

RADAR EQUATIONS

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JAMMING TO SIGNAL (J/S) RATIO - CONSTANT POWER [SATURATED] JAMMING

The following table contains a summary of the equations developed in this section.

<p style="text-align: center;">JAMMING TO SIGNAL (J/S) RATIO (MONOSTATIC)</p> <p style="text-align: center;">$J/S = (P_j G_{ja} 4\pi R^2) / (P_t G_t \sigma)$ (ratio form)* or:</p> <p>$10\log J/S = 10\log P_j + 10\log G_{ja} - 10\log P_t - 10\log G_t - 10\log \sigma^* + 10.99 \text{ dB} + 20\log R^*$</p> <p style="text-align: center;">Note (1): Neither f nor λ terms are part of these equations</p> <hr/> <p>If simplified radar equations developed in previous sections are used:</p> <p style="text-align: center;">$10\log J/S = 10\log P_j + 10\log G_{ja} - 10\log P_t - 10\log G_t - G_\sigma + \alpha_1$ (in dB)</p> <p style="text-align: center;">Note (2): the $20\log f_1$ term in $-G_\sigma$ cancels the $20\log f_1$ term in α_1</p>	<p style="text-align: center;">* Keep R and σ in same units</p> <p>Target gain factor, (in dB) $G_\sigma = 10\log \sigma + 20\log f_1 + K_2$</p> <p>$K_2$ Values (dB):</p> <table style="width: 100%; border-collapse: collapse;"> <tr> <td style="text-align: left;">RCS (σ)</td> <td style="text-align: center;">f_1 in MHz</td> <td style="text-align: center;">f_1 in GHz</td> </tr> <tr> <td style="text-align: left;">(units)</td> <td style="text-align: center;">$K_2 =$</td> <td style="text-align: center;">$K_2 =$</td> </tr> <tr> <td style="text-align: left;">m²</td> <td style="text-align: center;">-38.54</td> <td style="text-align: center;">21.46</td> </tr> <tr> <td style="text-align: left;">ft²</td> <td style="text-align: center;">-48.86</td> <td style="text-align: center;">11.14</td> </tr> </table>	RCS (σ)	f_1 in MHz	f_1 in GHz	(units)	$K_2 =$	$K_2 =$	m ²	-38.54	21.46	ft ²	-48.86	11.14						
RCS (σ)	f_1 in MHz	f_1 in GHz																	
(units)	$K_2 =$	$K_2 =$																	
m ²	-38.54	21.46																	
ft ²	-48.86	11.14																	
<p style="text-align: center;">JAMMING TO SIGNAL (J/S) RATIO (BISTATIC)</p> <p>R_{TX} is the range from the radar transmitter to the target. See note (1).</p> <p style="text-align: center;">$J/S = (P_j G_{ja} 4\pi R_{TX}^2) / (P_t G_t \sigma)$ (ratio form) * or:</p> <p>$10\log J/S = 10\log P_j + 10\log G_{ja} - 10\log P_t - 10\log G_t - 10\log \sigma^* + 10.99 \text{ dB} + 20\log R_{TX}^*$</p> <hr/> <p>If simplified radar equations developed in previous sections are used: see note (2).</p> <p style="text-align: center;">$10\log J/S = 10\log P_j + 10\log G_{ja} - 10\log P_t - 10\log G_t - G_\sigma + \alpha_{TX}$ (in dB)</p>	<p style="text-align: center;">One-way free space loss (dB)</p> <p>α_1 or $\alpha_{TX} =$ $20\log (f_1 R) + K_1$</p> <p>K_1 Values (dB):</p> <table style="width: 100%; border-collapse: collapse;"> <tr> <td style="text-align: left;">Range</td> <td style="text-align: center;">f_1 in MHz</td> <td style="text-align: center;">f_1 in GHz</td> </tr> <tr> <td style="text-align: left;">(units)</td> <td style="text-align: center;">$K_1 =$</td> <td style="text-align: center;">$K_1 =$</td> </tr> <tr> <td style="text-align: left;">NM</td> <td style="text-align: center;">37.8</td> <td style="text-align: center;">97.8</td> </tr> <tr> <td style="text-align: left;">km</td> <td style="text-align: center;">32.45</td> <td style="text-align: center;">92.45</td> </tr> <tr> <td style="text-align: left;">m</td> <td style="text-align: center;">-27.55</td> <td style="text-align: center;">32.45</td> </tr> <tr> <td style="text-align: left;">ft</td> <td style="text-align: center;">-37.87</td> <td style="text-align: center;">22.13</td> </tr> </table>	Range	f_1 in MHz	f_1 in GHz	(units)	$K_1 =$	$K_1 =$	NM	37.8	97.8	km	32.45	92.45	m	-27.55	32.45	ft	-37.87	22.13
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This section derives the J/S ratio from the one-way range equation for J and the two-way range equation for S, and deals exclusively with active (transmitting) Electronic Attack (EA) devices or systems. Furthermore, the only purpose of EA is to prevent, delay, or confuse the radar processing of target information.

By official definition, EA can be either Jamming or Deception. This may be somewhat confusing because almost any type of active EA is commonly called “jamming,” and the calculations of EA signal in the radar compared to the target signal in the radar commonly refer to the “jamming-to-signal” ratio (“J-to-S” ratio). Therefore this section uses the common jargon and the term “jammer” refers to any EA transmitter, and the term “jamming” refers to any EA transmission, whether Deception or Concealment.

Jamming: “Official” jamming should more aptly be called Concealment or Masking. Essentially, Concealment uses electronic transmissions to swamp the radar receiver and hide the targets. Concealment (Jamming) usually uses some form of noise as the transmitted signal. In this section, Concealment will be called “noise” or “noise jamming.”

Deception: Deception might be better called Forgery. Deception uses electronic transmissions to forge false target signals that the radar receiver accepts and processes as real targets.

“J” designates the EA signal strength whether it originates from a noise jammer or from a deception system.

Basically, there are two different methods of employing active EA against hostile radars:

Self Protection EA
Support EA

For most practical purposes, Self Protection EEA is usually Deception and Support EA is usually noise jamming. As the name implies, Self Protection EA is EA that is used to protect the platform that it is on. Self Protection EA is often called “self screening jamming,” “Defensive EA” or historically “Deception ECM.” The top half of Figure 1 shows self-screening jamming.

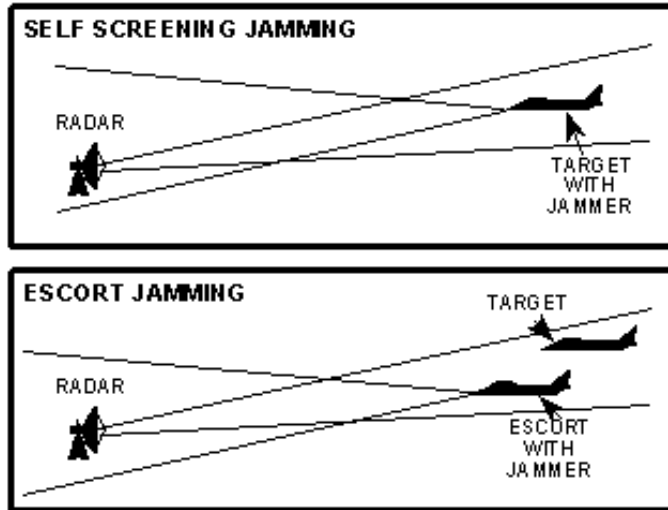


Figure 1. Self Protection and Escort Jamming.

The bottom half of Figure 1 illustrates escort jamming which is a special case of support jamming. If the escort platform is sufficiently close to the target, the J-to-S calculations are the same as for self protection EA.

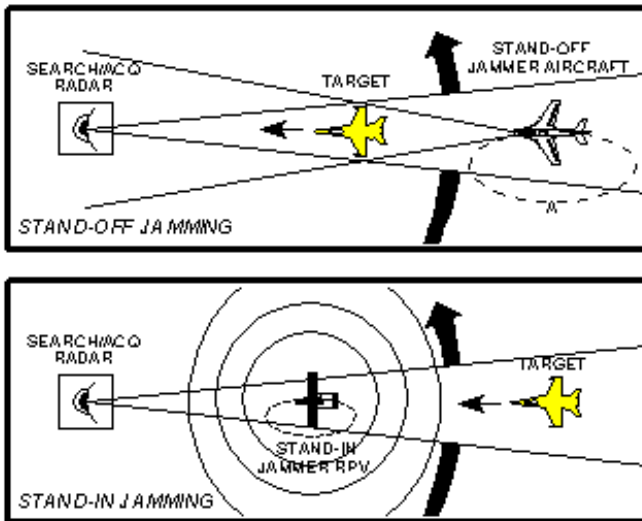


Figure 2. Support Jamming.

Support EA is electronic transmissions radiated from one platform and is used to protect other platforms or fulfill other mission requirements, like distraction or conditioning. Figure 2 illustrates two cases of support jamming protecting a striker - stand-off jamming (SOJ) and stand-in jamming (SIJ). For SOJ the support jamming platform is maintaining an orbit at a long range from the radar - usually beyond weapons range. For SIJ, a remotely piloted vehicle is orbiting very close to the victim radar. Obviously, the jamming power required for the SOJ to screen a target is much greater than the jamming power required for the SIJ to screen the same target.

When factoring EA into the radar equation, the quantities of greatest interest are “J-to-S” and Burn-Through Range.

“J-to-S” is the ratio of the signal strength of the jammer signal (J) to the signal strength of the target return signal (S). It is expressed as “J/S” and, in this section, is always in dB. J usually (but not always) must exceed S by some amount to be effective, therefore the desired result of a J/S calculation in dB is a positive number. Burn-through Range is the radar to target range where the target return signal can first be detected through the jamming and is usually slightly farther than crossover range where J=S. It is usually the range where the J/S just equals the minimum effective J/S (See Section 4-8).

The significance of “J-to-S” is sometimes misunderstood. The effectiveness of EA **is not** a direct mathematical function of “J-to-S.” The magnitude of the “J-to-S” required for effectiveness is a function of the particular EA technique and of the radar it is being used against. Different EA techniques may very well require different “J-to-S” ratios against the same radar. When there is sufficient “J-to-S” for effectiveness, increasing it will rarely increase the effectiveness at a given range. Because modern radars can have sophisticated signal processing and/or EP capabilities, in certain radars too much “J-to-S” could cause the signal processor to ignore the jamming, or activate special anti-jamming modes. Increasing “J-to-S” (or the jammer power) does, however, allow the target aircraft to get much closer to the threat radar before burn-through occurs, which essentially means more power is better if it can be controlled when desired.

IMPORTANT NOTE: If the signal S is CW or PD and the Jamming J is amplitude modulated, then the J used in the formula has to be reduced from the peak value (due to sin x/x frequency distribution). The amount of reduction is dependent upon how much of the bandwidth is covered by the jamming signal. To get an exact value, integrals would have to be taken over the bandwidth. As a rule of thumb however:

- If the frequency of modulation is less than the BW of the tracking radar reduce J/S by 10 Log (duty cycle).
- If the frequency of modulation is greater than the BW of the tracking radar reduce J/S by 20 Log(duty cycle).

For example; if your jamming signal is square wave chopped (50% duty cycle) at a 100 Hz rate while jamming a 1 kHz bandwidth receiver, then the J/S is reduced by 3 dB from the maximum. If the duty cycle was 33%, then the reduction would be 4.8 dB. If the 50% and 33% duty cycle jamming signals were chopped at a 10 kHz (vice the 100 Hz) rate, the rule of thumb for jamming seen by the receiver would be down 6 dB and 9.6 dB, respectively, from the maximum since the 10 kHz chopping rate is greater than the 1 kHz receiver BW.

J/S for SELF PROTECTION EA vs. MONOSTATIC RADAR

Figure 3 is radar jamming visualized. The Physical concept of Figure 3 shows a monostatic radar that is the same as Figure 1, Section 4-4, and a jammer (transmitter) to radar (receiver) that is the same as Figure 3, Section 4-3. In other words, Figure 3 is simply the combination of the previous two visual concepts where there is only one receiver (the radar’s).

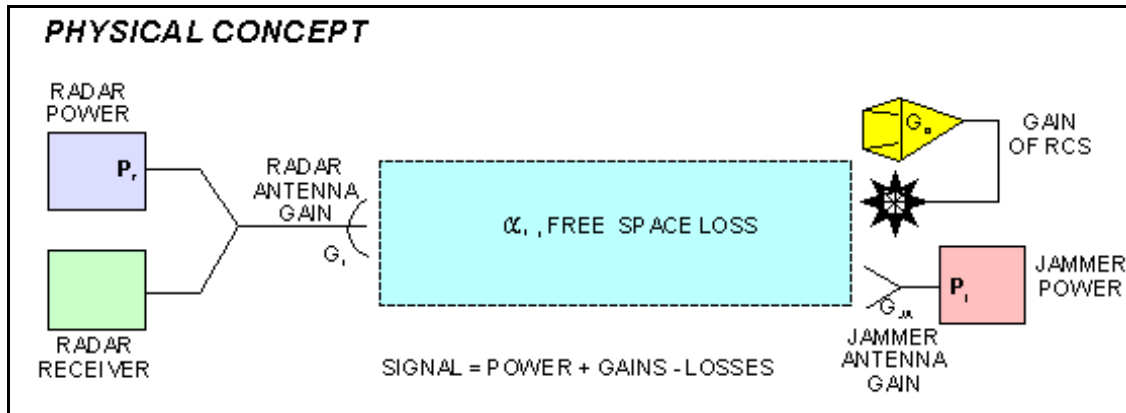


Figure 3. Radar Jamming Visualized.

The equivalent circuit shown in Figure 4 applies to jamming monostatic radars with either self protect EA or support EA. For self protect (or escort) vs. a monostatic radar, the jammer is on the target and the radar receive and transmit antennas are collocated so the three ranges and three space loss factors (α 's) are the same.

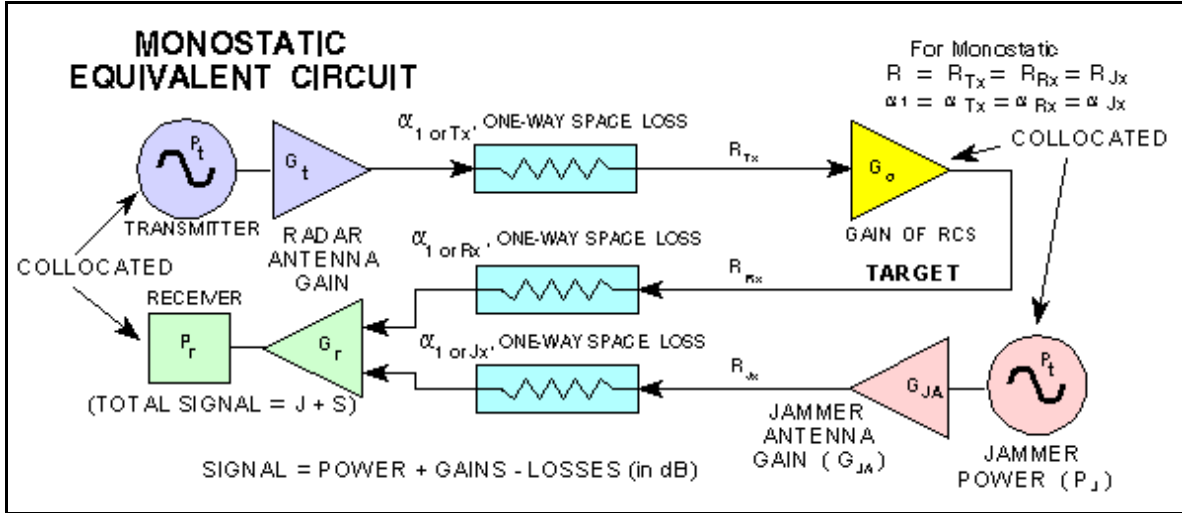


Figure 4. Monostatic Radar EA Equivalent Circuit.

J-S Ratio (Monostatic) - The ratio of the power received (P_{r1} or J) from the jamming signal transmitted from the target to the power received (P_{r2} or S) from the radar skin return from the target equals J/S.

$$\text{From the one way range equation in Section 4-3: } P_{r1} \text{ or } J = \frac{P_j G_{ja} G_r \lambda^2}{(4\pi R)^2} \quad [1]$$

$$\text{From the two way range equation in Section 4.4: } P_{r2} \text{ or } S = \frac{P_t G_t G_r \lambda^2 \sigma}{(4\pi)^3 R^4} \quad [2]$$

so

$$\frac{J}{S} = \frac{P_j G_{ja} G_r \lambda^2 (4\pi)^3 R^4}{P_t G_t G_r \lambda^2 \sigma (4\pi R)^2} = \frac{P_j G_{ja} 4\pi R^2}{P_t G_t \sigma} \quad (\text{ratio form}) \quad [3]$$

* Keep R and σ in the same units.

