Image Resolution

9.1. Introduction and Definitions

In very broad terms, *resolution* refers to the ability of a remote sensing system to record and display fine spatial, spectral, and radiometric detail. A working knowledge of resolution is essential for understanding both practical and conceptual aspects of remote sensing. Our understanding, or lack of understanding, of resolution may be the limiting factor in our efforts to use remotely sensed data, especially at coarse spatial resolution.

For scientists with an interest in instrument design and performance, measurement of resolution is of great significance in determining the optimum design and configuration of individual elements (e.g., specific lenses, detectors, or photographic emulsions) of a remote sensing system. Here our interest focuses upon understanding image resolution in terms of the entire remote sensing system, regardless of our interests in specific elements of the landscape. Whether our focus concerns soil patterns, geology, water quality, land use, or vegetation distributions, a knowledge of image resolution is a prerequisite for understanding the information recorded on the images we examine.

The purpose of this chapter is to discuss image resolution as a separate concept in recognition of its significance throughout the field of remote sensing. Thus it is primarily an effort to outline generally applicable concepts, but it does not ignore special and unique factors that apply in certain instances.

Estes and Simonett (1975) define resolution as "the ability of an imaging system . . . to record fine detail in a distinguishable manner" (p. 879). This definition includes several key concepts. The emphasis upon the imaging *system* is significant because in most practical situations it makes little sense to focus attention upon the resolving power of a single element of the system (e.g., the film) if another element (e.g., the camera lens) limits the resolution of the final image. "Fine detail" is, of course, a relative concept, as is the specification that detail be recorded in a "distinguishable" manner. Both of these aspects of the definition emphasize that resolution can be clearly defined only by operational definitions applicable under specified conditions.

For the present, it is sufficient to note that there is a practical limit to the level of detail that can be acquired from a given aerial or satellite image. This limit we define informally as the "resolution" of the remote sensing system, although it must be recognized that image detail also depends upon the character of the scene that has been imaged, atmospheric conditions, illumination, and the experience and ability of the image interpreter.

Most individuals think of resolution as *spatial resolution,* the fineness of the spatial detail visible in an image. "Fine detail" in this sense means that small objects can be identified on an image. But other forms of resolution are equally important. *Radiometric resolution* can be defined as the ability of an imaging system to record many levels of brightness. *Coarse* radiometric resolution would record a scene using only a few brightness levels or a few bits (i.e., at very high contrast), whereas *fine* radiometric resolution would record the same scene using many levels of brightness. *Spectral resolution* denotes the ability of a sensor to define fine wavelength intervals. Hyperspectral sensors (Chapter 14) generate images composed of 200 or more narrowly defined spectral regions—these data represent an extreme of spectral data relative to thematic mapper or Landsat MSS images, which convey spectral information in only a few rather broad spectral regions.

Finally, *temporal resolution* is an important consideration in many applications. Remote sensing has the ability to record sequences of images, thereby representing changes in landscape patterns over time. The ability of a remote sensing system to record such a sequence at relatively close intervals generates a data set with *fine* temporal resolution. In contrast, systems that can record images of a given region only at infrequent intervals produce data at *coarse* temporal resolution. In some applications, such as flood or disaster mapping, temporal resolution is a critical characteristic that might override other desirable qualities. Clearly, those applications that attempt to monitor dynamic phenomena, such as news events, range fires, land-use changes, traffic flows, or weather-related events, will have an interest in temporal resolution.

In many situations, there are clear trade-offs between different forms of resolution. For example, in traditional photographic emulsions, increases in spatial resolving power are based upon decreased size of film grain, which produces accompanying decreases in radiometric resolution (i.e., the decreased sizes of grains in the emulsion portray a lower range of brightnesses). In other systems there are similar trade-offs. Increasing spatial detail requires, in scanning systems, a smaller instantaneous field of view (i.e., energy reaching the sensor has been reflected from a smaller ground area). If all other variables have been held constant, this must translate into decreased energy reaching the sensor; lower levels of energy mean that the sensor may record less "signal" and more "noise," thereby reducing the usefulness of the data. This effect can be compensated for by broadening the spectral window to pass more energy (i.e., decreasing spectral resolution) or by dividing the energy into fewer brightness levels (i.e., decreasing radiometric resolution). Of course, overall improvements can be achieved by improved instrumentation or by altering operating conditions (e.g., flying at a lower altitude). The general situation, however, seems to demand costs in one form of resolution for benefits achieved in another.

9.2. Target Variables

Observed spatial resolution in a specific image depends greatly upon the character of the scene that has been imaged. In complex natural landscapes, identification of the essential variables influencing detail observed in the image may be difficult, although many of the key factors can be enumerated. Contrast is clearly one of the most important influences upon spatial and radiometric resolution. *Contrast* can be defined as the difference in brightness between an object and its background. If other factors are held constant, high contrast favors recording of fine spatial detail; low contrast produces coarser detail. A black automobile imaged against a black asphalt brightness are used. (Pixels darker than 5 in Figure 9.9 are coded 0 in Figure 9.10a; those brighter than 5 are coded 1.) At such coarse radiometric resolution few features in the original scene can be recognized, even though the spatial resolution remains constant from one to the other.

