Application Note

Measurement of Radar Cross Section Using the "VNA Master" Handheld VNA

By Martin I. Grace

Radar cross section RCS is the measure of an object's ability to reflect radar signal in the direction of the radar receiver i.e. it is the measure of the ratio of backscatter per steradian (unit solid angle) in the direction of the radar (from the target) to the power density that is intercepted by the target. This application note describes how a modern battery-powered / portable Microwave Vector Network Analyzer with Time Domain Gating can make it easy to do RCS tests on the flight line or in the field.

The RCS of a target can be visualized as a comparison of the power of the reflected signal from a target to the reflected signal from a perfectly conducting smooth sphere of RCS area of 1 m^2 as shown in figure (1).

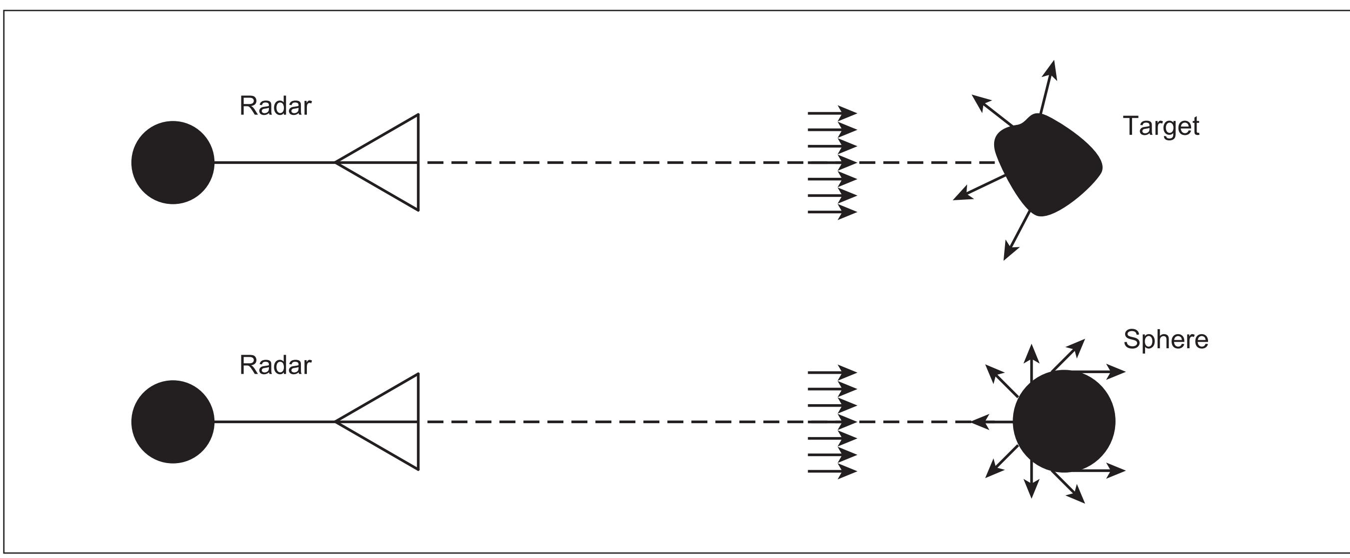

Figure 1. Concept of Radar Cross Section.

The RCS of a sphere is independent of frequency provided that the wavelength λ is much less than the range R >15 λ to the sphere and the effective sphere radius r_s >15 λ.

Radar Range Equation

The radar system as described in figure (2) transmits a pulse of energy through the transmit antenna of gain G_t. The amplitude of the signal at the output of the transmit antenna is reduced by the free space propagation loss. At the target some of the power (backscatter) is reflected back towards the radar. The ratio of the backscatter power to the incident power is the RCS (σ_{tgt}) of the target. The amplitude is then again further reduced by the free space propagation loss. The signal is then received by the receive antenna with gain G_r and detected in the receiver. The power level P_r in the receiver is[1]:

$$P_r = \frac{P_t \cdot G_t \cdot G_r \cdot \sigma_{target} \cdot \lambda^2}{(4\pi)^3 \cdot R^4}$$

