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

RADAR EQUIPMENT

Modern radars operate at frequencies from megahertz to hundreds of gigahertz and at power levels from milliwatts to megawatts. This means that many *RF* hardware components will vary greatly, whereas control and display systems will be functionally and physically similar. In recent years, the improvements in solid-state devices and the explosive growth in the capabilities of digital circuits and digital processors have provided new approaches to radar designs. Analog circuits, which tend to be smaller and have lower power consumption, are being replaced with digital circuits, which are more stable in the presence of varying temperature, vibration, and power supply voltages, while providing flexibility often unavailable in the analog domain.

Radar Frequencies

To provide some measure of security during World War II (*WWII*), letters were used to designate frequency bands instead of specifying frequencies. Although the electronic warfare community has adopted a sequentially lettered set of frequency bands, the original radar band designations were so commonly used that eventually a standard for letter designated radar bands (IEEE Std 521-1984) was developed. Table 1 (1) shows these bands and the actual frequency assignments designated for radar operation by the International Telecommunications Union (*ITU*) for North and South America (region 2). Note that no specifically assigned *HF* radar band exists and that the *UHF* radar band extends only to 1000 MHz, whereas the more common definition of UHF extends to 3000 MHz. The use of the millimeter designation is often applied to the frequencies above 40 GHz, thus including both the V and W bands.

The radar bands are grouped together with similar performance characteristics. The high frequency (*HF*) band requires physically large antennas but has negligible propagation losses and can take advantage of ionospheric bending at HF to support extended range, over-the-horizon (*OTH*) radars. The frequency of operation is usually adjusted to find the optimal propagation path to the desired target region of the globe as ionospheric conditions change. Very high frequency (*VHF*) and ultrahigh frequency (*UHF*) radars require parabolic reflectors that are too large to be practical and even yagi antenna arrays are a few meters long, but propagation losses because of atmospheric and weather effects are still negligible making VHF and UHF radars suitable for long range surveillance. Two-way losses through 10 to 20 m of foliage (typical of what might be seen from an aircraft) are about 3 to 6 dB (2–34), making VHF and UHF bands suitable for finding targets masked by trees. Two-way losses in these bands for sandy soils may run as low as 1 dB/m in dry soils to over 30 dB/m in damp soils, and above 100 dB/m in soils with high clay content, making it possible to detect subterranean targets at shallow depths depending on soil type (5–67).

L-band offers higher resolution with antenna reflectors approximately 10 m across, while propagation losses remain low (8). S-band and more notably C-band are suitable for medium-range operations as atmospheric and weather losses climb, but this also means they are useful for weather measurements (9,10). X-band and K_u-band can provide high resolution with meter-sized antennas but have noticeably more propagation losses, limiting their use to shorter ranges or clear weather operation. K_a-band and higher suffer high

Table 1. Standard Radar-Frequency Letter Band Nomenclature

Band Designation	Nominal Frequency Range	Radar Frequency Ranges Based on ITU Assignments for Region 2
HF	3–30 MHz	None
VHF	30–300 MHz	138–144 MHz
		216–225 MHz
UHF	300–1000 MHz	420–450 MHz
		890–942 MHz
L	1000–2000 MHz	1215–1400 MHz
S	2000–4000 MHz	2300–2500 MHz
		2700–3700 MHz
C	4000–8000 MHz	5250–5925 MHz
X	8000–12,000 MHz	8500–10,680 MHz
K_u	12–18 GHz	13.4–14.0 GHz
		15.7–17.7 GHz
K	18–27 GHz	24.05–24.25 GHz
K_a	27–40 GHz	33.4–36.0 GHz
V	40–75 GHz	59–64 GHz
W	75–110 GHz	76–81 GHz
		92–100 GHz
mm	110–300 GHz	126–142 GHz
		144–149 GHz
		231–235 GHz
		238–248 GHz

Source: IEEE Std 521-1984,

atmospheric losses and extreme rain losses and backscatter but provide very high resolution with physically small antennas that may be used in short range applications such as radar fuzing and fire control systems. The water absorption lines at 22.2 and 185 GHz and the oxygen resonance lines at 60 and 120 GHz produce such high losses as to limit operations near these frequencies. Lower loss "windows" in the atmospheric attenuation near 35 and 95 GHz provide the possibility of short-range operations but still at higher losses than K_u-band.

To meet system requirements, the radar designer must pick a range of components and frequency band that will support the desired performance. The basic radar range equation is

$$R^4 = \frac{P_t G_t L_t}{4\pi} \times \frac{A_e L_r \sigma}{4\pi k T_0 B F_n \mathrm{SNR}} \times L_p L_a \qquad (1)$$

The first group of terms is related to the transmitter, the second to the receiver, and the third to other propagation effects, where

R = Maximum radar range
P_t = Average transmit power
G_t = Gain of transmit antenna
L_t = Losses from transmitter to antenna (e.g., circulators, duplexers, transmission lines)

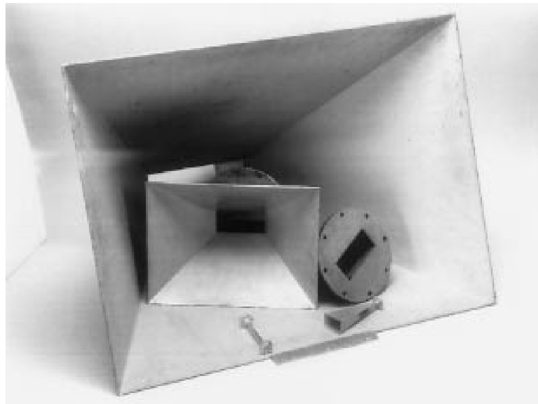

Fig. 1. A 15 dB gain L-band horn that contains the other items dwarfs the W-band waveguide and 25 dB gain horn sitting in front of an S-band coupler and 15 dB gain horn. US Army photo.

A_e = Effective antenna aperture of receive antenna (aperture area times efficiency)
L_r = Losses in receive path, similar to those for the transmit chain
σ = Radar cross section of target
k = Boltzmann's constant
T_0 = System reference temperature (typically 290 K)
B = Receiver bandwidth
F_n = Receiver noise figure
SNR = Signal-to-noise ratio required to meet detectability requirements (typically 12 to 15 dB)
L_p = Two-way antenna pattern losses
L_a = Two-way propagation losses (atmospheric, weather)

Note that there is no frequency-related term in Eq. (1). However, the effective aperture is related to the gain of the receive antenna by

$$G_r = \frac{4\pi A_e}{\lambda^2}$$

where λ is the wavelength. Thus, for a fixed aperture size, the gain increases with frequency. The choice of frequency is typically application driven, but since the size of many RF components scale inversely with frequency (see Fig. 1), the radar designer may choose a particular frequency band based on size and weight constraints if radar performance will not be adversely affected. Atmospheric and transmission line losses generally increase with frequency, and receiver noise figures degrade. The designer can improve transmit and receive gain by using a higher gain antenna, at the cost of a loss in area coverage and can increase signal-to-noise performance by using a narrower system bandwidth, or by effecting an equivalent bandwidth reduction with signal processing. Often the only choice left to the designer, to meet target detectability requirements, is to increase average power.

