Decades after the groundbreaking work of Hertz, Maxwell and Tesla, the fundamental concept still holds: metallic objects reflect radio waves. As derived in Part 1 of this series, the radar range equation captures the essential variables that define the maximum distance at which a given radar system can detect objects of interest. Because those variables relate directly to the major sections of a radar system block diagram, they provide a powerful framework for understanding, characterizing and verifying the actual performance of any radar system.

Making the transition from theoretical to practical, our next steps are to define the nature of actual radar signals and describe practical ways to measure the power in those signals. A radar transmitter is often a system’s most costly component. While it has the highest power consumption and the most stringent cooling requirements, the transmitter also has the greatest effect on system performance. For that reason and more, it will benefit from thorough and accurate measurements of the power in pulse-modulated signals. That is the focus of this application note.

1. See the Appendix on page x for a summary of the derivation.
Defining the Radar Signal

Every radar transmission starts with a known carrier signal, and today these typically operate at microwave or millimeter-wave frequencies. The carrier may be coded, in part because changes in the return signal provide a more accurate measurement of the distance to the target. In most cases, pulse modulation is also applied because, by controlling pulse duration, repetition rate and power, it enhances the resolution and maximum range of the radar system.

Optimizing pulse parameters

The characteristics of a pulsed radar signal largely determine the performance and capability of the system. Pulse parameters such as power, repetition rate, width and modulation are traded off to obtain the optimum combination for a given application (Figure 1). Pulse power directly affects the maximum range of detection. Droop across the pulse top indicates instability in the output power.

The time between pulses—the pulse-repetition interval (PRI)—determines the maximum unambiguous range to the target; pulse repetition frequency (PRF) is the inverse of PRI. The duration of the pulse—the pulse width—determines the spatial resolution of the radar: pulses must be shorter than the time it takes for the signal to travel between the target details; otherwise, the pulses overlap in the receiver.

Together, pulse width and pulse shape determine the spectrum of the radar signal. Decreasing the pulse width increases signal bandwidth; however, wider system bandwidth results in higher receiver noise for a given amount of power, and this reduces sensitivity. Also, the pulse spectrum may exceed regulated frequency allotments if the pulse is too short.

The shape can be the familiar trapezoidal pulse with rapid but controlled rise and fall times; it may also be any of a number of alternative shapes such as Gaussian and raised-cosine. Because the pulse shape can determine the signal bandwidth and also affect the detection and identification of targets, it is chosen to suit the application requirements.

Short pulses with a low repetition rate maximize resolution and unambiguous range, and high pulse power maximizes the radar’s range in distance. There are, however, practical limitations in generating short, high-power pulses. For example, higher peak power will shorten the life of tubes used in high-power amplifier designs. This conundrum would be a barrier to increasing radar performance if radar technology stopped here. However, complex waveforms and pulse-compression techniques can be used to greatly mitigate the power limitation on pulse width.
Adding pulse compression

Compression techniques allow relatively long RF pulses to be used without sacrificing range or resolution. The key to pulse compression is energy: using a longer pulse reduces the peak power of the transmitted pulse but maintains the same average pulse energy. The received pulse is compressed using a match-correlation filter, producing a shorter pulse of greater peak power and narrower width.

From this, a pulse-compressed radar realizes many of the benefits of a short pulse: improved resolution and accuracy; reduced clutter; better target classification; and greater tolerance to some electronic warfare (EW) and jamming techniques. One area that does not improve is minimum range performance: the long transmitter pulse may obscure targets that are too close to the radar.

The ability to compress the pulse with a match filter is achieved by modulating the RF pulse in ways that facilitate the compression process. The matching filter function can be achieved digitally using the cross-correlation function to compare the received and transmitted pulses. The sampled receive signal is repeatedly time shifted, fast Fourier transformed and multiplied by the conjugate of the Fourier transform of the sampled transmit signal (or a replica).

The output of the cross-correlation function is proportional to the time-shifted match of the two signals. A spike in the cross-correlation function or matching-filter output occurs when the two signals are aligned. This spike is the radar return signal, and it typically may be 1000 times shorter in time duration than the transmitted pulse.

