J. Webster (ed.), *Wiley Encyclopedia of Electrical and Electronics Engineering*

RADAR APPLICATIONS

Radar (radio detection and ranging) systems attempt to infer information about remotely located objects from reflections of deliberately generated electromagnetic waves at radio frequencies. Typically, the information sought is *detection* of the presence of target objects in the midst of clutter, *recognition* (classification) of targets, and *estimation* of target parameters such as range (distance from the radar antenna), bearing (azimuth and elevation), orientation, velocity, acceleration, or backscattering cross section (reflectivity) distribution.

Early radar systems could only scan the environment, to detect an aircraft when it appeared in their beam and to measure its range and bearing. The range resolution cell was determined by the length of the unmodulated transmitted pulse and was much larger than the aircraft. Thus, it was reasonable to model the aircraft as a point target and the system interference as white Gaussian thermal noise. Subsequently, the detection problem was reduced to that of detecting a point target in white Gaussian noise. Modern radar systems, however, are expected to perform the much more sophisticated tasks just stated for multiple targets simultaneously, at the finest possible target resolution and with the highest possible accuracy. Additionally, the domain of utilization of radar techniques has expanded beyond the traditional aircraft detection and ranges to applications such as estimation of the parameter (range, velocity, acceleration, and backscattering cross section) distribution of spread targets, aerial imaging, and ground or foliage penetrating radar imaging. To achieve their expanded tasks, modern radar systems combine high-quality hardware with sophisticated signal design and processing algorithm development and implementation based on statistical descriptions of both the target characteristics and the clutter distributions.

Applications of modern radar can be found in the military, the civilian, and the scientific regime. Military applications include search and surveillance of enemy targets; navigation, control, and guidance of weapons; battlefield surveillance; and antiaircraft fire control. Among civilian applications, prominent are those in air, water, and land transportation, including aircraft navigation; collision avoidance with both other aircraft and terrain obstacles; detection and avoidance of weather disturbances and clean-air turbulence; altimetry; air traffic control; shore-based ship navigation; collision avoidance for ships and small boats; harbor and waterway traffic control; collision avoidance of land vehicles; tracking of vehicles; and traffic law enforcement; as well as space applications in detection and tracking of satellites and control of rendezvous and docking of space vehicles. Finally, scientific applications include remote sensing of the Earth's environment from aircraft and satellites for planetary observation; weather radar for study and monitoring of precipitation, clouds, and major weather disturbances; ground mapping; ground-penetrating radar for detection of buried objects; foliage-penetrating radar for detection of hidden targets; and high-resolution imaging of objects and terrain via synthetic aperture imaging radars.

Radar Target Measurement Elements

Point-Target Measurements. Assume that the radar antenna transmits the narrow-band pulse

$$s_T(t) = u(t)e^{i2\pi f_0 t}, \quad 0 < t < T \tag{1}$$

where f_0 is the carrier frequency at which the radar operates and $u(t)$ is a pulse of duration T and bandwidth B smaller than the carrier frequency. The pulse illuminates a point target and gets reflected back towards the antenna. Let Δ be the round-trip delay between the time at which the rising edge of the pulse leaves the radar antenna, gets reflected by the target, and is received back at the antenna. Since the target is moving, this delay will be a function $\Delta(t)$ of time. Ignoring amplitude attenuation and constant phase shifts due to reflection, the received pulse will be

$$s_{\mathrm{R}}(t) = u[t - D(t)]e^{i2\pi f_0 [t-\Delta(t)]} \tag{2}$$

The information about the target motion is contained in the round-trip delay $\Delta(t)$ as a function of time and the distortion it causes on the received pulse $s_{\mathrm{R}}(t)$. The delay $\Delta(t)$ depends on the target position at the instant of reflection, which for a signal received at time t, occurs at time $t - \Delta(t)/2$. Thus:

$$\Delta(t) = \frac{2}{c}R\left(t - \frac{\Delta(t)}{2}\right) \tag{3}$$

where $R(t)$ is the target *range*, that is, the distance from the radar antenna to the target, as a function of time.

If the target moves slowly enough for the delay $\Delta(t)$ to be approximately constant within the duration T of the illuminating pulse, then the target can be regarded as stationary. However, it is often the case that the target moves very fast in comparison with the pulse duration and different instants of the pulse are differently delayed. In the general case, the relation among the target motion, the round-trip delay, and the received pulse is too complicated to be tractable. Several simplifications can lead, however, to tractable mathematical relations. Assume that the delay $\Delta(t)$ is a smooth enough time function to be expandable into a Taylor series around the time instant $t_0 = \Delta(t=0) \equiv \Delta_0$ at which the leading pulse edge is received back at the receiver:

$$\Delta(t) = \Delta_0 + \Delta_0^{(1)}(t-t_0) + \frac{\Delta_0^{(2)}}{2}(t-t_0)^2 + \frac{\Delta_0^{(3)}}{6}(t-t_0)^3 + \cdots \tag{4}$$

where $\Delta^{(k)}{}_0 = d^k\ \Delta/dt^k(t_0)$ is the kth derivative of the round-trip delay evaluated at the time instant t_0.