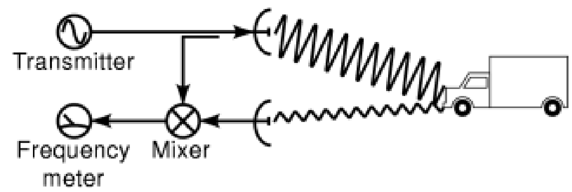

Fig. 2. Block diagram for a simplified CW Doppler radar.

Types of Radars

There are a number of basic variations in radar system designs. We will examine the operation of different types and some of the hardware specific to particular types.

Continuous Wave Doppler Radar. The simplest of all radars, and by far the most common, is the continuous wave (*CW*) Doppler radar. Its biggest advantage is also its biggest disadvantage (11). By operating at a 100% duty cycle, it maximizes the use of the transmit power and eliminates issues of Doppler ambiguity, but the receiver is forced to operate while the transmitter is on and no range information is available (although modulating the carrier frequency can provide range information). For a medium power, sensitive radar, two antennas are usually required to isolate the receiver from the large transmit signal and from the noise sidebands of the transmitter. Nearby fixed targets (clutter) can also have an impact on performance because they will also cause a large signal return that might overload the receiver. Most CW radars have homodyne (direct conversion) receivers; that is, the local oscillator for the mixer is at the same frequency of the transmitter. Figure 2 shows a simplified block diagram of a CW radar. The return signal from the target is shifted in frequency because of the radial component of the velocity of the target with respect to the radar (i.e., that portion of the motion that is toward or away from the radar v_{r}). A sample of the transmit signal f_0 is used as the local oscillator signal. This signal is mixed with the return signal from the target and the difference between these signals is the Doppler shift f_{d}, which is fed to a frequency meter. The sum frequency out of the mixer is usually so far beyond the response of such a meter that filtering is not necessary, although it can be easily provided with a simple low-pass filter. The Doppler shift is

$$f_{\mathrm{d}} = f_0 \frac{2v_{\mathrm{r}}}{c} = \frac{2v_{\mathrm{r}}}{\lambda} \quad (\text{for } v_r \ll c)$$

where the frequency is shifted up for approaching velocities and down for receding velocities. The factor of 2 is a result of the signal traveling both ways and can perhaps be more easily understood as a change in signal phase. If the target moves a half wavelength closer to the radar, the path length to the target and back changes by one wavelength.

The Doppler shift is in the human audible range for typical ground target speeds and operating frequencies in X-band and K_u-band, and a number of radars have been built. The basic output device of these radars is a set of headphones the operator wears. This is not as strange as it sounds because a trained operator can estimate velocity of the target. Other moving parts of the target (e.g., wheels, treads, propellers) provide secondary audible signatures so that the operator also can determine to what class the target belongs (such as wheeled vs. tracked vehicles or fixed wing vs. rotary wing aircraft) (12).

Small, low-power versions of CW Doppler radars are used as speed sensors (mostly well known in police radar applications), automatic door openers in warehouses and retail stores, intrusion detectors, vehicle detectors for traffic control, and proximity fuzes in rockets, bombs, and projectiles. In these applications, the range to the target is usually small, and the loss in sensitivity because of the use of a single antenna is acceptable.

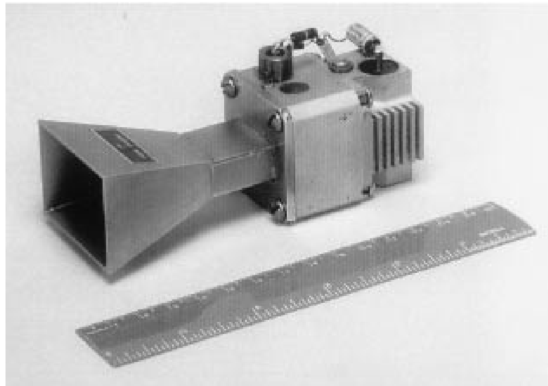

Fig. 3. An X-band Doppler transceiver and mating horn antenna. Mechanical tuning coarsely sets frequency, whereas fine tuning and AFC can be provided by modulating the operating voltage. US Army photo.

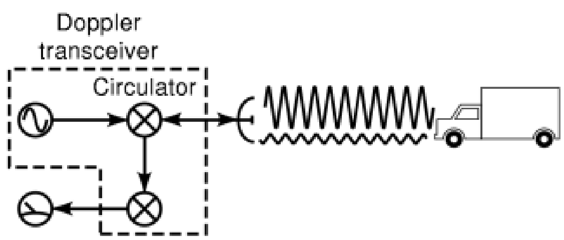

Fig. 4. Block diagram for a simple single-antenna CW Doppler radar based on a Doppler transceiver.

One of the parts that made designs of such radars simpler was the Microwave Associates (now M/A-COM) gunnplexer Doppler transceiver (Fig. 3), which packs a transmitter, ferrite circulator, and mixer into a single module. A Gunn oscillator is the basic transmitter, which is coupled to a single antenna through the circulator. Transmitter power reflected back from the antenna port acts as the local oscillator into the single balanced mixer (an adjustable screw allows intentional standing wave ratio (*SWR*) mismatch to force an adequate level of return signal). The addition of an antenna, frequency meter, and a direct current (*dc*) power source completes the radar (Fig. 4).

Pulse Radar. The pulse radar is what most people think of when they think of radar, which is the acronym for radio detection and ranging. A short burst of microwave energy is transmitted toward the target, and the time t for the echo to return in microseconds is measured to determine the range r to the target in meters where

$$r = c\frac{t}{2}$$

with the factor of 2 representing the path the signal takes to the target and back. The length of the pulse determines the capability of the radar to resolve two closely spaced targets, the basic limitation being that the echoes from the two targets will merge into a single return. At a pulsewidth of t_w μs, this merging occurs when the two targets are separated by approximately a distance r using the preceding formula. Decreasing the pulsewidth improves resolution capability at a cost of reduced average power levels.

The development in Britain of the magnetron (a pulsed power oscillator) during WW II made microwave pulse radar practical, and the magnetron (13) is still the most commonly used transmitter in pulse radars. It

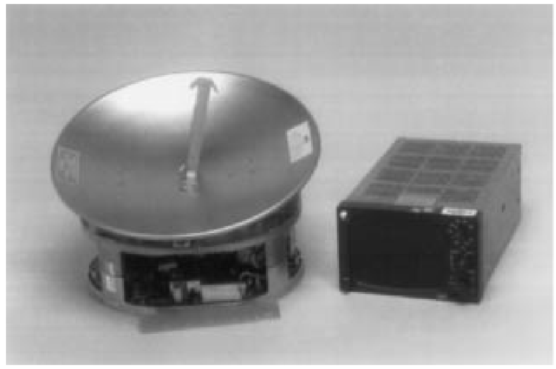

Fig. 5. An X-band weather radar designed for aircraft use. The transmitter and receiver are located in the assembly behind the reflector, and the control electronics are located in the display unit. The transmitter is a 3 kW magnetron that is approximately 60 cm^3. US Army photo.