Figure 9.10b shows the original scene recorded at finer radiometric resolution. Three brightness levels are formed by representing the original 0's, 1's, and 2's as 0's; the original 3's, 4's, 5's, and 6's as 1's; and the original 7's, 8's, and 9's as 2's. In this image the distinction between pasture and forest is evident, but the contrast between water and pasture is insufficient for these two categories to be represented as separate features.

Figures 9.10c and 9.10d show the effects of changing spatial resolution while retaining essentially the same level of radiometric resolution. In Figure 9.10c spatial resolution has been decreased to show one-fourth of the detail visible in Figure 9.9; each pixel is formed by the average of four of the smaller original pixels. Here many of the major features in the original scene are recognizable, although sizes, shapes, and positions are indistinct. Figure 9.10d shows the scene at extremely coarse spatial resolution; these values are formed by averaging brightness values over areas 16 times as large as those of the original pixels. Many of the major differences in brightness are distinguishable, although the pattern is greatly altered from the original distribution in Figure 9.9.

9.8. Interactions with the Landscape

Although most discussions of image resolution tend to focus upon sensor characteristics, understanding the significance of image resolution in the application sciences requires assessment of the effect of specific resolutions upon images of specific landscapes or classes of landscapes. For example, relatively low resolution may be sufficient for recording the essential features of landscapes with rather coarse fabrics (e.g., the broad-scale patterns of the agricultural fields of the North American Great Plains), but inadequate for imaging complex landscapes composed of many small parcels with low contrast.

Podwysocki's studies (1976a, 1976b) of field sizes in the major grain-producing regions of the world is an excellent example of the systematic investigation of this topic. His research can be placed in the context of the widespread interest in accurate forecasts of world wheat production in the years that followed large international wheat purchases by the Soviet Union in 1972. Computer models of biophysical processes of crop growth and maturation could provide accurate estimates of yields (given suitable climatological data), but estimates of total production also require accurate estimates of planted acreage. Satellite imagery would seem to provide the capability to derive the required estimates of area plowed and planted. Podwysocki attempted to define the extent to which the spatial resolution of the Landsat MSS would be capable of providing the detail necessary to provide the required estimates.

He examined Landsat MSS scenes of the United States, China, the Soviet Union, Argentina, and other wheat-producing regions, sampling fields for measurements of length, width, and area. His data are summarized by frequency distributions of field sizes for samples of each of the world's major wheat-producing regions. (He used his samples to find the Gaussian distributions for each of his samples, so he was able to extrapolate the frequency distributions to estimate frequencies at sizes smaller than the resolution of the MSS data.) Cumulative frequency distributions for his normalized data reveal the percentages of each sample that equal or exceed specific areas (Figure 9.11). For example, the curve for India reveals that 99% (or background will be more difficult to observe than a white vehicle observed under the same conditions.

The significance of contrast as an influence on spatial resolution illustrates the interrelationships between the various forms of resolution and emphasizes the reality that no single element of system resolution can be considered in isolation from the others. It is equally important to distinguish between contrast in the original scene and that recorded on the image of that scene; the two may be related, but not necessarily in a direct fashion (see Sections 3.4 and 4.2). Also, it should be noted that contrast in the original scene is a dynamic quality that, for a given landscape, varies greatly from season to season (with changes in vegetation, snow cover, etc.), and within a single day (as angle and intensity of illumination change).

The shape of an object or feature is significant. *Aspect ratio* refers to the length of a feature in relation to its width. Usually long thin features, such as highways, railways, and rivers, tend to be visible on aerial imagery, even in circumstances when their widths are much less than the nominal spatial resolution of the imagery. *Regularity of shape* favors recording of fine detail. Features with regular shapes, such as cropped agricultural fields, tend to be recorded in fine detail, whereas complex shapes will be imaged in coarser detail.

The *number* of objects in a pattern also influences the level of detail recorded by a sensor. For example, the pattern formed by the number and regular arrangement of tree crowns in an orchard favors the imaging of the entire pattern in fine detail. Under similar circumstances, the crown of a single isolated tree might not be visible on the imagery.

Extent and uniformity of background contributes to resolution of fine detail in many distributions. For example, a single automobile in a large, uniform parking area or a single tree positioned in a large cropped field will be imaged in detail not achieved under other conditions.

9.3. System Variables

Remember that the resolution of individual sensors depends in part upon the design of that sensor and in part upon its operation at a given time. In any specific situation these considerations must be acknowledged. Studies to determine their roles in defining resolution should be performed. For example, resolution of an aerial photograph (Chapter 3) is determined by the quality of the camera lens, the choice of film, flying altitude, scale, and the design of the aerial camera. For scanning systems such as the Landsat MSS/TM (Chapter 6) or thermal scanners (Chapter 8), the IFOV determines many of the qualities of image resolution. The IFOV depends, of course, upon the optical system (the angular field of view) and operating altitude. Speed of the scanning motion and movement of the vehicle that carries the sensor will also have their effects upon image quality. For active microwave sensors (Chapter 7), image resolution is determined by beamwidth (antenna gain), angle of observation, wavelength, and other factors discussed previously.

9.4. Operating Conditions

For all remote sensing systems, the operating conditions, including flying altitude and ground speed, are important elements influencing the level of detail in the imagery. Atmospheric conditions can be included as important variables, especially for satellite and high-altitude imagery.