On reducing the above equation to log form we have:

$$10 \log J/S = 10 \log P_j + 10 \log G_{ja} - 10 \log P_t - 10 \log G_t - 10 \log \sigma + 10 \log 4\pi + 20 \log R \quad [4]$$

or

$$10 \log J/S = 10 \log P_j + 10 \log G_{ja} - 10 \log P_t - 10 \log G_t - 10 \log \sigma + 10.99 \text{ dB} + 20 \log R \quad [5]$$

Note: Neither f nor λ terms are part of the final form of equation [3] and equation [5].

J/S Calculations (Monostatic) Using a One Way Free Space Loss - The simplified radar equations developed in previous sections can be used to express J/S.

From the one way range equation Section 4-3:

$$10\log (P_{r1} \text{ or } J) = 10\log P_j + 10\log G_{ja} + 10\log G_r - \alpha_1 \quad (\text{in dB}) \quad [6]$$

From the two way range equation in Section 4.4:

$$10\log (P_{r2} \text{ or } S) = 10\log P_t + 10\log G_t + 10\log G_r + G_\sigma - 2\alpha_1 \quad (\text{in dB}) \quad [7]$$

$$10\log (J/S) = 10\log P_j + 10\log G_{ja} - 10\log P_t - 10\log G_t - G_\sigma + \alpha_1 \quad (\text{in dB}) \quad [8]$$

Note: To avoid having to include additional terms for these calculations, always combine any transmission line loss with antenna gain. The $20\log f_1$ term in $-G_\sigma$ cancels the $20\log f_1$ term in α_1 .

Target gain factor, $G_\sigma = 10\log \sigma + 20\log f_1 + K_2$ (in dB)				One-way free space loss, $\alpha_1 = 20\log (f_1 R) + K_1$ (in dB)			
K_2 Values				K_1 Values	Range	f_1 in MHz	f_1 in GHz
(dB)	RCS (σ)	f_1 in MHz	f_1 in GHz	(dB)	(units)	$K_1 =$	$K_1 =$
	(units)	$K_2 =$	$K_2 =$		NM	37.8	97.8
	m ²	-38.54	21.46		km	32.45	92.45
	ft ²	-48.86	11.14		m	-27.55	32.45
					yd	-28.33	31.67
					ft	-37.87	22.13

J/S for SELF PROTECTION EA vs. BISTATIC RADAR

The semi-active missile illustrated in Figure 5 is the typical bistatic radar which would require the target to have self protection EA to survive. In this case, the jammer is on the target and the target to missile receiver range is the same as the jammer to receiver range, but the radar to target range is different. Therefore, only two of the ranges and two of the α 's (Figure 6.) are the same.

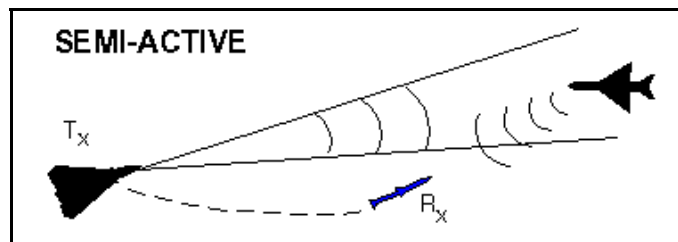


Figure 5. Bistatic Radar.

In the following equations:

α_{Tx} = The one-way space loss from the radar transmitter to the target for range R_{Tx}

α_{Rx} = The one-way space loss from the target to the missile receiver for range R_{Rx}

Like the monostatic radar, the bistatic jamming and reflected target signals travel the same path from the target and enter the receiver (missile in this case) via the same antenna. In both monostatic and bistatic J/S equations this common range cancels, so both J/S equations are left with an R_{Tx}^2 or $20 \log R_{Tx}$ term. Since in the monostatic case $R_{Tx} = R_{Rx}$ and $\alpha_{Tx} = \alpha_{Rx}$, only R or α_1 is used in the equations. Therefore, the

bistatic J/S equations [11], [13], or [14] will work for monostatic J/S calculations, but the opposite is only true if bistatic R_{Tx} and α_{Tx} terms are used for R or α_1 terms in monostatic equations [3], [5], and [8].

The equivalent circuit shown in Figure 6 applies to jamming bistatic radar. For self protect (or escort) vs. a bistatic radar, the jammer is on the target and the radar receive and transmit antennas are at separate locations so only two of the three ranges and two of the three space loss factors (α 's) are the same.

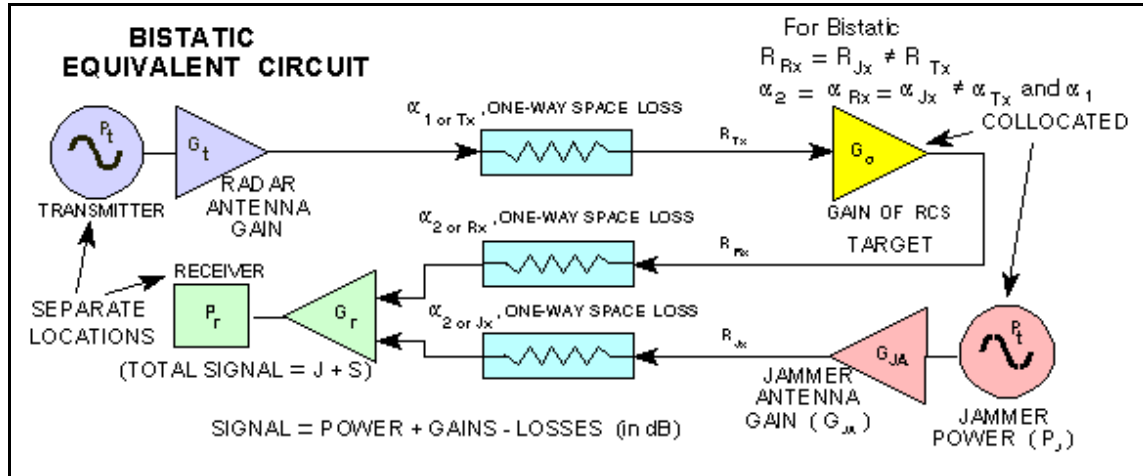


Figure 6. Bistatic Radar EA Equivalent Circuit.

J-to-S Ratio (Bistatic) When the radar's transmit antenna is located remotely from the receiving antenna (Figure 6), the ratio of the power received (P_{r1} or J) from the jamming signal transmitted from the target to the power received (P_{r2} or S) from the radar skin return from the target equals J/S. For jammer effectiveness J normally has to be greater than S.

$$\text{From the one way range equation in Section 4-3: } P_{r1} \text{ or } J = \frac{P_j G_{ja} G_r \lambda^2}{(4\pi R_{Rx})^2} \quad (R_{Jx} = R_{Rx}) \quad [9]$$

$$\text{From the two way range equation in Section 4.4: } P_{r2} \text{ or } S = \frac{P_t G_t G_r \lambda^2 \sigma}{(4\pi)^3 R_{Tx}^2 R_{Rx}^2} \quad [10]$$

$$\text{so } \frac{J}{S} = \frac{P_j G_{ja} G_r \lambda^2 (4\pi)^3 R_{Tx}^2 R_{Rx}^2}{P_t G_t G_r \lambda^2 \sigma (4\pi R_{Rx})^2} = \frac{P_j G_{ja} 4\pi R_{Tx}^2}{P_t G_t \sigma} \quad (\text{ratio form}) \quad [11]$$

* Keep R and σ in the same units.

On reducing the above equation to log form we have:

$$10 \log J/S = 10 \log P_j + 10 \log G_{ja} - 10 \log P_t - 10 \log G_t - 10 \log \sigma + 10 \log 4\pi + 20 \log R_{Tx} \quad [12]$$

$$\text{or } 10 \log J/S = 10 \log P_j + 10 \log G_{ja} - 10 \log P_t - 10 \log G_t - 10 \log \sigma + 10.99 \text{ dB} + 20 \log R_{Tx} \quad [13]$$

Note: To avoid having to include additional terms for these calculations, always combine any transmission line loss with antenna gain. Neither f nor λ terms are part of the final form of equation [11] and equation [13].

Bistatic J/S Calculations (Bistatic) Using a One Way Free Space Loss - The simplified radar equations developed in previous sections can be used to express J/S.

From the one way range equation in Section 4-3:

$$10\log (P_{r1} \text{ or } J) = 10\log P_j + 10\log G_{ja} + 10\log G_r - \alpha_{Rx} \quad (\text{all factors dB}) \quad [14]$$

From the two way range equation in Section 4-4:

$$10\log (P_{r2} \text{ or } S) = 10\log P_t + 10\log G_t + 10\log G_r + G_\sigma - \alpha_{Tx} - \alpha_{Rx} \quad (\text{all factors dB}) \quad [15]$$

$$10\log (J/S) = 10\log P_j + 10\log G_{ja} - 10\log P_t - 10\log G_t - G_\sigma + \alpha_{Tx} \quad (\text{all factors dB}) \quad [16]$$

Note: To avoid having to include additional terms for these calculations, always combine any transmission line loss with antenna gain. The $20\log f_1$ term in $-G_\sigma$ cancels the $20\log f_1$ term in α_1 .

Target gain factor, $G_\sigma = 10\log \sigma + 20\log f_1 + K_2$ (in dB)				One-way free space loss $\alpha_{Tx \text{ or } Rx} = 20\log f_1 R_{Tx \text{ or } Rx} + K_1$ (in dB)			
K₂ Values				K₁ Values			
(dB)	RCS (σ) (units)	f_1 in MHz $\underline{K}_2 =$	f_1 in GHz $\underline{K}_2 =$	(dB)	Range (units)	f_1 in MHz $\underline{K}_1 =$	f_1 in GHz $\underline{K}_1 =$
	m^2	-38.54	21.46		NM	37.8	97.8
	ft^2	-48.86	11.14		km	32.45	92.45
					m	-27.55	32.45
					yd	-28.33	31.67
					ft	-37.87	22.13

Saturated J/S (Monostatic) Example (Constant Power Jamming)

Assume that a 5 GHz radar has a 70 dBm signal fed through a 5 dB loss transmission line to an antenna that has 45 dB gain. An aircraft is flying 31 km from the radar. The aft EW antenna has -1 dB gain and a 5 dB line loss to the EW receiver (there is an additional loss due to any antenna polarization mismatch but that loss will not be addressed in this problem). The aircraft has a jammer that provides 30 dBm saturated output if the received signal is above -35 dBm. The jammer feeds a 10 dB loss transmission line which is connected to an antenna with a 5 dB gain. If the RCS of the aircraft is $9 m^2$, what is the J/S level received by the tracking radar?

Answer: The received signal at the jammer is the same as the example in Section 4-3, i.e. answer (1) = -32.3 dBm @ 5 GHz. Since the received signal is above -35 dBm, the jammer will operate in the saturated mode, and equation [5] can be used. (See Section 4-10 for an example of a jammer in the linear region.)

$$10\log J/S = 10\log P_j + 10\log G_{ja} - 10\log P_t - 10\log G_t - 10\log \sigma + 10.99 \text{ dB} + 20\log R$$

Note: the respective transmission line losses will be combined with antenna gains,

$$\text{i.e. } -5 + 45 = 40 \text{ dB} \ \& \ -10 + 5 = -5 \text{ dB.}$$

$$10\log J/S = 30 - 5 - 70 - 40 - 9.54 + 10.99 + 89.8 = 6.25 \text{ dB @ 5 GHz}^*$$

* The answer is still 6.25 dB if the tracking radar operates at 7 GHz provided the antenna gains and the aircraft RCS are the same at both frequencies.

In this example, there is inadequate jamming power at each frequency if the J/S needs to be 10 dB or greater to be effective. One solution would be to replace the jammer with one that has a greater power output. If the antenna of the aircraft and the radar are not the proper polarization, additional power will also be required (see Section 3-2).

BURN-THROUGH / CROSSOVER RANGE

The burn-through equations are derived in this section. These equations are most commonly used in jammer type of applications. The following is a summary of the important equations explored in this section:

<p>J/S CROSSOVER RANGE (MONOSTATIC) (J = S)</p> $R_{J=S} = [(P_t G_t \sigma) / (P_j G_{ja} 4\pi)]^{1/2} \quad (\text{dB Ratio})$ <p>or $20 \log R_{J=S} = 10 \log P_t + 10 \log G_t + 10 \log \sigma - 10 \log P_j - 10 \log G_{ja} - 10.99 \text{ dB}$</p> <p>If simplified radar equations already converted to dB are used: $20 \log R_{J=S} = 10 \log P_t + 10 \log G_t + G_\sigma - 10 \log P_j - 10 \log G_{ja} - K_1 - 20 \log f_1 \text{ (dB)}$</p>	<p>* Keep P_t & P_j in same units Keep R and σ in same units</p> <p>K₁ Values (dB):</p> <table style="width: 100%; border-collapse: collapse;"> <tr> <td style="text-align: left;">Range f_1 in MHz</td> <td style="text-align: center;">in GHz</td> </tr> <tr> <td style="text-align: left;">(units)</td> <td style="text-align: center;">$K_1 =$ $K_1 =$</td> </tr> <tr> <td style="text-align: left;">m</td> <td style="text-align: center;">-27.55 32.45</td> </tr> <tr> <td style="text-align: left;">ft</td> <td style="text-align: center;">-37.87 22.13</td> </tr> </table>	Range f_1 in MHz	in GHz	(units)	$K_1 =$ $K_1 =$	m	-27.55 32.45	ft	-37.87 22.13
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m	-27.55 32.45								
ft	-37.87 22.13								
<p>BURN-THROUGH RANGE (MONOSTATIC)</p> <p>The radar to target range where the target return signal (S) can first be detected through the EA (J).</p> $R_{BT} = [(P_t G_t \sigma J_{\min \text{ eff}}) / (P_j G_{ja} 4\pi S)]^{1/2} \quad (\text{dB Ratio})$ <p>or $20 \log R_{BT} = 10 \log P_t + 10 \log G_t + 10 \log \sigma - 10 \log P_j - 10 \log G_{ja} + 10 \log (J_{\min \text{ eff}}/S) - 10.99$</p> <p>If simplified radar equations already converted to dB are used: $20 \log R_{BT} = 10 \log P_t + 10 \log G_t + G_\sigma - 10 \log P_j - 10 \log G_{ja} - K_1 + 10 \log (J_{\min \text{ eff}}/S) - 20 \log f_1 \text{ (in dB)*}$ f_1 is MHz or GHz value of frequency</p>	<p>Target gain factor (dB)</p> $G_\sigma = 10 \log \sigma + 20 \log f_1 + K_2$ <p>K₂ Values (dB):</p> <table style="width: 100%; border-collapse: collapse;"> <tr> <td style="text-align: left;">RCS (σ) f_1 in MHz</td> <td style="text-align: center;">in GHz</td> </tr> <tr> <td style="text-align: left;">(units)</td> <td style="text-align: center;">$K_2 =$ $K_2 =$</td> </tr> <tr> <td style="text-align: left;">m²</td> <td style="text-align: center;">-38.54 21.46</td> </tr> <tr> <td style="text-align: left;">ft²</td> <td style="text-align: center;">-48.86 11.14</td> </tr> </table>	RCS (σ) f_1 in MHz	in GHz	(units)	$K_2 =$ $K_2 =$	m ²	-38.54 21.46	ft ²	-48.86 11.14
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ft ²	-48.86 11.14								
<p>BURN-THROUGH RANGE (BISTATIC)</p> <p>R_{Tx} is the range from the radar transmitter to the target and is different from R_{Rx} which is the range from the target to the receiver. Use Monostatic equations and substitute R_{Tx} for R</p>									

CROSSOVER RANGE and BURN-THROUGH RANGE

To present the values of J and S, (or J/S) over a minimum to maximum radar to target range of interest, equation [1], Section 4-7, which has a slope of $20 \log$ for J vs. range and equation [2], Section 4-7, which has a slope of $40 \log$ for S vs. range are plotted. When plotted on semi-log graph paper, J and S (or J/S) vs. range are straight lines as illustrated in Figure 1.

Figure 1 is a sample graph - it cannot be used for data.

The crossing of the J and S lines (known as crossover) gives the range where $J = S$ (about 1.29 NM), and shows that shorter ranges will produce target signals greater than the jamming signal.

