4

LAND AREA DETERMINATION

Generally speaking, foresters do not conduct many original property surveys. However, they often retrace old lines, locate boundaries, run cruise lines and transects, and so on. In fact, much forest mensurational work requires the location, delineation, preparation of maps, and determination of the magnitude of land areas and information on their characteristics and the organisms found thereon. Of prime importance are forestlands and their characteristics: topography, soils, water, forest and other vegetation, and wildlife. The methods and equipment to acquire and use this information go well beyond the field of forest mensuration and involve many other disciplines that cannot be covered here: They demand specialized training and references. Nevertheless, their existence and usefulness require brief mention.

For many years foresters have employed simple land surveying methods in fieldwork and have employed remote sensing from aerial photographs and from satellite imagery. Added to these techniques are the more recent developments of geographic information systems (GISs) and global positioning systems (GPSs).

In this book only a brief treatment of simple distance measurement and direction determination by magnetic compass is covered since, despite being approximate procedures, they are still of great use in fieldwork, especially in forest inventories. Although a text on forest mensuration cannot go into detail on aerial photographic interpretation, geographic information systems, or global positioning systems, mention must be made of their fundamentals and usefulness.

4-1. LAND DISTANCE AND AREA UNITS

Measurement of land distances and areas is a commonplace requirement in forest mensuration. Under the metric system the most important units are the meter and kilometer. Under the older English system, lengths are usually expressed in feet, yards, chains, or miles. However, older linear units are still often used or encountered in documents and deeds. The linear unit of a *chain* (often called *Gunter's chain*) is still used in much forest mensuration work and in land surveying. A chain is 66 ft long and is divided into 100 links, each 0.66 ft or 7.92 in. long.

Older length units that have fallen into disuse in land surveying (but may be found in older deeds) are poles, rods, and perches: 1 pole = 1 rod = 1 perch = 25 links = 16.5 ft. Four rods equal 1 chain. A length of 10 chains is a furlong.

Of primary importance in forest mensuration is the expression of land area. In the older English system, the most used expression of land area is the acre or fractions of it. An acre consists of 43,560 ft^2. This seemingly odd dimension is based on the older linear unit of a chain used in land surveying. One acre equals 10 square chains (10 ch × 1 ch or 660 ft × 66 ft = 43,560 ft^2). A mile is 5280 ft or 80 chains (80 × 66 = 5280). One square mile equals 640 acres ($5280^2/43{,}560 = 640$).

In the metric system the most commonly used expression of land area is the hectare. The hectare is an area of 10,000 m^2 or 0.01 km^2. Thus a land area of 100 m × 100 m or 0.1 km × 0.1 km is 1 hectare, approximately equivalent to 2.47 acres. Conversion factors for area between the English and metric systems are given in Appendix Table A-1.

4-2. MEASURING DISTANCES

In land surveying, the distance between two points is commonly meant to be the horizontal distance. Although slope distances are sometimes measured in the field, these distances are subsequently reduced to their horizontal equivalents, since horizontal distances are the ones used in the preparation of maps and in the computation of areas. The method used in obtaining the distance between two points is determined largely by the accuracy required. Traditional methods include pacing and chaining. Optical rangefinders and electronic distance measurement devices have been in use since the 1960s, but recent improvements in technology and reductions in costs have made these instruments more common. The accessibility of GPSs is revolutionizing the measurement of distances and areas in forest inventory work. GPS is described in Section 4-8; the other methods of distance measurement are described below.

4-2.1 Pacing

Where approximate results are sufficient, as in making tree-height measurements with certain hypsometers, in reconnaissance work, and in some types of cruising, distance can be obtained by *pacing*. Although many people think of a pace as a single step, the forester and others who work in natural resources often define a pace as a double step. Thus, as used here, a *pace* is two steps.

To graduate the pace, a recommended procedure is to establish a measured line of a convenient length such as 20 chains, 1320 ft or 400 m in terrain of the type encountered in fieldwork. Stakes should be set on the line at given distances: for example, in chains, at 0, 5, 10, 15, and 20 chains: in meters, at 0, 100, 200, 300, and 400 m. One should walk as naturally as possible, a minimum of four times over the line, record the number of paces between each pair of stakes, and compute the average number of paces between each pair of stakes and for each trip. From this, one can get a good picture of the consistency of the pacing and can determine the number of paces for the terrain. The pace should be graduated to meet the varying conditions encountered: wooded slopes of 0 to 10 percent, wooded slopes of 10 to 20 percent, open level woods, and so on. On slopes over 30 percent, in swamps, and in logged areas with slash on the ground, it is very difficult to pace accurately.

On steep slopes the method of *staff pacing* can be used. To staff pace one uses a 4.125-ft or 1.24-m staff. This gives 16 staffs to a chain, or 16 staffs to 20 m. The staff is used as follows for traveling uphill: While holding the staff horizontal, the ground position of the rear end of the staff is located by plumbing by eye and the forward end of the staff by contact with the ground. For traveling downhill: While holding the staff horizontal, the ground position of the rear end of the staff is in contact with the ground and the forward end is located by plumbing by eye.

With foot or staff pacing, an experienced pacer should consistently attain an accuracy of $\frac{1}{100}$ or better. Pacing skills need to be practiced regularly and checked periodically. Recent developments in affordable electronic distance measuring devices and GPS have resulted in pacing falling into disuse; however, these devices are subject to operational error, and pacing can be used as an important field check to identify and correct these errors.

4-2.2 Distances with Chains and Polytapes

The types of tapes commonly used by natural resource managers in North America to measure horizontal distances are the 100-ft *steel tape* and the steel *topographic trailer tape*. For measuring distances in meters, 30- and 50-m tapes are convenient to use. Tapes are usually constructed from steel, nylon-clad steel, fiberglass cloth, or plastic.

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The basic procedure for measuring distance with either chains or tapes requires two people, traditionally referred to as the *head chainman* and the *rear chainman*. On level terrain, the chain (or tape) can be stretched directly on the ground. The starting point is marked with a pin and the head chainman pulls the zero end of the tape forward following the desired compass bearing. The rear chainman checks direction and warns the head chainman when the end of the tape is approaching by shouting “Chain”. The head chainman pulls the tape taut until the rear chainman shouts “Stick”. The head chainman then marks the zero position with another pin and shouts “Stuck.” The rear chainman picks up the pin and follows the chain to the next pin and the head chainman pulls the chain forward to the next point. The procedure is repeated until the desired distance has been measured.

In rough terrain, the tape is held off the ground and plumb bobs are used to determine accurate pin placement. On very steep terrain, horizontal distances are obtained by either *breaking chain* or using a topographic trailer tape. Breaking chain is simply using shorter segments of the chain to hold a level line.

The topographic trailer tape is graduated in chains and links (Section 4-1). There are three tabs on a trailer tape: one at 0 links, one at 100 links (1 chain), and one at 200 links (2 chains). Beyond the 2-chain tab there is about $\frac{1}{2}$ chain of tape that trails the body of the tape. The trailer is used to convert slope distance to horizontal distance. The topographic trailer tape is used with a clinometer, such as an Abney level that has a *topographic (topo) arc*. The topographic arc is graduated in an angular unit that represents 1 unit vertically to 66 units horizontally. For example, a topo reading of +17 indicates a vertical rise of 17 ft per 66 ft, or 17 ft per chain.

Since a slope distance is greater than its horizontal equivalent, if one measures 2 chains along a slope, a correction must be added to obtain 2 chains of horizontal distance (Fig. 4-1). The trailer on the topographic trailer tape carries corrections for converting a slope distance of 2 chains to 2 chains of horizontal distance. These corrections are on the top of the tape. Corrections for converting a slope distance of 1 chain to 1 chain of horizontal distance are on the underside of the tape beyond the 1-chain tab. The corrections are applied as follows. For example, if a topo reading of 15 is obtained for a slope distance of 2 chains, and the trailer is let out to the 15 graduation, the slope distance becomes the hypotenuse of a right triangle whose horizontal leg is 2 chains. If a topo reading of 20 is obtained for a slope distance of 1 chain, the proper correction is applied when the tape is let out to the 20-graduation mark on the underside of the tape beyond the 1-chain tab.