9.5. Measurement of Resolution

Ground Resolved Distance

Perhaps the simplest measure of spatial resolution is *ground resolved distance* (GRD), defined simply as the dimensions of the smallest objects recorded on an image. One might speak of the resolution of an aerial photograph as being "2 m," meaning that objects of that size and larger could be detected and interpreted from the image in question. Smaller objects presumably would not be resolved, and therefore would not be interpretable.

Such measures of resolution may have utility as a rather rough suggestion of usable detail, but must be recognized as having only a very subjective meaning. The objects and features that compose the landscape vary greatly in size, shape, contrast with background, and pattern. Usually we have no means of relating a given estimate of GRD to a specific problem of interest. For example, the spatial resolution of U.S. Department of Agriculture (USDA) 1:20,000 black-and-white aerial photography is often said to be "about 1 m," yet typically one can easily detect on these photographs the painted white lines in parking lots and highways; these lines may be as narrow as 6 to 9 in. Does this mean that the resolution of this photography should be assessed as 6 in. rather than 1 m? Only if we are interested in the interpretation of long thin features that exhibit high contrast with their background could we accept such an estimate as useful. Similarly, the estimate of 1 m may be inappropriate for many applications.

Line Pairs per Millimeter

Line pairs per millimeter (LPM) is a means of standardizing the characteristics of targets used to assess image resolution. Essentially, it is a means of quantifying, under controlled conditions, the estimate of GRD by using a standard target, positioned on the ground, that is imaged by the remote sensing system under specified operating conditions.

Although many targets have been used, the resolution target designed by the U.S. Air Force has been a standard for a variety of studies (Figure 9.1). This target consists of parallel black

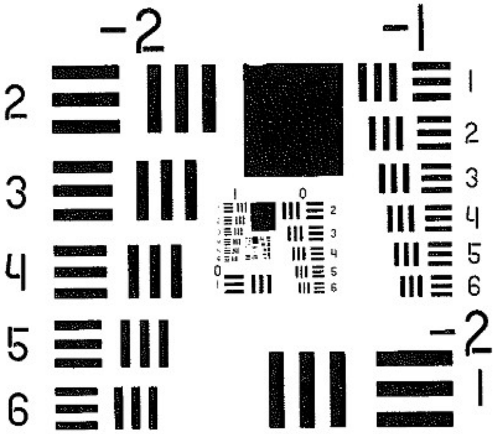

FIGURE 9.1. Bar target used in resolution studies.

lines positioned against a white background. The width of spaces between lines is equal to that of the lines themselves; their length is five times their width. As a result, a block of three lines and the two white spaces that separate them form a square. This square pattern is reproduced at varied sizes to form an array consisting of bars of differing widths and spacings. Sizes are controlled to produce changes in spacing of the bars (spatial frequency) of 12%. Repetition of the pattern at differing scales assures that the image of the pattern will include at least one pattern so small that individual lines and their spaces will not be fully resolved.

If images of two objects are visually separated, they are said to be "spatially resolved." Images of the resolution target are examined by an interpreter to find that smallest set of lines in which the individual lines are all completely separated along their entire length. The analyst measures the width of the image representation of one "line pair," (i.e., the width of the image of one line and its adjacent white space) (Figure 9.2). This measurement provides the basis for the calculation of the number of line pairs per millimeter (or any other length we may choose; "line pairs per millimeter" [LPM] is standard for many applications). For example, in Figure 9.2 the width of a line and its adjacent gap is measured to be 0.04 mm. From 1 line pair/0.04 mm we find a resolution of 25 LPM.

For aerial photography, this measure of resolution can be translated into GRD by the relationship:

$$\text{GRD} = \frac{H}{(f)(R)} \qquad \text{(Eq. 9.1)}$$

where GRD is ground resolved distance, in meters; H is the flying altitude above the terrain, in meters; f is the focal length, in millimeters; and R is the system resolution, in line pairs per millimeter.

Such measures have little predictable relationship to the actual size of landscape features that might be interpreted in practical situations because seldom will the features of interest have the same regularity of size, shape, and arrangement and the high contrast of the resolution target used to derive the measures. They are, of course, valuable as comparative measures for assessing the performance of separate systems under the same operating conditions or of a single system under different conditions.

Although the U.S. Air Force target has been widely used, other resolution targets have been developed. For example, a colored target has been used to assess the spectral fidelity of color films (Brooke, 1974), and bar targets have been constructed with contrast ratios somewhat closer to conditions observed during actual applications. The USGS target is a large array painted on the roof of the USGS National Center, in Reston, Virginia, as a means of assessing aerial imagery under operational conditions from high altitudes. The array is formed from large bar

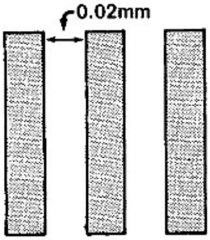

FIGURE 9.2. Use of bar target to find LPM.

targets, about 100 ft. in length, of known contrast, and a star target about 140 ft. in diameter designed for assessment of the resolution of nonphotographic sensors.

Modulation Transfer Function

The *modulation transfer function* (MTF) records system response to a target array with elements of varying spatial frequency (i.e., unlike the bar targets described above, targets used to find MTFs are spaced at varied intervals). Often the target array is formed from bars of equal length spaced against a white background at intervals that produce a sinusoidal variation in image density along the axis of the target.

