INTRODUCTION TO RCS MEASUREMENTS

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Abstract

In the 1980's new requirements were issued to make airframes meet criteria for low radar cross-section characteristics. These requirements simultaneously created a need for improvement of radar cross-section measurement techniques to validate the performance of the designs. Thus was the advent of the modern technologies of short pulse instrumentation radars, specially designed outdoor RCS ranges, advanced indoor compact ranges, and low RCS pylons for mounting and positioning the test articles. In this talk I review the current state of these technologies and the measurement systems they support.

Keywords: Radar Cross-Section, RCS, RCS Measurements, Microwave Scattering Measurements, Stealth

1. Introduction

This is an introductory presentation that will acquaint the general electromagnetics community with the critical performance parameters of test gear for making good RCS measurements: I review compact range designs that support RCS measurement -- background subtraction, minimization of secondary room scattering, and wideband low ringing feeds. I discuss the performance parameters of instrumentation radars, both compare short pulse and gated CW types. I discuss the different performance requirements for the radars dictated by outdoor and indoor ranges. I describe pylon target mounting schemes and show how the influence of the target support upon the RCS measurement can be reduced. I describe the features of RCS measurement systems that differentiate them necessarily from conventional systems for standard automated antenna measurements.

2. Definition of Radar Cross-Section

From the IEEE Standard Definitions of Terms, **radar cross section** is defined as follows:

> For a given scattering object, upon which a plane wave is incident, that portion of the scattering cross section corresponding to a specified polarization component of the scattered wave. See also **scattering cross section.** [1]

And **scattering cross section** is defined as follows:

> For a scattering object and an incident plane wave of a given frequency, polarization, and direction, an area that, when multiplied by the power flux density of the incident wave, would yield sufficient power that could produce, by isotropic radiation, the same radiation intensity as that in a given direction from the scattering object. [2]

When expressed as a mathematical equation, then the radar cross section σ may be written as

$$\sigma(\phi_i,\theta_i;\phi_s,\theta_s) \equiv 4\pi \frac{\Phi_{Scattered}(\phi_s,\theta_s)}{S_{incident}(\phi_i,\theta_i)} = 4\pi \frac{\text{Power per Steradian in Scattered Wave}}{\text{Power per Unit Area in Illuminating Wave}} = 4\pi\, R^2 \frac{|E_{scat}|^2}{|E_{inc}|^2} \qquad (1)$$

where R is the far-field distance. [2] Radar cross section is a far-field quantity and the illuminating and scattered waves can be taken as plane waves with complex amplitudes E_{inc} and E_{scat}. It is dependent upon the direction of arrival of the incident wave (ϕ_i,θ_i) and the direction of observation of the scattered wave (ϕ_s,θ_s) and is in general designated as the ***bistatic*** cross section. When the two directions are coincident it is known as the ***monostatic*** cross section. Radar cross section is the "capture area" of the object for incident radiation which is presumed to be then re-radiated isotropically. σ has the dimensions of area. A schematic diagram of a typical far field arrangement for making RCS measurements is shown in Fig. 1. Often the transmitter and receiver are separated by a small angle to improve the isolation and make the measurement more sensitive to small return signals. The target is rotated in either one or two axes, azimuth and elevation, to change the relative direction to the radar.

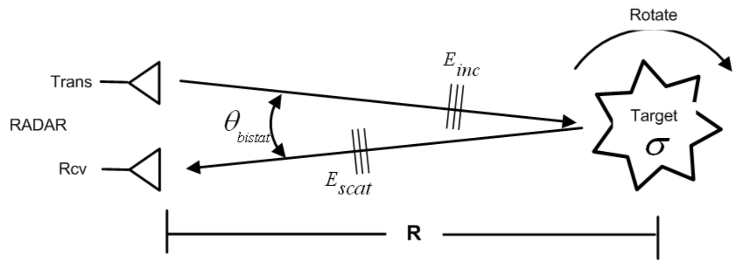

Fig. 1. Schematic of Bistatic Geometry for Measurement of Radar Cross Section

The radar cross section of an object is a measure of its degree of visibility to a radar. The cross section is typically expressed in dB relative to a square meter – dBsm. It is a function of direction, of frequency, and of the polarization of the incident wave. In general two scattered plane waves emerge for each direction of observation each corresponding to one of two orthogonal polarizations.