Even if two or more of the long transmitted pulses overlap in the receiver, the sharp rise in output occurs only when each pulse is aligned with the transmit pulse. This restores the separation between the received pulses and, with it, the range resolution. To reduce the time-domain sidelobes created during the cross-correlation process, the receive waveform can be processed with a windowing function of Hamming shape or similar.

Ideally, the correlation between the received and transmitted signals would be high only when the transmitted and received signals are exactly aligned. Many modulation techniques can be used to achieve this goal: linear FM sweep, binary phase coding (e.g., Barker codes), or polyphase codes (e.g., Costas codes).
Accounting for Doppler effects

Most targets of interest are moving. This causes the frequency of the returned signal to be shifted higher if the target is moving toward the radar and lower if the target is moving away. Unfortunately, this Doppler frequency shift can reduce the sensitivity of location detection.

As mentioned above, the output of the cross-correlation filter is proportional to the match between the received and transmitted signals. If the received signal is slightly lower or slightly higher in frequency, then the filter output is somewhat lower.

For a simple pulse, the filter response follows the familiar \( \sin(x)/x \) shape as a function of Doppler frequency. In extreme cases, the frequency of the received signal may shift far enough to correlate with a sidelobe of the transmit signal.

Note that short pulses have a relatively wide initial lobe in the \( \sin(x)/x \) response and so tend to be “Doppler tolerant” compared to longer pulses. In pulse compression schemes such as Barker coding, the matching-filter output drops off much faster than the \( \sin(x)/x \) of the simple pulse, making them “Doppler intolerant.”

Doppler shifts in linear FM pulses can create an error in the location information because the highest cross correlation occurs where the swept frequencies in the receive pulse are best aligned with the swept frequencies in the transmit pulse. This offset is directly proportional to the Doppler shift.

Bringing it all together

Graphs called ambiguity diagrams illustrate the performance of different pulse-compression schemes as a function of pulse width and Doppler frequency shift (Figure 2). Even though Doppler shift can reduce detector sensitivity and cause errors in time alignment, it also provides important information about the target.

<table>
<thead>
<tr>
<th><strong>Pulse type</strong></th>
<th><strong>Frequency domain</strong></th>
<th><strong>Ambiguity diagram</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Short RF pulse</td>
<td>-21 dB -1.2 GHz</td>
<td>Doppler frequency Pulse width*</td>
</tr>
<tr>
<td>Long RF pulse</td>
<td>-20 dB -1.2 GHz</td>
<td>Doppler frequency Pulse width*</td>
</tr>
<tr>
<td>Swept RF pulse</td>
<td>-3 dB -8 MHz</td>
<td>Doppler frequency Pulse width*</td>
</tr>
<tr>
<td>13-bit Barker coded RP pulse</td>
<td>-18 dB -16 MHz</td>
<td>Doppler frequency Pulse width*</td>
</tr>
</tbody>
</table>

Figure 2. The ambiguity diagrams illustrate location accuracy versus Doppler accuracy. This figure shows relative ambiguity diagrams for different types of radar pulses. *Note: in the ambiguity diagram, “pulse width” refers to the width at the output of the radar detector.
Measuring Radar Signals: Power Meters

As shown in Figure 3, we use a few different terms when talking about the power in a pulsed signal. Average power is the result of integrating over the “on” and “off” times of the complete waveform. If the pulse width and PRF are not constant, then the integration time must be long enough to represent all possible variations in duration. Parameters such as duty cycle, pulse width, PRF, rise time and fall time are also useful when characterizing the power of the radar signal.

Figure 3. A few essential pulse parameters are relevant to calculations of peak and average power.

In the radar range equation, the power term corresponds to the power of the transmit pulse. If we exclude the integration term, then the equation applies to a single pulse. This can be useful when examining peak and pulse power for individual pulses, something that is important in dynamic systems that adjust pulse width and PRF while also contouring the pulse profile to improve overall performance.