The point where the radar power overcomes the jamming signal is known as burn-through. The crossover point where $J = S$ could be the burn-through range, but it usually isn't because normally $J/S > 0$ dB to be effective due to the task of differentiating the signal from the jamming noise floor (see receiver sensitivity section). For this example, the J/S required for the EA to be effective is given as 6 dB, as shown by the dotted line. This required J/S line crosses the jamming line at about 2.8 NM which, in this example, is the burn-through range.

In this particular example, we have:

$$\begin{aligned} P_t &= 80 \text{ dBm} & G_t &= 42 \text{ dB} \\ P_j &= 50 \text{ dBm} & G_{ja} &= 6 \text{ dB} \\ \sigma &= 18 \text{ m}^2 & f &= 5.9 \text{ GHz (not necessary for all calculations)} \end{aligned}$$

A radar can be designed with higher than necessary power for earlier burn-through on jamming targets. Naturally that would also have the added advantage of earlier detection of non-jamming targets as well.

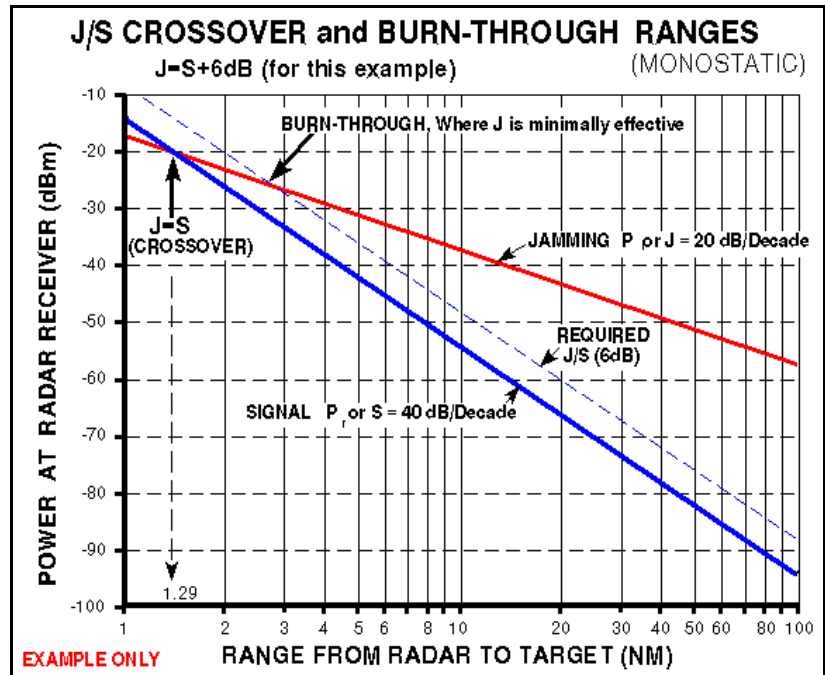


Figure 1. Sample J and S Graph.

Note: To avoid having to include additional terms for the following calculations, always combine any transmission line loss with antenna gain.

CROSSOVER AND BURN-THROUGH RANGE EQUATIONS (MONOSTATIC)

To calculate the crossover range or burn-through range the J/S equation must be solved for range. From equation [3], Section 4-7:

$$\frac{J}{S} = \frac{P_j G_{ja} 4\pi R^2}{P_t G_t \sigma} \quad (\text{ratio form}) \quad \text{Solving for R: } R = \sqrt{\frac{P_t G_t \sigma J}{P_j G_{ja} 4\pi S}} \quad [1]$$

BURN-THROUGH RANGE (MONOSTATIC) - Burn-through Range (Monostatic) is the radar to target range where the target return signal (S) can first be detected through the jamming (J). It is usually the range when the J/S just equals the minimum effective J/S.

$$R_{BT} = \sqrt{\frac{P_t G_t \sigma J_{\min \text{ eff}}}{P_j G_{ja} 4\pi S}} \quad (\text{burn-through range}) \quad [2]$$

or in dB form, (using $10\log 4\pi = 10.99$ dB):

$$20\log R_{BT} = 10\log P_t + 10\log G_t + 10\log \sigma - 10\log P_j - 10\log G_{ja} + 10\log (J_{\min \text{ eff}}/S) - 10.99 \text{ dB} \quad [3]$$

RANGE WHEN J/S CROSSOVER OCCURS (MONOSTATIC) - The crossover of the jammer's 20 dB/decade power line and the skin return signal's 40 dB/decade power line of Figure 1 occurs for the case where $J = S$ in dB or $J/S=1$ in ratio. Substituting into equation [1] yields:

$$R_{(J=S)} = \sqrt{\frac{P_t G_t \sigma}{P_j G_{ja} 4\pi}} \quad (\text{Crossover range}) \quad [4]$$

or in dB form:

$$20\log R_{J=S} = 10\log P_t + 10\log G_t + 10\log \sigma - 10\log P_j - 10\log G_{ja} - 10.99 \text{ dB} \quad [5]$$

Note: keep R and σ in same units in all equations.

CROSSOVER AND BURN-THROUGH EQUATIONS (MONOSTATIC) USING α - ONE WAY FREE SPACE LOSS

The other crossover burn-through range formulas can be confusing because a frequency term is subtracted (equations [6], [7] and [8]), but both ranges are independent of frequency. This subtraction is necessary because when J/S is calculated directly as previously shown, λ^2 or $(c/f)^2$ terms canceled, whereas in the simplified radar equations, a frequency term is part of the G_σ term and has to be cancelled if one solves for R. From equation [8], Section 4-7:

$$10\log J/S = 10\log P_j + 10\log G_{ja} - 10\log P_t - 10\log G_t - G_\sigma + \alpha_1 \quad (\text{factors in dB})$$

or rearranging: $\alpha_1 = 10\log P_t + 10\log G_t + G_\sigma - 10\log P_j - 10\log G_{ja} + 10\log (J/S)$

from Section 4-4: $\alpha_1 = 20\log f_1 R_1 + K_1$ or $20\log R_1 = \alpha_1 - K_1 - 20\log f_1$

then substituting for α_1 :

$$20\log R_1 = 10\log P_t + 10\log G_t + G_\sigma - 10\log P_j - 10\log G_{ja} - K_1 + 10\log (J/S) - 20\log f_1 \quad (\text{in dB}) \quad [6]$$

EQUATION FOR BURN-THROUGH RANGE (MONOSTATIC) - Burn-through occurs at the range when the J/S just equals the minimum effective J/S. G_σ and K_1 are as defined on page 4-8.1.

$$20\log R_{BT} = 10\log P_t + 10\log G_t + G_\sigma - 10\log P_j - 10\log G_{ja} - K_1 + 10\log (J_{\min \text{ eff}}/S) - 20\log f_1 \quad (\text{in dB}) \quad [7]$$

EQUATION FOR THE RANGE WHEN J/S CROSSOVER OCCURS (MONOSTATIC)

The J/S crossover range occurs for the case where $J = S$, substituting into equation [6] yields:

$$20\log R_{J=S} = 10\log P_t + 10\log G_t + G_\sigma - 10\log P_j - 10\log G_{ja} - K_1 - 20\log f_1 \quad (\text{factors in dB}) \quad [8]$$

BURN-THROUGH RANGE (BISTATIC)

Bistatic J/S crossover range is the radar-to-target range when the power received (S) from the radar skin return from the target equals the power received (J) from the jamming signal transmitted from the target. As shown in Figure 6, Section 4-7, the receive antenna that is receiving the same level of J and S is remotely located from the radar's transmit antenna. Bistatic equations [11], [13], and [14] in Section 4-7 show that J/S is only a function of radar to target range, therefore J/S is not a function of wherever the missile is in its flight path provided the missile is in the antenna beam of the target's jammer. The missile is closing on the target at a very much higher rate than the target is closing on the radar, so the radar to target range will change less during the missile flight.

It should be noted that for a very long range air-to-air missile shot, the radar to target range could typically decrease to 35% of the initial firing range during the missile time-of-flight, i.e. A missile shot at a target 36 NM away, may be only 12 NM away from the firing aircraft at missile impact.

Figure 2 shows both the jamming radiated from the target and the power reflected from the target as a function of radar-to-target range. In this particular example, the RCS is assumed to be smaller, 15 m² vice 18 m² in the monostatic case, since the missile will be approaching the target from a different angle. This will not, however, always be the case.

In this plot, the power reflected is:

$$P_{ref} = \frac{P_t G_t 4 \pi \sigma}{(4\pi R)^2}$$

Substituting the values given previously in the example on page 4-8.1, we find that the crossover point is at 1.18 NM (due to the assumed reduction in RCS).

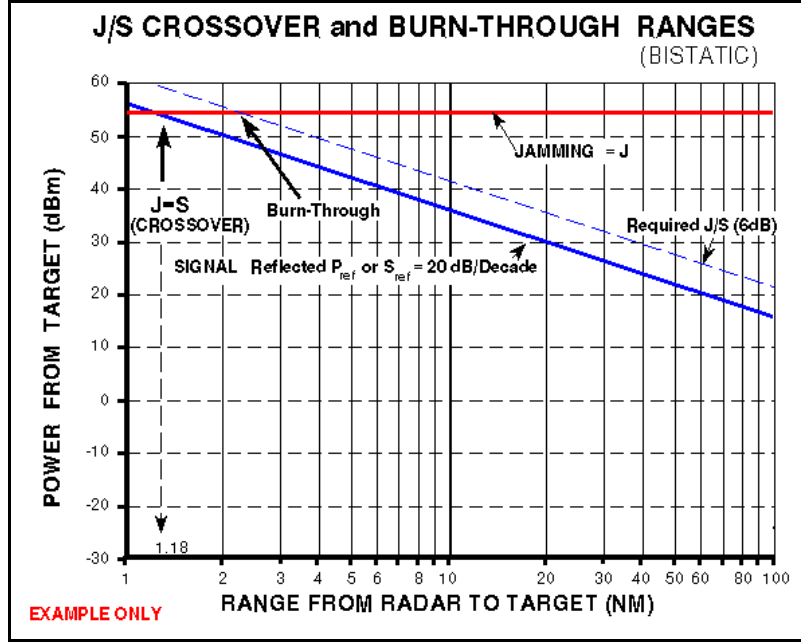


Figure 2. Bistatic Crossover and Burnthrough.

CROSSOVER AND BURN-THROUGH RANGE EQUATIONS (BISTATIC)

To calculate the radar transmitter-to-target range where J/S crossover or burn-through occurs, the J/S equation must be solved for range. From equation [11] in Section 4-7:

$$\frac{J}{S} = \frac{P_j G_{ja} 4 \pi R_{Tx}^2}{P_t G_t \sigma} \quad (\text{ratio form})$$

Solving for R_{Tx}:

$$R_{Tx} = \sqrt{\frac{P_t G_t \sigma J}{P_j G_{ja} 4 \pi S}} \quad [9]$$

Note:

Bistatic equation [10] is identical to monostatic equation [1] except R_{Tx} must be substituted for R and a bistatic RCS (σ) will have to be used since RCS varies with aspect angle. The common explanations will not be repeated in this section.

BURN-THROUGH RANGE (BISTATIC) - Burn-through Range (Bistatic) occurs when J/S just equals the minimum effective J/S. From equation [9]:

$$R_{Tx(BT)} = \sqrt{\frac{P_t G_t \sigma J_{\min \text{ eff}}}{P_j G_{ja} 4 \pi S}} \quad (\text{ratio form}) \quad [10]$$

or in dB form:

$$20\log R_{Tx(BT)} = 10\log P_t + 10\log G_t + 10\log \sigma - 10\log P_j - 10\log G_{ja} + 10\log (J_{\min \text{ eff}}/S) - 10.99 \text{ dB} \quad [11]$$

If using the simplified radar equations (factors in dB):

$$20\log R_{Tx(BT)} = 10\log P_t + 10\log G_t + G_\sigma - 10\log P_j - 10\log G_{ja} - K_1 + 10\log (J_{\min \text{ eff}}/S) - 20\log f_1 \quad [12]$$

Where G_σ and K_1 are defined on page 4-8.1

RANGE WHEN J/S CROSSOVER OCCURS (BISTATIC)

The crossover occurs when $J = S$ in dB or $J/S = 1$ in ratio.

$$R_{Tx(J=S)} = \sqrt{\frac{P_t G_t \sigma}{P_j G_{ja} 4\pi}} \quad (\text{ratio}) \quad [13]$$

or in log form:

$$20\log R_{Tx(J=S)} = 10\log P_t + 10\log G_t + 10\log \sigma - 10\log P_j - 10\log G_{ja} - 10.99 \text{ dB} \quad [14]$$

If simplified equations are used (with G_σ and K_1 as defined on page 4-8.1) we have:

$$20\log R_{Tx(J=S)} = 10\log P_t + 10\log G_t + G_\sigma - 10\log P_j - 10\log G_{ja} - K_1 - 20\log f_1 \quad (\text{factors in dB}) \quad [15]$$

Note: keep R and σ in same units in all equations.

DETAILS OF SEMI-ACTIVE MISSILE J/S

Unless you are running a large scale computer simulation that includes maneuvering, antenna patterns, RCS, etc., you will seldom calculate the variation in J/S that occurs during a semi-active missile's flight. Missiles don't fly straight lines at constant velocity. Targets don't either - they maneuver. If the launch platform is an aircraft, it maneuvers too. A missile will accelerate to some maximum velocity above the velocity of the launch platform and then decelerate.

The calculation of the precise variation of J/S during a missile flight for it to be effective requires determination of all the appropriate velocity vectors and ranges at the time of launch, and the accelerations and changes in relative positions during the fly out. In other words, it's too much work for too little return. The following are simplified examples for four types of intercepts.

In these examples, all velocities are constant, and are all along the same straight line. The missile velocity is 800 knots greater than the launch platform velocity which is assumed to be 400 kts. The missile launch occurs at 50 NM.

	J/S (dB)	Δ J/S (dB)
At Launch:	29	n/a
Intercept Type	At 2 sec. to Intercept:	
AAM Head-on:	23	-6
SAM Incoming Target:	25	-4
AAM Tail Chase:	29	0
SAM Outbound Target:	35	+6

For the AAM tail chase, the range from the radar to the target remains constant and so does the J/S. **In these examples** the maximum variation from launch J/S is ± 6 dB. That represents the difference in the radar to target range closing at very high speed (AAM head on) and the radar to target range opening at moderate speed (SAM outbound target). The values shown above are examples, not rules of thumb, every intercept will be different.

Even for the simplified linear examples shown, graphs of the J and S will be curves - not straight lines. Graphs could be plotted showing J and S vs. radar to target range, or J and S vs. missile to target range, or even J/S vs. time of flight. If the J/S at launch is just barely the minimum required for effectiveness, and increasing it is difficult, then a detailed graph may be warranted, but in most cases this isn't necessary.

