFS) and the aerial exposure index (AEI).

*Contrast* indicates the range of gray tones recorded by a film. *High contrast* means that the film records the scene largely in blacks and whites, with few intermediate gray tones. *Low con-*

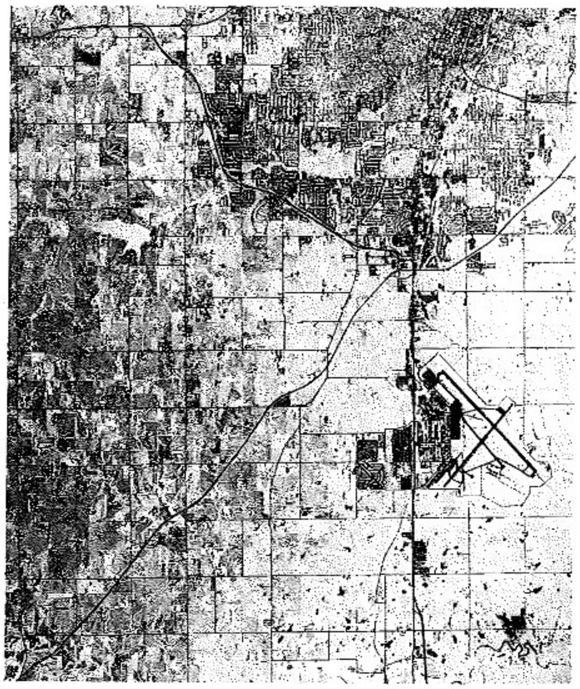


**FIGURE 3.9.** Black-and-white negative image.

*trast* indicates a representation largely in grays, with few really dark or really bright tones. Often the interpreter needs information about the intermediate brightnesses in a film, so for aerial photography low-contrast representation may be desirable. Fine-grained emulsions tend to have low contrast, so slower films tend to have higher spatial resolution and lower contrast than do the coarser-grained fast films. Emulsions on photographic papers typically have higher contrast than emulsions on films, so interpreters often prefer to use film transparencies if they are available.

*Spectral sensitivity* records the spectral region to which a film is sensitive (Figure 3.10). The spectral sensitivity curve for Kodak Tri-X Aerographic Film 2403 shows typical features of black-and-white films (Figure 3.10a). It is sensitive throughout the visible spectrum, but is also sensitive to ultraviolet radiation. Because of the scattering of these shorter (ultraviolet and blue) wavelengths, filters are often used with black-and-white aerial films to screen out blue light (Figure 3.11). This film presents a black-and-white representation of a scene (Figure 3.12a) that is essentially in accord with our view of the scene as we see it directly with our own eyes. This is because the Tri-X film is an example of a *panchromatic* film, an emulsion that is sensitive to radiation throughout the visible spectrum, much the same as the human visual system is sensitive throughout the visible spectrum. The term *orthochromatic* designates films with preferred sensitivity in the blue and green, usually with peak sensitivity in the green.

Figure 3.10 also shows the spectral sensitivity curve for Kodak Infrared Aerographic Film 2424, a black-and-white infrared film. Note that its sensitivity extends well beyond the visible into the infrared portion of the spectrum. Usually it is desirable to exclude visible radiation, so

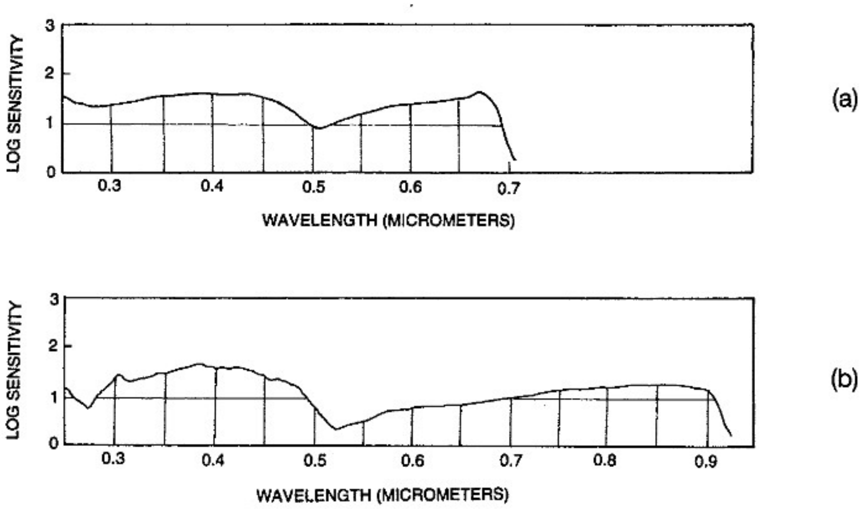


**FIGURE 3.10.** Spectral sensitivities of two photographic films. (*a*) Black-and-white panchromatic film (Kodak TRI-X Aerographic Film 2403). (*b*) Black-and-white infrared film (Kodak Infrared Aerographic Film 2424). Copyright Eastman Kodak Company. Permission has been granted to reproduce this material from *KODAK Data for Aerial Photography* (Code: M-29), courtesy of Silver Pixel Press, official licensee and publisher of Kodak books.

this film is often used with a deep red filter that blocks visible radiation, but allows infrared radiation to pass (Figure 3.11). An image recorded by black-and-white infrared film (Figure 3.12b) is quite different from its representation in the visible spectrum. For example, living vegetation is many times brighter in the near infrared portion of the spectrum that it is in the visible portion, so vegetated areas appear bright white on the black-and-white infrared image.

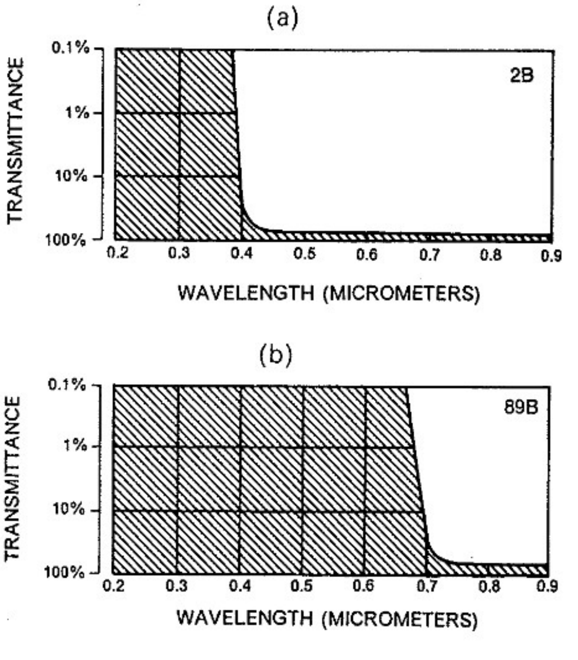


**FIGURE 3.11.** Transmission curves for two filters. (*a*) Pale yellow filter (Kodak filter 2B) to prevent ultraviolet light from reaching the film; it is frequently used with panchromatic film. (*b*) Kodak 89B filter used to exclude visible light, used with black-and-white infrared film. (Shaded portions of the diagrams signify that the filter is blocking transmission of radiation at specified wavelengths.) Copyright Eastman Kodak Company. Permission has been granted to reproduce this material from *KODAK Photographic Filters Handbook* (Code: B-3), courtesy of Silver Pixel Press, official licensee and publisher of Kodak books.

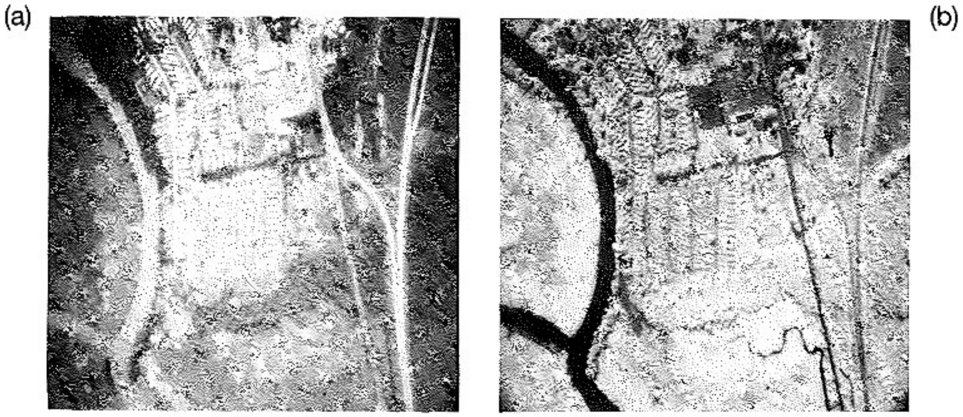


**FIGURE 3.12.** Aerial photographs. (*a*) Panchromatic film; (*b*) black-and-white infrared film. Both show Wayson's Corner, Maryland. Photographs courtesy of NASA.

### *The Characteristic Curve*

If we examine a negative after development and fixing, we find a pattern of dark and light related to the patterns of metallic silver formed in the processed film. Where the original scene was bright, the negative now has large amounts of silver, which create the dark areas. Where the original scene was dark, the film is clear, due to the absence of metallic silver.

We can see intermediate shades of brightness because the crystals in the emulsion are much smaller that the human eye can resolve. The areas that we perceive as shades of gray are actually variations in the abundance of the tiny grains of silver in the processed film. Thus each crystal is either present (black) or absent (clear), with shades of gray formed by variations in the abundance of crystals, which occur in proportion to the brightness of the original scene.

