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CHAPTER 1

Overview

1.1 Subsurface Imaging: Scope and Applications

Imaging is the measurement of the spatial distribution of some physical property of an object by use of an instrument such as a camera, an optical or ultrasonic scanner, a microscope, a telescope, a radar system, or an X-ray machine. The spatial scale of the object may range from subnanometer to light years, as illustrated by the pictorial examples in Fig. 1.1-1. Numerous medical, biological, geophysical, oceanographic, atmospheric, and industrial applications exist, and each field has its tools, methods, and nomenclature. However, despite the wealth of applications and the breadth of spatial scales, a number of basic principles and methodologies are common among all imaging systems. This book highlights these principles, with an ultimate goal of introducing a unified framework for these broad applications.

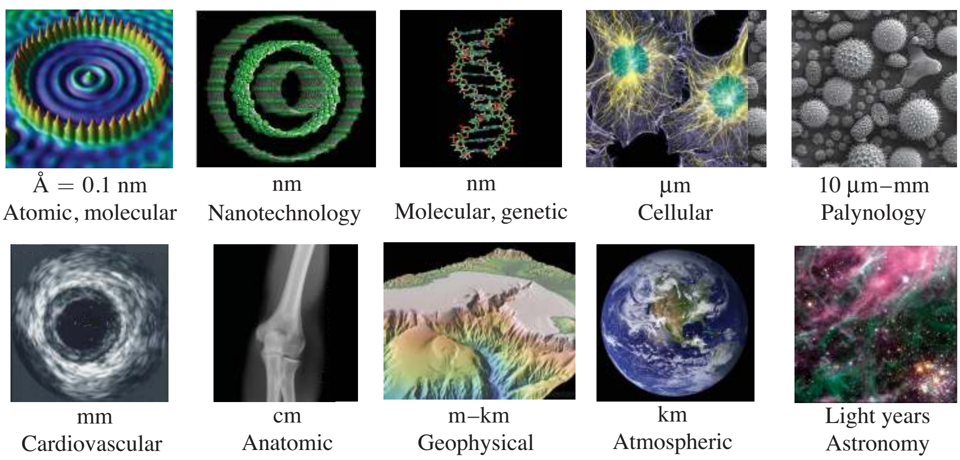


Figure 1.1-1 Imaging applications at various spatial scales.

Subsurface imaging (**SSI**) is the imaging of an object buried below the surface of a medium, such as soil, water, atmosphere, or tissue. The imaging process is mediated by some *field*, *wave*, or stream of *particles* that probe the medium, and is modified by the object before it is detected by a sensor, as illustrated in Fig. 1.1-2. A significant impediment is that the surface and the medium, and any clutter therein, also modify the probe (and possibly prevent it from reaching the object or the sensor). The imaging system must separate contributions made by the object from those made by the surface and volumetric clutter.

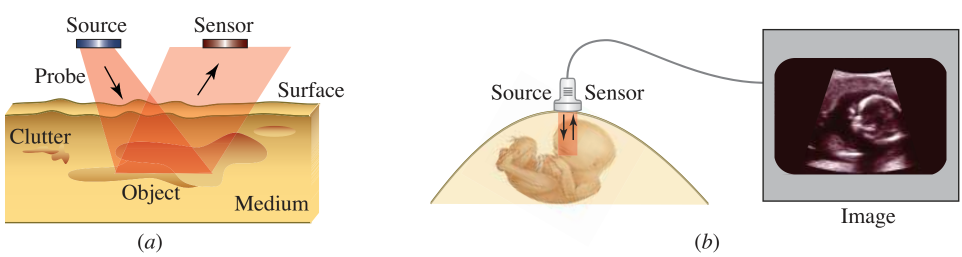


Figure 1.1-2 (*a*) SSI. (*b*) Ultrasonic imaging of a fetus as an example of SSI.

Imaging Probes. The imaging process is mediated by some *field*, *wave*, or stream of *particles*, which we generically call the *probe*[1] or the probing wave. The probe "reads" the object and communicates the information to the sensor.