A modern radar cross section range must be able to set and control the parameters that pertain to these quantities. An instrumentation radar typically can cover a continuous frequency range of 1.0 to 20 GHz or perhaps 0.1 to 40 GHz. It has the capability to switch among a set of antennas that correspond to individual bands within this range. It often can transmit and receive via each of two polarization channels on each antenna. It performs these measurements while controlling the target to execute step-scan azimuth-elevation motion presenting all of the desired aspect angles to the radar. All of this along with the capability to transmit and receive pulses of very short duration – typically 10 to 100 ns – and to digitize and record the received amplitude and phase of the scattered wave. The result of a typical measurement of a target with such a radar is a very large quantity of data that must be further processed for analysis and display. See Sections 7 and 8.

3. Classical Targets and Scattering Standards

The best known example of a radar target of known scattering properties is a conducting sphere whose backscatter cross section in the optical regime is given by the formula

$$\sigma_{sphere} = \pi r^2, \; r >> \lambda \tag{2}$$

where r is the radius of the sphere and λ is the wavelength of the radiation [2]. There are three scattering regimes for the sphere: (1) the Rayleigh region, (2) the resonance region and (3) the optical region. All three regions can often be used as a calibration standard for scattering measurements when the range is free of unwanted reflections.

Another classical target used as a standard is a rectangular flat plate of area A whose monostatic cross section is

$$\sigma_{plate} = 4\pi \frac{A^2}{\lambda^2} r^2, \quad \sqrt{\mathrm{A}} >> \lambda \tag{3}$$

Whereas the cross section of the sphere is independent of frequency in the optical regime and is equal to the area of the circle formed by its projection onto a plane, the cross section of the plate depends strongly on frequency and is much greater than its physical area by the factor, $4\pi \, \mathrm{A}/\lambda^2$, when its dimension is much greater than a wavelength. For a discussion of the RCS of simple shapes and examples of patterns, please see [3].

Experience on outdoor ranges and recent research and development efforts have led workers in the field to prefer short cylinders as calibration standards. They have the advantage of better rejection of unwanted signals along with insensitivity to directional variation. These are now available in various sizes and extensive modeling efforts provide accurate values for the backscatter cross section. [4].

4. Far Field Outdoor RCS Ranges

The need for RCS measurement technology arose as soon as radar began to be deployed for detection of aircraft. The first approach of mounting a sizable target on a range and isolating it from the effects of the ground was recognized early on as nearly impossible to achieve. It was realized that the most effective way of dealing with ground reflections was to exploit the ground surface as a participant in the process of illumination, creating what is known as the ground reflection range. A diagram of such a range is illustrated in Fig. 2. [5]

The advantage of this arrangement is that the ground is eliminated as a source of unwanted clutter signal. Furthermore because the ground reflection signals add in to both the illuminating and the scattered wavefronts

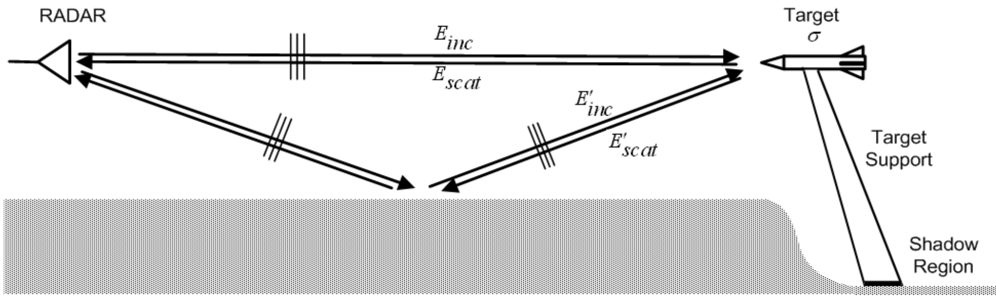

Fig. 2. Schematic of Ground Reflection Range with Shadow Region for Measurement of Ground-Based Radar Target

there is a signal strength advantage of +12 dB. The disadvantages of a ground reflection range is that the site must be extraordinarily flat and that the appropriate height of the radar antenna is dependent upon frequency because of the need for both the direct path signal and the reflected path signal to arrive at the target in the same phase. Also, the reflectivity of the ground depends both upon frequency and upon polarization.

