Chapter 2

Basic Radar Measurements

As seen in Chapter 1, radar systems are based on the detection and measurement of disturbances or reflections—the general terms is *scattering*—of electromagnetic waves by an object of interest. While there are a great many ways in which this can happen, as we shall see in later chapters, from the perspective of an observer at the location of the radar receiver, an electromagnetic signal possesses only a limited number of discernable characteristics or parameters. Radars operate on the basis of these physical properties—features of electromagnetic waves that we can isolate and measure—rather than some arbitrary, desirable characteristic that we might wish upon them. Here we summarize the basic properties of electromagnetic waves and identify associated *observables*, *i.e.*, measurable characteristics, that can serve as the basis for the design and operation of real systems, and give examples of basic system architectures.

2.1 Wave Observables

The simplest representation for an electromagnetic signal in free space wave is a linearly-polarized plane wave with cosinusoidal form, which we write as,

$$\mathbf{E}(t, \mathbf{r}) = \mathbf{A} \cos[2\pi f t - \mathbf{k} \cdot \mathbf{r} + \phi] \tag{2.1}$$

where $\mathbf{E}(t, \mathbf{r})$ represents the time, t, and space variation, x, of a electric-field plane wave propagating in the direction of the x-axis. While the individual variables on the right-hand side of Eq. 2.1 characterize four basic physical parameters of the wave: (i) the temporal rate of oscillation, or *frequency* f, of the wave, (ii) the spatial variation, or *wave vector* $\mathbf{k}$, with rate of spatial variation $|\mathbf{k}|$ and *direction of propagation* $\mathbf{k}/|\mathbf{k}|$, (iii) the angular offset of the source relative to the origin of our coordinate system, or *phase* ϕ, and (iv) the vector magnitude of the wave force, or *wave polarization*, $\mathbf{A}$, with *amplitude* $|\mathbf{A}|$ and *direction* of the field $\mathbf{A}/|\mathbf{A}|$. In addition, the total value of the argument of the cosine in Eq. 2.1 is the *instantaneous phase* which determines the value of the cosine at a point in space-time. A similar expression for the accompanying magnetic field, $\mathbf{H}$, would have the same form but with the orientation as prescribed by Maxwell's equations.

In addition to the four wave parameters above, there is an implicit, fifth observable, which we refer to as *modulation*, that depends on the manner in which the wave is manipulated at its source. Modulation imposes a *time variation* on the wave parameters. Most common, perhaps, is switching of the wave On and Off by forcing the magnitude $|\mathbf{A}|$ to vary between zero and some finite value. Modulation of the waveform allows measurement of the *time delay* or *flight time* between the instant in which a radar signal is emitted by the transmitter and that when it arrives at the receiver. This is accomplished by measuring the time that lapses between the imposition of a particular modulation pattern on the signal emitted by the radar transmitter and that time when the same pattern of time variation is observed in the received signal waveform. The ability to measure time delay between signal transmission and reception on the basis of time variation of the wave parameters is perhaps the most fundamental—certainly the most exploited—of the five observables in that it directly constrains any solutions for the transmitter-target-receiver path length in an accurate manner. Modulation can be applied to any of the physical parameters of the wave, so that in general we can have $\mathbf{A}(t)$, $f(t)$, $\mathbf{k}(t)$, and $\phi(t)$. It should be recognized, though, that these four are not all independent, as we shall see below.

Taking the four physical parameters in turn, the temporal frequency of a wave denotes the number of oscillations per unit time at a fixed point in space. As frequency is perhaps the best known and understood property of the wave, we do not discuss it further here.

The spatial rate of variation of the wave is proportional to temporal-frequency and inversely proportional to wavelength. This is inherent in magnitude of the wave vector,

$$|\mathbf{k}| = \frac{2\pi}{\lambda} = \frac{2\pi f}{c} \tag{2.2}$$

where λ is the wavelength and c is the speed of light in the medium. From this, $(\mathbf{k} \cdot \mathbf{r})/(2\pi f)$ is the time delay for a signal to reach position $\mathbf{r}$at the speed of light.

It is easy to show that the expression,

$$\mathbf{k} \cdot \mathbf{r} = \text{constant} \tag{2.3}$$

is the equation of a plane perpendicular to $\mathbf{k}$, and that the maximum rate of spatial change is in the direction $\mathbf{k}$.[1] Increasing the value of the constant on the right hand side of Eq. 2.3 by 2π changes the position of the plane by the one wavelength in the $\mathbf{k}$ direction. Viewed from another perspective, changing the position vector, $\mathbf{r}$, by one wavelength parallel to $\mathbf{k}$ changes the value of the dot product in Eq. 2.3 by 2π radians. From this, points of fixed instantaneous phase on the curve of the cosine line up along planes perpendicular to $\mathbf{k}$, and repeat, modulo(2π), regularly spaced by one wavelength in direction $\mathbf{k}$. Examination of the argument of the cosine, Eq. 2.1, as time progresses shows that the cosinusoidal waveform moves in the direction of $\mathbf{k}$ at the speed of light. Thus, Eq. 2.1 describes a wave propagating in the direction $\mathbf{k}$ while $\mathbf{k} \cdot \mathbf{r}$ describes the total phase retardation at position $\mathbf{r}$ with respect to the origin of our spatial coordinate system.

The phase offset, ϕ, is a measure of the timing offset of the oscillations of our wave relative to phase measured at the origin. Setting $\mathbf{r} = 0$ in Eq. 2.1 shows that the oscillations of the reference wave have a positive zero crossing of the cosine at time $t = -\phi/2\pi f$. Positive values of ϕ indicate that the field strength in Eq. 2.3 crosses zero going positive earlier than, *i.e.*, before, a reference wave with no phase offset, and vice versa for negative values of ϕ. Because of the cyclic nature of the cosine, the behavior of wave is repetitive for each change in ϕ by an integer multiple of 2π. For this reason, the use of ϕ as a measure of time is ambiguous by integer multiples of $1/f$. more in an appe

The polarization vector $\mathbf{A}$ describes both the strength of the wave and the direction in which the electric force acts. When we are concerned primarily with the wave strength we use the term amplitude to refer to $|\mathbf{A}|$. We reserve use the term polarization for instances in which the direction of the electromagnetic field, *i.e.*, the orientation of $\mathbf{A}$ is to be emphasized. Polarization of a radiated wave is determined by the structure of the transmitting antenna, but usually is modified by scattering interactions with the radar target, with objects along the propagation path, and in certain cases by propagation through anisotropic media such as

[1] Write out the vector form of Eq. 2.3, as a scalar equation by expanding the dot product, and then compare the result with the standard form for the equation of a plane. See Problem tbd

Earth's ionosphere. At the receiver, the component of a polarized wave sensed is determined by the structure of the receiving antenna.

