Techniques of Pulsed RF Signal Generation and Analysis for Radar and Electronic Warfare Applications

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Agenda

• Radar applications, types and measurements

• Basic pulse envelope measurements and tools
  • Power meters, signal analyzers, oscilloscopes, time interval analyzers

• Vector signal analysis
  • Modulation on pulse (MOP) measurements and tools

• Using a Wideband Arbitrary Waveform Generator for Advanced Signal Simulation
  • Upconversion of wideband signals

• Radar & Electronic Warfare Threat Simulation
  • Radar and countermeasures/ range equations
  • Pulse timing and pattern parameters
  • Antenna radiation patterns and scanning

• Coherent Multi-Channel & Diversity Systems
Radar Applications

- Surveillance
- Search
- Tracking
- Fire control
- Navigation
- Missile guidance
- Automotive collision avoidance
- Materials identification
- Atmospheric research

Radar altimeters
Proximity fuses
Weather
Ground mapping
Ground penetrating
Aircraft terrain avoidance
Law enforcement
Motion detectors
## Radar Types

<table>
<thead>
<tr>
<th>CW</th>
<th>Monopulse</th>
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<tbody>
<tr>
<td>Simple pulsed</td>
<td>Phased array</td>
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<tr>
<td>Pulse Doppler</td>
<td>Synthetic aperture (SAR)</td>
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<tr>
<td>Pulse compression</td>
<td>Instrumentation</td>
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<tr>
<td>Height finding</td>
<td>Over the horizon</td>
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<tr>
<td>Multi-Mode</td>
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Sample Radar Measurements

Basic measurements

- Pulse width
- PRI (Pulse Repetition interval)
- Pulse overshoot, undershoot, droop, rise and fall time
- Pulse to pulse jitter
- Pulse power
- Pulse amplitude
- Spur search
- Various carrier measurements
- PRI and modulation transition measures – mode changes
Pulse Measurements

- Peak Power
- Pulse Top Amplitude
- Pulse Width
- Duty Cycle
- Average Power
- Overshoot
- Pulse Delay
- PRI
- PRF/PRR
Tools for Measuring Pulsed Radar Waveforms

**General Purpose:**
- Power Meter (peak and average)
- Counter
- Spectrum Analyzer
- Oscilloscope

**Specialty:**
- Pulse Analyzer System (time interval analysis)
- Noise Figure Analyzer (component measurements)
- Vector Network Analyzer (component, antenna)

**Software:**
- Vector Signal Analysis (VSA), Pulse Analysis, Pulse building software, etc
Measurement Tool Comparison

**Spectrum Analyzer**
- Wide Frequency Range
- Good Dynamic Range
- Limited Instantaneous Bandwidth
- Limited Time Capture Length
- Difficult to Measure Pulse Parameters
- Traditionally doesn’t capture phase information

**Oscilloscope**
- Wide Bandwidth
- Flexible
- Limited Time Capture Length vs. Pulse Analyzer
- Greater Overhead (Samples)
- Limited Frequency Range (No internal down-converter)

**Pulse Analyzer**
- Very Long Time Captures
- Very Precise Pulse Time Information
- Amplitude Measurements Optional (Digitizer)
Peak power meter provides graphical view detailing pulse characteristics

Rise time, fall time, and pulse width are shown below the trace

Power meters are typically the most accurate tool for power measurements
Spectrum analyzers can be used like an oscilloscope to measure RF pulse time domain characteristics—in zero-span mode.

Trigger level and trigger delay controls allow viewing the rising edge of the pulse.

Peak search markers can be used to measure peak power.
Signal Analyzer Pulse Width Measurements

Increase trace points to suitable range

Ensure RBW is wide enough

Use delta markers on pulse to measure width.
Effects of RBW on pulse shape

Three pulse widths shown: 500 ns, 200 ns, and 100 ns

• To accurately measure peak power, the analyzer bandwidth must be wide enough to settle within the pulse width.
• Bandwidth should be at least as wide as the reciprocal of the pulse width.
SA Measurement of Pulse Repetition Interval (PRI)

Adjust display so that at least two pulses are displayed.

Use delta markers to display the pulse repetition time.
Other Common SA Pulse Measurements

- Line spectrum
- Pulse spectrum
- Pulse power
- Spur search
Using Oscilloscopes for RF Pulse Measurements
Oscilloscope Pulse Measurements (Direct Capture)

Captured with Oscilloscope
Analyzed with built in math functions
(Low Pass Filter) and Jitter analysis
(Trend and Statistics)
Scope Pulse Measurements (Direct Capture)

Direct capture maintains the modulation details
Use of Segmented Memory

Captured with Oscilloscope, 1GB of memory and 16 thousand 64k byte segments. Last burst 16 seconds after the first

150km unambiguous range – 1ms PRI

Sub picosecond resolution on segment timing
Scope PRI (Period) vs. Time

Measurement trending identifies RADAR mode changes vs. time
PW vs. Time can also be displayed
Triggering on change in PRI
Part of oscilloscope "Jitter" measurement package
Scope Pulse Envelope vs. Time