Nevertheless, in spite of the difficulties, ground reflection far-field ranges continue today to be a mainstay of RCS measurements. Far-field distances often require 5000 to 10000 feet of range length with a controlled ground surface to control reflections. [5]

5. Pylons for Mounting and Rotating Targets

To mount and rotate targets when their RCS is being measured, special pylons have been designed which have very low backscatter when viewed the radar. [6] This class of target mount is best described with reference to a photograph; please see Figs.3,4,5.

Fig.3 Photograph of Pylon Rotator

Fig. 4 Photo of Mounting Interface at the Top of the Pylon Base

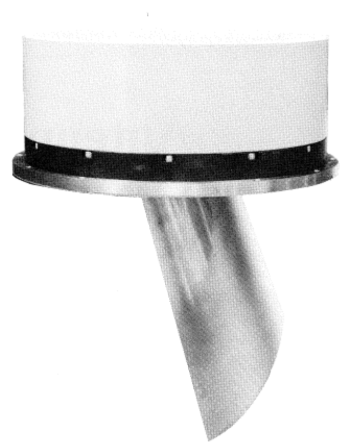

Fig. 5. Photo of Az/El Pylon Tip and the Interface for its its Rotator Mechanism

Typically the cross sectional shape of a pylon is ogival (two intersecting circles) and the pylon body tapers from its base to the top where a modest sized rotator attaches. The rotator is capable of rotating a target through 360 degrees in azimuth and through perhaps 45 degrees in elevation. The target and rotator are designed so that the rotator fits inside the target leaving only the pylon and the bottom surface of the rotator exposed to illumination.

The critical performance parameters for a pylon are its backscatter cross section and its physical capacity to support and rotate large masses. Load capacities are 500 to 5000 lbs or even 10,000 lbs; and, typical values for cross section are –25 to –45 dBsm. Typical positioning readout accuracy is on the order of ± 0.03 deg. Calibration of the pylon return is accomplished with ultra-low RCS terminations, such as the tear drop shaped NASA almond.

6. Compact Ranges for Indoor Measurements

A compact range is a device for creating plane-wave illumination in a laboratory at microwave frequencies. A photograph of a large range is shown in Fig 6, where a target, mounted on a pylon, is illuminated by the range.

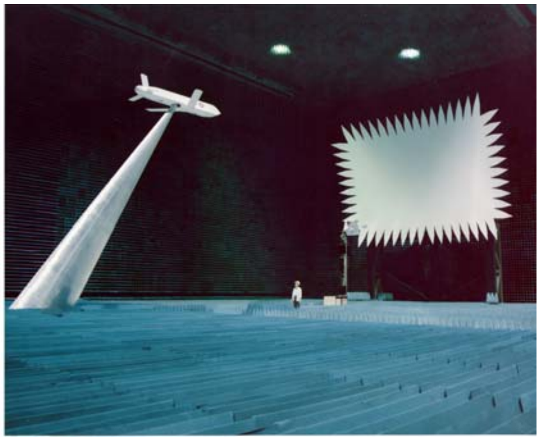

Fig. 6. Photo of a Point Source Compact Range for RCS Measurement

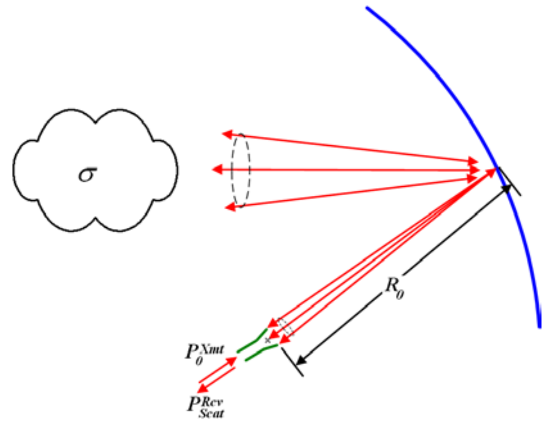

Fig. 7. Schematic of a Point Source Compact Range for RCS Measurement

The large reflector is an offset paraboloidal surface with a focal length of 32 ft or 384 in (975.40 cm). The reflector is fed by a wide-band horn located at the focus. An instrumentation radar generating short pulses is connected to the feed and thence to the host computer approximately 100 ft away in the range control room.

