Technical Report

Radar System Components and System Design

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Introduction

Radars are very complex electronic and electromagnetic systems. Often they are complex mechanical systems as well. Radar systems are composed of many different subsystems, which themselves are composed of many different components. There is a great diversity in the design of radar systems based on purpose, but the fundamental operation and main set of subsystems is the same. In this paper, I will discuss some of the subsystems and important components that are found in typical portable monostatic pulsed ground surveillance radar systems. I follow a bottom-up approach in developing this paper, first discussing components, then subsystems, and finally whole systems.

Antennas

The radar antenna acts as the interface between the radar system and free space through which radio waves are transmitted and received. The purpose of the radar antenna is to transduce free space propagation to guided wave propagation during reception and the opposite during transmission. During transmission, the radiated energy is concentrated into a shaped beam which points in the desired direction in space. During reception, the antenna collects the energy contained in the echo signal and delivers it to the receiver. In the radar range equation, these two roles were expressed by the transmitter gain, G, and effective receiving aperture, A_e, given by

$$G = \frac{4\pi R^2 P_T}{P_{in}} \tag{1}$$

$$A_e = \frac{P_{received}}{P_{incident}} \tag{2}$$

These two values are proportional, so optimizing for both transmitting and receiving is possible. The proportionality is given by

$$A_e = \frac{\lambda^2}{4\pi} G \tag{3}$$

One of the most widely used microwave antennas is the parabolic reflector. The geometric properties of the parabola are very useful in concentrating energy during reception, and creating plane constant-phase wavefronts during transmission. When a point source of radiation is placed at the focus, energy is emitted in all directions, striking points on the surface, such as *A* in Figure 1. This energy is reflected perpendicular to the axis. The distance in all such lines is the same, resulting in a constant-phase wavefront.

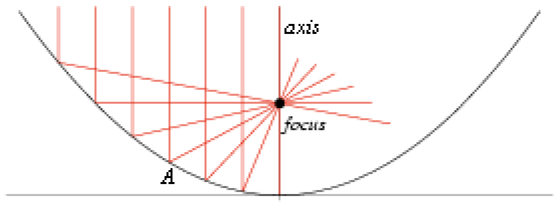

Figure 1. Parabola

A few different types of paraboloids are used in making parabolic reflectors. One of the commonly used paraboloids is the orange-peel paraboloid, shown in Figure 2. This is a section of a complete circular paraboloid. Since the reflector is narrow in the vertical plane, and wide in the horizontal plane, it produces a beam that is wide in the vertical plane and narrow in the horizontal plane. The microwave energy is sent into the parabolic reflector by an antenna feed (not shown in Figure 2).

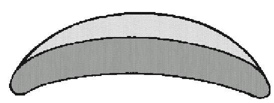
Figure 2. Orange-peel Paraboloid

Antenna feeds, or sources of illumination for parabolic reflectors, may employ either coaxial lines or waveguides and may be classified as front or rear feeds. In a rear feed, the line or guide projects through the reflector, whereas in a front feed, the line or guide approaches the reflector from the front. An antenna feed must satisfy two requirements: shape & location so as to illuminate the reflector in the correct manner; and termination of the waveguide or coaxial line so that the standing-line ratio is near unity in the line or feed. Horn radiators, fed by waveguides, are often used with orange-peel parabolic reflectors. The horn radiation pattern covers nearly the entire shape of the reflector, so almost all of the microwave energy strikes the reflector and very little escapes at the sides. The sectoral horn radiator is formed by flaring the wide cross-sectional dimension of a rectangular waveguide. The length and flare angle of the horn determine the directivity of the radiation that energizes the reflector and also the terminating impedance of the waveguide.

The reflecting surface of the parabolic reflector may be made of a solid sheet metal such as aluminum or steel. Often wire screen, metal grating, perforated metal, or expanded metal mesh is used to provide low wind resistance, light weight, and low cost. Reflector surfaces may also be formed from fiberglass resinated laminates with the reflecting surface made of embedded mesh.