If we shine a light of intensity $I_0$ through a very small area of the negative (perhaps a fraction of a mm in diameter), the brightness of the light measured on the other side ($I$) is a measure of darkness of that region of the film (Figure 3.13). $I$, of course, is less than $I_0$. The ratio

$$I_0/I \tag{Eq. 3.2}$$

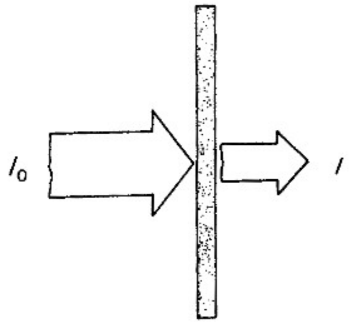


**FIGURE 3.13.** Measurement of opacity.

TABLE 3.1. Transmission, Opacity, and Density

| Percentage of light transmitted | Opacity | Density ($\log_{10}$ opacity) | Example |
|---|---|---|---|
| 100 | 100/100 = 1 | 0 | Clear |
| 80 | 100/80 = 1.25 | 0.09 | |
| 50 | 100/50 = 2 | 0.3 | |
| 20 | 100/20 = 5 | 0.7 | |
| 10 | 100/10 = 10 | 1.0 | |
| 5 | 100/5 = 20 | 1.3 | |
| 1 | 100/1 = 100 | 2. | Dark sunglasses |
| 0.1 | 100/0.1 = 1,000 | 3. | |
| 0.01 | 100/0.01 = 10,000 | 4. | Very dark |
| 0.0 | 100/0.0 = ∞ | — | Opaque |

is defined as the opacity. The darkness of the film is of interest because it is related to the brightness of the original scene. By convention, the darkness of the film is expressed as *density,* defined as the $\log_{10}$ of opacity (Table 3.1).

The effect of light upon the emulsion of a film is determined by the product of intensity ($i$) ("brightness," equivalent to irradiance) and time ($t$). For a given density, the product $i \times t$ has a constant value $D$, the exposure:

$$E = i \times t \qquad \text{(Eq. 3.3)}$$

In everyday photography we use this relationship whenever we compensate for use of a fast shutter speed by opening the aperture to allow more light to enter. The *characteristic curve* expresses the relationship between brightness in the scene and density on the film (Figure 3.14). Or, more formally, it is a plot of the relationship between the density of a negative and the $\log_{10}$ of exposure. A specific emulsion will be characterized by a set of characteristic curves that differ in slope as development times vary. For present purposes, it is sufficient to consider only a single curve as an example.

The S-shape is typical of the characteristic curve. The lower part (the *toe*) is curved; the cen-

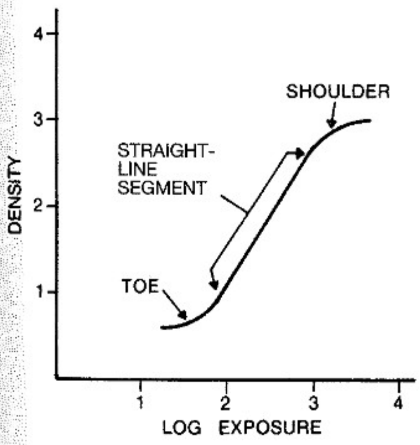


FIGURE 3.14. Characteristic curve of a photographic emulsion.

tral part forms a straight line (the *straight-line segment*), and the upper portion (the *shoulder*) is curved. For scientific purposes, the straight-line segment is of interest; for a range of exposures, there is a consistent relationship between exposure and density. If exposure is increased by a certain amount, then the relationship depicted by the characteristic curve permits prediction of the corresponding increase in image density. The predictability of this relationship permits scientists to define consistent relationships between the darkness in a photograph and the brightness in the original scene. Given suitable controls, an image scientist can use measurements from the photography to learn about brightnesses in the scene. Note that the lowest point of the curve does not reach the bottom of the graph; this difference is the *fog level*—a very small amount of density caused by the development process itself, unrelated to exposure. At the other extreme, the shoulder of the characteristic curve, the curved shape indicates that further increases in exposure will not produce a corresponding increase in density. This effect is referred to as *saturation*—the exposure is so extreme that the density will no longer have a predictable association with exposure.

Examine Figure 3.15; here two characteristic curves illustrate how differences in the slope of the straight-line segment translate a given *brightness range* (*BR*) into different *density ranges* (*DR*) in the final processed images. If the slope of the straight-line segment is steep, then a small range in exposure translates into a big range in density. Such an image has high contrast, meaning that the image displays a large range in brightness. If the slope is shallow (Figure 3.15b), a given range in scene brightness is translated into a smaller range in image brightness—a low-contrast image.

Note that the toe and the shoulder of the curve do not depict consistent relationships between exposure and density. This means that for very high and very low exposures, the film will not produce the predictable densities that it will for exposures in the straight-line segment. That is, the film is no longer a scientific tool for portraying scene brightness because we cannot measure a density and then relate the density to the brightness of the original scene. Often, professional photographers will use the toe or the shoulder to create artistic effects in photographs, but scientists always avoid use of image measurements that may be based on very

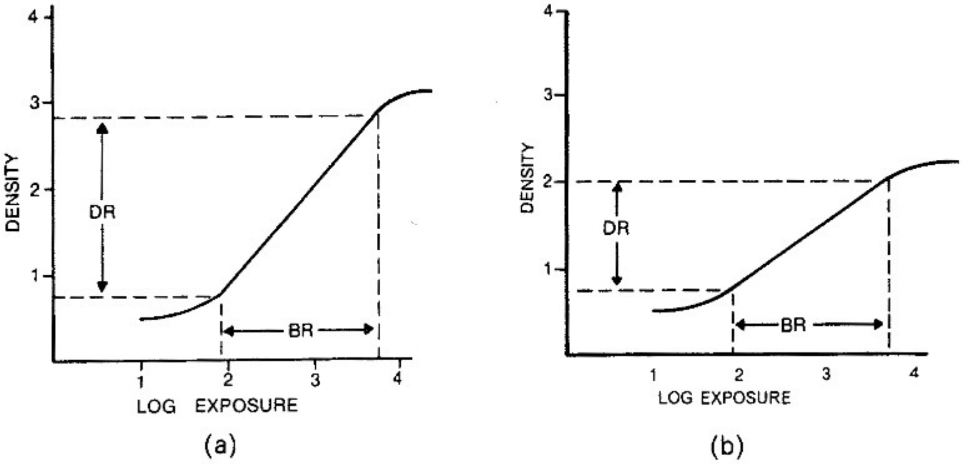


**FIGURE 3.15.** Examples of characteristic curves.

high or very low image densities—they have an unknown relationship to brightnesses in the scene they portray.

Because photographic films are used to record images acquired by nonphotographic sensors (as described in subsequent chapters), knowledge of the characteristic curve is especially important in the field of remote sensing. Such sensors often record a large range of brightnesses—a range so large that it may exceed the capability of the film to record it. If so, the photographic record of the image will inevitably be inaccurate as a record of scene brightness. The very dark areas, the very bright areas, or perhaps both will be represented in nonlinear portions of the characteristic curve, and the image will show only a small portion of the brightnesses present in the scene. It is partially for this reason that digital image data, which can represent very large ranges of brightnesses, often offer advantages in comparison with photographic images for some kinds of analyses.

## 3.5. Color Reversal Films

Many of the color films used in remote sensing are reversal films, similar to those used in handheld cameras for color slides. Their basic elements are similar to those of black-and-white photographic film, except that they are coated with three separate emulsions, each sensitive to one of the three additive primaries (Figure 3.16). The protective supercoat, the backing, and the subbing layer are present, and between the several emulsions are spacer layers of gelatin to prevent mixing of adjacent emulsions. The layer between the uppermost blue-sensitive emulsion and the middle (green-sensitive) emulsion is treated to act as a yellow filter to prevent blue light from passing through the upper layers to expose the lower emulsions. This filter is necessary because of the difficulty of manufacturing emulsions sensitive to red and green light without also sensitizing them to blue light.

Upon exposure, blue light exposes the blue layer, passes through the blue layer, but is prevented from exposing the other two layers by the yellow filter (Figure 3.17). Green light passes through the blue layer and exposes the green-sensitive emulsion. Red light passes through the upper emulsions to expose only the lower, red-sensitive layer.

After processing, all areas not exposed to blue light on the blue-sensitive emulsion are represented by a yellow dye, while those areas exposed to blue are left clear. Areas exposed by green

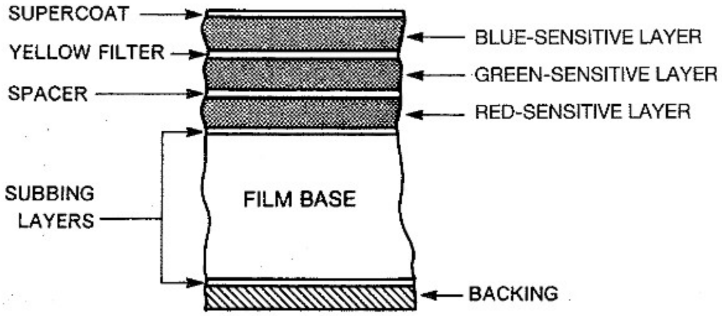


**FIGURE 3.16.** Idealized cross-sectional diagram of color reversal film.

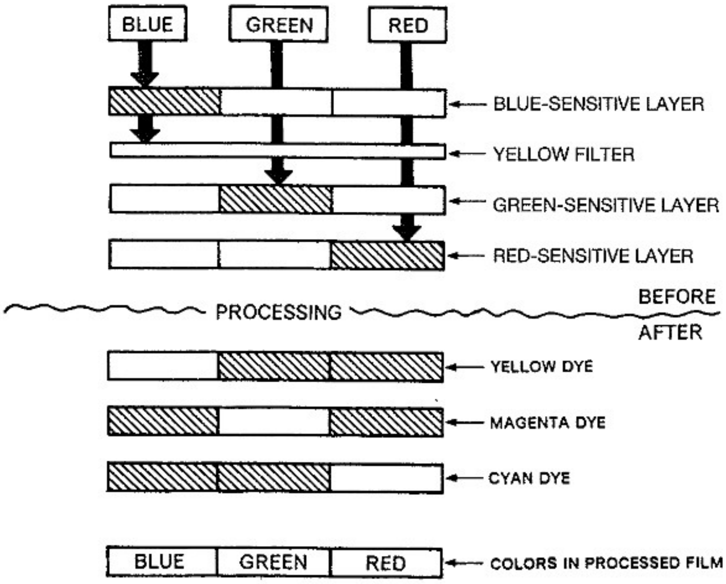


**FIGURE 3.17.** Color representation in color reversal film.

light on the green-sensitive emulsion are left clear; other areas are shown in magenta dye. Areas on the red-sensitive layer not exposed to red light are represented by cyan dye; images of red objects are clear on this emulsion. Thus each emulsion is sensitive to one of the additive primaries; after processing, each emulsion contains one of the subtractive primaries. The strategy of dying all areas not exposed in each separate emulsion differs fundamentally from the process used for the black-and-white films described earlier. Here there is no negative image; the dyes in the film processed combine to form a positive image in which brightness in the image corresponds (approximately) to brightness in the original scene.