Captured with Oscilloscope. Analyzed with built in Jitter analysis

Pulse Width Trend
Radar Pulse Analysis SW (SA and Scope)

Captured with Oscilloscope and Pulse Measurement Software

![Graph and Data Table](Image)

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Example Wideband LFM Chirp Measurements
Custom Radar Measurements with MATLAB in the Oscilloscope Signal Processing Path

1. Oscilloscope Waveform
2. Custom MATLAB Function
3. MATLAB Applied Trace
4. Perform Additional Scope Measurements
Start with Oscilloscope Waveform

1. Oscilloscope Waveform
2. Custom MATLAB Function
3. MATLAB Applied Trace
4. Perform Additional Scope Measurements
Operate on Scope Waveform with Custom MATLAB Function to Extract Pulsed RF Envelope

Custom MATLAB Function to Calculate RF Pulse Envelope with a Hilbert Transform

```matlab
% This takes the Hilbert Transform to extract the envelope and phase

I_Data = real(hilbert(SrcData));
Q_Data = imag(hilbert(SrcData));
EnvData = sqrt(I_Data .* I_Data + Q_Data .* Q_Data);
PhaseData = unwrap(atan(Q_Data ./ I_Data) * pi/180));
```
Display the RF Pulse Envelope

- Oscilloscope Waveform
- Custom MATLAB Function
- MATLAB Applied Trace
- Perform Additional Scope Measurements

RF Pulse Envelope Extracted from Custom MATLAB Function
Perform Scope Measurements on the RF Envelope

Pre-Configured Scope Measurements:
- Pulse Rise Time
- Pulse Fall Time
- Pulse Width
- Overshoot

Custom MATLAB Function

MATLAB Applied Trace

Perform Additional Scope Measurements

Oscilloscope Waveform

Drop Pre-Configured Scope Measurements on Displayed Envelope

Measure RF Pulse Rise Time
Using Segmented Memory to Optimize the Number of Radar Pulses Captured with 2 GSa Memory

Capture Only the “ON” Part of the Radar Pulse
Ignore the “OFF” Part of the Radar Pulse

Resulting Segmented Memory to Optimize the Number of Radar Pulses Captured
Segmented Memory:
Set Time Scale to Display the “ON” Part of the Radar Pulse
Segmented Memory:
Set the Number of Segments to Capture

[Image of a software interface showing the number of segments set to 256]
Segmented Memory:
Measure the Radar Pulse Parameters for Each Radar Pulse

Scroll Through Each Segment to Measure:
• Pulse Width
• Rise Time
• Fall Time
Of each individual pulse
Challenges for Radar Pulse Measurements

System level testing - characterize pulse timing for many scenarios

Field/Flight testing is expensive - capture signals and evaluate/characterize performance off-line

Need to evaluate a large number of pulses

Need to sort and categorize signals dependent on emitter characteristics
Oscilloscope Signal Analyzer (OSA) Software

Continuous Pulse Acquisition or Segmented Acquisition
OSA Segmented File Capture Mode: Timing Measurements

Binary files or .csv files for each segmented are stored in this directory to analyze off-line.

Set Number of Segments (e.g. 200)

Enable Auto-Analyze to Automatically Display Data
OSA Segmented File Capture Mode: Frequency Measurements

Select File >
Save >
Table Data to store .csv file

Frequency Excursion and Frequency Deviation of Each Pulse
OSA Segmented File Capture Mode: Histogram Displays

Sort through and view only pulses >1.8 GHz frequency deviation and >1 uSec pulse width
Evaluating Complex Waveforms: Frequency Hopped Example
Vector Signal Analysis of Pulses
RF Pulses with Modulation Embedded

Measurements for modulation on pulse (MOP)

- Modulation type (verify proper modulation)
- Modulation quality (e.g. distortions and nonlinearities)
- Phase vs. time or frequency
- Time and frequency selective measurements
- I/Q modulator gain/phase imbalance
- Demodulation analysis for pulse compression applications
Vector vs. Scalar Measurements

Scalar

Power Meter
magnitude vs. time

RF → Video

Spectrum analyzer
magnitude vs. frequency
magnitude vs. time

RF → IF → Video

Vector

Vector Signal Analyzer
magnitude vs. freq. or time
phase vs. freq. or time
gain, group delay
waveform capture
modulation analysis

RF → IF

ADC → I

ADC → Q
What is VSA?

