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Cunningham, Forrest Truesdell.

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Forrest Truesdell Cunningham

United States
Naval Postgraduate School

THESIS

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RADAR CROSS SECTION MEASURING TECHNIQUE

by

Forrest Truesdell Cunningham

Thesis Advisor: D. B. Hoisington

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The Implementation of a Dynamic Radar Cross Section Measuring Technique

by

Forrest Truesdell Cunningham
Lieutenant Commander, United States Navy
B.S., Bethany Nazarene College, 1958
B.S., Naval Postgraduate School, 1965

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ABSTRACT

The instrumentation of a Mk-25 Radar Fire Control System to perform radar cross section measurements of airborne targets on a pulse-to-pulse basis is described.

Instrumented signals available within the radar are conditioned, recorded on magnetic tape, and forwarded for digital computer processing.

A discussion of this radar cross section measurement method, a description of its implementation and assessment of its validity are presented.

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LIST OF SYMBOLS AND ABBREVIATIONS

Ae	Effective antenna aperture
AFC	Automatic frequency control
AGC	Automatic gain control
C	Speed of light
dB	Decibel
DC	Direct current
e	2.718
f	Frequency
fo	Center frequency
FM	Frequency modulation
G	Gain
IF	Intermediate frequency
ips	Inches per second
K(v)	Radar performance function
K(v)s	Radar performance function for a sphere
K(v)t	Radar performance function for a target
MHz	Megahertz
N(v)	A function
PRF	Pulse repetition frequency
PRR	Pulse repetition rate
Pt	Transmitted power
R	Range
r	radius
RF	Radio frequency

Rs	Range to a sphere
rs	Radius of a sphere
Rt	Range to a target
S	Received signal
T-R	Transmit-Receive
V	Video signal
Vs	Video signal of a sphere
Vt	Video signal of a target
γ	Conductivity
Δf	3 dB frequency interval
δ	Skin depth
ε	Permitivity
λ	Wavelength
μr	Relative permeability
π	3.1416
ρr	Relative resistivity
σ	Radar cross section
σs	Radar cross section of a sphere
σt	Radar cross section of a target
ω	Radian frequency

I. INTRODUCTION

The considerable interest which exists in being able to describe the radar cross section of an airborne target can perhaps be justified by enumerating just three of several pertinent applications:

1. Primarily because of costs, it has become necessary to accomplish most of the testing and evaluation of radar sensor weapon systems by means of computer simulations. An integral part of any properly designed simulation is the use of an appropriate mathematical model of the target. The average value and statistical variation of the target's radar cross section are probably the most important parameters of the target model. Therefore, the desire for valid simulation results necessitates a proper description of target radar cross section.

2. Radar system performance must ultimately be demonstrated by operational testing. An empirical determination of radar detection performance can be obtained only by operating against a real target. As shown by the radar range equation, the range at which the target is detected increases with an increase in the value of the target's radar cross section. Consequently, a significant error in the value of cross section would provide a misleading assessment of radar detection performance.

3. The designer of a radar receiver wishes to maximize the liklihood of detecting an airborne target. He knows that the probability of detection is quite dependent on the fluctuation statistics of the energy returned from the target. Therefore, before he can optimize his receiver design, he must have a proper appreciation of the probability density function describing the radar cross section of the airborne target.

Before proceeding further it would be well to define the target radar cross section parameter, σ. Skolnik [1] defines it as "the area intercepting that amount of power which, when scattered equally in all directions, produces an echo at the radar equal to that from the target." Although the idea of isotropic reradiation is suggested in this definition, it in fact never actually occurs. Consequently, the impinging energy is scattered in a non-uniform manner. This fact helps account for the phenomenon that radar cross section is related only in the grossest sense to the physical size of the target, and that for complex shaped targets, the values of cross section are highly aspect sensitive.

In general there have been three methods (one analytical and two empirical) by which values of radar cross section have been determined. The analytical approach is very useful when the geometric shape of the target is simple or when the target can be closely approximated by a simple shape. Under these conditions one attempts to establish the proper boundary conditions and then to solve Maxwell's equations for the re-radiated energy from the object. The simplest and perhaps

most useful geometric shape to be considered is the sphere. Its most important property is that, regardless of its orientation, it presents but a single aspect to the viewer. Therefore, the energy backscattered from this shape should be constant no matter how it is turned. Ruck et.al. [2] show that for a sphere, which is a perfect conductor and whose circumference is sufficiently large when compared to a wavelength, the backscatter radar cross section is equal to its geometric cross section and is defined as:

$$\sigma = \pi r^2$$

where:

σ = radar cross section in square meters

r = radius of sphere in meters

This useful and unique identical aspects property of the sphere, which makes possible this constant backscatter radar cross section, is indespensible to the success of dynamic radar cross section measurements.

Perhaps the most common method of determining radar cross section of a complex target is to construct a scaled model of the target and illuminate it with energy at a proportionally scaled radio frequency. The energy backscattered is measured, and σ is determined as a function of target aspect. Usually these measurements take place in anechoic chambers or on specially constructed outdoor ranges where the background radiation can be controlled and/or minimized. There are several distinct advantages inherent to this procedure. First

of all, the conditions under which data are collected are well controlled. Signal sources and receivers are of high quality. If a test is performed in a suitable anechoic chamber, background noise and its effects on the results are minimized. The frequencies employed can be readily changed so that target data can be obtained over a broad range of frequencies. The placement of the target on the measuring pedestal can be done with sufficient precision so that the aspect of the target is quite well defined. Finally, because of the tightly controlled conditions, the measurement can be repeated with a high degree of certainty. Repeatable performance permits the operator to use this method with considerable confidence.

Dissatisfaction with this method generally centers around questions concerning the validity of the model and the fact that the values tabulated are derived from static measurements. If an X-Band measurement of aircraft radar cross section is performed using a 1/10 scaled model and a 10/1 scaled frequency, a quick calculation reveals that the 1/4 wavelength dimension on the model is of the order of one millimeter. The kind of precision suggested by these numbers places severe requirements on the model maker which tend to increase the cost of the model and the time it takes to construct it. In addition, the requirement for electrical similarity between the target and the model may not always be realized. The model is constructed of a continuously smooth skin of high conductivity aluminum or copper. To what extent it is electrically different from an aircraft, whose outer surface may be

composed of fiberglass, plexiglas, partially painted sections of rivited aluminum and other possible materials, is not known. Other questions could be asked concerning differences in conductivity and skin effect due to scaling. As a matter of practice one usually postulates that the electrical similarities are quite good and any existing discrepencies are ignored. One other area of difference between model and aircraft is configuration. The target model is usually constructed free of pylons, external stores, antennas or radar dishes, any or all of which might exist on the original airframe and which can significantly affect the target's radar cross section at certain aspects and frequencies.

An important limitation with static measurements of σ is that time variational values of target cross section simply cannot be obtained with this method, since flight dynamic alterations in target shape and aspect do not exist on the model. Unavailable are data on such interesting and important phenomena as target scintillations, glints, radar-cross-section amplitude fluctuations and the effects due to engine-turbine modulation. Consequently, it might be argued that without these time variation effects, an accurate assessment of radar cross section might not be obtainable. It appears, however, that where only a single value of σ is desired for each frequency and aspect of a generally configured target, a properly controlled static measurement of a good model in an anechoic chamber produces results which are generally quite acceptable.

The third method of determining radar cross section of a complex airborne target is to actually measure the cross section with the aircraft in dynamic flight. This permits a measurement to be made of the entire target as it exists, whether clean or augmented, and regardless of its configuration, type or model. The measurement is made in the airborne target's own operating environment and is able to include the effects of minor pilot and environment induced target aspect changes, control surface movements, wing flexure, engine turbine modulation and other legitimate causes of target signature scintillations. These scintillations are extremely influential in describing the probability density function for time varying values of σ and the power spectral density of the reflected target energy. This method is relatively uncomplicated since, in addition to the measuring radar system itself, only a small number of additional standard ancillary equipments are required. Time efficiency is another virtue of this method in that, including equipment warm-up and calibration time, cross section measurements of a target may be made within a matter of hours. A high degree of operational flexibility is possible in that targets can be replaced and reconfigured as required without affecting the measuring process in any manner.

A very important constraint imposed by this technique is the requirement for good equipment stability. The actual values of the gains or the sensitivities of the radar are not as important as the fact that these gains and sensitivities

remain constant from the time the system is calibrated through the completion of the target measurement.

Weather conditions are also an influential factor in this measurement technique. A preferred operating environment would include uniform weather conditions throughout the testing area, a minimum of cloud cover and no abrupt atmospheric pressure or temperature changes. While standard day atmospheric conditions are not required, thunder storms, rain squalls, and storm fronts should be avoided. Even under ideal weather conditions atmospheric attenuation effects might be a serious cause for error. According to Fig. 1, at 10 gigahertz about 0.02 dB/kilometers in atmospheric absorption can be expected. If, for example, errors of less than one dB (at 10 gigahertz) are desired, the target should not be tracked at ranges greater than 25,000 yards. In the present method of computation, atmospheric attenuation effects are ignored.

Another disadvantage of this method is its cost. To fly aircraft for the sole purpose of obtaining radar cross section information can be quite expensive. Fortunately, it is possible to measure the target of interest during or at the conclusion of other flight operations, thereby getting the aircraft flight time at no cost. Nor are flight costs involved in measuring targets of opportunity.

Compared with anechoic chamber measurements, repeatability is not so readily achieved with this method. This is due to the fact that there are more variables not under the control of the one conducting the measurement. The exact aspect of