When the processed film is viewed as a transparency against a light source, the magenta and cyan dyes present in those areas exposed to blue light combine to form a blue color. Likewise yellow and cyan combine to represent green, and yellow and magenta combine to form red (Figure 3.17 and Plate 1). This process is the same as that used for production of the 35-mm color slides that are familiar to many readers, so it should be easy to visualize the result of this process, even though the explanation shown in Figure 3.17 may seem rather abstract.

## 3.6. Color Infrared Films

Color infrared (CIR) films are based upon the same principles as color reversal films except for differences in the sensitivity of the emulsions and conventions in representation of colors. This film is used with a yellow filter to prevent blue light from entering the camera. The blue-sensitive layer is replaced by an emulsion sensitive to a portion of the near infrared region (Figure 3.18). After developing, representation of colors in the scene is shifted one position in the spectrum, so that green in the scene appears as blue on the image, red appears as green, and objects reflecting strongly in the near infrared are depicted in red. The comparison with normal color films can be represented schematically as follows:

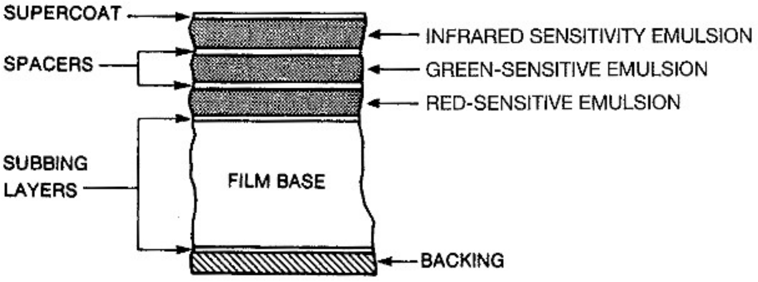


**FIGURE 3.18.** Idealized cross-sectional diagram of color infrared film.

| | | | | |
|---|---|---|---|---|
| Object in the scene reflects: | Blue | Green | Red | Infrared |
| Color reversal film represents the object as: | Blue | Green | Red | ***** |
| Color infrared film represents the object as: | **** | Blue | Green | Red |

Most objects, of course, reflect in several portions of the spectrum, so the CIR image shows a variety of colors derived from the varied reflectances in the scene. CIR film is designed in a manner analogous to, but not identical to, that of color reversal film (Figure 3.19). A yellow filter over the camera lens excludes all blue light. Green light exposes the green-sensitive layer red light exposes the red-sensitive layer, and IR radiation exposes the IR-sensitive layer. After processing, areas not exposed to the green light are colored in yellow dye. Areas not exposed to red light are colored magenta. And areas not exposed to IR radiation are represented as cyan. In the final transparency, cyan and magenta combine to represent green areas as blue, cyan and yellow combine to represent red areas as green, and yellow and magenta combine to form the red color that represents objects that reflect strongly in the near infrared (Plate 1).

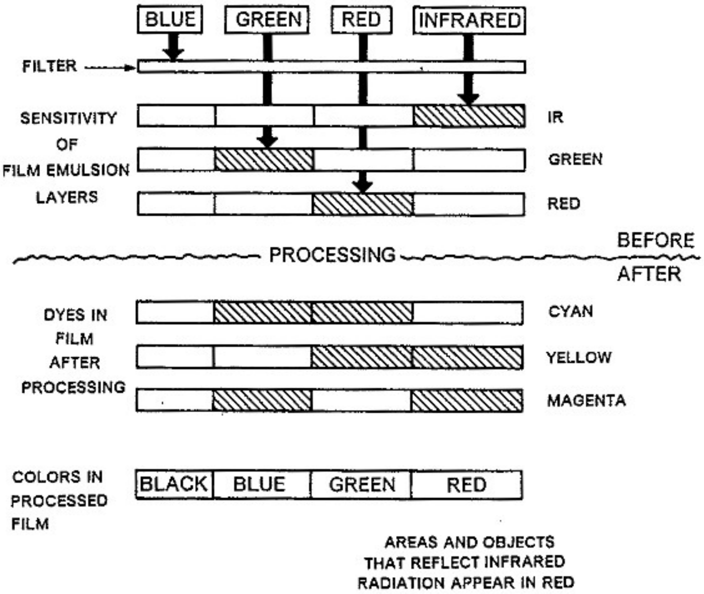


**FIGURE 3.19.** Color representation in color infrared film.

## 3.7. Film Format and Annotation

The term *format* designates the size of the image acquired by a camera. Mapping cameras generally produce a square image, with a size controlled by the width of the film. Common formats are 23 cm × 23 cm (approximately 9 in. × 9 in.) and 5.7 cm × 5.7 cm (approximately 2.5 in. × 2.5 in). Film 35 mm in width (24 mm × 36 mm image format) has also been used for specialized purposes, although generally it is not practical for routine applications of remote sensing. The 23-cm format is a standard for most cartographic cameras; paper prints made directly from the negative (*contact prints*) are among the most frequently used form of aerial photography. Although enlargements of the original negative can be made to any size desired, the 23-cm format is convenient for storage and handling, and because the prints are made directly from the negative without enlargement, the image retains maximum detail and sharpness.

In some instances, paper prints are not made, and the film is examined simply as a strip of film—a *positive transparency*—wound on large spools, and viewed against an illuminated background (Chapter 5). Because emulsions of transparencies typically represent a greater range of image tones than do paper prints, positive transparencies are often preferred for detailed interpretations, and especially for color and color infrared films.

Most aerial photographs carry some form of *annotation,* markings that identify the photographs and provide details concerning their acquisition. Typically, aerial photographs are annotated in the forward edge of the photograph (Figure 3.20). Annotation consists of a series

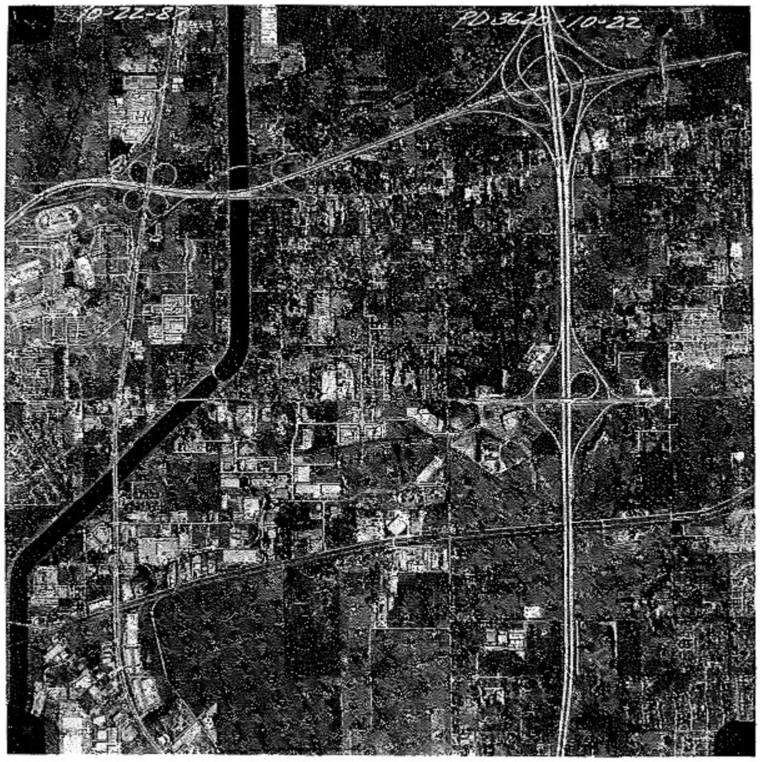


**FIGURE 3.20.** Vertical aerial photograph.

of letters and numerals that can vary in meaning from one aerial survey firm to the next, but usually they include the *date* of the photography, a series of letters and numbers that *identify each project,* and the *film roll* number. Usually the last three digits specify the *frame number,* which shows the sequence in which photographs were taken. Other annotations, such as *image scale,* may also be included. In some instances the information may be recorded directly by the camera itself as the image is acquired; in other instances it may be added later as the film is processed and prepared for dissemination. The most sophisticated cameras may record on each frame information such as date, project identifier, focal length, time, image of a bubble level to indicate degree of tilt, and locational coordinates provided by onboard global positioning systems.

## 3.8. Geometry of the Vertical Aerial Photograph

Aerial photographs can be classified according to the orientation of the camera in relation to the ground at the time of exposure (Figure 3.21). *Oblique* aerial photographs have been acquired by cameras oriented toward the side of the aircraft. *High oblique* photographs (Figure 3.21a and Plate 2) show the horizon; *low oblique* photographs (Figure 3.21b and Plate 3) are taken with the camera aimed more directly toward the ground surface and do not show the horizon. Oblique photographs have the advantage of showing very large areas in a single image. Often those features in the foreground are easily recognized, as the view in an oblique photograph may resemble that from a tall building or mountain top. However, oblique photographs are not widely used, primarily because the drastic changes in scale that occur from foreground to background prevent convenient measurement of distances, areas, and elevations.