The governing equation for operation of a point source compact range for RCS measurement is [7]

$$\frac{P_{Scat}^{Rcv}}{P_0^{Xmt}} = \frac{1}{(4\pi)^3}\left(\frac{\sigma}{\lambda^2}\right)\left(\frac{\lambda}{R_0}\right)^4 G_F^2 \qquad (4)$$

where

P_{Scat}^{Rcv} = Power Scattered by the Target and Received by the Radar

P_0^{Xmt} = Power from the Transmitter Accepted by the Feed

λ = Wavelength of Radiation

R_0 = Distance from the Focus to the Reflector Along the Principal Ray

G_F = Gain of the Feed

This is written as a series of dimensionless factors. Note that this equation has the form of the far-field radar equation. However, rather than the distance between the reflector and the target, the equation contains the quantity R_0, the distance from the feed to the reflector; and, rather than the gain of the entire reflector, the equation contains the gain of the bare feed antenna. In spite of the close proximity of the target to the reflector, the modest gain of the feed antenna and the factor of (λ/R_0) to the fourth power serve to make the received power difficult to detect easily. For example, for a 0 dBsm target at 10 GHz, a feed gain of G_F = +8 dB, and a focal length of 32 ft, from Eqn. (4), the received power in ratio to the transmitted power is –115 dB ! Thus, on such a large compact range, to see targets having RCS values of –60 dBsm one needs transmit power levels from the radar on the order of 1 kW -- +60 dBm -- and a receiver sensitivity for the radar of –115 dBm ! Meanwhile consideration of the clutter on such a range brings on a requirement that the pulse widths be much shorter than the pulse widths for conventional far-field ranges on the order of nanoseconds rather than microseconds.

Feeds for single reflector RCS compact ranges have proven difficult to realize because of two requirements. The first is for a nearly uniform amplitude distribution across the full test zone; -usually less than 1 dB of amplitude taper (on a one-way transmit basis.) This implies a very broad beamwidth feed pattern. The second is for a very wide bandwidth and a non-ringing time domain characteristic. Only non-ringing sinuous feeds have met these requirements. [8] An alternative is ridged horns but with less performance due to the unstable phase center [9]

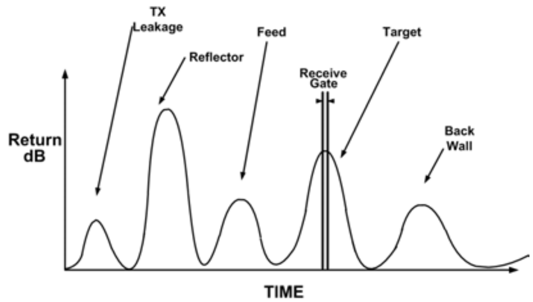

Fig. 8. Schematic Radar Return versus Time in a Compact Range

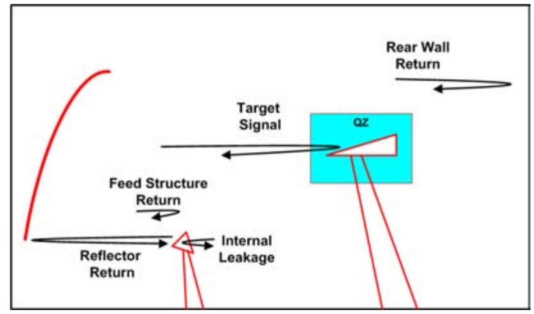

Fig. 9. Schematic- Some Sources of Radar Return in a Compact Range

Fig. 8 shows schematically what the returning signal from a compact RCS range might look like versus time. Fig. 9 illustrates the locations of the corresponding sources of the returning signals. Only the backscatter from the target is desired but it is often submerged amidst unwanted clutter. The solution is to employ a pulsed transmit signal and time gating of the returning waveform to retrieve the signal from the target under study. To achieve high levels of rejection for clutter signals closely spaced in time to the signal of interest, one requires pulses with very rapid risetimes – several nanoseconds or less. This in turn requires high instantaneous bandwith for the transmit and receive channels – as much as 200 MHz. [10]

