Signature Studies for a Re-Entry System

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The Eastern Test Range (ETR) has recently experienced increasing demands for signature data. Satisfying these demands requires the use of specialized equipment, techniques, and personnel of varied backgrounds. Since this capability has recently been expanded here at the ETR, it is the intent of this paper to present a broad survey of the techniques and equipment being used. Because of the complexity of the subject matter and security requirements it was necessary to avoid greater detail. Much of the information presented here was extracted from unclassified sources and the figures and data that describe the hypothetical test are based on several different tests. These data have been completely modified so that they do not reflect the characteristics of any specific vehicle or test.

Signature Analysis (SA) is a technique which uses various sensing devices (radar, optoradiometric) in attempts to identify unknown objects in space and during re-entry. Identification is based upon characteristic signal returns for a specific sensing device. For example, using radar one can determine, to a certain degree, the size and shape of an unknown object by analyzing AGC records or video returns.

Figure 1 shows characteristic returns from a sphere and a tumbling cylinder. The reason the amplitude of the sphere is relatively constant (neglecting range) is that regardless of the position of the sphere relative to the radar beam, the cross-sectional area of the reflecting surface is always constant. However, this is not the case for any geometric shape other than a sphere. In these cases the amplitude of the returned signal is a function of the aspect angle and the physical size and shape of the object being tracked. The pattern presented in Figure 1 represents a tumbling cylinder moving directly toward the tracking source. The four major peaks represent a 360° rotation of the cylinder, with each of the peaks indicating maximum signal return from broadside and end-on views of the cylinder to the radar beam. The lobe widths and relative amplitudes are functions of a number of variables among which are body shape and radar frequency.

Cross-sectional area of each target is related to the various parameters of the radar by the classical radar range equation. The cross-sectional area may be presented in logarithmic form referenced to a one-square meter target. Thus:

\[
S = \frac{P_T \lambda^2 G^2 \sigma}{4\pi^3 R^4 L}
\]

or,

\[
\sigma = \frac{SR^4 L 4\pi^3}{P_T \lambda^2 G^2}
\]

finally, \( \text{DBSM} = 10 \log \frac{\sigma}{\sigma_0} \)
Later figures will be presented as db above or below a one square meter target.

![Characteristics of Radar Returns for a Sphere and Cylinder](image)

**Figure 1. Characteristic Radar Returns for a Sphere and Cylinder**

Figures 2 through 4 present signature obtained by long range optics and opto-radiometric devices. (1)

Signature Analysis finds application in many fields. For example, it is used by manufacturers of ICBM or IRBM re-entry body systems and associated interference systems to evaluate the effectiveness of their systems, and by researchers in developing effective anti-ballistic missile systems.

These introductory remarks have been rather fundamental. In actuality, the field is very complex, touching on many other sciences. For example, in studying the re-entry of an ICBM nose cone into the atmosphere, a crucial period for analysis, one should be familiar with the fields of electro-magnetic theory, aerodynamics and fluid-mechanics in order to properly analyze the phenomena and reach a valid conclusion.

Since the field of SA involves so many factors and one could talk for hours on any particular phase of this subject, a hypothetical test report based on radar signature will be used as a vehicle for discussing the various subjects relating to SA.

**Pre-Test Activities**

Prior to any mission, a number of pre-test meetings are held at which the range user describes the mission and his requirements for data. At subsequent meetings the range contractor submits plans for data collection and assigns specific responsibilities to each of the downrange stations. Those assignments are made according to equipment complex and geographic location, assuring the range user the best possible data.
Reproduction of a frame taken with a long focal length telescope. The object was a re-entry vehicle at an altitude of about 80,000 feet. The illuminated wake or trail behind the vehicle is about 250 feet long.

**FIGURE 2. RE-ENTRY VEHICLE SHOWING ILLUMINATED WAKE**

\[
(\lambda_{\text{max}})(T) = 2897.9^\circ K/\mu
\]

\[
T = 2897.9^\circ K/\lambda_{\text{max}}
\]

\[
T \approx 3700^\circ K
\]

Relative Spectral Radiation of a Re-Entry Vehicle Taken on a Cinespectrograph. The plot is of the relative spectral radiant intensity of a re-entry vehicle at an altitude of 50,000 feet. A gray body curve fit (dashed lines) to these data indicates that the surface temperature was about 3700°K.

**FIGURE 3. OPTICAL SIGNATURE DATA - CINESPECTROGRAPH**
Spectral Radiant Intensity of a Re-entry Vehicle versus Range Time.

The radiometer measured the radiation in a bandwidth of 1.8 microns
to 3.1 microns. In the test illustrated
the maximum radiation occurs at an altitude of 80,000 feet.

FIGURE 4. SIGNATURE DATA - RADIOMETER

FIGURE 5. EASTERN TEST RANGE
For example, data on the initial phases of an ICBM trajectory would be collected by Stations 1 and 3; while mid-course data would be collected by Stations 7 and 40. Terminal data could be collected by Station 12 or by one or more of our specially equipped Advanced Range Instrumentation Ships (ARIS) and the American Mariner. Figure 5 indicates available radar coverage on the Eastern Test Range.

For the purpose of this discussion we will limit data requirements to the terminal phase of a ballistic missile, that is, just prior to and during re-entry.

The data will reflect the results of a series of hypothetical ICBM tests employing advanced re-entry body systems and penetration aids.