Examples of probes:

- An *electrostatic field* can be used to monitor the spatial distribution of the electric conductivity of an object. A *magnetic field* can be used to probe the presence of metal.
- *Electromagnetic waves* at various bands of the spectrum (low-frequency, radiowave, microwave, millimeter waves, terahertz, optical, X-rays, γ-rays) travel in the form of *waves* (which may be approximated by rays when the wavelength is short). They are commonly used for imaging a variety of objects. Likewise, *mechanical* and *acoustic waves* (e.g., seismic and ultrasonic) have widespread imaging applications.
- Beams of accelerated *particles* may also be used for imaging. For example, an electron beam is used in the scanning electron microscope (SEM), and nuclear particles are used in medical imaging.

This text emphasizes imaging by means of electromagnetic and acoustic fields and waves, but other probes are also discussed.

Imaging Configurations. Imaging systems can take several configurations. A self-luminous object generates its own signal (field, wave, or particles), which may be observed and used to construct the image without the need for an external probe, as illustrated in Fig. 1.1-3(a). Examples of this type of *passive* imaging are a star emitting electromagnetic radiation intercepted by a telescope in an observatory, a hot object sensed by a thermal imaging camera, or a biological organ injected with radioactive isotopes such as those used in nuclear medicine. Alternatively, in *active* imaging the image is formed by use of an external probe (field, wave, or particles) that interacts with the object. Such a probe may be transmitted through or reflected from the object, as illustrated in Fig. 1.1-3(b) and (c), respectively. In some applications, the probe excites *contrast agents* injected into the object, which emit radiation that is detected by the sensor. Examples include fluorescent dyes that emit visible light and bubbles that enhance the scattering of ultrasonic probes.

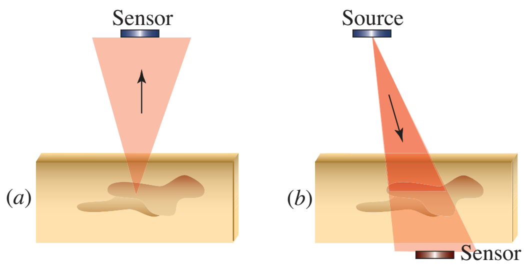


Figure 1.1-3 Imaging modalities. (a) Self-luminous object, which requires no probe. (b) Probe beam transmitted through the object. (c) Probe beam reflected or scattered from the object.

Imaged Physical Property. In this book, the physical property that is measured by the imaging system is called the **alpha** property, and is denoted by the symbol α. In most cases, α is a scalar function of position $\mathbf{r} = (x, y, z)$, i.e., is a three-dimensional (3D) distribution (a map). The actual physical nature of α depends on the probe used. Examples of physical parameters that are sensed by various probes are listed in Fig. 1.1-4.

[1] In medical imaging the term "probe" often refers to a contrast agent, a substance injected into the object to enhance contrast (see Sec. 2.4).

Electromagnetic	Optical	X-Ray	Acoustic	Particles
Permittivity	Refractive index	Absorption coefficient	Density	Scattering cross-section
Permeability	Absorption coefficient	Scattering coefficient	Compressibility	Scattering function
Conductivity	Scattering coefficient			Secondary emission rate
Density of nuclear spins	Diffusion coefficient			Nuclear emission rate
	Fluorescence rate			Chemical emission rate
	Fluorescence lifetime			

Figure 1.1-4 Examples of the physical property α for various probes. See also Table 9.1-1.

The sensed property α depends on the physical process involved in the interaction of the probe with the object, as described in some detail in Chapter 2.

Examples of interaction processes characterized by the sensed property α:

- Reflection or refraction at boundaries within the object
- Absorption
- Scattering from objects of various shapes
- Diffusion through random and turbid media
- Fluorescence (delayed re-emission at a different wavelength following absorption of electromagnetic radiation)
- Interaction of electric and magnetic fields with bound or free charges in insulating or conducting materials.
- Magnetic resonance (scattering of radiowaves from the spins associated with hydrogen atom nuclei subjected to a magnetic field)
- Thermal emittance (of a self-luminous source emitting infrared radiation).

Mapping Other Underlying Object Properties. The purpose of subsurface imaging may be the mapping of structural, mechanical, chemical, environmental, biological, physiological, or other functional properties that are not directly sensed by the probe. Such parameters, which are of interest to the user, are generically referred to in this book as the **beta** parameters β, and may be scalar or vector functions of position $\mathbf{r}$ and time t.

