Introduction to Radar System and Component Tests

White Paper

This White Paper provides a general overview of various military and commercial radar systems.

It also covers some typical measurements on such systems and their components.

White Paper

Roland Minihold, Dieter Bues
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ROHDE&SCHWARZ

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1 Abstract

RAdio Detection And Ranging (RADAR), much like SOund Navigation And Ranging (SONAR) is a technical equivalent of what nature blueprinted with the navigation and imaging used by bats. Incepted at the beginning of the 20th century, radar technology was developed in earnest the first time for a military purpose during World War II. Today, more than half a century later, there are much wider radar application areas beyond the military one. Radar is needed for weather forecast, airport traffic control and automotive applications such as adaptive cruise control (ACC), blind spot detection (BSD) and active pedestrian safety.

Radar technology was made affordable on a mass production basis due to highly integrated signal processing components which make it possible to detect even low power signals in applications where in former times much more RF energy was needed. Low power radar components as a side effect reduce cost and size. In addition there are a lot of Computer-Aided Design (CAD) tools available nowadays to deal with high frequencies of up to 110 GHz and beyond.

This White Paper gives an overview on radar systems and addresses some important measurements. An additional White Paper 1MA239 explains more advanced kinds of waveform for both A&D and automotive radar systems in detail and mentions future waveform trends briefly.

A corresponding application note 1MA127 goes into more detail explaining radar test technology along with the specific Rohde & Schwarz products that can be used to perform test and measurement.

Documents 1MA127, 1MA207 and 1MA239 and associated videos also address students who want to become familiar with radar techniques as well as the related test and measurement tasks.

2 Overview of Typical Radar Application and Radar Types

2.1 Typical Radar applications

Typical radar applications are listed to give an idea of the huge importance of radar:

- Surveillance: Military and civil air traffic control, ground-based, airborne, surface coastal, satellite-based
- Searching and tracking: Military target searching and tracking
- Fire control: Provides information (mainly target azimuth, elevation, range and velocity) to a fire-control system
- Navigation: Satellite, air, maritime, terrestrial navigation
- Automotive: Collision warning, adaptive cruise control (ACC), collision avoidance (CA), blind spot detection (BSD), pedestrian protection and active safety
- Level measurements: Monitoring e.g. fill levels of liquids
- Proximity fuses: Guided weapon systems require a proximity fuse to trigger the explosive warhead
- Altimeter: Aircraft or spacecraft altimeters for civil and military use
- Terrain avoidance: Airborne military use
- Secondary radar: Transponder in target responds with coded reply signal
- Weather: Storm avoidance, wind shear warning, weather mapping
- Space: Earth surveillance, ground mapping, and exploration of space environment
- Security: Hidden weapon detection, military earth surveillance, ground or through the wall penetration

2.2 Radar Frequencies, Bands, Wavelength and Applications

Radar Bands, -Frequencies, -Wavelengths and their Applications			
Band	Frequency	Wavelength	Application
HF	3 - 30 MHz	10 m – 100 m	Coastal radar systems, over-the-horizon (OTH) radars; 'high frequency'
P	30 - 300 MHz	1m – 10 m	applied retrospectively to early radar systems; 'P' for 'previous'
UHF	300 - 1000 MHz	0.3 m – 1 m	Very long range (e.g. ballistic missile early warning), ground penetrating, foliage penetrating; 'ultra high frequency'
L	1 - 2 GHz	15 cm – 30 cm	Long-range air traffic control and surveillance; 'L' for 'long'
S	2 - 4 GHz	7.5 cm – 15 cm	Terminal air traffic control, long-range weather, marine radar; 'S' for 'short'
C	4 – 8 GHz	3.75 cm – 7.5 cm	Satellite transponders, weather radar; a compromise (hence 'C') between X and S bands
X	8 – 12 GHz	2.5 cm – 3.75 cm	Missile guidance, marine radar, weather, medium-resolution mapping and ground surveillance; in the USA the narrow range 10.525 GHz ± 25 MHz is used for airport radar. Named X band because the frequency was kept secret during World War 2.
Ku	12 – 18 GHz	1.67 cm – 2.5 cm	High-resolution mapping, satellite altimetry; frequency just under K band (hence 'u')
K	18 – 27 GHz	1.11 – 1.67 cm	K band is used by meteorologists for detecting clouds and by police for speed enforcement. K band radar guns operate at 24.150 ± 0.100 GHz. Automotive radar uses 24 – 26 GHz
Ka	27 – 40 GHz	0.75 cm – 1.11 cm	Mapping, short range, airport surveillance, photo radar, used to trigger cameras that take pictures of license plates of cars running red lights, operates at 34.300 ± 0.100 GHz; frequency just above K band (hence 'a')
mm	40 - 300 GHz	1 mm – 7.5 mm	Millimeter band, subdivided as below. The letter designators appear to be random, and the frequency ranges dependent on waveguide size. Multiple letters are assigned to these bands by different groups, i.e. frequencies around 75 and 85 GHz are also referred to as Lower and Upper E-band, respectively.
Q	40 - 60 GHz	5 mm – 7.5 mm	Used for military communications
V	50 - 75 GHz	4 mm – 6 mm	Very strongly absorbed by the atmosphere
W	75 to 110 GHz	2.7 mm – 4 mm	76 GHz LRR and 79 GHz SRR automotive radar, high-resolution meteorological observation and imaging

3 Radar Equation

Radar allows to detect and measure range, radial velocity and angular information. While range is measured by signal propagation time, radial velocity is measured due to Doppler frequency shift.