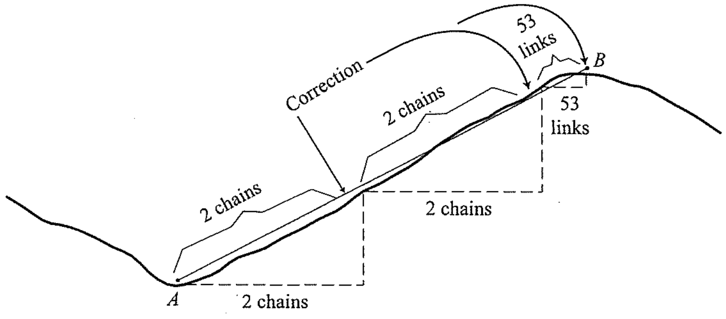


FIG. 4-1. Applying slope corrections.

When it is necessary to measure slope distances of less than 1 chain or between 1 and 2 chains, tables are used to obtain the necessary corrections. For example, Table 4-1 shows the amount that must be added per chain of slope distance on different grades to obtain 1 chain of horizontal distance. Table values are obtained from

$$\text{correction per chain} = \sqrt{1.0 + \left(\frac{\text{topo reading}}{66}\right)^2} - 1 \qquad (4\text{-}1)$$

Thus, for a topo reading of 33, the correction per chain of slope distance is 0.118 chain (11.8 links). For other slope distances on the same grade, the correction equals the slope distance times 0.118 chain. For a slope distance of 0.73 chain, the correction will be 0.118 times 0.73, or 0.086 chain (8.6 links). When $0.73 + 0.086 = 0.816$ chain (81.6 links) is measured along the slope, a horizontal distance of 0.73 chain will be obtained. For a distance of 1.50 chains, the correction would be 0.118 times 1.50, or 0.177 chain (17.7 links).

Despite technological developments, the topographic trailer tape continues to be an important tool in land measurement. In rough, wooded, wild lands where great accuracy in distance measurement is not required, it permits fast, cheap measurement of boundary lines, cruise lines, and traverse legs as well as inexpensive method of obtaining elevations. Careful chaining on horizontal distances by experienced foresters should result in accuracies of $\frac{1}{1000}$ to $\frac{1}{2500}$.

4-2.3 Optical Rangefinders

Optical rangefinders work on the same principle as focusing a single-lens reflex (SLR) camera. A split image or double image is created in the viewfinder using mirrors or prisms. A focusing knob is used to make the two images coincident. Distance is either read from a vernier scale on the focusing knob or is calculated electronically. There are two types of optical rangefinders: fixed base and fixed angle. In a *fixed-base rangefinder*, the distance between the mirrors is fixed and the angle is manipulated to bring the images coincident. In a *fixed-angle rangefinder*, the angle is fixed and the distance is manipulated to bring the two images coincident.

Optical rangefinders are compact, lightweight, and inexpensive. Models with a range of about 10 to 75 m (30 to 200 ft) are available for less than US\$50. Models with a range of 50 to 1000 m (150 to 3000 ft) cost around US\$300. Optical rangefinders must be calibrated periodically and offer an accuracy of $\frac{1}{100}$.

TABLE 4-1. Correction Factors to Add to a 1-Chain Slope Distance on Different Grades to Obtain a 1-Chain Horizontal Distance[a]

Topo Reading	Correction (chains per chain)	Topo Reading	Correction (chains per chain)	Topo Reading	Correction (chains per chain)	Topo Reading	Correction (chains per chain)
1	0.000	31	0.105	61	0.362	91	0.703
2	0.000	32	0.111	62	0.372	92	0.716
3	0.001	33	0.118	63	0.382	93	0.728
4	0.002	34	0.125	64	0.393	94	0.740
5	0.003	35	0.132	65	0.404	95	0.753
6	0.004	36	0.139	66	0.414	96	0.765
7	0.006	37	0.146	67	0.425	97	0.778
8	0.007	38	0.154	68	0.436	98	0.790
9	0.009	39	0.162	69	0.447	99	0.803
10	0.011	40	0.169	70	0.458	100	0.815
11	0.014	41	0.177	71	0.469	101	0.828
12	0.016	42	0.185	72	0.480	102	0.841
13	0.019	43	0.194	73	0.491	103	0.854
14	0.022	44	0.202	74	0.502	104	0.866
15	0.026	45	0.210	75	0.514	105	0.879
16	0.029	46	0.219	76	0.525	106	0.892
17	0.033	47	0.228	77	0.537	107	0.905
18	0.037	48	0.236	78	0.548	108	0.918
19	0.041	49	0.245	79	0.560	109	0.931
20	0.045	50	0.255	80	0.571	110	0.944
21	0.049	51	0.264	81	0.583		
22	0.054	52	0.273	82	0.595		
23	0.059	53	0.283	83	0.607		
24	0.064	54	0.292	84	0.619		
25	0.069	55	0.302	85	0.631		
26	0.075	56	0.311	86	0.643		
27	0.080	57	0.321	87	0.655		
28	0.086	58	0.331	88	0.667		
29	0.092	59	0.341	89	0.679		
30	0.098	60	0.351	90	0.691		

[a] Correction factors for other than 1-chain distances are obtained by multiplying the correction factor by the slope distance in chains.

4-2.4 Electronic Distance Measurement Devices

The past decade has seen major improvements in laser technology. A number of laser-based rangefinders and distance measurement devices are currently available. These devices measure distance by measuring the flight time of short pulses of infrared light. Using the speed of light, the distance to an object is estimated by measuring the time it takes a laser pulse to travel to the target and back to the receiver.

Most laser rangefinders operate with or without reflectors. Without reflectors, the effective distance of most devices in forest conditions is about 20 m (Peet et al., 1997). Understory vegetation limits the effective range of most reflectorless lasers. With a reflector, most devices have an effective range of 50 to 100 m, depending on understory vegetation and weather conditions.

Accuracy of handheld laser-based rangefinders varies from about $\frac{1}{250}$ to $\frac{1}{2000}$ depending on laser strength, mode (reflectorless versus reflector), weather conditions, understory vegetation, and the surface roughness of the object being sighted. Accuracy of most devices is improved by using reflectors and/or tripods. Laser-based rangefinders vary in cost from about US$300 to US$3000.

Ultrasonic rangefinders are also used in forestry applications. These devices emit a narrow beam of sound waves that bounce off solid targets and return to the receiver. Using the speed of sound and elapsed time, the distance to the object is estimated. Effective use of most ultrasonic rangefinders in forestry conditions requires the use of a transponder. In this case, the receiver emits a sonic pulse, and when the transponder detects the pulse, the transponder emits a pulse back to the receiver. Most handheld sonic devices have a maximum range of about 20 to 30 m (60 to 100 ft). Sonic devices need to be calibrated frequently, especially if temperatures are fluctuating. Ultrasonic rangefinders vary in cost from about US$150 to US$1000.

4-2.5 Maps and Photos

Field distances can be determined using maps and aerial photographs of known scale. Distances along edges of cuts or other identifiable boundaries or between two points are measured on the map or photograph in inches or centimeters. These "map" distances are converted to ground distances using the map scale.

Map scales are generally given as representative fractions. A *representative fraction* (RF) specifies the number of ground units of distance represented by 1 unit of map distance. For example, an RF of 1:15000 means that 1 in. of map distance represents 15,000 in. on the ground. Generally, ground distances are specified in feet or meters rather than in inches or centimeters; therefore, representative fractions are often converted to dimensional equivalents by dividing the right-hand side of the RF by 12 to obtain ground feet per map inch, or by 100 to obtain ground meters per map centimeter. Map scales may also be shown graphically in the form of a *bar scale*. The bar scale depicts the map distances for standard ground distances such as 100 ft or 100 m using alternating strips of black and white rectangular bars. Bar scales are extremely useful when maps are reduced or enlarged from their original scales since the change in bar scale will be the same as the change in map scale.

The following example illustrates the conversion of map distance to ground distance. The distance between two points on a 1:15,000 scale photo was determined to be 6.8 in. (17.3 cm). With an RF of 1:15,000, 1 in. = 15,000/12 = 1250 ft; therefore, 6.8 in. on the photo = 6.8(1250) = 8500 ft on the ground. In metric units, with an RF of 1:15,000, 1 cm = 15,000/100 = 150 m; therefore, 17.3 cm = 17.3(150) = 2595 m on the ground.