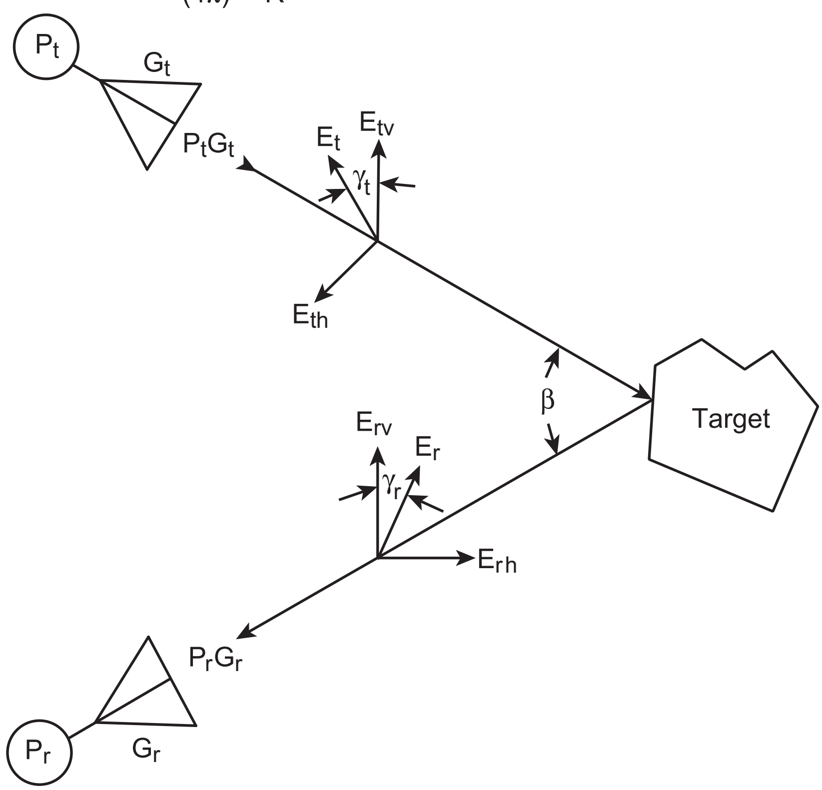

Figure 2. Typical Radar showing transmitter and receiver separated by the angle β, for a monostatic radar both transmit and receive antenna are identical (angle β = 0) and are located a distance R from the target. Arbitrary transmitted and received polarizations may be resolved as shown.

Most radars operate in a monostatic configuration, where both transmit and receive antenna are common and a duplexer is used to separate transmit and receive signals.

[1] www.tscm.com/2waymon.pdf

The block diagram describing the physical representation of the radar is shown in figure (3).

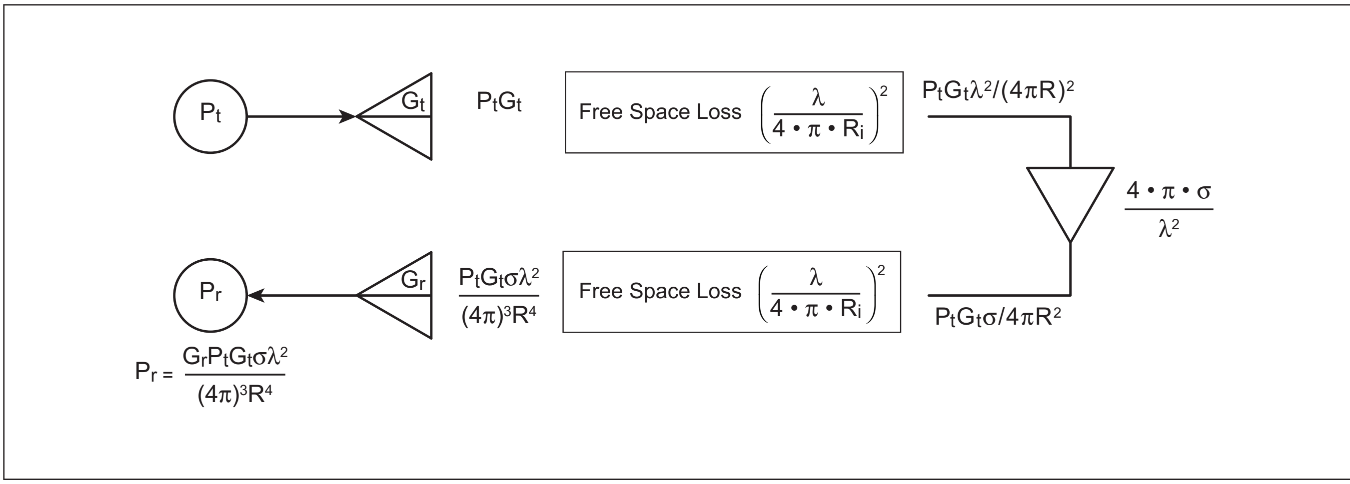

Figure 3. Physical Block diagram for the RCS measurement.