Figure 3-1 shows the basic principle of radar transmitting an electromagnetic wave of power P_t and receiving the radar echo, partly reflected by a target after a certain time delay. By time delay and speed of light range is estimated.

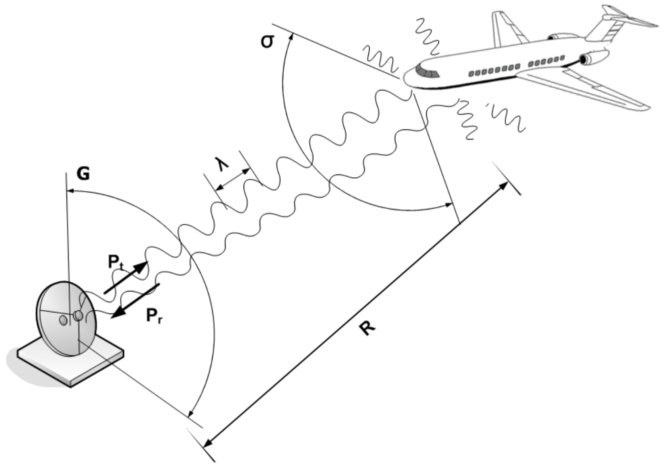

Figure 3-1: Radar principle

Receiving a radar echo signal of sufficient signal-to-noise (SNR) is the main task and together biggest challenge of radar systems, as SNR determines detection probability and measurement accuracy of any target. The "Radar Equation" describes the echo signal power P_r according to the following parameters:

$$P_r = \frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 R^4}$$

- P_t [dBm]: The power transmitted by the antenna. e.g. 20 dBm for 24 GHz Automotive Radar
- G [dBi]: Gain of the transmitting and receiving antenna (hence squared in the equation). e.g. 12 dBi for a BiQuad antenna and 70 dBi for a highly focusing parabolic antenna.
- λ [m]: wavelength of the transmitted signal, which is directly calculated from the carrier frequency. e.g. 0.03 m for 10 GHz
- σ [m^2]: Radar cross section (RCS), is a virtual area representing the intensity of the reflection and describes somehow the e.g. material, reflection area in terms of wavelength of the target. Depending on wavelength e.g. 12 m^2 for a commercial plane, 1 m^2 for a person or 0.01 m^2 for a bird. Refer to [18], page 6665 for further examples.
- R [m]: Range between the transmitting antenna and the reflecting object.

4 Common Radar Types

In any radar system range is measured using the delay caused by signal propagation time τ between transmit and receive signal. The signal propagation time describes the elapsed time the transmitted radar signal takes to travel to an object in range R, where it reflects and travels back to its origin.

A technical strength of radar is to measure the exact radial velocity of an object by using the Doppler-effect (named after physicist Christian Doppler). The Doppler-effect describes the apparent change in frequency of a signal emitted or reflected to an observer if an object is moving relative towards or away from its observer. In the special case of radar, the observer is also the emitter of the signal, see Figure 4-1 where the radar transmits a wave and observes a moving object where the frequency in the direction of motion is increases or decreases in opposite direction.

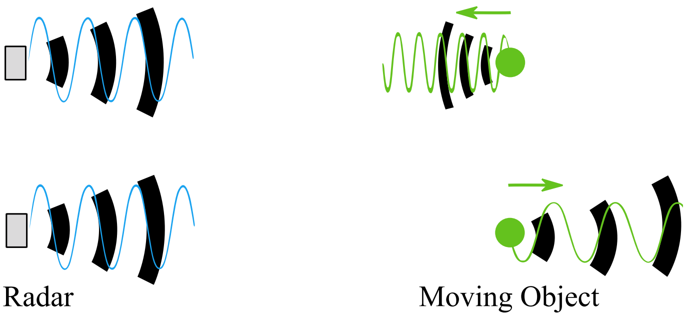

Figure 4-1: Principal operation of radial velocity measurement.

The following sub-sections list the most common types of radar systems with brief explanations. More detailed information about certain waveforms can be found in the White Paper "1MA239 Radar Waveforms for A&D and Automotive Radar".

4.1 Pulse Radar

Pulse radar estimates range by measuring the time difference between the transmission and reception of a single pulse. While pulse width determines range resolution, pulse repetition frequency (PRF) determines the range where measurement results are unambiguous.

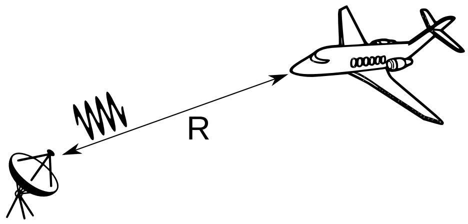

Figure 4-2: Pulse radar principle.

Angular information such as elevation and azimuth is measured using a narrow transmit antenna beam and mechanical steering. By the known position of the antenna beam azimuth angle is estimated.

Important measurements on (non-coherent) radar equipment are range accuracy and resolution, Automatic Gain Control (AGC) settling time of the receiver, peak power, frequency stability, phase noise of the local oscillator (LO) and all pulse parameters.