Measuring average power is a relatively simple process and can be performed with low-cost test equipment. If pulse characteristics such as duty cycle are known, then the pulse power can be derived or estimated based on the measured average power. Note, though, that the derived result does not provide information about peak excursions that occur due to ringing or overshoot, nor does it provide any information about droop.

Spectrum shape is another way to verify efficient operation of the radar system. For example, an incorrect or asymmetrical shape indicates suboptimal operation. In such cases the radar may be wasting power by transmitting power at unwanted frequencies and causing out-of-band interference (e.g., “splattering”). This is why some systems use pulse shaping to reduce the level of the spectral sidelobes, thereby improving the efficiency and lifespan of radar components and also reducing bandwidth.

Accommodating maximum power

Several types of test equipment can measure radar power, pulse characteristics and spectrum shape: power meters, spectrum analyzers, signal analyzers and vector signal analyzers. Because each has advantages and limitations, the best choice depends on the measurement objectives and the relevant constraints on the radar and the test equipment. For example, parameters such as frequency, antenna match, pulse width (PW), pulse repetition time (PRT) and pulse duty cycle will affect power measurements and the best choice of measurement hardware.

The other crucial parameter is the maximum RF power produced by the transmitter. RF and microwave instruments have internal protection that can withstand a limited amount of either peak or average power. Because radar systems can generate pulse power of approximately 1 MW, a directional coupler is needed at the instrument input. The coupler will sample the transmitter power and present a safe drive level to the instrument.
Measuring pulse power with a power meter

Perhaps because a power meter is the lowest-cost solution, it is also the most commonly used way to measure pulse power. A full-featured model can measure average power, peak power, duty cycle and a variety of power statistics.

The power meter uses a transducer called a power sensor. The sensor converts high-frequency power into a DC or low-frequency signal that the power meter can then measure relative to a specific RF or microwave power level.

Power sensors are available in various types—continuous wave, average, peak and average—and cover numerous frequency and power ranges. Internally, they employ technologies such as thermistors, thermocouples and diode detectors, each of which has advantages and limitations.

- **Thermistor-based power sensors:** These implement a balanced Wheatstone bridge. When RF power is applied, the thermistor warms and its resistance decreases. This unbalances the bridge and produces a differential input to its amplifier, causing the feedback mechanism to decrease the DC bias and bring the bridge back into balance. The power meter measures the difference in DC power and translates that value into the equivalent RF power incident on the thermistor. Because these sensors are sensitive to changes in the ambient temperature, some contain a second thermistor that detects and corrects for the ambient temperature.

- **Thermocouple-based power sensors:** These are based on two properties of metals: temperature differences between hot and cold junctions will generate a voltage; and different metals generate different voltages. Because the voltage changes are quite small, many such junctions are connected in series to form a thermopile. The sensor uses this behavior to detect and correlate the voltage changes caused by the RF power incident on the thermopile.

- **Diode-based power sensors:** These use a matching resistor (approximately 50 Ω) to terminate the incoming RF signal. The sensor rectifies the RF voltage and produces a DC voltage at the diode. A bypass capacitor serves as a low-pass filter that removes any RF signals that pass through the diode. This type of sensor is highly sensitive, enabling power measurements as low as −70 dBm (100 pW).

Thermistor- and thermocouple-based sensors can be used to measure average power. However, because these sensors rely on a heating element, they are typically too slow to directly measure peak power.

Currently, many average power measurements require a dynamic range greater than 50 dB. Keysight meets this need by creating average power sensors that incorporate diode stacks, trading sensitivity for the ability to handle higher power levels.

The diode-based U2020 X-Series USB peak and average power sensors provide measurement speed of more than 25,000 readings per second in a compact, easy-to-use design. Two models are available: U2021XA, 50 MHz to 18 GHz; and U2022XA, 50 MHz to 40 GHz.

- Internal zeroing and calibration while connected to the unit under test
- Measure peak and average power
- Wide peak power dynamic range of −30 to +20 dBm
- Built-in trigger in/out eliminates need for an external module or power supply

A free copy of the license-based N1918A Power Analysis Manager software is included with the U2020X Series. Its power panel subset puts a variety of displays—with markers and gated measurements—on the screen of a PC or instrument. Power Analyzer software adds trace-overlay graphs, CCDF displays, pulse characterization, and long-term data logging.