*Vertical* photographs are acquired by a camera aimed directly at the ground surface from above (Figures 3.20 and 3.21c). Although objects and features are often difficult to recognize from their representations on vertical photographs, the map-like view of the earth, and the predictable geometric properties of vertical photographs provide practical advantages. It should be noted that few, if any, aerial photographs are truly vertical; most have some small degree of tilt due to aircraft motion and other factors. The term *vertical photograph* is commonly used to des-

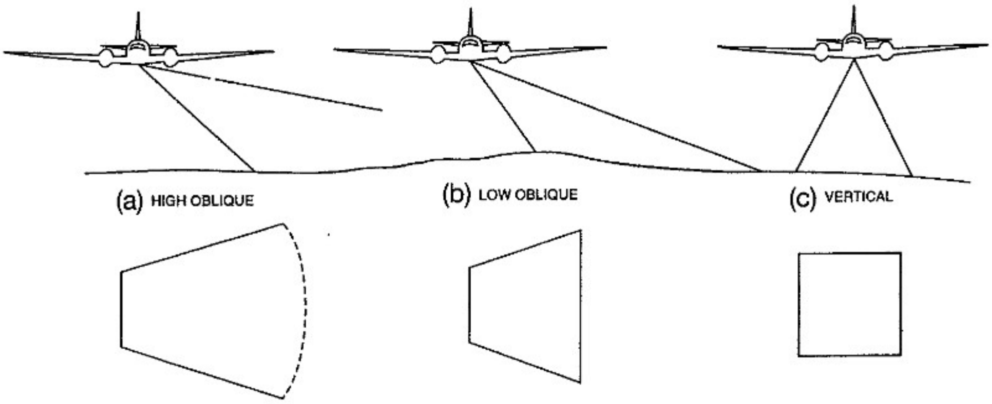


FIGURE 3.21. Oblique and vertical aerial photographs.

ignate aerial photographs that are within a few degrees of a corresponding (hypothetical) truly vertical photograph.

Because the geometric properties of vertical and nearly vertical aerial photographs are well understood and can be applied to many practical problems, they form the basis for making accurate measurements using aerial photographs. The science of making accurate measurements from aerial photographs (or from any photograph) is known as *photogrammetry*. The following paragraphs outline some of the most basic elements of introductory photogrammetry; the reader should consult a photogrammetry text (e.g., Wolf, 1983) for complete discussion of this subject. Aerial cameras are manufactured to include adjustable index marks attached rigidly to the camera so that the positions of the index marks are recorded on the photograph during exposure. These *fiducial marks* (usually four or eight in number) appear as silhouettes at the edges and/or corners of the photograph (Figures 3.20 and 3.22; in Figure 3.20 they appear in the corners). Lines that connect opposite pairs of fiducial marks intersect to identify the *principal point,* the optical center of the image. The *ground nadir* is defined as the point on the ground vertically beneath the center of the camera lens at the time the photograph was taken (Figure 3.23). The *photographic nadir* is defined by the intersection with the photograph of the vertical line that intersects the ground nadir and the center of the lens (i.e., the image of the ground nadir).

The *isocenter* can be defined informally as the focus of tilt. Imagine a truly vertical photograph that was taken at the same instant as the real, almost-vertical, image. The almost-vertical image would intersect with the (hypothetical) perfect image along a line that would form a "hinge"; the isocenter is a point on this hinge. On a truly vertical photograph, the isocenter, the principal point, and the photographic nadir coincide. The most important positional, or geometric, errors in the vertical aerial photograph can be summarized as follows.

1. *Optical distortions* are errors caused by an inferior camera lens, camera malfunction, or similar problems. These distortions are probably of minor significance in most modern photography flown by professional aerial survey firms.

2. *Tilt* is caused by displacement of the focal plane from a truly horizontal position by aircraft motion (Figure 3.23). The focus of tilt, the isocenter, is located at or near the principal

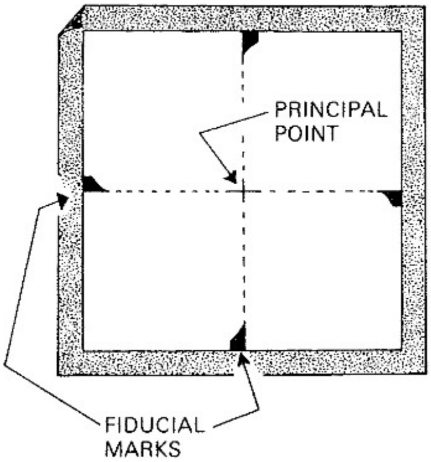


**FIGURE 3.22.** Fiducial marks and principal point.

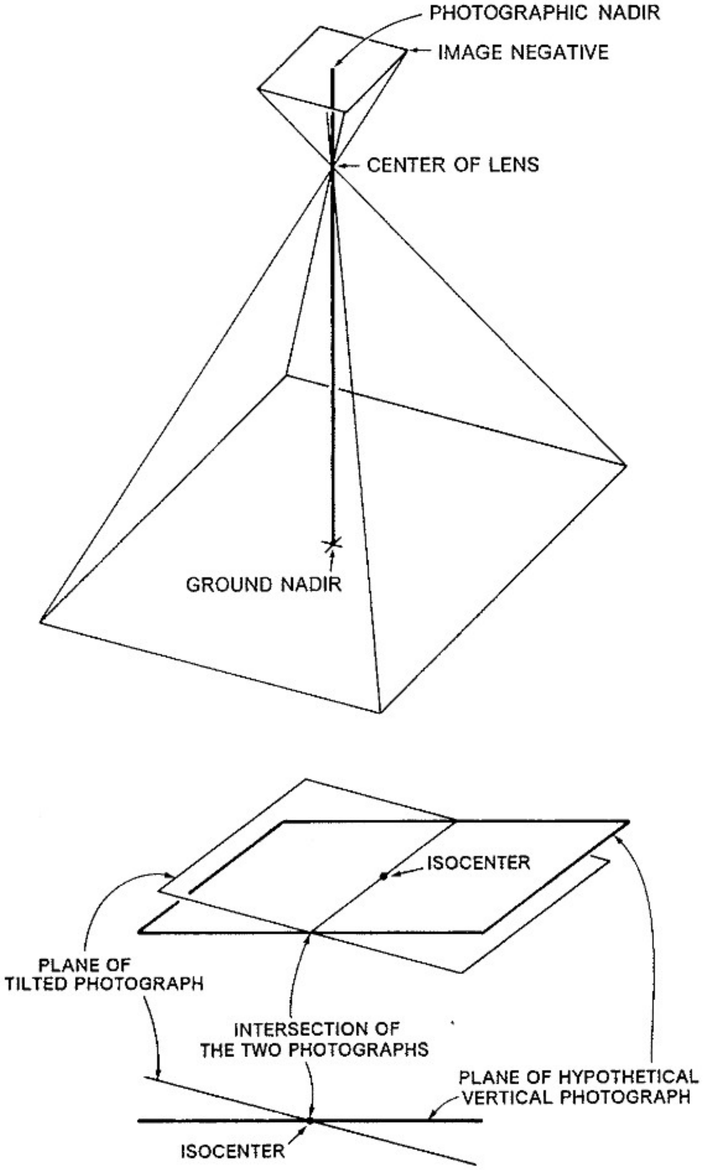


**FIGURE 3.23.** Schematic representation of terms to describe geometry of vertical aerial photographs.

point. Image areas on the upper side of the tilt are displaced further away from the ground than is the isocenter; these areas are therefore depicted at scales smaller than the nominal scale. Image areas on the lower side of the tilt are displaced down; these areas are depicted at scales larger than the nominal scale. Therefore, because all photographs have some degree of tilt, measurements confined to one portion of the image run the risk of including systematic error caused by tilt (i.e., measurements may be consistently too large or too small). To avoid this effect, it is a good practice to select distances used for scale measurements (Chapter 5) as lines that pass close to the principal point; then errors caused by the upward tilt compensate for errors caused by the downward tilt. The resulting value for image scale is not, of course, precisely accurate for either portion of the image, but it will not include the large errors that can arise in areas located further from the principal point.

Because of routine use of high-quality cameras and careful inspection of photography to monitor photo quality, today the most important source of positional error in vertical aerial photography is probably *relief displacement* (Figure 3.24). Objects positioned directly beneath the center of the camera lens will be photographed so that only the top of the object is visible (e.g., object A in Figure 3.24). All other objects are positioned such that both their tops and their sides are visible from the position of the lens. That is, these objects appear to lean outward from the central perspective of the camera lens (e.g., see objects in Figure 3.24). Correct planimetric positioning of these features would represent only the top view, yet the photograph shows both the top and sides of the object. For tall features, it is intuitively clear that the base and the top cannot both be in their correct planimetric positions.

This difference in apparent location is due to the height (*relief*) of the object and forms an important source of positional error in vertical aerial photographs. The direction of relief displacement is always radial from the nadir; the amount of displacement depends upon (1) the height of the object and (2) the distance of the object from the nadir. Relief displacement increases with increasing heights of features and with increasing distances from the nadir. (It also depends upon focal length and flight altitude, but these may be regarded as constant for a few sequential photographs.)

Relief displacement forms the basis of measurements of heights of objects, but its greatest sig-

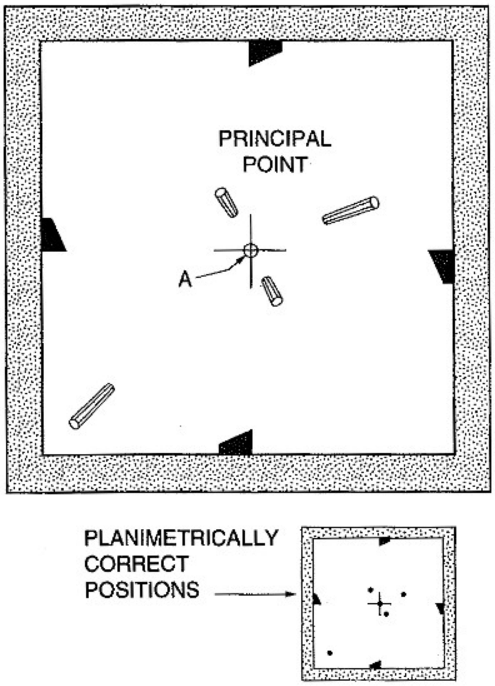


**FIGURE 3.24.** Relief displacement. The diagram depicts a vertical aerial photograph of a level terrain with five towers of equal height located at different positions with respect to the principal point. Images of the tops of towers are displaced away from the principal point along lines that radiate from the nadir, as discussed in the text.

nificance is its role as a source of positional error. Uneven terrain can create significant relief displacement, so all measurements made directly from uncorrected aerial photographs are suspect.