Duplexer

When a single antenna is used for both transmission and reception, as in most monostatic radar systems, a duplexer must be used. A duplexer switches the radar system from transmit mode to receive mode. There are four main requirements that must be met by an effective radar duplexing system. During transmission, the switch must connect the antenna to the transmitter and disconnect it from the receiver. The receiver must be thoroughly isolated from the transmitter during the transmission of the high-power pulse to avoid damage to sensitive receiver components. After transmission, the switch must rapidly disconnect the transmitter and connect the receiver to the antenna. For targets close to the radar to be detected, the action of the switch must be extremely rapid. The switch should have very little insertion loss during both transmission and reception.

The simplest solution to the duplexer problem is to use a switch to transfer the antenna connection from the receiver to the transmitter during the transmitted pulse and back to the receiver during the return pulse. Since no practical mechanical switches are available that can open and close in a few microseconds, electronic switches are used. For radars with waveguide antenna feeds, waveguide junction circulators are often used as duplexers. A circulator is a nonreciprocal ferrite device, which contains three or more ports. A three-port ferrite junction circulator, called the Y-junction circulator, is most commonly used. The Y-junction circulator uses spinel ferrites or garnet ferrites in the presence of a magnetic bias field, to provide a non-reciprocal effect. A schematic diagram is shown in Figure 3.

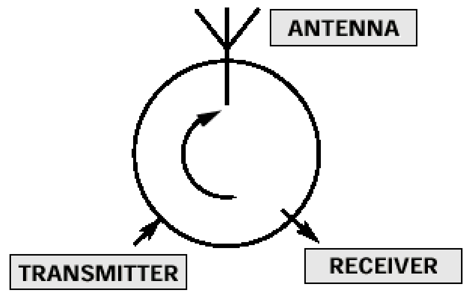

Figure 3. Circulator Schematic

If a signal is applied at the transmitter port, it will emerge from the antenna port with a loss characteristic called insertion loss. Typical values of insertion loss are 0.1 to 0.5 dB. In the reverse direction, there will be leakage at the receiver port from the incoming signal at the transmitter port. This leakage, called isolation, is typically 20 dB below incoming power at the transmitter port. Due to the symmetry of the Y-junction, the behavior is the same for the other ports, with respect to other port pairs.

Radio Frequency Subsystem

The Radio Frequency (RF) system takes a signal from the transmitter and eventually propagates it in free space during transmission. The RF system takes a signal from free space and passes it to the receiver during reception. The RF system generally consists of an antenna feed and antenna, a duplexer, and some filters. Often devices are needed to convert waveguide propagation into coaxial cable propagation. Filtering is used to attenuate out-of-band signals such as images and interference from other radars or high-powered electrical devices during reception. During transmission, filtering is used to attenuate harmonics and images. The preselector filter is a device that accomplishes these two filtering objectives. The duplexer provides isolation between the transmitter and receiver to protect the sensitive receiver during the high energy transmit pulse. The antenna feed collects energy as it is received from the antenna or transmits energy as it is transmitted from the antenna. The antenna is the final stage in the RF system during transmission or the first stage during reception. It is the interface with the medium of radio wave propagation.

Digital Waveform Generator

Digital waveform generators are constructed by linking a digital signal source with a digital to analog (D/A) converter. In general, digital memories are used to store the signal waveform. The memory is read out based on the timing characteristics of the desired waveform. There is a great deal of flexibility with digital waveform generators, which is not present for analog signal generators. Waveform design is a complex topic that will not be treated in this paper. The purpose of the radar, and the expected characteristics of the targets, in addition to the demands of moving target indication (MTI), electromagnetic compatibility (EMC), and electronic counter-countermeasures (ECCM) are some of the factors that determine waveform design.

Frequency Synthesizers and Oscillators

Oscillators represent the basic microwave energy source for microwave systems such as radars. A typical oscillator essentially consists of an active device and a passive frequency-determining resonant element. Dielectric resonant oscillators (DROs) are fixed-frequency oscillators that use a dielectric resonator as the frequency-determining element. Tunable oscillators often use varactors as the tunable oscillator. A voltage controlled oscillator (VCO) is an oscillator where the principal variable or tuning element is a varactor diode. The VCO is tuned across its band by a clean direct current (DC) voltage applied to the varactor diode. Phase Locked Loop (PLL) circuits are used for frequency control of VCOs. A PLL is basically a feedback control system that controls the phase of a VCO. The input signal is applied to one input of a phase detector. The other input is connected to the output of a divider. The output of the phase detector is a voltage proportional to the phase difference between the two inputs. This signal is applied to a loop filter. The filtered signal controls the VCO. Dual modulus prescalers are often used as the divider in PLL circuits.