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SUPPORT JAMMING

The following table contains a summary of equations developed in this section:

<p style="text-align: center;">MAIN LOBE JAMMING TO SIGNAL (J/S) RATIO (For SOJ/SIJ)</p> $J/S = (P_j G_{ja} 4\pi R_{Tx}^4) / (P_t G_t \sigma [BW_j/BW_R] R_{jx}^2) \quad (\text{ratio form})^*$ $10\log J/S = 10\log P_j - 10\log[BW_j/BW_R] + 10\log G_{ja} - 10\log P_t - 10\log G_t - 10\log \sigma + \downarrow$ $10.99 \text{ dB} + 40\log R_{Tx} - 20\log R_{jx} \quad * \quad \leftarrow \leftarrow$ <p>or if simplified radar equations are used:</p> $10\log J/S = 10\log P_j - BF + 10\log G_{ja} - \alpha_{jx} - 10\log P_t - 10\log G_t - G_\sigma + 2\alpha_1 \quad (\text{in dB})^*$	<p>Target gain factor, $G_\sigma = 10\text{Log}\sigma + 20\text{Log}f_1 + K_2$ (in dB) K₂ Values (dB):</p> <table style="width: 100%; border-collapse: collapse;"> <tr> <td style="text-align: center;">RCS (σ)</td> <td style="text-align: center;">f_1 in MHz</td> <td style="text-align: center;">f_1 in GHz</td> </tr> <tr> <td style="text-align: center;">(units)</td> <td style="text-align: center;">$K_2 =$</td> <td style="text-align: center;">$K_2 =$</td> </tr> <tr> <td style="text-align: center;">m^2</td> <td style="text-align: center;">-38.54</td> <td style="text-align: center;">21.46</td> </tr> <tr> <td style="text-align: center;">ft^2</td> <td style="text-align: center;">-48.86</td> <td style="text-align: center;">11.14</td> </tr> </table>	RCS (σ)	f_1 in MHz	f_1 in GHz	(units)	$K_2 =$	$K_2 =$	m^2	-38.54	21.46	ft^2	-48.86	11.14									
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m^2	-38.54	21.46																				
ft^2	-48.86	11.14																				
<p style="text-align: center;">SIDE LOBE JAMMING TO SIGNAL (J/S) RATIO (For SOJ/SIJ)</p> $J/S = (P_j G_{ja} G_{r(SL)} 4\pi R_{Tx}^4) / (P_t G_t G_{r(ML)} \sigma [BW_j/BW_R] R_{jx}^2) \quad (\text{ratio form})^*$ $10\log J/S = 10\log P_j - BF + 10\log G_{ja} + 10\log G_{r(SL)} - 10\log P_t - 10\log G_t - 10\log G_{r(ML)} + \rightarrow \downarrow$ $10.99 \text{ dB} - 10\log \sigma + 40\log R_{Tx} - 20\log R_{jx} \quad * \quad \leftarrow \leftarrow$ <p>or if simplified radar equations are used (in dB)*:</p> $10\log J/S = 10\log P_j - BF + 10\log G_{ja} + 10\log G_{r(SL)} - \alpha_{jx} - 10\log P_t - 10\log G_t - 10\log G_{r(ML)} - G_\sigma + 2\alpha_1$	<p>One-way free space loss, α_1 or $\alpha_{Tx} = 20\text{Log}(f_1 R) + K_1$ (in dB) K₁ Values (dB):</p> <table style="width: 100%; border-collapse: collapse;"> <tr> <td style="text-align: center;">Range</td> <td style="text-align: center;">f_1 in MHz</td> <td style="text-align: center;">f_1 in GHz</td> </tr> <tr> <td style="text-align: center;">(units)</td> <td style="text-align: center;">$K_1 =$</td> <td style="text-align: center;">$K_1 =$</td> </tr> <tr> <td style="text-align: center;">NM</td> <td style="text-align: center;">37.8</td> <td style="text-align: center;">97.8</td> </tr> <tr> <td style="text-align: center;">Km</td> <td style="text-align: center;">32.45</td> <td style="text-align: center;">92.45</td> </tr> <tr> <td style="text-align: center;">m</td> <td style="text-align: center;">-27.55</td> <td style="text-align: center;">32.45</td> </tr> <tr> <td style="text-align: center;">yd</td> <td style="text-align: center;">-28.33</td> <td style="text-align: center;">31.67</td> </tr> <tr> <td style="text-align: center;">ft</td> <td style="text-align: center;">-37.87</td> <td style="text-align: center;">22.13</td> </tr> </table> <p style="text-align: right;">* Keep R and σ in same units</p>	Range	f_1 in MHz	f_1 in GHz	(units)	$K_1 =$	$K_1 =$	NM	37.8	97.8	Km	32.45	92.45	m	-27.55	32.45	yd	-28.33	31.67	ft	-37.87	22.13
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<table style="width: 100%; border-collapse: collapse;"> <tr> <td style="width: 10%;">R_{jx}</td> <td>Range from the support jammer transmitter to the radar receiver</td> </tr> <tr> <td>R_{Tx}</td> <td>Range between the radar and the target</td> </tr> <tr> <td>BF</td> <td>10 Log of the ratio of BW_j of the noise jammer to BW_R of the radar receiver</td> </tr> <tr> <td>$G_{r(SL)}$</td> <td>Side lobe antenna gain</td> </tr> <tr> <td>$G_{r(ML)}$</td> <td>Main lobe antenna gain</td> </tr> <tr> <td>α_{jx}</td> <td>One way free space loss between SOJ transmitter and radar receiver</td> </tr> <tr> <td>α_1</td> <td>One way space loss between the radar and the target</td> </tr> </table>	R_{jx}	Range from the support jammer transmitter to the radar receiver	R_{Tx}	Range between the radar and the target	BF	10 Log of the ratio of BW_j of the noise jammer to BW_R of the radar receiver	$G_{r(SL)}$	Side lobe antenna gain	$G_{r(ML)}$	Main lobe antenna gain	α_{jx}	One way free space loss between SOJ transmitter and radar receiver	α_1	One way space loss between the radar and the target								
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Support jamming adds a few geometric complexities. A SOJ platform usually uses high gain, directional antennas. Therefore, the jamming antenna must not only be pointed at the victim radar, but there must be alignment of radar, targets, and SOJ platform for the jamming to be most effective. Two cases will be described, main lobe-jamming and side-lobe jamming.

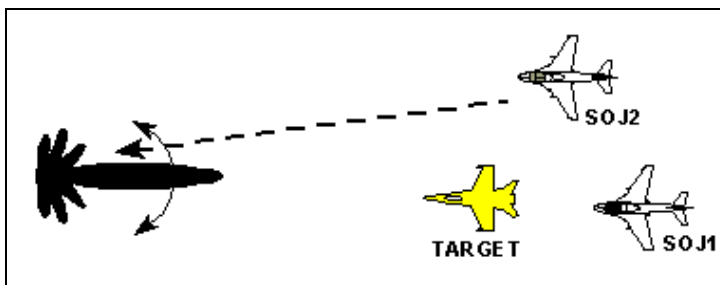


Figure 1. Radar Antenna Pattern.

Support jamming is usually applied against search and acquisition radars which continuously scan horizontally through a volume of space. The scan could cover a sector or a full 360°. The horizontal antenna pattern of the radar will exhibit a main lobe and side lobes as illustrated in Figure 1. The target is detected when the main lobe sweeps across it. For main lobe jamming, the SOJ platform and the target(s) must be aligned with the radar's main lobe as it sweeps the target(s).

For side lobe jamming, the SOJ platform may be aligned with one or more of the radar's side lobes when the main lobe sweeps the target. The gain of a radar's side lobes are many tens of dB less (usually more than 30 dB less) than the gain of the main lobe, so calculations of side lobe jamming must use the gain of the side lobe for the radar receive antenna gain, not the gain of the main lobe. Also, because many modern radars

employ some form of side lobe blanking or side lobe cancellation, some knowledge of the victim radar is required to predict the effectiveness of side lobe jamming.

All radar receivers are frequency selective. That is, they are filters that allow only a narrow range of frequencies into the receiver circuitry. Deceptive EA, by definition, creates forgeries of the real signal and, ideally, are as well matched to the radar receiver as the real signal. On the other hand, noise jamming probably **will not match** the radar receiver bandwidth characteristics. Noise jamming is either spot jamming or barrage jamming. As illustrated in Figure 2, spot jamming is simply narrowing the bandwidth of the noise jammer so that as much of the jammer power as possible is in the radar receiver bandwidth. Barrage jamming is using a wide noise bandwidth to cover several radars with one jammer or to compensate for any uncertainty in the radar frequency. In both cases some of the noise power is “wasted” because it is not in the radar receiver filter.

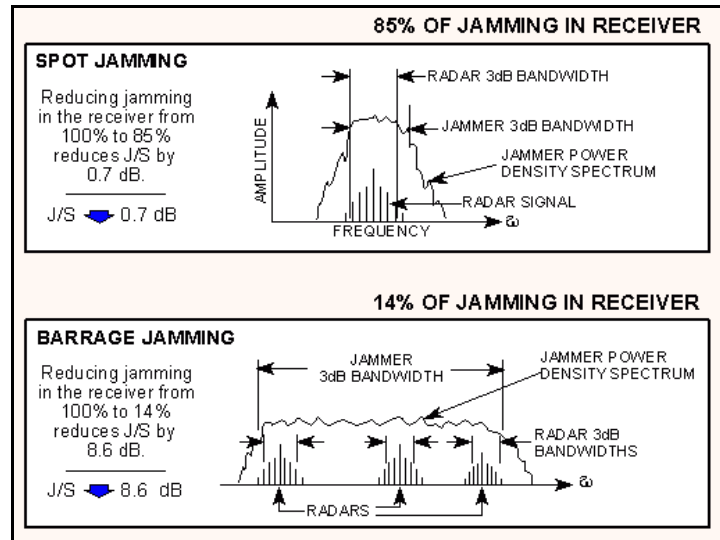


Figure 2. Noise Jamming.

In the past, noise jammers were often described as having so many “watts per MHz.” This is nothing more than the power of the noise jammer divided by the noise bandwidth. That is, a 500 watt noise jammer transmitting a noise bandwidth of 200 MHz has 2.5 watts/MHz. Older noise jammers often had noise bandwidths that were difficult, or impossible, to adjust accurately. These noise jammers usually used manual tuning to set the center frequency of the noise to the radar frequency. Modern noise jammers can set on the radar frequency quite accurately and the noise bandwidth is selectable, so the noise bandwidth is more a matter of choice than it used to be, and it is possible that all of the noise is placed in the victim radar’s receiver.

If, in the example above, the 500 watt noise jammer were used against a radar that had a 3 MHz receiver bandwidth, the noise jammer power applicable to that radar would be:

$$3 \text{ MHz} \times 2.5 \text{ watts/MHz} = 7.5 \text{ watts} _ 38.75 \text{ dBm} \quad [1]$$

The calculation must be done as shown in equation [1] - multiply the watts/MHz by the radar bandwidth first and then convert to dBm. You can’t convert to dBm/MHz and then multiply. (See derivation of dB in Section 2-4)

An alternate method for dB calculations is to use the bandwidth reduction factor (BF).

The BF is:
$$BF_{dB} = 10 \text{ Log} \left[\frac{BW_J}{BW_R} \right] \quad [2]$$

where: BW_J is the bandwidth of the noise jammer, and BW_R is the bandwidth of the radar receiver.

The power of the jammer in the jamming equation (P_j) can be obtained by either method. If equation [1] is used then P_j is simply 38.75 dBm. If equation [2] is used then the jamming equation is written using ($P_j - BF$). All the following discussion uses the second method. Whichever method is used, it is required that $BW_j \geq BW_R$. If $BW_j < BW_R$, then all the available power is in the radar receiver and equation [1] does not apply and the $BF = 0$.

Note: To avoid having to include additional terms for the following calculations, always combine any transmission line loss with antenna gain.

MAIN LOBE STAND-OFF / STAND-IN JAMMING

The equivalent circuit shown in Figure 3 applies to main lobe jamming by a stand-off support aircraft or a stand-in RPV. Since the jammer is not on the target aircraft, only two of the three ranges and two of the three space loss factors (α 's) are the same. Figure 3 differs from the J/S monostatic equivalent circuit shown in Figure 4 in Section 4-7 in that the space loss from the jammer to the radar receiver is different.

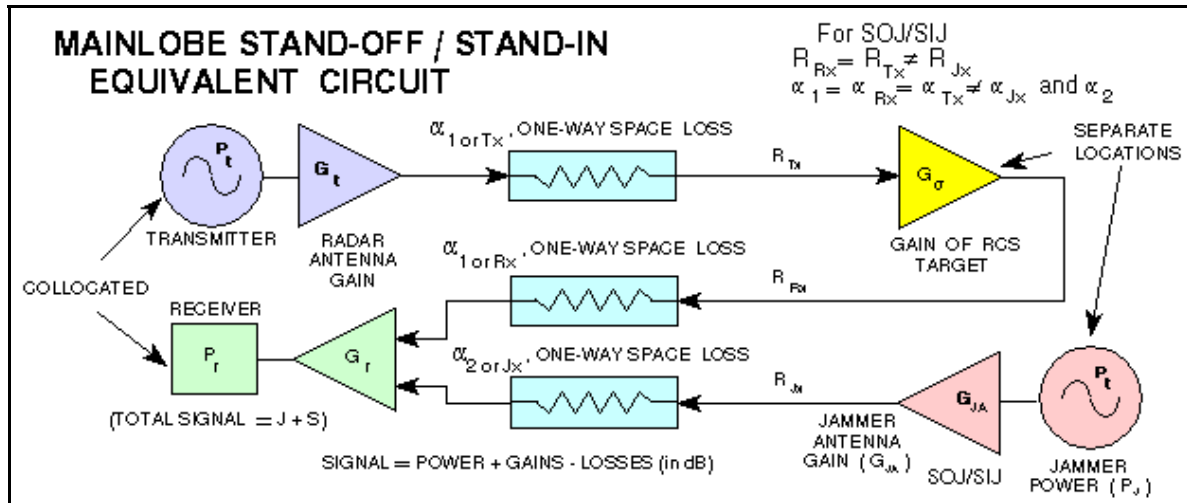


Figure 3. Main Lobe Stand-Off / Stand-In EA Equivalent Circuit.

The equations are the same for both SOJ and SIJ. From the one way range equation in Section 4-3, and with inclusion of BF losses:

$$P_r, 1 \text{ or } J = \frac{P_j G_{ja} G_r \lambda^2 BW_R}{(4\pi R_{Jx})^2 BW_J} \quad [3]$$

From the two way range equation in Section 4.4:

$$P_r, 2 \text{ or } S = \frac{P_t G_t G_r \lambda^2 \sigma}{(4\pi)^3 R_{Tx}^4} \quad [4]$$

so

$$\frac{J}{S} = \frac{P_j G_{ja} G_r \lambda^2 (4\pi)^3 R_{Tx}^4 BW_R}{P_t G_t G_r \lambda^2 \sigma (4\pi R_{Jx})^2 BW_J} = \frac{P_j G_{ja} 4\pi R_{Tx}^4 BW_R}{P_t G_t \sigma R_{Jx}^2 BW_J} \quad (\text{ratio form}) \quad [5]$$

Note: Keep R and σ in the same units. Converting to dB and using $10 \log 4\pi = 10.99 \text{ dB}$:

$$10 \log J/S = 10 \log P_j - 10 \log [BW_j/BW_R] + 10 \log G_{ja} - 10 \log P_t - 10 \log G_t - 10 \log \sigma + 10.99 \text{ dB} + 40 \log R_{Tx} - 20 \log R_{Jx} \quad [6]$$

If the simplified radar equation is used, the free space loss from the SOJ/SIJ to the radar receiver is α_{Jx} , then equation [7] is the same as monostatic equation [6] in Section 4-7 except α_{Jx} replaces α , and the bandwidth reduction factor [BF] losses are included:

$$10 \log J = 10 \log P_j - BF + 10 \log G_{ja} + 10 \log G_r - \alpha_{Jx} \quad (\text{factors in dB}) \quad [7]$$

Since the free space loss from the radar to the target and return is the same both ways, $\alpha_{Tx} = \alpha_{Rx} = \alpha_1$, equation [8] is the same as monostatic equation [7] in Section 4-7.

$$10 \log S = 10 \log P_t + 10 \log G_t + 10 \log G_r + G_\sigma - 2\alpha_1 \quad (\text{factors in dB}) \quad [8]$$

and $10 \log J/S = 10 \log P_j - BF + 10 \log G_{ja} - \alpha_{Jx} - 10 \log P_t - 10 \log G_t - G_\sigma + 2\alpha_1 \quad (\text{factors in dB}) \quad [9]$

Notice that unlike equation [8] in Section 4-7, there are two different α 's in [9] because the signal paths are different.

SIDE LOBE STAND-OFF / STAND-IN JAMMING

The equivalent circuit shown in Figure 4. It differs from Figure 3, (main lobe SOJ/SIJ) in that the radar receiver antenna gain is different for the radar signal return and the jamming.

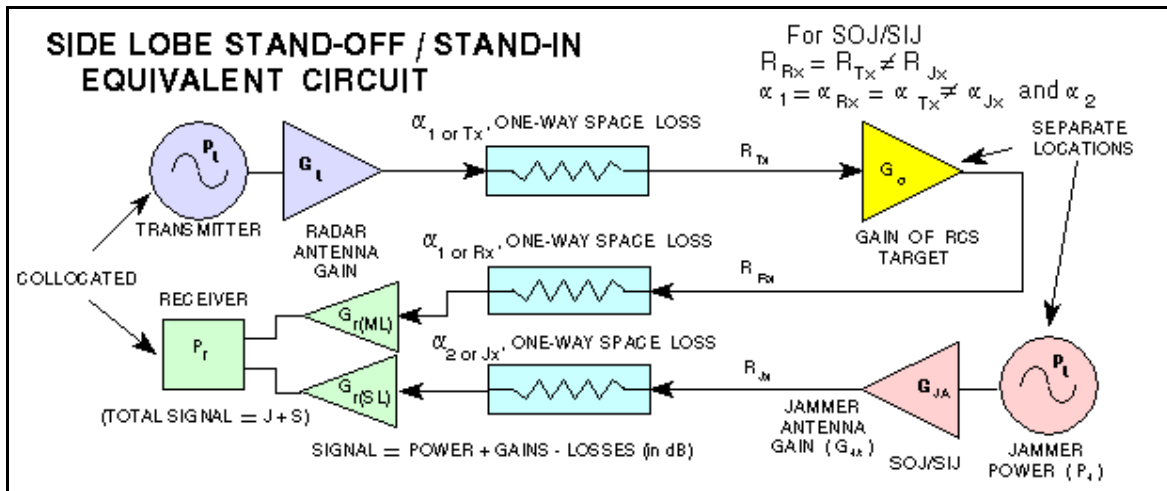


Figure 4. Side Lobe Stand-Off / Stand-In EA Equivalent Circuit.