## 3.9. Coverage by Multiple Photographs

Pilots normally acquire vertical aerial photographs by flying a series of parallel flight lines that together build up complete coverage of a specific region. Each flight line consists of individual frames, usually numbered in sequence (Figure 3.25). Often the camera operator can view the area to be photographed through a viewfinder attached to the camera or through a telescope-like instrument that observes the ground area below the plane. With the aid of these devices, the operator can manually trigger the shutter as aircraft motion brings predesignated landmarks into the field of view or can set controls to automatically acquire photographs at intervals tailored to provide the desired coverage.

Individual frames form ordered strips, as shown in Figure 3.25a. If the plane's course is deflected by a crosswind, the positions of ground areas shown by successive photographs form the pattern shown in Figure 3.25b, known as *drift. Crab* (Figure 3.25c) is caused by correction of the flight path to compensate for drift without a change in the orientation of the camera.

Usually flight plans call for a certain amount of *forward overlap* (Figure 3.26), duplicate coverage by successive frames in a flight line, usually by about 50 to 60% of each frame. If forward overlap is 50% or more, then the image of the principal point of one photograph is visible on the next photograph in the flight line. These are known as *conjugate principal points* (Figure 3.26). When it is necessary to photograph large areas, coverage is built up by means of several parallel strips of photography; each strip is called a *flight line.* Sidelap between adjacent flight lines may vary from about 5 to 15%, in an effort to prevent gaps in coverage of adjacent flight lines.

However, as pilots and other crew members collect complete photographic coverage of a region, there may still be gaps (known as *holidays*) in coverage due to equipment malfunction, navigation errors, cloud cover, or other problems. Sometimes photography flown later to cover holidays differs noticeably from adjacent images with respect to sun angle, vegetative cover, and other qualities. For planning flight lines, the number of photographs required for each line can be estimated using the relationship:

$$\text{Number of photos} = \frac{\text{Length of flight line}}{(gd \text{ of photo}) \times (1 - \text{overlap})} \qquad \text{(Eq. 3.4)}$$

where *gd* is the ground distance represented on a single frame, measured in the same units as the length of the planned flight line. For example, if a flight line is planned to be 33 mi. in length, each photograph is planned to represent 3.4 mi. on a side, and forward overlap is to be 0.60, then $33/[3.4 \times (1 - .60)] = 33/(1.36) = 24.26$, or about 25 photographs are required. (Chapter 5 shows how to calculate the coverage of a photograph for a given negative size, focal length, and flying altitude.)

### *Stereoscopic Parallax*

If we have two photographs of the same area taken from different perspectives (i.e., from different camera positions), we observe a displacement of images of objects from one image to the

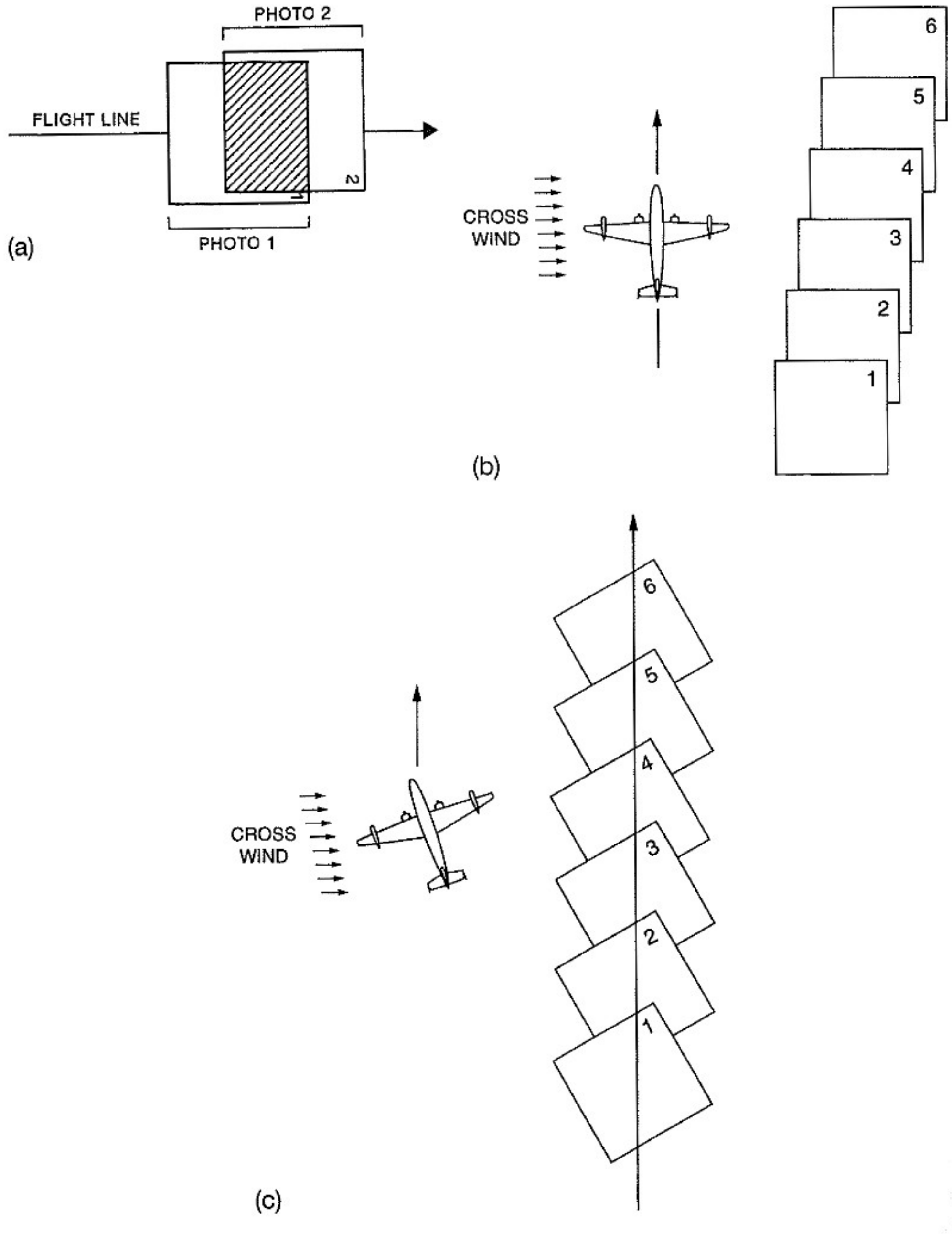


**FIGURE 3.25.** Aerial photographic coverage: (*a*) forward overlap, (*b*) drift, and (*c*) crab.

other. You can observe this effect now by simple observation of nearby objects. Look up from this book at the objects near you. Close one eye, then open it and close the other. As you do this you observe a change in the appearance of objects from one eye to the next. Nearby objects are slightly different in appearance because one eye tends to see, for example, only the front of an object, whereas the other, because of its position (about 2.5 in.) from the other, sees the front and some of the side of the same object. This difference in appearances of objects due to change

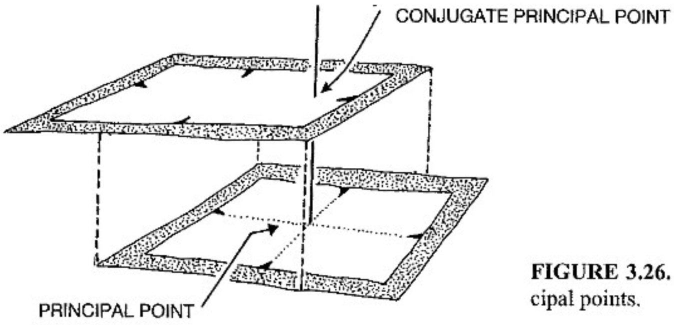


**FIGURE 3.26.** Forward overlap and conjugate principal points.

in perspective is known as *stereoscopic parallax*. The amount of parallax decreases as objects increase in distance from the observer (Figure 3.27). If you repeat the experiment looking out the window at a landscape you can confirm this effect by noting that distant objects display little or no observable parallax.

Stereoscopic parallax can therefore be used as a basis for measuring distance or height. Overlapping aerial photographs record parallax due to the shift in position of the camera as aircraft motion carries the camera forward between successive exposures. If forward overlap is 50% or more, then the entire ground area shown on a given frame can be viewed in stereo using three adjacent frames (a *stereo triplet*). Forward overlap of 50 to 60% is common. This amount of overlap doubles the number of photographs required, but assures that the entire area can be viewed in stereo because each point on the ground will appear on two successive photographs in a flight line.

Displacement due to stereo parallax is always parallel to the flight line. Tops of tall objects, nearer to the camera, show more displacement than do shorter objects, which are more distant from the camera. Measurement of parallax therefore provides a means of estimating heights of objects. Manual measurement of parallax can be accomplished as follows. Tape photographs of a stereo pair to a work table so the axis of the flight line is oriented from right to

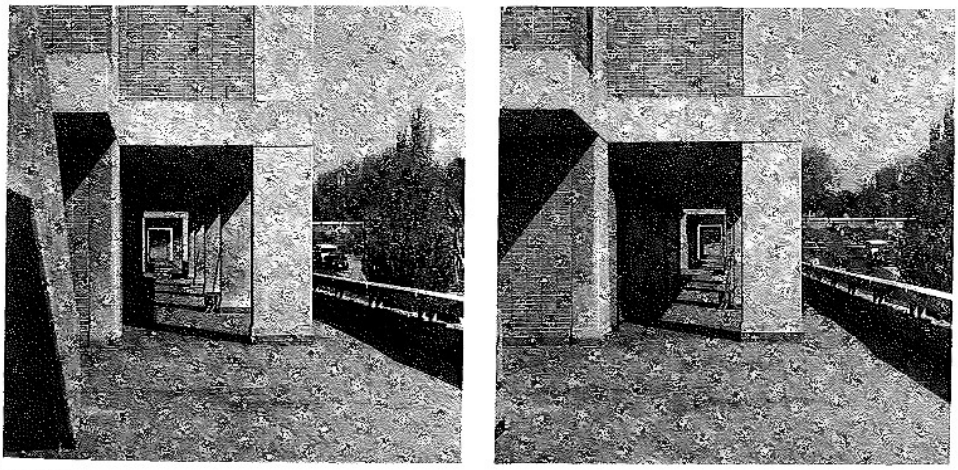


**FIGURE 3.27.** Stereoscopic parallax. These two photographs of the same scene were taken from slightly different positions. Note the differences in the appearances of objects due to the difference in perspective; note also that the differences are greatest for objects nearest the camera and least for objects in the distance.