Mixer

Mixers are used to transform signals in one spectrum range to some other spectrum range. In radar transmitters, mixers are used to transform intermediate frequency (IF) signals produced by the waveform generator into RF signals. This process is called upconversion. In radar receivers, the opposite operation is performed. RF signals are downconverted into IF signals. This process is demonstrated in Figure 4.

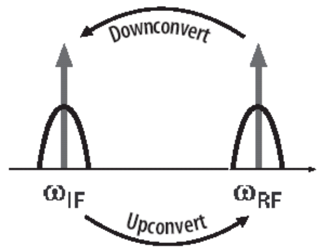

Figure 4. Upconversion and Downconversion Operations of a Mixer

Mixing is accomplished by combining either the RF or IF signal with another signal of known frequency from the local oscillator (LO), as shown in Figure 5. What results is either the sum or difference between the two, for upconversion and downconversion, respectively. Various kinds of oscillators and frequency synthesizers are used as the LO. Silicon point-contact and Schottky-barrier diodes based on the nonlinear resistance characteristics of metal-to-semiconductor contacts have been used as the mixing element.

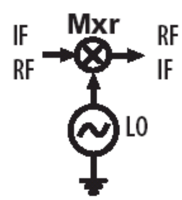

Figure 5. Mixer Schematic

Power Amplifier

Power amplifiers are used to amplify the RF waveform for transmission. Historically, tube amplifiers, such as grid controlled tubes, magnetrons, klystrons, traveling-wave tubes (TWTs), and crossed field amplifiers (CFAs) have been used as power amplifiers for radar transmitters. These amplifiers generate high power, but usually operate with low duty cycle. The klystron amplifier offers higher power than the magnetron at microwave frequencies, and also allows the use of more complex waveforms. The TWT is similar to the klystron, but with wider bandwidth. CFAs are characterized by wide bandwidth, modest gain, and compactness. Solid State Power Amplifiers (SSPAs) support long pulses and high duty cycle waveforms. Individual SSPA elements can be combined to produce sufficient amplification, despite the fact that individual SSPA elements have low power amplification. Silicon Bipolar transistors, and gallium arsenide Metal Semiconductor Field Effect Transistors (MESFETs), bulk-effect diodes, and avalanche diodes are some of the solid state elements used in SSPAs.

Transmitter Subsystem

The transmitter system is generally the main consumer of the power, cost, and weight budgets, and is the prime thermal load of radar systems. The transmitter must be of adequate power to obtain the desired radar range. The radar range equation shows that the transmitter power depends on the fourth power of radar range. Hence, to double the range, it is necessary to increase transmitter power 16-fold. The three main components in transmitters are the waveform generator, the upconverting mixer, and the power amplifier, although it is possible to leave out one of these components. The transmission waveform is generated by the digital waveform generator. This waveform is in the baseband frequency range. The waveform is converted into the RF frequency range by a mixer or series of mixers, the mixers using either fixed or variable oscillators as the LO. Finally the power amplifier provides amplification for the transmit signal before it enters the RF system.

Low Noise Amplifier

The purpose of a low noise amplifier (LNA) is to boost the desired signal power while adding as little noise and distortion as possible so that retrieval of this signal is possible in the later stages in the system. An LNA is an amplifier with low noise figure. Noise figure is defined as the input signal to noise ratio (SNR) divided by the output SNR. For an amplifier, it can also be interpreted as the amount of noise introduced by the amplifier seen at the output besides that which is caused by the noise of the input signal. LNAs are used as the front end of radar receivers. There are a few different kinds of amplifiers that can provide suitably low noise figures. Parametric amplifiers have low noise figure, especially at high microwave frequencies. The transistor amplifier can be applied over most of the range frequencies used for radar. The silicon bipolar transistor and the gallium arsenide field effect transistor have also been used as amplifiers. The lower the noise figure of the receiver, the less need there is for be transmitter power for the same performance. In addition to noise figure, cost, burnout, and dynamic range must also be considered when selecting a receiver front end.