Modulation refers to changes in the widths and spacings of the target. *Transfer* denotes the ability of the imaging system to record these changes on the image—that is, to "transfer" these changes from the target to the image. Because the target is explicitly designed with spatial frequencies too fine to be recorded on the image, some frequencies (the high frequencies at the closest spacings) cannot be imaged. The "function" then shows the degree to which the image records specified frequencies (Figure 9.3).

Although the MTF is probably the "best" measure of the ability of an imaging system as a whole or of a single component of that system to record spatial detail, the complexity of the method prevents routine use in many situations. The MTF can be estimated using simpler and more readily available targets, including the USAF target described above (Welch, 1971).

9.6. Mixed Pixels

As spatial resolution interacts with the fabric of the landscape, a special problem is created in digital imagery by those pixels that are not completely occupied by a single, homogeneous category. The subdivision of a scene into discrete pixels acts to average brightnesses over the entire pixel area. If a uniform or relatively uniform land area occupies the pixel, then similar brightnesses are averaged, and the resulting digital value forms a reasonable representation of the brightnesses within the pixel. That is, the average value does not differ greatly from the values that contribute to the average. However, when a pixel area is composed of two or more areas that differ greatly with respect to brightness, then the average is composed of several very different values, and the single digital value that represents the pixel may not accurately represent any of the categories present (Figure 9.4).

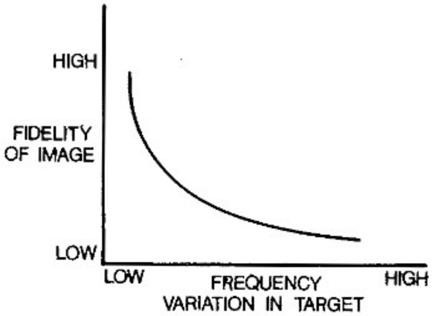

FIGURE 9.3. Modulation transfer function.

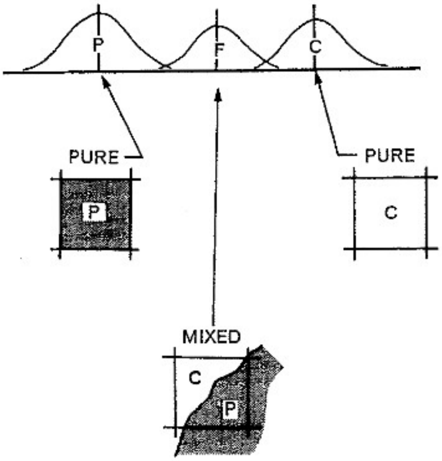

FIGURE 9.4. False resemblance of mixed pixels to a third category.

An important consequence of the occurrence of mixed pixels is that pure spectral responses of specific features are mixed together with the pure responses of other features. The mixed response sometimes known as a *composite signature* does not match the *pure signatures* that we wish to use to map the landscape. Note, however, that sometimes composite signatures can be useful because they permit us to map features that are too complex to resolve individually.

Nonetheless, mixed pixels are also a source of error and confusion. In some instances, the digital values from mixed pixels may not resemble any of the several categories in the scene; in other instances, the value formed by a mixed pixel may resemble those from other categories in the scene but not actually present within the pixel—an especially misleading kind of error.

Mixed pixels occur often at the edges of large parcels, or along long linear features, such as rivers or highways, where contrasting brightnesses are immediately adjacent to one another (Figure 9.5). The edge, or border, pixels then form opportunities for errors in digital classification. Scattered occurrences of small parcels (such as farm ponds observed at the resolution of the Landsat MSS) may produce special problems because they may be represented *only* by mixed pixels, and the image analyst may not be aware of the presence of the small areas of high contrast because they occur at subpixel sizes. An especially difficult situation can be created by landscapes composed of many parcels that are small relative to the spatial resolution of the sensor. A mosaic of such parcels will create an array of digital values, *all* formed by mixed pixels (Figure 9.6).

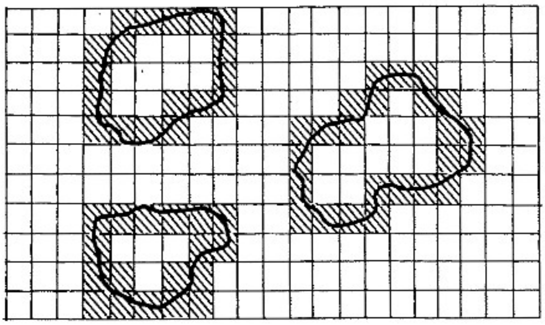

FIGURE 9.5. Edge pixels.

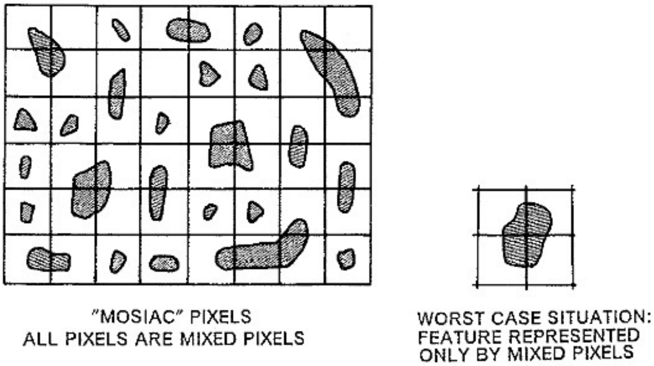

FIGURE 9.6. Mixed pixels generated by image of landscape composed of small parcels.