4-3. MEASURING AREA IN THE FIELD

In situations where recent maps or photographs are not available, it may be necessary to determine the area of cuts or other management blocks using simple closed traverses made with a hand or staff compass and chain or other measuring tape. Starting at the most reliable corner available, the distances and bearings to each point, typically called a *station*, are measured and recorded. Backsights and frontsights are generally recorded and stakes driven into the ground at each station. The block boundary is traversed back to the origin. After the traverse is completed, the interior angles at each station are computed. If the bearings have been read and recorded properly, the sum of the interior angles should be equal to 180°($n - 2$), where n is the number of sides in the traverse. All basic surveying textbooks describe methods for adjusting the interior angles for errors. Once the interior angles are checked and adjusted, the traverse is plotted at a convenient scale. If the horizontal distances have been measured and recorded correctly, the traverse should *close* (i.e., form a complete loop). The tract area can be determined using one of the methods described below or calculated using the double meridian distance method. An introductory surveying textbook such as Wilson (1989) or McCormac (1999) should be consulted for detailed descriptions of field and analysis methods for closed traversing. GPS technology can also be used to determine areas in the field (Section 4-8.5).

4-4. MEASURING AREA USING MAPS AND PHOTOS

Areas of polygons on maps or aerial photographs can be digitized and determined using techniques provided by GISs (see Section 4-9). Alternatively, areas may be determined using older, manual methods such as calculation by coordinates, line transects, dot grids, or planimeters.

4-4.1 Area by Coordinates

Data from a closed traverse (Section 4-3) are often plotted as part of the process of checking the closure error. The points representing the stations can be converted to X–Y coordinates and the area calculated using the *continuous product method*. Given the direction and distance between two points A and B (Fig. 4-2) of each line forming the boundary of an area, the X and Y coordinates at the ends of each line can be calculated. The north–south vector is Y and the east–west vector is X. The coordinates of all vertices are obtained by addition or subtraction of successive vectors (Fig. 4-2), and the area of the figure, which must be closed, can be calculated by the continuous product method. If the X coordinates are designated as $X_1, X_2, X_3, \ldots, X_n$ and the Y coordinates as $Y_1, Y_2, Y_3, \ldots, Y_n$ the area of the polygon whose vertices are $(X_1, Y_1), (X_2, Y_2), (X_3, Y_3), \ldots, (X_n, Y_n)$ is

$$\text{area} = \tfrac{1}{2}[(X_1Y_2 + X_2Y_3 + \cdots + X_nY_1) - (X_2Y_1 + X_3Y_2 + \cdots + X_1Y_n)] \quad (4\text{-}2)$$

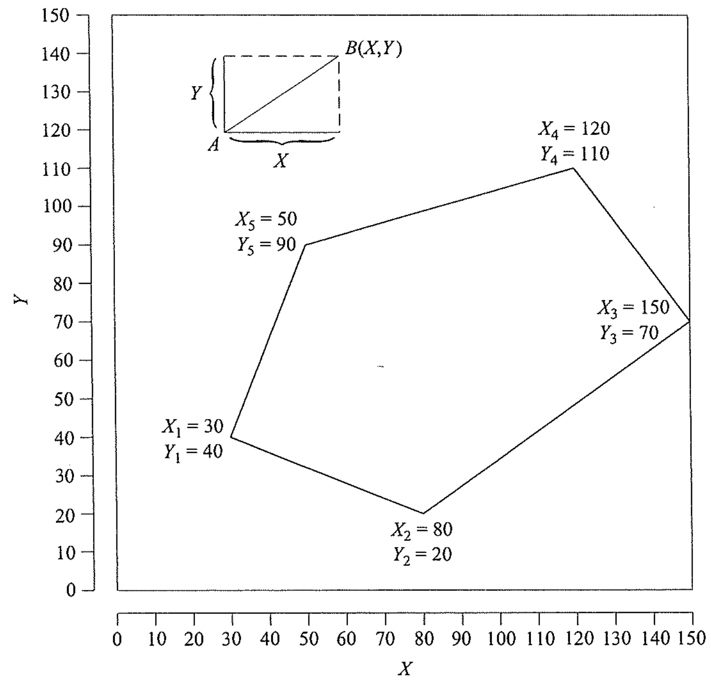


FIG. 4-2. Coordinates for vertices of a polygon.

Using the coordinate values given in Fig. 4-2, the area of the polygon is

$$\begin{aligned} \text{area} &= \tfrac{1}{2}\{[30(20) + 89(70) + 150(110) + 120(90) + 50(40)] \\ &\quad - [80(40) + 150(20) + 120(70) + 50(110) + 30(90)]\} \\ &= \tfrac{1}{2}(35{,}500 - 22{,}800) \\ &= 6350 \text{ square units} \end{aligned}$$

4-4.2 Area by Dot Grids and Line Transects

If a plane figure is drawn on rectangular coordinate paper consisting of uniform squares of known area (e.g., $0.01\ \text{in}^2$), the area of the figure can be estimated by counting the number of squares that fall within the boundaries of the figure. Where boundary lines include only portions of squares, one must estimate these portions and add their total to the total number of whole squares within the boundaries. If the figure represents an area drawn to a scale (e.g., a timber type), the area of the figure can be converted to the area represented by computing, for the known scale, the appropriate scale conversion (e.g., acres per square inch or hectares per square centimeter).

If a dot is placed in the center of each square on the rectangular coordinate paper and the lines are removed, a *dot grid* is formed. (Of course, the lines may be retained, if desired.) Each dot now represents an area equal to that of the square. The area of a plane figure can then be estimated by counting the number of dots that fall within the boundaries of the figure and can be converted to the area represented by computing the appropriate scale conversion. Dot grids, generally on transparent sheets, can be prepared or purchased with varying numbers of dots per unit area.

For example, in Fig. 4-3, a dot grid has been placed over a photo. There are 64 dots per square inch, so each dot represents $0.016\ \text{in}^2$. In the area outlined, 375 dots are counted. The area on the map is then $0.016 \times 375 = 5.86\ \text{in}^2$. The photo scale is 1:7920; therefore, $1\ \text{in.} = 7920/12 = 660\ \text{ft}$ and $1\ \text{in}^2 = 660^2 = 435{,}600\ \text{ft}^2 = 10\ \text{acres}$. The ground area is then found to be $5.86 \times 10 = 58.6$ acres. For a more accurate estimate of area, the procedure should be repeated several times. Each time, the dot grid is randomly placed over the photo and the number of dots counted. The average number of dots is then determined and the areas calculated.

In addition to being used to obtain the area of individual figures, dot grids may be used to obtain area ratios. For example, a dot grid can be placed over a map or aerial photograph on which numerous forest types are outlined, and the number of dots within each type counted. Then the ratio of the number of dots in each type to the total number of dots on the map or photograph can be computed. The total area of the map or photograph can then be multiplied by the ratios to obtain the type areas.

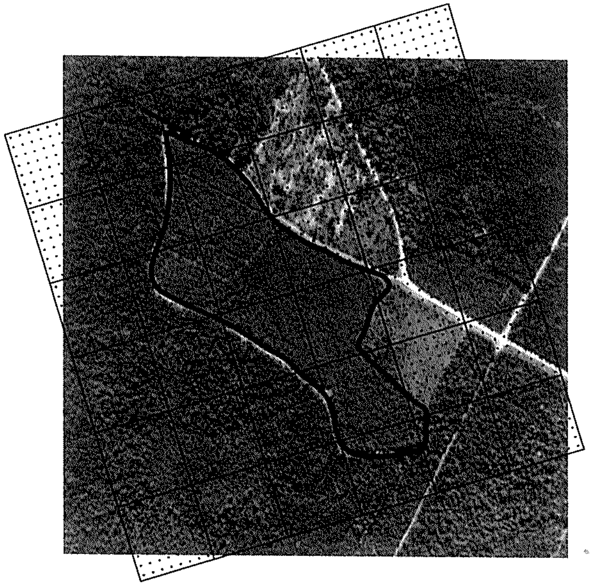


FIG. 4-3. Area by dot grid.

An analogous procedure for determining the area of plane figures is the *line-transect method*, which is used to determine area ratios. For example, equally spaced lines are drawn on a map or an aerial photograph on which numerous forest types are outlined, and the lengths of lines within each type are measured. Then the ratios of the lengths in each type to total line length on the map or aerial photograph can be computed. These ratios can be used in the same manner as ratios computed by the use of dot grids.