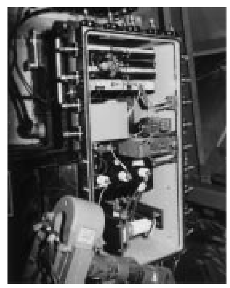

Fig. 6. A 1 MW X-band magnetron transmitter. The power supply/modulator is in the upper left with its 20 cm × 40 cm cover removed. The large rectangular device to the right of the water-cooled heat exchanger is the pulse-forming network. US Army photo.

is capable of producing peak power levels of kilowatts through megawatts in compact packages (Figs. 5 and 6). A simplified block diagram of a magnetron-based pulse radar is shown in Fig. 7. The power supply/modulator provides the high-voltage pulse at the desired pulse repetition frequency (*PRF*) to drive the magnetron. The PRF is usually set to guarantee that there is enough time between pulses to receive a return from the farthest expected target range. The transmit/receive (T/R) switch, or duplexer, automatically connects the transmitter to the antenna, while effectively disconnecting the receiver from the antenna. The T/R switch in high-powered radars is often based on a gas-filled tube that conducts in the presence of the RF field (14), but in lower-powered sets, these functions may be assumed with circulators or positive–intrinsic–negative (*pin*) diode switches (15). The receiver protector is typically a diode limiter that further restricts the voltage developed across the receiver input, whereas the transmitter is operating to protect sensitive low-noise preamplifiers in the receiver.

Referring again to the radar range equation, we note that the return signal for a fixed-size target varies as the fourth power of the range to the target. This means that a target at 1 km will be 80 dB stronger than that target at a range of 100 km. The sensitivity-time-control (*STC*) increases the gain of the receiver versus the time elapsed from when the pulse was transmitted (this is effectively the range to a target) so that there is less change in signal dynamic range as the range to target varies (16), and allows choosing an analog-to-digital converter (*ADC*) with fewer bits to support the receiver output. R^4 correction will produce a constant radar cross-sectional output but will usually require controlling the gain of multiple stages of the receiver. However, the targets are often not the limiting factor in setting dynamic range limits. In ground-based radars, clutter

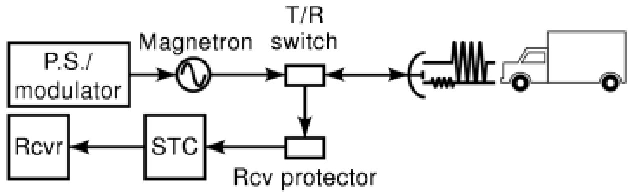

Fig. 7. Block diagram of a magnetron-based pulse radar.

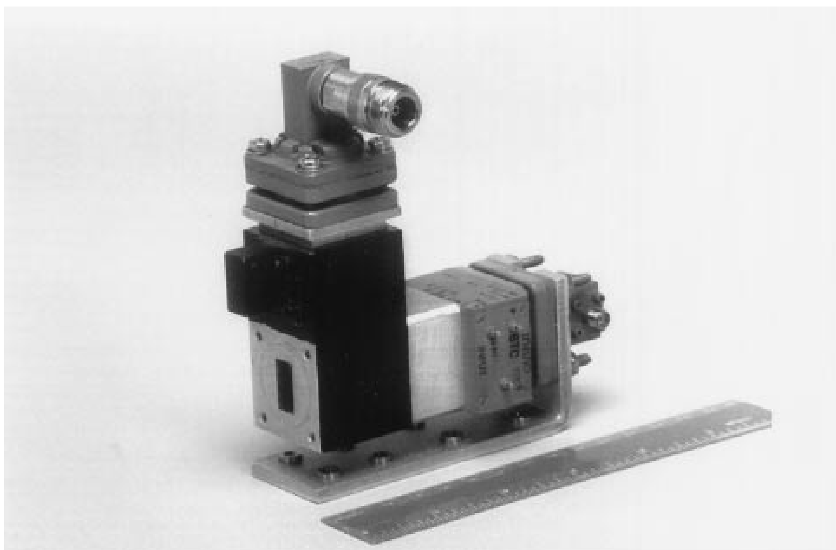

Fig. 8. A 500 W K_u-band duplexer with a combined receiver protector/STC module attached. Antenna connection is made to the open waveguide connection on the left, and the transmitter is connected to the RF connector on the top. The receiver protector can be run in a self-rectifying mode or can be driven by an external DC signal. STC control range is about 30 to 40 dB. US Army photo.

(undesired wide area returns from natural or cultural objects) is usually larger than the desired targets, and the amount of clutter region illuminated by a radar beam increases as range increases; so in this case, an r^3 gain correction is a better choice. Weather radars, on the other hand, respond to the backscatter return from a volume of space, so a constant target return is best obtained with an r^2 correction. Figure 8 shows a combined receiver protector/STC module attached to the duplexer of a low-power radar.

Moving Target Detecting Radars. As mentioned in the previous paragraph, in a ground-based radar, a large region of high-strength undesired radar signals from fixed targets (clutter) masks the moving targets the radar is typically designed to detect. A moving target indication (*MTI*) radar attempts to minimize the response from the clutter to enhance the signal-to-clutter ratio and improve target detectability. A simple block diagram of how this can be accomplished is shown in Fig. 9. A sample of the received signal is delayed by one pulse repetition interval (*PRI*—the inverse of PRF) and subtracted from the current input signal. This can be a rather long delay and was often provided by multiple reflections within a multifaceted bulk quartz delay line. Such long delays can also be provided by digital shift registers or memory circuits, in which the subtraction is provided after the *ADC* stage. The digital approach has the advantages of stability in time and temperature, whereas the analog approach reduces the dynamic range into the ADCs, relaxing the requirements for the number of bits required. Proper cancellation of the clutter requires being able to compensate for the delays and

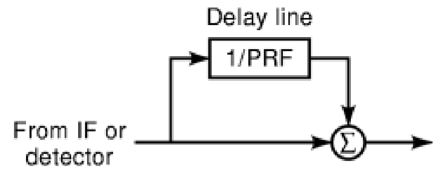

Fig. 9. Block diagram of a simple one-pulse canceler.

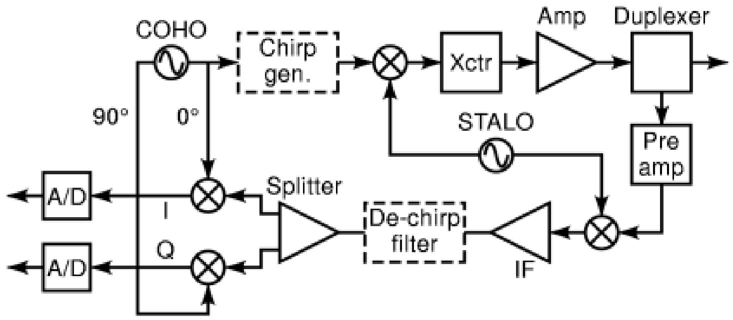

Fig. 10. Block diagram of a coherent transceiver for use in pulse-Doppler radar. The stable local oscillator (*STALO*) provides the translation frequency from RF to IF. Optional chirp modules are denoted by the dashed boxes.

losses through the delayed path, and in this case the digital approach also has an advantage, as the analog approach typically requires constructing a circuit path that duplicates the attenuation of the delay line and the gain, delay, and nonlinearities of the delay line amplifier chain to provide proper cancellation. As long as the radar has adequate stability, the fixed targets will maintain the same phase from pulse to pulse and will be canceled, whereas the moving targets will vary in phase, thus producing a time-varying output. However, realize that the moving targets must have a radial component of motion with respect to the radar location for this phase difference to occur. Targets that move tangentially to the radar will be canceled, as if they were not moving, because no phase change is observed. Note also that a pulsed radar is basically a sampled data system, which leads to a similar problem if the target is moving at a rate such that its Doppler frequency is equivalent to the PRF, or a multiple thereof, because this is equivalent to sampling a signal a number of complete cycles later, and no phase difference will be observed from sample to sample. These target velocities are referred to as blind speeds because targets moving at these speeds will not be detected by an MTI radar (17).