The AGC circuit of the receiver protects the radar from overload conditions due to nearby collocated radars or jamming countermeasures. The attack and decay time of the AGC circuit can be varied based on the operational mode of the radar. Since the roundtrip of a radar signal travels approximately 150 meters per microsecond, it is important to measure the response of the AGC for both amplitude and phase response when subject to different overload signal conditions. The measured response time influences the minimum detection range of the radar (the so-called "blind range").

4.2 Pulse Doppler Radar

Pulse Doppler radar transmits consecutive pulses and measures the phase difference in-between their received echoes to provide radial velocity in addition to range measurement.

In case of coherent operation of the radar transmitter and receiver, radial velocity is derived from the pulse-to-pulse phase variations.

Pulse Doppler radar systems normally use various pulse repetition frequencies ranging from several hundred Hz up to hundreds of kHz and change during operation in order to solve range and Doppler ambiguities. Important criteria to achieve good performance in pulse Doppler radar include very low LO phase noise, low receiver noise and low I/Q gain phase mismatch (to avoid "false target indication") in addition to the measurement parameters listed above.

When measuring the performance of a pulse Doppler radar transmitter the uncertainty of the measurement system for accurate Doppler measurements is influenced by several parameters:

- Signal-to-noise ratio (SNR) of the radar echo signal: signals with high SNR can be detected with higher probability and allow deriving target parameters more accurately.
- Signal bandwidth (BW): bandwidth of the IF acquisition system must be sufficient to accurately represent the rise time of the pulsed signal. Bandwidth is also directly related to range resolution.
- Reference clock stability.
- Jitter or uncertainty due to the measurement point of the rising edge of the signal: rising edge interpolation or signals that have changing edges.
- Overshoot and preshoot of rising and falling edges: any ringing on the rising and falling edges can impact the measurement points adversely on a pulse-to-pulse basis. It is important that the measurement point, or the average set of measurement points, are sufficiently far spaced in time from the leading and falling edges of a pulse. Applying a Gaussian filter to smooth the impact of the rising and falling edges can reduce this phenomena and is often implemented in the Doppler filter of a radar receiver.

- Time between measured signals: due to the Pulse Repetition Interval (PRI) of the measured signal, the close-in phase noise of the measurement system needs to be considered due to integration time at lower offset frequencies.
- The same variables can also contribute to the uncertainty in the signal generator when testing the receiver circuit and Doppler measurement accuracy.

4.3 Pulse Compression Radar

Classical pulse and pulse Doppler radar transmit extremely short pulses. On the one hand, by increasing the pulse width the radar system achieves greater ranges as there is much more power in the pulse. On the other hand decreasing the width of the transmit pulses provides better range resolution of the radar system. However, there are also technical boundaries which limits the maximum transmit power. Pulse compression combines the power-related benefits of very long pulses (long range) with the benefits of very short pulses (high range resolution), Figure 4-3.

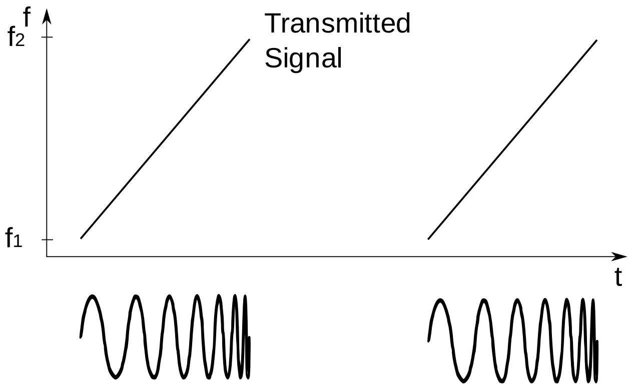

Figure 4-3: Pulse Compression Radar using LFM.

For pulse compression several different modulation techniques are used.

- Linear frequency modulation (LFM)
- Non-linear frequency modulation (NLFM)
- Encoded pulse phase modulation (e.g. Barker code)
- Polyphase modulation and time-frequency coded modulation

Next to these advantages of pulse compression radar, a drawback is an increased blind range due to longer pulse duration. As this would be a major disadvantage especially in air traffic control, some radars use both compressed and uncompressed techniques. Some ATC radars switch between frequency-modulated pulses of high average power for long range measurement and very short uncompressed pulses to cover the area nearby.

- LFM is most common in older radar systems, e.g. air-defense radar RRP-117 [4].
- NLFM is becoming more widespread due to various practical benefits such as inherently low range side lobes [16].
- Encoded pulse phase modulation, particularly Barker codes with lengths of 11 and 13 [15].

- Polyphase pulse compression is also used increasingly with special codes in advanced military radar systems [14].

As to measurements, pulse compression radar signals require

- baseband IQ collection of the signal covering the bandwidth of the pulse rise time,
- wideband analog FM demodulation or vector demodulation,
- display for analysis (amplitude, frequency, and phase vs. time), and
- demodulation including EVM measurement for BPSK/QPSK modulations.

4.4 Continuous Wave Radar

A continuous wave (CW) radar system with a constant frequency is used to measure radial velocity. However, it does not provide any range information.