P_t = Radar transmitter power
P_r = Radar receive power
G_t = Radar transmit antenna gain
G_r = Radar Receive antenna gain
G_σ = equivalent Gain of the RCS
A_e = Radar Receive antenna effective area (meters)^2
R = Range to target (meters)
λ = Wavelength (meters)
σ_{tgt} = Radar Cross Section of the target (meters)^2 (Defined as kP_r/P_t where k is a constant)

The RCS is given by:

$$\sigma_{target} = \frac{P_r}{P_t} \cdot \left[\frac{(4\pi)^3 \cdot R^4}{G_t \cdot G_r \cdot \lambda^2}\right] = k \cdot \frac{P_r}{P_t}$$

The equivalent circuit description of the Radar is shown in figure (4). The transmit and receive antenna gains are represented by amplifiers as is the RCS of the target.

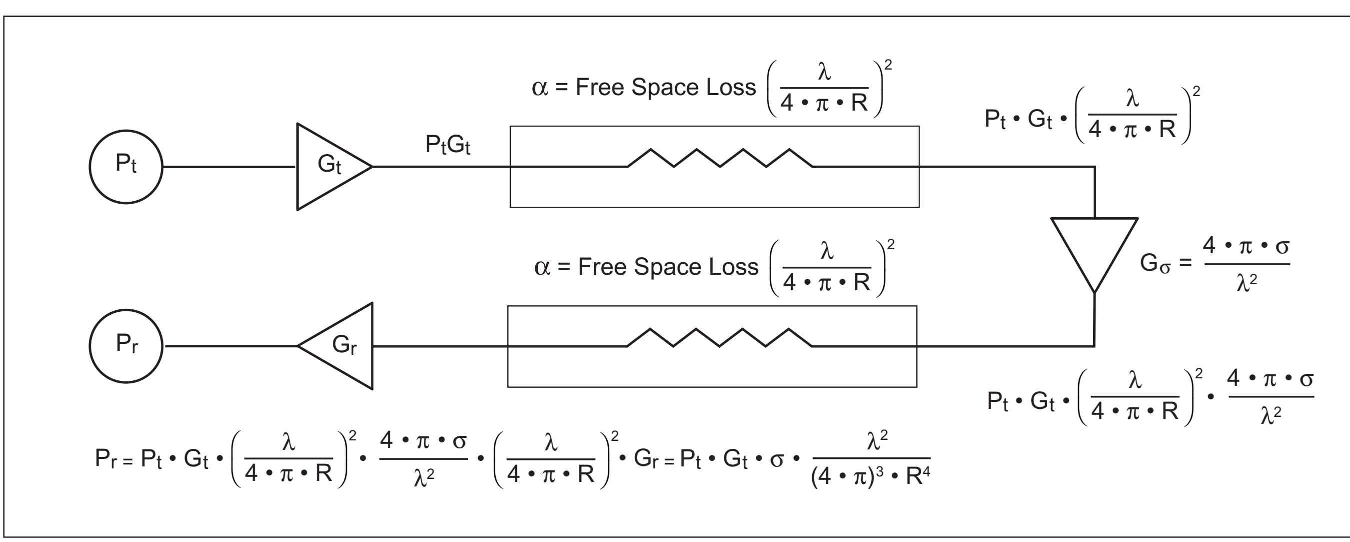

Figure 4. Circuit Block Diagram for the RCS measurement.

Resistors are used to represent the propagation losses. The VNA system when used to measure S21 has the same equivalent circuit description as the radar. The VNA measures the frequency domain response S21 of the system when Port 1 of the VNA is connected to the transmit antenna and Port 2 is connected to the receive antenna.

Although Vector Network Analyzers are most commonly used to provide measurements vs. frequency, the addition of Time Domain analysis and Time Gating help simulate pulsed radar functionality by removing reflections distances not associated with the target. The 12 term error correction of the VNA will minimize the systematic errors due to mismatch, leakage and accurately establish a reference plane.

Polarization[2]

The polarization of the electric field vector of the reflected signal can be different than that of the transmitted radar signal. The shape of the target is responsible for the depolarizing characteristics (angular difference γ_t - γ_r) as described in figure (2).