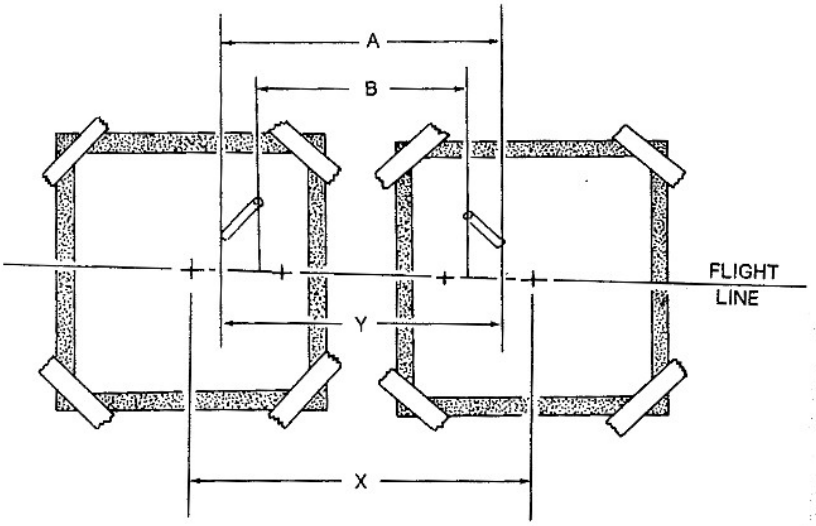
left (Figure 3.28). For demonstration purposes, distances can be measured with an engineer's scale.

1. Measure the distance between two principal points (*X*).
2. Measure the distance between separate images of the base of the object as represented on the two images (*Y*). Subtract this distance from that found in (1) to get *P*.
3. Measure top-to-top distances (*B*), and base-to-base (*A*) distances, then subtract to find *dp*.

In practice, parallax measurements can be made more conveniently using a *parallax wedge,* or *parallax bar* (Chapter 5), devices that permit accurate measurement of small amounts of parallax.

### *Mosaics*

A series of vertical aerial photographs that show adjacent regions on the ground can be joined together to form a mosaic. Aerial mosaics belong to one of two classes. *Uncontrolled mosaics* are formed by placing the photographs together in a manner that provides continuous coverage of an area, without concern for preservation of consistent scale and positional relationships. The most rudimentary form of uncontrolled mosaic is formed simply by placing the photographs in their correct sequence, but with only rough alignment at their edges (Figure 3.29). Then another



$$h = \frac{H \times dp}{P + dp}$$

H = FLYING HEIGHT OF AIRCRAFT

dp = DIFFERENTIAL PARALLAX = A - B

P = X - Y

h = HEIGHT OF THE OBJECT

**FIGURE 3.28.** Measurement of stereoscopic parallax.

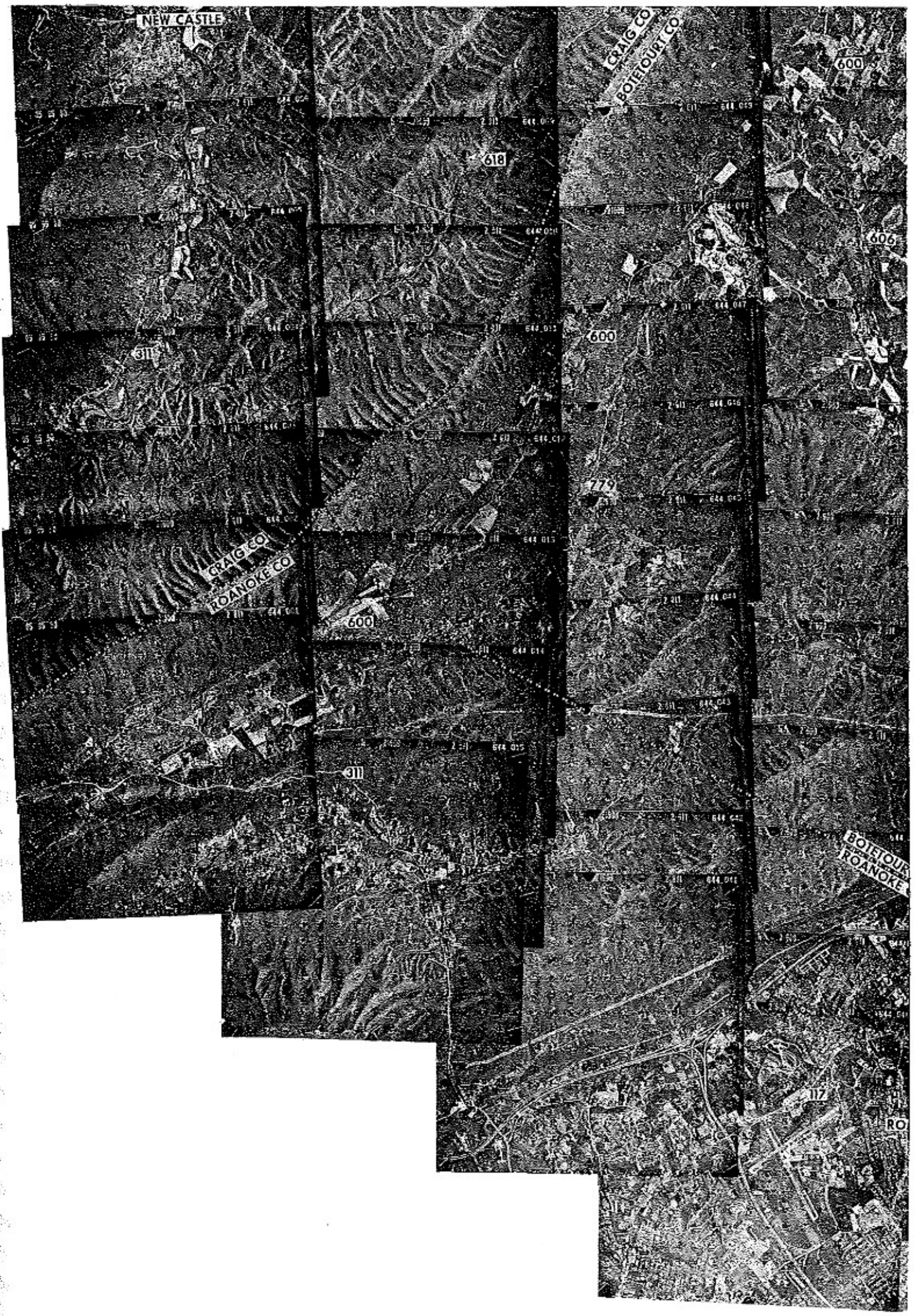


FIGURE 3.29. Uncontrolled mosaic.

photograph is taken of these individual photographs, forming a single image that gives an overview of the landscape within a given region. An uncontrolled mosaic of this kind is often used as an *aerial index*—a key to the locations and coverages of the individual photographs. An aerial index provides a means of identifying those particular photographs that might be needed for a specific purpose, and does give a small-scale overview of a particular region. Uncontrolled mosaics cannot be used for measurements of distance or area because no effort has been made to ensure that images are positioned in their correct relative positions. Other kinds of uncontrolled mosaics can be made using only the center sections of individual photographs, with efforts to improve matching of detail at edges of images. Such mosaics are more attractive, but still lack the geometric accuracy necessary to provide a basis for accurate measurement. *Controlled mosaics* are formed from individual photographs assembled in a manner that preserves correct positional relationships between the features they represent. Often the most accurate region of each photograph, that near the principal point, is cut out, and used for the mosaic. Locational control must, of course, be provided by ground survey or by information from accurate maps. Controlled mosaics can be very expensive, but may have sufficient accuracy to serve as a map substitute in some instances.

### *Orthophotos and Orthophotomaps*

Aerial photographs are not planimetric maps because they have geometric errors, most notably the effects of relief displacement, in the representations of the features they show. That is, objects are not represented in their correct relative positions and as a result the images cannot be used as the basis for accurate measurements.

Stereoscopic photographs can be used to generate a corrected form of an aerial photograph known as an *orthophoto* that shows photographic detail without the errors caused by tilt and relief displacement. An instrument known as an orthophotoscope can, for a given instant, project a corrected version of a very small portion of an image. An orthophotoscope is an optical–mechanical instrument that, instead of exposing an entire image from a central perspective (i.e., through a single lens), exposes each small section individually in a manner that corrects for the elevation of that small section. The result is an image that has orthographic properties rather than those of the central perspective of the original aerial photograph. The orthophotoscope is capable of scanning an entire image piece by piece to generate a corrected version of that image. The projection orientation is adjusted to correct for tilt, and the instrument continuously varies the projection distance to correct for relief displacement. Thus, as the instrument scans an image the operator views the ground surface in stereo and the new image is formed as a geometrically correct version of the original image. The result is a photo image that shows the same detail as the original aerial photograph but without the geometric errors introduced by tilt and relief displacement. *Orthophotomaps* therefore can be used for most purposes as maps, because they show correct planimetric position and preserve consistent scale throughout the image. Orthophotographs form the basis for orthophotomaps, which are orthophotographs presented in map format, with annotations, scale, and geographic coordinates.

Orthophotomaps (Figure 3.30) are valuable because they show the fine detail of an aerial photograph without the geometric errors that are normally present, and they can be compiled

FIGURE 3.30. Orthophoto.

much more quickly and cheaply than the usual topographic maps. Therefore, they can be very useful as map substitutes in instances where topographic maps are not available; or as map supplements when maps are available, but the analyst requires the finer detail, and more recent information, provided by an image.