A signal at a certain frequency is transmitted via an antenna. It is then reflected by a target moving with a certain speed relative to the receiver beam. This causes Doppler frequency shift in the radar echo signal. Comparing the transmitted frequency with the received frequency radial velocity can be determined, see Figure 4-1. Note that any tangential component will not be taken into account; hence a plane travelling at high speed in an exact circle around a rotating radar antenna would record a zero result for radial velocity.

Radar speed traps operated by law enforcement use CW radar technology. They typically are compact handheld units or completely automatic systems with an integrated camera to take a picture if a certain speed is exceeded, example see Figure 4-4.

Figure 4-4: Mobile traffic monitoring radar, MultaRadar CD – Mobile speed radar for speed enforcement from Jenoptic

Radar motion sensors, i.e. for anti-burglary use, are based on the same principle, but they must also be capable of detecting slow changes in the received field strength due to variable interference conditions and possible very slow target movement.

In military applications, CW radars are also used for target "illumination". The radar beam is kept pointing at a moving target by linking it to a target tracking radar for range, radial velocity and angle information estimation.

CW radars are somewhat hard to detect, which is why they are classified as low-probability-of-intercept radars.

CW radar also lends itself well to detecting low-flying aircraft that attempting to overcome an enemy's air defense. The reason for this is that pulse radar has difficulties in discriminating between ground clutter and low-flying aircraft. CW radar can close this gap because it is blind to slow-moving ground clutter [7].

4.5 Frequency Modulated Continuous Wave Radar

Constant-frequency CW radar measures radial velocity with high accuracy and resolution due to long illumination. However, one drawback of CW radar systems is they cannot measure range due to a missing timing reference.

For measuring range and radial velocity simultaneously, Frequency Modulated Continuous Wave (FMCW) radar can be used. This waveform is a signal whose frequency changes. A received radar echo signal will have

- a delay like in pulse radars,
- a Doppler frequency shift like in CW radars.

Range and radial velocity can be measured in case of a single target and multiple frequency measurements. Frequency patterns with triangular form and periodic repetition are transmitted to resolve range and radial velocity. However, ambiguities can occur in a multi-target situation, which is why different patterns are transmitted, Figure 4-5, (please see White Paper 1MA239 for more detailed information on this waveform).

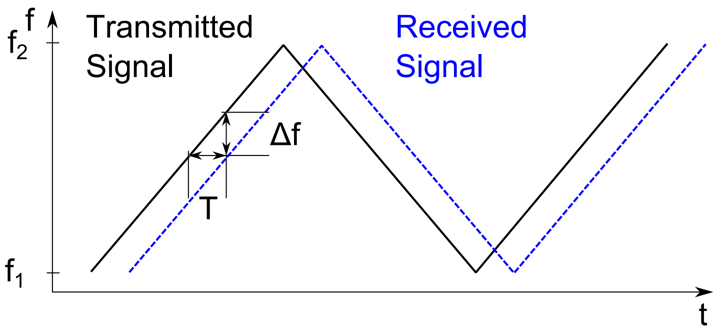

Figure 4-5: Basic principle of FMCW radar.

FMCW radar is used in aircraft as radio altimeter or as ground tracking radar to measure altitude above ground. Because ground can be considered a single fixed target in these applications, FMCW can unambiguously measure range.

FMCW radar is also commonly used commercially for measuring distances e.g. as used in level indicators. Some automotive radar sensors also apply FMCW, e.g. for Adaptive Cruise Control (ACC).

4.6 Frequency Agile Radar

Frequency hopping is an effective technique for a radar system to avoid system dropout by enemy jamming. Hence Frequency Agile Radar (FAR) is primarily used in military radar applications.

Due to the frequency hopping, ground clutter effects may increase as it cannot be suppressed well anymore. Reason is that a change of carrier frequency changes the radar cross section of a target, thus the radar echo signal power and hence the amplitude of the clutter is not constant through consecutive measurements anymore. Sub-microsecond switching times and bandwidths ranging from several hundred MHz in the X-Band to over 2 GHz at 95 GHz are typical for FAR systems.

Measurement parameters that are relevant in FAR include

- frequency switching/settling time,
- hopping sequence,
- switching spurious measurement, and
- broadband amplitude and phase stability.

FAR should be tested across the whole BW of interest. Oscilloscopes with FFT analysis often need to be employed to assess hopping performance and anomalies due to the frequency hopping modes.

4.7 Stepped Frequency Radar

Stepped Frequency Radar (SFR) applies bandwidth from a few MHz up to several GHz to reach the desired range resolution. One application of SFR is Synthetic Aperture Radar (SAR) for ground mapping [17].

The SFR waveform increases frequency by a fixed step size f_{step} from pulse to pulse up to N steps/pulses, Figure 4-6.

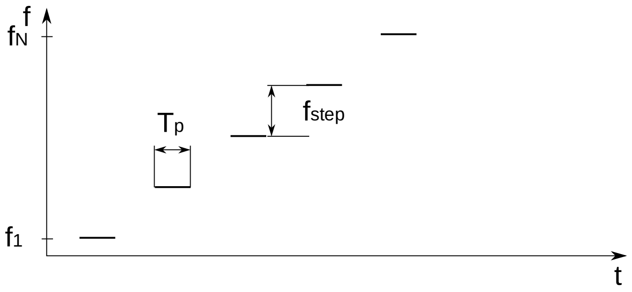

Figure 4-6: Stepped Frequency Radar

The individual bursts typically consist of pulse sequences up to e.g. 128 or 256 pulses. As in FMCW radar, there is no need for large capture bandwidth in SFR. Due to the wide RF bandwidth of the transmitter and receiver, these subsystems must exhibit excellent stability in order to obtain the desired high resolution.