Define now the target parameters of interest:

$$\begin{array}{ll} t_0 = \Delta_0 & \text{delay coefficient} \\ v_0 = -f_0\Delta_0^{(1)} & \text{Doppler (velocity) coefficient} \\ \gamma_0 = -f_0\dfrac{\Delta_0^{(2)}}{2} & \text{acceleration coefficient} \\ \epsilon_0 = -f_0\dfrac{\Delta_0^{(3)}}{6} & \text{hyperacceleration coefficient} \end{array}$$

and use Eqs. (3) and (4) to relate them to the target range and its derivatives. Algebraic manipulation gives the target parameters as the following functions of the range $R_0 = R(t_0/2)$ and its derivatives $R^{(k)}{}_0 = (d^k/dt^k)R(t_0/2)$ at time $t_0/2$:

$$t_0 = \frac{2R_0}{c} \tag{5}$$

$$v_0 \approx -f_0 \frac{2R_0^{(1)}}{c} \tag{6}$$

$$\gamma_0 \approx -f_0 \frac{R_0^{(2)}}{c} \tag{7}$$

$$\epsilon_0 \approx -f_0 \left[\frac{R_0^{(3)}}{3c} - \left(\frac{R_0^{(2)}}{c} \right)^2 \right] \tag{8}$$

The approximations in Eqs. (6)–(8) are valid simplifications for the practical cases of $R^{(1)}{}_0 \ll c$ of the exact expressions on p. 59 in Ref. 1.

From Eq. (8), it is seen that even the simplified expression for the target hyperacceleration ϵ_0 is still a complicated function of target range derivatives. Higher-order terms in Eq. (4) have coefficients that are nonmanageable functions of target range derivatives. Fortunately, practical radar systems need only deal with targets moving sufficiently smoothly for only the delay and Doppler coefficients and, occasionally, the acceleration coefficient (and, rather rarely, the hyperacceleration coefficient) to be significant in the expansion in Eq. (4). Additionally, only the delay term t_0 is significant in the complex envelope $u[t - D(t)]$, while the higher-order terms affect only the phase in the exponential in Eq. (2). That is, the pulse received by the radar from a single target illuminated with the pulse of Eq. (1) is

$$s_{\mathrm{R}}(t) \approx u(t - t_0) e^{i2\pi[f_0(t-t_0) + v_0(t-t_0) + \gamma_0(t-t_0)^2 + \epsilon_0(t-t_0)^3]} \tag{9}$$

where t_0, v_0, γ_0, and ϵ_0 are the target delay, Doppler (velocity), acceleration, and hyperacceleration parameters.

Matched-Filter Response to Received Pulse. The received pulse is processed through a bank of filters, each matched to a different set of values of the target parameters. The filter matched to the set of parameter values $(\tau, v, \gamma, \epsilon)$ has impulse response

$$\begin{aligned} h(t; \tau, v, \gamma, \epsilon) &= u^*(-t-\tau) e^{-i2\pi[f_0(-t-\tau) + v(-t-\tau) + \gamma(-t-\tau)^2 + \epsilon(-t-\tau)^3]} \\ &= u^*(-t-\tau) e^{i2\pi[f_0(t+\tau) + v(t+\tau) - \gamma(t+\tau)^2 + \epsilon(t+\tau)^3]} \end{aligned} \tag{10}$$

Assume now that the input to this matched filter is the received pulse in Eq. (9), multiplied by an unknown complex-valued amplitude $Ae^{i\delta}$ and corrupted by additive noise, that is, $Ae^{i\delta}\, s_{\mathrm{R}}(t) + n(t)$.The output of the filter will be

$$
\begin{aligned}
&\eta_{\tau,v,\gamma,\epsilon}(t) \\
&= \int_0^{T_0} [Ae^{i\delta} s_{\mathrm{R}}(\xi) + n(\xi)] h(t-\xi)\, d\xi \\
&= Ae^{i\delta} e^{i2\pi f_0 (t+\tau-t_0)} \chi(t+\tau-t_0, v-v_0, \gamma-\gamma_0, \epsilon-\epsilon_0) \\
&\quad + \int_0^{T_0} n(\xi) h(t-\xi)\, d\xi
\end{aligned}
\tag{11}
$$

where T_0 is the time interval during which the radar is in receive mode (e.g., the time interval between two successive pulse transmissions). Equation (11) consists of two terms: a term due to noise and a signal term containing the ambiguity function

$$
\chi(\tau, v, \gamma, \epsilon) = \int_{-\infty}^{\infty} u(\xi) u^*(\xi-\tau) e^{-i2\pi[v(\xi-\tau)+\gamma(\xi-\tau)^2+\epsilon(\xi-\tau)^3]}\, d\xi
\tag{12}
$$