As indicated above, the basic electromagnetic wave characteristics of amplitude, frequency, phase, and polarization are often functions of time resulting from a combination of intentional modulation of the radiated signal imposed at the transmitter, propagation through a time-varying transmission medium, and from scattering by moving or fluctuating objects. Variations of $\mathbf{k}$ also occur, but are almost always a consequence of a change in the frequency at the transmitter or as a result of the Doppler effect.

Apart from temporal variations of $\mathbf{k}$, there are situations in which the engineering and scientific analysis is simplified by considering $\mathbf{k}$ as the independent variable. Rewriting Eq. 2.1 to reflect the possiblity of time variation of these parameters we can express the right-hand side as,

$$\mathbf{A}(t)\cos[2\pi f(t)t - \mathbf{k}(t)\cdot\mathbf{r}(t) + \phi(t)] \tag{2.4}$$

This more general form is used often throughout the remainder of this book. As an example, modulation of the transmitted signal can be thought of as a means for 'labeling' segments of the transmitted waveform by introducing known time variations into the amplitude, frequency, phase, or polarization at the transmitter. Unlike phase, which is always ambiguous on the scale of the wavelength, the use of simple waveforms for the modulation can result in deterministic relationships between the signal time of flight and the distances of transmitter and receiver along direct and/or scattered paths.

2.2 Application of Wave Observables

From the above it is apparent that the number of variables available for manipulation in radar signal design is limited. Similarly, the number of wave parameters that can be measured and interpreted is also small. Nonetheless these may be exploited to infer many properties of the objects observed by radar, with broad applications as follow:

Amplitude and intensity describe the strength of the wave, which is often an important factor in the interpretation of the physical characteristics of the echoing object. When the polarization vector $\mathbf{A}$ represents the electric field strength $\mathbf{E}$ V/m. The wave intensity is given by $I = |\mathbf{E}|^2/2\eta$ W/m^2, where η is the wave impedance of the the medium. In some applications it is more convenient to use the scalar amplitude $|\mathbf{E}|$ rather than the intensity, however, so both are important. Obviously, the intensity and amplitude are equivalent scalar measures of the wave strength.

Frequency, or more precisely, the change in frequency associated with motion of a scattering object, allows precise determination of the motion of scattering objects based on the Doppler effect, and is commonly used for this purpose. In addition time manipulation of the transmitted frequency represents an important, fundamental method of modulation.

Phase provides for precise measurements of relative signal arrival times at two or more receivers, which can be used to determine direction of arrival, as well as to determine small changes in radar signal time of flight. Such information is useful in determining the position, *i.e. localization*, of points within a scene or of individual scattering features relative to the radar. Given accurate observations, changes in position can be determined on the scale of the radar wavelength.

Time of flight is a measure of the radar propagation path length between transmitter, T, and receiver, R, followed by the signal. This quantity is given by $\Delta t = \overline{\mathsf{TR}}/c$, and also is referred to as the *flight time* and the *propagation time delay* of the signal.

Polarization is useful in interpreting characteristics of the echo source objects. Echoes from smooth objects and/or regularly structured objects tend to be more systematically polarized than those from irregular ones.

Wave vector orientation of a radar signal at the receiver is synonymous with the wave direction of arrival, which is related to the location of a scattering object. Some systems are able to extract the three-dimensional direction of the wave vector although only two is more common. [HZ.. what do we mean by last sentence? L.] 3-D direction of

Every radar measurement and application is based on the use of one or more of the six observables above. Some systems quantitatively extend the observational set, for example, by resorting to simultaneous independent measurements at multiple frequencies, or by measurements of the variation in observable parameters as functions of frequency and time. Although such extensions can lead to very complex systems, the complexity should not be allowed to obscure the basic constraint that all inferences from radar must be based on observations of some or all of the six parameters described above. In working through the remainder of this book, it is helpful to keep in mind the opportunities opened up when combinations of these observables are available, as well as fundamental limitations imposedz by the basic properties of electromagnetic waves. [Add ideas that: there are many design possibilities; infinite choices of modulation; several predicated on statistical measures and geometry.] The form of emporal modulation employed strongly affects the accuracy and precision with which various of these characteristics can be measured while providing the means to sort out the time-history of the transmissions and echo signals. The principal ways in which this can be accomplished and the basis for selection of particular temporal waveforms is a major topic in the latter sections of this book.

NEEDS MORE WORK

Is last sentence true? L

2.3 Use of Time and Frequency Measurements in Simple Radars

Improved instrumentation later led to use of the Doppler effect to improve the precision of relative velocity estimates, and this type of measurement forms the basis, for example, of precision tracking of spacecraft, as well as more prosaic applications, such as the use of radar 'guns' to measure the speed of a pitcher's fastball. In this section we outline the basic measurement of time-delay and Doppler shift and relate these to basic properties of the radar signal. We illustrate how measurements of range, supplemented by those of direction, can be used to monitor the landing of aircraft. Similarly, measurements of Doppler shift can be used determine the speed of a baseball.

2.3.1 Timing Measurements

In modern radar, the time delay of the echo signal was the first, and continues to be the most widely used of the basic wave properties. That historically radar development was driven by a military need to measure the distance, or range. Subsequent realization that time-differenced values of range measurements normalized by time difference between observations yield the relative velocity between the radar instrument and reflecting objects led to additional applications.

Consider a thought experiment in which an electromagnetic pulse of energy is radiated from an antenna, propagates to a reflecting object and returns to its site of origin where it is

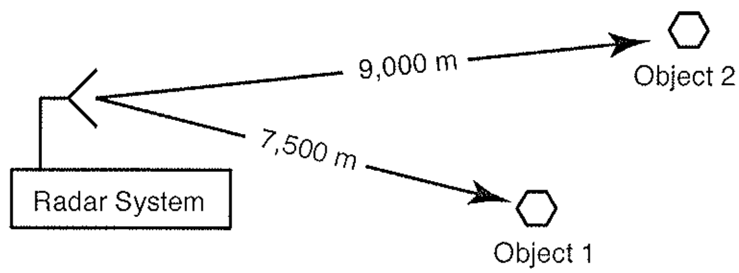

Figure 2.1: Radar system with two reflecting objects. Schematic defining range relationship between two objects sensed by a single radar. For distances as shown the round trip path followed by the radar signal is twice the distances shown.