4-4.3 Area by Planimeters

The *planimeter*, invented in 1854 by Jacob Amsler, is a mechanical device for measuring the area of plane figures. With this instrument, areas can be obtained on maps, photographs, drawings, and diagrams. Over the years, Amsler's polar planimeter has been greatly improved, and other forms, such as the rolling disk planimeter, have been developed. In addition, computing planimeters with built-in calculators that can be programmed for any scale ratio are available.

The traditional polar planimeter consists of a *pole arm*, a *tracing arm*, and a *carriage*. The carriage furnishes bearings for a vertical measuring wheel that revolves on a horizontal axis. When set in position, the instrument rests on three points: a fixed point at the end of the pole arm, the measuring wheel, and the tracing point. As the tracing point is moved about, the instrument pivots about the fixed point and the wheel revolves. To determine an area, one simply moves the tracing point once around the boundary of a figure and reads the resulting movement of the measuring wheel, which is graduated for this purpose. In effect,

$$\text{area} = 2\pi r \cdot \text{TB} \cdot n \tag{4-3}$$

where r = radius of measuring wheel
TB = length of planimeter tracing arm
n = algebraic sum of rotations of measuring wheel

[Note that $2\pi r \cdot \text{TB}$ is a constant for a given planimeter. Thus the measuring wheel is graduated in terms of n times this constant.]

Modern digital planimeters work on a similar concept. The planimeter shown in Fig. 4-4 consists of a roller arm, tracing arm, integrating wheel, and encoder. The tracing point is moved once around the boundary to obtain area. The planimeter pivots on the roller arm as the tracing point is moved around the boundary.

4-5. DETERMINATION OF PHOTO SCALE

Photographs may be taken from the air or the ground. If an aerial photograph is exposed with the camera axis vertical, or nearly vertical, it is called a *vertical photograph*. If an aerial photograph is exposed with the camera axis intentionally tilted, it is called an *oblique photograph*. An oblique photograph in which the apparent horizon is shown is a *high oblique*; one in which the apparent horizon is not shown is a *low oblique*. If a photograph is taken from a fixed position on the ground, it is called a *terrestrial photograph*. Foresters deal primarily with vertical aerial photographs. However, one should understand that both oblique and terrestrial photographs have important mensurational applications.

Aerial photographs play an important role in forest mensuration. Most forest stand maps are prepared based on aerial photographs. Variables used to delineate stands vary from organization to organization, but in general include species composition, crown cover, density, and height. The resulting stand maps often form the basis of many forest inventory designs (Chapter 13). In addition to mapping, many aspects of forest mensuration, such as height measurement, can be made using stereoscopic photographs. The treatment of these subjects is beyond the scope of this book. For a detailed treatment of the interpretation and mensuration of aerial photographs, see Paine (1981).

Scale of an aerial photograph can be determined easily using a few simple formulas. The *scale*, or *representative fraction*, of a vertical photograph is the ratio of a distance on the photograph to the corresponding distance on the ground when the object and image planes are parallel. From Fig. 4-5, the scale S is

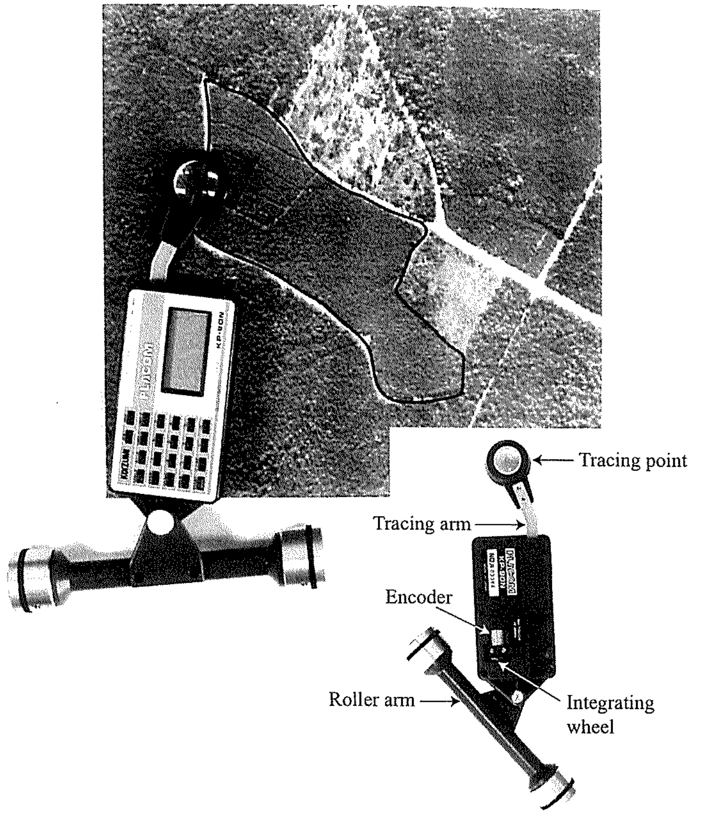


FIG. 4-4. Area measurement with planimeter.

$$S = \frac{\text{photo distance}}{\text{ground distance}} = \frac{ab}{AB} \tag{4-4}$$

Scale can also be determined as the ratio of focal length f and altitude $(H - h)$:

$$S = \frac{f}{H - h} \tag{4-5}$$

It should be noted that scale is expressed as a fraction with 1 as the numerator. Thus a photograph that has a scale of 1:12,000 has 1 unit on the photograph equal to 12,000 units on the ground.

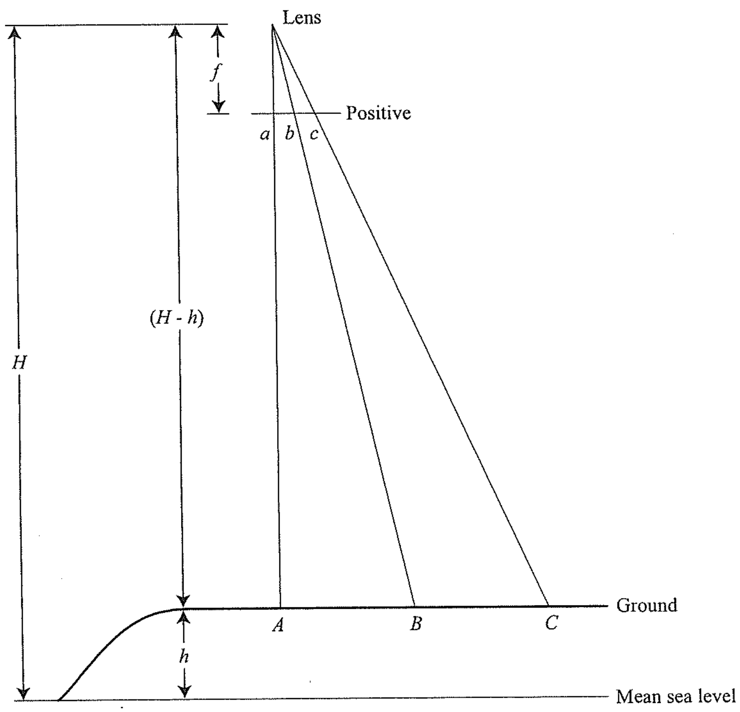


FIG. 4-5. How ground objects are imaged in the positive plane for vertical photographs. a, b, and c are photo images of ground points A, B, and C. Thus ab is photo distance, AB is ground distance, H is the height of the lens above mean sea level, h is the height of the terrain above mean sea level, and $H - h$ is the height of the lens above the ground (i.e., flying height above the ground).

To facilitate calculations, it is desirable to use the photo scale reciprocal ($\mathrm{PSR} = 1/S$) instead of scale. Then

$$\mathrm{PSR} = \frac{AB}{ab} \tag{4-6}$$

and

$$\mathrm{PSR} = \frac{H - h}{f} \tag{4-7}$$

Note that in all of the formulas above, distances must be in the same units.

From eqs. (4-6) and (4-7), the following relationship is obtained, from which other photo mensurational formulas can be derived:

$$\frac{AB}{ab} = \frac{H - h}{f} \tag{4-8}$$

Another useful relationship utilizes PSR and MSR (map scale reciprocal):

$$\frac{\mathrm{PSR}}{\mathrm{MSR}} = \frac{\text{map distance}}{\text{photo distance}} \tag{4-9}$$

A few examples will illustrate the use of the equations above and some scale conversions that are best computed from the PSR.