Clearly, the magnitude of the signal term at any time t is maximized if the filter parameters are selected equal to the target parameters, that is, if $\tau = t_0$, $v = v_0$, $\gamma = \gamma_0$, and $\epsilon = \epsilon_0$. Target *detection* can be performed by monitoring thematched-filter outputs at each instant t and examining whether they exceed a preset threshold or not. If the threshold is exceeded, then target detection is declared. If a target is thus detected, its parameters are subsequently *estimated* as the parameters of the matched filter that produces maximum output. A simplification to this target detection or estimation rule can be achieved by noticing that the matched-filter delay τ is not significant in that it only corresponds to a shift in the time instant of occurrence of the maximum of the matched-filter output. Indeed, a change in the round-trip delay t_0 only changes the time at which the maximum occurs. Thus, only a bank of matched filters needs to be used, in which the delay τ is fixed to zero and the target range is estimated from the time instant of occurrence of the maximum of the matched-filter output. If, however, the other target parameters are significant, an entire bank of filters needs to be used, with each filter matched to different target parameter values. In summary, the criterion for declaring target detection is

$$
\max_{t,v,\gamma,\epsilon} |\eta(t)| \geq \text{ threshold}
\tag{13}
$$

and the set of values ($\hat{t}$, $\hat{v}$, $\hat{g}$, $\hat{\epsilon}$) that provides the maximum constitutes the target parameter estimates. The threshold is set so as to keep the probability of a false alarm below a specified maximum tolerance. Since the complex amplitude $Ae^{i\delta}$ is unknown and varying, *constant false alarm* (*CFAR*) techniques need to be utilized to set the threshold adaptively.

Distributed-Target Measurements. The theory of single-target measurements needs to be modified and extended if the radar is to operate at a resolution that is sufficiently high for the spread of one or more target parameters to exceed the corresponding resolution bin. Examples of such targets include the terrain, vegetation foliage, extended manmade objects such as buildings with more than one smooth surface, or even aircraft when the resolution bin is significantly smaller than its typical dimensions. In these cases, the pulse received at the radar antenna can be considered as the superposition of a small or large or even infinite number of reflections from individual scattering centers on the target.

Serious difficulties in extending the theory of single- to multiple- (distributed-) target measurements arise if the scattering centers of the target are not stationary during illumination with the radar pulse or new ones emerge or several disappear due to target motion. Additionally, the target may be dispersive, that is, its significant scattering centers may vary with frequency, making the target behavior rather complex. For the theory of distributed-target measurements to remain tractable, the assumption needs to be made that the target is represented by a possibly infinite, yet fixed, set of scattering centers. Additionally, no dispersion can be allowed, that is, the scattering centers need to be frequency independent.

With these assumptions in mind, consider a target consisting of N scattering centers illuminated with the pulse of Eq. (1). The reflected pulse measured at the radar antenna will be

$$s_R(t) = \sum_{n=1}^{N} A_n e^{i\delta_n} u(t-t_n) e^{2\pi[f_0(t-t_n)+v_n(t-t_n)+\gamma_n(t-t_n)^2+\epsilon_n(t-t_n)^3]} \tag{14}$$

producing the signal part at the output of the matched filter of Eq. (10):

$$\eta_{\tau,v,\gamma,\epsilon}(t) = \sum_{n=1}^{N} A_n e^{i\delta_n} \chi(t+\tau-t_n, v-v_n, \gamma-\gamma_n, \epsilon-\epsilon_n) \tag{15}$$

Under the assumptions of stationarity of the target scattering centers during illumination with the radar pulse and their independence, cross terms in the signal part of the magnitude squared of the matched-filter output will be relatively small. Thus

$$|\eta_{\tau,v,\gamma,\epsilon}(t)|^2 \approx \sum_{n=1}^{N} |A_n|^2 |\chi(t+\tau-t_n, v-v_n, \gamma-\gamma_n, \epsilon-\epsilon_n)|^2 \tag{16}$$

Considering the limit of $N \to \infty$ densely packed scattering centers, the magnitude squared of the matched-filter output becomes

$$|\eta_{\tau,v,\gamma,\epsilon}(t)|^2 = \int\int\int\int |A(t_0, v_0, \gamma_0, \epsilon_0)|^2 |\chi(t+\tau-t_0, v-v_0, \gamma-\gamma_0, \epsilon-\epsilon_0)|^2 \, dt_0 \, dv_0 \, d\gamma_0 \, d\epsilon_0 \tag{17}$$

In Eq. (17), $|A(t_0, v_0, \gamma_0, \epsilon_0)|^2$ is the target backscattering cross-section distribution as a function of the delay, Doppler (velocity), acceleration, and hyperacceleration parameters. Clearly, if the magnitude squared of the ambiguity function consists of a single central spike with very narrow width, that is, if

$$|\chi|^2 \approx \delta(t+\tau-t_0, v-v_0, \gamma-\gamma_0, \epsilon-\epsilon_0) \tag{18}$$

then

$$|\eta_{\tau,v,\gamma,\epsilon}(t)|^2 \approx |A(t+\tau, v, \gamma, \epsilon)|^2 \tag{19}$$

In other words, the matched-filter response represents (and measures) the target backscattering cross section for the particular values of delay, Doppler, acceleration, and hyperacceleration coefficients to which the filter is matched. Consequently, a bank of matched filters, each adjusted to a different delay, Doppler, acceleration, and hyperacceleration parameters, yields the entire target cross-section distribution. A simplification can be obtained by considering only matched filters corresponding to the delay $\tau = 0$ in the bank and utilizing the entire matched-filter output for parameter distribution estimation.