To calculate side lobe jamming, the gain of the radar antenna's side lobes must be known or estimated. The gain of each side lobe will be different than the gain of the other side lobes. If the antenna is symmetrical, the first side lobe is the one on either side of the main lobe, the second side lobe is the next one on either side of the first side lobe, and so on. The side lobe gain is G_{SLn} , where the 'n' subscript denotes side lobe number: 1, 2, ..., n.

The signal is the same as main lobe equations [4] and [8], except $G_r = G_{r(ML)}$

$$P_r \text{ or } S = \frac{P_t G_t G_{r(ML)} \lambda^2 \sigma}{(4\pi)^3 R_{Tx}^4} \quad (\text{ratio form}) \quad [10]$$

If simplified radar equations are used:

$$10\log S = 10\log P_t + 10\log G_t + 10\log G_{r(ML)} + G_\sigma - 2\alpha_1 \quad (\text{factors in dB})$$

The jamming equation is the same as main lobe equations [3] and [7] except $G_r = G_{r(SL)}$:

$$J = \frac{P_j G_{ja} G_{r(SL)} \lambda^2 BW_R}{(4\pi R_{Jx})^2 BW_J} \quad [11]$$

$$10\log J = 10\log P_j - BF + 10\log G_{ja} + 10\log G_{r(SL)} - \alpha_{Jx} \quad (\text{factors in dB}) \quad [12]$$

so

$$\frac{J}{S} = \frac{P_j G_{ja} G_{r(SL)} 4\pi R_{Tx}^4 BW_R}{P_t G_t G_{r(ML)} \sigma R_{Jx}^2 BW_J} \quad (\text{ratio form}) \quad [13]$$

Note: keep R and σ in same units. Converting to dB and using $10\log 4\pi = 10.99$ dB:

$$10\log J/S = 10\log P_j - BF + 10\log G_{ja} + 10\log G_{r(SL)} - 10\log P_t - 10\log G_t - 10\log G_{r(ML)} - 10\log \sigma + 10.99 \text{ dB} + 40\log R_{Tx} - 20\log R_{Jx} \quad (\text{factors in dB}) \quad [14]$$

If simplified radar equations are used:

$$10\log J/S = 10\log P_j - BF + 10\log G_{ja} + 10\log G_{r(SL)} - \alpha_{Jx} - 10\log P_t - 10\log G_t - 10\log G_{r(ML)} - G_\sigma + 2\alpha_1 \quad (\text{in dB}) \quad [15]$$

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JAMMING TO SIGNAL (J/S) RATIO - CONSTANT GAIN [LINEAR] JAMMING

JAMMING TO SIGNAL (J/S) RATIO (MONOSTATIC)

$$\frac{J}{S} = \frac{G_{ja(Rx)} G_j G_{ja(Tx)} \lambda^2}{4\pi\sigma} = \frac{G_{ja(Rx)} G_j G_{ja(Tx)} c^2}{4\pi\sigma f^2} \quad (\text{ratio form})$$

$G_{ja(Rx)}$ = The Gain of the jammer receive antenna
 G_j = The gain of the jammer
 $G_{ja(Tx)}$ = The Gain of the jammer transmit antenna

or:

$$10\log J/S = 10\log G_{ja(Rx)} + 10\log G_j + 10\log G_{ja(Tx)} - 10\log (4\pi\sigma/\lambda^2)$$

or if simplified radar equations developed in previous sections are used:

$$10\log J/S = 10\log G_{ja(Rx)} + 10\log G_j + 10\log G_{ja(Tx)} - G_\sigma \quad (\text{dB})$$

* Keep λ and σ in same units. Note: $\lambda = c/f$

Target gain factor,
 $G_\sigma = 10\log \sigma + 20\log f_1 + K_2 \quad (\text{dB})$

K_2 Values (dB):

RCS (σ)	f_1 in MHz	f_1 in GHz
(units)	$K_2 =$	$K_2 =$
m^2	-38.54	21.46
ft^2	-48.86	11.14

JAMMING TO SIGNAL (J/S) RATIO (BISTATIC)

Same as the monostatic case except G_σ will be different since RCS (σ) varies with aspect angle.

Since the jammer on the target is amplifying the received radar signal before transmitting it back to the radar, both J and S experience the two way range loss. Figure 1 shows that the range for both the signal and constant gain jamming have a slope that is 40 dB per decade. Once the jammer output reaches maximum power, that power is constant and the jamming slope changes to 20 dB per decade since it is only a function of one way space loss and the J/S equations for constant power (saturated) jamming must be used.

Normally the constant gain (linear) region of a repeater jammer occurs only at large distances from the radar and the constant power (saturated) region is reached rapidly as the target approaches the radar. When a constant gain jammer is involved it may be necessary to plot jamming twice - once using J from the constant power (saturated) equation [1] in Section 4-7 and once using the constant gain (linear) equation [4], as in the example shown in Figure 1.

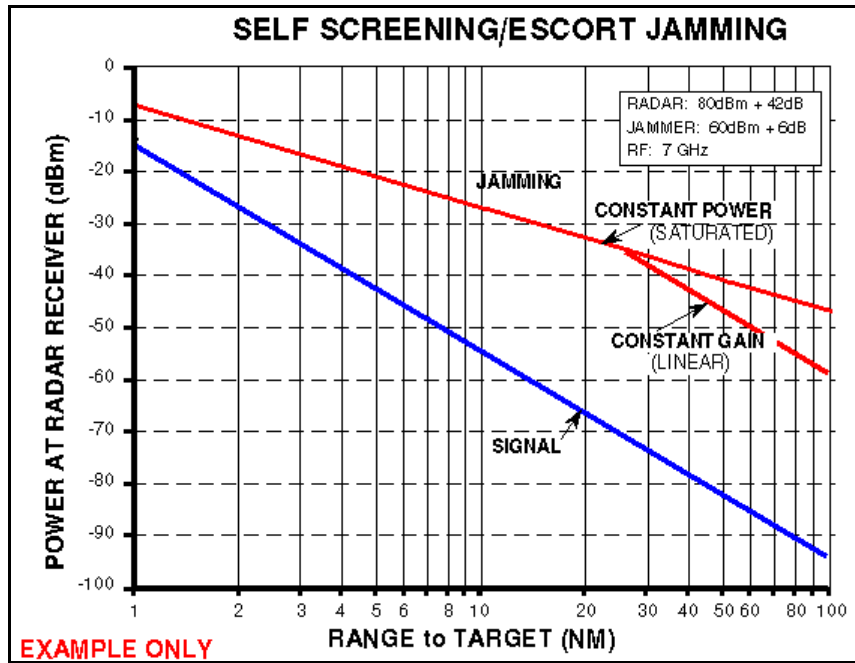


Figure 1. Sample Constant Gain / Constant Power Graph.

CONSTANT GAIN SELF PROTECTION EA

Most jammers have a constant power output - that is, they always transmit the maximum available power of the transmitter (excepting desired EA modulation). Some jammers also have a constant gain (linear) region. Usually these are coherent repeaters that can amplify a low level radar signal to a power that is below the level that results in maximum available (saturated) power output. At some radar to target range, the input signal is sufficiently high that the full jammer gain would exceed the maximum available power and the jammer ceases to be constant gain and becomes constant power.

To calculate the power output of a constant gain jammer where:

- S_{Rj} = The Radar signal at the jammer input (receive antenna terminals)
- $G_{ja(Rx)}$ = The Gain of the jammer receive antenna
- G_j = The gain of the jammer
- α_{Tx} = The one-way free space loss from the radar to the target
- P_{jCG} = The jammer constant gain power output
- P_j = The maximum jammer power output
- L_R = The jammer receiving line loss; combine with antenna gain $G_{ja(Rx)}$

From equation [10], Section 4-3, calculate the radar power received by the jammer.

$$10\log S_{Rj} = 10\log P_t + 10\log G_t - \alpha_{Tx} + 10\log G_{ja(Rx)} \quad (\text{factors in dB}) \quad [1]$$

The jammer constant gain power output is: $10\log P_{jCG} = 10\log S_{Rj} + 10\log G_j \quad [2]$

and, by definition: $P_{jCG} \leq P_j \quad [3]$

MONOSTATIC

The equivalent circuit shown in Figure 2 is different from the constant power equivalent circuit in Figure 4 in Section 4-7. With constant gain, the jamming signal experiences the gain of the jammer and its antennas plus the same space loss as the radar signal.

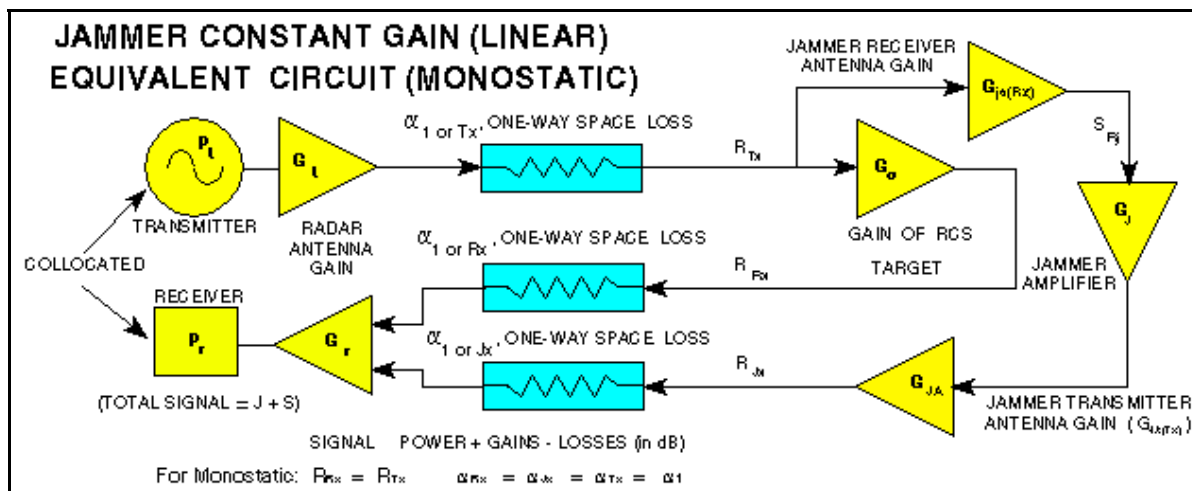


Figure 2. Jammer Constant Gain EA Equivalent Circuit (Monostatic).

To calculate J, the one way range equation from Section 4-3 is used twice:

$$J = \frac{P_t G_t G_{ja(Rx)} \lambda^2}{(4\pi R)^2} \frac{G_j G_{ja(Tx)} G_r \lambda^2}{(4\pi R)^2} \quad [4]$$

From the two way range equation in Section 4-4: $S = \frac{P_t G_t G_r \lambda^2 \sigma}{(4\pi)^3 R^4}$ [5]

Terms cancel when combined: $\frac{J}{S} = \frac{G_{ja(Rx)} G_j G_{ja(Tx)} \lambda^2}{4\pi\sigma}$ *Keep λ and σ in same units* [6]

Or in dB form: $10\log J/S = 10\log G_{ja(Rx)} + 10\log G_j + 10\log G_{ja(Tx)} - 10\log (4\pi\sigma/\lambda^2)$ [7]

Since the last term can be recognized as minus G_σ from equation [10] in Section 4-4, where the target gain factor, $G_\sigma = 10\log (4\pi\sigma/\lambda^2) = 10\log (4\pi\sigma f^2/c^2)$, it follows that:

$10\log J/S = 10\log G_{ja(Rx)} + 10\log G_j + 10\log G_{ja(Tx)} - G_\sigma$ (factors in dB) [8]

Target gain factor, $G_\sigma = 10\log \sigma + 20\log f_1 + K_2$ (in dB)			
K ₂ Values			
(dB)	RCS (σ)	f_1 in MHz	f_1 in GHz
	(units)	$K_2 =$	$K_2 =$
	m ²	-38.54	21.46
	ft ²	-48.86	11.14

BISTATIC

The bistatic equivalent circuit shown in Figure 3 is different from the monostatic equivalent circuit shown in Figure 2 in that the receiver is separately located from the transmitter, $R_{Tx} \neq R_{Rx}$ or R_{Jx} and G_σ will be different since the RCS (σ) varies with aspect angle.

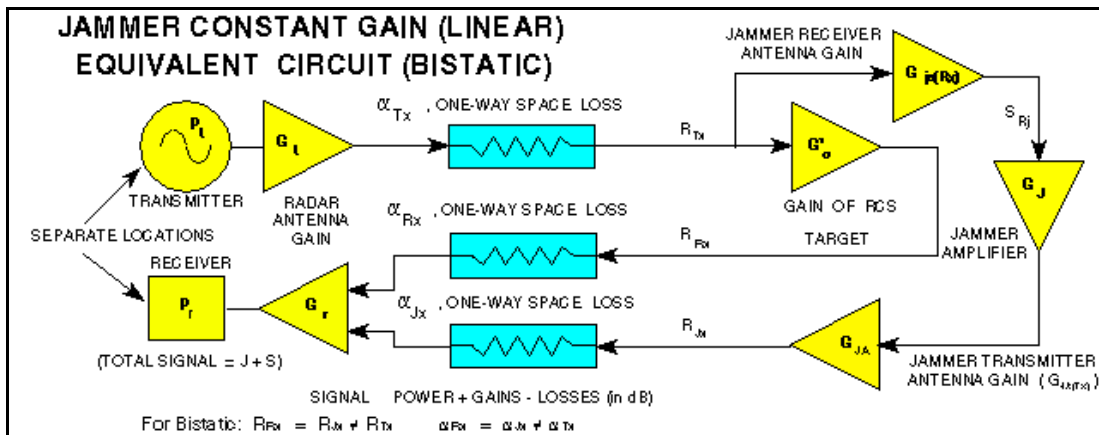


Figure 3. Jammer Constant Gain EA Equivalent Circuit (Bistatic).

To calculate J, the one way range equation from Section 4-3 is used twice:

$$J = \frac{P_t G_t G_{ja(Rx)} \lambda^2}{(4\pi R_{Tx})^2} \frac{G_j G_{ja(Tx)} G_r \lambda^2}{(4\pi R_{Rx})^2} \quad (R_{Jx} = R_{Rx}) \quad [9]$$

From the two way range equation in Section 4-4: $S = \frac{P_t G_t G_r \lambda^2 \sigma'}{(4\pi)^3 R_{Tx}^2 R_{Rx}^2}$ (σ' is bistatic RCS) [10]

Terms cancel when combined: $\frac{J}{S} = \frac{G_{ja(Rx)} G_j G_{ja(Tx)} \lambda^2}{4\pi\sigma'}$ *Keep λ and σ in same units* [11]

Or in dB form: $10\log J/S = 10\log G_{ja(Rx)} + 10\log G_j + 10\log G_{ja(Tx)} - 10\log (4\pi\sigma'/\lambda^2)$ [12]

Since the last term can be recognized as minus G_σ from equation [10] in Section 4-4, where the target gain factor, $G_\sigma = 10\log (4\pi\sigma'/\lambda^2) = 10\log (4\pi\sigma'f^2/c^2)$, it follows that:

$$10\log = 10\log G_{ja(Rx)} + 10\log G_j + 10\log G_{ja(Tx)} - G_\sigma' \quad (\text{factors in dB}) \quad [13]$$

Target gain factor, $G_\sigma = 10\log \sigma + 20\log f_1 + K_2$ (in dB)			
K ₂ Values			
(dB)	RCS (σ)	f_1 in MHz	f_1 in GHz
	(units)	$K_2 =$	$K_2 =$
	m ²	-38.54	21.46
	ft ²	-48.86	11.14

Linear J/S (Monostatic) Example (Linear Power Jamming)

Assume that a 5 GHz radar has a 70 dBm signal fed through a 5 dB loss transmission line to an antenna that has 45 dB gain. An aircraft that is flying 31 km from the radar has an aft EW antenna with -1 dB gain and a 5 dB line loss to the EW receiver (there is an additional loss due to any antenna polarization mismatch but that loss will not be addressed in this problem). The received signal is fed to a jammer with a gain of 60 dB, feeding a 10 dB loss transmission line which is connected to an antenna with 5 dB gain.

If the RCS of the aircraft is 9 m^2 , what is the J/S level received at the input to the receiver of the tracking radar?