Example 1. The distance between two road intersections is 3350 ft on the ground and 4.22 in. on a photo. What is the PSR of the photo? Using eq. (4-6) gives us

$$\mathrm{PSR} = \frac{AB}{ab} = \frac{12(3350)}{4.22} = 9526$$

Example 2. Find the PSR of a photograph taken with a 152.36-mm focal-length camera at an elevation of 1981 m above mean sea level over terrain that is 300 m above mean sea level. Using eq. (4-7), we have

$$\mathrm{PSR} = \frac{H - h}{f} = \frac{1000(1981 - 300)}{152.36} = 11,033$$

Example 3. A photographic crew has a camera with an 8.25-in. focal-length lens. At what altitude (in feet) above the ground must they fly to produce prints with a scale of 1:20,000 (i.e., $\mathrm{PSR} = 20{,}000$)? Using eq. (4-7) and solving for $H - h$ yields

$$H - h = \frac{f \cdot \mathrm{PSR}}{12} = \frac{8.25(20{,}000)}{12} = 13{,}750 \text{ ft}$$

Example 4. Suppose that the smallest image that can be distinguished consistently on aerial photographs has a diameter of 0.002 in. If you fly some photographs with an 8.25-in. focal-length camera at an altitude of 11,000 ft above ground, what would be the ground distance of the smallest tree crown you could distinguish? Using eq. (4-8) and solving for AB, we obtain

$$AB = ab\frac{H - h}{f} = 0.002\frac{11{,}000(12)}{8.25} = 32 \text{ in.}$$

Example 5. Assume that you desire the PSR of a photograph depicting some of the same area covered by a quadrangle map. You measure the distance between two road intersections across the center of the photo and find it to be 6.35 in. The corresponding distance on the map is 4.36 in. If the MSR is 24,000, what is the PSR? Using eq. (4-9) and solving for PSR gives us

$$\text{PSR} = \text{MSR}\frac{\text{map distance}}{\text{photo distance}} = 24{,}000\left(\frac{4.36}{6.25}\right) = 16{,}742$$

Example 6. Compute the following scale conversions for a 9 in. × 9 in. vertical photograph with a scale of 1:20,000 (i.e., PSR = 20,000): feet per inch, chains per inch, miles per inch, and acres per square inch.

$$\text{feet per inch} = \frac{\text{PSR}}{12} = \frac{20{,}000}{12} = 1666.67$$

$$\text{chains per inch} = \frac{\text{PSR}}{12(66)} = \frac{20{,}000}{792} = 25.25$$

$$\text{miles per inch} = \frac{\text{PSR}}{12(5280)} = \frac{20{,}000}{63{,}360} = 0.3157$$

$$\text{acres per square inch} = \left(\frac{\text{PSR}}{12}\right)^2 \frac{1}{43{,}560} = \frac{400{,}000{,}000}{144}\left(\frac{1}{43{,}560}\right) = 63.77$$

When one desires the reverse of any of these equations (e.g., inches per mile instead of miles per inch), one computes the reciprocal of the appropriate value. For example, if miles per inch = 0.3157, inches per mile = 1/0.3157 = 3.17.

4-6. DETERMINATION OF DIRECTION USING A COMPASS

The compass was one of the most important surveying instruments in the early centuries of the modern era for determining the direction of a line. It is not, however, an instrument of precision; results of great accuracy are not to be expected in compass surveys. On the other hand, it has the advantage of speed, economy, and simplicity. It is useful in retracing lines of old surveys established by compass, in running all types of boundary lines, in maintaining the direction of cruise lines, and so on. Many cases also arise in which the forester must depend on the compass for direction.

The direction of a line is generally indicated by the angle between the line and some line of reference (i.e., by an azimuth or a bearing). The line of reference is generally a true meridian or a magnetic meridian. The axis on which Earth rotates is an imaginary line cutting Earth's surface at two points: the north geographic pole and the south geographic pole. The *true meridian* at any location is the great circle drawn on Earth's surface passing through both poles and the location.

A compass consists of a magnetic needle on a pivot point, enclosed in a circular housing that is graduated in degrees. Most compasses have a sighting base attached so that it is possible to measure the angle between the line of sight and the position of the needle. An angle measured relative to the magnetic needle is referred to as a *magnetic azimuth* or *magnetic bearing*. Azimuths are horizontal angles measured clockwise from due north, whereas bearings are measured relative to a quadrant of the compass (i.e., NE, SE, SW, NW). Azimuths range from 0 to 360°, while bearings range from 0 to 90° referenced within a quadrant. For example, a bearing of N30°E corresponds to an azimuth of 30°, and a bearing of S30°E corresponds to an azimuth of 150°.

4-6.1 Magnetic Declination

The magnetic azimuth or bearing of a line can be determined by direct reading of a compass. Converting magnetic readings to true readings by applying the magnetic declination for the location can approximate the true azimuth or bearing in question. Many compasses used by foresters have the capability of being adjusted for declination. The *magnetic declination* is the angle between the true meridian and the magnetic meridian; it is considered east if the magnetic north is east of true north and west if magnetic north is west of true north (Fig. 4-6). Declination is often called *variation of the compass* or simply *varia-*

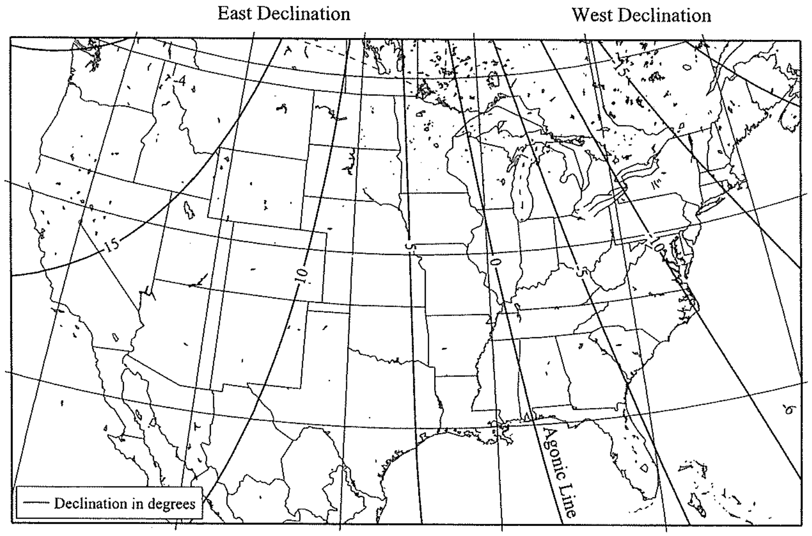


FIG. 4-6. Magnetic declination map of the United States. (From USGS National Geomagnetic Information Center.)

tion. When it is desired to attach a sign to declination east declination is considered positive, and west negative. The declination at any point can be measured with the compass when the true direction of a line can be obtained from isogonic charts such as those available from the U.S. Geological Survey. On these charts, *isogonic lines* are drawn through points where the magnetic declination is the same; the *agonic line* passes through points where the declination is zero.

At any specific point, Earth's declination is continually changing. These changes are daily variation, irregular, secular, and annual variation. *Daily variation* is a fairly systematic departure of the declination from the daily mean value. This repeats itself with fair regularity day after day. The amount of departure, however, depends on the time of day, the season, and other factors not entirely understood.

Usually, superimposed on the regular daily variation are *irregular* changes. When they become large, we say that there is a magnetic storm. These are associated with sunspots and are characterized by auroral displays and pronounced disturbances in radio-wave transmission. Since the amplitude of daily variation and irregular changes is not predictable for any one day, these changes are not considered in compass surveys.

In general, the average value of declination changes from one year to the next, and the change usually continues in one direction for many years. This is *secular* change. The amount of change in one year is called the *annual variation*. Unfortunately, there is sometimes an abrupt, unpredictable change in the rate of secular change. Thus secular change can be determined only by observations at magnetic observatories. Information from such observations are available in the United States for each state from the earliest date of valid observations to the present, at 10-year intervals up to 1900 and at 5-year intervals thereafter. This information, which is often needed for rerunning old survey lines and reestablishing corner markers in the United States, may be obtained from the National Geophysical and Solar Terrestrial Data Center at Boulder, Colorado by specifying latitude and longitude of the point in question.