To correct for the depolarization, full polarization matrix imaging is utilized by measuring both the vertical and horizontal components of the electric field independently. This will require two transmit and two receive polarizations (horizontal H and vertical V).

Transmit	**Receive**
Vertical Polarization	Vertical Polarization/ Horizontal Polarization
Horizontal	Vertical Polarization/ Horizontal Polarization

From the above measurements a polarization matrix is generated to describe the effect of the polarization to correct for the depolarization.

$$E_t = E_{tv} \cdot \cos(\gamma_t) + E_{th} \cdot \sin(\gamma_t)$$
$$E_r = E_{rv} \cdot \cos(\gamma_r) + E_{rh} \cdot \sin(\gamma_r)$$

E_t and E_r are decomposed to:

$$E_{rv} = S_{w} \cdot E_{tv} + S_{hv} \cdot E_{th}$$
$$E_{rh} = S_{vh} \cdot E_{tv} + S_{hh} \cdot E_{th}$$

S_{xx} is a complex number defining the 4 possible measurement conditions

$$S = \begin{pmatrix} S_{vv} & S_{hv} \\ S_{vh} & S_{hh} \end{pmatrix}$$

Where:

S_{vv}: transmit vertical polarization, receive vertical polarization
S_{vh}: transmit vertical polarization, receive horizontal polarization
S_{hv}: transmit horizontal polarization, receive vertical polarization
S_{hh}: transmit horizontal polarization, receive horizontal polarization

The resulting RCS:

$$\sigma = \begin{pmatrix} \sqrt{\sigma_{vv}} & \sqrt{\sigma_{hv}} \\ \sqrt{\sigma_{vh}} & \sqrt{\sigma_{hh}} \end{pmatrix}$$

If the transmit antenna is vertically polarized, the RCS is:

$$\sigma = (P_{rv} + P_{rh})/P_t$$

[2] Radar cross section measurements Eugene F. Knott - 2006 - Technology & Engineering – pages 17-21

VNA Measurements

The VNA shown in figure (5) measures the S-parameters in the frequency domain. The frequency range for the measurements is chosen to correspond to the radar frequency band (8.2 – 12.4 GHz for WR-90 X-band waveguide). The time domain function of the VNA will transform the S-parameter frequency domain measurement (Γ vs. frequency) to the time domain (Γ vs. time or distance).

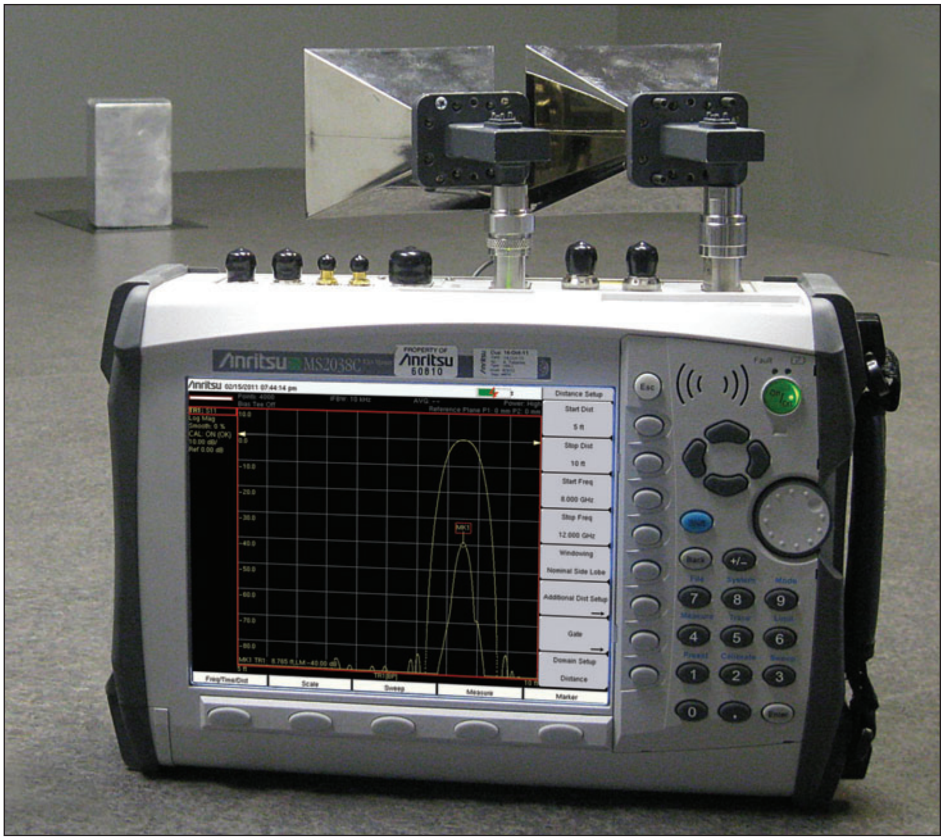

Figure 5. Photograph of the MS2028C/2038C with waveguide antennas.