- Vector Signal Analyzer (VSA)
  - Vector detect an input signal (measure magnitude and phase of the input signal)
- Measurement receiver with system architecture that is analogous to a digital communications system
  - In some sense the ultimate Software Defined Radio (SDR)
- Similar to FFT analyzer, but VSAs have powerful vector/modulation-domain analysis for complex RADAR
  - Time data Real I(t) & Imaginary Q(t)
  - Phase verses Time or Frequency
  - Time and frequency selective measurements
  - Demodulates Carrier and extracts AM, PM, & FM
  - User definable digital demodulator
  - I-Q Modulator Gain/Phase Imbalance
Signal Changes or Modifications (Polar Graph)

Magnitude Change

Phase Change

Frequency Change

Both Change
VSA Software Used in Digital, IF and RF Domains

**DUT**

- DSP
- Digital (SSI)
- BB (I-Q)
- IF/RF

- Logic Analyzer
- Oscilloscope
- Signal Analyzer

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90000X Wideband LFM Chirp Measurement with 89600 VSA
90000X Wideband LFM Chirp Measurement with 89600 VSA
Vector Signal Analysis (Beyond Pulse Shape)

Pulse measurements help characterize a radar system, Vector Signal Analysis helps detect the modulation (signal changes)
Example of Chirp Demodulation

VSA software used to demodulate a linear FM chirped radar signal.

Displays of the signal spectrum, pulse envelope, phase verses time, and frequency verses time are shown.

200 MHz LFM chirp measurement
Example of 7-Level Barker Code

89601A VSA used to analyze a 7-bit barker coded pulse

±180° phase modulation in pattern of + + + - - + - applied to pulse

Displays of pulse spectrum, IQ, pulse envelope, and phase versus time are shown.
Spectrogram of Frequency Hopper

Spectrogram shows frequency on the X-axis, time on the Y-axis, and amplitude as color.

The spectrogram is an excellent tool for analyzing events that are rapidly changing in time.
Frequency vs. Time

Spectrogram shows temperature graded power over time
Using a Wideband Arbitrary Waveform Generator for Advanced Signal Simulation
Currently Available High-Speed AWGs

SFDR 1)

<table>
<thead>
<tr>
<th>SFDR</th>
<th>40</th>
<th>50</th>
<th>60</th>
<th>70</th>
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<tbody>
<tr>
<td>0.5</td>
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<td>8</td>
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1) SFDR across Nyquist range with $f_{out} = 150$ MHz
2) Bandwidth of a single channel AWG output

What could you do if you had something here?

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High-Precision AWG Example: CW Signal

Single tone
555 MHz

Fs = 7.2 GHz

Spurs: < -86 dBc
High-Precision AWG Example: Multi-Tone Signal

Multi-tone signal with 200 tones, 3 GHz bandwidth

Fs = 7.2 GHz without amplitude correction
Amplitude Correction Setup

• AWG and spectrum analyzer are remotely controlled by a PC running an amplitude correction routine.

• Magnitude of each tone in the multi-tone signal is measured and frequency response stored in a file.

• Pre-distorted multi-tone signal calculated based on measurement.

• Multi-tone and equalization scripts are available for free.
High-Precision AWG Example: Multi-Tone Signal

Multi-tone signal with 200 tones, 3 GHz bandwidth

$F_s = 7.2 \text{ GHz}$

with amplitude correction
High-Precision AWG Example: Pulsed Radar

Pulsed Radar:
2 GHz Linear Chirp
Pulse width: 6 ms

Fs = 7.2 GHz
with amplitude correction
High-Precision AWG Example: Pulsed Radar

Pulsed Radar:
2 GHz Linear Chirp
Pulse width: 6 μs

Fs = 7.2 GHz
with amplitude correction
High-Precision AWG Example: Pulsed Radar

Pulsed Radar:
2 GHz Linear Chirp
Pulse width: 6 μs

Fs = 7.2 GHz
with amplitude correction
High-Precision AWG Example: Fast Frequency Switching

Switching between frequencies in a 2 GHz bandwidth in less than 500 ps

Fs = 7.2 GHz with amplitude correction
Upconversion of Wideband Signals
Two Upconversion Methods for Generating Complex Signals

**Direct IF Upconversion**
- Does not require correction for I-Q impairments
- Simple to implement
- Lower cost AWG
- Lower total cost
- Must filter off unwanted sideband

**Baseband I-Q Upconversion**
- Requires an I-Q AWG
- Requires correction for I-Q impairments (skew, offset error, gain imbalance, timing error)
- At least 2X greater bandwidth for same AWG clock rate
Analog vs. Digital I/Q Modulation

Analog I/Q modulation –
Analog I and Q signals are generated using an AWG. An I/Q modulator generates the IF or RF signal

Digital up-conversion –
I/Q modulation is performed digitally – either in real-time (in hardware) or up-front in software
Analog I/Q Modulation Example (1/4)

Multi-tone signal with 20 tones spanning 2 GHz

Asymmetric with respect to the carrier frequency

Notice:
- Images
- Carrier feed-through
- Non-Flatness
Analog I/Q Modulation Example (2/4)

Adjusting the skew and relative amplitude between the I and Q signals reduces the images. Typically, they can be reduced to about -30 dBc.
Analog I/Q Modulation Example (3/4)

Adjusting the differential offset of the I and Q signals reduces the carrier feed-through.
Amplitude Correction Setup

- AWG and spectrum analyzer are remotely controlled by a PC running an equalization routine.