Examples of user property β:

- Density, pressure, temperature
- Young's modulus of elasticity, bulk modulus and fluid elasticity, viscosity
- Humidity, moisture content, porosity, pH number, thermal resistivity
- Molecular or ion concentration, chemical composition
- Crystallographic atomic structure
- Biological and physiological properties such as blood flow, tissue oxygenation, hemoglobin concentration, metabolic rates, and membrane integrity; in medical imaging, the term **functional imaging**, as opposed to **structural imaging**, is used for such measurements
- Concentration of extrinsic markers such as dyes, chemical tags, chromophores and fluorphores, and fluorescence protein markers
- Gene expression, cellular differentiation, morphogenesis.

Ideally, the sensed spatial distribution α is proportional to the functional distribution β, and sometimes α is itself β. However, the two distributions may be related by some mathematical relation (e.g., time delay, time average over some duration, spatial average over some local neighborhood, or a nonlinear operation such as saturation). This is represented by the system illustrated in Fig 1.1-5.

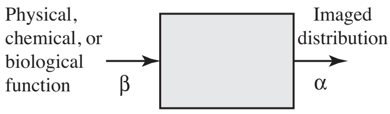


Figure 1.1-5 Relation between the sensed physical distribution α and an underlying distribution β that is useful to the user.

Image-Understanding Applications. In certain applications, obtaining the full spatial distribution of α or β may not be necessary. The user may only be interested in estimating some property of the object, such as:

- *Shape*, *size*, or *location* of the center of some target
- *Number* of targets of certain type
- *Average value* of a property such as humidity, oxygenation, or temperature
- Statistical measures of a random distribution, such as average *contrast*, *graininess*, or *orientation* and *anisotropy* of the scene texture.

In other applications, the user may be interested in detecting the presence or absence of a particular material (such as underground oil, water, minerals, or pollution plumes; explosives in luggage; or cardiovascular plaque), a hidden target (such as landmine, weapon, wreck site, or archaeological artifact), or some feature or anomaly in the object (such as a crack or cavity). In any of these applications, the goal is to reach a binary decision on the presence or absence of something. Detailed examples of **detection** problems are provided in Chapter 9.

One may also be interested in classifying objects based on features exhibited in the sensed distribution α or the underlying distribution β. For example, an underwater imaging system may aim at classifying various regions into classes such as deep water, sand, reef crest, mangrove, or sea grass. Detailed examples of **classification** problems are provided in Chapter 6. In any case, it is essential that the imaging system be designed with the ultimate goal of the application in mind.

1.2 Challenges of Subsurface Imaging

A. Limited Resolution

A principal challenge in imaging is *localization*, which is the ability of the imaging instrument to extract information on an effect or a property at a single point without being "contaminated" by similar effects at other neighboring points. An instrument with this capability can measure the entire spatial distribution of the property by means of point-by-point scanning. Perfect localization is, of course, an idealization. Real imaging instruments using waves, fields, or particles can localize within a spot of finite dimensions, rather than a point. The size of that spot determines the spatial **resolution** of the instrument, i.e., the dimension of the finest spatial detail that can be discerned by the instrument.

Localization

Localization in 2D Imaging. For a two-dimensional (2D) object, such as a planar surface, a probe beam can be focused to intersect the object plane at a tiny spot centered at the point of interest. The full spatial distribution of the object is constructed by point-by-point scanning, as depicted in Fig. 1.2-1(a). The resolution is determined by the dimensions of the probe spot. Alternatively, a sensor collecting only from a tiny spot in the plane of a uniformly illuminated object may be used in a scanning mode, as shown in Fig. 1.2-1(b). A parallelized version of this configuration, which does not require scanning, uses a set of sensor rays directed through a pinhole, as illustrated schematically in Fig. 1.2-1(c). This configuration is implemented in optical imaging by use of a lens, as shown in Fig. 1.2-1(d). The **lens** has the remarkable capability of collecting light emitted from each point in the object plane *in any direction* and directing it to a single conjugate point in the image plane. The object and image planes are located at distances from the lens satisfying the imaging equation ($1/d_1 + 1/d_2 = 1/f$, where f is the focal length). The sensor, e.g., a CCD camera, detects emissions from all points of the object simultaneously, but each element of the CCD corresponds to a single conjugate point (or, in reality, a tiny spot) on the object, so that no scanning is required.