SFR measurements with regard to testing each pulse require highly precise tools for pulse-to-pulse coherence analysis (magnitude and phase stability is most important). As in frequency agile radar, the settling time of the local oscillator is also an important measurement parameter.

4.8 Moving Target Indicator Radar

The idea behind a moving target indicator (MTI) radar is to suppress radar echo signals from stationary or slow-moving targets such as buildings, mountains, waves, clouds, etc. and thus obtain an indication of the moving targets of interest.

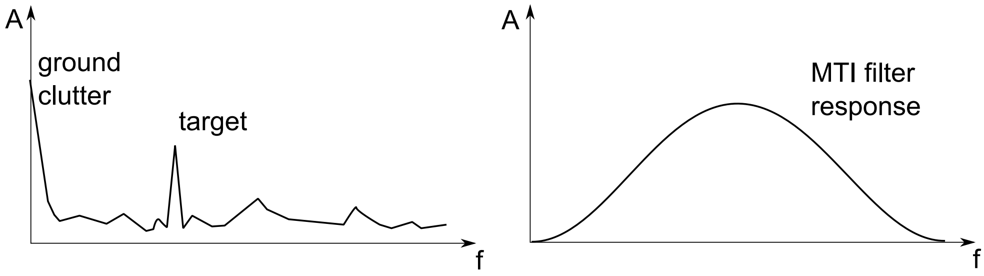

Figure 4-7: Radar echo and MTI filter response

Unwanted radar echo signals are generally referred to as clutter, which is normally distributed around zero Doppler frequency and multiples of the pulse repetition frequency, Figure 4-7. One possible implementation of a MTI is a delay line canceler, which stores the last radar echo in order to be subtracted from the actual radar echo. In case of a stationary target the difference value becomes zero, while for the remainder represents the moving targets.

Optimizing MTI requires the use of staggered PRF (variable PRF) in order to offset "blind velocities" or in order to make them visible.

Important measurement parameters in optimizing MTI or clutter suppression include:

- Pulse-to-pulse phase and amplitude stability of the transmit signal,
- LO phase stability and generally a low phase and broadband noise in the radar system,
- Lowest close-to-carrier phase noise particularly in low radial velocity applications.

4.9 Synthetic Aperture Radar

Synthetic Aperture Radar (SAR) is a coherent radar system often mounted on satellites or aircrafts. It provides very high image resolution by using the flight path to simulate an extremely large antenna aperture.

A technique referred as Inverse SAR (ISAR) uses the same technique, but utilizes the motion of a target rather than that of the emitter, by which the synthetic aperture is then created.

Due to its all-weather and day-or-night capability SAR is used for surveillance, terrain mapping (interferometry using two receive antennas), ground penetration and many other applications where it shows advantages over optical sensor systems while offering high resolution.

The basic principle behind SAR is similar to a phased array antenna. But unlike parallel antenna array elements, SAR uses parts of the (virtual) antenna area in time multiplex. The antenna position is known precisely, and moves perpendicularly to the radiation direction over time. All radar echo signals containing their respective amplitude and phase components are stored over time and processed.

Today's SAR systems apply a signal bandwidth of several GHz in order to achieve a resolution of centimeters. Some SAR systems also use stepped carrier frequency, polarization switching and other complex techniques (e.g. intra-pulse beam steering, multi-aperture recording in azimuth, spatiotemporal waveform encoding, e.g. in the TerraSAR X), see [5], [6], [19] for more details.

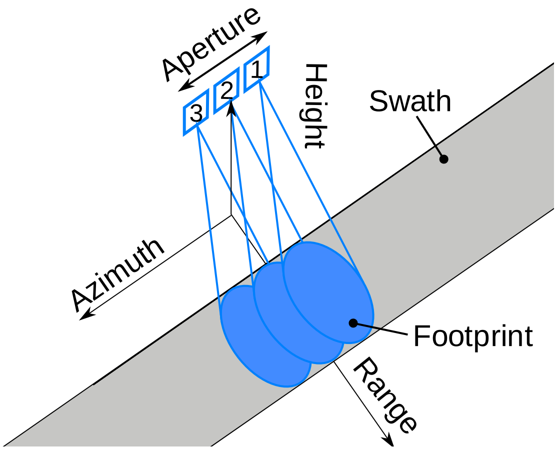

Figure 4-8: Synthetic Aperture Radar (SAR)

Requirements for successful SAR processing are an extremely stable "fully coherent" transmitter, powerful signal processing and the exact knowledge of flight path and ego velocity.

Test challenges are the bandwidth of interest for the SAR's generation and analysis tools. There is a trade-off between stepped frequency vs. single frequency operation e.g. effort for coherent pulse-to-pulse analysis vs. amount of analysis bandwidth required.

4.10 Bistatic Radar

Radar systems where transmitter and receiver are located at the same position are called monostatic radar. In bistatic radars, one transmitter and one receiver of the radar system are located at different positions. Their distance is typically chosen to be comparable to the expected target distance.