In most regions the changes above are gradual enough so that one can use the same declination throughout an area for an entire season. But in some regions *local disturbances* cause large differences within small areas, sometimes several degrees within a short distance. These disturbances may be artificial, caused by human interference due to apparel worn by the observer, such as buckles, zippers, or glasses. Deposits of magnetite usually cause natural, local disturbances of several degrees. Other ores and geological formations cause smaller irregularities. However, even in undisturbed regions, minor irregularities are common. Almost anywhere, the declination at two points a short distance apart, such as 100 ft, may differ by a few minutes. Such disturbances are responsible for many of the shortcomings of the compass as a surveying instrument.

A compass survey should be made with the instrument in good condition, observing the instructions in the manual for the instrument. Although a compass may be in good operating condition, it may have an appreciable *index correction*; that is, there may be an angle between the real magnetic north and the direction shown by the compass. This correction for a specific compass may be determined by observation at a magnetic station (i.e., a marked point on the ground where the magnetic and true meridians have been determined accurately). In the United States, the National Geophysical and Solar Terrestrial Data Center at Boulder, Colorado can provide the description of the nearest magnetic station if one specifies the location of interest.

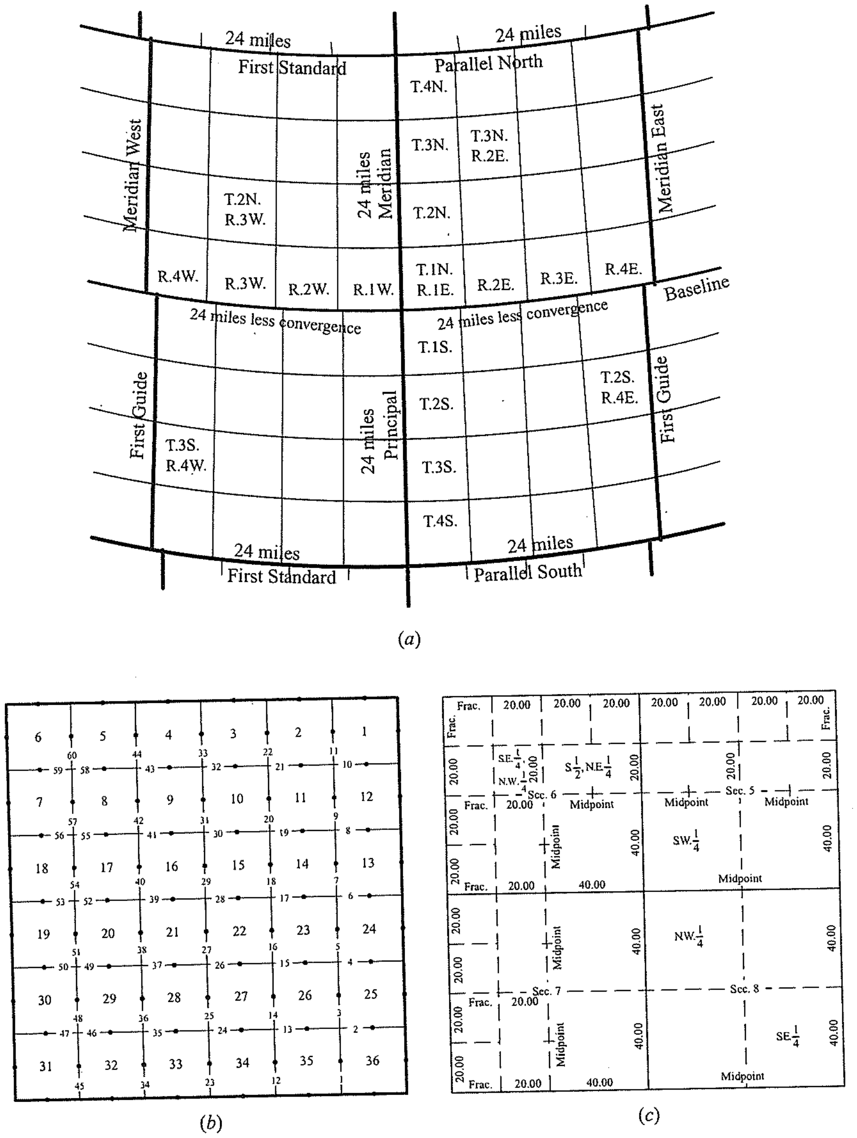
4-7. U.S. PUBLIC LAND SURVEYS

The U.S. rectangular surveying system was devised to establish legal subdivisions for describing and disposing of the public domain under the general land laws of the United States. The system uses chain units for length measurements and acres for area measurements, as described in Section 4-1. The system has been used in most of the United States with the exception of the older states along the Atlantic seaboard and in a few states where lands were in private hands before the federal government was founded. Many of the land holdings in states that do not use the U.S. rectangular surveying system are described by *metes and bounds* (*metes* means to measure or to assign by measure; *bounds* refers to a boundary); the length and direction of each side of the boundary are determined and the corners marked with survey monuments. The description of old surveys of this type are often vague and the corners difficult or impossible to relocate.

The Ordinance of 1785 established the rectangular surveying system. The system provides for townships 6 miles square, containing 36 sections 1 mile square. In any given region, the survey begins from an *initial point*. Through this point is run a meridian, called the *principal meridian*, and a parallel of latitude, called the *baseline* (Fig. 4-7*a*). With the establishment of an initial point, the latitude and longitude of the point are determined by accurate astronomical methods. Monuments are placed on the principal meridian and on the baseline at intervals of 40 chains.

Standard parallels or *correction lines* are then run for the district being surveyed. These lines, which are parallels of latitude, are established in the same manner as the baseline. They are located at intervals of 24 miles north and south of the baseline and extend to the limits of the district being surveyed. Standard parallels are numbered as First, Second, Third, and so on, Standard Parallel North, or South (Fig. 4-7*a*).

The survey district is next divided into tracts approximately 24 miles square by means of guide meridians. These lines are true meridians that start at points on the baseline, or standard parallels, at intervals of 24 miles east and west of the principal meridian, and extend north to their intersection with the next standard parallel. Because of the convergence of meridians, the distance between these lines is 24 miles only at the starting points. At all other points,



(*a*)

(*b*)

(*c*)

FIG. 4-7. U.S. Public Land Survey: (*a*) standard parallels and guide meridians; (*b*) subdivision of township; (*c*) subdivision of sections.

the distance between them is less than 24 miles. Guide meridians are numbered as First, Second, Third, and so on, Guide Meridian East, or West. Note that two sets of monuments are found on the standard parallels. The monuments that were set when the parallel was first located are called *standard corners* and govern the area north of the parallel. The second set, found at the intersection of the parallel with the meridians from the south, is referred to as the *closing corners* and govern the area south of the parallel.

The townships of a survey district are numbered meridionally (east–west) into ranges and latitudinally (north–south) into tiers from the principal meridian and the baseline of the district. As illustrated in Fig. 4-7*a*, the third township south of the baseline is in tier 3 south. Since the word *township* is frequently used instead of *tier*, any township in this tier is often designated as township 3 south. The fourth township west of the principal meridian is in range 4 west. By this method of numbering, any township is located if its tier, range, and principal meridian are given as Township 3 South, Range 4 West, of the Fourth Principal Meridian, abbreviated as T.3S., R.4W., 4th P.M.

In subdividing a township into 36 *sections*, the aim is to secure as many sections as possible that will be 1 mile on a side. To accomplish this, the error due to convergence of meridians is thrown as far to the west as possible by running lines parallel to the east boundary of the township, rather than running them as true meridians. Errors in linear measurements are thrown as far to the north as possible by locating monuments at intervals of 40 chains along the lines parallel to the east boundary of the township, all the accumulated error falling in the most northerly half-mile, which may be more or less than 40 chains in length.

The system used in numbering the sections of a township was established in 1796. This numbering system and the most recent order in which the lines are run to subdivide the township into sections (indicated by the numbers on the lines) are shown in Fig. 4-7*b*. This system of subdividing a township throws the errors due to survey and losses from convergence into the extreme north and west sections. Other sections, however, may contain more or less than 640 acres, due to survey errors. Nevertheless, the established boundaries are final, regardless of errors made in the original survey.