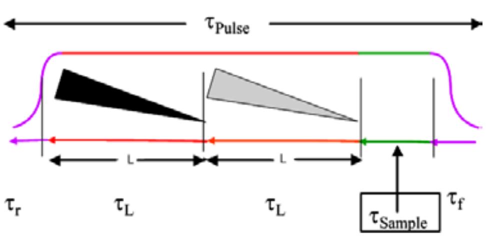

Fig. 10. Schematic – Rule for Length of Pulse

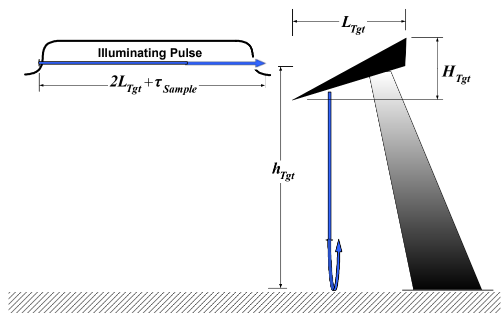

Fig. 11. Schematic –
Rule for Height of Target Mount and Pylon

To achieve the equivalent of a CW measurement with pulses, one must make the length of the pulse cover the target. The leading edge of the pulse should be allowed to travel the full length of the target and return to the front of the target to form the complete radar signature; only then, once this composite signal has reached the receiver, does one want to open the receive gate of the radar. Thereupon it is left open for a period of time τ_S, corresponding to the sampling window of the receive gate. Please refer to Fig.10. The requirement for the pulse width may be written mathematically as

$$\tau_{Pulse} \geq \tau_{\mathrm{Rise}} + 2\tau_{\mathrm{L}} + \tau_{\mathrm{Sample}} + \tau_{\mathrm{Fall}} \tag{5}$$

In making RCS measurements with time-gated waveforms, one must choose the height of the pylon and the distance of the target above the ground sufficiently large that the ground bounce ray does not illuminate the target during the time interval when the target return signal is being formed. Please see Fig. 11.

$$h_{Tgt} \geq \frac{1}{2}(2L_{Tgt} + \tau_{Sample}) \tag{6}$$

When the sample time is much less that the time required to travel the length of the target, which is the case for a short pulse radar and a large target, these reduce to the rules that the target should be mounted at least two target lengths above the ground and that the illuminating pulse width should be at least two target lengths plus a sample interval. The sample interval might be as short as 2 ns for a short pulse radar or as long as 10 ns for a gated CW radar. Equations (5) and (6) apply equally well on indoor and outdoor ranges. Equations (5) and (6) also set the minimum height and width for the rectangular compact range chamber dimensions. On a compact range the target should be at least two target dimensions away from the side walls and ceiling.

7. RCS Measurement Systems

In Fig. 12 is illustrated a block diagram of an automated system for making RCS measurements. [11] It is based upon an antenna measurement receiver that is designed to operate in continuous wave (CW) mode.