recognized as an echo of the original, transmitted pulse. Here the observable is the time delay between the switching of $|\mathbf{A}(t)|$ from zero to some finite value, thereby initiating radiation of a signal towards the target, and the time that the beginning of the returning echo waveform is observed at the receiver. The measured time delay between transmission and reception of the pulse corresponds to the time that the electromagnetic was in flight. This time depends on the path traveled by the energy pulse and its speed along that path, as suggested by the observing geometry as illustrated for two targets in Fig. 2.1. HZ, pls note qu

Because the speed of light in the atmosphere is known and nearly constant, it is straightforward to infer the distance from the radar to the reflecting object from a measurement of the time delay. Usually the receiver will be nearly co-located with the transmitter, although in bistatic geometries the transmitter and receiver subsystems can be widely separated. The time delay from transmission of a radar pulse to its reception is the the ratio of the round-trip distance to the speed of light, and is easily discerned on a plot of signal intensity versus time provided that the signal levels are adequate relative to the system noise. Such a plot is illustrated in Fig. 2.2. In this simple example, the total round trip distance is 15,000 m for Object 1 located at a distance of 7,500 m from the radar, and is 18,000 m for Object 2 at a distance of 9,000 m. At the speed of light, for the echo from Object 1, the time delay is,

$$\tau_1 = \frac{\text{distance}}{\text{speed of light}} = \frac{15 \times 10^3 \text{ m}}{3 \times 10^8 \text{ m/s}} = 50 \ \mu\text{s} \tag{2.5}$$

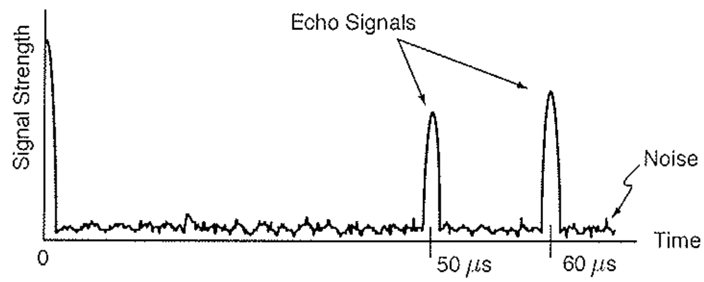

Figure 2.2: Echos from two objects. Plot shows variation of received signal power as a function of time with echos from objects a ranges of 7,500 and 9,000 m, as in Fig. 2.1. Plot is typical of echo signals in the presence of noise.

while for Object 2 the result is,

$$\tau_2 = \frac{18 \times 10^3 \text{ m}}{3 \times 10^8 \text{ m/s}} = 60 \ \mu\text{s} \tag{2.6}$$

It is usually more convenient to think of the distance between the measurement site and the scattering object, or R, than it is the round-trip distance.

In monostatic observing geometries, the expected time delay will be the distance from the instrument to the target divided by the propagation velocity, multiplied by two to account for the round-trip distance in which the signal traverses the same path twice. Expressing range R as a function of time delay, τ for this case,

$$R = \frac{c\tau}{2} \tag{2.7}$$

where c is the speed of light in the mediium. Equivalently, we can think of the ratio of the distance to time delay as one half that of the speed of light,

$$\frac{R}{\tau} = \frac{c}{2} = \begin{array}{l} 150 \text{ Mm/s} \\ 150 \text{ km/ms} \\ 150 \text{ m/}\mu\text{s} \\ 150 \text{ mm/ns} \end{array} \tag{2.8}$$

Thus, the relationship between time delay and distance may be considered simply as a distance of 150 m for each microsecond of time delay, a useful conversion factor to keep in mind for many common radar problems. When considering longer distances, such as determining the distance to the moon or other planetary bodies, a more appropriate conversion factor might be 150 km per millisecond delay, or even 150,000 km per second of delay.[2] para still a 'lil a

Often, it is more convenient to think directly in terms of the *flight time* of the radar pulse than range. In many instances we refer to this as the *light time*, in order to emphasize that this is the time required at the speed of light for the pulse to make the round trip from transmitter to scattering object and back. We observe the time interval between the transmission of the signal and the reception of its echo.[3]

Armed with only the above analysis, we can easily understand one common radar application—a system that can track the relative positions of aircraft approaching an airport in order to allow air traffic controllers to sequence landings safely. For this purpose, suppose that in Fig. 2.1 the radar system is located near the runways and that the reflectors represent not fixed targets but incoming aircraft instead. In this scenario, each aircraft will produce an echo signal at a time delay proportional to its distance from the airport. If, in addition, the radar antenna creates a narrow rotating beam to scan the horizon, then the direction of arrival of the echo, as determined from the antenna pointing direction at the time the echo is observed, reveals the angular position, or *azimuth* compass direction, of each aircraft. It is straightforward to present the results in polar coordinates using the observed azimuth angle and range coordinates as the plotting variables. The resulting display device, called a Plan Position Indicator, or PPI, originally comprised a large circular cathod ray tube displaying a line from the center to the perimeter sweeping out a narrow area indicating the instantaneous pointing direction of the radar antenna, Fig. 2.3. The angle of reference line was syncronized with a rotating radar antenna, while the line itself was actually swept from the display center outwards in syncronization with the time delay corresponding to echoes from increasing ranges. An air traffic controller, by examining a series of plotted radar positions as displayed on the PPI, can direct each plane to adjust its approach speed so that only one will require use of the runway at any particular arrival time. Analog radars such as these were closely coupled to the physics of the observations. Air traffic control radars augment our natural vision by supplying information needed to operate safely at night, in other conditions of obscured vision, and during rough

[2]Yet another value is approximately one astronomical unit, or $\approx 3 \times 10^{11}$ m per 1,000 s of round trip flight time delay!

[3]In planetary radar astronomy and in tracking deep space vehicles the term *round-trip light time* is used.

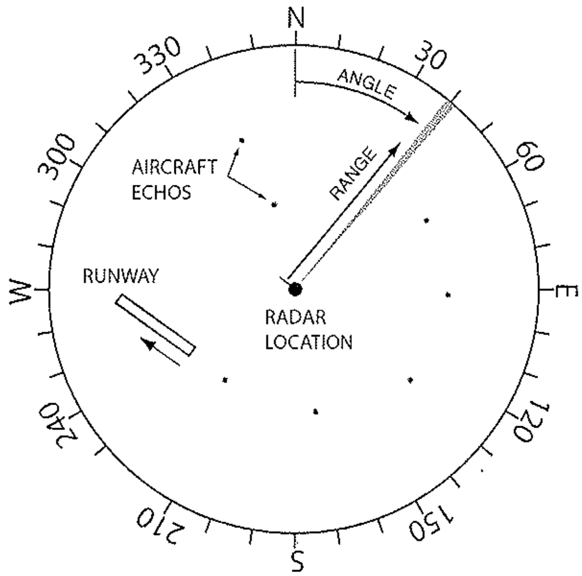

Figure 2.3: A Plan Position Indicator display, or PPI. The radar is located at the center of the map display; scanning of the area within the range circle is accomplished by rotation of a narrow beam tranmitting/receiving antenna represented by narrow wedge emanating from the radar location. Any backscattering objects appear as small dots which are mapped onto a polar plot labeled in distance (range) and compass direction (azimuth angle). Arriving aircraft are sequenced to approach the runway in an orderly fashion. Here, the approach path is CW around the radar location, as suggested by the dots, each of which represents a single observation.