An advantage of bistatic radar sites is an easier detection of stealth targets, as these targets typically are designed to minimize reflection of power into the direction of the source. Bistatic receivers thus may detect stealth targets. These systems also have practical applications in weather radar, see [9].

Bistatic radars by their nature rely on enhanced accuracy in timebase and network synchronization. Measurement systems must have best synchronization and lowest clock jitter performance in order to yield meaningful measurement results. This gets even more important in low-phase noise applications i.e. if slow-moving target detection is an extra requirement.

4.11 Passive Radar

In conventional radar, the system is formed of at least one transmitter and at least one receiver section. Passive radar does not actively transmit electromagnetic energy in order to detect targets.

Instead, reflections and Doppler frequency shift of targets caused by known broadcast transmitters, mobile radio transmitters and other systems are evaluated, Figure 4-9.

Therefore the signal from a known transmitter is measured. Echoes from targets illuminated by chance are also measured. Passive radar systems are difficult to locate, since they do not transmit any signals. This is a decisive advantage in military applications, next to the ability to detect stealth aircrafts, which is very limited with existing active radar technology [10].

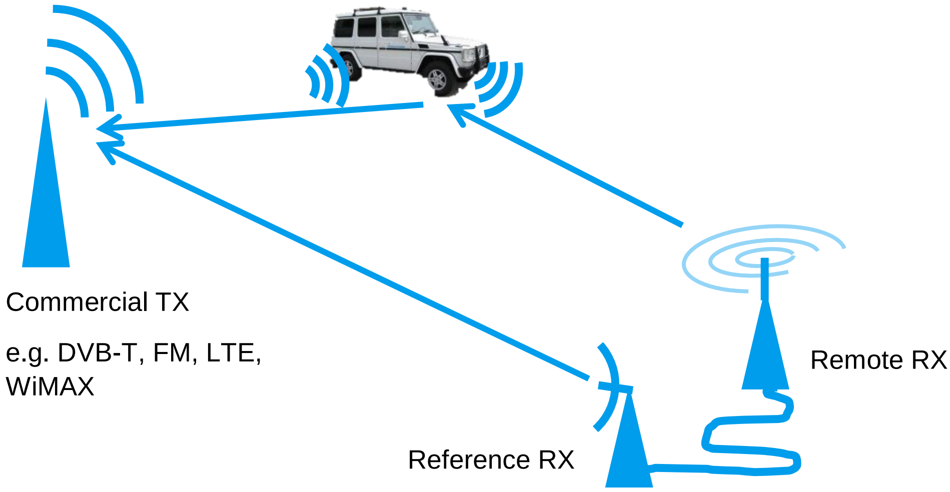

Figure 4-9: Passive Radar

Signal collection systems need to cover the BW of the signals of opportunity that should be analyzed. For instance, signal collection equipment with 80 MHz BW mounted close to airports can cover most kinds of cellular infrastructure for a given cellular band.

Other variants of passive radars use FM radio stations, while some also make use of new digital video signals (DVB) which must be collected over wider spans.

The collection of passive radar signals is continually evolving as new wireless cellular infrastructure, digital video, and digital audio terrestrial broadcast stations are deployed worldwide.

For test of passive radar known signals have to be recorded or generated to test e.g. signal processing and hardware.

4.12 Multimode Radar

Many radar systems used nowadays in airborne applications (e.g. from reconnaissance, to maritime helicopter to airstrike jets) are multimode radar systems and handle a wide range of different tasks, such as target searching and tracking, weapon guidance, air-to-ground ranging, high-resolution ground mapping, weather detection, terrain following and avoidance, electronic counter-countermeasures (ECCM) etc..

Therefore radar systems use various frequency bands ranging from 100 MHz to 100 GHz, switch between different PRF modes, including FM chirp, Barker phase modulation or complex modulation and SAR processing. These radars often use frequency hopping over a very wide range and intra-pulse polarization to avoid jamming.

Growing areas are Active Electronically Scanned Array (AESA) antennas, radars that steer their antenna beams flexibly.

Testing a multimode radar system of this sort is complex and costly. Fast, fully automated test systems are needed. Test & Measurement needs are equivalent to the aggregate of what has been described in the preceding sections.

4.13 Angular Measurement Techniques

Angular measurement in radar techniques can be performed using several different approaches by single transmit signal. Azimuth α and elevation angle β is measured as an additional target parameter next to range and radial velocity. Due to azimuth information target tracking accuracy is improved.

Some radar systems apply mechanical rotation to steer a very narrow antenna beam into the direction of targets. Azimuth angle is then determined by the angle of the antenna position. Other possibilities are

- sequential lobing,
- amplitude or phase mono-pulse and phased arrays,
- active electronically scanned arrays (AESA),

are common and their alternative or combined use depends on the application. Fighter jets or naval radars for example use AESA technique to steer a beam of nearly arbitrary shape into any arbitrary desired direction. Automotive radars are more likely to apply phased array or mono-pulse techniques [20].

4.13.1 Mono-Pulse

Mono-pulse radar systems are characterized by the use of at least two spatially distributed antenna groups [13].

One approach is to compare the amplitudes of a single target at two receive antennas. Another approach is to estimate the phase difference from a radar echo signal at these two receive antennas while azimuth angle is then determined by trigonometry.