A property of the transform process is the Alias Free Range (AFR). The transform is a circular function and repeats itself periodically outside of its inherent time range that is t = 1/(Frequency Step Size). The frequency step size is proportional to the frequency span and inversely proportional to the number of data points.

Inherent time range: t = (N-1)/(Frequency Span)

For example at X-band using a 4.0 GHz. frequency span and 4,001 data points, the (AFR) is:
4000/4.0 GHz = 1000 nanoseconds corresponding to a 300 meter alias free range. The 300 meter range is the round trip time thus the target should not be placed more than 150 meters from the VNA.

A typical aircraft RCS measurement configuration using a VNA is shown in figure (6). The transmit antenna (connected to port 1 of the VNA) and receive antenna (connected to port 2 of the VNA) are positioned in the same plane as shown. The measurement target consists of the aircraft either mounted on a low reflection pedestal or a stand alone on a flight line.

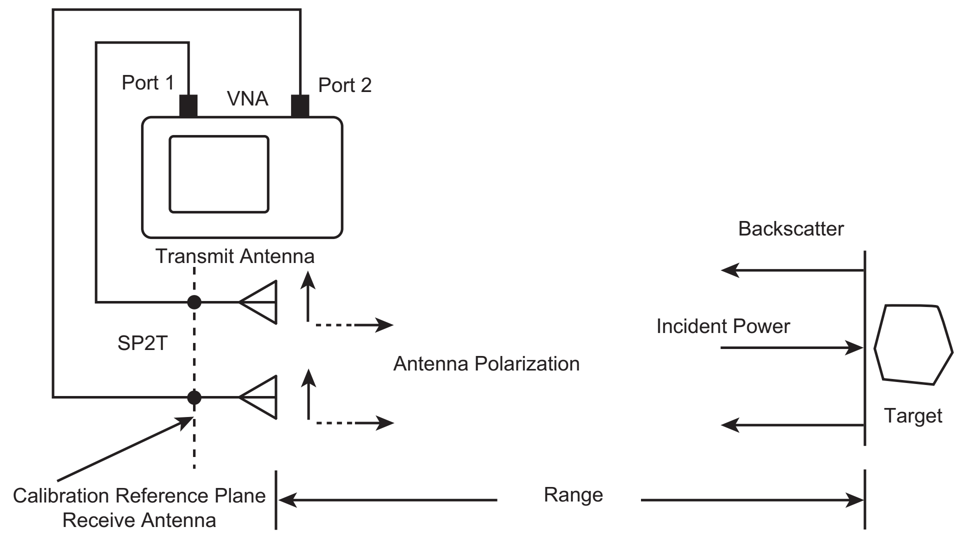

Figure 6. Block diagram for VNA measurement of RCS.

The operation of a $S21_{(f)}$ measurement for the VNA is shown to be the equivalent to Radar when configured as shown. The coaxial cable output of port 1 is connected to the coax to rectangular waveguide transition (E field in the vertical direction). The output of port 2 is connected to the output of the receive waveguide antenna. Both antennas are located as close as possible, in either the vertical or horizontal plane. To develop the polarization matrix both transmit and receive antenna should be capable of 90 degree rotation.

The target should be located at a distance less that AFR/2 but far enough from the antenna to insure that the entire target is within in the beam of the antennas.

Antenna System Calibration

The RCS of known target geometries and their corresponding cross-section are shown in figure (7). The ideal standard to use is a conducting sphere of a known diameter. For example a 1.13 m diameter sphere has a RCS of 1 m^2 that is independent of frequency. You can choose the diameter of the sphere whose RCS corresponds closely to the expected RCS. You can use any other geometry if so desired.