- Magnitude of each tone in the multi-tone signal is measured and frequency response stored in a file.

- Pre-distorted multi-tone signal can be calculated.
Analog I/Q Modulation Example (4/4)

With amplitude correction, the frequency response can be adjusted to be flat within less than 0.5 dB.
Digital I/Q Up-Conversion (1/2)

Digital up-conversion avoids a few of the problems associated with analog I/Q modulators:

- No (in-band) carrier feed-through
- No (in-band) images

BUT: Frequency response is still not flat
Digital I/Q Up-Conversion (1/2)

With amplitude correction, an almost distortion-free RF signal can be generated.
Agilent M8190A Arbitrary Waveform Generator

• Precision AWG with DAC resolution of:
  – 14 bit up to 8 GSa/s
  – 12 bit up to 12 GSa/s*)
• Up to 2 GSa Arbitrary Waveform Memory per channel
• 5 GHz analog bandwidth per channel
• 3 selectable output paths: direct DAC, DC *) and AC*)
• SFDR goal: < -75 dBc typical (f_out < 1 GHz, 14 bit mode, across Nyquist range)
• Harmonic distortion goal: < -65 dBc typical
• Advanced sequencing scenarios define stepping, looping, and conditional jumps of waveforms or waveform sequences*)
• 2 markers per channel*) (does not reduce DAC resolution)

*) not available at initial product release
Radar & Electronic Warfare Threat Simulation
Why is Threat Simulation Important?

• Real-world conditions may not be available to test a radar or EW system
• Some system components may not be available and may need to be simulated
• Less costly than flight testing
• Simulated emitters can be mixed with real-world emitters to create a more realistic electromagnetic environment for flight or static testing.
Fidelity of Simulation

What level of fidelity or quality is required?

• Fidelity of the model and data presented to systems and operators must be adequate.
• In training simulation must be good enough to prevent the operator from noticing any inaccuracies.
• In T&E simulation, must be adequate to provide injected signal accuracy better than the perception threshold of the system under test (SUT).
• In most cases, cost rises exponentially as a function of fidelity provided. At some point a situation of diminishing returns can be quickly reached.
What Signal Characteristics are Generally Simulated?

- Frequency, may include Doppler & possibly hopping
- Power or amplitude, generally adapted to changes in:
  - Threat position, location, or attitude relative to SUT
  - Operating mode of threat system
  - Antenna patterns, including side and back lobes
  - Antenna scanning characteristics
  - Antenna polarization
- Modulation on pulse: AM, PM, FM, or other
- Pulse width (PW), can be mode dependent
- Pulse repetition time (PRT), also mode dependent
- Multiple threats and or Complex electronic order of battle (EOB)
Radar and Countermeasures
Some EW Terms

**EA:** Electronic Attack involves the use of EM energy or anti-radiation weapons to attack personnel, facilities, or equipment

**ECM:** Electronic counter measures, such as jamming and chaff, used to deny or degrade the enemy’s use of communications or radar systems

**DECM:** Defensive ECM, such as a jammer used to protect an aircraft from missile fire

**ECCM:** Electronic counter-counter measures, countermeasures used to protect a radar from a jammer

**RWR:** Radar Warning Receiver, warns a pilot of a SAM or radar lock on

**Jammer:** EW transmitter used to interfere, upset, or deceive a victim radar, communications, or navigation system

- **EP:** Actions taken to protect personnel, facilities, and equipment from any effects of friendly or enemy use of EMS
- **ES:** Electronic Warfare Support is a subdivision of EW involving search for, intercept, identify, and locate sources of EM energy for the purpose of threat recognition or targeting
- **EME:** Electromagnetic Environment
- **EOB:** Electronic Order of Battle
- **SIGINT:** Signal Intelligence
- **ELINT:** Electronic Intelligence
- **COMINT:** Communications Intelligence
- **ESM:** Electronic Warfare Support Measures, equipment to identify and locate radar systems or EM emitters
- **J/S:** Jam to signal ratio
Radar Jammer Types

- **CW**
- **Barrage Jammers**: An attempt to “outshout” the opposing equipment through continuous or high-duty cycle power within the desired frequency band—blot out the sun technique.
- **Noise Jammer**: Brute-force jamming by modulating the jamming signal with AM or phase noise.
- **Deceptive**: Uses a repeater or frequency memory to provide a precise return that is modified in time or frequency to interfere with missile fire control.
- **Repeater Jammer**: A jammer that modifies and retransmits hostile radar signals to deny accurate position data.
- **Transponder Jammer**: A repeater jammer that plays back a stored replica of the signal after being triggered by the radar.
- **Set-On-Jammer**: A jammer that measures the threat radar frequency and adjusts a sine-wave oscillator to retransmit the threat frequency.
- **Swept Spot Jammer**: A jammer that sweeps an oscillator over a band of frequencies to excite receivers tuned to frequencies in the band.
- **Stand-In-Jamming (SIJ)**: A Jammer (aircraft) that accompanies a strike force into combat air space—inside the range of defensive weapons.
- **Stand-Off-Jamming (SOJ)**: A system which provides jamming coverage for a strike force, but does not enter inside the range of defensive weapons.
A portion of the transmitted energy is intercepted by the target and reradiated in all directions.