Answer:

$$10\log J/S = 10\log G_{\text{ja(Rx)}} + 10\log G_j + 10\log G_{\text{ja(Tx)}} - G_\sigma$$

$$G_\sigma = 10\log \sigma + 20\log f_1 + K_2 = 10\log 9 + 20\log 5 + 21.46 = 44.98 \text{ dB}$$

Note: The respective transmission line losses will be combined with antenna gains, i.e. $-1 -5 = -6 \text{ dB}$ and $-10 + 5 = -5 \text{ dB}$

$$10\log J/S = -6 + 60 - 5 - 44.98 = 4.02 \text{ dB @ 5 GHz}$$

The answer changes to 1.1 dB if the tracking radar operates at 7 GHz provided the antenna gains and aircraft RCS are the same at both 5 and 7 GHz.

$$G_\sigma = 10\log 9 + 20\log 7 + 21.46 = 47.9 \text{ dB}$$

$$10\log J/S = -6 + 60 - 5 - 47.9 = 1.1 \text{ dB @ 7 GHz}$$

Separate J (-73.5 dBm @ 5 GHz and -79.34 dBm @ 7 GHz) and S (-77.52 dBm @ 5 GHz and -80.44 dBm @ 7 GHz) calculations for this problem are provided in Sections 4-3 and 4-4, respectively. A saturated gain version of this problem is provided in Section 4-7.

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RADAR CROSS SECTION (RCS)

Radar cross section is the measure of a target's ability to reflect radar signals in the direction of the radar receiver, i.e. it is a measure of the ratio of backscatter power per steradian (unit solid angle) in the direction of the radar (from the target) to the power density that is intercepted by the target.

The RCS of a target can be viewed as a comparison of the strength of the reflected signal from a target to the reflected signal from a perfectly smooth sphere of cross sectional area of 1 m² as shown in Figure 1.

The conceptual definition of RCS includes the fact that not all of the radiated energy falls on the target. A target's RCS (σ) is most easily visualized as the product of three factors:

$\sigma = \text{Projected cross section} \times \text{Reflectivity} \times \text{Directivity}$.

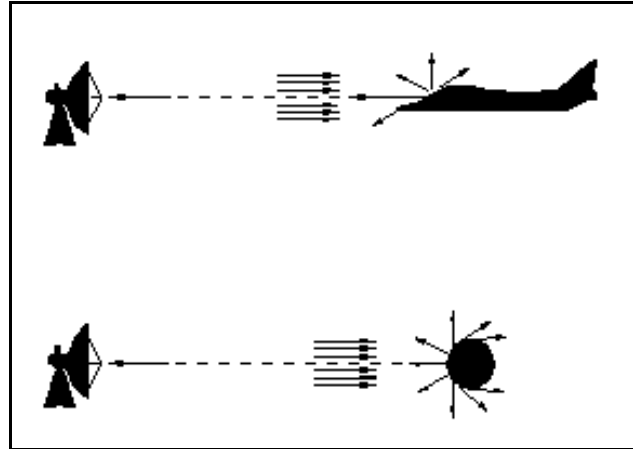


Figure 1. Concept of Radar Cross Section.

RCS(σ) is used in Section 4-4 for an equation representing power reradiated from the target.

Reflectivity: The percent of intercepted power reradiated (scattered) by the target.

Directivity: The ratio of the power scattered back in the radar's direction to the power that would have been backscattered had the scattering been uniform in all directions (i.e. isotropically).

Figures 2 and 3 show that RCS does not equal geometric area. For a sphere, the RCS, $\sigma = \pi r^2$, where r is the radius of the sphere.

The RCS of a sphere is independent of frequency if operating at sufficiently high frequencies where $\lambda \ll \text{Range}$, and $\lambda \ll \text{radius (r)}$. Experimentally, radar return reflected from a target is compared to the radar return reflected from a sphere which has a frontal or projected area of one square meter (i.e. diameter of about 44 in). Using the spherical shape aids in field or laboratory measurements since orientation or positioning of the sphere will not affect radar reflection intensity measurements as a flat plate would. If calibrated, other sources (cylinder, flat plate, or corner reflector, etc.) could be used for comparative measurements.

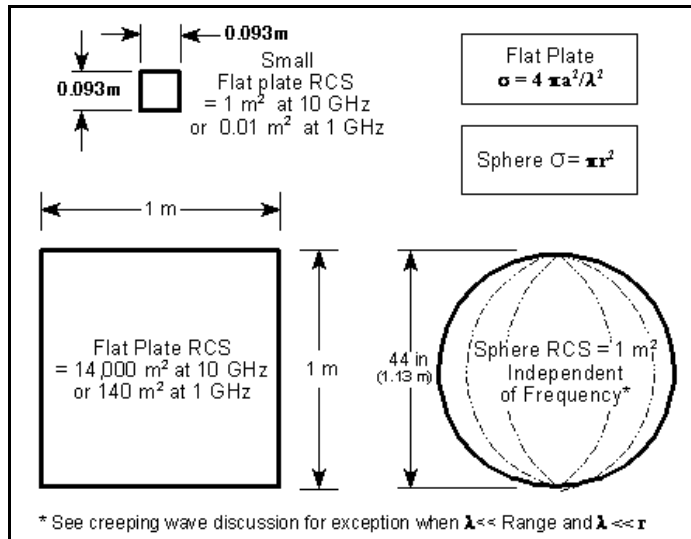


Figure 2. RCS vs. Physical Geometry.

To reduce drag during tests, towed spheres of 6", 14", or 22" diameter may be used instead of the larger 44" sphere, and the reference size is 0.018, 0.099, or 0.245 m² respectively instead of 1 m². When

smaller sized spheres are used for tests you may be operating at or near where $\lambda \sim$ radius. If the results are then scaled to a 1 m^2 reference, there may be some perturbations due to creeping waves. See the discussion at the end of this section for further details.

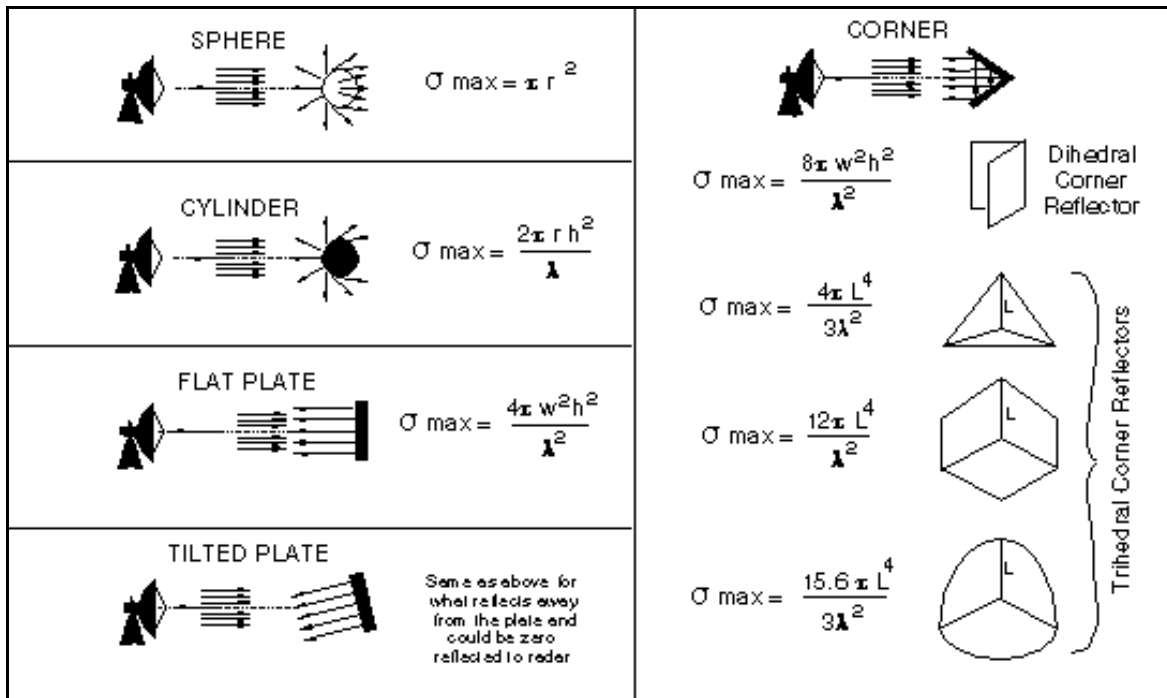


Figure 3. Backscatter From Shapes.

In Figure 4, RCS patterns are shown as objects are rotated about their vertical axes (the arrows indicate the direction of the radar reflections).

The sphere is essentially the same in all directions.

The flat plate has almost no RCS except when aligned directly toward the radar.

The corner reflector has an RCS almost as high as the flat plate but over a wider angle, i.e., over $\pm 60^\circ$. The return from a corner reflector is analogous to that of a flat plate always being perpendicular to your collocated transmitter and receiver.

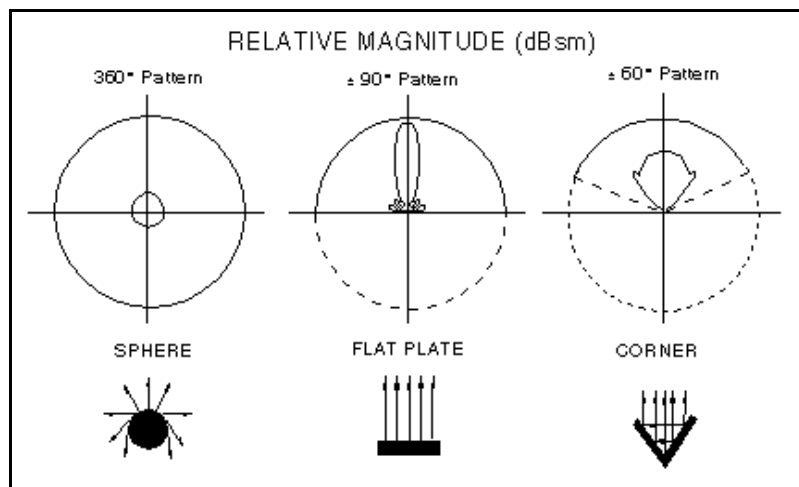


Figure 4. RCS Patterns.

Targets such as ships and aircraft often have many effective corners. Corners are sometimes used as calibration targets or as decoys, i.e. corner reflectors.

An aircraft target is very complex. It has a great many reflecting elements and shapes. The RCS of real aircraft must be measured. It varies significantly depending upon the direction of the illuminating radar.

Figure 5 shows a typical RCS plot of a jet aircraft. The plot is an azimuth cut made at zero degrees elevation (on the aircraft horizon). Within the normal radar range of 3-18 GHz, the radar return of an aircraft in a given direction will vary by a few dB as frequency and polarization vary (the RCS may change by a factor of 2-5). It does not vary as much as the flat plate.

As shown in Figure 5, the RCS is highest at the aircraft beam due to the large physical area observed by the radar and perpendicular aspect (increasing reflectivity). The next highest RCS area is the nose/tail area, largely because of reflections off the engines or propellers. Most self-protection jammers cover a field of view of +/- 60 degrees about the aircraft nose and tail, thus the high RCS on the beam does not have coverage. Beam coverage is frequently not provided due to inadequate power available to cover all aircraft quadrants, and the side of an aircraft is theoretically exposed to a threat 30% of the time over the average of all scenarios.

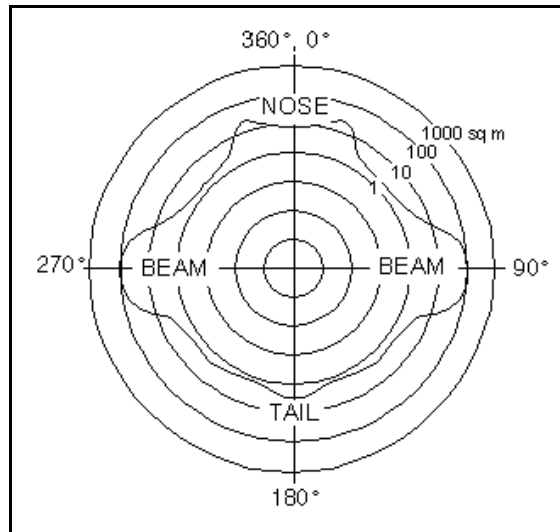


Figure 5. Typical Aircraft RCS.

Typical radar cross sections are as follows: Missile 0.5 sq m; Tactical Jet 5 to 100 sq m; Bomber 10 to 1000 sq m; and ships 3,000 to 1,000,000 sq m. RCS can also be expressed in decibels referenced to a square meter (dBsm) which equals $10 \log(\text{RCS in m}^2)$.

Again, Figure 5 shows that these values can vary dramatically. The strongest return depicted in the example is 100 m^2 in the beam, and the weakest is slightly more than 1 m^2 in the $135^\circ/225^\circ$ positions. These RCS values can be very misleading because other factors may affect the results. For example, phase differences, polarization, surface imperfections, and material type all greatly affect the results. In the above typical bomber example, the measured RCS may be much greater than 1000 square meters in certain circumstances ($90^\circ, 270^\circ$).

SIGNIFICANCE OF THE REDUCTION OF RCS

If each of the range or power equations that have an RCS (σ) term is evaluated for the significance of decreasing RCS, Figure 6 results. Therefore, an RCS reduction can increase aircraft survivability. The equations used in Figure 6 are as follows:

Range (radar detection):
From the 2-way range equation in Section 4-4:

$$P_r = \frac{P_t G_t G_r \lambda^2 \sigma}{(4\pi)^3 R^4} \text{ Therefore, } R^4 \propto \sigma \text{ or } \sigma^{1/4} \propto R$$

Range (radar burn-through):
The crossover equation in Section 4-8 has:

$$R_{BT}^2 = \frac{P_t G_t \sigma}{P_j G_j 4\pi} \text{ Therefore, } R_{BT}^2 \propto \sigma \text{ or } \sigma^{1/2} \propto R_{BT}$$

Power (jammer): Equating the received signal return (P_r) in the two way range equation to the received jammer signal (P_r) in the one way range equation, the following relationship results:

$$P_r = \frac{P_t G_t G_r \lambda^2 \sigma}{(4\pi)^3 R^4} = \frac{P_j G_j G_r \lambda^2}{(4\pi R)^2}$$

\uparrow
S

\uparrow
J

Therefore, $P_j \propto \sigma$ or $\sigma \propto P_j$

Note: jammer transmission line loss is combined with the jammer antenna gain to obtain G_t .

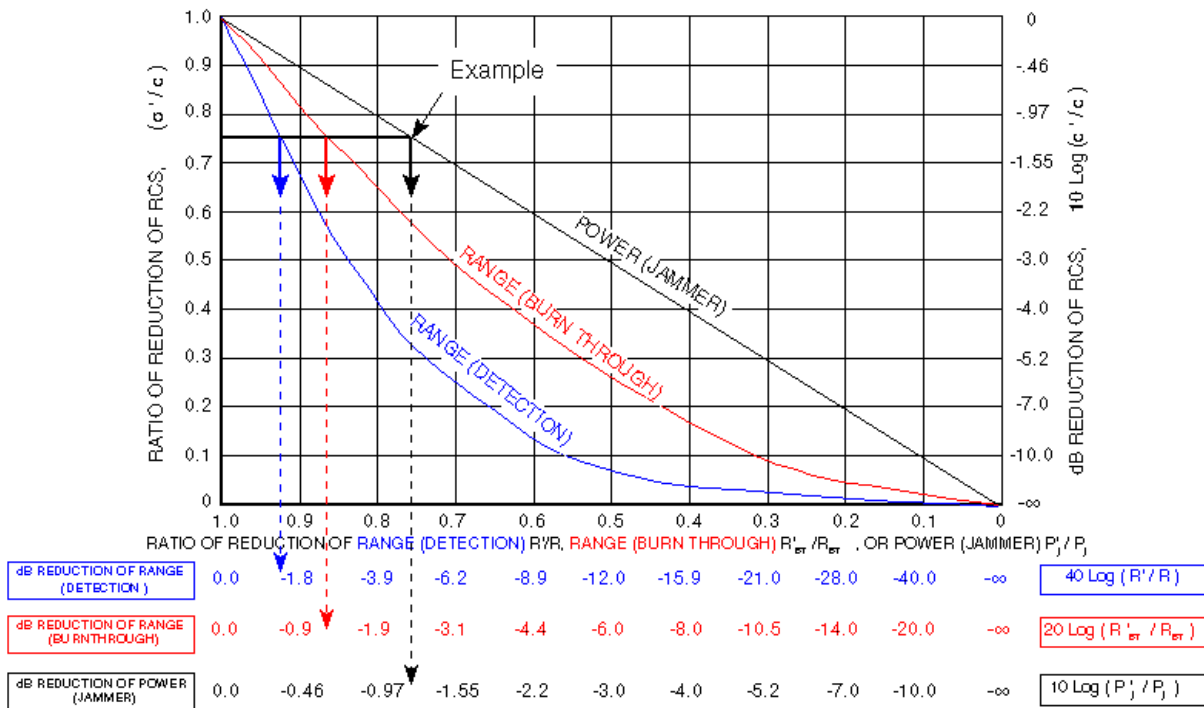


Figure 6. Reduction of RCS Affects Radar Detection, Burn-through, and Jammer Power.