In case of amplitude mono-pulse radar, two antennas illuminate a symmetrically but displaced focal point, see Figure 4-11. A radar echo signal with a certain azimuth angle will cause different receive amplitudes so that the direction of arrival can be calculated.

Phase mono-pulse divides the aperture and produces two sub apertures with identical amplitude vs. angle pattern response, Figure 4-10.

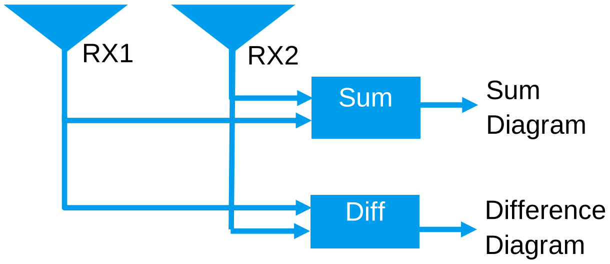

Figure 4-11: Mono-Pulse Technique (Amplitude)

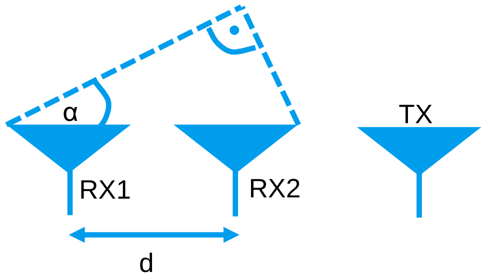

Figure 4-10: Mono-Pulse Technique (Phase)

In case of a received radar echo signal under a certain azimuth angle amplitude will be the same, but time of arrival will be different, which is measured in phase difference. By knowing the wavelength and distance between two or more receive antennas the azimuth angle is estimated.

Measurement challenges include the fact that antenna beam patterns haves to be known exactly. Channel matching of the different channels is important in mono-pulse radar systems and must be characterized next. Multi-channel phase-coherent synthesizers with adjustable phase offsets are typically used for this purpose. Phase coherent multichannel analysis e.g. by means of a high performance digital oscilloscope with IQ interface becomes important for testing the transmitter coherence.

4.13.2 Phased Array, Digital Beamforming and Active Electronically Scanned Array

Radar applications desire dynamic beam steering, as the area of a static electromagnetic beam is not wide enough to cover the entire area of interest, especially within A&D applications. In classical radar systems mechanical devices have been used in order to move the radar beam to cover a certain area, e.g. the 360-degree rotating antenna in air surveillance systems. Older fighter jets also are using mechanically rotating radar antennas. However, mechanical systems are both, heavy and failure-prone, which can be serious drawbacks for equipment being used in safety-critical applications.

High performance Digital Signal Processing along with affordable and small, highly integrated hardware systems have made digital beamforming (DBF) possible. DBF always relies on antenna arrays which allow steering the beam in a desired direction by adjusting phase and amplitude of each single transmitter / receiver [2]. Therefore each antenna element is equipped with a complete up- and down-converter unit.

Figure 4-12: 360-degree rotating antenna (left) of an air surveillance system and electronically steered antenna (right)

In the example shown in Figure 4-13 signals of electrical energy supply several isotropic antennas. Each single isotropic antenna is radiating equally in all directions if no phase shift is applied. The resulting power of the radiated sum beam in forward direction is very close to the sum of the sine signals. Depending on the phase shift between the transmit antenna signals, the beam can be steered into a certain direction. The phase shift of the antenna signals causes the final signal to be reduced in amplitude as compared to a signal being added up in forward direction without phase shift.

Phase shift of antenna array signals can be generated in various ways. One way is to use supply cables of different lengths. Another method is to implement phase-shifting elements in the appropriate antenna supply circuits, see Figure 4-13.

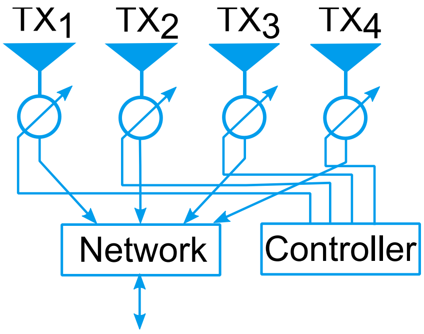

Figure 4-13: Basic Principle of DBF

Application Note 1MA127 describes an integrated circuit performing digitally controlled phase shifting. It is also shown how such phase shifters can be controlled digitally by test instruments such as network analyzers.

A high performance digital scope is highly suited to test the transmitted delay between up to 4 channels of T/R modules if the skew between the scope channels is sufficiently low (<< 1 ns).

Phased-array radar antennas have hundreds or even thousands of individual radiating elements (as opposed to a reflector antenna with a single radiator). The magnitude and phase of the power fed to the elements can be individually controlled, making it possible for the overall antenna to generate wave-fronts with nearly any desired shape. In real-world operation, the pattern can be turned by about ±60°. The efficiency of the antenna drops at larger angles. Unlike a conventional antenna that is moved mechanically, a phased array can rotate its pattern in space with practically no delay.

Since phased-array antennas are very costly, they are used primarily in military and SAR satellite applications. The current state of the art is an active phased array radar (or AESA) based on many individual, small Transmit/Receive (TRX) modules, whereas the passive variant (PESA) uses a common shared RF source whose signal is modified using digitally controlled phase shifter modules.