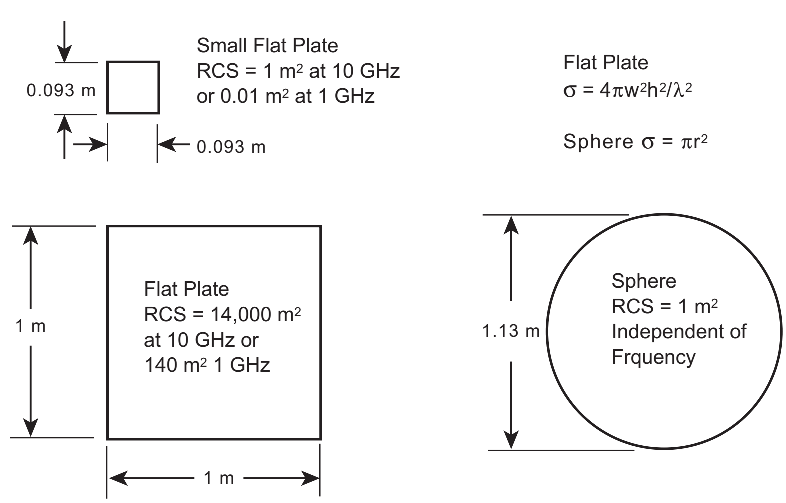

Figure 7. RCS vs. Physical Geometry.

RCS Measurement

A full 12-term calibration is performed at the output of the coaxial cables to establish the reference plane for the RCS measurements. A $S21_{(f)}$ frequency domain measurement is performed on the target area. The S-parameter data $S21_{(f)}$ is transformed to the distance domain mode $S21_{(D)}$ using band-pass processing. All reflections from the target area or support structure are shown in figure (8). You can calibrate the system in RCS by measuring a target of known RCS and referencing all other targets to the known target.

A $S21_{(f)}$ frequency domain measurement is performed on the standard to be measured. The S-parameter data is transformed to the time domain mode and an appropriate time gate is placed at the standards location. The magnitude of the $S21_{(std)}$ amplitude of the standard reflection is measured.

This measured value is the reference for the RCS measurement. If the standard were a sphere of having a RCS of 1 m^2 then the RCS of the target is given by:

$$RCS_{tgt}\ (dBsm) = RCS_{std}\ (dB) - RCS_{tgt}\ (dB)$$

The data is expressed in dBsm, or decibels referenced to one square meter. Radar cross section in square meters can be converted to dBsm by the following equation.

$$dBsm = 10Log(RCS_{m}{}^{2}) \quad (dB)$$

The target in this case is a known calibration standard which is positioned in the target area. The calibration standard reflection is identified and a range gate is placed on the calibration standard to remove all other reflections as shown in figure (9). The amplitude $S21_{tstd}$ of the calibration standard reflection is measured. The S21 measurement in dB corresponds to the known RCS (in meters^2).

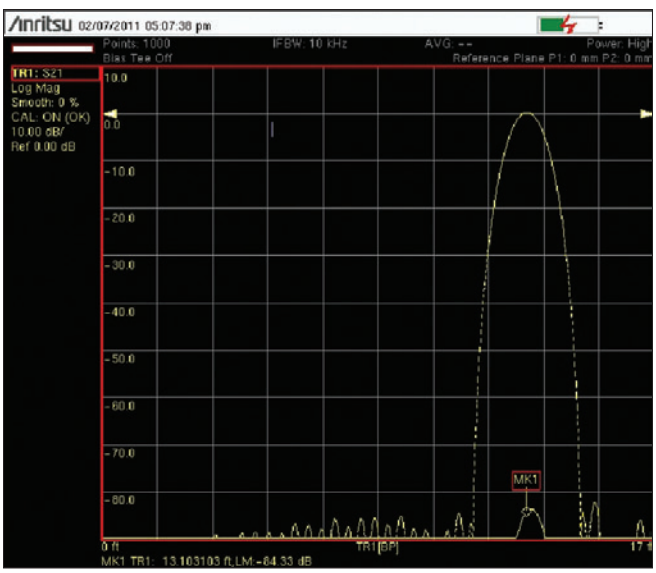

Figure 8. All reflections from calibration area.