It is interesting to examine the relationships between the numbers of mixed pixels in a given scene and the spatial resolution of the sensor. Studies have documented the increase in numbers of mixed pixels that occurs as spatial resolution decreases. Because the numbers, sizes, and shapes of landscape parcels vary greatly with season and geographic setting, there can be no generally applicable conclusions regarding this problem. Yet examination of a few simple examples may help us understand the general character of the problem.

Consider the same contrived scene that is examined at several different spatial resolutions (Figure 9.7). This scene consists of two contrasting categories with two parcels of one superimposed against the more extensive background of the other. This image is then examined at four levels of spatial resolution; for each level of detail, pixels are categorized as "background," "interior," or "border." (Background and interior pixels consist only of a single category; border pixels are those composed of two categories.) A tabulation of proportions of the total in each category reveals a consistent pattern (Table 9.1). As resolution becomes coarser, the number of

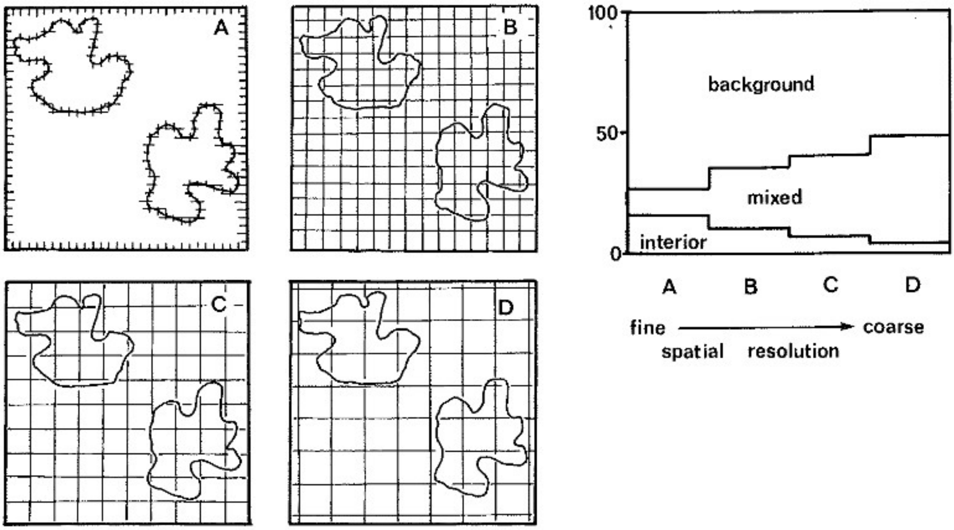

FIGURE 9.7. Influence of spatial resolution on proportions of mixed pixels.

TABLE 9.1. Summary of Data Derived from Figure 9.7

Spatial resolution		Total	Mixed	Interior	Background
Fine	A	900	109	143	648
	B	225	59	25	141
	C	100	34	6	60
Coarse	D	49	23	1	25

mixed pixels increases (naturally) at the expense of the number of pure background and pure interior pixels. In this example, interior pixels experience the larger loss, but this result is the consequence of the specific circumstances of this example, and is unlikely to reveal any generally applicable conclusions.

If other factors could be held constant, it would seem that fine spatial resolution would offer many practical advantages, including capture of fine detail. Note, however, the substantial increases in the total numbers of pixels required to achieve this advantage; note too that increases in the numbers of pixels produce compensating disadvantages, including increased costs. Also, this example does not consider another important effect often encountered as spatial resolution is increased: the finer detail may resolve features not recorded at coarser detail, thereby increasing, rather than decreasing, the proportions of mixed pixels. This effect may explain some of the results observed by Sadowski and Sarno (1976), who found that classification accuracy decreased as spatial resolution became finer.

Marsh et al. (1980) have reviewed strategies for resolving the percentages of components that compose the ground areas with mixed pixels. The measured digital value for each pixel is determined by the brightnesses of distinct categories within that pixel area projected on the ground, as integrated by the sensor over the area of the pixel. For example, the projection of a pixel on the earth's surface may encompass areas of open water (W) and forest (F). Assume that we know that (1) the digital value for such a pixel is "mixed," not "pure"; (2) the mean digital value for water in all bands is i (W_i); (3) the mean digital value for forest in all bands is (F_i); and (4) the observed value of the mixed pixel in all spectral bands is (M_i). We wish then to find the areal percentages P_W and P_F that contribute to the observed value M_i.

Marsh et al. outline several strategies for estimating P_W and P_F under these conditions; the simplest, if not the most accurate, is the weighted average method:

$$P_W = (M_i - F_i)/(W_i - F_i) \qquad \text{(Eq. 9.2)}$$

An example can be shown using the following data:

	Band			
	1	2	3	4
Means for the mixed pixel (M_i):	16	12	16	18
Means for forest (F_i):	23	16	32	35
Means for water (W_i):	9	8	0	1

Using Equation 9.2, the areal proportion of the mixed pixel composed of the water category can be estimated as follows:

Band 1: $P_W = (16 - 23)/(9 - 23) = -7/-14 = 0.50$
Band 2: $P_W = (12 - 16)/(8 - 16) = -4/-8 = 0.50$
Band 3: $P_W = (16 - 32)/(0 - 32) = -16/-32 = 0.50$
Band 4: $P_W = (18 - 35)/(1 - 35) = -17/-34 = 0.50$

Thus the mixed pixel is apparently composed of about 50% water and 50% forest. Note that in practice we may not know which pixels are mixed, and may not know the categories that might contribute to the mixture. Note also that this procedure may yield different estimates for each band. Other procedures, too lengthy for concise description here, may give more suitable results in some instances (Marsh et al., 1980).