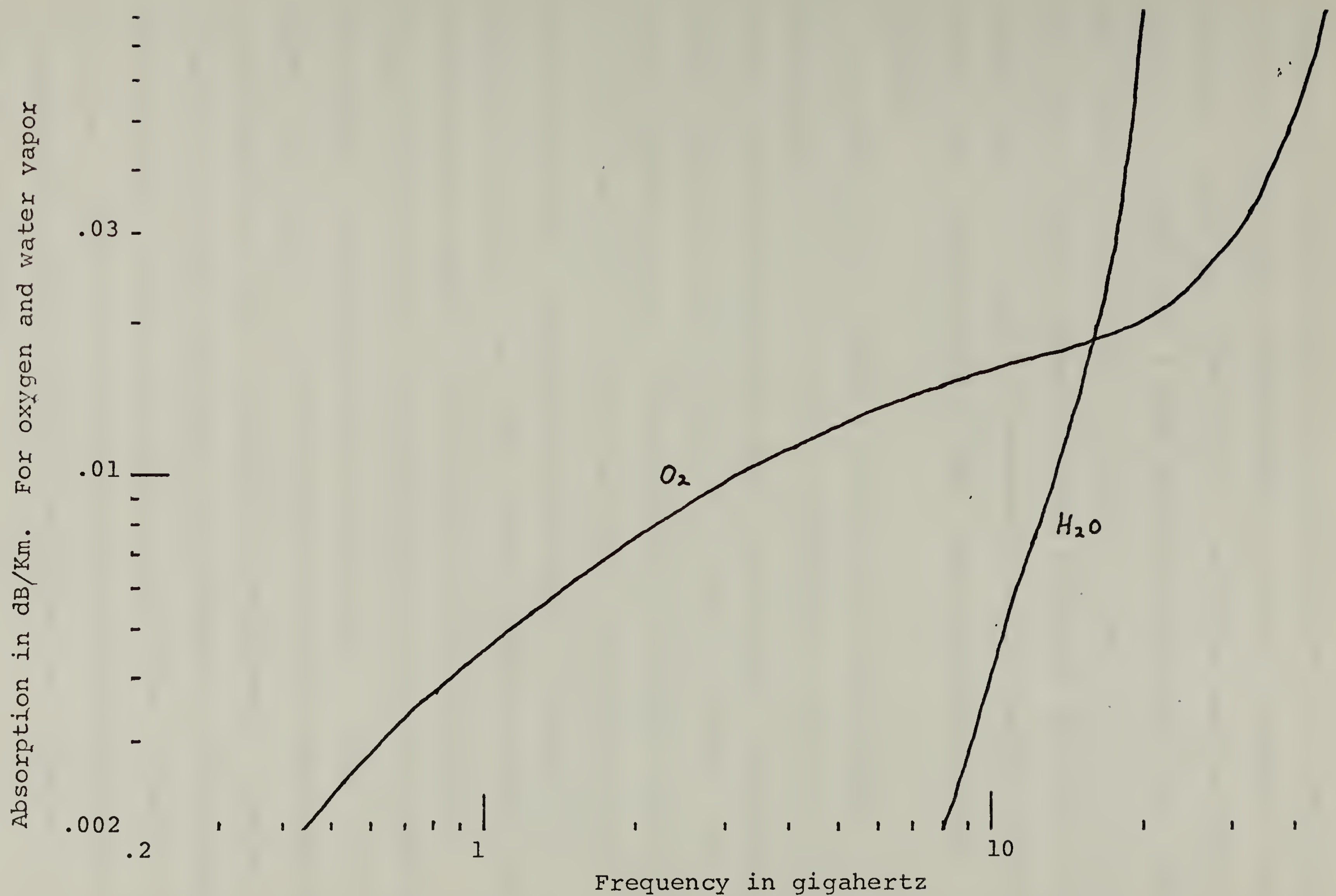


Figure 1. Atmospheric Absorption versus frequency. From Westman [4], p. 26-28

the target is not duplicated on repeated trials. Different pilots cause the aircraft to perform differently. Weather and turbulence create differences in aircraft movement and behavior. These and other similar variables are the chief culprits in precluding a high degree of repeatability. The best answer to this valid criticism is that this is the way the target actually behaves and the resulting data for any given trial is an accurate assessment of the target's cross section and its fluxuations under those operating circumstances.

In spite of its inherent difficulties, the dynamic measurement method has much to recommend it, and it is this method which has been implemented at the Naval Postgraduate School utilizing a Mk-25 Radar Fire-Control System. The theory, mechanization, and operational procedures associated with the institution of this method are described in subsequent sections. Chapter two describes the theoretical basis of this method and shows how derivitives of the radar range equation support the validity of this technique. Chapter three discusses the necessary and desirable attributes of equipment to be used in this measurement. Chapter four gives a description of the equipments actually used along with an evaluation of their strengths and weaknesses. Chapter five delineates the operational requirements of this method and indicates how they are presently satisfied. Chapter six provides a review of this method's present deficiencies and suggests areas for improvement and expansion. Chapter seven presents a conclusion.

II. THEORY

The theoretical foundation for the dynamic radar cross section measurement method can be obtained from the radar range equation. A basic simplified form of the equation can be stated as:

$$R = \left[\frac{Pt\ G\ Ae\ \sigma}{(4\pi)^2\ S}\right]^{1/4}$$

or:

$$R^4 = \frac{Pt\ G\ Ae\ \sigma}{(4\pi)^2\ S} \qquad (1)$$

where:

R = range in meters

Pt = transmitted power in watts

G = antenna gain

Ae = effective antenna aperture in square meters

σ = radar cross section in square meters

S = received signal in watts

The method employed is to calibrate most all of the parameters associated with the measuring radar and ancillary equipment by tracking a target of a known radar cross section and comparing the results with those obtained from tracking the target of unknown size. The ideal calibration target, a spherical conductor with a large circumference to wavelength ratio, is used as this target of known cross section. By

using the same measuring radar system to track both the calibration target and the target of unknown radar cross section, the Pt, G, Ae and $(4\pi)^2$ terms in equation (1), can be considered as constant between the two measurements. To make the constant assumption for these terms, it is quite necessary that the equipment calibration and the unknown target measurement be accomplished within a short time interval. This helps satisfy the requirements for equipment stability, weather constancy and the minimization of any other time varying parameters associated with the measurement method.

The received signal S is not the best parameter to utilize in this instance because it usually can not be conveniently measured to the desired accuracy. As defined in equation (1), the signal exists at the transmitted frequency and may be extremely weak. It would be more convenient to use some video signal, V, within the radar system which is a function of S. V would be characterized by possessing a voltage level which varies with the amount of power, S, in each echo pulse returned from the target. The relationship between S and V is rather tenuous as the signal frequency must be converted to intermediate frequencies and ultimately to a video signal all the while undergoing amplification and detection, a non-linear process. Because of the known existence of non-linearities in the amplifying stages of radar receivers (particularly if the values for S vary over a significant dynamic range) and because the unit watts is proportional to volts

squared, it is quite obvious that the relationship can be expressed as follows:

$$S = N(v)\ V^2$$

where:

V = a voltage indicative of target signal received

$N(v)$ = a non-linear function of V (in units of watts/volts squared)

Now combining and substituting the previously constant terms and the non-linear function N(v), equation (1) can be rewritten as:

$$R^4 = \frac{K(v)\ \sigma}{V^2} \qquad (2)$$

K(v) is a function which is defined as representing the performance of the measuring radar system and its associated ancillary equipment. The radar range equation has now been reduced to a form which contains the unknown term, σ, two values, R and V, which can be measured from the radar system itself and a system parameter, K(v). The value of the function K(v) is determined by the calibration process. Recalling the previous discussion of ideal spherical conductors, it was stated that if all the proper criteria were met, the backscatter cross section of such a sphere would be:

$$\sigma s = \pi\ (rs)^2 \qquad (3)$$

Because the dimensions of the calibrating sphere can be measured, σs is now no longer an unknown quantity but a computed constant.

Rewriting equation (2) with regard to the sphere yields:

$$K(v)s = \frac{(Rs)^4 (Vs)^2}{\sigma s}$$

Also rewriting equation (2) specifically with regard to the target produces:

$$\sigma t = \frac{(Rt)^4 (Vt)^2}{K(v)t}$$

Since the same radar equipments which track the calibrating target also track the unknown target and since the time interval between the two tracks is minimized (to satisfy the stability criterion), it will be true, provided Vt = Vs, that:

$$K(v)t = K(v)s$$

This equation is also constrained by the fact that for any given value of Vt there must be a previously recorded identical value of Vs which was produced during the calibration process.

Since K(v)t = K(v)s and Vt = Vs, a substitution, recombination and division of terms result in:

$$\sigma t = \frac{(Rt)^4 \sigma s}{(Rs)^4}$$

To produce this value of target cross section Rt is measured directly from the radar and σs is the previously computed constant. The value of Rs is determined by the associated but identical values of V produced during both the target measurement and calibration runs. Thus a value of target radar cross section is determined for each set of Rt and Vt values selected.

III. MECHANIZATION REQUIREMENTS

The equipments necessary to this measurement technique can be divided into three functional groupings. Firstly, there is the measuring radar system itself. Secondly, there is the calibrating target. And finally, there is the equipment used to record the data signals and preserve them for the computerized data reduction processing which follows. It is apparent that the equipment utilized in performing these measurements must contain certain attributes in order to ensure valid results.

A. RADAR SYSTEM

A suitable radar system would be one which would continually track the target in range using a monopulse tracking scheme, possess good target resolution characteristics, and exhibit a high degree of tracking accuracy. It should have a pulse repetition frequency (PRF) low enough to prohibit range ambiguities, but one high enough to permit the discovery of any high frequency spectral components present in the energy returned from the target. It should possess a receiver bandpass which is sufficiently large to accept substantially all of the frequency components present in each pulse backscattered from the target. It should also be capable of generating internally those properly conditioned data signals whose values are required in the computation of a target's

radar cross section. In addition, the radar receiver should possess a great dynamic range to permit various sized targets to be tracked through widely different ranges.

Many radar fire control systems possess these attributes in sufficient degree to be considered acceptable for radar cross section measurement purposes. It in no way affects the validity of a measurement if several measuring radars differ in such significant parameters as PRF, antenna beam width, noise figure, duty cycle or bandpass, provided that the values of these parameters are nominal and not extreme or limiting. This is because the value of the radar cross section of a target is a fundamental and intrinsic property of that target and (with the exception of the frequency used in the measurement, the polarization of the antenna and in some instances the pulse width) is independent of any parameter of the measuring system.

The dependence of the value of radar cross section on frequency might be better appreciated if we consider the target to be modeled (because of its structural size, shape and configuration) as a grouping of reflective structures and elements. This analogy appears to assume some validity in light of the phenomonon of "glints" or energy "hot spots" which have been noted eminating from different areas on the surface of radar targets. To better understand the nature of these hypothesized reflective elements and their energy backscatter performance as a function of frequency, the following example is offered to provide illustration. As a worse-case situation consider an airborne target 25 meters

long and postulate the existence of a large reflective structure placed at each end of the target. Assume a frequency of 10.0 gigahertz, a wavelength of 3.0 centimeters and a constant "head-on" aspect viewing angle of zero degrees. These two relective elements, seperated by 25 meters, can now be considered as 733 wavelengths apart. The two-way path length from one to the other is 1466 wavelengths or 2833 half-wavelengths. The backscattered energy from these two reflectors can either combine in phase or out of phase, depending on the wavelength and the total difference in path length. Therefore, since the two-way path length is constant because of constant aspect, the total energy reflected will vary from a maximum to a minimum, if the wavelength of the radiating energy is altered by only 0.042 percent. Parenthetically, this same maximum to minimum variation can also be achieved if the frequency is held constant and the aspect angle shifted by 1.5 degrees. This wavelength increment can either be added or subtracted. Therefore, where as a 3.0 centimeter wavelength might have a maximum energy return, either a wavelength or approximately 3.001 or 2.999 centimeters will yield a minimum. Using the expression:

$$f = \frac{C}{\lambda}$$

where:

f = frequency in hertz

C = speed of light in meters

λ = wavelength in meters

It is found that the minimum backscatter frequencies are approximately 9.9965 gigahertz or 10.0035 gigahertz respectively. Compared with the original 10.0 gigahertz it is seen that, under the limiting conditions of this example, a 3.5 megahertz change in frequency means the difference between a maximum and a minimum energy backscatter. If only the frequency region between the three dB backscatter power limits is considered, the permitted frequency interval, (Δf), about a center frequency (f_o) of 10.0 gigahertz, is approximately 1.2 megahertz. The amount of frequency stability suggested by this sample calculation should be within the frequency stability specifications of any radar system that possesses automatic frequency control (AFC) circuitry. This value of Δf also should suggest the range of frequencies over which the measured data, using a radio frequency of (f_o), should be considered valid. It should be evident, from the above, that values of radar cross section, to be quantitatively useful, must be frequency qualified to a great degree. On the other hand, sufficient latitude is available so that any minor problems associated with tuning precision and frequency stability can usually be ignored. If, for example, the detection range performance of a new radar is being tested, it would be most appropriate to tune the cross section measuring radar to the same frequency. However, considering reasonable tuning accuracy and AFC circuits, a closely adjacent frequency (conservatively within an estimated value of Δf) could also be utilized without jeopardizing the validity of the measurement result.

Because of obvious aerodynamic considerations, aircraft are constructed so as to have greater dimensions in the horizontal plane than in the vertical plane when flying in straight and level flight. From a head-on point of view one sees wide thin wings, an oval fuselage, and perhaps a moderately tall and thin vertical stabilizer. These marked geometric dissimilarities between the vertical and horizontal axies of the aircraft should suggest that the polarization of the antenna of the measuring radar is a significant factor in the value of radar cross section. These differences have, in fact, been confirmed by experimental data. As a result, it is considered necessary to qualify values of target radar cross section with a statement concerning antenna polarization.