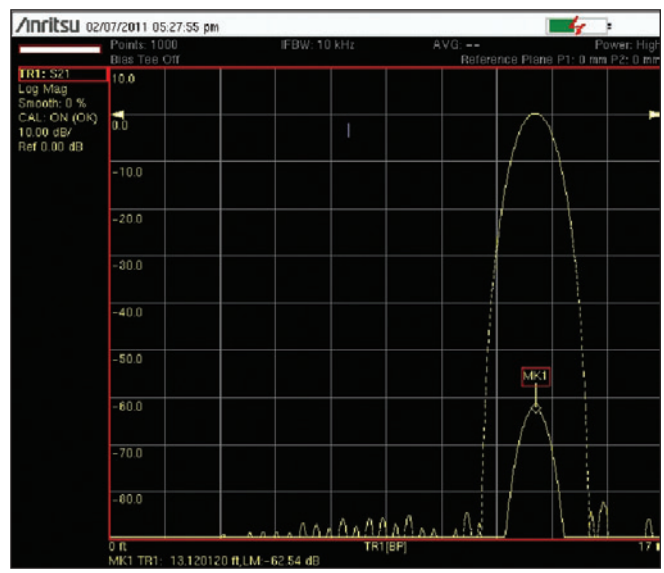

Figure 9. Target reflection from a 6" Diameter Calibration Sphere (RCS = 0.018 m^2).

Measurement Procedure for non-polarizing target

Set up for VNA based RCS measurement system S21 measurement

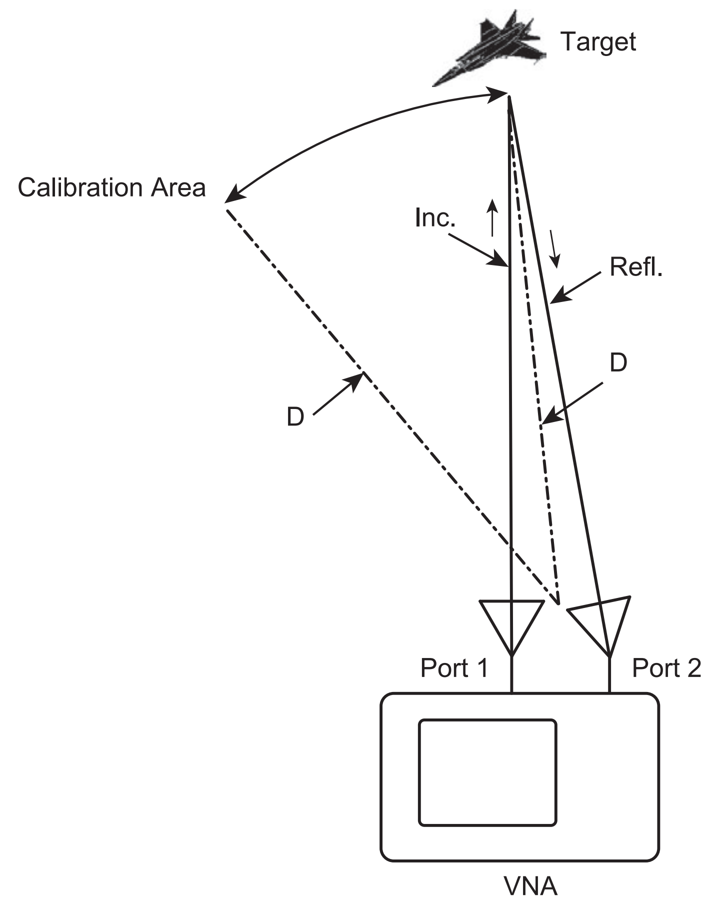

Figure 10. Set-up for the RCS measurement system using VNA (assuming non - polarization effects).

1. Connect port 1 to the Transmit $S21_{(V)}$ antenna and port 2 connections to the corresponding receive $S21_{(V)}$ waveguide horn antenna. Both antennas will have the same polarization
2. Measure the $S21_{(f)}$ reflection of the target area or target support structure (str). This is accomplished by removing the target from the area or pointing the antennas in a direction away from the target and insuring that there are no objects at the same distance from the antenna. (See figure 10).
3. Measure the $S21_{(f)}$ parameter. Transform the data to the distance domain $S21_{(D)}$ and store to memory (insure that $D > 20\lambda$ and that the target dimensions are within –1 dB azimuth and elevation angles of the antenna beam dimensions). Place a time gate centered at the distance (D) to the target and set gate width greater than the observed size of the target.
4. If a target support structure is used, measure $S21_{(D)}$ of the target support structure with the target removed. The measured value should be less than 20 dB lower than that of the estimated target RCS ($S21_{support\ structure} \ll S21_{target}$). If not add additional microwave absorbing material around the support structure to reduce it's RCS to the acceptable value.
5. Measure the calibration standard at the above location specified and plot $S21_{(D)}$ in time domain with the range gate set at the target distance and apply to the target $S21_{(D)}$. Store the distance domain $S21_{std}$ into the trace memory. The RCS of the standard should be slightly smaller than the estimated RCS of the target.