9.7. Spatial and Radiometric Resolution: A Simple Example

Some of these effects can be illustrated by an artificial example. The contrived scene in Figure 9.8 is composed of two water bodies (W), several areas of forest (F), a large area of pasture (*P*), and a cultivated region (A) composed of a pattern of agricultural fields, some with mature crops, others composed of plowed bare ground. A digital representation of this scene might resemble Figure 9.9, the product of an imaginary sensor with fine spatial and radiometric resolution operating in the near infrared portion of the spectrum.

This hypothetical sensor records the scene at 10 brightness levels, from "0" (very dark) to "9" (very bright). In digital representation, the water bodies are very dark, mainly "0's" and "1's"; forest is brighter, "3's" and "5's." Pasture has an intermediate brightness of "2." Agricultural land is represented either as "0" (the dark areas of bare soil) or "9" (the brighter areas of living vegetation).

Figure 9.10a represents the same scene as portrayed at high spatial resolution, but very low radiometric resolution; the sizes of the pixels are the same as in Figure 9.9, but only two levels of

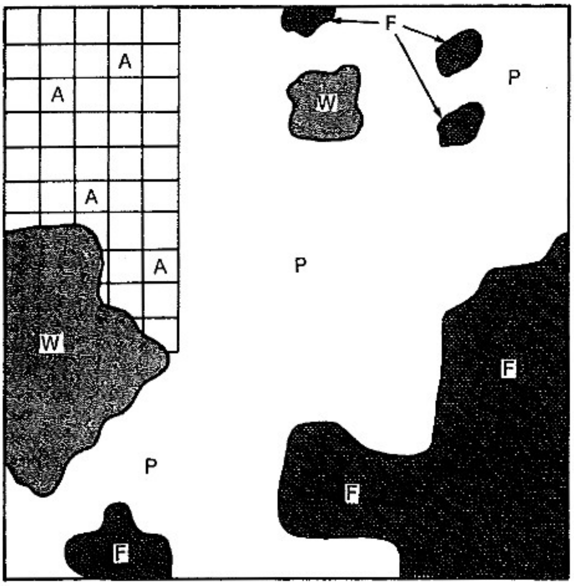

FIGURE 9.8. Hypothetical landscape.

0	9	0	9	9	2	2	2	3	2	2	3	2	2	2	2
9	9	9	9	9	3	2	2	2	2	2	2	3	2	2	2
9	0	0	9	9	2	2	2	0	1	2	3	2	2	2	2
9	9	9	9	0	3	2	2	0	0	2	2	3	2	3	2
9	8	9	9	9	3	2	2	2	2	2	2	2	2	2	2
8	6	9	8	0	2	2	2	2	2	2	2	2	3	2	2
1	0	0	6	9	2	2	2	2	2	2	2	2	2	2	5
1	0	1	9	8	2	2	2	2	2	2	2	2	5	5	5
0	0	0	0	7	2	2	2	2	2	2	2	5	5	5	5
0	1	0	1	0	2	2	2	2	2	2	2	3	5	5	5
0	0	0	0	2	2	2	2	2	2	2	2	5	3	5	3
0	0	0	2	2	2	2	2	5	5	2	2	5	5	3	3
2	1	2	2	2	2	2	2	3	5	5	5	5	3	5	3
2	2	2	3	2	2	2	2	5	5	5	3	5	5	3	5
2	2	3	5	5	2	2	2	2	2	2	2	5	3	3	3
2	2	2	5	5	3	2	2	2	2	2	2	3	5	5	5

FIGURE 9.9. Digital representation of Figure 9.8.

(a)

0	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0
1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0
1	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0
1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0
1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0
1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	1
0	0	0	1	1	0	0	0	0	0	0	0	0	1	1	1
0	0	0	0	1	0	0	0	0	0	0	0	1	1	1	1
0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1
0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0
0	0	0	0	0	0	0	0	1	1	0	0	1	1	0	1
0	0	0	0	0	0	0	0	0	1	1	1	1	0	1	0
0	0	0	0	0	0	0	0	1	1	1	0	1	1	0	1
0	0	0	1	1	0	0	0	0	0	0	0	1	1	1	1
0	0	0	1	1	0	0	0	0	0	0	0	1	1	1	1

(b)

0	2	0	2	2	0	0	0	1	0	0	1	0	0	0	0
2	2	2	2	2	1	0	0	0	0	0	0	1	0	0	0
2	0	0	2	2	0	0	0	0	0	0	1	0	0	0	0
2	2	2	2	0	1	0	0	0	0	0	0	1	0	1	0
2	2	2	2	2	0	0	0	0	0	0	0	0	0	0	0
2	1	2	2	0	0	0	0	0	0	0	0	0	1	0	0
0	0	0	1	2	0	0	0	0	0	0	0	0	0	0	1
0	0	0	2	2	0	0	0	0	0	0	0	0	1	1	1
0	0	0	0	2	0	0	0	0	0	0	0	1	1	1	1
0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1
0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1
0	0	0	0	0	0	0	0	1	1	0	0	1	1	1	1
0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1
0	0	0	1	0	0	0	0	1	1	1	1	1	1	1	1
0	0	1	1	1	0	0	0	0	0	0	1	1	1	1	1
0	0	0	1	1	0	0	0	0	0	1	1	1	1	1	1