Normally, pulse width is not a consideration except in those cases where it is so short that its spacial length approaches the overall depth of the target. Obviously, if the pulse width were shorter than the depth of the target, it would be impossible to determine the maximum amount of reradiated energy the target was capable of returning to the radar. Consequently the "long pulse" value of radar cross section could not be determined. For long pulse measurements the minimum pulse duration indicates that the pulse width should be at least three times the length of the target. This ratio should ensure the return of a trapazoidal shaped pulse with sufficiently steep leading and trailing edges and with a constant amplitude section of sufficient duration to accurately represent the amount of energy backscattered

from the target. Figure 2 shows the general shape of such a trapazoidal shaped target return where the pulse width is 0.25 microseconds and the target length is 24 meters.

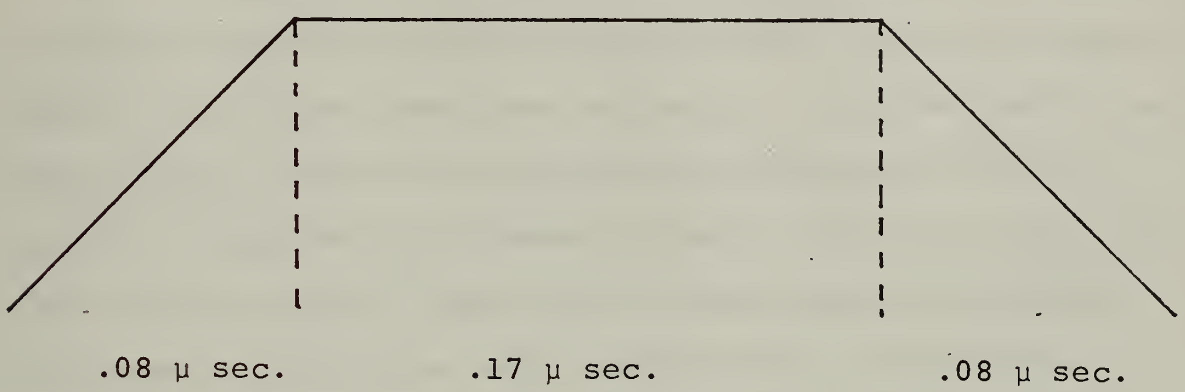


Figure 2. Ideal return of a .25 microsecond radar pulse from a 24 meter long target

B. CALIBRATION TARGET

The requirements for the calibrating target will now be considered. By far the most useful of calibrating targets is a perfectly conductive metal sphere of sufficient size. As previously noted, its advantages lie in its constant value of backscatter cross section regardless of the aspect from which it is viewed and the fact that this value can be determined analytically. (See equation (3))

The metal sphere will be considered as perfectly conductive if it is constructed of material which is a good conductor. The determination of whether a material is a good conductor is based on the following inequality:

$$\frac{\gamma}{\omega\varepsilon} > 100 \qquad (4)$$

where:

γ = conductivity of the material (mhos per meter)

ω = radian frequency

ε = permitivity of the material (farads per meter)

An additional factor must be considered in the case where the sphere is a hollow shell and not solid. In this case it must assured that the shell thickness is sufficiently great to impose no impedance to induced currents flowing on the surface of the sphere. This can be accomplished by ensuring that several electrical skin depths exist in the shell. A skin depth (δ) is that distance below the surface of a conductor where the current density has diminished to 1/e of its value at the surface. The shell is considered electrically as a solid conductor if:

shell thickness > 5δ

The skin depth is computed as:

$$\delta = \frac{6.61}{f^{1/2}} \left[\frac{\rho r}{\mu r}\right]^{1/2} \qquad (5)$$

where:

δ = skin depth in centimeters

f = frequency in hertz

ρr = relative resistivity (copper = 1)

μr = relative permeability (μr = 1 for non magnetic materials)

The question of whether the sphere is of sufficient size is determined by the amount of its circumference to wavelength

ratio. This ratio should be in excess of 10 for energy scattering to take place in the optical region, which is the region of validity for equation (3). If the wavelength is of the same order of magnitude as the circumference, then resonance scattering takes place and the value of backscatter cross section must be modified depending on an exactly determined wavelength-circumference relationship. For values of wavelength greater than the circumference, Rayleigh region scattering properties ensure that practically no energy is backscattered from the target which is for all practical purposes invisible to the tracking radar. Figure 3 delineates the aforementioned regions and graphically portrays normalized values of radar cross section of a sphere as a function of wavelength-circumference ratios.

The target tracked by the radar is usually more than just a metal sphere. Standard procedure calls for the sphere to be lofted by a helium-filled balloon. If such a device is used it must be insured that it contributes no significant backscattered energy which would be added to that energy returned from the sphere. Were this to occur, the calibration effort would be biased to the extent that the balloon contributed to the calibration target size. To preclude this undesirable effect, the balloon must be transparent to or an excellent absorber of the energy impinging upon it. One way to accomplish this invisibility would be to have the balloon composed entirely of a perfect dielectric material. Under these conditions there would be no reflections from the

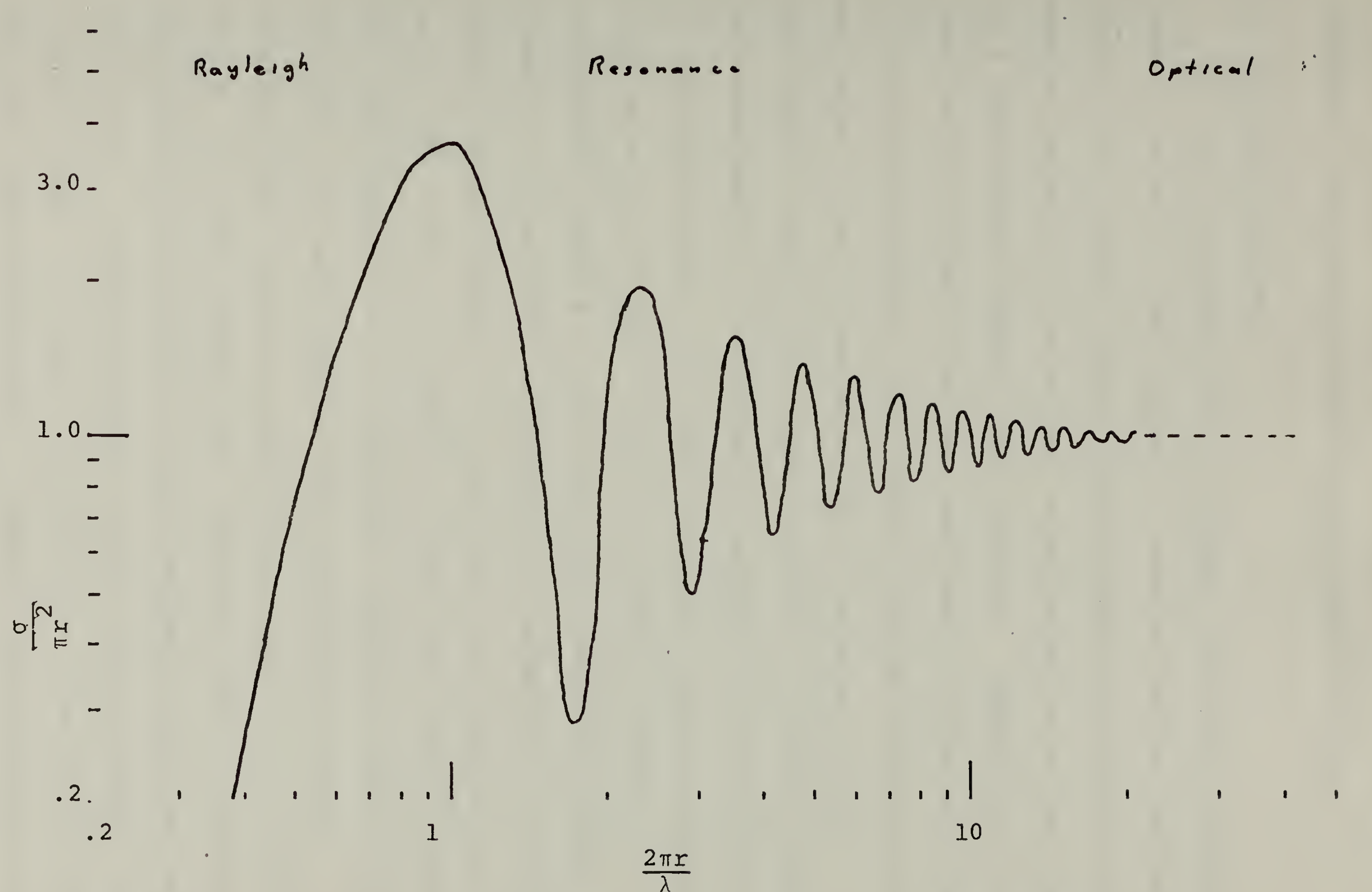


Figure 3. Variation in cross section of a sphere. From Cunningham [3], p. 8.

balloon as all of the energy entering it would be transmitted. Therefore, the backscattered energy would be zero.

C. RECORDING SYSTEMS

The final hardware area to consider are those equipments used to record the data signals. Assuming one has available the use of a digital computer and an analog-to-digital conversion capability, the signal recording may be accomplished on a multichannel magnetic tape recorder. Although only two required data signals have been mentioned, (range and video) it would be desirable if the recorder had up to seven tracks available. This is because it may be necessary and/or desirable to record other signals either to actually perform the measurement or to enhance the meaning and significance of the data results. Some other possible signal candidates could be a sync signal, a signal to indicate amounts of attenuation inserted in the signal path and antenna angle signals. The recorder should have the capability to record signals either directly or in the form of a frequency modulation (FM). This is because, for any given signal, either the high-frequency or low-frequency components might be more important. On most magnetic tape recorders the direct recording mode responds to high frequencies but is insensitive to low audio frequencies. Conversly, the FM recording mode although restricted to audio frequency ranges can record down to DC. It should possess a large enough bandpass, when in the FM mode, to record with sufficient fidelity the high-data-rate radar video signal. Because measurements are being

made on a pulse-to-pulse basis, the fundamental data rate frequency of this signal is equal to the PRF of the radar. As a consequence the upper frequency limit when recording in the FM mode should be at least twice the PRF. This FM frequency response should be accomplished without using high tape speeds. If the recording speed is too fast, the risk exists that all the tape would be expended before the entire mission is completed. A desirable frequency response-tape speed relationship is five kilohertz at 15 inches per second (ips). There should be sufficient tape available to allow for a minimum of 30 minutes of recorded data. At 15 ips the amount of tape required is 2400 feet. The recorder should have both a record and replay capability. In addition each channel should have a high input impedance on the order of 100 kilohms. This amount of input impedance should ensure that the addition of the tape recorder as a load doesn't affect the functioning of the radar circuits or degrade the quality of the signals being recorded.

A second recorder is highly desirable. This should be a pen recorder. Its purpose is to give the test conductor a real time view of the signals going onto the tape. This visual record goes a long way in promoting confidence in the progressive success of the measurement. The strip chart produced by this recorder makes available to the test conductor the opportunity of scribing notations, descriptions, or explanations on events as they occur during the measuring process. The requirements for this recorder are not great. It should have a channel capacity sufficient to display all

the signals in which the test conductor is interested in viewing. Like the magnetic tape recorder, it too should have a sufficiently high input impedance so that it, acting as a load, doesn't reflect back into the radar circuitry and thereby cause undesired perturbations.

IV. EQUIPMENTS UTILIZED

Specific equipments which are presently utilized at the Naval Postgraduate School to perform these measurements include a Mk-25 radar fire-control system as the measuring radar system; a six inch diameter spherical aluminum shell lofted by a helium-filled neoprene balloon as the calibrating target and an Ampex Model SP 300 magnetic tape recorder and a Cleveite Mark 220 brush recorder to satisfy the data recording requirements.

A. RADAR SYSTEM

This Mk-25 satisfies most of the requirements for a measuring radar system. This system is designed to operate in the X-Band frequency range and can be tuned over a wide range of frequencies within that band. It satisfies the radar requirements for PRF, range tracking accuracy, angle tracking accuracy and exhibits good target resolution characteristics. It has sufficient peak power, its pulse width is sufficiently long for aircraft target measurement purposes and the radar receiver has a wide bandpass. The radar antenna is vertically polarized and is located on the roof of the Spanagal Hall on the campus of the Naval Postgraduate School. As can be seen in Fig. 4 the antenna possesses an unobstructed view throughout most all its 360 degree azmuth coverage. The remainder of the radar equipment is located in a room immediately under the antenna.