Although magnetrons do not have pulse-to-pulse phase stability, they have reasonable short-term stability in frequency, and it is possible to synchronize the final receiver local oscillator (the coherent oscillator, or *COHO*) phase to that of the transmitter on each pulse (known as a coherent-on-receive system) and thus provide magnetron-based radars with an MTI mode of operation. Area MTI is another approach to clutter reduction, and one that does not require a coherent radar system in which a complete scan of the radar video is stored in memory and subtracted from the next scan. In a digital image, this operation is equivalent to a pixel-by-pixel subtraction and will mask small targets located over large areas of clutter (cities, forests) as the larger signal returns from the two samples of the clutter regions are subtracted from each other, leaving a small residue. Area MTI does have the advantage that tangentially moving targets are highlighted because they will have moved far enough between scans to appear in a different position on the screen.

Another approach to detecting moving targets is the pulse-Doppler radar: a coherent transmitter-receiver (Figs. 10 and 11) processes the received signals, not only into range bins but also into multiple Doppler bins.

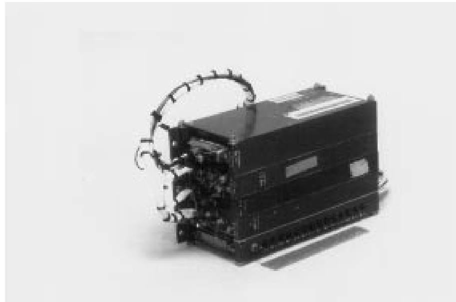

Fig. 11. The Eaton/AIL G-199 K_u-band transceiver for the AN/TPS-74(V) modular radar. Various modules could be substituted to provide options for ground or airborne applications. This specific assembly contains modules for power supply, exciter, STALO, receiver, and antenna pedestal control.

This processing is done most easily with a digital signal processor (18), providing the temporary storage for a group of pulse returns and typically a Fourier transform to provide the bank of filters. The quadrature mixer of Fig. 10 provides both in-phase (I) and quadrature (Q) outputs to a pair of ADCs to support complex fast Fourier transforms (*FFT*s). There are now purely digital approaches (19,20) that can provide I and Q outputs from a single, higher sample-rate ADC. The advantage of the digital approach is that there are no problems in balancing gain and phase in the two channels. Having both I and Q outputs allows sorting the Doppler bins into incoming (Doppler above the carrier frequency) and outgoing (Doppler below the carrier frequency) velocities. The zero frequency (dc) filter output is where the bulk of the clutter lies, and it is discarded. Motion of the clutter or the radar may spread the clutter energy into adjacent frequency bins, and they may be discarded as well, either automatically or under operator control. If the radar is on an airborne platform (Fig. 12), then returns from large clutter patches on the ground can be used to select the Doppler bin or bins that represent the clutter velocity in the direction of look (21). As previously mentioned, the Doppler frequencies depend on the radial component of the target velocity. Dopplers that exceed the Nyquist criteria will be interpreted as having a direction opposite to their actual direction of travel, and blind speeds will again occur at multiples of the PRF. Increasing the PRF can eliminate this ambiguity in Doppler determination, at the cost of creating an ambiguity in range. Range ambiguity can occur when the PRF is high enough that a target return from a far-range target generated by an earlier pulse appears in the range processing time of the current pulse (22). Dithering the PRF or switching between multiple PRFs can allow Doppler and range ambiguities to be resolved (17,23), but such an approach will not work with the simple fixed-delay MTI of Fig. 9. Modern air traffic control radars (Fig. 13) use a combination of MTI techniques to improve detection of targets because aircraft often circle the airport as well as make direct approaches and departures.

Because we already have a coherent transceiver that allows us to recover the phase of the received signal, a number of improvements to the radar system performance are possible by modulating the transmitted waveform. This modulation increases the bandwidth of the transmitted signal, which, when processed in the receiver, provides improved resolution, while maintaining a longer pulsewidth to improve the average signal power. The disadvantage is that a long pulse limits the ability to detect targets close to the radar, in what is called the eclipsing zone, because returns from these targets will arrive at the receiver while the transmitter is still on. The most common modulation approach is to use linear FM, or chirp, modulation (24). This can be provided simply with a surface acoustic wave (*SAW*) device in the transmit chain (Fig. 14) and a complementary compressive SAW device in the receiver intermediate frequency (*IF*), returning a signal with a pulsewidth equivalent to that of the modulation bandwidth. Alternately, high-speed synthesizers can provide the transmit modulation (25), while digital signal processors can provide the compressive function.

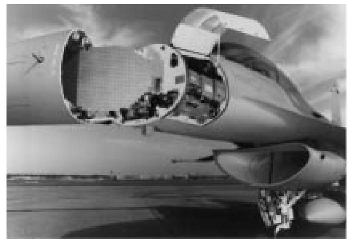

Fig. 12. The electrically driven antenna of an F-16 equipped with one of Northrop Grumman's APG-66/68(V) family of coherent radars. The radar supports 25 air-to-air, air-to-ground, and mapping modes that provide target detection, acquisition, and tracking in both benign and hostile electromagnetic emissions environments. Photo courtesy of Northrop Grumman Corporation.

Fig. 13. The Northrop Grumman ASR-12 is a modular, fully solid-state, S-band airport surveillance radar. It uses a moving target detection scheme that combines adaptive Doppler filter and fine-scale clutter mapping to enhance the returns from tangential targets. Photo courtesy of Northrop Grumman Corporation.

Synthetic Aperture Radar. Although we have now seen a way to improve the resolution in range, it would seem that the only way to improve the resolution in cross-range is to increase the size of the antenna system, narrowing the beamwidth of the radar. In synthetic aperture radar (*SAR*), cross-range resolution improvement is accomplished by moving an antenna in space (26), creating an effective aperture that is much larger than the physical antenna (Fig. 15). Returns from targets in the direction of motion of the radar are shifted up in frequency, whereas those behind the radar are shifted down in frequency, allowing the contributions from various points in the range swath to be separated. Typically, an SAR will also have a high resolution in range, requiring a large amount of frequency content in the transmitted waveform and thus a wide IF bandwidth and a high-speed ADC. If chirp modulation is used to generate the bandwidth, then by reproducing the slope of the modulating waveform in the receiver mixer (an approach called stretch processing), these bandwidths can be reduced (27). Modern direct digital synthesizers (*DDS*) (Fig. 16) allow such flexibility in frequency control. In addition, they are able to compensate for distortions in amplitude and phase response because of the transmit-receive chain (28). Combining the return signals from all the aperture positions usually requires a high-speed processor (Fig. 17) capable of processing a large number of two-dimensional FFTs, but the resulting imagery (Fig. 18) is almost photographic in clarity.