(c)

7	7	7	7	6	6	2	2	2	2	2	2	2	2	2	2
7	7	7	7	6	6	2	2	2	2	2	2	2	2	2	2
7	7	7	7	4	4	2	2	0	0	3	3	2	2	2	2
7	7	7	7	4	4	2	2	0	0	3	3	2	2	2	2
8	8	9	9	4	4	2	2	2	2	2	2	2	2	2	2
8	8	9	9	4	4	2	2	2	2	2	2	2	2	2	2
0	0	4	4	5	5	2	2	2	2	2	2	3	3	4	4
0	0	4	4	5	5	2	2	2	2	2	2	3	3	4	4
0	0	0	0	3	3	2	2	2	2	2	2	4	4	5	5
0	0	0	0	3	3	2	2	2	2	2	2	4	4	5	5
0	0	0	0	2	2	2	2	4	4	2	2	4	4	4	4
0	0	0	0	2	2	2	2	4	4	2	2	4	4	4	4
2	2	2	2	2	2	2	2	4	4	4	4	4	4	4	4
2	2	2	2	2	2	2	2	4	4	4	4	4	4	4	4
2	2	4	4	4	4	2	2	2	2	3	3	4	4	4	4
2	2	4	4	4	4	2	2	2	2	3	3	4	4	4	4

(d)

7	7	7	7	3	3	3	3	2	2	2	2	2	2	2	2
7	7	7	7	3	3	3	3	2	2	2	2	2	2	2	2
7	7	7	7	3	3	3	3	2	2	2	2	2	2	2	2
7	7	7	7	3	3	3	3	2	2	2	2	2	2	2	2
5	5	5	5	4	4	4	4	2	2	2	2	3	3	3	3
5	5	5	5	4	4	4	4	2	2	2	2	3	3	3	3
5	5	5	5	4	4	4	4	2	2	2	2	3	3	3	3
5	5	5	5	4	4	4	4	2	2	2	2	3	3	3	3
0	0	0	0	2	2	2	2	2	2	2	2	4	4	4	4
0	0	0	0	2	2	2	2	2	2	2	2	4	4	4	4
0	0	0	0	2	2	2	2	2	2	2	2	4	4	4	4
0	0	0	0	2	2	2	2	2	2	2	2	4	4	4	4
2	2	2	2	2	2	2	2	4	4	4	4	4	4	4	4
2	2	2	2	2	2	2	2	4	4	4	4	4	4	4	4
2	2	2	2	2	2	2	2	4	4	4	4	4	4	4	4
2	2	2	2	2	2	2	2	4	4	4	4	4	4	4	4

FIGURE 9.10. Figure 9.9 represented at (*a*) coarse radiometric resolution, (*b*) at modest radiometric resolution, (*c*) at a modest level of spatial resolution, and (*d*) at coarse spatial resolution.

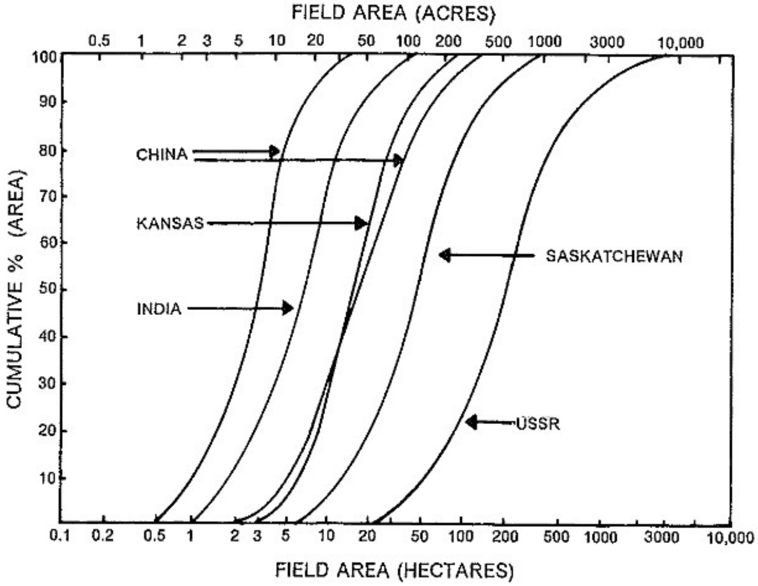

FIGURE 9.11. Field size distributions for selected wheat-producing regions (Podwysocki, 1976a).

more) of this sample were at least 1 ha in size, and that all were smaller than about 100 ha (247 acres), and that we can expect the Indian wheat fields to be smaller than those in Kansas. These data, and others presented in his study, provide the basis for evaluating the effectiveness of a given resolution in monitoring features of specified sizes. This example is especially instructive because it emphasizes not only the differences in average field size in the different regions (shown in Figure 9.11 by the point where each curve crosses the 50% line), but also the differences in variation of field size between the varied regions (shown in Figure 9.11 by the slopes of the curves).