Receiver Subsystem

The function of the radar receiver is to detect wanted echo signals in the presence of noise, clutter, and interference. It must separate desired signals from undesired signals, and amplify the desired signals for later processing. Receiver design depends on the design of the transmitted waveform, the nature of the targets, and the characteristics of noise, clutter, and interference. The goal of receivers is to maximize the SNR of the returned echo signal. The receiver system generally consists of an LNA, and downconverting mixers. Limiters are often built into the front end to prevent inadvertent damage from reflected transmitter power or the high power signal which may enter the system. Sometimes analog to digital (A/D) converters are placed at the end of the receiver signal path, if digital signal processing is to take place.

Signal Processing/Data Processing/Control Subsystems

Various signal processing techniques can be performed on raw receiver signals. Some common radar signal processing techniques are correlation, apodization, Doppler filtering, image rejection, detection processing, and tracking. Almost all modern radars use digital signal processors to perform these signal processing operations. These digital processors are very complex chips, implementing very complex algorithms. Specific signal processing techniques will not be discussed in this paper.

Data processors are used to convert data produced by the signal processor into a form that is readily interpretable by radar operators. Human machine interface (HMI) designs are generally implemented in the data processing system. Data processors are also used to process inputs received from the operator. Often times tactical information is stored and used by the data processing system

The different subsystems of the radar are coordinated by the Control subsystem. Precise timing of events is required to optimize performance. As an example, the switch between transmit and receive mode for a pulsed radar requires a complete transformation that must occur in as little time as possible. Often the entire radar system is synchronized to a single clock, produced and distributed by the control subsystem.

Antenna Positioning System

In some radar systems, antennas are positioned manually. In others, motors are used to rotate and position radar antennas. If an antenna is required merely to rotate at constant speed, a simple motor is sufficient. If several different motions, such as constant-speed rotation, scanning over a sector, and tracking a moving object, are required, then servomechanisms are used. Servomechanisms supply the large torque necessary to turn radar antennas, and also determine the antenna position. A servomechanism is comprised of an error indicator and a controller connected to an input shaft and an output shaft. The object of the servomechanism is to cause the output shaft to mirror the motion of the input shaft by keeping the error angle, deviation in angular position of output shaft from input shaft, as close to zero as possible. The error indicator determines the magnitude and direction of the error angle. Under control of the signal from the error indicator, the controller exerts a torque on the output shaft in a direction to reduce the error. The servo is a feedback system, because a signal applied to the controller causes rotation of the output shaft and thus changes the error angle with the result that an additional signal is applied to the controller. The error indicator is most frequently a synchro. A synchro is a small a-c machine used for the transmission of angular position data. The controller must include a servomotor or some other device for developing output torque. Most radar servos use electric servomotors.

Power System

Radars are complex electromechanical systems. Each of the components requires power to operate. In general, different components need different voltage levels. To satisfy these different voltage requirements, using only a single external voltage source, voltage converters are required. A DC to DC converter is a device that accepts a DC input voltage and produces a DC output voltage. Typically the output produced is at a different voltage level than the input. DC to DC converters often use switching regulators. A switching regulator is a circuit that uses an inductor, a transformer, or a capacitor as an energy-storage element to transfer energy from input to output in discrete packets. Feedback circuitry regulates the energy transfer to maintain a constant voltage within the load limits of the circuit. The basic circuit can be configured to step up (boost), step down (buck), or invert output voltage with respect to input voltage. Using a transformer as the energy-storage element also allows the output voltage to be electrically isolated from the input voltage. The one disadvantage of the switching regulator is noise. Any time charge is moved in discrete packets, noise or ripple is created. The noise can often be minimized by using specific control techniques, such as synchronization.

Whole System

A radar system is composed of many different subsystems. The main subsystems were discussed in previous sections. In a pulsed radar system, there is a portion of time devoted to transmission, and another portion of time devoted to reception. The transmission time is called the pulse width. A pulse is transmitted at regular intervals. The repetition interval is called the pulse repetition interval (PRI). During transmission, the transmitter produces a waveform. This is passed to the RF system, through which the waveform is transmitted into the medium of propagation. When the waveform reaches a target, it is reflected back towards the radar. By then, the radar system should be in reception mode. At this time, the reflected echo is intercepted by the RF system. The echo is then passed to the receiver, which passes it on to the signal processor. After signal processing, the data processor displays data for the operator, through the HMI. Power and Control are provided to each of the subsystems as necessary. The antenna is generally repositioned after a certain number of pulse transmissions. A schematic of the radar system is shown in Figure 6.