6. Replace the calibration standard with the target or rotate the antennas toward the target and repeat step (4). Measure the $S21_{tgt}$ and perform the trace math (memory – data) = [$S21_{std} - S21_{tgt}$]
7. The RCS of the target is calculated using the VNA trace math following derivation from the Radar Range equations:

$$P_{str} = \frac{P_t \cdot G_t \cdot G_r \cdot \lambda^2 \cdot \sigma_{str}}{(4\pi)^3 \cdot R^4} \qquad P_{std} = \frac{P_t \cdot G_t \cdot G_r \cdot \lambda^2 \cdot \sigma_{std}}{(4\pi)^3 \cdot R^4} \qquad P_{tgt} = \frac{P_t \cdot G_t \cdot G_r \cdot \lambda^2 \cdot \sigma_{tgt}}{(4\pi)^3 \cdot R^4}$$

Where: std refers to the RCS standard, tgt refers to the target and str refers to the target support structure.

$$S21_{std} = 10 \cdot \log\left(\frac{P_{std}}{P_t}\right) \qquad S21_{tgt} = 10 \cdot \log\left(\frac{P_{tgt}}{P_t}\right) \qquad S21_{str} = 10 \cdot \log\left(\frac{P_{str}}{P_t}\right)$$

$$\frac{P_{std}}{P_t} = 10^{\frac{S21_{std}}{10}} \qquad \frac{P_{tgt}}{P_t} = 10^{\frac{S21_{tgt}}{10}} \qquad \frac{P_{str}}{P_t} = 10^{\frac{S21_{str}}{10}}$$

To calculate the RCS of the Target the following equations are applied.

$$\frac{P_{tgt}}{P_{std}} = \frac{\sigma_{tgt}}{\sigma_{std}} = 10^{\left(\frac{S21_{tgt} - S21_{std}}{10}\right)} \qquad \sigma_{tgt} = \sigma_{std} \cdot 10^{\left(\frac{S21_{tgt} - S21_{std}}{10}\right)}$$

Example of a RCS measurement

Figure (11) shows the RCS measurement for the target (12'' diameter sphere) and figure (8) shows the RCS for the calibration standard (6" diameter sphere). The difference in dBsm = (P_{tgt} - P_{std}).

The RCS of the target in m^2 is given by;

$$\sigma_{tgt} = \sigma_{std} \cdot 10^{\left(\frac{S21_{tgt} - S21_{std}}{10}\right)} = 0.06\ m^2$$

The theoretical value for the 12" sphere is 0.073 m^2. The percentage measurement error is 17.8 % or 0.77 dB in dBsm. Most of the error was attributed to small movements in the VNA support structure during the measurement.

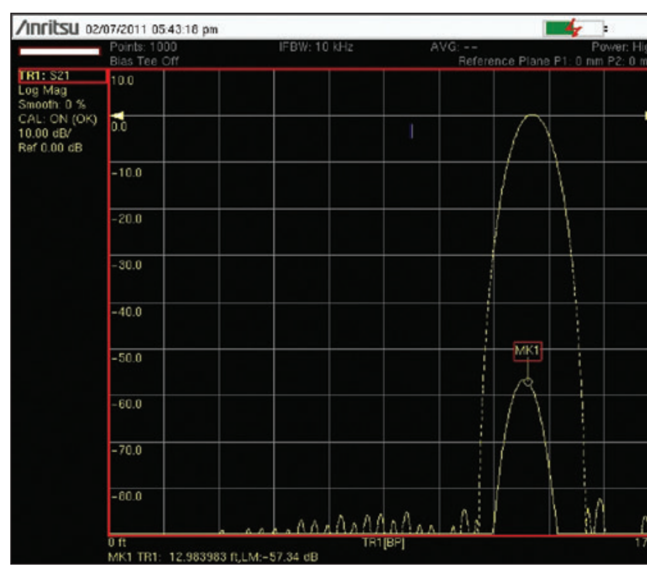

Figure 11. Measured $S21_{tgt}$ for 12" sphere.

Notes

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