Example of Effects of RCS Reduction - As shown in Figure 6, if the RCS of an aircraft is reduced to 0.75 (75%) of its original value, then (1) the jammer power required to achieve the same effectiveness would be 0.75 (75%) of the original value (or -1.25 dB). Likewise, (2) If Jammer power is held constant, then burn-through range is 0.87 (87%) of its original value (-1.25 dB), and (3) the detection range of the radar for the smaller RCS target (jamming not considered) is 0.93 (93%) of its original value (-1.25 dB).

OPTICAL / MIE / RAYLEIGH REGIONS

Figure 7 shows the different regions applicable for computing the RCS of a sphere. The optical region (“far field” counterpart) rules apply when $2\pi r/\lambda > 10$. In this region, the RCS of a sphere is independent of frequency. Here, the RCS of a sphere, $\sigma = \pi r^2$. The RCS equation breaks down primarily due

to creeping waves in the area where $\lambda \sim 2\pi r$. This area is known as the Mie or resonance region. If we were using a 6" diameter sphere, this frequency would be 0.6 GHz. (Any frequency ten times higher, or above 6 GHz, would give expected results). The largest positive perturbation (point A) occurs at exactly 0.6 GHz where the RCS would be 4 times higher than the RCS computed using the optical region formula. Just slightly above 0.6 GHz a minimum occurs (point B) and the actual RCS would be 0.26 times the value calculated by using the optical region formula. If we used a one meter diameter sphere, the perturbations would occur at 95 MHz, so any frequency above 950 MHz (~1 GHz) would give predicted results.

CREEPING WAVES

The initial RCS assumptions presume that we are operating in the optical region ($\lambda \ll \text{Range}$ and $\lambda \ll \text{radius}$). There is a region where specular reflected (mirrored) waves combine with back scattered creeping waves both constructively and destructively as shown in Figure 8. Creeping waves are tangential to a smooth surface and follow the "shadow" region of the body. They occur when the circumference of the sphere $\sim \lambda$ and typically add about 1 m^2 to the RCS at certain frequencies.

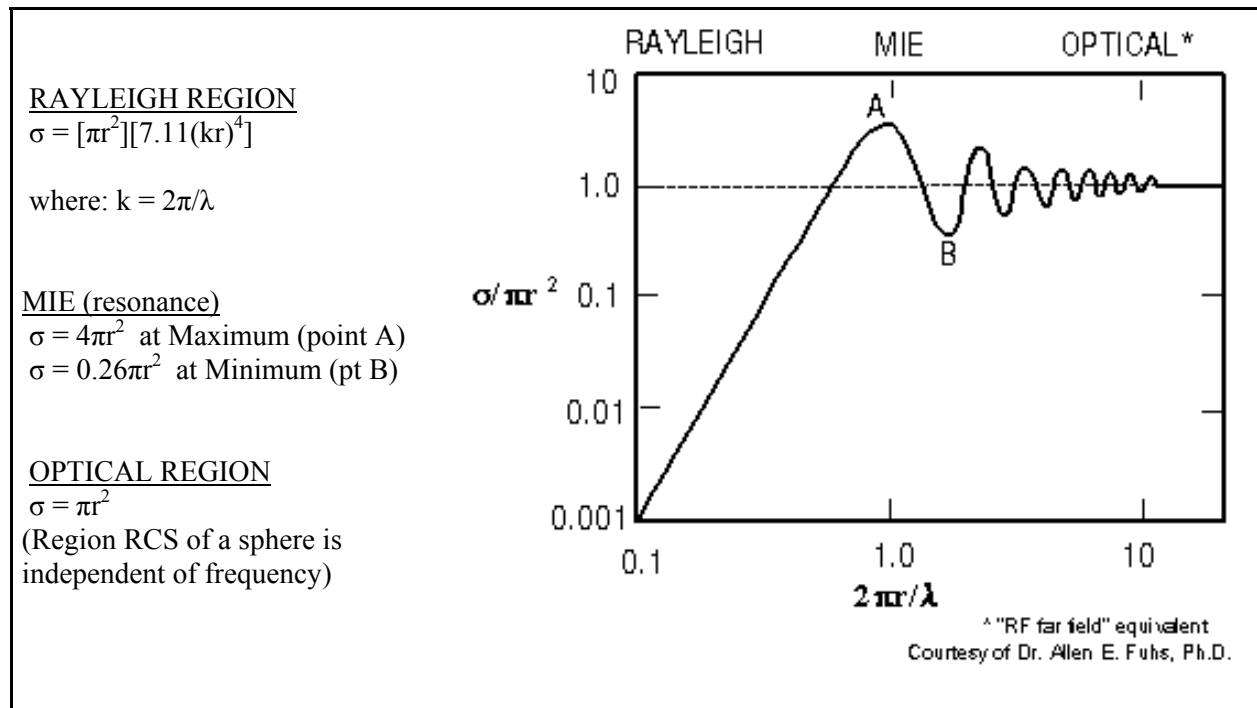


Figure 7. Radar Cross Section of a Sphere.

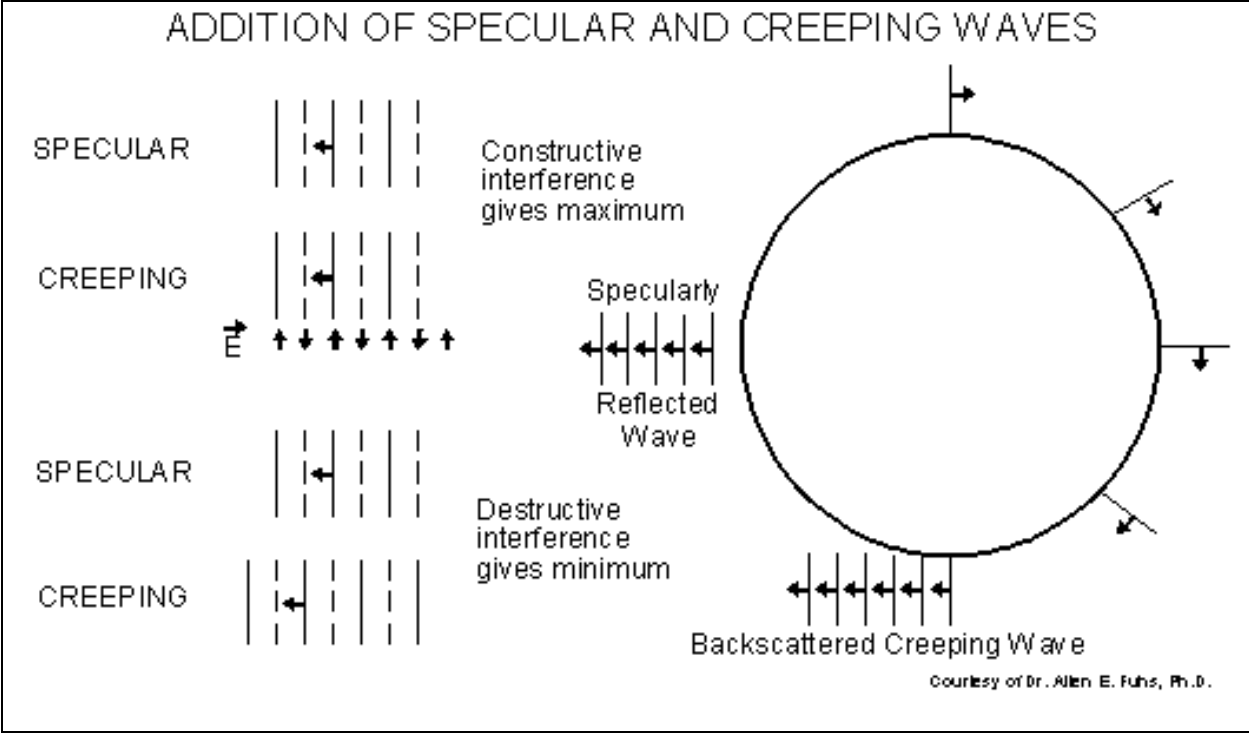


Figure 8. Addition of Specular and Creeping Waves.

EMISSION CONTROL (EMCON)

When EMCON is imposed, RF emissions must not exceed -110 dBm/meter^2 at one nautical mile. It is best if systems meet EMCON when in either the Standby or Receive mode versus just the Standby mode (or OFF). If one assumes antenna gain equals line loss, then emissions measured at the port of a system must not exceed -34 dBm (i.e. the stated requirement at one nautical mile is converted to a measurement at the antenna of a point source - see Figure 1). If antenna gain is greater than line loss (i.e. gain 6 dB , line loss 3 dB), then the -34 dBm value would be lowered by the difference and would be -37 dBm for the example. The opposite would be true if antenna gain is less.

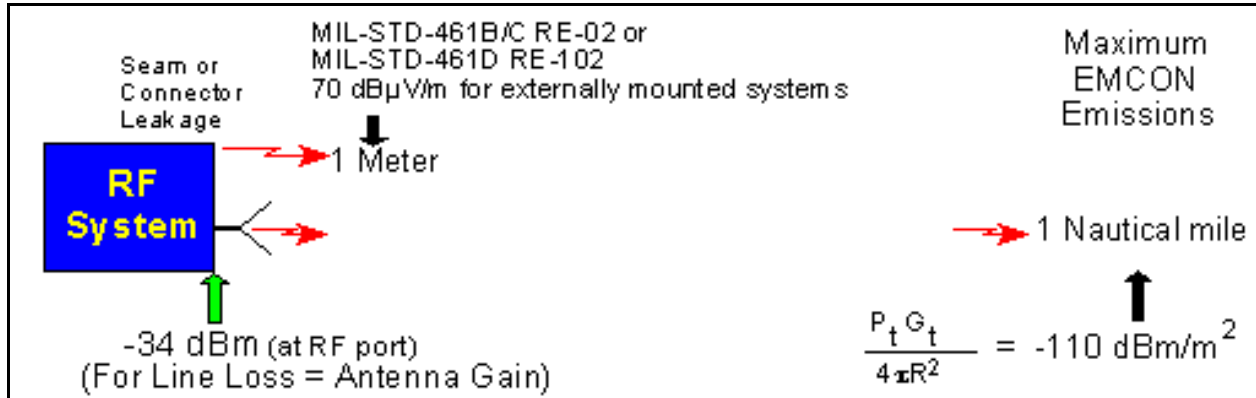


Figure 1. EMCON Field Intensity / Power Density Measurements.

To compute the strength of emissions at the antenna port in Figure 1, we use the power density equation (see Section 4-2)

$$P_D = \frac{P_t G_t}{4\pi R^2} \quad [1] \quad \text{or rearranging} \quad P_t G_t = P_D (4\pi R^2) \quad [2]$$

Given that $P_D = -110 \text{ dBm/m}^2 = (10)^{-11} \text{ mW/m}^2$, and $R = 1 \text{ NM} = 1852 \text{ meters}$.

$$P_t G_t = P_D (4\pi R^2) = (10)^{-11} \text{ mW/m}^2 (4\pi)(1852\text{m})^2 = 4.31(10)^{-4} \text{ mW} = -33.65 \approx -34 \text{ dBm}$$

at the RF system antenna as given.

or, the equation can be rewritten in Log form and each term multiplied by 10:

$$10\log P_t + 10\log G_t = 10\log P_D + 10\log (4\pi R^2) \quad [3]$$

Since the m^2 terms on the right side of equation [3] cancel, then:

$$10\log P_t + 10\log G_t = -110 \text{ dBm} + 76.35 \text{ dB} = -33.65 \text{ dBm} \approx -34 \text{ dBm} \text{ as given in Figure 1.}$$

If MIL-STD-461B/C RE02 (or MIL-STD-461D RE-102) measurements (see Figure 2) are made on seam/connector leakage of a system, emissions below $70 \text{ dB}\mu\text{V/meter}$ which are measured at one meter will meet the EMCON requirement. Note that the airframe provides attenuation so portions of systems mounted inside an aircraft that measure $90 \text{ dB}\mu\text{V/meter}$ will still meet EMCON if the airframe provides 20 dB of shielding (note that the requirement at one nm is converted to what would be measured at one meter from a point source).

The narrowband emission limit shown in Figure 2 for RE02/RE102 primarily reflect special concern for local oscillator leakage during EMCON as opposed to switching transients which would apply more to the broadband limit.

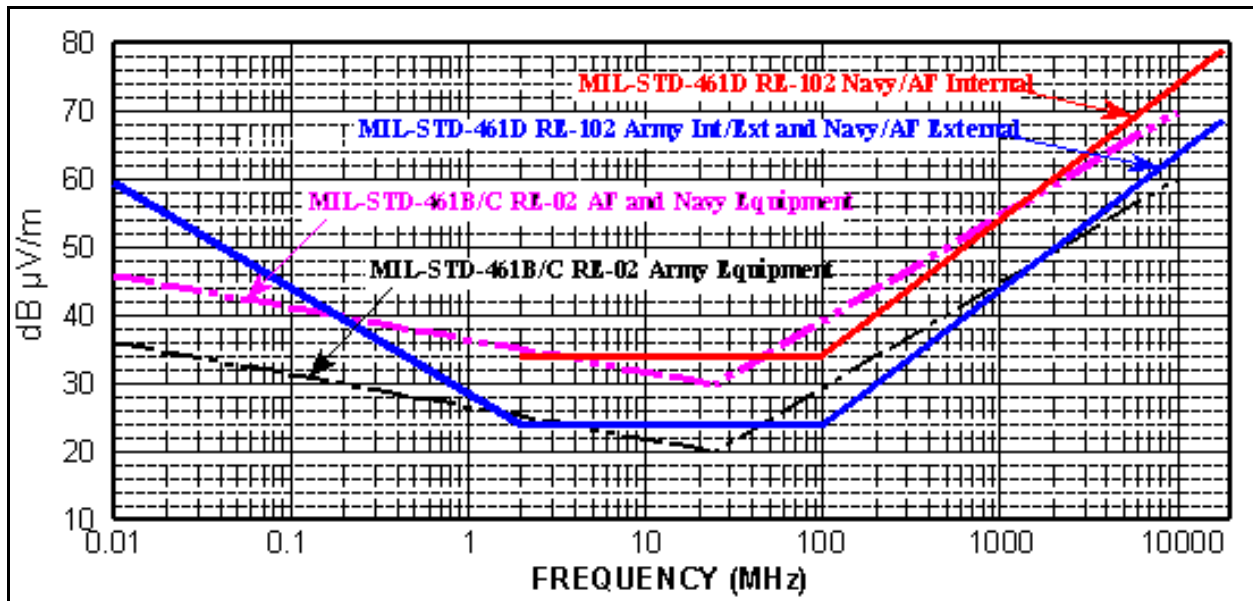


Figure 3. MIL-STD-461 Narrowband Radiated Emissions Limits.

Note that in MIL-STD-461D, the narrowband radiated emissions limits were retitled RE-102 from the previous RE-02 and the upper frequency limit was raised from 10 GHz to 18 GHz. The majority of this section will continue to reference RE02 since most systems in use today were built to MIL-STD-461B/C.

For the other calculation involving leakage (to obtain 70 dBμV/m) we again start with: $P_D = \frac{P_t G_t}{4\pi R^2}$ and use the previous fact that: $10\log(P_t G_t) = -33.6 \text{ dBm} = 4.37 \times 10^{-4} \text{ mW}$ (see Section 2-4).

The measurement is at one meter so $R^2 = 1 \text{ m}^2$

we have: $\frac{4.37 \times 10^{-4} \text{ mW}}{4\pi} \text{ mW/m}^2 = .348 \times 10^{-4} \text{ mW/m}^2 = -44.6 \text{ dBm/m}^2 = P_D @ 1 \text{ meter}$

Using the field intensity and power density relations (see Section 4-1)

$$E = \sqrt{P_D Z} = \sqrt{3.48 \times 10^{-8} \cdot 377 \Omega} = 36.2 \times 10^{-4} \text{ V/m}$$

Changing to microvolts ($1\text{V} = 10^6 \mu\text{V}$) and converting to logs we have:

$20 \log(E) = 20 \log(10^6 \times 36.2 \times 10^{-4}) = 20 \log(.362 \times 10^4) = 71.18 \text{ dB}\mu\text{V/m} \approx 70 \text{ dB}\mu\text{V/m}$ as given in Figure 1.