Figure 4. A view of the radar antenna.

There are three characteristics of the Mk-25 which diminish its usefulness as a measuring radar. Firstly, it uses a conical scan tracking scheme vice monopulse. Secondly, as the radar is presently configured its receiver has insufficient dynamic range. Finally, the required data signals to be produced by the radar are insufficiently conditioned to permit immediate recording on magnetic tape.

The undesirability of conical scan tracking is evidenced by a more inaccurate track of the target and the insertion of an amplitude modulation on the target echos when target azimuth or elevation angles are changing. It is well known fact that a monopulse system is capable of tracking a target with a smaller angular error than does a conical scan system. What this means from a measurement point of view is that the center of the antenna beam with its maximum gain property, is more likely to be on target and to stay on target during the tracking operation. However, because of the calibration feature in this measurement method, the more inaccurate qualities of the conical scan system tend to be neutralized so that this effect on the resulting cross section results is not pronounced.

Of more significance, however, is the insertion of amplitude modulation on the returned target signals due to the conical scan operation. Because the radar nutates about the target line-of-sight axis in an unsymmetrical fashion, those target echos being received when the center of the beam is most closely aligned with this axis are augmented in magnitude, when compared to the mean value of returned signal if there

was no tracking error. Those returns occuring after the beam axis is rotated 180 degrees are diminished in magnitude when compared with the mean. These increasing and decreasing signal strengths represent a sinusoidal amplitude variation on the returning target echos which occurs at the beam nutation rate. As a consequence, the strength of the signal returned to the radar has been artificially altered by an amount which depends on where in the nutation cycle it occured. In the measurement process as presently implemented these conical scan effects on the value of radar cross section are ignored as no steps have been taken to neutralize this induced error. Consequently, when azimuth or elevation angles are changing a nutating frequency sinusoidal bias exists on the measured data.

The problem of insufficient dynamic range for the radar receiver was largely created by the decision to disable the automatic gain control (AGC) feedback circuit. Parenthetically, while AGC voltage is a signal within the radar which is related to the returned signal S and a possible candidate for recording, its composition solely of very low frequency components makes it unsuitable for use as the parameter V. This is readily seen when considering the frequency response requirements necessitated by the high data rates of pulse-to-pulse measurement. The decision to eliminate AGC feedback was prompted by the fact that the forward gain of the receiver is a function of the amount of AGC voltage fed back to the various amplifier stages. Under conditions of AGC feedback the values of the previously defined function K(v) would now

be dependent upon values of AGC voltage as well as being a function of V. Therefore, in addition to the instrumentation requirement for a new signal i.e. AGC voltage, a whole family of S versus V or N(v) curves would now have to be produced, each one for a different value of AGC voltage. The prospect of performing a number of different calibration runs depending on the desired interval size of AGC voltage immediately adds orders of magnitude of difficulty to the calibration problem and violates the spirit of simplicity which made the measurement method so attractive in the first place. Consequently, it was decided that a single calibration would have to suffice, that AGC feedback voltage would be disabled and that the desire for increased receiver dynamic range would have to be satisfied by other means.

With the AGC voltage disabled, measurements on the radar receiver revealed a useful dynamic range of about 40 dB. As desired amounts of dynamic range were estimated to be 80 to 90 dB, the existing capabilities of the installed linear radar receiver were woefully inadequate. One solution was to substitute a logrithmic intermediate frequency (IF) receiver for the linear one. However, cost and hardware availability mitigated against this choice. Another approach was to somehow keep the values of target signals within the dynamic range of the existing receiver or, more specifically, within the calibrated portion of the dynamic range. This was the method selected, and an attenuator network was designed and constructed. The function of this attenuator network is to reduce the amount of target signal by some known quantity

prior to its detection. Since the last stages of an amplifier chain are usually the ones to saturate first, this attenuation is inserted between the preamplifier and main IF amplifier stages while the signal is still at 60 MHz in frequency and still relatively small in amplitude.

The attenuator itself was built in a three pole, 11 position rotary switch which not only provides for IF step attenuation but produces instrumentable switch position voltages. The attenuation takes place in approximately six dB steps and ranges from zero to 42 dB (three switch positions are not utilized). The exact amounts of attenuation for each switch position are determined using a signal generator and these measured quantities are converted to equivalent values of radar cross section and used by the computer program to correct the computed value of cross section. The switch position instrumentation signal is a DC voltage ranging from zero to seven volts in one volt steps. This voltage is recorded on the magnetic tape recorder with the various values of voltage representing corresponding positions of the attenuator switch and consequently the amount of attenuation inserted. Figure 5 shows the construction the rotary switch step attenuator. Figure 6 shows the switch in its shield can. Figure 7 is a schematic of the switch and attenuator network and the values of the components used.

The problem of insufficient signal conditioning is not a surprising one. The original purpose of the Mk-25 radar system was not to perform radar cross section measurements of

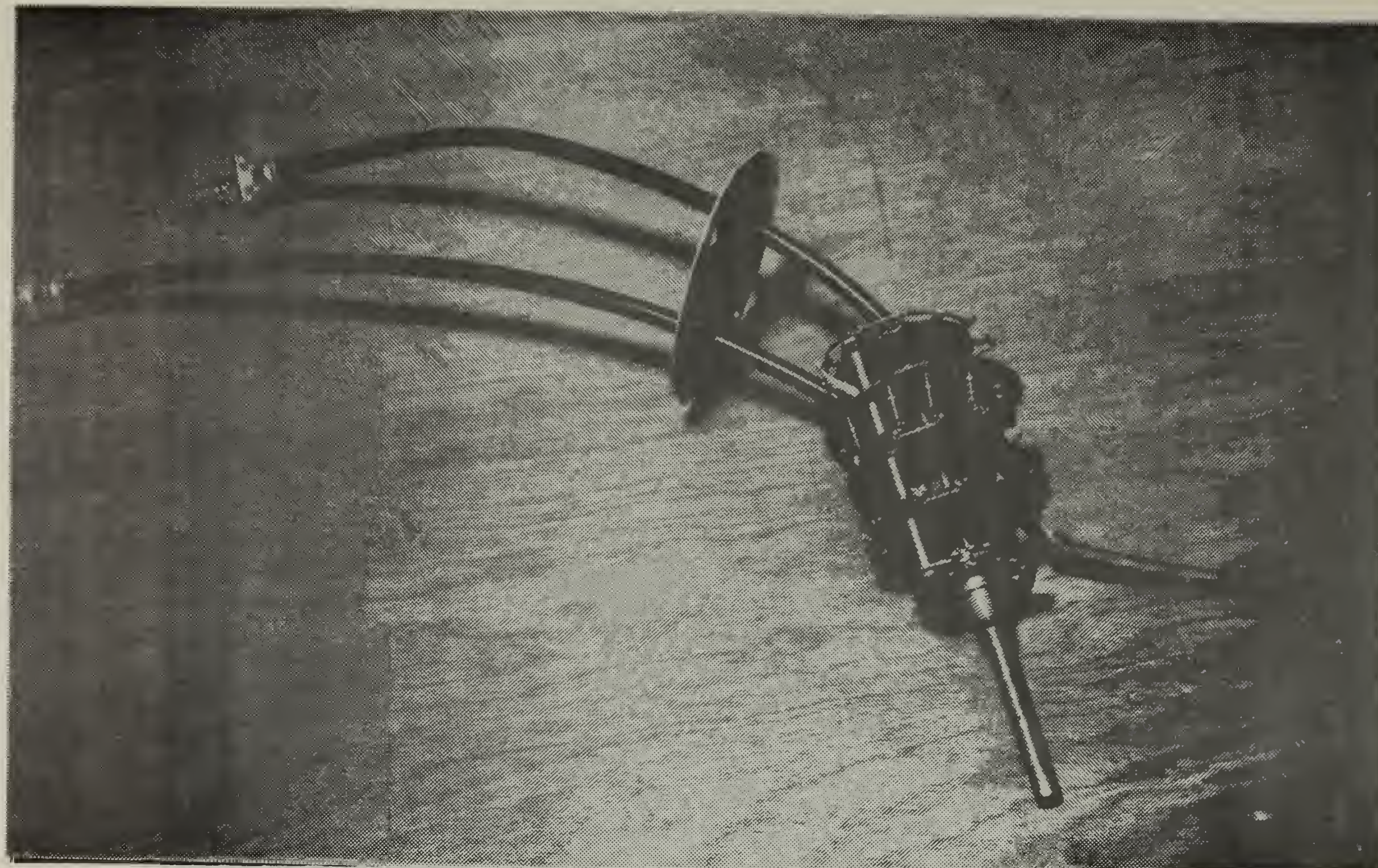


Figure 5. An internal view of the rotary switch attenuator.

Figure 6. The rotary switch attenuator within its shield can.

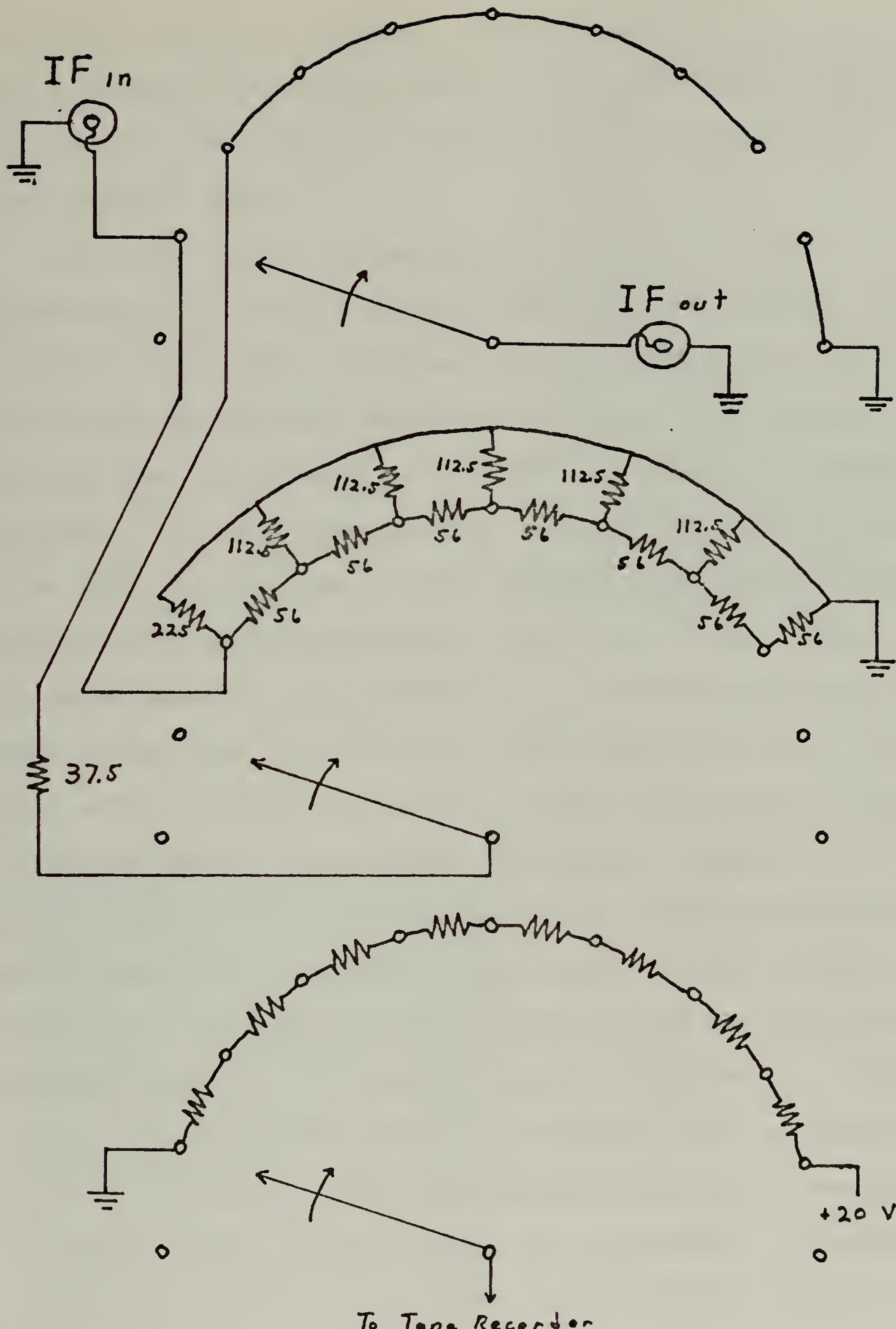


Figure 7. Schematic Diagram of rotary switch attenuator.

airborne targets on a pulse to pulse basis. However, there are available within the radar all of the signals required to make this measurement and these can be recorded with only minor modifications.