Search (Surveillance or Acquisition), Tracking, and Navigation Radar

Search Radar. A *search* (also known as surveillance or acquisition) radar uses an efficient scan pattern to cover an angular sector with a narrow pencil beam in order to detect the presence of a suspected target. Typical scan patterns include the helical, the Palmer, the spiral, the raster (or TV), and the nodding patterns. In the helical pattern, the beam is continuously rotated in azimuth while it is simultaneously raised or lowered in elevation. The Palmer pattern consists of a rapid circular scan about the antenna axis, combined with a linear movement of the axis of rotation, and is suited to a search area which is larger in one dimension than the other. The spiral scan covers an angular search volume with circular symmetry. Both the Palmer and the spiral scans need to vary the scanning speed during the scan cycle for all parts of the scan volume to receive the same energy. The raster scan is produced by oscillating the antenna beam fast in azimuth and slowly in elevation, while the nodding scan is produced by oscillating the antenna fast in elevation and slowly in azimuth. Both the raster and the nodding scans cover a rectangular area, but they can also be used to obtain hemispherical coverage. Hemispherical coverage can also be obtained by the helical pattern.

Tracking Radar. A *tracking* radar measures the coordinates of a target found by a search radar and provides data that can be used to determine the target path and predict its future position. All or part of the available data (range, elevation and azimuth angle, Doppler frequency shift, acceleration, and hyperacceleration) may be used in predicting future target position. Correspondingly, the radar may track in range, in angle, in Doppler velocity, in acceleration, in hyperacceleration, or in any combination of those. Tracking radars either supply continuous tracking data on a particular target (continuous tracking radar) or supply sample data on one or more targets (track-while-scan) radar. The target parameters in a continuous tracking radar are tracked by a servocontrol loop activated by an error signal generated at the radar receiver. The information available from a tracking radar can either be displayed on a cathode-ray-tube display for action by a human operator, or may be supplied to a digital computer and automatically processed to determine the target path and predict its probable future course. The latter is usually called automatic detection and track mode or integrated automatic detection and track mode when the outputs from more than one radars are automatically combined.

Sequential Lobing Radar. The difference between the target angular position and a reference direction, usually the antenna axis, is the *angular error.* The tracking radar attempts to position its antenna to make the tracking error zero and thus locate the target along the reference direction. One method to obtain the direction and the magnitude of the angular error in one coordinate is by alternately switching the antenna beam between two positions. This is called *lobe switching*, sequential switching, or sequential lobing. The difference in amplitude between the voltages in the two switched positions is a measure of the angular displacement of the target from the switching axis. The sign of the difference determines the direction that the antenna must be moved in order to align the switching axis with the direction of the target. Two additional positions are needed to obtain the angular error in the orthogonal coordinate. Thus, a two-dimensional sequentially lobing radar might consist of a cluster of four feed horns illuminating a single antenna, arranged so that the right-left-up-down sectors are covered by successive antenna positions. Both transmission and reception are accomplished at each position.

Conical Scan Radar. Conical scan tracking radar uses continuous rotation of an offset antenna beam rather than discontinuous stepping between four discrete positions. The angle between the rotation and the antenna axes is called the *squint angle*. The echo signal is modulated at the frequency of the beam rotation. The phase of the modulation depends on the angle between the target and the rotation axis and can be used to locate the target and continuously position the rotation axis on it.

Monopulse Tracking Radar. The sequential-lobing and conical-scan tracking radars require a train of echo pulses in order to extract the angular error signal. This echo train must contain no amplitude-modulation components other than the modulation produced by the scanning; otherwise the tracking accuracy will be degraded. On the other hand, pulse-to-pulse amplitude modulations have no effect on tracking accuracy if the angular measurement is based on a single pulse rather than on several. If more than one antenna beam is used simultaneously, it is possible to extract angular error information from a single pulse from the relative phase or the relative amplitude of the echo signal received in each beam. Tracking radars that derive angular error information from a single pulse are known as *simultaneous lobing* or monopulse radars. An example of a simultaneous lobing technique is the *amplitude-comparison monopulse*, in which the echos received from two offset antenna beams are combined so that both the sum and the difference signals are obtained simultaneously. The sum signal provides range information, while the difference signal provides angular error information in one angular direction.

Track-While-Scan Radar. A search radar can obtain the track of a target by marking the coordinates of the target from scan to scan. Such a radar is called *track-while-scan* radar and either requires a human monitor to mark the target path manually or uses a digital computer to perform automatic detection and tracking. The automatic detection is achieved by quantization of the range into intervals equal to the range resolution. At each range bin, the detector integrates the number of pulses expected to be returned from a target as the antenna scans past and compares them with a threshold to indicate the presence or absence of a target. When a new detection is received, an attempt is first made to associate it with an existing track. When the detection is declared independent of existing tracks, the radar attempts to make a smooth estimate of the target's present position and velocity, as well as a predicted position and velocity. One method to achieve this is by using either the so-called α-β tracker or a Kalman filter that utilizes a dynamic model for the trajectory of a maneuvering target and the disturbance or uncertainty of the trajectory.