### *Digital Orthophoto Quadrangles*

*Digital Orthophoto quadrangles* (*DOQs*) are orthophotos prepared in a digital format, designed to correspond to the 7.5-minute quadrangles of the U.S. Geological Survey (USGS). DOQs are presented either as black-and-white or as color images that have been processed to attain the geometric properties of a planimetric map.

DOQs are prepared from National Aerial Photography Program (NAPP) photography (high-altitude photography described in Section 3.13), at 1:40,000, supplemented by other aerial photography as needed. The rectification process is based upon the use of DEMs to represent variations in terrain elevation. The final product is presented to correspond to the matching USGS 7.5-minute quadrangle, with a supplementary border of imagery representing 50 to 300 m beyond the limits of the quadrangle, to facilitate matching and mosaicking with adjacent sheets. DOQs provide image detail equivalent to 2 m or so for DOQs presented in the quadrangle format, and finer detail for quarter-quad DOQs. The USGS has responsibility for leading the U.S. federal government's effort to prepare and disseminate digital cartographic data. For more information on DOQs, visit the USGS web site at:

*http://edc.usgs.gov/glis/hyper/guide/usgs_doq*

## 3.10. Photogrammetry

*Photogrammetry* is the science of making accurate measurements from photographs. Photogrammetry applies the principles of optics and knowledge of the interior geometry of the camera and its orientation to reconstruct dimensions and positions of objects represented within photographs. Therefore, its practice requires detailed knowledge of specific cameras and the circumstances under which they were used and accurate measurements of features within photographs. Photographs used for photogrammetry have traditionally been prepared on glass plates or other dimensionally stable materials (i.e., materials that do not change in size as temperature and humidity change).

Photogrammetry can be applied to any photograph, provided the necessary information is at hand. However, by far the most frequent application of photogrammetry is the analysis of stereo aerial photography to derive estimates of topographic elevation for topographic mapping. With the aid of accurate locational information describing key features within a scene (*ground control*), photogrammetrists estimate topographic relief by estimating stereo parallax for any array of points within a region. Although stereo parallax can be measured manually, it is far more practical to employ specialized instruments designed for stereoscopic analysis.

Such instruments, known as *analytical stereoplotters*, first designed in the 1920s, reconstruct the orientations of photographs at the time they were taken. Operators then can view the image in stereo; by maintaining constant parallax visually, they can trace lines of uniform elevation. The quality of information derived from such instruments depends upon the quality of the photography, the accuracy of the data, and the operator's skill in setting up the stereo model and tracing lines of uniform parallax. As the design of instruments improved, it eventually became possible to automatically match corresponding points on stereo pairs and thereby identify lines of uniform parallax with limited assistance from the operator.

## 3.11. Digital Photography

Photographs can be electronically scanned to record the patterns of blacks, grays, and whites as digital values, each representing the brightness of a specific point within the image. Although these values can be displayed in the form of a conventional photograph, the digital format offers advantages of compact storage and the power of numerical representation (Chapters 4 and 11). Further, it is possible to manufacture cameras that replace the film in the focal plane with an array of light-sensitive detectors (Chapter 4) that directly record images in digital form, thereby bypassing the scanning step. For example, Plate 4 shows a high-resolution digital CIR image acquired using a proprietary imaging system employed by Emerge, Inc., a subsidiary of Litton TASC, Inc. Because this imaging system collects navigational and positional data that can be used with elevation data of the region imaged, it can produce imagery of high positional accuracy.

## 3.12. Softcopy Photogrammetry

With further advances in instrumentation, it became possible to extend automation of the photogrammetric process so as to conduct the analysis completely within the digital domain. Satellite images or aerial photographs can be acquired digitally (or conventional photographs can be scanned to create digital products). With the use of global positioning systems (GPSs; Chapter 15) to acquire accurate positional information and the use of data recorded from the aircraft's navigational system to record the orientations of photographs, it then became feasible to reconstruct the geometry of the image using those data gathered as the image was acquired.

This process forms the basis for *softcopy photogrammetry,* so named because it does not require the physical (*hardcopy*) form of the photograph necessary for traditional photogrammetry. Instead the digital (*softcopy*) version of the image is used as input for a series of mathematical models that reconstruct the orientation of each image to create planimetrically correct representations. This process requires specialized computer software installed in workstations, which analyze digital data specifically acquired for the purpose of photogrammetric analysis. Softcopy photogrammetry offers advantages of speed and accuracy, and also creates output data that are easily integrated into other production and analytical systems, including GIS (Chapter 15).

## 3.13. Sources of Aerial Photography

Aerial photography can be acquired by (1) the user or (2) purchased from organizations that serve as repositories for imagery flown by others (*archival imagery*). In the first instance, aerial photography is produced upon request by firms that specialize in taking high-quality aerial photography. Such firms are listed in the business sections of most metropolitan phone directories. Customers may be individuals, governmental agencies, or other businesses that use aerial photography. Such photography is, of course, customized to meet the specific needs of customers with respect to date, scale, film, and coverage. As a result, costs may be prohibitive for many noncommercial uses.

Thus, for financial reasons, many users of aerial photography turn to archival photography as a means of acquiring the images they need. Although such photographs may not exactly meet users' requirements with respect to scale or date, low costs and ease of access may compensate for any shortcomings. For some tasks that require reconstruction of conditions at earlier dates (such as the Environmental Protection Agency's search for abandoned toxic waste dumps), the archival images may form the only source of information.

It is feasible to take "do-it-yourself" aerial photography. Many small cameras are suitable for aerial photography. Often the costs of local air charter services for an hour or so of flight time are relatively low. Small-format cameras, such as the usual 35-mm cameras, can be used for aerial photography if the photographer avoids the effects of aircraft vibration (Do not rest the camera against the aircraft!). If the altitude is low and the atmosphere is clear, ordinary films can produce satisfactory results. Be sure to use a high-wing aircraft to ensure that the photographer will have a clear view of the landscape. If the camera can accommodate filters, it is possible to use other films (such as infrared or color infrared) similar to those described above. Some experimentation may be necessary for the first-time user to obtain proper exposures, but most people can learn rather quickly to take satisfactory photographs. Usually the best lighting is when the camera is aimed away from the sun. Photographs acquired in this manner (Figure 3.31) may be useful for illustrative purposes, although for scientific or professional work, the large-format, high-quality work of the fully equipped air survey firm is probably necessary.

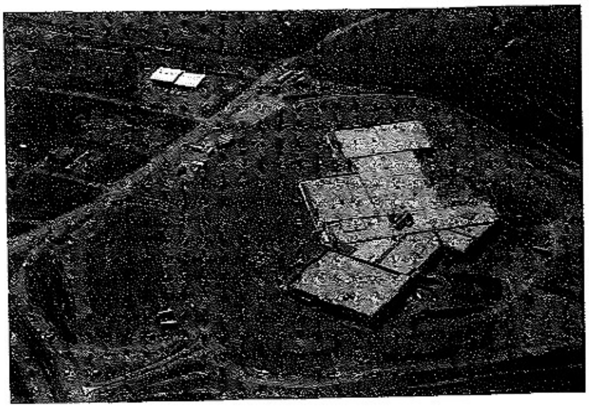


**FIGURE 3.31.** Aerial photograph taken with a handheld camera.

### *EROS Data Center*

The EROS Data Center (EDC), in Sioux Falls, South Dakota, is operated by the USGS as a repository for aerial photographs and satellite images acquired by NASA, the USGS, and other agencies. A computerized database at EDC provides an indexing system for information pertaining to aerial photographs and satellite images. For more information contact:

Customer Services
U.S. Geological Survey
EROS Data Center
47914 252nd Street
Sioux Falls, SD 57198-0001
Voice: 800-252-4547 or 605-594-6151
Fax: 605-594-6589
E-mail: *custserv@usgs.gov*
EDC home page: *http://edc.usgs.gov/*

### *Earth Science Information Center*

The Earth Science Information Center (ESIC) is operated by the USGS as a central source for information pertaining to maps and aerial photographs: ESIC has a special interest in information pertaining to federal programs and agencies, but also collects data pertaining to maps and photographs held by state and local governments. The ESIC headquarters is located at Reston, Virginia, but ESIC also maintains seven other offices throughout the United States; 31 other federal agencies have affiliated offices. ESIC can provide information to the public concerning the availability of maps and remotely sensed images. The following sections describe two programs administered by ESIC that can provide access to archival aerial photography.

#### *Aerial Photography Summary Record System*

The Aerial Photography Summary Record System (APSRS) is maintained by USGS as a computer-based information system for recording detailed information pertaining to aerial photography held by numerous federal, state, and private organizations. Prior to the establishment of centralized records in 1975, citizens desiring comprehensive information on coverage by aerial photographs were required to query holdings by numerous agencies, which each followed different conventions in reporting coverage. After 1975, users could obtain information on the integrated holdings of numerous agencies, reported in a standard format.

Those who request information from APSRS receive information sorted by date; describing image scale, cloud cover, and camera focal length; and identifying the organization holding the photography. Coverage is indexed by USGS 7.5-minute quadrangles, which are listed by the latitude and longitude of the southeastern corner of each quadrangle. Users first identify the quadrangle that covers their area of interest, and then use the latitude and longitude to search for coverage of the region. For each photographic mission, APSRS provides a listing giving the date of coverage, amount of cloud coverage, scale, film type and format, focal length, and other qualities. Also listed is the agency that holds the photography; these listing are keyed to a directory that lists addresses so that the user can order copies of the photographs. Listings also include the Federal Information Processing Standards (FIPS) code for each area, which permits cross-reference to political and census units.

The APSRS database is available as IBM-compatible CD-ROMs. Inquiries for specific areas can be researched by contacting:

Earth Science Information Center
U.S. Geological Survey
APSRS Data Base Manager
509 National Center
Reston, VA 20192
Voice: 703-648-5903
URL: *http://ask.usgs.gov/*

### *National Aerial Photography Program*

The National Aerial Photography Program (NAPP) acquires aerial photography for the coterminous United States, according to a systematic plan that ensures uniform standards. NAPP was initiated in 1987 by the USGS as a replacement for the National High Altitude Aerial Photography Program (NHAP), begun in 1980 to consolidate the many federal programs that use aerial photography. The USGS manages the NAPP, but it is funded by the federal agencies that are the primary users of its photography. Program oversight is provided by a committee of representatives from the USGS, the Bureau of Land Management, the National Agricultural Statistics Service, the National Resources Conservation Service (NRCS; previously known as the Soil Conservation Service), the Farm Services Agency (previously known as the Agricultural Stabilization and Conservation Service), the U.S. Forest Service, and the Tennessee Valley Authority. Light (1993) and Plasker and TeSelle (1988) provide further details.