Make problem based on PPI? HZ. PPI example should include aircraft-like targets?

weather.

2.3.2 Doppler Measurements

Another fundamental property of a radar target, the radial component of its velocity, can be inferred directly from its radar echo. Specifically, the radial motion of an object toward or away, can be inferred from *range-rate* infomation inherent in the echo. One method for obtaining $\dot{R}$, mentioned above, is to estimate the value from the change in range between observations made at two different time. For this,

$$v_{\text{radial}} = \dot{R} \simeq \frac{R_2 - R_1}{t_2 - t_1} = \frac{\Delta R}{\Delta t} \quad \text{(m/s)} \tag{2.9}$$

where, v_{radial}, measured as expected with positive sign for increasing range, is the radial component of the target velocity relative to the radar, and the differences in positions over the time interval approximates the derivative.

A second method is to exploit the Doppler shift. In classical terms, the Doppler shift observed by radar is the result of reflections from a moving object. For backscatter, to first order, the Doppler shift is,

$$\Delta f_{\text{dop}} = f_{\text{rec}} - f_{\text{trans}} = -\frac{2\dot{R}}{\lambda}\ (\text{Hz}) \tag{2.10}$$

where f_{rec} and f_{trans} are the received and transmitted frequencies, respectively, λ is the wavelength of the transmitted signal, and $\dot{R} = dR/dt$. Note that in this formulation we can think of the round-trip Doppler effect as just twice the radial velocity measured in units of radar wavelength, together with an appropriate sign, Eq. 2.10. One also can use the more conventional formula,

$$\Delta f_{\text{dop}} = -2\frac{f}{c}\dot{R}\ (\text{Hz}) \tag{2.11}$$

or

$$v_{\text{radial}} = -\lambda\frac{\Delta f_{\text{dop}}}{2}\ (\text{m/s}) \tag{2.12}$$

As is the case of the range formulas, the factor of two in the expressions above results from two-way propagation of the signal along the path because the round trip path length changes at twice the rate of change of range. Physically, ignoring relativitic effects, the round-trip Doppler effect can be thought of in terms of a signal that undergoes two intermediate frequency shifts. The first of these is associated with interaction of the transmitted signal with the moving target in which the frequency 'seen' by the target is Doppler shifted by $\dot{R}/\lambda$; scattered energy re-radiated back toward the receiver of a monostatic radar undergoes a second frequency shift of the same sign and essentially the same value as that when the illumination signal first arrived at the target. In the second part of this calculation we often can ignore the small difference in frequency due to the first Doppler shift in the calculation of the second. Taken together, the result is to double the one-way effect. derive exact clas

Equations. 2.10 and 2.11 are accurate for measurements of objects moving at speeds that are very much less than the speed of light, *i.e.*, less than about $c/10$. For most applications this accommodates all terrestrial flying objects and space vehicles in Earth orbit.

Since we are usually interested in the motion of the radar 'target,' and recognizing that $\dot{R}$

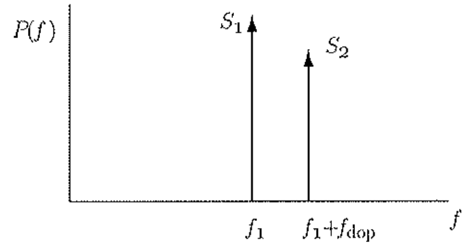

Figure 2.4: Illustrating a Doppler shifted waveform. Power spectum of a transmitted narrow bandwidth signal is shifted in frequency by interaction with a moving object. Received echo appears at a frequency that is different that that transmitted by f_{dop}, Eq. 2.10. For monstatic radar, frequency is increased if the scattering object is moving towards the radar, is unchanged if motion is transverse to radar line-of-sight, and is negative if object is moving away from radar. More complex waveforms with broad spectral features behave in the same manner.

is the component of velocity along the line-of-sight from the radar, we can write,

$$v_{\text{radial}} = -\lambda \frac{\Delta f_{\text{dop}}}{2} \quad (\text{m/s}) \tag{2.13}$$

where v_{radial} is explicitly the radial velocity.

Doppler shift can be observed in a number of ways. Conceptually simplest and most convenient, perhaps, is to view the frequency of the echo signal on a spectrum analyzer, in which case the frequency change appears as a shift in the position of the spectral line or lines associated with the echo waveform. An example is suggested by Fig. 2.4. Realistic systems that are designed to measure the velocity of objects often use a single frequency, or continuous wave, 'CW,' waveform.

Change figure to line spectra for consistency with text

An example of a radar system using Doppler information is that of a pitching coach employing a radar 'gun' to determine the speed of a baseball passing over home plate. Speed guns operate by (i) radiating a CW signal and (ii) using a small fraction of the transmitter output as a comparison signal for determining the Doppler shift of echoes from an approaching pitched ball. The second step typically is accomplished by taking the algebraic product of the received signal with the sample of the transmitted signal, a process knows as 'mixing' of the two. The Doppler shift is given by low-pass filtered output of the mixer. Fig. 2.5 indicates the basic functional elements of a speed gun. In this application, distance from the radar to the target is not of concern, but the relative velocity of the two is. By counting the frequency of

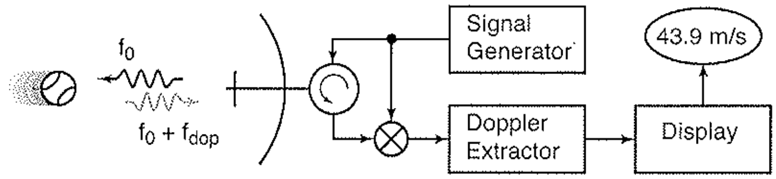

Figure 2.5: Block diagram of radar speed gun. A radar 'gun' measures the Doppler shift induced by a moving object. Speed of approach can be calculated from Eq. 2.13. Connection among signal generator, antenna, and mixer, $\otimes$, is accomplished with a 'circulator,' a non-linear device structured so that a signal entering one port is connected to the adjacent port located CCW from the entry port, $\circlearrowleft$. Output from the signal generator at frequency f_0 flows to the antenna, and is radiated; input signals received by the antenna at frequency $f_0 + f_{\rm dop}$ flow to the mixer. Output of the mixer is the product of the echo signal and a sample of the transmitted signal.

the extracted, Doppler shifted, waveform and by knowing the wavelength of the transmitted signal, we can calculate the speed of the ball with respect to the radar by applying Eq. 2.13 above. add speed gun p

Measurements of echo signal intensity and polarization are also useful in specialized radar systems. As we shall see, in addition to it range, the intensity of scattering from any object is related to a combination of the object's shape, structure, and material properties; echo polarization depends on the target structure primarily, and less so on the materials.