The first signal to consider is a sync signal. The requirement for such a signal comes from the analog-to-digital conversion process. In order to ensure that each video pulse is sampled at the same relative position, it is necessary to provide the analog to digital converter with an external trigger. With the availability of such a trigger a variable time delay is inserted in the conversion process to sample exactly at the desired point on the video pulse shape. Since the measurement is proceeding on a pulse-to-pulse basis the sync signal must occur at the pulse repetition rate (PRR) of the radar. Because the value of each video signal pulse, V, is determined by the quantity of signal located in the target tracking gate, it is also necessary to have the sync signal associated with this gate. This ensures proper signal synchronism and eleminates variable time delays normally caused by various ranges to the target. Fortunately, such a signal is readily available from radar test point 9 and is shown in Fig. 8. It is the range-gate unblanking pulse. Because of its association with the range gate, it keeps a constant position relative to each pulse of the video signal V. In addition to possessing the proper timing qualities, the unblanking pulse is 40 microseconds wide, which is of sufficient duration to effectively trigger the analog-to-digital conversion process. The voltage excursion ranges from zero

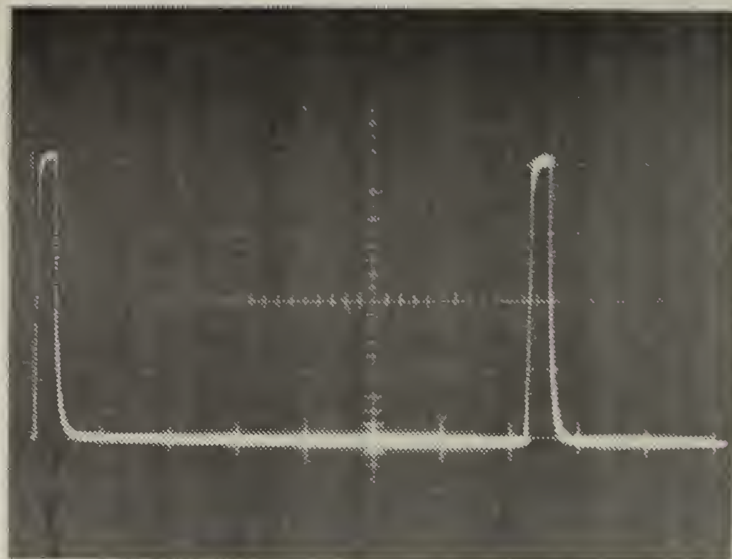


Figure 8

Sync signal at radar's test point 9

0 to +84 volt range

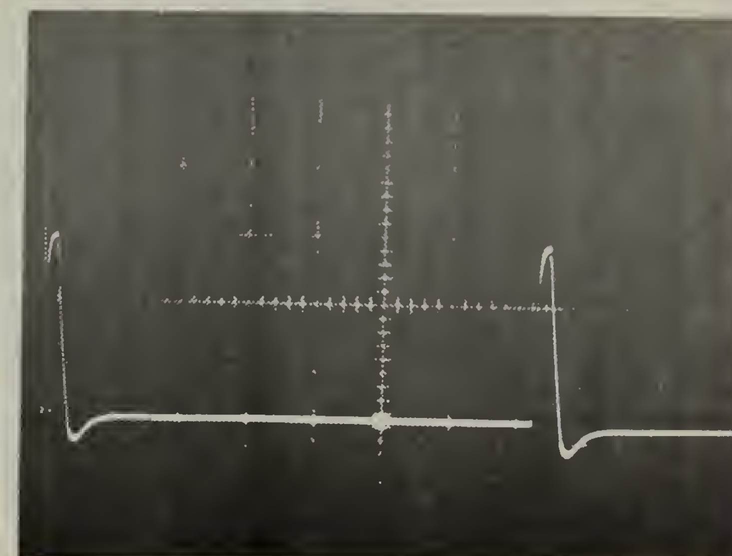
horizontal scale .1 milisec./cm.
vertical scale 20 volts/cm.

Figure 9

Value of video signal, V, as a result of a maximum input signal, S, at radar's test point 16

-40 to +20 volt range

horizontal scale .1 milisec./cm.
vertical scale 20 volts/cm.



to 84 volts which is far in excess of input limits to the tape recorder. To deal with this problem a 300 kilohm resistor is placed between test point 9 and the input to the tape recorder. Not only does this addition provide a sufficient reduction in the voltage levels, but supplies a high input impedance to the signal coming from the radar. The 300 kilohm value was selected after considering the maximum value of signal voltage, the tape recorder's input voltage limitations and its value of input impedance. This series resistor provides a satisfactory solution to the signal conditioning problem for the sync pulse.

Another important signal to examine is the video signal V. A stated requirement for V was that it should be a voltage which is functionally related to the input signal S. Since input signals exist only for the duration of the returning pulse and are arriving at the pulse repitition rate, it would be desirable to determine the value of the signal S (or more appropriately the voltage V) when it is available in the gate and to hold that value until the next input pulse arrived. If this were properly done by a sample and hold or a boxcar circuit, a series of voltage levels occuring at the pulse repetition rate would be produced. This to a large degree is what the radar system has provided at test point 16. The signal here is a boxcar video signal most of which is proportional to the quantity of returned pulse energy. Although the signal commences each period with a sometimes large but very narrow pulse of voltage it nevertheless resides at the

appropriate constant voltage level for the last 90 percent of its duration. Figures 9, 10, and 11 show the overall shapes of the video signal V as a result of maximum, nominal and zero values of the input signals. Of particular note are the amplitudes of the beginning spike and the remaining voltage level values. It appears that if this video signal can be recorded with sufficient fidelity and if the analog to digital convertor can be delayed to sample during the latter portion of the pulse period, then an accurate value of this data signal V is made a part of the computer record. Unfortunately, as the signal exists at test point 16, it can extend in value from about -45 to +10 volts. These values are in excess of the input voltage limits of the tape recorder. The problem is easily solved with a series resistor of 240 kilohms. This additional resistance produces the same results as it did with the sync signal, i.e., voltage reduction and proper input impedance. The signal is now capable of being recorded by the magnetic tape recorder.

A range voltage is readily available from this radar system. As presently configured, a 20 volt DC power supply is connected to a linear potentiometer which makes one complete revolution for every 2000 yards in range. Consequently, the voltage output of the potentiometer moves from zero to 20 volts as a target moves from zero to 2000 yards or additional increments thereof. The typical voltage waveform produced by a target increasing in range is a sawtooth. For a closing target the waveform is also a sawtooth, except that the voltage slopes are now reversed. Because 20 volts is in

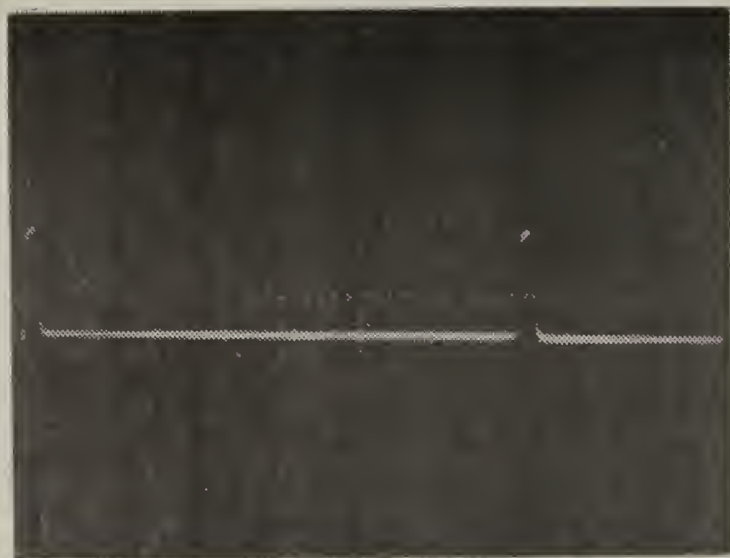


Figure 10

Value of video signal, V, as a result of a nominal input signal, S, at radar's test point 16

-12 to +19 volts range

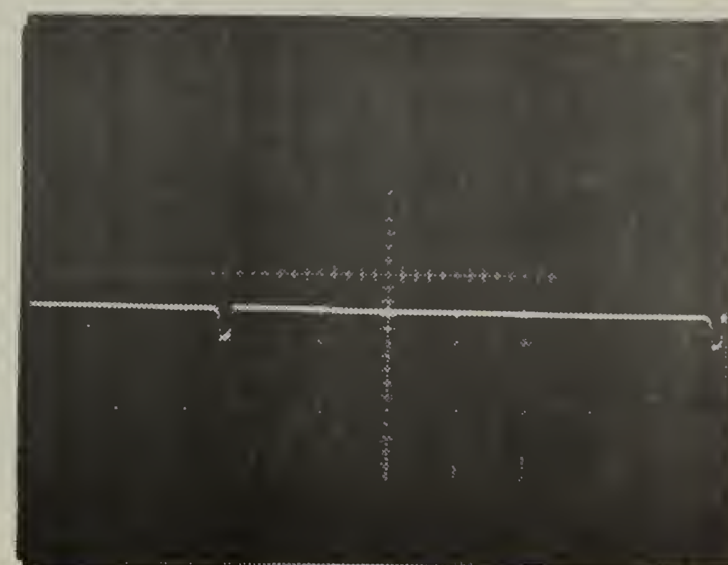
horizontal scale .1 milisec./cm.
vertical scale 20 volts/cm.

Figure 11

Value of video signal, V, as a result of a zero input signal, S, at the radar's test point 16

+11 to +20 volt range

horizontal scale .1 milisec./cm.
vertical scale 20 volts/cm.



excess of the input voltage limits of the tape recorder, the insertion of a 100 kilohm series resistor provides an adequate solution to the problem.

The final signal to be recorded is an instrumentation voltage provided by the attenuation network. As previously described, the actual value of this instrumentation voltage is indicative of the amount of deliberate attenuation inserted in the radar's IF signal path. The production of this voltage is the result of a simple voltage division network (see Fig. 7). The required network input voltage of +20 volts is achieved by placing a 100 kilohm resistor between the switch and a +120 volt source readily available within the radar.

For ease of handling and configuration, all of these signals and voltage reduction networks have been brought together in a junction box arrangement as shown is Fig. 12. Figure 13 is a schematic diagram for that box.

B. CALIBRATION TARGET

The calibration target used is a standard six-inch calibration sphere which has been produced specifically for this purpose. It consists of a pair of hemispherical shells which are physically joined together by a "ball-in-groove" technique. The result is an aluminum spherical shell which is characterized by a shell thickness of about one millimeter and an overall diameter of six inches. Figure 14 shows one of these spheres.

The computed value of radar cross section for this sphere using equation (3) is 0.018 square meters. This value is

Figure 12. Junction Box.