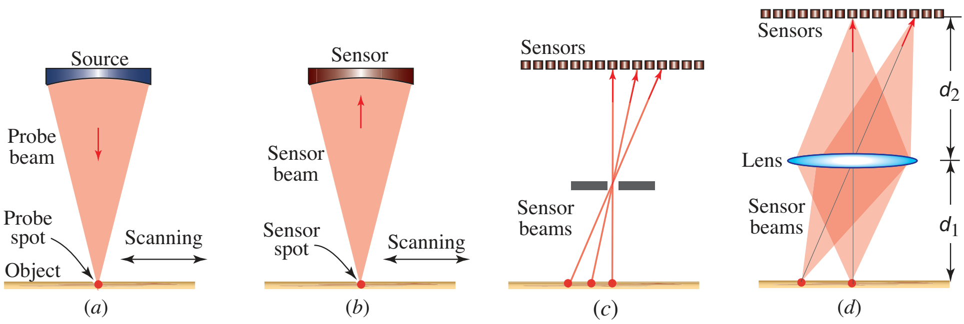
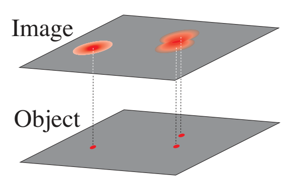


Figure 1.2-1 Configurations for imaging a 2D object. (a) Scanning by use of a focused probe beam intersecting the object plane at a single point (spot). The sensor collects from *all* points of the object uniformly. (b) Scanning a uniformly illuminated object, or a self-luminous object, by use of a sensor collecting from only a single point (spot) of the object. (c) Parallel scanning of a uniformly illuminated object using a pinhole camera (a *camera obscura*). (d) A single-lens imaging system.



Resolution. The resolution of an imaging system is the dimension of the finest spatial detail in the object that can be discerned in the acquired image. This length equals the width of the scanned spot (the small circle in Fig. 1.2-1). If an object with a single bright *point*, in an otherwise dark field, is imaged with such a scanning spot, the result will be an image with a single bright *spot*, so that the point is seen as a spot. Two bright points in the object separated by a distance smaller than the width of scanned spot cannot by easily resolved since their image is two overlapping spots. Since it is not possible to focus a wave to a spot of size much smaller than the wavelength, the resolution is most often (but not always) limited by the wavelength. The shorter the wavelength, the better the resolution. For example, X-rays form images with better resolution than infrared light, while microwaves or radiowaves have worse resolution under otherwise equal conditions.

Localization in 3D Imaging. Since imaging is a noncontact process mediated by waves, fields, or particles, which must travel through other points of the 3D object on their way to and from a selected internal point, localization can be very challenging. As it travels through the object, a focused probe beam illuminates a region shaped like an apex-to-apex double-cone with the apexes at the focus, as depicted in Fig. 1.2-2(a). We call this illuminated volume the **probe spot**. Likewise, as shown in Fig. 1.2-2(b), a sensor cannot be sensitive to only a single isolated point inside the 3D object; it rather responds to points within an extended volume, which we call the **sensor spot**, e.g., having the same double-cone shape if a focusing element is used. In the pinhole camera, shown in Fig. 1.2-2(c), the sensor spot is approximately a straight line passing through the pinhole. In the single-lens imaging system shown in Fig. 1.2-2(d), the sensor spot has the double-cone shape, or a tilted version thereof. The image of a 3D object recorded by such a system contains a "perfect" replica of the slice of the object passing through the focus (i.e., satisfying the imaging equation), contaminated by blurred images of all of the out-of-focus planes.