The U2020 X-Series also includes a copy of Keysight BenchVue software. BenchVue makes it easy to control the sensor to log data and visualize measurements without any programming. Upgrading to the paid BenchVue Power Meter Pro version provides unrestricted data logging.
Comparing average and peak power meters

Choosing an average or peak power meter depends on the nature of the signals to be measured. Table 1 compares the relative, best-fit performance for each type relative to six key parameters.

Table 1. Average power meters and peak power meters offer distinct advantages and limitations.

<table>
<thead>
<tr>
<th></th>
<th>Average power meter</th>
<th>Peak power meter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency range</td>
<td>110 GHz</td>
<td>40 GHz</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>Broadband average</td>
<td>Narrow</td>
</tr>
<tr>
<td>System rise time</td>
<td>Slow</td>
<td>Fast</td>
</tr>
<tr>
<td>Pulse parameter analysis capability</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Power range</td>
<td>~96 dB</td>
<td>~55 dB</td>
</tr>
<tr>
<td>Dynamic range</td>
<td>High</td>
<td>Low</td>
</tr>
</tbody>
</table>

An average power meter can be used to report average power and pulse power if the pulse duty cycle is known. While its results are accurate for ideal or nearly ideal pulses, aberrations such as overshoot, ringing, non-zero droop and non-zero rise time will induce errors.

The combination of a peak power meter and a power sensor can directly measure peak power and pulse power. This is especially useful for shaped or modulated pulses because any derivation of pulse power based on average power becomes less accurate as the pulse deviates farther from the ideal shape.
Trading off flatness for responsiveness and bandwidth

In a spectrum analyzer, video bandwidth (VBW) is a form of analog averaging that smooths noisy signals. Choosing a narrow VBW setting creates a slower response, and choosing a wide VBW—or turning it off—enables a faster response.

In a power meter, the VBW value gives an indication of how quickly it can track signal variations in the peak-power envelope. VBW also affects the modulation bandwidth that can be accurately measured.

When measuring pulsed radar signals, turning off the VBW filter provides the fastest response time and widest bandwidth. It also avoids the ringing that can occur due to the interaction between the sharp rolloff of the filter and the fast rising edge of the radar pulse (Figure 4).

The downside: the VBW filter enhances the amplitude flatness of the meter and this benefit is lost when the filter is off. However, for a pulsed radar spectrum that falls off as \( \sin(x)/x \), the advantage of this correction is small enough that it’s reasonable to trade it for improved bandwidth and responsiveness. Figure 5 graphs the flatness of a Keysight P-Series power meter with its 30 MHz VBW filter turned on (blue) and turned off (black).
Simplifying Pulse Characterization

The Keysight P-Series peak power meters excel in this application. The meter operates by continuously sampling the input signal with a 100 MSa/s digitizer, buffering the data, and calculating the result. This provides greater versatility, including flexible triggering, single-shot measurements, and time gating with multiple gates.

Figure 6 shows example measurements of peak and pulse power performed with a P-Series meter. The figure also highlights the P-Series’ trace display, which allows you to view the envelope of the pulsed signal along with the essential readings of average power, peak power and peak-to-average ratio (calculated as the difference between average and peak values in decibel form).

The P-Series includes a “time gate” function that enables measurement of a single pulse. Activating the “perpetual” mode turns on an automatic gating feature that simplifies pulse measurements by repositioning the gates to match dynamic changes in the pulse width. This simplifies measurements of pulse power when the pulse width is not known beforehand.

In the time-gating mode, the meter reports peak power, average power, and peak-to-average ratio values within the gated area (Figure 7). In this example, the reported average power of –0.09 dBm is equal to the pulse power because the gate width equals the pulse width. The peak power reading of 0.24 dBm is likely due to overshoot in the pulse. The P-Series also provides automatic measurements of pulse width, pulse period, rise time, and fall time (Figure 8).