Navigation Radar. *Navigation radar* is used to provide the necessary data for piloting an aircraft from one position to another without any need for navigation information transmitted to the aircraft from a ground station. A self-contained aircraft navigation system utilizes a continuous-wave Doppler radar to measure the drift angle and true speed of the aircraft relative to the Earth. The drift angle is the angle between the centerline (heading) of the aircraft and the horizontal direction (ground track). A navigation radar requires at least three non-coplanar beams to measure the vector velocity, that is, the speed and its direction, of the aircraft. Such a radar measures the vector velocity relative to the frame of reference of the antenna assembly. This vector velocity can be converted to a horizontal reference on the ground by determining the direction of the vertical and the aircraft heading by some auxiliary means. Usually, the radar uses four beams initially symmetrically disposed about the aircraft axis, with two facing forward and two facing rearward. If the aircraft vector velocity is not in the direction of the aircraft heading, the two forward-facing beams will not read the same Doppler frequency. This Doppler difference can be fed in a servomechanism that will align the axes of the antennas with the ground track of the aircraft. The angular displacement of the antennas from the aircraft heading is the drift angle, and the magnitude of the Doppler frequency is a measure of the speed along the ground track. The use of the two rearward beams is similar, but improves the accuracy considerably by reducing the errors caused by vertical motion of the aircraft and pitching movements of the antennas.

High-Resolution Imaging Radar

A *radar image* is a visual representation of the spatial microwave reflectivity distribution of a target illuminated by the electromagnetic radiation emitted by the radar. Equivalently, a radar image represents a collection of reflection coefficients assigned to an array partitioning the target space. Thus, a radar image is generated by the same physical mechanism that generates an optical image observed by a human observer, in which the optical reflectivity distribution is reconstructed. In humans, however, the aperture size of the imaging system is on the order of 10,000 wavelengths, orders of magnitude (in wavelengths) greater than the aperture size of the corresponding radar imaging systems. Since the resolution of an imaging system, that is, its ability to represent distinctly two closely spaced elements, is inversely related to its aperture size, radar imaging systems would appear primitive when compared to their optical counterparts. Whereas a single optical image is usually sufficient for target recognition, several radar images of the same target, corresponding to various viewing angles, are usually required. However, the usefulness of radar imaging systems is not undermined by their lower-resolution capabilities. Advantages of radar imaging systems over their optical counterparts include their day or night capability, since they supply their own illumination and their all-weather capability, since radio waves propagate through clouds and rain with only limited attenuation. Additionally, larger aperture sizes (and, thus, higher resolution) can be synthesized from the given physical aperture using techniques such as those described later in this article.

Direct Imaging Radar. Direct imaging radar systematically scans a three-dimensional volume in angle and range with short pulses emitted from a pencil-beam antenna and range gating and displays the intensity of the received signals as a function of the spatial coordinates interrogated. The spatial resolution is established by the angular (beam width) and range (pulse duration) resolution of the sensor without subsequent processing. If range gating is not used, then range is not resolved and the radar image is a two-dimensional projection of the reflectivity distribution along the radar line-of-sight. Direct imaging is the simplest form of radar imaging, requiring minimal data processing and allowing the target to be stationary. However, it requires very large aperture and subnanosecond pulses for a high degree of spatial resolution, while, due to beam widening, its cross-range resolution degrades as the range increases.

Synthetic Imaging Radar. Synthetic imaging radar attempts to overcome the limitations of direct imaging radar and create fine spatial resolution by synthetic means in which results from many observations of the target at different frequencies and illumination angles are coherently combined. The term *synthetic* here refers to the synthesis of resolution commensurate with short-pulse, large-aperture illumination from a number of elemental measurements of illumination with not-as-short pulses and not-as-large aperture.

Range Processing Radar. The first task of imaging radar involves discrimination on the basis of range. High resolution in the determination of range is achieved when the transmitted pulse duration T is narrowed down and the corresponding system bandwidth B is increased, so that the time–bandwidth product (TB) is constant. Maximum sensitivity is accomplished when the time–bandwidth product is set to unity, that is, $TB = 1$. Thus, the required range resolution can be achieved when target reflections are measured over a band of frequencies. Any radar waveform that supports an extended bandwidth can be used, the specific type of waveform only determining the necessary implementation of the receiver for coherently processing the wide-band signal.