Under NHAP, photography was acquired under a plan to obtain complete coverage of the coterminous 48 states, then to update coverage as necessary to keep pace with requirements for current photography. Current plans call for updates at intervals of 5 years, although the actual schedules are determined in coordination with budgetary constraints. NHAP flight lines were oriented north–south, centered on each of four quadrants systematically positioned within USGS 7.5-minute quadrangles, with full stereoscopic coverage at 60% forward overlap and sidelap of at least 27%. Two camera systems were used to acquire simultaneous coverage: black-and-white coverage was acquired at scales of about 1:80,000 using cameras with focal lengths of 6 in. Color infrared coverage was acquired at 1:58,000 using a focal length of 8.25 in. Plate 5 shows a high-altitude CIR image illustrating the broad-scale coverage provided by this format.

Dates of NHAP photography varied according to geographic region. Flights were timed to provide optimum atmospheric conditions for photography and to meet specifications for sun angle, snow cover, and shadowing, with preference for autumn and winter seasons to provide images that show the landscape without the cover of deciduous vegetation.

Specifications for NAPP photographs differ from those of NHAP. NAPP photographs are acquired at 20,000-ft. altitude using a 6-in focal length lens. Flight lines are centered on quarter quads (1:24,000-scale USGS quadrangles). NAPP photographs are planned for 1:40,000, black-and-white or color infrared film, depending on specific requirement for each area.

Photographs are available to all who may have an interest in their use. Their detail and quality permit use for land-cover surveys; assessment of agricultural, mineral, and forest resources; as well as examination of patterns of soil erosion and water quality. Photography is archived, and available from:

Customer Services
USGS EROS Data Center
Sioux Falls, SD 57198-0001
url: *http://edc.usgs.gov/glis/hyper/guide/napp*

or from USGS Earth Science Information Centers.

Two other important sources of aerial photography include:

USDA Aerial Photography Field Office:
*http://www.apfo.usda.gov/*

National Achieve and Records Administration
*http://www.nara.gov/nara/nn/nns/nnscord.html*

See also Table 4.4.

## 3.14. Summary

Aerial photography is a simple, reliable, and inexpensive means of acquiring remotely sensed images. It has been used to make images from very low altitudes and from earth-orbiting satellites, so it can be said to be one of the most flexible strategies for remote sensing. Aerial photography is useful mainly in the visible and near infrared portions of the spectrum, but its principles are important throughout the field of remote sensing. For example, lenses are used in many nonphotographic sensors and photographic films are used to record images acquired by a variety of instruments.

Aerial photographs form the primary source of information for compilation of many maps, especially large-scale topographic maps. Vertical aerial photographs are valuable as map substitutes or as map supplements. Geometric errors in the representation of location prevent direct use of aerial photographs as the basis for measurement of distance or area. But, as these errors are known and are well understood, it is possible for photogrammetrists to use photographs as the basis for reconstruction of correct positional relationships and the derivation of accurate measurements. Aerial photographs record complex detail of the varied patterns that constitute any landscape. Each image interpreter must develop the skills and knowledge necessary to resolve these patterns by disciplined examination of aerial images.

## Review Questions

1. List several reasons why time of day might be very important in flight planning for aerial photography.
2. Outline advantages and disadvantages of high-altitude photography. Explain why routine high-altitude aerial photography was not practical until infrared films were available.
3. List several problems that you would encounter in acquiring and interpreting large-scale aerial photography of a mountainous region.
4. Speculate upon the likely progress of aerial photography since 1890 if George Eastman had not been successful in popularizing the practice of photography to the general public.
5. Is an aerial photograph a "map"? Explain.
6. Assume you have recently accepted a position as an employee of an aerial survey company; your responsibilities include preparation of flight plans for the company's customers. What are the factors that you must consider as you plan each mission?
7. If color films and color infrared films are now available, why are black-and-white films still widely used?
8. Suggest circumstances in which oblique aerial photography might be more useful than vertical aerial photography. Identify situations in which oblique aerial photography would clearly *not* be suitable.
9. It might seem that large-scale aerial photographs might always be more useful than small-scale aerial photographs, yet larger scale images are not always the most useful. What are disadvantages to the use of large-scale images?
10. A particular object will not always appear the same when photographed by an aerial camera. List some of the factors that can cause the appearance of an object to change from one photograph to the next.

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## YOUR OWN INFRARED PHOTOGRAPHS

Anyone with even modest experience with amateur photography can take infrared photographs using commonly available materials. A 35-mm camera, with some of the usual filters, will be satisfactory. Infrared films can be purchased at camera stores (but are unlikely to be available at stores that do not specialize in photographic supplies). Infrared films are essentially similar to the usual films, but should be used promptly, as the emulsions deteriorate much more rapidly than do those of normal films. To maximize life of the film, it should be stored under refrigeration according to manufacturer's instructions.

Black-and-white infrared films should be used with a deep red filter to exclude most of the visible spectrum. Black-and-white infrared film can be developed using normal processing for black-and-white emulsions, as specified by the manufacturer.

Color infrared (CIR) films are also available in 35-mm format. They should be used with a yellow filter, as specified by the manufacturer. Processing of CIR film will require the services of a photographic laboratory that specializes in customized work, rather than the laboratories that handle only the more popular films. Before purchasing the film, it is best to inquire concerning the availability and costs of processing.

Results are best with bright illumination. The photographer should take special care to face away from the sun while taking photographs. Because of differences in the reflectances of objects in the visible and the near infrared spectrums, the photographer should anticipate the nature of the scene as it will appear on the infrared film. Artistic photographers have sometimes used these differences to create special effects.

The camera lens will bring infrared radiation to a focal point that differs from that for visible radiation, so infrared images may be slightly out of focus if the normal focus is used. Some lenses have special markings to show the correct focus for infrared films.

## YOUR OWN 3D PHOTOGRAPHS

You can take your own stereo photographs using a handheld camera simply by taking a pair of overlapping photographs. Two photographs of the same scene, taken from slightly different positions, create a

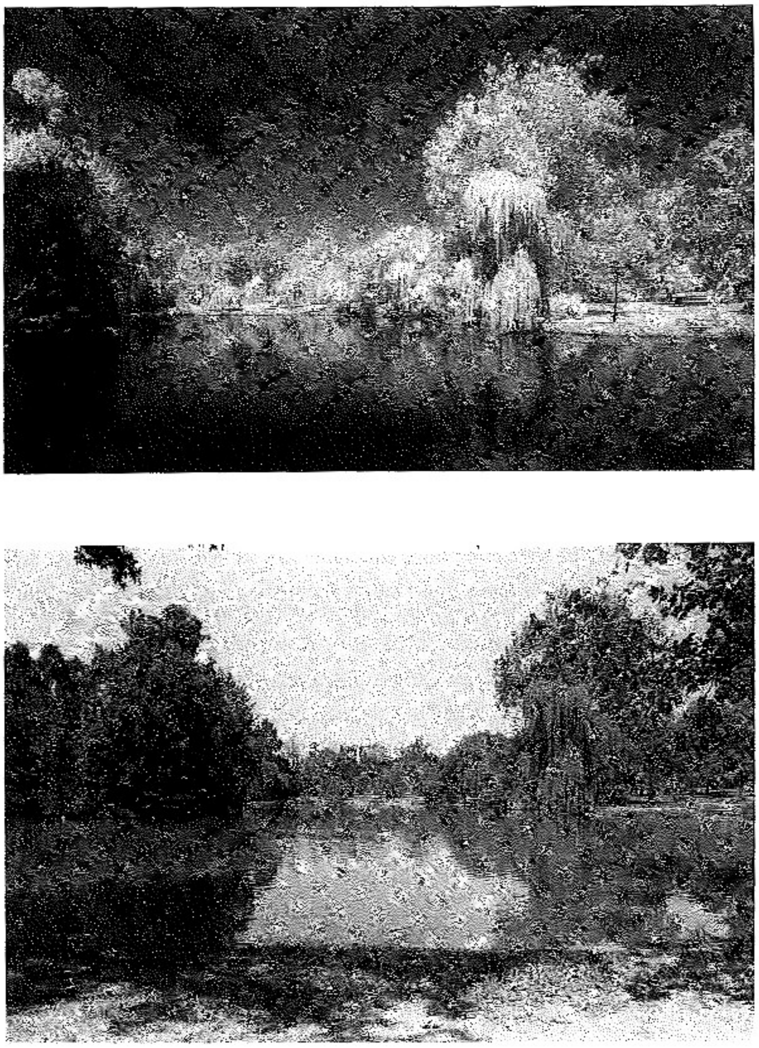

**FIGURE 3.32.** Black-and-white infrared photograph (top), with a normal black-and-white photograph of the same scene (bottom) shown for comparison.

**FIGURE 3.33.** Stereo photographs.

stereo effect in the same manner that overlapping aerial photographs provide a three-dimensional view of the terrain. This effect can be accomplished by aiming the camera to frame the desired scene, taking the first photograph, then moving the camera laterally a short distance, then taking a second photograph that overlaps the field of view of the first. The lateral displacement need only be a few inches (equivalent to the distance between the pupils of a person's eyes), but a displacement of a few feet will often provide a modest exaggeration of depth that can be useful in distinguishing depth. However, if the displacement is too great, the eye cannot fuse the two images to simulate the effect of depth.

Prints of the two photographs can then be mounted side by side to form a stereo pair that can be viewed with a stereoscope, just as a pair of aerial photos can be viewed in stereo. Stereo images can provide three-dimensional ground views that illustrate conditions encountered within different regions delineated on aerial photographs. Section 5.13 provides more information about viewing of stereo photographs.