In a different analysis of relationships between sensor resolution and landscape detail, Simonett and Coiner (1971) examined 106 sites in the United States, each selected to represent a major land-use region. Their study was conducted prior to the launch of Landsat 1 with the objective of assessing the effectiveness of MSS spatial resolution in recording differences between major land-use regions in the United States. Considered as a whole, their sites represent a broad range of physical and cultural patterns in the 48 coterminous states.

For each site they simulated the effects of imaging with low-resolution imagery by superimposing grids over aerial photographs, with grid dimensions corresponding to ground distances of 800, 400, 200, and 100 ft. Samples were randomly selected within each site. Each sample consisted of the *number* of land-use categories within cells of each size, and thereby formed a measure of landscape diversity, as considered at several spatial resolutions. For example, those landscapes that show only a single land-use category at the 800-ft. resolution have a very coarse fabric, and would be effectively imaged at the low resolution of satellite sensors. Those landscapes that have many categories within the 100-ft. grid are so complex that very fine spatial resolution would be required to record the pattern of landscape variation. Their analysis grouped sites according to their behavior at various resolutions. They reported that natural landscapes appeared to be more susceptible than man-made landscapes to analysis at the relatively coarse resolutions of the Landsat MSS.

Welch and Pannell (1982) examined Landsat MSS (bands 2 and 4) and Landsat 3 RBV images (in both pictorial and digital formats) to evaluate their suitability as sources of landscape information at levels of detail consistent with a map scale of 1:250,000. Images of three study areas in China provided a variety of urban and agricultural landscapes for study, representing a range of spatial detail and a number of geographical settings. Their analysis of modulation transfer functions reveals that the RBV imagery represents an improvement in spatial resolution of about 1.7 over the MSS imagery, and that Landsat 4 TM provided an improvement of about 1.4 over the RBV (for target:background contrasts of about 1.6:1).

Features appearing on each image were evaluated with corresponding representations on 1:250,000 maps in respect to size, shape, and contrast. A numerical rating system provided scores for each image based upon the numbers of features represented and the quality of the representations on each form of imagery. MSS images portrayed about 40 to 50% of the features shown on the usual 1:250,000 topographic maps. MSS band 2 was the most effective for identification of airfields; band 4 performed very well for identification and delineation of water bodies. Overall, the MSS images achieved scores of about 40 to 50%. RBV images attained higher overall scores (50 to 80%), providing considerable improvement in representation of high-contrast targets, but little improvement in imaging of detail in fine-textured urban landscapes. The authors concluded that spatial resolutions of MSS and RBV images were inadequate for compilation of usual map detail at 1:250,000.

9.9. Summary

This chapter highlights the significance of image resolution as a concept that extends across many aspects of remote sensing. Although the special and unique elements of any image must always be recognized and understood, many of the general aspects of image resolution can assist us in understanding how to interpret remotely sensed images.

Although there has long been an intense interest in measuring image resolution, especially in photographic systems, it is clear that much of our more profound understanding has been developed through work with satellite scanning systems such as the Landsat MSS. Such data were of much coarser spatial resolution than any studied previously. As more and more attention was focused upon their analysis and interpretation (Chapters 11 and 12), it was necessary to develop a better understanding of image resolution and its significance for specific tasks. Now much finer resolution data are available, but we can continue to develop and apply our knowledge of image resolution to maximize our ability to understand and interpret these images.

Review Questions

1. Most individuals are quick to appreciate the advantages of fine resolution. However, there may well be *disadvantages* to fine-resolution data, relative to data of coarser spatial, spectral, and radiometric detail. Suggest what some of these effects might be.

2. Imagine that the spatial resolution of the digital remote sensing system is increased from about 80 m to 40 m. List some of the consequences, assuming that image coverage remains the same. What would be some of the consequences of *decreasing* detail from 80 m to 160 m?

3. You examine an image of the U.S. Air Force resolution target and determine that the image distance between the bars in the smallest pair of lines is 0.01 mm. Find the LPM for this image. Find the LPM for an image in which you measure the distance to be 0.04 mm. Which image has finer resolution?

4. For each object or feature listed below, discuss the characteristics that will be significant in our ability to resolve the object on a remotely sensed image. Categorize each as "easy" or "difficult" to resolve clearly. Explain.

   a. A white car parked alone in an asphalt parking lot.
   b. A single tree in a pasture.
   c. An orchard.
   d. A black cat in a snow covered field.
   e. Painted white lines on a crosswalk across an asphalt highway.
   f. Painted white lines on a crosswalk across a concrete highway.
   g. A pond.
   h. A stream.

5. Write a short essay describing how spatial resolution, spectral resolution, and radiometric resolution are interrelated. Is it possible to increase one kind of resolution without influencing the others?

6. Review Chapters 1–8 to identify the major features that influence spatial resolution of images collected by the several kinds of sensors described. Prepare a table to list these factors in summary form.

7. Explain why some objects might be resolved clearly in one part of the spectrum yet resolved poorly in another portion of the spectrum.

8. Although the U.S. Air Force resolution target is very useful for evaluating some aspects of remotely sensed images, it is not necessarily a good indication of the ability of a remote sensing system to record patterns that are significant for environmental studies. List some of the reasons this might be true.

9. Describe ideal conditions for achieving maximum spatial resolution.

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