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- 5 ns system rise/fall time
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- Automated droop and delay measurements
- Multi-pulse analysis with optional software
- Internal zeroing and calibration

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Conclusion

Measuring the power in a pulse-modulated radar signal presents a variety of challenges, ranging from coping with the tremendous power in the signal to accurately calculating average power for a non-ideal pulse shape. Low-cost power meters are the most commonly used way to measure pulse power. A full-featured model can measure and display average power, peak power, duty cycle, rise time, fall time, and a variety of power statistics. Choosing the right power meter and its companion power sensor, or alternatively a USB or LAN power sensor, will ensure the most accurate power measurements and provide full coverage of your test needs.

Subsequent application notes in this series will continue to focus on the major sections of the block diagram: transmitter, receiver, duplexer and antenna. As these blocks are expanded, we will continue to associate the parameters of the range equation with each block or component.

Related Information

- Application Note: A Framework for Understanding: Deriving the Radar Range Equation, publication 5992-1386EN
- Application Note: Radar Measurements, publication 5989-7575EN
- Application Note: New Pulse Analysis Techniques for Radar and EW, publication 5992-0782EN
- Application Note: Using SystemVue’s Radar Library to Generate Signals for Radar Design and Verification, publication 5990-6919EN
- Application Note: Radar Development Using Model-Based Engineering, publication 5992-0544EN
- Application Note: Best Practices for Making the Most Accurate Pulse Measurements, publication 5991-0434EN
- Webcast: Precision Validation of Radar System Performance in the Field
- Poster: Radar Fundamentals, publication 5991-4907EN
- Poster: Electronic Warfare Fundamentals, publication 5992-0741EN
- Data Sheet: N1911A/N1912A P-Series Power Meters and N1921A/N1922A Wideband Power Sensors, publication 5989-2471EN
- Data Sheet: U2020 X-Series USB Peak and Average Power Sensors, publication 5991-0310EN
- Data Sheet: U2040 X-Series Wide Dynamic Range Power Sensors, publication 5992-0040EN
- Data Sheet: N1918A Power Analysis Manager, publication 5989-6612EN
- Data Sheet: BenchVue Software v3.0 (BV0000A), publication 5991-3850EN
- Data sheet: 8990B Peak Power Analyzer and N1923A/N1924A Wideband Power Sensors, publication 5990-8126EN
Appendix: The Radar Range Equation

Part 1 of this series presented a derivation of the radar range equation. As a refresher, here is the simplified version of the equation expressed in log form (dB):

\[
40 \log(R_{\text{max}}) = P_t + 2G + 20 \log \lambda + \sigma + E_i(n) + 204 \text{ dBW/Hz} - 10 \log(B_n) - F_n - (S/N) - L_t - L_r - 33 \text{ dB}
\]

Where:
- \( R_{\text{max}} \) = maximum distance in meters
- \( P_t \) = transmit power in dBW
- \( G \) = antenna gain in dB
- \( \lambda \) = wavelength of the radar signal in meters
- \( \sigma \) = RCS of target measured in dB\m or dB relative to a square meter
- \( F_n \) = noise figure (noise factor converted to dB)
- \( S/N \) = minimum signal-to-noise ratio required by receiver processing functions to detect the signal in dB

The 33 dB term comes from \( 10 \log(4\pi)^3 \), which can also be written as \( 30 \log(4\pi) \), and the 204 dBW/Hz is from Johnson noise at room temperature. The decibel term for RCS (\( \sigma \)) is expressed in dB\m or decibels relative to a one-meter section of a sphere (e.g., one with cross section of a square meter), which is the standard target for RCS measurements. For multiple-antenna radars, the maximum range grows in proportion to the number of elements, assuming equal performance from each one.

Figure A1 shows an expanded view of the transmitter and receiver sections of a typical block diagram. It shows a hybrid analog/digital design that enables many of the latest techniques. The callouts indicate the location of key variables within the simplified radar equation.

![Figure A1. The variables in the radar range equation relate directly to key elements of this expanded block diagram.](image-url)
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