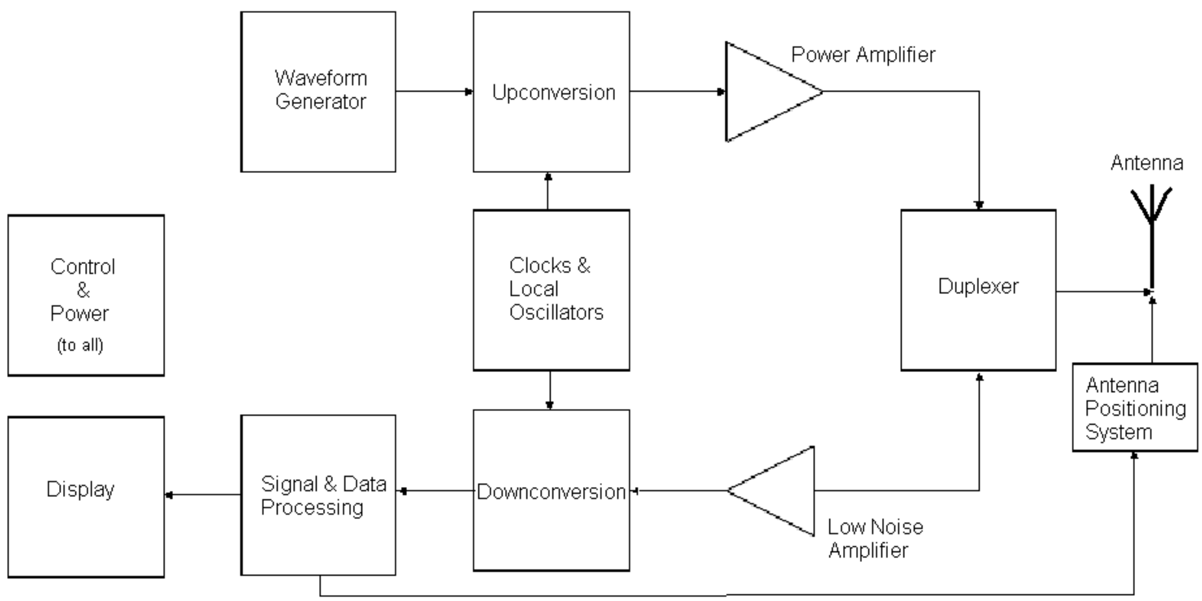

Figure 6. Radar System Schematic

List of Acronyms

A/D	Analog to Digital
CFA	Crossed Field Amplifier
D/A	Digital to Analog
DC	Direct Current
DRO	Dielectric Resonant Oscillator
ECCM	Electronic Counter-Countermeasures
EMC	Electromagnetic Compatibility
HMI	Human Machine Interface
IF	Intermediate Frequency
LNA	Low Noise Amplifier
LO	Local Oscillator
MESFET	Metal Semiconductor Field Effect Transistor
MTI	Moving Target Indication
PLL	Phase Lock Loop
PRI	Pulse Repetition Interval
RF	Radio Frequency
SNR	Signal to Noise Ratio
SSPA	Solid State Power Amplifier
TWT	Traveling-Wave Tube
VCO	Voltage Controlled Oscillator

Figures

Figure 1: Weisstein, Eric W., *Parabola*, CRC Press LLC, 1999. [Online]. Available: http://mathworld.wolfram.com/Parabola.html.

Figure 2: *Radar Principles,* United States Navy Electrical Engineering Training Series. [Online]. Available: http://www.tpub.com/neets/book18/index.htm.

Figure 3: *Ferrite Devices,* Temex Microwave, [Online]. Available: http://www.temex-components.com/temex/catalog/agalinfogyro.pdf.

Figures 4,5: Abidi, Asad A., *Upconversion and Downconversion Mixers for CMOS Wireless Transceivers*, University of California, Los Angeles. [Online]. Available: http://www.icsl.ucla.edu/aagroup/PDF_files/shcourse.PDF

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