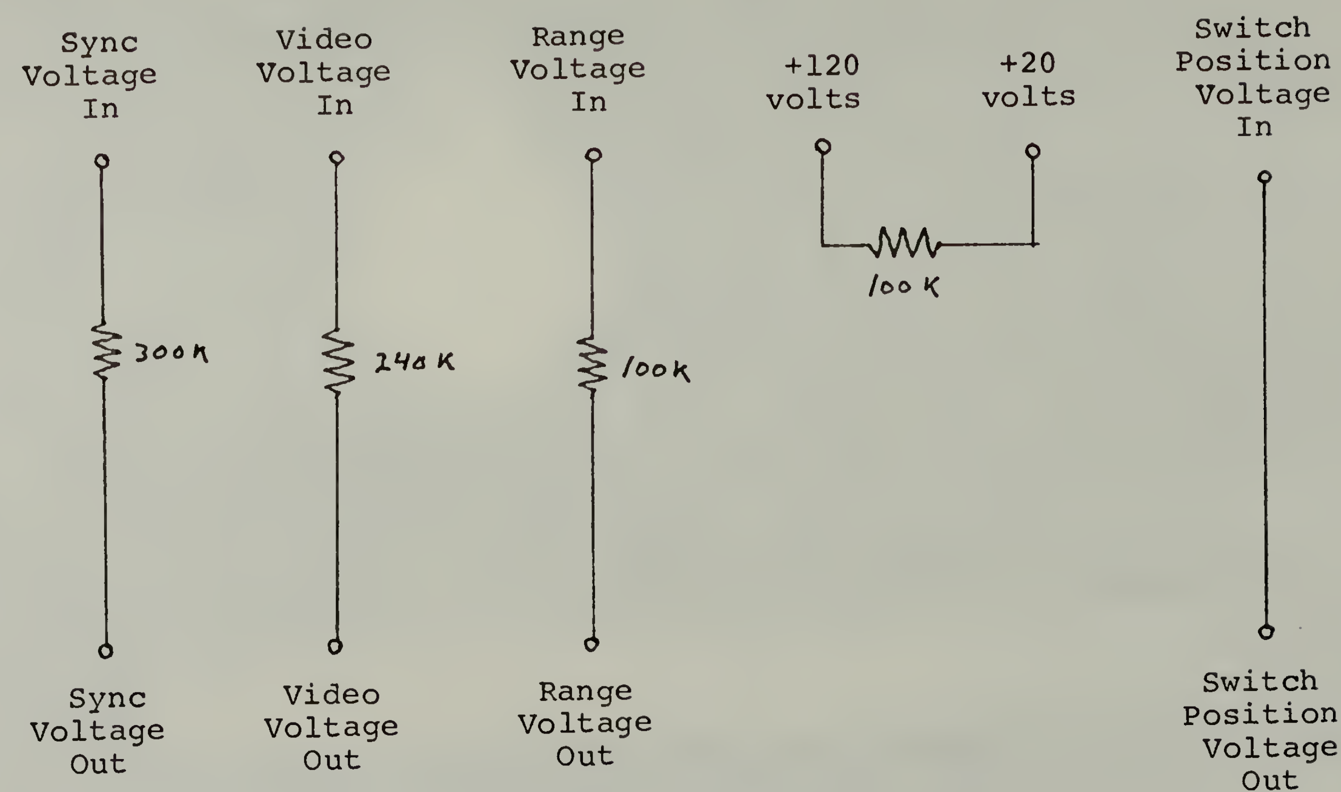


Figure 13. Schematic Diagram of Junction Box.

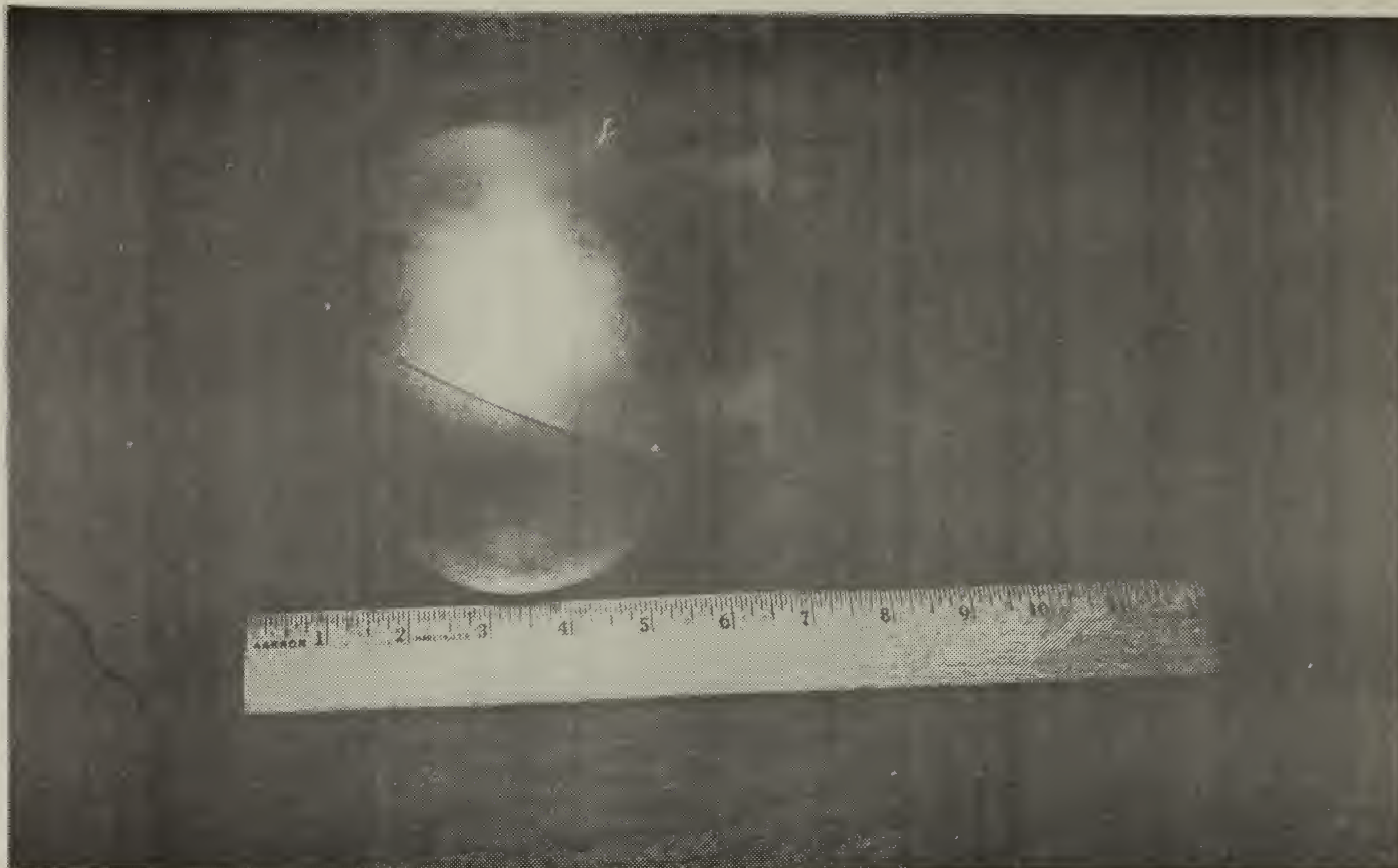


Figure 14. Calibration Sphere.

permitted to stand without modification because at the radiating frequencies of the Mk-25 radar the circumference to wavelength ratio is about 14. This ratio is considered sufficiently large to guarantee optical region scattering properties (refer to Fig. 3).

The sphere is constructed of aluminum. The conductive properties for this metal at the frequencies of concern can be derived by using inequality (4) where for aluminum at X-Band frequencies:

$\gamma = 3.5 \times 10^{7}$ mhos per meter

$\varepsilon = 3.85 \times 10^{-12}$ farads per meter

$\omega = 2\pi \times 10^{10}$ radians per second

and therefore:

$$\frac{\gamma}{\omega\varepsilon} = 6.3 \times 10^{7} > 100$$

The results indicated by this inequality suggest that aluminum is an excellent conductor at X-Band frequencies and therefore the perfectly-conducting-sphere assumption can be made in safety.

To ensure the existance of a sufficient number of skin depths in this aluminum shell at X-Band frequencies, equation (5) is utilized. For aluminum at X-Band:

$\rho r = 1.64$

$\mu r = 1$

$f = 10^{10}$

and therefore:

$$\delta = \frac{6.61}{10^{5}} (1.64)^{1/2} = 8.84 \times 10^{-4} \text{ millimeters}$$

Considering a one millimeter shell thickness, simple arithmetic indicates that there are about 1000 skin depths available under these conditions. This more than meets the requirements for at least five skin depths and therefore it is concluded that this calibrating target appears as a solid conducting sphere to the energy impinging upon it.

While the main emphasis is on the conducting sphere and previous paragraphs confirm its properties through analytical procedures, it must not be forgotten that the lofting balloon is also part of the total calibrating target. The balloon utilized is made of a neoprene rubber and is inflated with helium gas. It is usually inflated to such a size that its nominal geometric cross section is about five square meters. The question, however, is to determine its radar cross section.

Compared with the spherical conductor this is most difficult to do analytically. From various reference sources it can be determined that neoprene has a relative resistivity ρr, of 4.7×10^{18} and a dielectric constant at X-Band frequencies of 4.0. It possesses an X-Band dissipation factor (defined as the ratio of the energy dissipated to the energy stored in the dielectric per cycle) of 0.03. A calculation using inequality (4) reveals that at X-Band frequencies an expected skin depth is on the order of a kilometer. Taken all together the material properties and effects of neoprene would seem to support the intuitive conclusion that the amount of energy backscattered from the balloon is nil.

This conclusion is further bolstered by two pieces of empirical evidence. The first is that efforts to track just the balloon without the sphere with the Mk-25 radar have proven unsuccessful. Even with optical tracking at close-in ranges, i.e. 1000-2000 yards, the quantity of energy returned to the radar is below the detection threshold. This signal level compares with that from the sphere-balloon combination target at a range of 16,000 yards. Automatic track of this target usually cannot be maintained beyond this range because of insufficient signal. Since:

$$R^4 \alpha \frac{1}{S}$$

a nine dB change in R leads to a 36 dB change in S. Therefore, a crude approximation leads to the conclusion that the radar cross section of the balloon is at least 30 dB below that of the sphere.

The second is found in a technical memorandum by Cunningham [3] in which it is reported that anechoic chamber measurements performed on helium inflated neoprene balloons showed that any backscattered energy was at least 20 dB below that which would be produced by a six inch aluminum sphere. Therefore, it is concluded that, although the total calibrating target being tracked in this measurement technique is a combination of sphere and balloon, the entire amount of energy backscattered to the radar is produced solely by the six inch aluminum sphere and it is considered to be the only effective reradiating target.

One final observation about the calibration sphere should be made. As shown in Fig. 14 there exists an "equatorial" seam and a partially exposed cotter pin at the "north pole." It would appear that these properties of construction might adversly affect the value of radar cross section of the sphere. To preclude the possibility of any reflective perturbations, the cotter pin is removed from external exposure and placed inside the sphere. The seam, on the other hand, appears to have no adverse effect on the backscattered properties of the sphere. Cunningham [3] also reported that anechoic chamber measurements of several spheres along both the "equatorial" and "polar" planes indicated the invisibility of the seam and confirmed the electrical continuity of the sphere. In summary, this particular sphere, though not an ideal or perfect calibrating target, is quite satisfactory. It is inexpensive, readily available, and exhibits the required electrical properties.

C. RECORDERS

The Clevite brush recorder is a satisfactory solution to the requirement for a real-time visual display of the recorded signals. Utilized in this manner its most significant features are its two-channel recording capability, its high input impedance and its lowpass frequency response characteristics.