In contrast to direct imaging methods, in which all the spectral components of the signal must be present simultaneously, synthetic imaging methods require that the spectral components be present sequentially. In the simplest implementation of high range resolution by synthetic means, several narrow-band measurements are made at discrete frequency increments. Such radars are called *stepped-frequency* systems and can be either continuous wave, at each frequency emitting an unmodulated sinusoid, or pulsed, amplitude-modulating each frequency sinusoid. Stepped-frequency continuous-wave systems are susceptible to aliased responses and transmitter coupling, shortcomings alleviated by pulsing the transmitter and time-gating the receiver as in a pulsed, stepped-frequency system. Although individual narrow-band responses have insignificant resolution potential, the coherent combination of the responses provides the resolution allowed by the total bandwidth spanned. Alternatively, high range resolution can be accomplished using *swept-frequency* (linear FM) systems and corresponding wide-band receivers. Range resolution in swept-frequency systems is achieved by measuring the difference in instantaneous frequency between the instant of emission of the radar pulse by the transmitter and the instant of its reception back at the receiver.

Synthetic Aperture Processing Radar. High resolution in the cross-range direction can be obtained by scanning a focused beam across the object. If the aperture that forms the scanning beam is focused at the target plane, the minimum lateral extent of the focused spot is approximately

$$\Delta = \frac{\lambda R}{D} \tag{20}$$

where λ is the wavelength, R is the observation distance, and D is the aperture dimension. Resolution of two adjacent object points on a plane perpendicular to the line-of-sight of the radar is possible if their distance is greater than the spot dimension. Thus, for a fixed wavelength and observation distance, the resolution is increased by increasing the aperture size. High-resolution direct imaging radars would, therefore, need to have physically large aperture.

Synthetic imaging radars synthesize equivalent large aperture for high-resolution cross-range imaging by sequentially stepping a sensor through small incremental distances and storing samples of the amplitudes of the corresponding received signals. The stored signals are coherently summed to produce signals equivalent to those that would be received by the corresponding large physical aperture. In effect, *synthetic aperture* radars (*SARs*) coherently process signals scattered from the same target for various viewing angles by utilizing relative motion between the sensor and the target. Depending on the type of relative motion between sensor and target, synthetic aperture radars can be linear, spotlight, or inverse.

Linear Synthetic Aperture Radar. In linear SAR, also called *stripmap* SAR, the radar sensor is moved along a linear path and images stationary targets in its line-of-sight. Linear SAR is widely used for mapping terrain features and ground-based objects from airborne platforms.

Spotlight Synthetic Aperture Radar. Spotlight SAR involves observing a target with the radar antenna fixed on it while the viewing angle is changed.

Inverse Synthetic Aperture Radar. Inverse SAR involves a stationary radar viewing targets rotating about an axis perpendicular to the line-of-sight.

Doppler Processing Radar. Spatial resolution in cross range, that is, along an axis perpendicular to the radar line-of-sight, can be obtained if a target rotates relative to the radar sensor and the target reflections are Doppler processed. This is possible since the Doppler frequency shift in waves reflected by a rotating target is proportional to the lateral offset of the reflector along an axis normal to the axis of rotation and the line-of-sight. Indeed, if d and R_0 ($R_0 \gg d$) are the distances of a reflecting point and the radar sensor, respectively, from the center of a target rotating at an angular velocity Ω, then the distance of the reflecting point from the radar sensor at time t is approximately

$$r(t) = R_0 - d\sin(\Omega t) \tag{21}$$

According to Eq. (6), the Doppler coefficient at time t in the received wave will be

$$v_0(t) = \frac{-2}{c}\frac{dr(t)}{dt} = \frac{2d\Omega}{c}\cos(\Omega t) \tag{22}$$

From Eq. (22), it is clear that the Doppler coefficient for every reflecting point in a target rotating with angular velocity Ω is a harmonic function of time, the amplitude of which is proportional to the instantaneous lateral distance of the reflecting point from the center of rotation. Doppler processing of the received signal for cross-range resolution can be done on-line by either a bank of contiguous filters or by first sampling it and then analyzing it with Fourier transform processors of sufficiently high speed. Off-line processing, on the other hand, can be performed by recording the received signal for later processing. In either case, the signal is usually frequency translated to retain only its complex envelope.

Holographic Processing Radar. Optical holography records the spatial distribution of the intensity of the interference of light waves diffracted by an object and a reference beam in a hologram. This overcomes the difficulty associated with lack of optical phase sensitive storage media. Later, the hologram can be used to reconstruct the light waves associated with the original object by illumination with the reference beam used in the recording step. A holographic reconstruction allows a viewer the perception of a virtual image of the original object.

Microwave holography follows recording and reconstruction procedures analogous to optical holography. In microwave holography, the field amplitude scattered from an object coherently illuminated from a transmitter is mapped over a prescribed recording aperture by a coherent detector that is scanned over the aperture. The detected bipolar signal, representing the complex envelope of the time-varying field, is added to a bias level sufficient to make the resultant always positive. The resulting signal is used to produce a film transparency with an amplitude transmittance function that is real and positive. The area probed by the detector represents the hologram aperture, the reference signal for the coherent detector represents the reference beam, and the signal scattered from the object is the object beam. A variation, known as *scanned holography*, of the (conventional) procedure described previously attempts to scan the transmitter and the receiver independently and offers some advantages in resolution.