Sometimes both range and Doppler measurements are combined in a more complex system. Suppose that the air traffic control radar described previously measures not only the time delay of the radar pulses, but also the Doppler shift. Then the flight controllers could know the radar-to-aircraft line-of-sight velocity of each approaching aircraft as well as its distance; this is effective if the radar is positioned roughly along the flight path. Alternatively, the total velocity can be estimated by converting the range-azimuth PPI display, Fig. 2.3, to rectangular coordinates and differencing the sequential two-diminsional position measurements. In practice both types of measurement are employed, but the choice between the two depends on considerations related to specific applications. Air traffic control radars use the latter method as the total velocity is needed, independently of an individual aircraft's direction of flight. Doppler measurements, for example, are used in modern weather radar radars to determine wind speeds within thunderstorms and tornados, since the motion of the airmass is such that the important aspects of the motion can be inferred from line-of-sight observations alone.

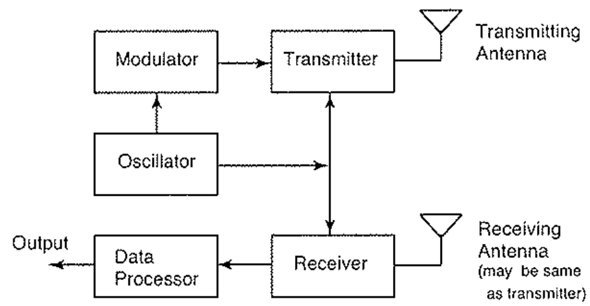

Figure 2.6: Generic radar block diagram. Functional elements common to all radars. *v.*, text.

2.3.3 System Elements

The example measurements above and in previous discussions suggest a wide variety of applications for similar measurements of time-delay and frequency. In fact, all share a a few common functional elements. And all radars comprise subsystems that include, in some form, the system elements of Table 2.1.

Table 2.1: Elements & functions common to all radars. C.f. Fig. 2.6

System Element	*Function*
Oscillator	Provide clock signal for other system elements
Modulator	Generate and conditions signal waveforms
Transmitter	Amplify signals
Antenna(s)	Transmit and receive signals
Receiver	Amplify and filters echo signals, convert to digital form
Data Processor	Apply various algorithms to extract information from echo signals

Using these elements we can draw a generic block diagram applicable to all conventional radar systems. This is given in Fig. 2.6. Similar elements will be found in derivative systems, such as *sonars*, *i.e.*, echoing systems based on sound waves, and lidars, *i.e.*, echoing systems based on optical technology.

2.4 Side-Looking Radar Concept: An Imaging Radar System

In this section we introduce the concept of *side-looking radar*, or SLR, designed for the purpose of creating two-dimensional images of surface reflectivity. This type of radar is a powerful tool for remote sensing, and very different from the systems with rotating dish antennas typically seen in films and introduced conceptually above. Rather, SLR systems employ a radar in translational motion, with a narrow-beam antenna directed to one side of the radar path, together with measurements of signal intensity vs. range to produce high-resolution images of Earth's surface.

The purpose of this type of imaging radar is to sort out the locations of all the scatterers on the surface, and display the brightness from each scatterer in a systematic way. The product of these systems is an 'image strip' representing the scattering properies of the terrain parallel to the flight path of the aircraft or spacecraft that serves as the radar platform. Instead of a rotating antenna to scan an area surrounding a fixed point, an SLR system transmits a series of pulses to illuminate a *swath* of ground located to the side of the path defined by the motion of the platform carrying the radar. Scattering from each point on the ground within the illumination pattern of the antenna returns some of the incident energy to the radar. Figure 2.7 provides a simplified view of the geometry in which the coordinates are defined with respect to an idealized linear flight path followed by the radar platform.

In contrast with the systems intended to measure range and velocity of individual objects, an SLR characterizes an entire 'scene' made up of myriad discrete resolution elements, each of which characterizes the composite scattering from a small, well-defined area within the imaged swath. While we think of the scene as being scanned as a result of the motion of the radar platform, sensing of the scene remains within the province of radar scattering from each resolution element. Obviously, scanning of the scene requires a very different approach from that intended to monitor a fixed, localized region of space, as described to this point. Nevertheless, SLR and the range and Doppler systems described above have much in common.

Here we describe a *real-aperture* SLR, in which the radar discriminates among echo signals from multiple locations abeam on side of a well-defined flight path by recording the time that points on the surface are illuminated by the antenna beam. As we shall see, a measurement of time of flight, together with the known geometry is suffienct to determine the locations of all scattering elements in the scene. Identification and discrimination among surface features

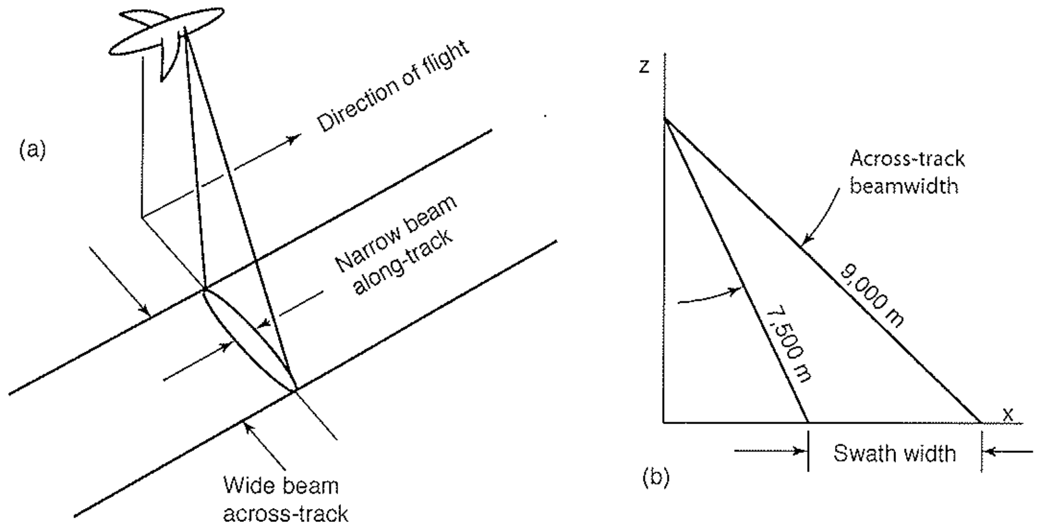

Figure 2.7: Side-looking radar geometry. (a) Radar carried on aircraft has antenna pattern directed to the right-hand side of flight path. Highly elliptical beam pattern progressively illuminates a swath parallel to aircraft track. At each position the antenna beam pattern defines a narrow strip in the across-track direction; range measurements define locations within the illuminated strip. (b) Example range triangle viewed along the direction of flight. Minimum and maximum ranges to edges of illuminated swath are determined by the across-track antenna beamwidth and the altitude of the vehicle. Ranges here correspond to example in Figs. 2.1 and 2.2, for illustration only.