Since there are four signals being recorded at any one time, it might be suggested that a four-channel pen recorder would be required. However, a close examination reveals that

the sync signal contains no information at all about the status of the mission and the attenuator switch position voltage is equally uninteresting. If knowledge about the amount of inserted attenuation is desired it can be determined directly by observing the position of the switch. This leaves the video signal and range voltage as the two desirable signals to be displayed on the pen recorder.

The range voltage is quite important in giving the test conductor a feel for the progress of the measurement process. Consequently it is properly scaled and inserted on one of the two recorder channels. Likewise, the strength of the video signal is important. However, because of the recorder's lowpass-filter characteristic, the many high frequency components of the video signal are eliminated. In addition, this signal causes a wild mechanical agitation of the pen. Since the human observer can't cope with the high data rate of this signal anyway, all that is really required are the DC and low audio frequency components. As a consequence what is normally plotted is the radar receiver's AGC voltage. Since it is derived from this video signal and contains nothing but low-frequency components, it satisfies all the requirments for real time signal viewing. Therefore, the two signals visually recorded as operational aids to the test conductor are the system AGC voltage and the target range voltage.

The Ampex SP300 magnetic tape recorder is only marginally satisfactory. Although it has a sufficient number of recording channels (seven) and the adverse effects of its inadequate 20 kilohm input impedance are effectively eliminated by the

insertion of a large series resistor in each recording channel, it is nevertheless severely bandpass limited. All of the signals except the sync signals are FM recorded. This is because the DC components of those signals contain the desired information. This is fairly obvious for the DC step attenuator switch position voltage and the slowly varying sawtooth range voltage. This is also true for the video signal where the value of the constant voltage level during each period is the quantity desired. Therefore, since FM recording on the Ampex SP300 permits all frequencies from zero to 2500 hertz at a tape speed of 15 ips, this is the mode utilized. The sync signal on the other hand is recorded in the direct mode which has a bandpass of 50 hertz to 40 kilohertz at 15 ips. In this case the high frequency components which produce sharp leading edges are required for this pulse to act as a good trigger for the analog-to-digital conversion process.

The principle recording difficulty lies in trying to place a signal with a data rate of 1320 bits per second (a signal which ideally is a squarewave with various amplitude steps) on a recorder channel whose upper bandpass limit is 2500 hertz. To illustrate this problem a time response test using a step input was performed on the recorder. Figure 15 shows the results of that test. From this figure, oscillations (both overshoots and undershoots) in the response can be detected as the output value approaches that of the input. Of particular interest is the fact that as the end of one pulse period (about 0.75 miliseconds) some small amount

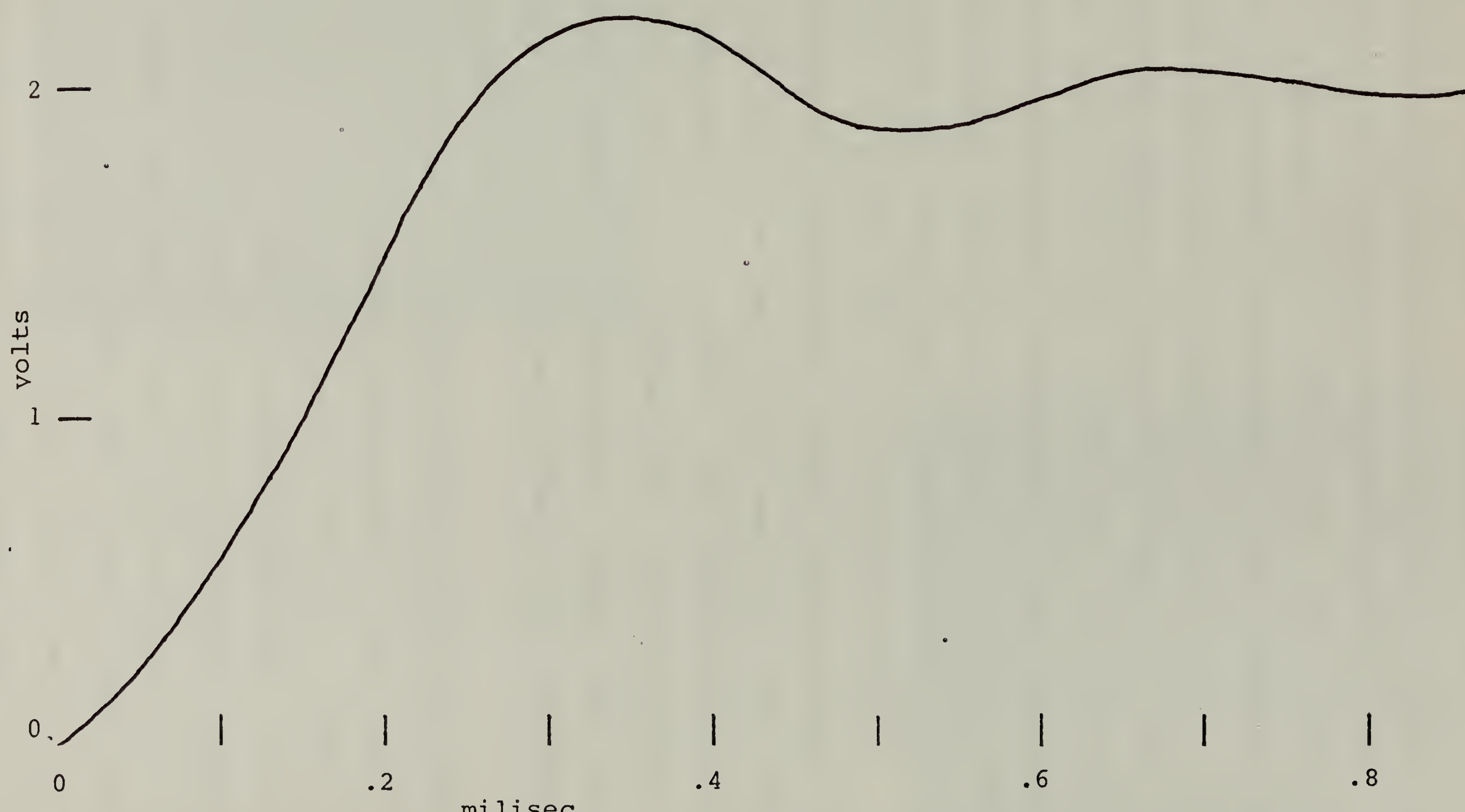


Figure 15. Time response of the tape recorder in the FM mode to a step input.

of undulation is still present. Consequently, under these circumstances, particular care must be taken as to where on this response curve the analog-to-digital sampling takes place. The sampling point selected is that axis crossing that occurs at about 0.615 miliseconds. This amount of delay is inserted in the analog-to-digital conversion delay line which means that sampling of the analog signal will take place 0.615 miliseconds after the trigger. This cross-over point was selected because the existence of any significant delay timing errors would cause the minimum amount of error on the value of the sampled data. Parenthetically, if it were possible to sample after a 1.3 milisecond delay or correspondingly to increase the recorder bandpass from 2500 hertz to 5000 hertz, the oscillations would have been damped out and consequently of no effect. The significance of this is that with a 2500 hertz bandpass and a 0.615 milisecond sample delay, the value of the previous voltage level does not affect the value of the present sample which eliminates any problem with aliasing.

This video signal is not of the ideal square-wave form since it contains a large but narrow pulse at the beginning of each period. As seen previously in Figs. 9, 10, and 11, this pulse is on the order of 30 microseconds wide. Fortunately the pulse is so narrow, and in this case the bandpass of the recorder sufficiently low, that the response effects from this pulse are quite minimized. Figure 16 shows what is in essence the worse case result of this pulse and the amount of output undulation or ripple can be noted. In fact,

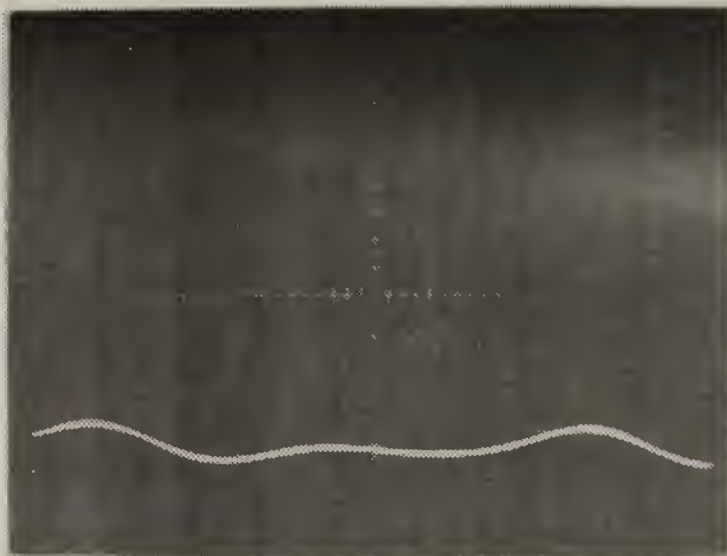


Figure 16

Worse case ripple conditions produced on the video signal, V, as seen at the output of the tape recorder.

Voltage level approximately -2.2 volts

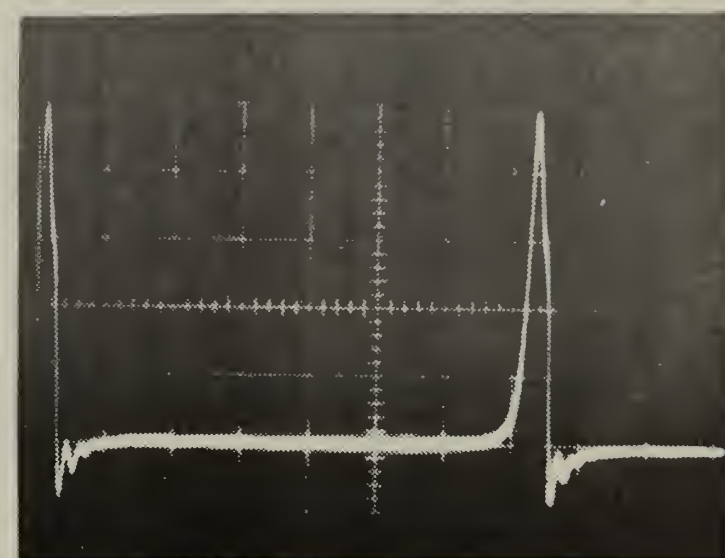
horizontal scale .1 milisec./cm.
vertical scale 1 volt/cm.

Figure 17

Value of sync signal at the output of the tape recorder

-1 to +5 volt range

horizontal scale 1 volt/cm.
vertical scale 1 volt/cm.



the error in the output signal in the neighborhood of the 0.6 milisecond point due to this "impulse" is practically imperceptible and its effects are ignored. In summary, the Ampex SP300 magnetic tape recorder is adequate to the task of recording these types of data signals although a greater FM recording frequency response would be highly desirable.

V. OPERATIONS

There are several operational requirements which should be satisfied to ensure valid results with this radar-cross-section measuring method. These include constraints on the angular position of the radar antenna, the range of the radar's tracking gate, sufficient equipment warm-up time and proper signal calibration.

As shown in Fig. 4, the radar antenna is located where its field of view is essentially unrestricted throughout 360 degrees of azimuth coverage. Even so there exists within the radar's tracking gate at very short ranges the effects of clutter from nearby objects which enter in through the antenna's side and back lobes. In addition, there also exists at these short ranges an apparent clutter due to the deionization effects of the radar's T-R tubes. Although it is possible to detect and track the real target in this clutter region, the video signal values are quite suspect since they contain in addition to target return a clutter bias. These values should be excluded from the measurement data. For this radar the clutter region extends out to 1000 yards in range. Therefore this minimum range restriction is imposed on all data collected.

A minimum elevation angle requirement is also needed. It should be apparent that if the radar antenna is sufficiently depressed while tracking a target so that part of the main beam impinges on the earth's surface, that the portion of ground return within the range tracking gate will be added to the return from the target giving a false indication of

target size. To guard against this eventuality a minimum antenna elevation angle of three degrees is imposed. This value is derived from considerations of the beam width, the radius of the conical scan pattern and empirical testing against the far horizon. There are of course many azimuth sectors where this elevation angle must be increased because of surrounding hills.