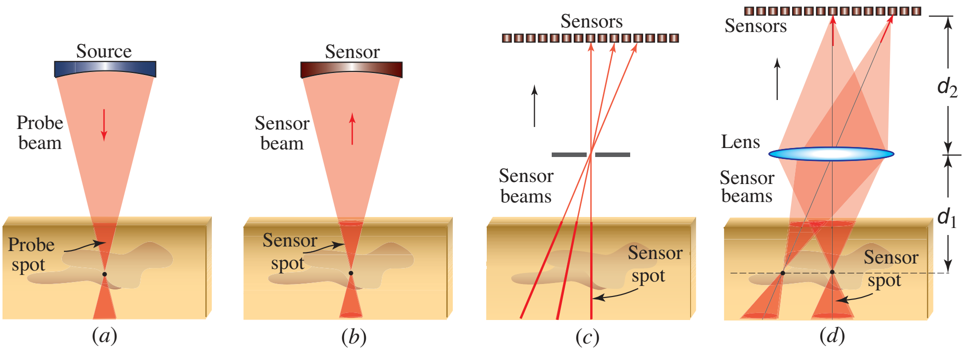


Figure 1.2-2 Four inadequate configurations for imaging a 3D object. (*a*) Scanning using a focused probe beam. The sensor collects from all points uniformly. (*b*) Scanning a uniformly illuminated (or self-luminous) object by use of a focused sensor beam. (*c*) Imaging by use of rays passing through a pinhole. Each sensor beam (ray) is defined by a single sensor and the pinhole. (*d*) An ideal single-lens image-forming system. In all cases, each sensor is responsive to an extended region (volume or line) in the object, instead of a single point.

Multiple Scattering

Another principal challenge in 3D imaging is that the probe wave, on its way to a selected point inside the object, may change its direction as a result of scattering from scatterers at intervening points within the object or in neighboring clutter. Scattering from clutter creates background noise that contaminates the measurement. Also, on its way to the sensor, the wave modified by one point within the object may be modified again by other scatterers in the object before it reaches the sensor. This type of multiple scattering, which causes cross-interaction among points of a thick object, thwarts localization and diminishes resolution. Multiple scattering does not occur in the 2D imaging of a thin planar object since the probe wave accesses each point of the object directly, and the modified wave reaches the sensor without encountering other points.

Multiple scattering makes the imaging equation generally **nonlinear**, i.e., the sensed wave is not a weighted superposition of contributions from various points in the object. Nonlinear processes are difficult to model and analyze. Consider, for example, the imaging of two scatterers in a homogeneous medium, as illustrated in Fig. 1.2-3. An incoming probe wave may be scattered from each of the scatterers independently, as illustrated in Fig. 1.2-3(*a*). For this type of scattering, the principle of superposition applies, and the field sensed by the sensor is simply the weighted sum of contributions from each of the scatterers, i.e., the imaging is **linear**.

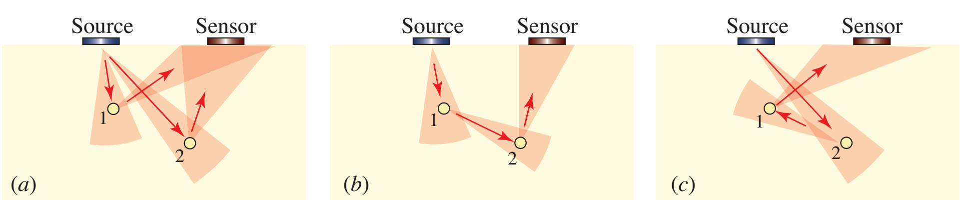


Figure 1.2-3 Scattering of a probe wave from two scatterers. (*a*) Direct scattering. (*b*) Double scattering from scatterer 1 followed by scatterer 2. (*c*) Double scattering from scatterer 2 followed by scatterer 1.

In the double scattering scenarios shown in Fig. 1.2-3(*b*) and (*c*), the wave scattered from the first scatterer may be scattered again from the second, or vice versa. In a triple scattering process, one of the scatterers is visited twice. For a larger number of scatterers, the possibilities for multiple scattering are endless and the complexity of the problem can be enormous. It is fortunate, however, that in many applications of SSI, the scattering is sufficiently weak so that the contribution of double scattering is small, and contributions of multiple scattering are even smaller. Approximations, such as the *Born approximation*, which is described in Chapter 2, exploit the weakness of the scattering effect to develop linearized models of imaging. This book is primarily concerned with this linearized regime.