The energy that is reradiated back to the radar is of prime interest to the radar.

The receiving antenna collects the returned energy and delivers it to the receiver, where it is processed to:

- Detect the target
- Extract its location and relative velocity

Direction, or angular position, of the target may be determined from the direction of arrival of the returned signal, assuming a narrow antenna beam.

If relative motion exists between the target and radar, the shift in carrier frequency of the reflected wave (Doppler Effect) is a measure of relative radial velocity of the target and can be used to distinguish moving targets from stationary objects.
Radar Range Measurement

- The maximum unambiguous range of a radar is the distance in which a transmitted pulse can make a round trip at the speed of light before the next pulse is transmitted.

\[ R_{unamb} = \frac{c}{2PRF} = c \frac{PRI}{2} = 150 \text{ (m/µs)} \times PRI \]

- Therefore, long-range radars use very long pulse repetition times to avoid range ambiguities.

Example: The maximum unambiguous range of a radar with a 1000 us PRT would be \(150 \text{ m/µs} \times 1000 \text{ µs} = 150 \text{ km}\)
Spectrum of a Video Pulse Train

\[ V(f) = \frac{\tau}{T} + \frac{2\tau}{T} \sum_{n=0}^{\infty} \frac{\sin(n\pi\tau / T)}{n\pi\tau / T} \]
Velocity Measurement

Another important target characteristic measured by radar systems is target velocity. This is accomplished by measuring the Doppler shift of the transmitted signal.

The Doppler Frequency, \( f_d \) is: 

\[
f_d = \frac{2}{\lambda} v \hat{R} = \frac{2f_0}{c} v \hat{R}
\]

This is the result of the radial velocity difference between the radar and the target. Therefore, the general equation would be the vector dot product of the velocity vector and the radial unit vector, or

\[
f_d = \frac{2f_0}{c} (v \cdot \hat{R}) = \frac{2f_0v}{c} \cos \theta
\]
Doppler Example

If a 10 GHz aircraft radar were designed to handle an engagement with a maximum closing velocity of 500 m/s (~ Mach 1.5) the maximum Doppler frequency would be:

\[ f_D = \frac{2V}{\lambda} = \frac{2(500\text{m/s})(10\times10^9\text{m/s})}{3\times10^8} = 33\text{kHz} \]

Recall from a couple of slides back that the spectrum of the pulse modulated signal will have frequency lines that are spaced at intervals equal to the PRF or 1/PRT. If the PRT were 1 ms then the frequency lines would be 1 kHz apart. Each spectral line will also be Doppler shifted and could be processed by the Velocity tracking circuits of the radar, thus producing velocity ambiguities, if they are less than the maximum Doppler frequency. Therefore:

- The lower the PRF > frequency ambiguity
- The higher the PRF > range ambiguity
Three PRF Modes for Pulse Doppler

- Low PRF is unambiguous in range, but is highly ambiguous in Velocity and is excellent for target acquisition.

- Medium PRF radar:
  - Is ambiguous in both range and velocity. It is very useful in a tail-chase engagement where closing velocities are low.
  - May use multiple PRFs, each creating ambiguity zones in the range / velocity matrix. Processing can provide unambiguous range and velocity.

- High PRF radar is unambiguous in velocity and may be used in a velocity only mode making it ideal for a high-speed head-on engagement.
Review of RF Pulse Characteristics

For simulation:

• Multiple PRF modes may be require to properly simulate a given radar
• Complex dithering, wobbulation, or stagger of both PW and PRF may be required in your simulation
• For an exacting simulation, PW and PRF jitter (caused by poor power supply filtering in the radar) may also need to be simulated.
Radar and Jammer Range Equation
Prediction of Maximum Radar Range

By equating our equation for minimum signal with the equation describing signal level as a function of power, antenna gain, and range we can solve for the maximum range of our radar system

\[
S_{\text{min}} = kT_0B_nF_n\left(\frac{S_o}{N_o}\right)_{\text{min}} = \frac{P_TG^2\lambda^2\sigma}{(4\pi)^3 R^4_{\text{max}}}
\]

\[
R^4 = \frac{P_TG^2\lambda^2\sigma E_i(n)}{kTB_nF_n(S / N)(4\pi)^3 L_T L_R}
\]

As you can see we’ve added three new terms to account for system losses and integration improvement

Now, we will convert our equation to log (dB) form

\[
40\log(R) = P_T + 2G + 20\log_{10}\lambda + \sigma + E_i(n) + 204dBW / Hz - 10\log(B_n) - F_n - (S / N) - L_T - L_R - 33dB
\]
The Jammer Range Equation

Since the jammer signal only has a one-way path to the radar it will only experience a $1/R^2$ loss, verses the $1/R^4$ loss experienced by the radar.