Weather Observation Radar

Radar is a powerful research instrument in meteorology and also for telecommunications at frequencies higher than 1 GHz, since it allows for the gathering of considerable quantities of data on the three-dimensional structure of the atmosphere in a flexible, efficient, and rapid manner. Radar applied to hydrometeor observation provides two types of information: (1) quantitative information on the local distribution of the reflectivity and speed distribution in the scattering medium and (2) qualitative information on the small- and medium-scale structure of the targets, their evolution and movement, and other information heuristically extracted by expert analysts. This information can be used to describe atmospheric phenomena and study radio wave propagation, such as the provision of various statistics on precipitation and attenuation.

Precipitation Measurements. The most frequent quantitative application of the radar observation is to distinguish ice and liquid phases of precipitation. This task is particularly challenging in convective storms, where liquid water can exist at temperatures colder than 0 °C and ice can be found at temperatures warmer than 0 °C. Equally important and challenging is the task of quantifying rain-, snow-, and hail-fall rates, where the difficulty lies in the dependence of the rates on detailed knowledge of the drop size distributions. Although radar techniques have practical limitations and their accuracy is highly suspect, they offer important advantages over conventional methods based on pluviometer array measurements: they allow for spatial continuity of the observations and improved access to the observation of the variability of the precipitation; they make it possible to observe the three-dimensional structure of the system generating the precipitation, as well as survey over a wide area from a single measurement point in real time; data acquisition, storage, and processing are simple. Radars capable of measuring multiple parameters (e.g., vertical and horizontal reflectivities and/or a spectrum of terminal velocities) in each resolution cell, in combination with satellites, rain gauges, and other instruments, may give the desired accuracy in measuring rainfall rates and discriminating rain from frozen precipitation.

Storm and Wind Observation. A pulsed Doppler radar can estimate the reflectivity and range velocity distribution inside a storm's shield of clouds. If a single beam is used, a three-dimensional picture of a storm typically requires 2 min to 5 min of data collection time. This delay is imposed not only by antenna rotation limitations, but also by the requirement for collection of a large number of radar echos for reduction of the statistical uncertainty in the reflectivity and velocity estimates. Although the storm can change significantly during this period, with subsequent distortion of the reflectivity and velocity radar images, the returned estimates are considered highly valuable.

Practically, more significant than the reflectivity and velocity distributions are estimates of the rainfall rate and wind velocity. Doppler radar, however, measures the range velocity of hydrometeors rather than air, and often this differs significantly from the range component of wind. Nevertheless, since hydrometeors quickly respond to wind forces, their terminal velocities give negligible bias estimates of the range component of the wind.

Turbulence Measurement. The mean velocity and spectrum width measured by Doppler radar are weighted averages of point velocities. Therefore, they are sufficient to depict motion on scales larger than the resolution cell, but cannot infer the details of the flow inside the cell. Nevertheless, Doppler radar offers the possibility of measurement and study of turbulence on scales smaller than the resolution cell if a firm connection between the statistical-physical properties of the atmosphere and Doppler-derived measurements is established.

Clean Air Observation. A radar designed to identify and track precipitating storms can also detect echos from scatterers in fair weather. In such cases, the distribution of spatial reflectivity in clean air can be associated with meteorological phenomena such as turbulent layers, waves, and fronts, flying birds and insects, or atmospheric pollutants. Clean air echos not related to any visible scatterers have been conclusively proven to emanate from refractive-index irregularities.

Waves reflected by sharp, quasipermanent changes in the dielectric permittivity of the atmosphere form the coherent component in the echo received by the radar. Coherent echos exist if the scattering medium does not time-modulate the amplitude or phase of the transmitted radar pulses, even though spatial variations may exist. Coherent echos appear as peaked and narrow components in the Doppler spectrum. On the other hand, incoherent components are contained in the echo signal if time-varying (turbulent) scatter is present. Incoherent echos demonstrate themselves as broad components in the Doppler spectrum.

Laser Radar Systems

It is natural to attempt to extend radar techniques to the optical portion of the electromagnetic spectrum. The fact that optical wavelengths are orders of magnitude smaller than their radio counterparts allows for very fine resolution in the estimation of target parameters, such as angular position, range, and tangential and radial velocity. The first optical radar systems investigated used incoherent light from xenon or other flash lamps. With the invention of the *laser* (light amplification by stimulated emission of radiation), however, they were replaced by systems that employed coherent laser light. Such systems were initially called *lidar* (light detection and ranging) and, in more advanced, higher-performance versions, *ladar* (laser detection and ranging) in complete analogy to radar.

The development of practical ladar systems followed a path similar to the development of radar systems: Reflectivity and backscattering cross-section data were collected and tabulated for a number of targets at available laser operating wavelengths; laser pointing could be accomplished by mounting the laser on existing radar platforms; the scan patterns of radar were employed in ladar systems as well; the signal design and processing techniques of radar were also applicable to ladar systems.