B. Limited Penetration and Weak Contrast

Penetration Depth. Subsurface imaging is often hindered by a medium that absorbs or scatters the incoming probe wave, preventing it from reaching the target. Likewise, emission from a self-luminous object may be absorbed or scattered by the medium and never reaches the sensor. A necessary condition for successful subsurface imaging is that the wave reaching the sensor must retain sufficient power so that it is detectable with sufficient accuracy. As described in Chapter 2, the penetration depth (the distance at which the power of the probe is reduced by a certain factor) depends on the properties of the medium and the nature of the wave, including its wavelength. For example, a medium may be totally opaque to light, but penetrable by sound or X-rays. Subsurface imaging may not at all be possible for objects that are deeply buried below or behind a sufficiently thick layer of a highly absorbing medium.

Tradeoff between Penetration and Resolution. Waves of higher frequencies (shorter wavelengths) can be configured in narrower beams and focused into tighter spots. However, high-frequency waves often encounter greater attenuation in the medium and, therefore, have shorter penetration depth. The tradeoff between depth penetration and angular or transverse localization is exemplified in **ground-penetrating radar** (**GPR**), which is based on measurement of the echo signal at locations along parallel lines (see Fig. 1.2-4). This technique is used in geophysical applications, including detection of buried objects or boundaries in a variety of media, including soil, rock, pavements, fresh water, and ice. When transverse localization is difficult because the wavelength is long, imaging may be accomplished with “fat” overlapping beams, in which case tomographic reconstruction is necessary, as described in Sec. 1.3B and later in Sec. 4.2B.

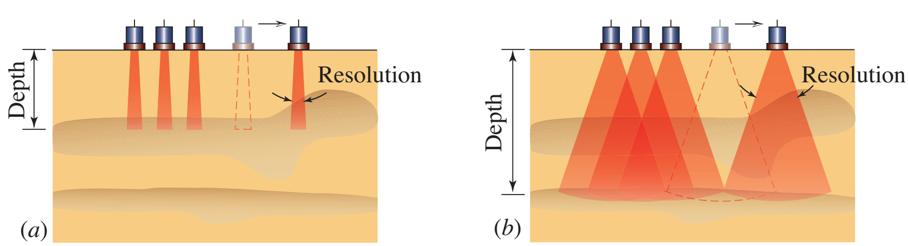


Figure 1.2-4 Tradeoff between penetration and resolution. (*a*) GPR imaging at high frequency; angular resolution is good, but the penetration depth is poor. (*b*) GPR imaging at lower frequency; angular resolution is poor, but the penetration depth is greater. Tomographic reconstruction may be necessary.

Contrast. In many applications the selected probing wave translates large variations of the β property, which the user desires to know, into small variations of the observed α property. The result is an image of weak contrast, which may not be adequate to recognize the target features or distinguish it from the surrounding background noise. For example, when a biological cell is viewed under the conventional optical microscope, which measures optical absorption, various morphological structures are hardly visible since their optical absorption is practically the same. However, viewing the cell under the phase-contrast microscope, which measures the refractive index, can reveal morphological features. One must therefore use the imaging modality that is most sensitive to the object property of interest. Another approach is to change the object itself by injecting an extrinsic substance to which the probing wave is more sensitive. Known as **contrast agents**, such substances attach themselves selectively to various elements of the object, as illustrated pictorially in Fig. 1.2-5. An example is the use of optically absorbing stains and dyes, which are distributed selectively within biological cells, to view internal morphological structures.

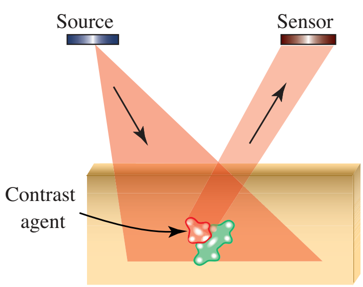


Figure 1.2-5 Imaging an object with injected contrast agents that are attached selectively to certain targets.

Noise and Clutter. Noise arises from random fluctuations within the detector or from extraneous waves that reach the detector independent of the target. As illustrated in Fig. 1.2-6, such waves may be created by scattering from clutter or random inhomogeneities in the medium, or from rough surfaces and boundaries that must be crossed by the incoming and/or the outgoing waves. In the presence of high noise, meaningful variations of the sensed property of the object must have greater contrast in order to be distinguished from the background random fluctuations. Known clutter may be avoided by use of carefully selected directions of view (or multiple views) bypassing clutter centers, as well as advanced detection algorithms.