In SAR, there is the need to have relative motion between the radar and the target, but the motion does not need to be along straight line, nor does the antenna need to be oriented normal to the flight path. Some of the more common variations of SAR include spotlight SAR and inverse SAR (*ISAR*). In spotlight SAR (29) the antenna is continually pointed toward the area of interest, by rotating the antenna as the aperture is flown,

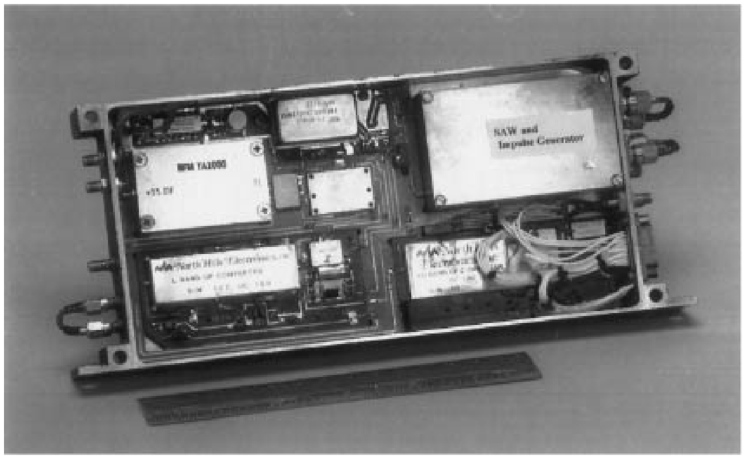

Fig. 14. An exciter module from the AN/TPS-74(V) showing in the upper right the 60 MHz impulse generator and mating SAW chirp unit. For this unit, the 10 μs transmit pulse was compressed to a 0.5 μs pulse in the receiver for a 20:1 compression ratio. US Army photo.

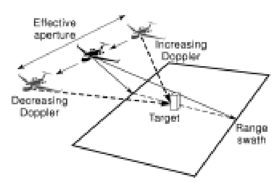

Fig. 15. Synthetic aperture radar. As the antenna is moved, radar returns from all the surveillance areas are collected and stored to be later processed as if there was a single antenna the size of the aperture flown.

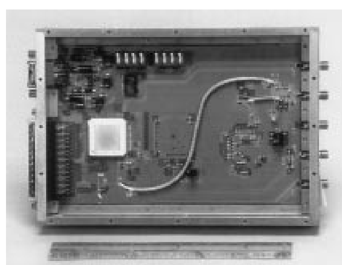

Fig. 16. An experimental direct digital synthesizer. DDS technology has an advantage over other traditional waveform-generation techniques—it can arbitrarily create different waveforms in a small, lightweight, cost-effective package. The Sciteq DDS architecture is a double-accumulator GaAs linear frequency modulation synthesizer that allows input of the starting frequency and chirp rate and has a separate phase modulation port. Maximum output bandwidth is 230 MHz, with 24-bit frequency resolution, updated at a 2 ns rate, and spurious responses below −50 dBc. US Army photo.

or by flying an aperture in the shape of an arc (30). This allows larger than normal apertures to be flown (thus improving resolution) as well as allowing use of higher gain, narrower beamwidth antennas. ISAR is typically viewed as having the radar fixed and the target moving; more generally, however, both can move as in the cases of airborne radars imaging ships. In ISAR, the motion of the maneuvering target is used to provide additional detail of the target for target recognition (31) and possibly allowing 3-D reconstruction of the target. This

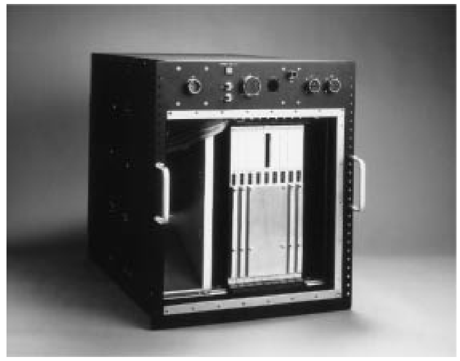

Fig. 17. A large number of calculations are necessary to process SAR data. This radar signal processor, used in a Northrop Grumman SAR, consists of nine 9U VME cards, each containing 16 Intel i860 array processors. Each processor card has an aggregate rating of 1.28 GFLOPS. Photo courtesy of Mercury Computer Systems, Inc.

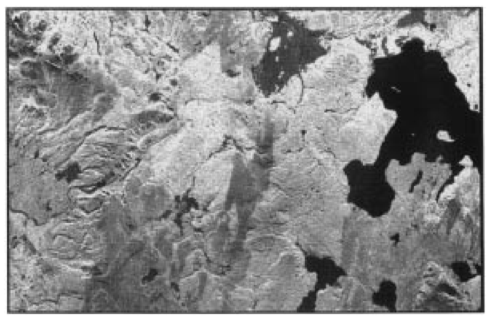

Fig. 18. A NASA SAR image of Yellowstone National Park, Wyoming. The image was obtained using the L-band radar channel, with vertical transmit polarization and horizontal receive, on the shuttle's 39th orbit on October 2, 1994. The large dark feature at the right is Yellowstone Lake, which appears this way because the bulk of the transmit energy is forward-scattered off the relatively smooth lake surface.

implies that existing radars could gain from added signal processing capabilities, but the processing burden is high, as the path and maneuvering nature of the target is unknown and must also be extracted from the data to correctly focus the target (32).

Impulse Radar. An impulse radar is perhaps the simplest form of pulse radar. An extremely short pulse, or a single cycle of a sine wave, which has a very wide bandwidth, is radiated from an antenna that typically sets the useful radar bandwidth of the system (33,34). The short pulsewidth provides an inherent high-range resolution capability. Most of these systems are denoted ultra wideband (*UWB*) radars because their bandwidth is greater than half their center frequency, and many of them operate in the VHF and/or UHF region to provide foliage or ground penetration capability. Because the frequency coverage and bandwidth can be provided by other means (such as chirp), the advantages that the impulse radar offer are the capability to detect close-in targets (as in ground contact radars) because of the small eclipsing zone and simple and highly efficient transmitters that are low in size and weight (Fig. 19).

Bistatic Radar. Some of the problems with radars are that they are active devices, and therefore susceptible to detection; they can have large, high-power transmitters that reduce their mobility; and they detect Doppler shifts only from the radial component of target velocities. One way to improve the situation is to separate the transmitter and to provide remote, receive-only radar systems (Fig. 20). Such systems are called

Fig. 19. The PowerSpectra BASS-02X is a bulk avalanche semiconductor switch activated by a semiconductor laser. Rise times are about 150 ps with a fall time of approximately 2 ns. Peak output power is approximately 2 MW, and average power is approximately 1.5 W. Prime power is 28 VDC, and the unit weighs approximately 2 kg. US Army photo.