in the direction perpendicular to the flight path are achieved by the range to the surface, while resolution parallel to the path is provided by the transverse resolution of the antenna. Figure 2.8 provides a simplified example of a real-aperture system showing that the radar need only perform a few simple functions to capture the obserational data required to form the image. For improved performance, the Doppler frequency of each echo can be incorporated into the radar processor to obtain finer along-track resolution, as described in detail in Chpt(s). ??.

Returning to Fig. 2.7, the term *across track* refers to the direction on the mapped surface perpendicular to the flight path; similarly, the term *along track* refers to the direction on the surface parallel to the flight path. Assume, for example, that the geometry and radar parameters are such that the range at the near edge of the illuminated swath is 7,500 m, and 9,000 m at the far edge, so that the swath width corresponds to a 1,500 m change in the range direction as measured along the slant path between the aircraft and the ground, perpendicular to the flight path. With a judicious choice of antenna, a narrow cross segment of the swath in the along-track direction can be selected by the antenna beam, as this is essentially the only area illuminated

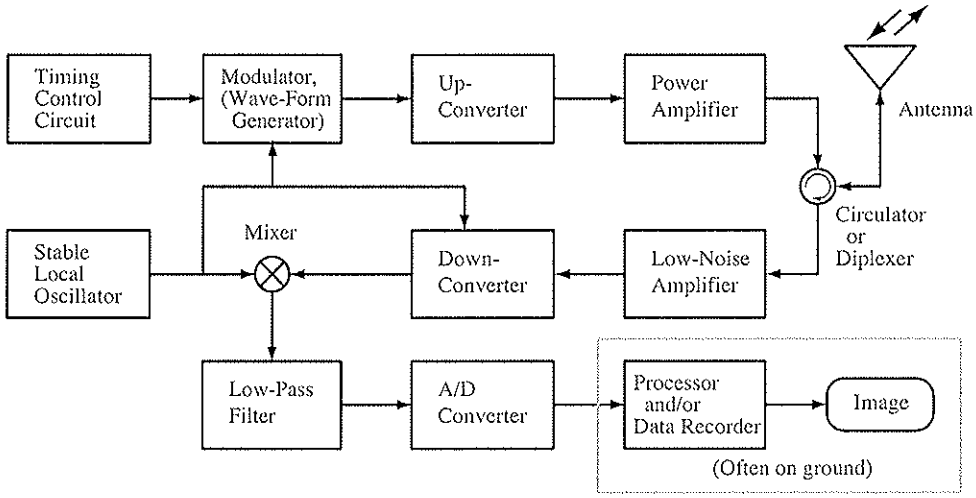

Figure 2.8: Simplified block diagram for side-looking imaging radar. System requires same elements and functions identified in Table 2.1 and Fig. 2.6. Upper path comprises modulator and transmitter; middle path includes reference oscillator used to derive transmitter and provide receiver reference signals, elements of a super-heterodyne receiver, and mixer to prepare for signal processing; lower path contains signal-processing elements.

by the transmitted waveform and from which echos are sensed. If a suitable radar waveform is employed to define particular segments in the range direction, then a two-dimensional map of the radar reflectivity within the swath can be formed as the radar moves along the flight track.

In its simplest realization, the transmitted waveform is a short pulse of energy radiated periodically as the radar moves along the flight path, sequentially illuminating strips of the surface perpendicular the long dimension of the swath. The areal resolution of this map depends on the combination of the resolutions in range for the cross-track direction and in antenna beamwidth for the along-track direction. Modern imaging radar systems operate in a manner similar to that just described, but make use of complex signal waveforms and apply precise signal processing to the problem.

In visualizing the operation of an SLR system, keep in mind the very large difference between the speed of the aircraft and the speed at which the radar range changes. In our example the radar pulse scans the 1,500 m cross-track distance in only 10 μs (cf Figs. 2.1, 2.2). Even a very high speed aircraft, moving in the along-track direction at, say, 300 m/s, travels only 3 mm in the 10 μs interval between the time of the echo from the nearest point on the swath and that when the echo is received from the far side of the swath. Similarly, an Earth-orbiting satellite moves much less than 1 m in this same time interval. Consequently, for the purpose of visualizing the geometriy, an aircraft can be considered as stationary during the time of each

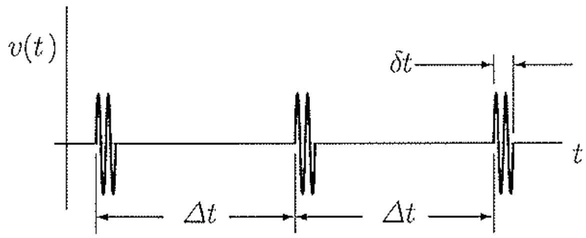

Figure 2.9: Transmitted waveform of a simple imaging radar. Plot depicts the radiated waveform of the transmitted signal. Transmitted signal comprises a brief oscillatory pulse. In a conventional radar system employing simple pulses the difference between the time separation of the pulses, Δt, and the pulse duration, δt, typically is orders of magnitude. For example, ranges of $\Delta t \sim 0.001$ to 0.1 s and $\delta t \sim 0.000,000,1$ to $0.000,01$ s are common.

observation, while changing observation points along the path between observations of echos. Later, when considering more advanced systems, we shall see that even the relatively slow motion of the radar platform can be put to very good use in refined designs, however. Even then it is helpful to maintain the perspective here of the large difference between the speed of platform and that of the radar signals in space.