The necessity for equipment stability and environmental constancy has been previously stated. In order to actually bring about the conditions to satisfy these requirements the following procedures have been instituted.

1. After the radar system has been brought up to a full radiate condition it is maintained in this status for a full hour before any data is taken. Likewise all ancillary equipments are turned on and allowed to warm up for an hour before actual operational use.

2. Only a minimum time lapse is permitted between the calibration of the radar system and the measurement track of the target.

The warm up time is intended to permit all the system parameters to settle down to their steady-state values prior to calibration. The short time lapse between calibration and measurement is designed to minimize the effect of any system transient or environmental change which might occur during the target measuring process.

To permit the maximum resolution of the data signals and to take advantage of the full dynamic range of the recording

equipment, the recorder output of the various data signals must be properly adjusted.

In the case of the sync signal the adjustment is trivial. The output of this recorder channel is observed on an oscilloscope and the gain of the channel is varied until the output trigger pulse has an amplitude greater than two volts but less than the saturating level of the recorder. (See Fig. 17 for a sample output trigger).

The calibration of the video signal is more complex. First of all the radar range gate is moved in to zero range and is locked on the "main bang" of the transmitter. This of course, introduces a very strong signal into the radar. The radar receiver is switched from AGC to manual gain control. The receiver gain control is turned completely down so that the video signal appearing at the input to the tape recorder represents the weakest of all possible targets, i.e., no target at all. As can be seen in Fig. 18 this results in an input signal to the tape recorder that has a DC voltage level of about +0.8 volts. However, as seen in Fig. 19 the DC value of this signal coming out of the tape recorder is about zero volts. This downward biasing is produced by the introduction of a "bucking voltage" resulting from a screw driver adjustment on the tape recorder. This adjustment is set so that this minimum valued video signal will produce an output of zero volts. About thirty seconds of this minimum valued signal is recorded on magnetic tape. Now the gain of the radar receiver is turned up to maximum value permitting the "main bang" to saturate the receiver. The video signal now

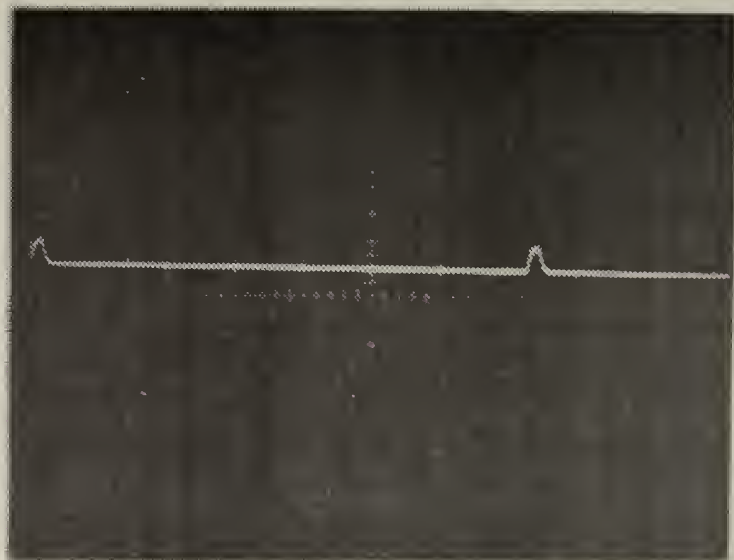


Figure 18

Minimum value of the video signal, V, of the input to the tape recorder

+.8 to +1.3 volts

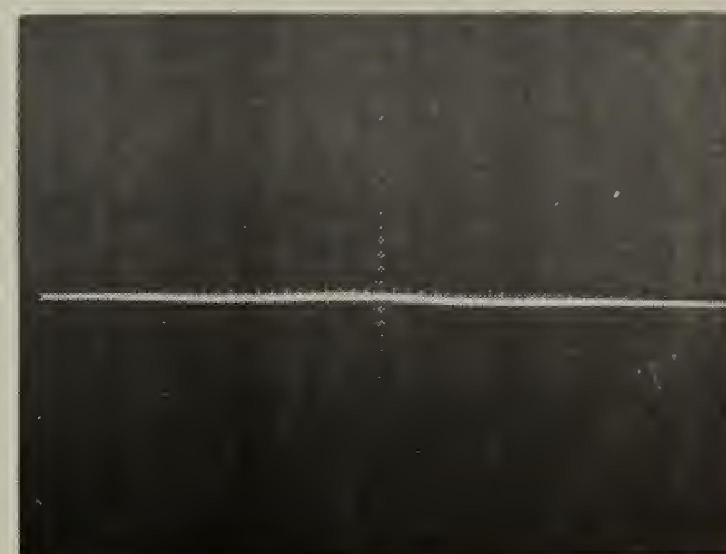
horizontal scale .1 milisec./cm.
vertical scale 2 volts/cm.

Figure 19

Minimum value of the video signal, V, at the output of the tape recorder

approximately 0 volts

horizontal scale .1 milisec./cm.
vertical scale 1 volt/cm.



appearing at the input to the tape recorder represents the largest of all signals, i.e., a saturated receiver condition. The gain control on the tape recorder channel is now adjusted to give the maximum signal output without overdriving the recorder or distorting the signal in any fashion. Figure 16 shows the DC value of this signal to be slightly in excess of -2 volts. About thirty seconds of this maximum valued signal is recorded on magnetic tape. It is very unlikely that actual target returns will ever produce a video signal approching either of these calibrated extremes. For weak signals the radar will drop out of automatic track before the zero signal condition is reached. For strong signals the ability to attenuate the video signal up to 42 dB should be sufficient to keep the receiver out of saturation. Having ensured that the value of the video signal will always lie between the two calibrated extremes, it can safely be assumed that this signal out of the recorder is of high fidelity and is spread over a maximum dynamic range.

The range voltage is ambiguous every 2000 yards and pro-duces a sawtooth waveshape when plotted against range. Consequently, minimum and maximum values of range voltage occur immediately on either side of the voltage sawtooth discontinuity. Since the range gate is already positioned at zero yards in range, very slight movements in range about this point of discontinuity will produce the extreme values of range voltage. Thirsty second samples of each value are recorded after the tape recorder channel gain control has been

adjusted so that the output values are zero volts for the minimum and about one volt for the maximum.

The inputs to the tape recorder from the attenuator switch are zero to seven volts DC in one volt steps. Once again the gain control of the recorder channel is adjusted so that the signal values out of the recorder range from zero to 0.7 volts in 0.1 volt steps. About thirty seconds of each of these eight different voltage levels are recorded on the magnetic tape.

In a similar manner the pen recorder is adjusted with the minimum and maximum values of AGC and range voltages. The operational procedures required to perform a measurement can be described by the sequential listing of the following events.

1. Allow the measuring radar system sufficient time to warm up by permitting it to radiate for about an hour.

2. Allow all other ancillary equipment sufficient warm-up time.

3. Prepare the calibrating target by inflating the balloon with helium and attaching the aluminum sphere underneath. The sphere should be closely examined to ensure the absence of dents or other structural flaws. Care also should be taken to place the cotter pin inside the spherical shell so as to not distort the backscatter pattern of the sphere.

4. When the required warm-up time is completed, adjust the output levels of the recording equipment and record thirty second samples of all appropriate data signal voltages.

5. Release the balloon and commence tracking the calibrating target. When track is established and at ranges in excess of 1000 yards turn on both recorders to collect calibration data.

6. When the calibration sphere can no longer be automatically tracked secure both recorders.

7. Commence track of the target aircraft. When a good lock on has been achieved, start both recorders.

8. Continue tracking as long as data is required or as long as data is valid. Annotate the stripchart with initial tracking range values and any other pertinent operational remarks.

9. Secure the measuring equipment and take the magnetic tape and the brush recorder strip chart (containing all pertinent test conductor comments and initial condition data) to the computer center for data reduction.

VI. AREAS FOR IMPROVEMENT

To increase the accuracy of the collected data and to expand the usefullness of the computed cross section values, several additions and changes should be made to this measurement technique.

Primarily, a different fire control radar system should be used to perform the measurements. A system particularly recommended is the NIKE-AJAX radar system. It possesses all of the positive qualities of the Mk-25 plus the additional advantage of using monopulse tracking. This feature is particularly desirable in that, it produces a greater system gain, reduces the tracking error, and eliminates the conical scan amplitude modulation error. The elimination of this modulation error would represent a great improvement in the quality of the measurement data. In addition, serious consideration should be given to utilizing within this radar system a receiver which has an inherent dynamic range of about 80-90 dB. Although the use of the attenuator switch (which artificially increases the dynamic range) appears satisfactory, a receiver with this capability already built in would eliminate another potential source of error.

A big improvement in measurement quality would occur if another magnetic tape recorder were used. The requirements for an ideal tape recorder would include an upper bandpass frequency of at least 5000 hertz when recording in the FM

mode. This frequency bandpass must occur coincidently with a 40 minute tape capacity for the recorder. Another desirable feature would be a recorder input impedance of at least 100 kilohms. Several modern portable tape recorders with at least seven channels, an ability to record in both FM and Direct modes and satisfying the frequency and tape capacity requirements are currently available and one should be procured for this data recording purpose.

Another important area of technique improvement lies in associating each value of computed target cross section with the particular aspect of the target. To accomplish target aspect determination the measuring radar system's antenna position angles should be instrumented and the values recorded. The angle values would be time correlated with the Rt and Vt values. The data reduction computer program should then be augmented to determine the time derivitive of these angles, i.e., azimuth and elevation angular rates. Angular rates as a function of range and range rate can produce an indication of the target's aspect by computing the target's velocity vector and relating it to the radar/target line of sight. If wind velocities were known it would be possible to modify the target's track and thereby correct the computed aspect angle for the effects of wind induced crabbing. It might even be possible to determine the velocities of winds aloft by the track of the balloon and sphere during the calibration run. These computed aspect values could be associated with the computed values of radar cross section. This ability to relate σ to the target aspect makes the cross

section data much more meaningful and causes a quantum increase in operational flexibility. This means that useful data can be derived from targets of opportunity and that the pilot is under no significant operational constraints imposed by the measurement method. Radar cross section can then be plotted as a function of target aspect or the computer could be programmed to select only those values of cross section within any desired aspect limits.

In conclusion there are two miscellaneous improvements that can be made to enhance the quality of the measurement. Firstly, a computer subroutine can be written to compensate for the effects of atmospheric attenuation based on the data revealed in Fig. 1. This corrective factor should truly make the values of target cross section independent of range.

Finally, an exact value of the backscatter cross section of the sphere could be computed based on a precisely determined relationship between the sphere's dimensions and the wavelength. Figure 3 applies.

VII. CONCLUSION

Efforts to date, which have sought to establish a dynamic radar cross section measuring facility at the Naval Postgraduate School, have resulted in an instrumented radar, the ability to calibrate the measuring equipment, to record the necessary data, to perform data reductions and produce a computed value of target radar cross section. The initial data results are admittedly crude and are not indicative of the full potential of this measurement technique. However, the methodology has been proven and operational procedures have been established and the paths to much greater capabilities have been suggested. An assessment of this measurement technique suggests that it is quite valid in its approach to the problem and that it holds the potential of revealing a great deal of information about the nature of the radar cross section of airborne targets.

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13. ABSTRACT

The instrumentation of a Mk-25 Radar Fire Control System to perform radar cross section measurements of airborne targets on a pulse-to-pulse basis is described.

Instrumented signals available within the radar are conditioned, recorded on magnetic tape, and forward for digital computer processing.

A discussion of this radar cross section measurement method, a description of its implementation and assessment of its validity are presented.

KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Radar						
Radar Cross Section						
Target						
Measurement						