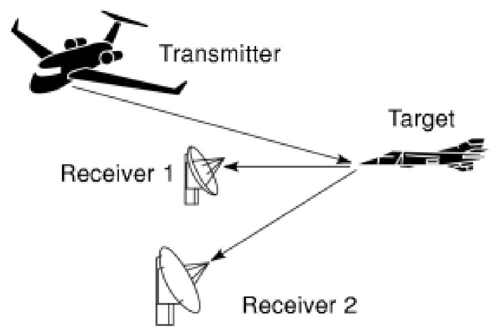

Fig. 20. In a bistatic radar, the transmitter and receivers are physically separated, and multiple receivers are serviced by the same transmitter.

bistatic radars, or more appropriately multistatic radars when multiple transmitters and receivers are used (35). Forward-scattered energy from large regions is often much stronger than the backscattered energy and may give clues as to the texture or construction of the region. Existing radars (designed for other purposes) are often used as the transmit source, whereas smaller, cheaper receivers take advantage of the existing signals to provide simple low-cost radars at multiple sites, all serviced by the existing emitter. Bistatic radars have been used for semiactive missile guidance (the missile carries only the receiver, while the launching platform usually supports the transmitter), low-cost passive cuing of target angle of approach, examining heavenly bodies (from separated earth locations or with an earth receiver and a satellite transmitter) and providing simultaneous reception from multiple sites to develop three-dimensional models of ionospheric or atmospheric events (36).

Radar Nomenclature

No standards exist for the identification of commercial radar systems, although many manufacturers will number a series of products with a common name or common acronym descriptive of their purpose. The most common nomenclature system is the Joint Electronics Type Designation System (*JTEDS*, MIL-STD-196D, 1985), which is an outgrowth of the Joint Army-Navy Nomenclature System (*AN* System) and the Joint Communications-Electronics Nomenclature System developed during WW II in the United States. Although

Table 2. Equipment Indicators

Installation	Type of Equipment	Purpose
A–Piloted aircraft	A–Invisible light, heat radiation	A–Auxiliary assembly
B–Underwater mobile, submarine	C–Carrier	B–Bombing
D–Pilotless aircraft	D–Radiac	C–Communications
F–Ground, fixed	E–Laser	D–Direction finder
G–Ground, general	G–Telegraph/teleytype	E–Ejection/release
K–Amphibious	I–Interphone/public address	G–Fire control/searchlight directing
M–Ground, mobile	K–Electromechanical/inertial wire	H–Recording/reproducing
P–Portable	L–Countermeasures	K–Computing
S–Water	M–Meteorological	M–Maintenance/test
T–Ground, transportable	N–Sound in air	N–Navigational
U–General utility	P–Radar	Q–Special/combined purposes
V–Ground, vehicular	Q–Sonar/underwater sound	R–Receiving/passive detecting
W–Surface and underwater combination	R–Radio	S–Detecting/range/bearing/search
Z–Airborne vehicle combination	S–Special/combinations of types	T–Transmitting
	T–Telephone (wire)	W–Automatic or remote control
	V–Visual/visible light	X–Identification and recognition
	W–Armament	Y–Surveillance and control
	X–Facsimile/television	
	Y–Data processing	

Note: Special suffix T is reserved for training, and suffixes X, Y, and Z are reserved for changes in voltage, phase, or frequency. (V) designates variable groupings of equipment and (P) designates units accepting plug-ins. (Xnn) designates developmental units with the second (and third) letter used to designate the developmental agency. Open ( ) (called bowlegs) designate developmental equipment or generically indicate equipment families.
Adapted from MIL-STD-196D, 1985.

the JTEDS nomenclature scheme also covers units and subgroups of systems, it is best known for its distinctive sequence of the letters AN followed by a forward slash, followed by a three-letter indicator series, followed by a dash, and then followed by a sequence number and possibly suffixes designating variations in the design. The three indicator letters (Table 2) describe the type of installation, type of equipment, and purpose of the system. Radar systems will always have a middle letter P, although some systems with a P may not be radars because this equipment type also covers radar detectors, electronic recognition and identification (*IFF*) equipment, radar beacons, and pulse-type navigational aids. The system has been extended to include other English-speaking countries with blocks of sequence numbers being assigned to various countries. Canada is assigned sequence numbers 500–599 and 2500-2599, Australia has the block 2000–2099, New Zealand has 2100–2199, and the United Kingdom has 2200–2299. Thus the designator AN/APS-506 identifies a Canadian airborne search radar, whereas AN/PPS-15A is the first upgrade to a U.S. man-portable search radar.

The U.S. National Weather Service designates its radars as *WSR* (originally for Weather Service Radar, now more commonly Weather Surveillance Radar) followed by a number, which is the last two digits of the year the radar was put into service. Thus the WSR-57 is a unit that was first placed into service in 1957. Later units had alphabetic suffixes designating the radar band in which they operated, such as WSR-74C and the WSR-74S. Most recently, the letter designator has been used for other purposes as well, as in the WSR-88D (the NEXRAD system radar) where the D designation stands for Doppler. The Federal Aviation Administration (*FAA*) has a series of radars for air traffic control, which typically are designated by their task name acronyms

Fig. 21. The ARSR-4 is a long-range, three-dimensional, solid-state surveillance system. It was specifically designed as a joint-use radar for the FAA, the US Air Force, and the US Navy. The ARSR-4 detects all aircraft out to 463 km through all weather and clutter conditions as well as man-made interference. Photo courtesy of Northrop Grumman Corporation.

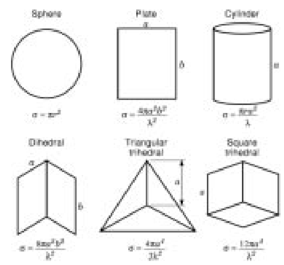

Fig. 22. Common radar targets and their equivalent radar cross section σ, where r is the radius of the circular objects.

and a sequence number. Examples of current equipment include the long-range air route surveillance radars (ARSR-4) (Fig. 21), the terminal surface monitoring airport surveillance radars (ASR-9 and 11) and airport surface detection equipment (ASDE-3); the windshear products, which include the shared NEXRAD system and the terminal Doppler weather radar (*TDWR*); and the secondary surveillance radar designated as the precision runway monitor (*PRM*).

Radar Targets

It is useful to have a set of standard radar targets that can be used to test, evaluate, or measure the performance of radar systems (37). The most common of these are simple geometric shapes; their radar cross section (*RCS*) is easily calculable and have been extensively studied in the literature. The sphere is the best-known of these targets, reradiating uniformly in all directions, but it does not present a very large RCS for its physical size. A specular reflector, like the flat plate, presents a much larger cross section, especially at higher frequencies, but this larger return happens only over a small angular region, near the normal to the surface. Corner reflectors have a wider angle of acceptance, in at least one dimension, as does a cylinder. Figure 22 shows a number of radar targets and their approximate RCS, based on geometric optics. For these RCS values to be realistic, target dimensions need to be about 10λ. As target dimensions approach 1λ, or less, diffraction effects must be considered, and the target cross sections should be calculated using physical optics, uniform theory of diffraction, or computational electromagnetics (38).