Important in AESA is the uniformity of the different modules in terms of amplitude and phase, which involves considerable test and calibration effort. Very fast automated test systems are required to align an array of hundreds, sometimes thousands of TRX elements to achieve very good radar performance.

4.14 Future of Radar Systems

In the future, multisensory systems that combine radar and infrared (or other) systems will be encountered. These techniques combine the benefits of the different types of systems while suppressing certain weaknesses [11]. Military onboard radar systems will be increasingly confronted with improved stealth technology of future aircrafts. The contradiction between different requirements imposed on aircraft must be solved (i.e. planes should exhibit stealth properties while not revealing their position through the use of onboard radar). One possibility could involve bistatic radar systems using a separate illuminator and a receiver on-board the aircraft. Another option is passive radar which provides anti-stealth defense options.

In today's radar antenna research there is a huge trend towards AESA antennas. The next generation of AESA radars used on-board of aircraft will likely have more than one fixed array and an increased number or TRX modules. Also there could be additional integration of antenna structures onto the aircraft body, wings, ship's hull or other platforms. This is also partly driven due to technology like Unmanned Aerial Vehicles (UAV) where radar is used.

Radar sensors allowing vision through a building wall applying extremely wide bandwidth to gather very good resolution will be an additional demand.

For many new radar systems transmit and receive modules using semiconductor materials such as gallium arsenide (GaAs) or gallium nitride (GaN) could take the place of magnetrons while increasing performance, shrinking system size / weight and allowing more flexible filtering of transmit signals. These systems are supported by integrated circuits employing Direct Digital Synthesis (DDS) which allow a more flexible generation of radar signals. Future price drops in DDS will lower the barrier to apply DDS also in automotive radar sensors.

Performance requirements on the digital back-end equipment used for processing radar raw data increases. Through parallel processing, throughput as needed for high-resolution radar operating modes can be provided [12].

Additional challenges to radar detection caused by wind farms or increased mobile communication using Long Term Evolution (LTE) will have to be covered by radar system processors. Impacts on ATC radar through LTE equipment have already been measured and shown to be an issue. The huge variety of radar systems and applications causes a wide area of demand for suitable measurement equipment.

Appendix

A Common Radar Abbreviations

Common Radar Abbreviations	
Abbreviation	Meaning
ACC	Adaptive Cruise Control
AESA	Active Electronically Scanned Array
AEW	Airborne Early Warning
AFC	Automatic-Frequency-Control
AGC	Automatic Gain Control
APAR	Active Phase Array Radar
ASR	Airport Surveillance Radar
ASR-S	Airport Surveillance Radar Mode-S (Mode S is an extension to secondary radar. Mode S makes it possible to query additional information, e.g. the speed of the aircraft.)
ATC	Air Traffic Control
BARDS	Baseband Radar Detection Sensor
BSD	Blind Spot Detection
BW	Bandwidth (or Beamwidth)
CFAR	Constant False Alarm Rate
CMOS	Complementary Metal-Oxide Semiconductor
COHO	Coherent Local Oscillator
DOA	Direction of Arrival
DoD	Department of Defense
DTM	Digital Terrain Model
ECCM	Electronic Counter-Countermeasures
EIRP	Effective Isotropic Radiated Power
ELINT	Electronic Intelligence (electronic acquisition of radar parameters)
EMPAR	European Multifunction Phased Array Radar
EMV	Electromagnetic Vulnerability
ESA	Electronically Steerable Array

Common Radar Abbreviations	
Abbreviation	Meaning
ESM	Electronic Warfare Support Measures
FCW	Forward Collision Warning
FFT	Fast Fourier Transform
FMCW	Frequency Modulated Continuous Wave
GCA	Ground-Controlled Approach
LPI	Low Probability of Intercept
LRR	Long Range Radar
MTD	Moving Target Detection
OTH	Over-The-Horizon
PAR	Phased-Array-Radar
PDF	Pulse Desensitization Factor
PESA	Passive Electronically Scanned Array
PRF	Pulse Repetition Rate or Frequency
PRI	Pulse Repetition Interval
PRT	Pulse Repetition Time
RCS	Radar Cross-Section
RDF	Range and Direction Finding
RS	Ramp Slope
SAR	Synthetic Aperture Radar
SRR	Short Range Radar
SSR	Secondary Surveillance Radar
TBD	Track-Before-Detect
TRM	Transmitter-Receiver Module
ULA	Uniform Linear Array

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Regional contact

Europe, Africa, Middle East
+49 89 4129 12345
customersupport@rohde-schwarz.com

North America
1-888-TEST-RSA (1-888-837-8772)
customer.support@rsa.rohde-schwarz.com

Latin America
+1-410-910-7988
customersupport.la@rohde-schwarz.com

Asia/Pacific
+65 65 13 04 88
customersupport.asia@rohde-schwarz.com

China
+86-800-810-8228 /+86-400-650-5896
customersupport.china@rohde-schwarz.com

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Rohde & Schwarz GmbH & Co. KG
Mühldorfstraße 15 | D - 81671 München
Phone + 49 89 4129 - 0 | Fax + 49 89 4129 – 13777

www.rohde-schwarz.com