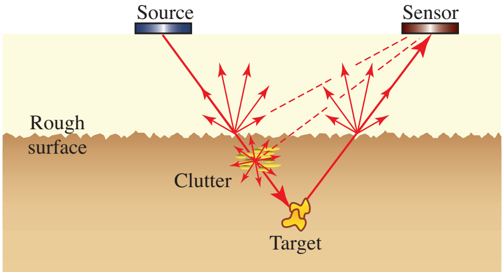


Figure 1.2-6 Scattering from a rough surface or from clutter or random inhomogeneities in the medium can reach the sensor and constitute background noise contaminating the signal received from the probed target.

1.3 Localized and Tomographic Imaging

There are two distinct approaches for addressing the localization challenge of 3D imaging:

- **Localized Imaging.** In this approach, the probe and sensor spots are configured such that their intersection, which we call the **scanned spot**, is a single point (or tiny volume). This ensures that, for each measurement, the sensor is responsive to approximately a single point in the object. The full 3D distribution is, of course, constructed by scanning over all points of the object. We will refer to this configuration simply as localized imaging.
- **Tomographic Imaging.** In this approach, physical localization is replaced with computational localization. The scanned spot is an extended region, so that a single measurement by the instrument is responsive to the sum of contributions from many points of the object within that spot. The measurement is repeated from multiple views such that these spots intersect, enabling each point of the object to contribute to multiple measurements. Taken together, these measurements are used to compute the individual contributions of all points. This form of **computational imaging** will be referred to in this book as **tomographic imaging**, **multiview tomography**, or simply **tomography**.

Localized and tomographic imaging are described in some detail in Chapter 3 and Chapter 4, respectively. The following are short previews.

A. Localized Imaging

Spatial Localization. A number of configurations can be used to ensure that the scanned spot (the intersection of the probe and the sensor spots) is a single point (or a tiny volume). In the configuration shown in Fig. 1.3-1(a), the two conical spots associated with focused beams intersect at a single point (i.e., the apexes of the cones coincide). This is the basis of **confocal imaging**, which is used in **laser scanning fluorescence confocal microscopy**, as will be described in Chapter 3 (Sec. 3.2B). In the example depicted in Fig. 1.3-1(b), the probe beam illuminates a single planar slice of the 3D object so that the probe spot is a sheet. The scattered waves generated at points of that slice are observed by normal 2D imaging using a lens, for example, so that the sensor spot is a double-cone region intersecting the sheet at a point. The process is repeated slice by slice. This configuration is adopted in the **slit-lamp ophthalmoscope**, which is used to examine different planes of the human eye (the lens, vitreous humor, retina, and optic nerve).

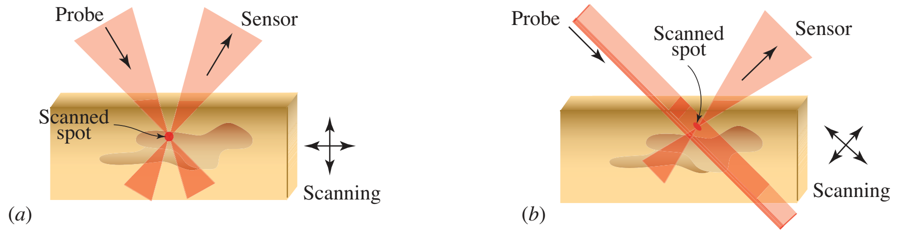


Figure 1.3-1 (a) In confocal imaging, the probe and sensor spots are co-focused onto the same point. (b) The probe beam illuminates a 2D slice of the 3D object and each slice is viewed by the sensor.

Time-of-Flight Localization. Another type of localization is based on the use of a pulsed narrow probe beam and a time-sensitive sensor. The pulse travels through the object and is reflected from interior boundaries, creating echos that are detected by the sensor. A time trace of the received signal reveals the times of arrival and the strengths of the echos. An echo arriving after a roundtrip time t originates from a reflector at a depth $d = vt/2$, where v is the pulse propagation velocity, assumed to be constant