Although it is not the optimal solution (39), the triangular plate trihedral is the most commonly used specular target, having a reasonably wide angle of operation in both elevation and azimuth and having simple assembly requirements. The RCS of a 30 cm radius sphere is 0.28 m^2, whereas a triangular trihedral with sides 30 cm long has a maximum RCS of 37.7 m^2, at 10 GHz. These targets are usually placed a number of

Fig. 23. A motorized set of trihedrals provides a moving target for W-band. Note the angle offset between the support arm and the trihedrals. This offset was designed so that the "flash" from the arm, as it becomes normal to the radar wave, will not occur at the same time as the peak of the trihedral response.

Fig. 24. A K_u-band electronic moving target simulator. One horn receives the transmitted signal, which is mixed down with one STALO and mixed back up with another matched STALO. A discriminator circuit provides a visual indication of target Doppler frequency and direction. An attenuator provides control over the radar cross section of the return signal.

wavelengths above the ground to help reduce multipath interference and oriented to maximize target return in the expected direction of the radar.

These targets are useful for evaluating pulse radars, but for evaluating MTI and pulse-Doppler radars, a moving target is needed. Figure 23 shows a simple approach to the problem, but one in which the radial velocity of the target varies over the angle swept by the motorized arm. Electronic simulators have the advantage that RCS and Doppler can be varied by simple choice of circuit parameters, and with the addition of a delay line, even the range to the target can appear to vary. This delay can allow the target return to be placed in a range cell that differs from the one the simulator occupies, thus eliminating possible corruption of the signal because of the clutter return from the simulator itself. The target simulator is often a simple superhetrodyne receiver that uses a single sideband modulator to add the desired Doppler signal to the IF output, which is then upconverted back to the initial radar band with the same local oscillator chain. The choice of upper or lower sideband will, respectively, make the target appear as either incoming or outgoing. The addition of an extremely long delay line can allow such an electronic simulator to be used in a laboratory setting while making targets appear as if they are kilometers away. A simpler, although less time and temperature stable, approach to designing a target simulator is shown in Fig. 24, in which the return frequency is simply shifted.

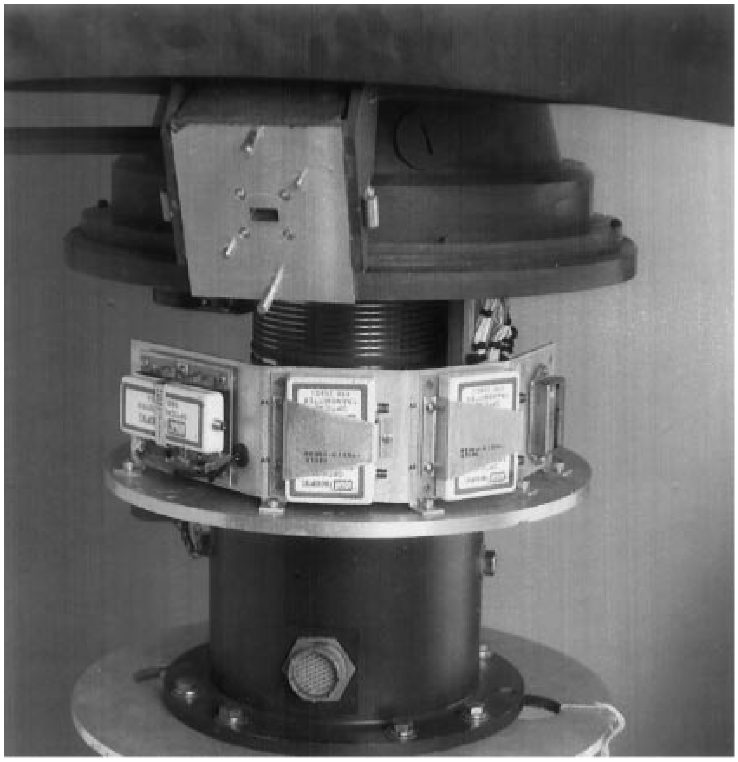

Fig. 25. The slip ring assembly for the AN/TPS-74(V) showing the fiber optic transceivers. Only dc power and digital signals pass through the slip rings.

Scanning the Scene

The typical surveillance radar antenna (Fig. 13) rotates through 360° of azimuth and possibly some amount of elevation. RF is usually supplied through a rotary joint for azimuth and through another rotary joint for elevation, or for limited angles, through flexible waveguide. For lower radar frequencies, the losses may be low enough, and for fixed installations, usually an abundance of transmitter power is available. But at higher frequencies, the losses and noise because of these feed mechanisms may be objectionable. One approach to avoid these losses, for lower-power mobile systems, is to mount the radar transceiver at the antenna (Fig. 25), or at least part of the RF assembly at the antenna. Figure 26 shows the large rotating antenna radomes of the E-2C. The larger, and perhaps more well-known, E-3 Sentry airborne warning and control system (*AWACS*) sports a similar 9.1 m diameter rotodome, which rotates at 6 rpm over a Boeing 707. However, vertical scanning and height finding are performed by electronic scanning techniques using ferrite phase-shifters. The phase-shifters, phase-control electronics, receiver protectors, and receiver preamplifiers are mounted on back of the antenna. A better view of an electronic elevation scan can be seen in the picture of the ARSR-4 antenna in Fig. 27. Many applications require much less than 360° coverage, and with the radar transceiver mounted at the antenna, often flexible cables can supply power and control signals. Another approach is shown in Fig. 5, in which azimuth scanning is provided by tilting the reflector left and right, while elevation is accomplished by moving the feed horn.

It is possible to provide 360° coverage and elevation control in a phased-array-based antenna system. The Aegis weapons system (Fig. 28) is based on the AN/SPY-1D multifunction phased-array S-band radar, which

Fig. 26. A pair of Northrop Grumman E-2C Hawkeyes are easily identified by their distinctive 7.3 m (24 ft) diameter rotodomes, which contain both the low sidelobe radar antenna and the IFF antenna. A Lockheed Martin AN/APS-145 radar system automatically detects, identifies, and tracks targets at ranges exceeding 300 miles. US Naval Institute collection.