When compared to radar, ladar systems exhibit advantages and disadvantages, both due to their use of very short wavelengths. On one hand, very short wavelengths result in very high information bandwidths and very fine resolution. Exploitation of the bandwidth can be achieved with today's advanced signal-processing techniques and hardware. Additionally, unlike the use of solid-state lasers in early ladars, which allowed only for signal-envelope processing, today's ladars use gas lasers, which also allow for signal-phase processing. On the other hand, however, very short wavelengths result in low power efficiency and high atmospheric propagation losses. As a result, ladar is preferable to microwave and millimeter-wave radar for long-range ground-to-space and space-to-space applications or short-range atmospheric applications, in which the propagation loss penalty does not outweigh fine resolution.

Ladar Information Processing. A ladar measures a target's range, position, velocity, and motion by modulating its laser beam, detecting the reflected return, and processing the return signal to derive the desired information. Methods have been developed for amplitude, frequency, and phase modulation and for modulation by polarization. Laser radiation can be modulated both by direct action on coherent signals inside the laser during their generation (internal modulation) and through action on the radiated light outside the laser (external modulation). A number of electro-optical, acousto-optical, and mechanical beam modulation devices are available with different inherent modulation rates, yielding amplitude or frequency modulation of the transmitted beam.

Solid-state lasers cannot provide the necessary spectral purity to utilize phase processing of ladar signals. Gas lasers, such as helium-neon and carbon dioxide, however, have high spectral purity and can be modulated in amplitude or frequency with bandwidths of up to 525 MHz (yielding a resolution of approximately 30 cm) with relatively low drive powers. Ladar signal-processing techniques are similar to those used in microwave radar. In fact, the same circuits for signal-envelope processing may be employed in many cases. The use of ladar allows the exploitation of highly precise and unique methods for angle estimation and tracking.

Ground- and Foliage-Penetrating Radar

In the recent years, an attempt has been made to use radar to detect and map "targets" buried under the Earth's surface or obscured by foliage. Primarily, interest arises from a number of potential applications, such as detecting and locating unexploded ordnance in a battlefield, manmade objects in landfills, buried hazardous waste, subsurface plumes of refined hydrocarbons, or military equipment hidden in forest vegetation. The radar is either spaceborne, airborne, or ground-towed and possibly operates in SAR mode. The radar needs to utilize *ultra-wide-band* (*UWB*) signals, containing both low- (for deeper penetration) and high- (for higher resolution) frequency components. This can be achieved in two ways: (1) by emission of pulses that are very short in duration (and, subsequently, ultra-wide in bandwidth) or (2) by sequential emission of narrow-band signals of carrier frequency increases in steps, covering a wide frequency band.

Even though the perspective of ground- or foliage-penetrating radar from initial tests has been encouraging, a number of difficulties have delayed the development of this technology. These include:

- High electromagnetic wave absorption, especially under moist soil conditions
- Random distributions of soil particles, such as rocks, that tend to scatter the electromagnetic energy, increase propagation losses, and reduce the image contrast
- High clay content to which water binds, and thus dipolar relaxation loss mechanisms are encouraged
- Roughness of the air-soil interface that tends to increase backscattering that interferes with the penetrating radar signature

Similar factors affect the development of foliage penetrating radar systems.

To date, the success of ground- and foliage-penetrating radar surveys seems to be absolutely site dependent. A thorough understanding of a site's geology, hydrology, and topography is of paramount importance. Before undertaking a radar survey, it is necessary to obtain as much information as possible about the physical characteristics of the specific site. If boring log or monitor well data are available, they should be analyzed to determine soil stratigraphy and hydrology. If such data are not available, it is prudent to gather representative soil samples.

The applications for radar in subsurface target detection seem to fall into two broad categories, depending on the scale of the system, target, terrain structures, and search volumes. The case of large scales is made if the targets sought are large relatively to the average wavelength and the soil inhomogeneities. In this case, imaging would play a (secondary) role in reducing the number of false alarms of the detection procedure. If small targets, such as mines or weapons, are of interest, they would be hard to distinguish from clutter and the role of imaging would be enhanced. Thus, it is difficult or perhaps pointless to develop a single radar system for the detection of both large or deep and small or shallow targets. The wide-frequency-range requirement imposes stringent requirements in the range of both the electronics and the size of the relevant antennae and contributes to the delay of development of this significant radar application. However, ground- or foliage-penetrating radar technologies are presently an area of significant research investigation.

Current Trends

Besides research in ground- and foliage-penetrating radar technologies, significant research is also conducted in the development of, so-called, *space-time adaptive processing* (STAP) algorithms. STAP refers to multidimensional adaptive filtering algorithms that simultaneously combine the signals from the elements of an array antenna and the multiple pulses of a coherent radar waveform. STAP can improve the detection of low-velocity targets obscured by mainlobe clutter, detection of targets masked by sidelobe clutter, and detection in combined clutter and jamming environments.

Significant research is also conducted into the use of signal processing tools other than the traditional Fourier transform–based ones for target detection and recognition. Such tools are, for example, based on the theories of, so-called, *wavelet-induced multiresolution analyses* (*WIMA*) of signals. A WIMA allows for the decomposition and simultaneous representation of a signal in time and scale and, therefore, is capable of processing signals at different scales. WIMA-based radar target detection and recognition is being actively researched.

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