If any of the monuments of an original survey are missing, surveyors must know and observe the methods used in the original survey as well as the principles that have been adopted by the courts, in order to restore the missing corners correctly. Procedures for relocating original survey lines and corners are described in the U.S. Department of the Interior's (1973) *Manual of Instructions for the Survey of Public Lands in the United States.*

After all the original monuments have been found or any missing ones have been replaced, the first step in the subdivision is the location of the center of the section. Regardless of the location of the section within the township, this point is always at the intersection of the line joining the east and west quarter-section corners with the line joining the north and south quarter-section corners. By locating these lines on the ground, the section is divided into quarter sections containing approximately 160 acres each (Fig. 4-7*c*).

The method of dividing these quarter sections into 40-acre parcels depends on the position of the section within the township. For any section except those along the north and west sides of the township, subdivision is accomplished by bisecting each side of the quarter section and connecting the opposite points by straight lines (e.g., Sec. 8 in Fig. 4-7*c*). The intersection of these lines is the center of the quarter section. The method of subdividing the sections along the north and west sides of the township is shown in Fig. 4-7*c*. The corners on the north–south section lines are set at intervals of 20.00 chains, measured from the south, the discrepancy being thrown into the most northerly quarter-mile. Similarly, the monuments on the east–west lines are set at intervals of 20.00 chains, measured from the east, the discrepancy being thrown into the most westerly quarter-mile.

The rectangular system of subdivision provides a convenient method of describing a piece of land that is to be conveyed by deed from one person to another. If the description is for a 40-acre parcel, the particular quarter of the quarter section is first given, then the quarter section in which the parcel is located, then the section number, followed by the township, range, and principal meridian. Thus the 40-acre parcel labeled in Sec. 6 of Fig. 4-7*c* can be described as the S.E.$\frac{1}{4}$, N.W.$\frac{1}{4}$, Sec. 6, T.3S., R.4W., 4th P.M. The legal descriptions of other parcels appear in the figure.

4-8. GLOBAL POSITIONING SYSTEMS

Global positioning systems (GPSs) are used to determine accurately locations on Earth's surface. The technology has revolutionized surveying and fieldwork in almost all natural resource professions. Although the traditional methods described above are still widely used in forestry, GPS technology is being used to determine block boundaries, locate field plots, delineate special features such as wetlands, unique vegetation pockets, stream buffers and other protected areas, and laying out roads and trails. The components of the GPS system, how GPS works, and applications of GPS to forest mensuration are discussed here briefly. For a more complete treatment of GPS theory and applications, see Leick (1995) and Oderwald and Boucher (1997).

4-8.1 Components of GPS

The global positioning system consists of three components: a satellite segment, a control segment, and a user segment (Fig. 4-8*a*). The *satellite segment* consists of a network of 24 satellites in orbit around Earth at an altitude of 10,900 nautical miles. Each satellite completes an orbit around Earth every 12 hours. The network is configured so that the entire surface of Earth has complete satellite coverage 24 hours a day. The satellite system is called the NAVSTAR system and is operated by the U.S. Department of Defense.

The *control segment* is a series of six ground stations located around the world. The master control station (MCS) is located at Schriever Air Force Base near Colorado Springs, Colorado. The MCS receives data from the monitoring stations in real time 24 hours a day and uses that information to determine if the satellites are experiencing clock or ephemeris changes, and to detect equipment malfunctions. New navigation and ephemeris information is calculated from the monitored signals and uploaded to the satellites once or twice per day. There are five passive monitoring stations, located at Colorado Springs, Hawaii, Ascencion Island, Diego Garcia, and Kwajalein. The monitor stations send the raw data back to the MCS for processing.

The *user segment* is the user and a GPS receiver. A GPS receiver is a specialized radio receiver, designed to listen to the radio signals being transmitted from satellites and to calculate a position based on that information.

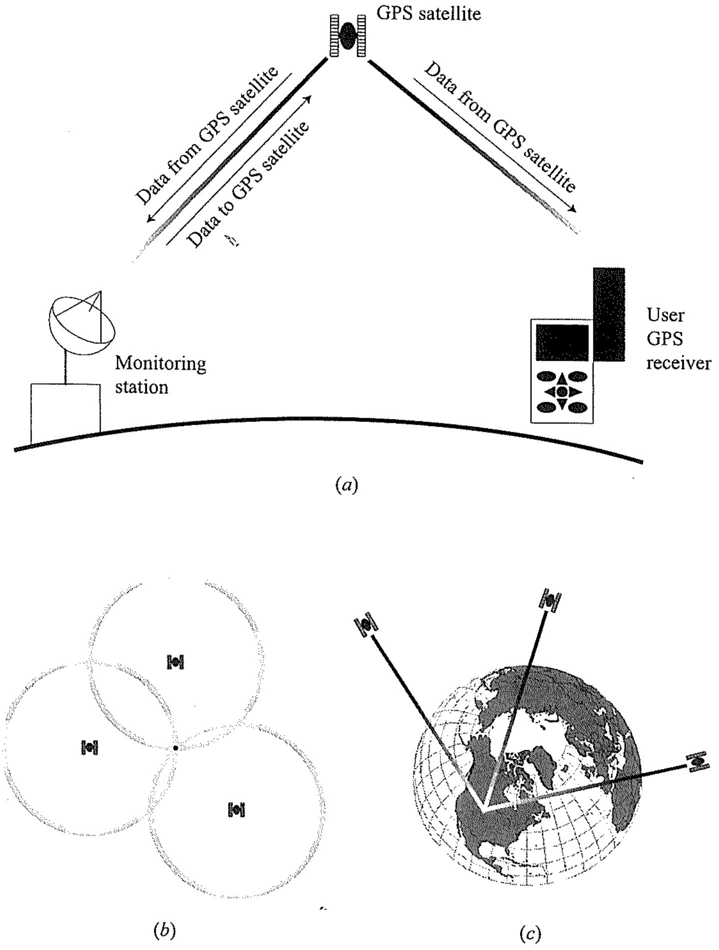


FIG. 4-8. GPS basics: (*a*) components of the system; (*b*) triangulation; (*c*) triangulation via satellite signal.

GPS receivers come in many different sizes, shapes, and price ranges. GPS receivers used for forestry applications are described in Section 4-8.4.

4-8.2 How GPS Works

GPS works using triangulation (Fig. 4-8*b*). The GPS satellites emit a radio signal in the L-band region of the microwave spectrum. These signals travel at the speed of light (186,000 miles per second). Distances between satellites and a receiver are determined by measuring the time required for the signal to reach the receiver. Each satellite's signal contains an *ephemeris* (its own location), an *almanac* (the locations of other satellites), and clock information. Four satellites are required to establish the X, Y, Z (latitude, longitude, and elevation) coordinates for a location: one satellite to establish the time and three satellites for triangulation. The radio signals propagate from the satellite as a sphere; intersection of the three spheres determines the location of the receiver (Fig. 4-8*c*).

4-8.3 Accuracy of GPS

Accurate triangulation requires that distances between the receiver and satellites be determined precisely. Distance is determined in a number of ways using the various signals broadcast from the satellites. Two signals, the coarse acquisition code and the carrier phase code, are used in civilian applications. The precise code, a third type of signal is used primarily by military and other authorized personnel.

The *coarse acquisition code* (C/A) is the most widely used GPS signal. GPS satellites have very precise clocks that are monitored and updated from the master control station. A GPS receiver generates codes that match the codes generated by the satellites at the same time. Distance is estimated using the time between a signal being emitted from the satellite and the time the signal is received. Because the clock on the receiver never has exactly the same time as the clock on the satellite, the distances are really estimates and are referred to as *pseudoranges*. A signal takes only $\frac{1}{20}$ of a second to travel from the satellite to the receiver, so even very small differences in clock times can result in large errors in distance. Because of the error in distance estimation, satellite triangulation establishes a region in which the location is likely to be located (Fig. 4-8*b*).

The *carrier phase code* is a continuous signal, and distance is determined by counting the number of complete and fractional wavelengths between two locations. Carrier phase location is much more accurate than C/A location, but acquisition of carrier phase data is time consuming and requires expensive receivers.

Prior to May 2000, the U.S. government deliberately introduced error in the satellite signals. This error was called *selective availability* (SA). With SA, location accuracies in the range of ±100 m or more were common. Since May 2000, the SA has been eliminated, except on a regional basis during periods of military conflict or other crises. Even inexpensive receivers now have accuracies of ±10 to 20 m. There are also a number of correction methods that can be applied to raw GPS location data to improve accuracies.