verify calcs of platform motion

In practice, the duration of the transmitted pulse might be very brief, or it might be a modulated transmission, lasting longer than a simple pulse, in which fine range resolution is obtained by use of time-waveform compression. In either instance, the pulse waveform is transmitted repetitively so that the transmitted signal might have the appearance of that in Fig.2.9. The received waveform, on the other hand, is always made up of a sequence of echos that are longer than the transmitted signal as a result of interaction with the extended area of the surface in the cross-track direction of the swath. The stretched echo begins at the time of first reception from points located at the near edge of the swath and continues until the return at greatest range is reached at the most distant point across the swath. The intensity of the received echo as a function of time is controlled by the combination of varying range and the strength of the radar backscattering across the illuminated surface. Thus, the strength of the received waveform is controlled by the degree to which the surface returns radar energy to the receiver as a function of time delay, with the overall echo duration controlled by the difference in echo times from the near- and far-swath locations. An SLR echo from a fairly uniform surface might resemble the sketch in Fig. 2.10. On the other hand, if the scene within the swath were to contain a single strong reflector point amidst many weaker ones, then the response

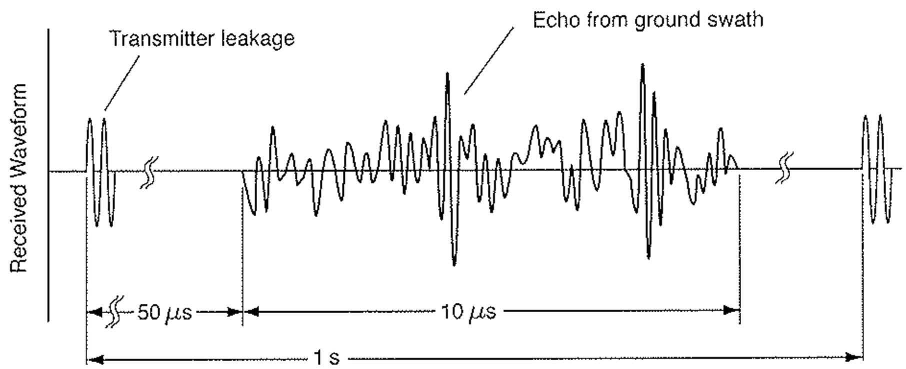

Figure 2.10: Received waveform from within a side-looking swath. Figure illustrates the relationship of transmitted pulse and echo from an extended swath. Trace represents the signal at the terminals of the receiving antenna of our simple SLR. Some portion of the transmitter pulse is always present in the receiver output as the result of finite isolation between the transmitting and receiving elements of the system. Transmitter leakage signal can be used as a fiducial mark in the receiver data. Echo signal from the image mapping strip on the ground is spread out in time as a result of the range variation across the ground swath. In our example, the first ground echo appears 50 μs after start of the transmitter pulse radiation and continues for 10 μs. Here the interval between transmitted pulses is 1 s. Note breaks in scale.

Add variables to axes, here an elsewhere

corresponding to single transmitted pulse would more closely resemble that in Fig. 2.11. revise figures

As suggested above, assume that the antenna beamwidth is quite narrow in the along-track direction. There are many techniques to generate such a narrow antenna patterns, ranging from use of a very long structure parallel to the flight path, which is impractical on most aircraft, to the use of signal processing techniques to create a virutal, but functionally effective, 'synthetic aperture,' which we discuss in Chpt. ??. Regardless of the processing approach, we build an image of the ground by observing a series of echoes from repeating transmitted pulses emitted sequently along the flight path and displaying these in a raster format, in which the trace of each echo is written directly adjacent to its predecessor. If we were to observe a region containing two bright point scattering points located on the surface, and then lay down a series of echo lines corresponding to the narrow antenna beam next to each other, we might obtain a result similar to that in Fig. 2.12. The figure is idealized in that it shows two echoes of equal strength

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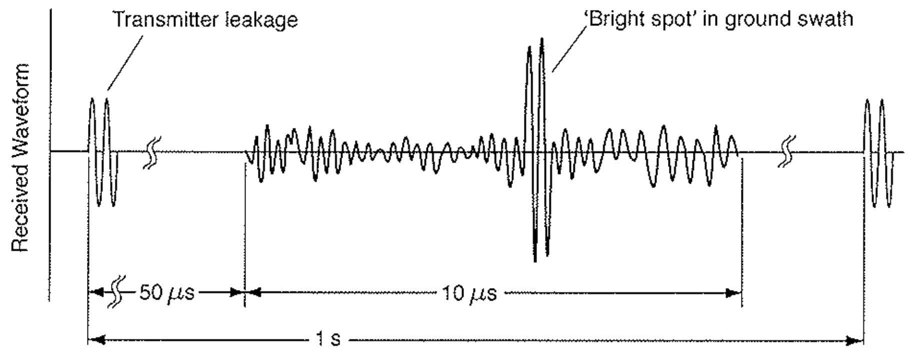

Figure 2.11: Received waveform with echo containing a strongly reflecting feature. 'Bright spot' within the swath occurs when a point within the antenna beam includes an unusually strong, localized scattering feature or area. This appears in the echo waveform as a brief interval of markedly increased amplitude of the received waveform. C.f., Fig. 2.10.

registered with the the transmission time coordinates.

Displaying the same data as above in image format, we obtain Fig. 2.13, where the representation is in terms of signal intensity within the transmission-time, echo-delay space. A full image requires more closely spaced pulse transmissions in the along-track dimension, which can be achieved by decreasing the intervals between pulse transmissions or reducing the speed of the radar platform. The size of the bright points represents the response of the radar to a point target in echo delay, as controlled primarily by system bandwidth, and in the along-track direction, as controlled primarily by the width of the antenna beam in the along-track direction.

rework discussion of image response. 1st draft here. lt. 2/03

We can convert the time delays to actual distances to form more useful geometric maps of the surface. The across-track range direction separation, ΔR, as determined from the difference of the time delay Δt to the two points is,

$$\Delta\tau = 2.5\ \mu\text{s} \Rightarrow \Delta R = \frac{3 \times 10^{8} \times 2.5 \times 10^{-6}}{2} = 375\ \text{m} \tag{2.14}$$

Keep in mind that in Eq. 2.14, the range coordinate is based on the flight time of the radar pulse that travels on a straight line path between the radar and a given location on the surface. Consequently, *e.g.*, the abscissa in Fig. 2.12 gives the slant distance from the radar to points on the mapped surface; this distance is always greater than the distance along the surface within the swath (cf. Fig. 2.7(b)). Further geometric transformations are required to relate the