Again, we will start by looking at the free-space power density at the radar as produced by the jammer, assuming spherical scattering.

$$\rho_j = \frac{P_j G_j}{(4\pi)R^2}$$

The input power to the radar receiver, from the jammer, will then be the jammer’s power density multiplied by the effective area of the radar’s antenna.

$$S_{JR} = \frac{P_j G_j A_e}{4\pi R^2}$$

Where: $$A_e = \frac{G \lambda^2}{4\pi}$$

Therefore:

$$S_{JR} = \frac{P_j G_j G_R \lambda^2}{(4\pi)^2 R^2}$$
Range Equation for the Jammer Cont’d.

Now we have an equation for the jammer’s signal power at the radar we can compare it to the equation previously developed for the signal power at the radar’s receiver due to the target’s skin return.

For the Jammer:  \[ S_{jR} = \frac{P_j G_j G_R \lambda^2}{(4\pi)^2 R_j^2} \]

And for the radar:  \[ S = \frac{P_T G_T G_R \lambda^2 \sigma}{(4\pi)^3 R_R^4} \]

It is often convenient to relate the jamming signal strength to that of the radar’s skin return strength as a jam to signal ratio (J/S).

\[ \frac{J}{S} = \frac{P_j G_j (4\pi) R_R^4}{P_T G_T \sigma R_j^2} \]

If the jammer and radar range are equal, then \[ \frac{J}{S} = \frac{P_j G_j (4\pi) R^2}{P_T G_T \sigma} \]

Note: The above analysis assumes that the jammer antenna and the radar antenna are pointed directly at each other (main lobe), which is very seldom the case. Generally jamming is done on the radar antenna’s side lobes and a function must be used to account for the difference in antenna gain. However, from this analysis it is easy to see that the jammer has the advantage in most situations.
Antenna Pattern of a Pencil-Beam Antenna
Rectangular Aperture w/Uniform Weighting

Directivity

1st Side Lobe
Level = -13.26

Main Beam

Side Lobes

Angle (Degrees)
Typical Aircraft Jammer Antenna

Frequency: 1GHz

Frequency: 10GHz

Gain (dBi)

Frequency (GHz)

3dB Beamwidth (deg): 108.30
3dB Beamwidth (deg): 114.06

3dB Beamwidth (deg): 69.74
3dB Beamwidth (deg): 69.94
Jammer Power Budget Example

\[
\left( \frac{J}{S} \right)_{dB} = P_j(dBW) + G_j(dBi) + 11dB + 20\log_{10} R_m - P_T(dBW) - G_T(dBi) - \sigma_{dBsm}
\]

**Victim Radar**
- Power \( P_T = 250 \text{ kW} = 54 \text{ dBW} \)
- Ant Gain \( G_T = 30 \text{ dBi} \)
- RCS = \( \sigma = +20 \text{ dBsm} \)

**Jammer**
- Power \( P_J = 1 \text{ kW} = 30 \text{ dBW} \)
- Ant Gain \( G_J = 6 \text{ dBic} \)
- Correction to H-Pol = -3 dB
- Range = 50 km = 94 dB

\[
J/S = 30 \text{ dBW} + 6 \text{ dBic} - 3dB + 11 \text{ dB} + 94 \text{ dB} - 54 \text{ dBW} - 30 \text{ dBi} - 20 \text{ dBsm}
\]

\[
= 34 \text{ dB}
\]

With 34 dB J/S the jammer could maintain a minimum 10 dB J/S ratio and still fully Jam the radar down to a – 24 dB side-lobe level, which would obliterate radar performance over most of the radar scan.
Noise Jamming on Sidelobes
Agilent N7620A Signal Studio for Pulse Building Software
User Interface Enhancements

- Two new pattern tabs: PRI and Antenna
- New graphical window displaying antenna scanning & timing patterns
- New graphical windows documenting antenna & timing patterns properties
- Flexible pattern table
Pulse Timing and Pattern Parameters

**Pulse Repetition Interval**
- Constant (none)
- Gaussian Jitter
- Uniform Jitter
- U shaped Jitter
- Linear Ramp
- Stepped
- Staggered
- Bursted
- Saw tooth Wobbulation
- Sinusoidal Wobbulation
- Triangle Wobbulation

**Pulse Width Patterns**
- Constant
- Gaussian Jitter
- Uniform Jitter
- Linear Ramp
- Stepped

**New Features**
- Option 205 - QAWG
- Option 206 – PSG/ESG
Pulse Repetition Interval Timing—Staggered

- **PRI Time**

- **Pri Pattern**
  - **Staggered**
  - **Repeats**: 50

- **Staggered (Five Level) – Five Alternating PRIs**
  - 1.0 ms, 1.50 ms, 1.80 ms, 2 ms, 3 ms