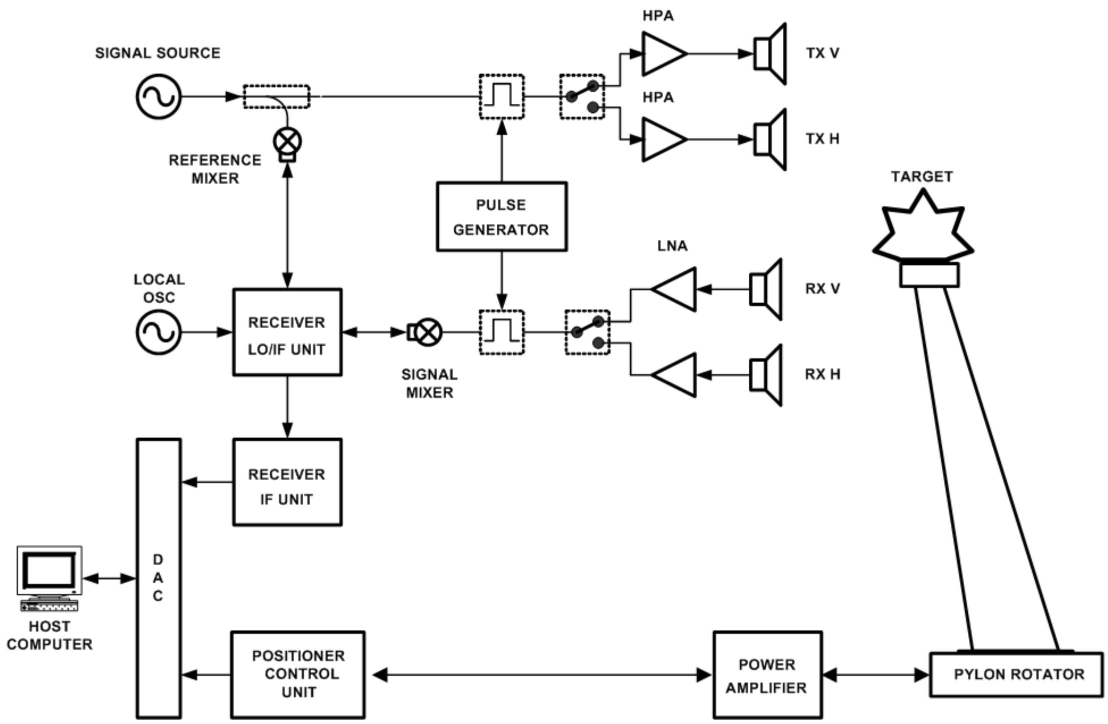

Fig. 13. Block Diagram of an Automated RCS Measurement System

The performance parameters are summarized in Table 1 below.

Table 1. Typical Performance Parameters of a Gated CW Radar

Frequency Range	2 to 40 GHz
Pulse Repetition Frequency	Up to 5 MHz
Transmit & Receive On/Off Ratio	120 dB
Transmit to Receive Isolation	130 dB
Transmit Pulse Width	10 to 499 ns
Receive Gate Width	10 to 499 ns
Receive Delay	30 to 499 ns
Rise/Fall Time	< 2 ns
Jitter	0.03%, plus 25 ps

This system represents a design of modest performance that would be appropriate for compact ranges of intermediate size – 12 ft (3.66 m) focal lengths and test zone dimensions of 4 to 6 ft (1.2 to 1.8 m). It can achieve a sensitivity of –70 dBsm at frequencies below 18 GHz. Clutter levels of –60 to –65 dBsm are attainable in chambers of sufficient size. In some cases the target supports based upon foam columns above a simple azimuth rotator are preferred over metal pylons.

One technique for reducing the range clutter is "background subtraction." The technique consists of first measuring an empty chamber without the target mounted and saving the phase/amplitude data file, designating the data as characteristic of the chamber background. Then the same measurement is repeated with the target now mounted in place. This second data set is considered to represent the phasor sum of the target plus the chamber background. The improved data consists of the subtracted difference between the two files and is considered to represent the scattering characteristic of the target alone. Of course the entire complement of chamber and hardware must be stable over time and temperature for this method to work. To use it one assumes that there is no "shadowing" of the chamber by the mounted target so that the background is not affected by the presence of the target.

The difference between "short pulse" and gated CW RCS measurement systems is the bandwidth of the receiving IF subsystem. Necessarily the transmitter must have a wide bandwidth to produce narrow pulses with fast nanosecond risetimes; and the front end of the receiving subsystem must have wide bandwidth to gate the returning signal. But the intermediate frequency receiving subsystem may be of the narrow bandwidth type often found on antenna ranges – or, it may be capable of preserving the rise- and fall- times of the individual pulses. There is a large gap in complexity and cost between these two regimes. Often gated CW system adapt microwave network analyzers to serve as the IF measurement receiver. But, only specially designed wide bandwidth IF amplifier and A/D converter chains are capable of processing individual pulses. For more information on short pulse instrumentation radars please see Reference [10].

8. Imaging of RCS Data

Automated RCS measurement systems readily acquire RCS data as functions of frequency and aspect angle. Because the waveforms are pulsed, the pulse width and repetition rate of the transmitted pulse is set through by computer control as well as the delay and width of the receive gate. Typically multiple polarization states of the incident and returning waves are also controlled. Some types of data acquisition and processing routines are listed below:

RCS vs Aspect Angle
Set the frequency to a fixed value and scan the azimuth and/or elevation axes of the target rotator. This is the classical RCS pattern measurement.

RCS vs Frequency
Set the azimuth and elevation position angles of the target to fixed values and step or sweep frequency through a range of values.

RCS vs Range (Range Walk)
Set the azimuth and elevation position angles and step the gate delay through a set of values starting at zero and ending with the range length beyond the target. This is used to identify range artifacts and to confirm the choice of range gate delay setting in the two measurement procedures above.

RCS vs Cross Range
By performing a Fourier transform on an "RCS vs Azimuth" data trace, one obtains an "RCS vs Cross Range data trace, where the cross range coordinate is in units of distance measured laterally across the target on a horizontal line that is perpendicular to the range axis.

RCS vs Down Range
By performing an inverse Fourier transform on an "RCS vs Frequency" data trace, one obtains an "RCS vs Radial Distance" along the range axis.