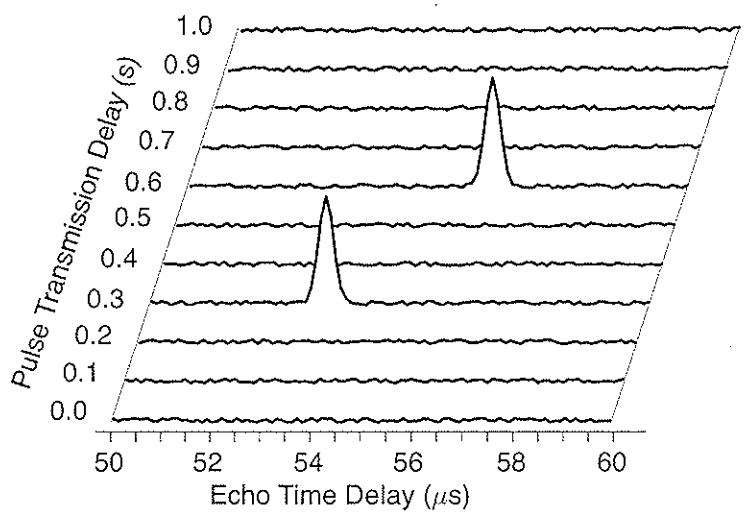

Figure 2.12: Received waveform with echoes from two bright points. Echos are identified by strong signal for which echo strength clearly exceeds small flucuations in baseline due to system noise. Echo from transmission at 0.3 s is received 53.5 μs later; echo from transmision at 0.6 s is received after 56 μs. Plot depics a system in which the along-track width of antenna beam on the surface is sufficient to isolate echoes from points separated in the along-track direction by the distance the radar moves in 0.1 s.

time-delay of SLR observations to locations in true surface coordinates.

In the along-track direction the radar sample lines are in turn separated by 0.3 s. If the aircraft velocity is 200 m/s, then,

$$\Delta a_z = 0.3 \text{ s} \times 200 \text{ m/s} = 60 \text{ m} \tag{2.15}$$

In this instance, the distance between the two positions in the ground is the same as the distance moved by the radar between two successive pulses.

The minimum detectable separation of two objects at the same along-track range, or the *along-track resolution*, of our simple radar is set by the projection of the antenna pattern the surface. While faster pulsing of the transmitter leads to more frequent measurements, and hence observations which are more closely spaced in the along-track direction, the ability to discriminate among closely-spaced targets in the along track dimension is limited by the effectiveness of the antenna response in restricting the observed echo energy to a thin swath on the ground. To see how this works, consider that at sufficiently low rates of pulse transmission, the motion of the platform causes the antenna beam to illuminate entirely new areas with each individual pulse. As the interval between pulse transmissions decreases, at some point the areas

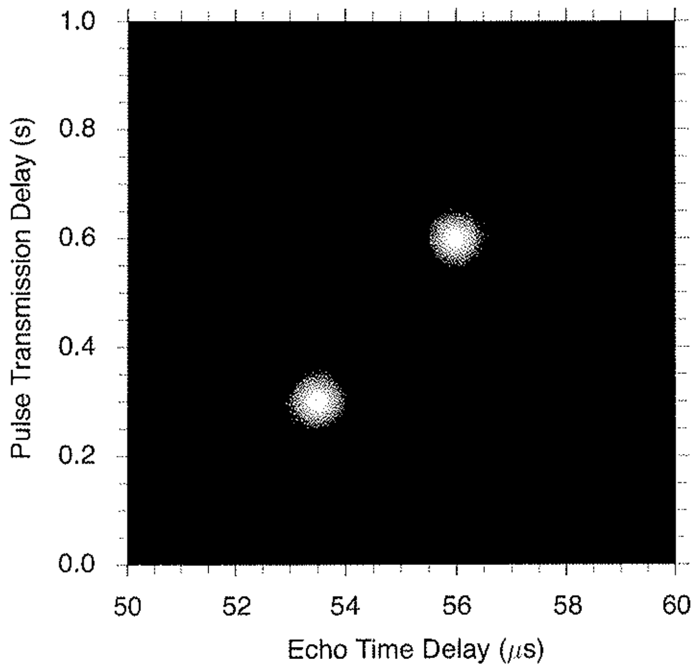

Figure 2.13: Image containing two bright points. Radar and scattering point geometry is same as for Fig. 2.12. An image such as this requires either much higher sampling rates or interpolation to display the features of the response. In a simple radar, this is achieved by decreasing the along-track pulse separation to the point where the antenna response from adjacent scans begin to overlap, which accounts for the spreading of the point response in the vertical dimension of the image.

illuminnated by two successive pulses must overlap in the along-track direction. This occurs when the along-track separation between pulses is less than the along-track dimension of the antenna footprint in the swath—the point at which our ability to discriminate between distinct scattering features in two successive pulse transmission/reception cycles begins to be degrade. From this we see that the width of the antenna beam in the along-track direction ultimately limits the along-track resolution. On the other hand, the scene is undersampled when the rate of pulsing is too low.

Similarly, our ability to discriminate among distinct scattering features in the cross-track direction can be lost as a result of ambiguity if the pulse repetition rate becomes too high, making the interpretation of the image difficult or impossible. In our example the swath is 10 μs in time corresponding to 1,500 m in range, which is consistent with the cross-track antenna beamwidth, as suggested in Fig. 2.1(b). It follows that transmission of pulses more frequently than once each 10 μs—as might be desirable in connection with a more complex waveform than the simple pulse used here—would result in simultaneous, overlaped reception of at least two echos from the same across-track range swath. another good H

For the reasons above the interval between pulses, the choice of the swath width, and the design of the antenna beam are all interrelated. Obviously, the most straightforward resolution of this conflict is to transmit one pulse each time the antenna is moved one beamwidth. As we shall see, there are elegant, well developed, design approaches for managing such conflicks while optimizing radar system performance. But a firm understanding of the fundamental geometric considerations we have explored here are key to understanding this field.

2.5 Basis for More Complex Systems

Most, but not all, radars determine range by a rather direct measurement of time delay, which is then related to distance by $R = (c\tau)/2$. A myriad of applications follow from this simple relationship. Advanced radars also employ measurements of Doppler frequency shift to determine range rate by $\Delta f = 2\dot{R}/\lambda$, again an extremely useful relationship which permits additional inferences regarding target location and motion. All radars make use of the wave observables introduced at the beginning of this chapter, and all are constructed of basic building blocks that include the elements listed in Table 2.1.

Many ingenuous methods for construction, combination, and configuration of the basic elements exist, supporting the range of applications discussed in the Chapter 1. Likewise, the theory describing these elements is both complex and highly developed, much more so than one might imagine from the simple pictures just presented. At the same time the basic physical pictures such as the two simples examples above should be kept in mind when evolving complexity begins to obscure the underlying principles. HZ: elaborate o