- **Index | PRIs**
  - 1 | 1 ms
  - 2 | 1.5 ms
  - 3 | 1.6 ms
  - 4 | 2 ms
  - 5 | 3 ms
Pulse Repetition Interval Timing—Stepped
Pulse Repetition Interval Timing—Sine Wobbulation
Pulse Repetition Interval Timing—Linear Ramp
Antenna Radiation Patterns and Scanning
Antenna Parameters

Antenna Scanning Modes
- None
- Custom
- Circular
- Conical
- Bidirectional Sector
- Unidirectional Sector
- Bidirectional Raster
- Unidirectional Raster

Antenna Radiation Patterns
- Blackman
- Hamming
- Hanning
- Rectangular
- 3 Term
- Cosine1
- Cosine2
- Cosine3
- Cosine4
- Cosine5
- Programmable

Antenna Properties
- Azimuth 3 dB Beam Width
- Elevation 3 dB Beam Width
- Null depth - dB

EuMW 2011
Pulse Builder Option 205/206 New Antenna Scanning
Antenna Properties and Definitions

- **Bore-Sight** – Maximum gain of the antennas main lobe or beam pointing at the target.

- **Bearing Angle** - The bearing angle of the target can be determined by moving the antenna beam to the maximum return.

- **Beam width** – ½ Power points in the main lobe measured in angular width AZ/EL degrees.

- **Side Lobe Level** - the level of energy on the side lobes relative to the main lobe or beam

- **Back Lobe** – the energy emitting in the opposite direction of the main beam.
Antenna Pattern—Rectangular Aperture w/ Uniform Weighting

- 1st Side Lobe Level = -13.26
- 3 dB Beam Width
- Main Beam
- Side Lobes
- Side Lobe Roll Off

Equation: EuMW 2011
Circular Antenna Pattern vs. Aperture Windowing Functions
(3 dB Beam Width AZ/EL = 2 Degrees, 7.2 degrees ~ 2% of scan)
Generic Circular Antenna Scan

Circular Azimuth Scan

Scan Rate RPM

Receiver Horizontal Location

Receiver Vertical Location

(Elevation) Degrees

0°

+270°

+90°

+180°

(Azimuth) - Degrees

PPI

EuMW 2011
Generic Conical Antenna Scan
feed horn nutating in a small circular orbit

Conical Scan – Nutating Feed

(Elevation) Degrees

Conic Radius - Degrees
Generic Bidirectional Raster Antenna Scan

Bidirectional Raster Scan

- Scan Start
- Scan Rate $X^\circ$/s
- Retrace Flyback Time
- Raster Width (Elevation) Degrees
- Bar 1
- Bar 2
- Bar 3
- Bar 4
- Bar N-1
- Receiver Horizontal Location
- Raster Width (Azimuth) - Degrees
- Receiver Vertical Location
- Bar Width

EuMW 2011
Generic Unidirectional Antenna Scan

Unidirectional Raster Scan

- Scan Start
- Scan Rate $X^\circ$/s
- Retrace Time
- Total Bar Width (Elevation) Degrees
- Bar Width
- Receiver Vertical Location
- Receiver Horizontal Location
- Raster Width (Azimuth) - Degrees

C-SCOPE

Target

Azimuth

Elevation

Agilent Technologies

EuMW 2011
Bi-Directional Sector Scan

Bidirectional Sector Scan

Sector (Elevation) Degrees

Scan Start

Scan Rate $X^\circ$/ s

DUT

Receiver Horizontal Location

Receiver Vertical Location

Sector Width (Azimuth) - Degrees

Azimuth

Target

RANGE

SECTOR PPI

Agilent Technologies

EuMW 2011
Unidirectional Sector Antenna Scan

Unidirectional Sector Scan

Sector (Elevation) Degrees

Scan Start

Scan Rate X°/s

DUT

Receiver Horizontal Location

Retrace Flyback Time – Sec.

Receiver Vertical Location

Sector Width (Azimuth) - Degrees

SECTOR PPI
Coherent Multi-Channel & Diversity Systems
Spatial Diversity Techniques

- Switched Diversity
- Beamforming
- Maximal Ratio Combining
- Transmit Diversity
Phased Array Antennas & Beam Forming
Direction Finding
Phase interferometer angle of arrival (AoA) measurement

\[ \sin \theta = \frac{a}{d} \]

\[ \phi = \omega \Delta \tau = \frac{2 \pi f}{c} = \frac{2 \pi (d \sin \theta)}{\lambda} \]
Geo-Location Application

Interferometric Synthetic Aperture Radar (InSAR) is used in monitoring the effects of earthquakes & floods, land subsidence, glaciers, crop sizes, etc.