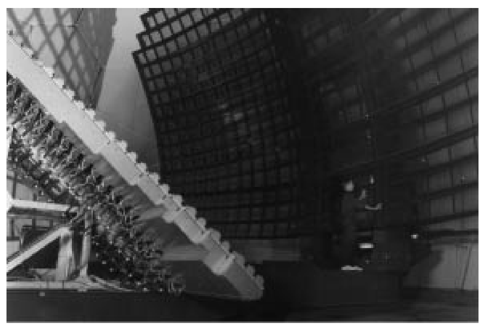

Fig. 27. The view inside the radome of the ARSR-4, long-range L-band radar, exposes the phased array feed that supports up to nine simultaneous elevation beams that can be steered up to 30°. The reflector/feed assembly rotates mechanically through 360° azimuth. Photo courtesy of Northrop Grumman Corporation.

is able to perform search, track, and missile guidance functions simultaneously with a track capacity of over 100 targets. Four antenna panels, situated around the deckhouse, provide full 360° coverage. Each array has 4100 discrete elements and measures 3.65 m × 3.65 m. Output power is approximately 4 MW and is provided by a four-stage amplifier employing traveling wave tubes (*TWT*) and cross-field amplifiers (*CFA*). It is possible to build high-power solid-state radars while avoiding the need for high-power phase shifters to provide beam steering. T/R modules allow the construction of large-phased arrays in which the output of literally hundreds of low-power solid-state amplifiers are spatially combined. Common phase-shifters and built-in RF switching in such modules means that beam steering works the same on both transmit and receive. Figure 29 shows a 6 to 18 GHz dual channel T/R module that uses a single vector modulator in each channel to provide phase and amplitude control for both the receive and transmit paths. Each channel also supports a vertical and horizontal antenna channel so that multiple polarizations can be used, including, with the addition of a 90° phase-shifter, circular polarization. A common serial digital control circuit runs both channels to minimize control lines and provides control over the T/R switches, the 5-bit phase-shifters, and the 4-bit attenuators. The preamplifiers and output amplifiers both have nominal gains of 20 dB with typical noise figures of less than 8 dB and output powers of 26 dBm (40).

Fig. 28. The Arleigh Burke (DDG-51) Aegis system is based on the AN/SPY-1D multifunction phased-array S-band radar. The SPY-1 antennas are the octagonal panels on the corners of the deckhouse. The inset in the upper left shows an antenna being installed in a deckhouse. US Naval Institute collection.

Radar Displays

The original radar displays, developed during WW II, were assigned alphabetic designators (A, B, etc.) and were based on oscilloscope technology. Many of the display types were developed to satisfy special needs, typically to present additional information on the screen (41). Displays can be broken into three general types: one-axis, two-axis, and plan view. In the A-scope (Fig. 30), the most common one-axis display, the amplitude of the radar return is plotted against radar range, which is usually derived from a linear time-based sweep circuit. The sweep circuit allows the operator to change the sweep speed to change the range coverage being displayed. Two-axis displays are based on an *x–y* oscilloscope and use intensity modulation to indicate the amplitude of the return signal. The most common two-axis display is the B-scope, in which azimuth position

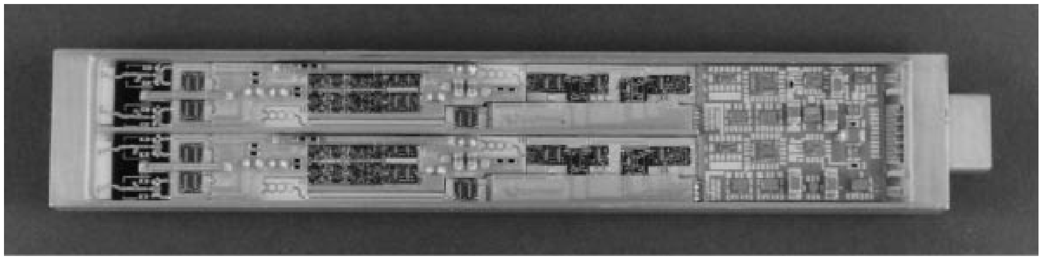

Fig. 29. The Lockheed Sanders Mark IV microwave module is a two-channel MMIC T/R module that covers 6 to 18 GHz in a package of which its volume is less than 16 cm^3 (cubic centimeters). The module is 2.1 cm wide × 11.9 cm long. © Lockheed Martin Corporation 1991.

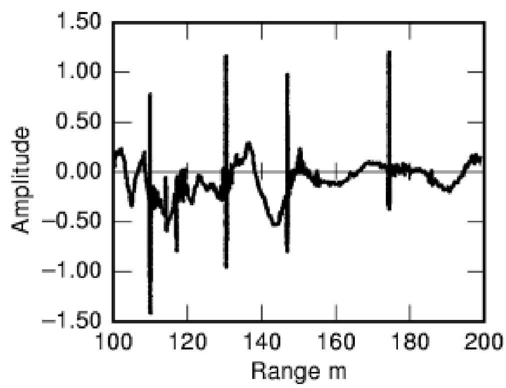

Fig. 30. An A-scope display from a high-resolution impulse radar. The large spikes are the result of trihedral targets in the scene. The slower variations in the baseline value are due to the clutter return from the surrounding terrain.

is plotted on the horizontal axis and range is plotted on the vertical axis. Elevation is the next most commonly used variable in a two-axis display. The problem with two-axis displays is the geometric distortion that results from plotting angular displacements on a linear axis. Plan displays solve this distortion problem by plotting in cylindrical coordinates, or sectors of cylindrical coordinates. The most common of these displays is the plan position indicator (*PPI*) or type P display. Early PPI displays rotated the deflection assembly of the CRT in synchronism with the rotation of the radar antenna so that the range sweep started at the center of the CRT and moved out radially in the direction the antenna was currently pointing.

More recently, the large use of computers in radar processing has resulted in the use of computer-driven displays to generate synthetically plan view plots of radar data while adding both coordinate and cultural features on the same display (Fig. 31), virtually eliminating the need for plastic plotting boards for keeping track of targets. The explosive growth of the personal computer has led to a large number of computer-driven raster display systems. Monochrome, color, and LCD displays are typically available for small shipboard radar systems, whereas high-resolution color graphic displays are now being used in military and air traffic control radar systems. These displays (Fig. 32) allow the radar operator to overlay map information, weather data, satellite photos, target identification indicators, as well as system status information on a single screen.

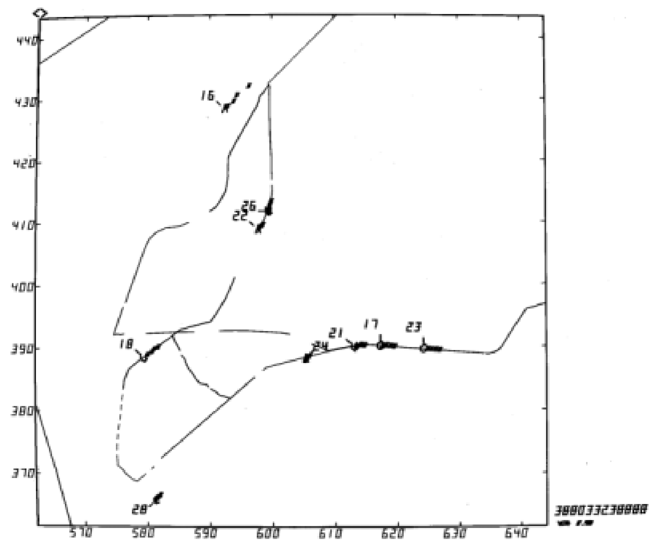

Fig. 31. A computer-driven vector scope displays a plan view of an area registered to UTM map coordinates and includes digitized road networks over which radar targets can be plotted. Moving targets that are being automatically tracked are plotted as numbered symbols with “tails” that show a recent history of past locations.

Fig. 32. A modern synthetic radar display that allows overlay of map data, weather data, air traffic controller to pilot data links, and IFF information to generate a powerful airspace management tool. Photo courtesy of Northrop Grumman Corporation.

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