Some Words of Caution

A common error is to only use the one-way free space loss coefficient α_1 directly from Figure 6, Section 4-3 to calculate what the output power would be to achieve the EMCON limits at 1 NM. This is incorrect since the last term on the right of equation [3] ($10 \text{ Log}(4\pi R^2)$) is simply the Log of the surface area of a sphere - **it is NOT** the one-way free space loss factor α_1 . You cannot interchange power (watts or dBW) with power density (watts/m² or dBW/m²).

The equation uses power density (P_D), **NOT** received power (P_r). It is independent of RF and therefore varies only with range. If the source is a transmitter and/or antenna, then the power-gain product (or EIRP) is easily measured and it's readily apparent if $10\log(P_t G_t)$ is less than -34 dBm. If the output of the measurement system is connected to a power meter in place of the system transmission line and antenna, the -34 dBm value must be adjusted. The measurement on the power meter (dBm) minus line loss (dB) plus antenna gain (dB) must not be higher than -34 dBm.

However, many sources of radiation are through leakage, or are otherwise inaccessible to direct measurement and P_D must be measured with an antenna and a receiver. The measurements must be made at some RF(s), and received signal strength is a function of the antenna used therefore measurements must be scaled with an appropriate correction factor to obtain correct power density.

RE-02 Measurements

When RE-02 measurements are made, several different antennas are chosen dependent upon the frequency range under consideration. The voltage measured at the output terminals of an antenna is not the actual field intensity due to actual antenna gain, aperture characteristics, and loading effects. To account for this difference, the antenna factor is defined as:

$$AF = E/V \quad [4]$$

where E = Unknown electric field to be determined in V/m (or $\mu\text{V/m}$)
 V = Voltage measured at the output terminals of the measuring antenna

For an antenna loaded by a 50Ω line (receiver), the theoretical antenna factor is developed as follows:

$$P_D A_e = P_r = V^2/R = V_r^2/50 \text{ or } V_r = \sqrt{50 P_D A_e}$$

From Section 4-3 we see that $A_e = G_r \lambda^2 / 4\pi$, and from Section 4-1, $E^2 = 377 P_D$ therefore we have:

$$AF = \frac{E}{V} = \frac{\sqrt{377 P_D}}{\sqrt{50 P_D (\lambda^2 G_r / 4\pi)}} = \frac{9.73}{\lambda \sqrt{G_r}} \quad [5]$$

Reducing this to decibel form we have:

$$20 \log AF = 20 \log E - 20 \log V = 20 \log \left[\frac{9.73}{\lambda \sqrt{GSUBr}} \right] \text{ with } \lambda \text{ in meters and Gain numeric ratio (not dB)} \quad [6]$$

This equation is plotted in Figure 3.

Since all of the equations in this section were developed using far field antenna theory, use only the indicated region.

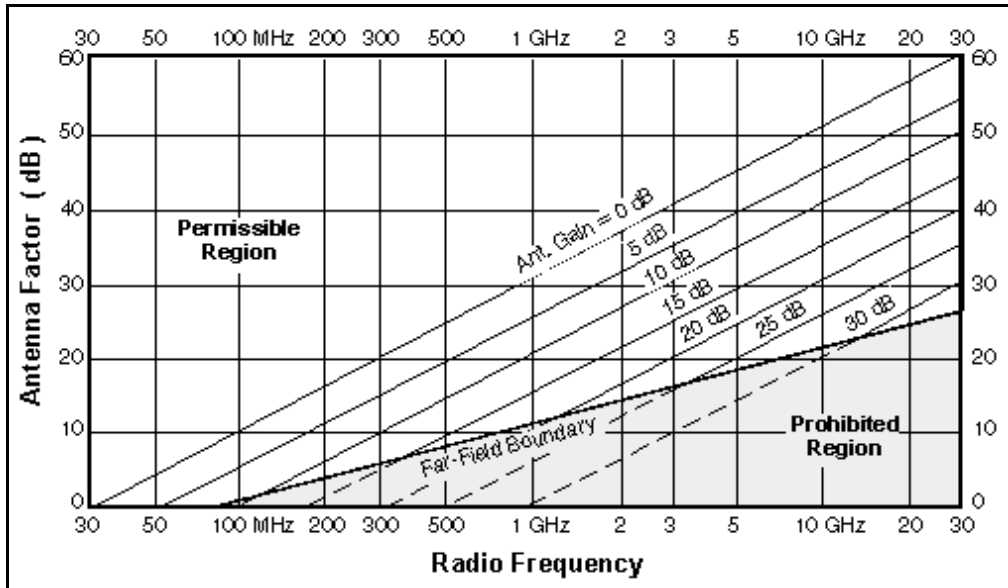


Figure 3. Antenna Factor vs. Frequency for Indicated Antenna Gain.

In practice the electric field is measured by attaching a field intensity meter or spectrum analyzer with a narrow bandpass preselector filter to the measuring antenna, recording the actual reading in volts and applying the antenna factor.

$$20 \log E = 20 \log V + 20 \log AF \quad [7]$$

Each of the antennas used for EMI measurements normally has a calibration sheet for both gain and antenna factor over the frequency range that the antenna is expected to be used. Typical values are presented in Table 1.

Table 1. Typical Antenna Factor Values.

Frequency Range	Antenna(s) Used	Antenna Factor	Gain(dB)
14 kHz - 30 MHz	41" rod	22-58 dB	0 - 2
20 MHz - 200 MHz	Dipole or Biconical	0-18 dB	0 - 11
200 MHz - 1 GHz	Conical Log Spiral	17-26 dB	0 - 15
1 GHz - 10 GHz	Conical Log Spiral or Ridged Horn	21-48 dB	0 - 28
1 GHz - 18 GHz	Double Ridged Horn	21-47 dB	0 - 32
18 GHz - 40 GHz	Parabolic Dish	20-25 dB	27 - 35

The antenna factor can also be developed in terms of the receiving antenna's effective area. This can be shown as follows:

$$AF = \frac{E}{V} = \frac{\sqrt{377 P_D}}{\sqrt{50 P_D A_e}} = \frac{2.75}{\sqrt{A_e}} \quad [8]$$

Or in log form:

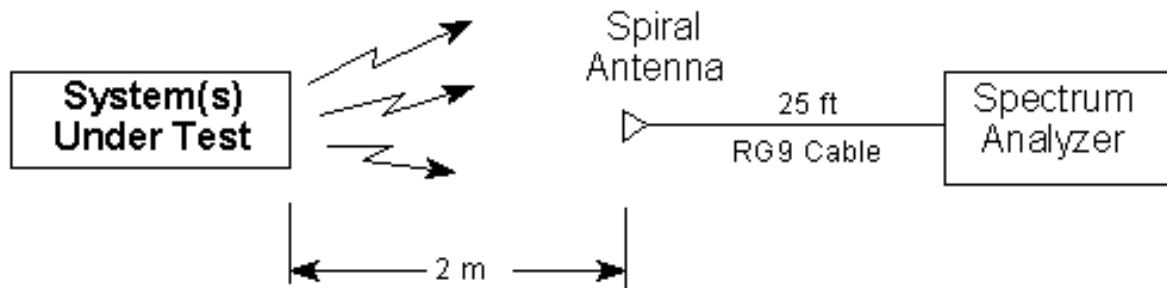
$$20 \log AF = 20 \log E - 20 \log V = 20 \log \left[\frac{2.75}{\sqrt{A_e}} \right] \quad [9]$$

While this relation holds for any antenna, many antennas (spiral, dipole, conical etc.) which do not have a true "frontal capture area" do not have a linear or logarithmic relation between area and gain and in that respect the parabolic dish is unique in that the antenna factor does not vary with frequency, only with effective capture area. Consequently a larger effective area results in a smaller antenna factor.

A calibrated antenna would be the first choice for making measurements, followed by use of a parabolic dish or "standard gain" horn. A standard gain horn is one which was designed such that it closely follows the rules of thumb regarding area/gain and has a constant antenna factor. If a calibrated antenna, parabolic dish, or "standard horn" is not available, a good procedure is to utilize a flat spiral antenna (such as the AN/ALR-67 high band antennas). These antennas typically have an average gain of 0 dB (typically -4 to +4 dB), consequently the antenna factor would not vary a lot and any error would be small.

EXAMPLE:

Suppose that we want to make a very general estimation regarding the ability of a system to meet EMC requirements. We choose to use a spiral antenna for measurements and take one of our samples at 4 GHz. Since we know the gain of the spiral is relatively flat at 4 GHz and has a gain value of approximately one (0 dB) in that frequency range. The antenna is connected to a spectrum analyzer by 25 feet of RG9 cable. We want to take our measurements at 2 meters from the system so our setup is shown as follows:



Our RG9 cable has an input impedance of 50Ω, and a loss of 5 dB (from Figure 5, Section 6-1).

First, let's assume that we measure -85 dBm at the spectrum analyzer and we want to translate this into the equivalent strength at 1 NM. Our power received by the antenna is: $P_r = -85 \text{ dBm} + 5 \text{ dB line loss} = -80 \text{ dBm}$

$$\text{also } P_D = P_r/A_e \text{ and } A_e = G\lambda^2/4\pi = (G/4\pi) \cdot (c/f)^2 = (1/4\pi) \cdot (3 \times 10^8 / 4 \times 10^9)^2 = 4.47 \times 10^{-4} \text{ m}^2$$

$$\text{in log form: } 10 \text{ Log } P_D = 10 \text{ Log } P_r - 10 \text{ Log } A_e = -80 \text{ dBm} + 33.5 = -46.5 \text{ dBm/m}^2 \\ \text{at our 2 meter measuring point}$$

To convert this to a value at 1 NM, we use

$$P_t G_t = P_{D@1 \text{ nm}} 4\pi R_1^2 = P_{D@2 \text{ m}} 4\pi R_2^2 \text{ and we solve for } P_{D@1 \text{ nm}}$$

in log form after cancelling the 4π terms:

$$10 \text{ Log } P_{D@1 \text{ nm}} = 10 \text{ Log } P_{D@2 \text{ m}} + 10 \text{ Log } (R_{2\text{m}}/R_{1\text{nm}})^2 = -46.5 \text{ dBm/m}^2 - 59.3 \text{ dB} = -105.8 \text{ dBm/m}^2 \\ \text{which is more power than the maximum value of } -110 \text{ dBm/m}^2 \text{ specified.}$$

If we are making repetitive measurement as we might do when screening an aircraft on the flight line with numerous systems installed, or when we want to improve (reduce) the leakage on a single system by changing antennas, lines, connectors, or EMI gaskets or shielding, this mathematical approach would be unnecessarily time consuming since it would have to be repeated after each measurement. A better approach would be to convert the -110 dBm/m² value at 1 NM to the maximum you can have at the measuring instrument (in this case a spectrum analyzer), then you could make multiple measurements and know immediately how your system(s) are doing. It should be noted that -90 to -100 dBm is about the minimum signal level that can be detected by a spectrum analyzer, so you couldn't take measurements much further away unless you used an antenna with a much higher gain.

In order not to exceed EMCON, the power density must not exceed -110 dBm/m² at 1 NM, which is 10^{-11} mW/m^2 .

$$P_t G_t = P_{D@1 \text{ nm}} 4\pi R_1^2 = P_{D@2 \text{ m}} 4\pi R_2^2$$

$$\text{we solve for } P_{D@2 \text{ m}} = 10^{-11} (1852\text{m})^2 / (2\text{m})^2 = 8.57 \times 10^{-6} \text{ mW/m}^2 = -50.7 \text{ dBm/m}^2$$

We'll be using a spectrum analyzer, so we want to compute what the maximum power or voltage may be.

Method 1 - Using the Power Density Approach

Using logs/dB and the values of $P_{D@2 \text{ m}}$ and A_e determined previously:

$$10 \text{ Log } P_r = 10 \text{ Log } P_D + 10 \text{ Log } A_e = -50.7 - 33.5 = -84.2 \text{ dBm}$$

taking line loss into account we have: $-84.2 - 5 \text{ dB} = \underline{-89.2 \text{ dBm}}$ as the maximum measurement reading.

If we wanted to calculate it in volts, and take into account our line impedance we would have the following:

$$P_r = P_D A_e = V^2/R = V^2/50\Omega \quad \text{also} \quad A_e = G\lambda^2/4\pi \quad \text{so solving for V we have:}$$

$$V = \sqrt{P_D \left[\frac{G_r \lambda^2}{4\pi} \right] R} = \sqrt{P_D \left[\frac{G_r \left(\frac{c}{f} \right)^2}{4\pi} \right] R} = \sqrt{8.57 \times 10^{-9} \left[\frac{1 \left(\frac{3 \times 10^8}{4 \times 10^9} \right)^2}{4\pi} \right] 50\Omega} = 1.38 \times 10^{-5} \text{ volts (before line loss)}$$

since our line loss is 5 dB, we have $-5 \text{ dB} = 20 \text{ Log } V_2/V_1$. Solving for V_2 we get 7.79×10^{-6} volts or -89 dBm as a maximum at our measurement device input. We can see immediately that our value of -85 dBm that we measured on the previous page would not meet specifications, and neither would any signal with more power than -89 dBm.

Method 2 - Using the Antenna Factor Approach

Starting with the same value of power density that we obtained above ($8.57 \times 10^{-9} \text{ W/m}^2$), we find the field intensity from Table 1, Section 4-1 to be approximately 65 dB $\mu\text{v/m}$. Also from Figure 3 in this section, AF = 43 dB @ 4 GHz (by calculating with equation [6], the exact value is 42.3 dB).

From equation [6]:

$$20 \log V = 20 \log E - 20 \log \text{AF}$$

$$20 \log V = 65 - 43 = 22 \text{ dB}\mu\text{v/m.}$$

Since $\text{dB}\mu\text{v/m} = 20 \log (V)(10^6) = 20 \log V + 20 \log 10^6 = 20 \log V + 120$, we see that to get an answer in dBv we must subtract 120 from the dB $\mu\text{v/m}$ value so: $V_{\text{dB}} = 22 - 120 = -98 \text{ dBv}$. We then subtract our line loss (-5 dB) and we have:

$$V = -98 - 5 = -103 \text{ dBv} = 17 \text{ dB}\mu\text{v} = \underline{7.1 \times 10^{-6} \text{ volts}}$$

using the fact that $P = V^2/R$ and for the input line $R = 50\Omega$, $P = 1 \times 10^{-12} \text{ W} = -120 \text{ dBW} = \underline{-90 \text{ dBm}}$

Although this method is just as accurate as that obtained using method 1, the values obtained in Table 1, Section 4-1, and Figure 3 must be interpolated, and may not result in values which are as precise as the appropriate formulas would produce.

Sample Problem: What is the approximate transmit power from a receiver?

- | | | | | | |
|----|-------------------------------|----|-------------------|----|-----------------|
| A. | 1 nanowatt (nW) | F. | 100 μW | K. | 10 W |
| B. | 10 nW | G. | 1 milliwatt (mW) | L. | 100 W |
| C. | 100 nW | H. | 10 mW | M. | 1 kilowatt (kW) |
| D. | 1 microwatt (μW) | I. | 100 mW | N. | 10 kW |
| E. | 10 μW | J. | 1 watt (W) | O. | 100 kW |

The question may seem inappropriate since a receiver is supposedly a passive device which only receives a signal. If the receiver was a crystal video receiver as shown in Section 5-3, it wouldn't transmit power unless a built-in-test (BIT) signal was injected after the antenna to periodically check the integrity of the microwave path and components. The potential exists for the BIT signal to leak across switches and couple back through the input path and be transmitted by the receiver's antennas.

If the receiver uses a local oscillator (LO) and a mixer to translate the signal to an intermediate frequency (IF) for processing (such as a superhet shown in Section 5-3), there is the potential for the CW LO signal to couple back through the signal input path and be transmitted by the receiver's antenna. Normally a mixer has 20 dB of rejection for the reverse direction. In addition, the LO may be further attenuated by receiver front end filters.

In both cases, the use of isolators described in Section 6-7 could be used to further attenuate any signals going in the reverse direction, i.e. back to the antenna. A good receiver design should ensure that any RF leakage radiated by the receiver will not exceed the EMCON level.

In answer to the initial question, "transmit" leakage power should be less than -34 dBm (0.4 μ W) to meet EMCON. Therefore, the real answer may be "A," "B," or "C" if EMCON is met and could be "D" through possibly "G" if EMCON is not met.