Phase coherent, spatially separated receiving system using multiple receivers to determine not only the position of a target but also provide a 3-D image.

When testing the receivers, input signals to each antenna must be phase coherent.
The Problem: Need Complete Control of Relative Phase, Time, and Frequency of Multiple Signals

A common reference provides frequency coherence but not full phase coherence

Two separate synthesizer paths

Not coherent - phase drifts over time

AWG timebase not synchronized. Non-synchronous triggering can cause timing errors

10 MHz

EuMW 2011
LO vs. Reference Locked Configurations

Note the difference in the Time and Phase Offset scales

Most of the phase drift in the coherent case can be attributed to the measuring receiver (2 channel scope)
LO Locked Phase Coherent System

Multiple coherent outputs using synthesizer split technique

One synthesizer path

Both are coherent

Separate modulation chains

Outputs 1 & 2 are constrained to have the same carrier frequency
LO Locked Phase Coherent System

Baseband time and phase alignment

Coherent Synthesizer

Timebase

X2^N

I/Q Mod

Mod

Detector

ALC Loop

Synthesizer 1

Output 1

Power Splitter/Amp

 External Sample Clock

Common External Sample Clock

Trigger

ARB

Clock

Synthesizer 2

Output 2

Common sample clock enables baseband coherency

Trigger simultaneously for baseband time alignment

RF coherency

External Sample Clock

Sample

External Clock

Common External Sample Clock
The Solution:
Using the baseband generator (AWG) to control phase time and frequency

Fixed phase offset between sources changes with frequency, amplitude and temperature

The phase offset of each signal generator can be corrected by changing the starting phase of the I/Q waveform

Fixed phase offset due to group delay of components after synthesizer split

EuMW 2011
Frequency Reference and Phase Coherence Options for the PSG

Option HCC > 3.2 GHz

Divider to achieve frequencies below 3.2 GHz

Fractional-N Synthesizer

Sampler / Oscillator Loop

Fine tunes frequency setting

External Reference

Option H1S (1 GHz)

10 MHz Reference In

1 GHz

10 MHz

Reference

Option H1G (1 GHz)

Phase stability for 100 kHz – 250 MHz

Output
Bypassing the internal reference enables much improved phase stability (20 x improvement). Note the correlation in time of day suggesting room temperature and air conditioning play a big factor in the phase drift.
Phase Coherency on N5182A MXG (Option 012)
Configurations for 2 to 16 units

N5181A Master LO

4 way splitter

RF Output

10MHz Out

REF IN

EVENT 1

PATT TRIG

RF Output

10MHz Out

REF IN

EVENT 1

PATT TRIG

RF Output

10MHz Out

REF IN

EVENT 1

PATT TRIG

RF Output

10MHz Out

REF IN

Event 1

PATT TRIG

RF Output

10MHz Out

REF IN

Event 1

PATT TRIG

RF Output

10MHz Out

Signal Studio Software
WLAN or LTE for MIMO applications

Master MXG

Slave MXG(s)

Agilent Technologies
EuMW 2011
Additional Baseband Time Delay Adjustment
Phase Shift Capability

Analog phase shift for standalone operation (ESG, PSG, MXG)

Vector phase shift for phase coherent operation (MXG)

Will not independently adjust the phase of the waveform in a phase coherent configuration.

Independently adjusts the phase of phase coherent MXG signal generators without updating the waveform.
Modifying and downloading a new waveform file is not needed to adjust MXG phase coherent offsets.
Waveform Creation Software Needed

Time and phase alignment
• Measure with network analyzer or oscilloscope
• Shift waveform to time and phase align
  – Embedded phase shift capability in the MXG
  – Add phase shift in waveform file

Waveform creation software
• Agilent Signal Studio for pulse building
• ADS and SystemVue modeling and simulation tools
• MATLAB
I/Q Waveform Polar & Rectangular Representation

\[ \Theta = 0 \text{ deg} \]
Adding Phase to a Waveform File

A waveform file is made up of a series of I/Q pairs

(1) \[ |A| = \sqrt{I^2 + Q^2} \] Where A is the baseband waveform amplitude

(2) \[ A = I + jQ \] Complex representation

(3) \[ A = |A|(\cos \Theta + j\sin \Theta) \] A & \( \Theta \) are the polar coordinates of the I & Q pair

- To add phase \( \Phi \) to the I/Q constellation Phasor Q, multiply (3) by \( (\cos \Phi + j\sin \Phi) \)
- Convert back to the form of (2) getting \( A = I' + jQ' \)
- Scaling of the new waveform \( (I'/Q' \) pairs) will be required to maintain the identity (1) where “A” must remain constant
Summary and Conclusion

• Many methods for analyzing RF pulses
  – Envelope
  – Time interval
  – Vector analysis of modulation on pulse

• Simulation of pulsed RF signals
  – Arbitrary Waveform Generators (AWG)
  – Radar and electronic warfare
  – Phase coherent signal generation
Questions?