There are a number of factors that influence GPS accuracies:

- *Ephemeris data errors*. A satellite, at any given time, is never in its precisely assigned orbit. Satellite location errors generally result in location errors of about 1 m.
- *Satellite clock errors*. The satellite clocks are very precise and are frequently updated from the MCS. Each satellite signal carries the clock error so that satellite time can be corrected. Uncorrected clock errors generally result in location errors of about 1 m.
- *Atmospheric errors*. The ionosphere and troposphere cause signal interference. The amount of interference is dependent on weather conditions and the location of the satellite. Satellites directly overhead have smaller amounts of interference than do satellites near the horizon. Atmospheric errors generally create location errors in the range 3 to 5 m.
- *Multipath errors*. Multipath errors result from delays in signal reception caused by the signal bouncing off objects between the satellite and the receiver. Large buildings, mountains, and hills cause the greatest amount of multipath error; however, trees can also result in multipath error. Location error due to multipaths generally is in the range 2 to 3 m.
- *Receiver Noise*. Noise errors are the combined effect of code noise (around 1 m) and noise within the receiver (around 1 m).

Other errors, such as receiver malfunction and user mistakes, can result in blunders of unknown size.

4-8.4 GPS Receivers

Many different types of GPS receivers are available. Handheld receivers are used primarily in field applications. Handheld GPS units consist of an antenna, the GPS engine, a microprocessor to calculate and store locations, and a battery. The main difference between most receivers is the number of channels available to track satellites.

Receivers are categorized as either navigating receivers or mapping receivers. *Navigating receivers* are intended primarily for recreation uses, such as navigating to large features such as lakes or cabins. Most navigation receivers allow only single-point readings and dynamic lines. Navigation receivers are the least accurate of GPS receivers but are adequate for the applications intended. Costs, portability, and extended battery life are important considerations when selecting a navigating receiver. Navigation receivers cost between US$150 and about US$400.

Mapping receivers typically have many more options than navigating receivers, including the number of channels available, multiple point readings, static and dynamic lines, increased storage capacity, and the ability to interface with geographic information systems. For a comparison of the performance of different mapping receivers under forestry conditions, see Courteau and Darche (1997). High-quality mapping receivers cost between US$3000 and US$12,000.

4-8.5 Using GPS Data in Forest Mensuration

GPS data has a variety of applications in forest mensuration. Plot locations can be marked and cruise lines mapped. Block boundaries can be traversed and areas determined. Property boundaries, roads, and streams can be mapped. Data can be downloaded to geographic information systems and analyzed further or used to produce maps. Plot locations and cruise lines can also be located on geographic information systems and these data uploaded to the GPS receiver. The GPS receiver can then be used as a navigation tool for traversing cruise lines and locating plots.

To utilize GPS data effectively, one must understand how the GPS data are collected and analyzed. GPS data are typically represented as either points or lines. Points are estimates of location at a particular instant in time. Points may be based on single readings or multiple readings. A *single-reading point* is an estimate of location based on all available satellites at a single point in time. A *multiple-reading point* is the average of several single-reading estimates of the same location. Multiple-reading points are generally more accurate than single-reading points, however, more field time is required to obtain multiple readings.

Lines are connected points. In most GPS receivers, lines are created by collecting single-reading points at a specified time interval. These lines are typically called *dynamic lines* because they are created as the GPS receiver is moving. Lines can be created by connecting a series of multiple-reading points. These lines are called *static lines* because the GPS receiver must be held stationary at each point during the multiple-reading phase. Static lines are more accurate than dynamic lines; however, dynamic lines are generally quite accurate because the line is based on several connecting single-reading points.

Most GPS receivers are capable of calculating areas based on line data collected in the same manner as a closed traverse. Starting at a fixed location, the boundary of the block is traversed, with the GPS receiver collecting dynamic line data. The boundary is followed around to the starting point. The GPS receiver will ensure closure and calculate area. Area may also be calculated by connecting a series of multiple-reading points that close.

4-9. GEOGRAPHIC INFORMATION SYSTEMS

Geographic information systems (GISs) are powerful computer database programs that have the capability to input, store, manipulate and analyze, and

output spatially referenced information (Longley, 1999). The organization and presentation of spatial information is crucial to many aspects of modern forest management (Reed and Mroz, 1997).

Different types of data within a GIS are stored as *layers* (Fig. 4-9). The GIS provides the capability of overlaying different layers or combining different layers through data manipulation and analyses to produce sophisticated maps. The ability to combine and manipulate different types of data rapidly makes GIS an ideal tool for foresters. For example, a forester might combine a soils layer with a forest cover layer and a roads layer to develop a map to identify which types of machinery to use for harvesting different blocks of timber. A layer identifying the location of unique or protected areas could be added to ensure that adequate buffers are provided to protect these features.

GIS data can be stored as either vector data or raster data. *Vector-based systems* use points, lines, or polygon areas stored as series of $X-Y$ coordinates. Various attributes, such as soil type, elevation, and forest cover type, are associated with the vector elements. In *raster-based systems*, the area is divided into a matrix of cells. Data attributes for a given layer are assigned on a cell-by-cell basis. Raster-based systems are generally faster than vector-based systems and perform overlays more efficiently. Vector-based systems have more compact data structures, tend to have higher spatial accuracy, and perform calculations related to the distribution of features more efficiently. Systems that can handle both types of data are available.

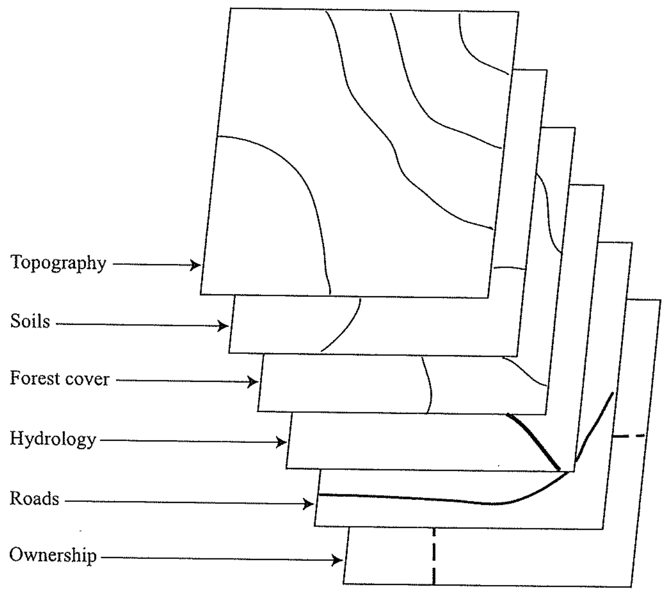


FIG. 4-9. Data layers in GIS. (Adapted from Reed and Mroz, 1997.)

The applications of GIS to forestry are immense. Applications of GIS of particular interest to forest mensuration are discussed below. Descriptions of the technology involved, data sources and structures, and the manipulation and analysis of data are beyond the scope of a forest mensuration textbook. For more information the reader is referred to one of the numerous books dedicated to GIS theory and practice (e.g., Aronoff, 1989, Longley, 1999; Longley et al., 2001). A brief but complete description of GIS is given in Landres et al. (2001).

4-9.1 Applications of GIS to Forest Mensuration

The ability to locate points, draw lines, and measure areas makes GIS an ideal tool for inventory design. The sample designs discussed in Chapter 13 can generally be developed using a GIS. For example, if random sampling is being used, most GIS systems can generate random X–Y coordinates to use as plot centers. These coordinates can be combined with other desired layers to produce maps useful for locating the plots in the field. The data can be uploaded to GPS receivers and the receivers used to navigate to the plot locations. Some GIS packages even have the capability of determining distances and bearings between plots and can design optimal routes.

By combining desired layers, forests can be stratified in a number of ways. The areas associated with different strata can be determined and stratified sampling designs developed.

Results of inventories can be added to a GIS database as another layer. Volume per unit area or other stand parameters (Chapter 8) can be combined with other layers to produce useful maps for harvesting and other forest management activities. Data from previous inventories may be used in the design of new inventories. By comparing multiple inventories, changes such as growth, regeneration, and harvesting can be tracked.