RCS Image Formation or Inverse Synthetic Aperture Radar (ISAR) Imaging
By performing a two-dimensional Fourier transform on a data set that is RCS vs Azimuth Angle & Frequency, one obtains a two-dimensional data set that is RCS vs cross range distance & down range distance. This resulting data set is termed an "Image of the Target" because of it can be readily compared to a perspective optical view of the target. See Fig. 14.

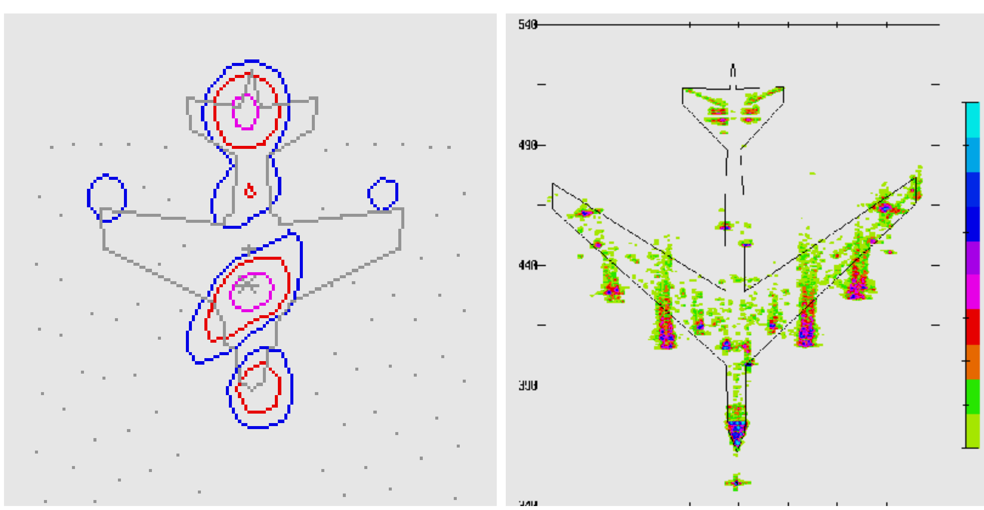

Fig.14. Example - Overlay of Two-Dimensional RCS Images with Envelope of Aircraft Outlines- Plan View

RCS imaging has become a widely used diagnostic technique in industries that develop airframes having low radar cross section characteristics. The reason is that it affords engineers a tool that can be used systematically to adjust and measure the effects of individual details that contribute to the full body RCS return. The technique first came into wide use in the United States in the early 1980's when the development of stealth aircraft designs was undertaken on a broad basis. [12] Investigations of image artifacts were reported at technical meetings that provided users with guidance on how to avoid aliasing, how to improve resolution, how to utilize DSP windowing to eliminate the artifacts of data truncation and how to interpret measured data when cavities in the test body give rise to fictitious time delays. [13]

A recent paper from MI Technologies, authored by Baggett and Thomas, reports an especially sensitive measurement result. They demonstrated clutter levels below –75 dBsm using a gated CW radar on a large 32 ft focal length compact range. They employed imaging with background subtraction to distinguish clearly three small –61dBsm spheres resting upon a foam column. See Fig. 15. [14] These data were obtained at Ku band.

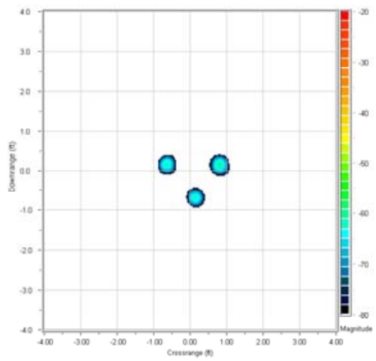

Fig.15. RCS Image of Three Spheres Each Having a –61 dBsm Cross Section. Color Scale is –20 to –80 dBsm

9. Summary

The era of stealth technology, which began in secret in the 1970's and came into public view in the early 1980's, is now more than 30 years old. When the era began, RCS measurements were carried out a single frequency at a time with background signals nulled out by CW cancellation. Stealth measurement technology has been greatly influenced by the advances afforded by digital computers and computer control of instrumentation. Wide bandwidth microwave measurement systems have enabled us to realize microwave imaging for diagnostics of stealth airframes. Meanwhile compact range technology has made it possible to move much of the measurement activity from out of doors to the indoor laboratory environment, making techniques, such as background subtraction and ISAR imaging, powerful means of measuring RCS characteristics of large airframes accurately.

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