The assumed objectives, according to priority as defined by the range user are listed below: (2)

1) Primary: Signature and trajectory data on the re-entry body from 300,000 to 50,000 feet.
2) Secondary: Signature and trajectory data on the penetration aids from 300,000 to 50,000 feet.
3) Tertiary: Perform chaff mapping to determine characteristics and coverage following impact.
4) Other: Signature data for any other targets of opportunity.

Specific responsibility for this phase of the mission was assigned to the General H.H. Arnold, one of the Advanced Range Instrumentation Ships. The reasons responsibilities have been assigned to this ship are two-fold: first, it can be optimally located to collect data during re-entry, and second, because of its special tracking equipment and associated calibration and data reduction routines.

Equipment Characteristics of the General H.H. Arnold

Briefly, its electronic equipment consists of three integrated tracking radars operating in the C-, L- and X-bands. (The H.S. Vandenberg, a sister ship to H.H. Arnold has UHF capability in lieu of X-band.) The C-band is the main tracking radar with the L- and X-band antennas slaved to the C-band. The C-band is capable of simultaneously tracking a prime target and any two ancillary targets which fall within the C-band antenna coverage and within +16 nautical miles of prime target (Figure 6). Once acquired by the C-band the targets can also be tracked in range by the L- and X-band radar.

Signature data capability is enhanced by diversity of frequency bands and by using both horizontally and vertically polarized transmission and reception. Each radar on the Arnold has two transmitter chains, one horizontal and one vertical, operating alternately at a 160-pulse repetition frequency. Because of this feature the system provides 12 signature outputs plus metric data in real time for each of three tracked targets.

Long range capability with excellent range resolution is accomplished through pulse compression. A skin pulse of 30 usec is transmitted and then compressed by the receiver to less than 1 usec before angle error and signature data are extracted. Early target acquisition is enhanced by the simultaneous beacon interrogation mode which enables beacon interrogation.
SECONDARY TARGET NO. 1
PRIMARY TARGET
SECONDARY TARGET NO. 2

32 NM RANGE INTERVAL
(±16 NM REF. TO PRIMARY TARGET)

BEAM COVERAGE
C-BAND (.5° BEAM WIDTH)

L- & X-BANDS
C-BAND

FIGURE 6. ARIS C-BAND RADAR COVERAGE CHARACTERISTICS
through the vertical as well as horizontal polarization at horizontal time. A side lobe blanking feature is incorporated through use of a wide beam antenna and the C-band vertical skin channel. This feature prevents the radar from locking on a side lobe during beacon acquisition.

Raw video is recorded on magnetic tape for post-flight playback tracking of all video. Video is recorded on strip film for all frequency bands. Figure 7 summarizes the operating parameters of the system.

Calibrations

Prior to and immediately following each test the ship performs a comprehensive system calibration to ensure the validity of the data. Figure 8 is a simplified drawing of the calibration and data processing procedure.

Pre- and post-test calibrations include receiver response, antenna pattern and servo-measurements.

The receiver is calibrated by inserting a signal of sufficient amplitude to cause saturation. Then attenuators of known value are inserted until the signal level decreases to noise. The calibration performed on the ARIS receivers is a relative calibration, that is, the magnitude of the input signal is not known, but it is attenuated in known amounts so that the receiver characteristic is relative and a point of reference must be found in another manner.

The next step in the calibration procedure serves two purposes: 1) to establish an absolute level from which cross-sectional area can be derived, and 2) to determine the relationship between the tracking error voltages and the angular offset of a target relative to the radar beam's center. This is necessary in order to be able to compensate for the loss of signal strength caused by off-angle track of the two ancillary targets. This type of calibration requires a target to be tracked with some means of offsetting the radar from the target and then measuring, very precisely, this offset. In the case of the ARIS, it is done by tracking a 6-inch metal sphere hanging below a balloon and inserting fixed voltage errors into the tracking system to offset the radar from this balloon.

Thus, the six-inch sphere establishes an absolute reference for all targets. Furthermore, amplitude errors generated during off-angle track can be compensated for by correlating the received error signal with antenna gain.

The resulting antenna pattern fit from one of these calibrations was derived by taking the sum channel output and converting it to relative db by using the receiver response curve. The various outputs are then utilized in the data reduction routines.

The pre-test and post-test calibration and data reduction routines have been refined to the point where the overall accuracy of signature data is less than 3 db.

Pre-Test Information

Pre-test information provided by the range user facilitates data acquisition and analysis by the range contractor. This information includes
<table>
<thead>
<tr>
<th></th>
<th>C-Band</th>
<th>L-Band</th>
<th>X-Band</th>
<th>UHF-Band (H.S. Vandenberg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antenna:</td>
<td>30 Foot parabolic</td>
<td>40 Foot parabolic</td>
<td>19 Foot parabolic</td>
<td>40 Foot parabolic</td>
</tr>
<tr>
<td></td>
<td>Horizontal &amp; vertical</td>
<td>Horizontal &amp; vertical</td>
<td>Vertical</td>
<td></td>
</tr>
<tr>
<td></td>
<td>51 db</td>
<td>41 db</td>
<td>40.5 db</td>
<td>33.5 db</td>
</tr>
<tr>
<td></td>
<td>0.9 degrees</td>
<td>1.2 degrees</td>
<td>0.4 degrees</td>
<td>5.0 degrees</td>
</tr>
<tr>
<td>Transmitter:</td>
<td>5.4 to 5.9 GC</td>
<td>1215 to 1365 mc</td>
<td>3 db (paramp in)</td>
<td>8850 to 9200 mc</td>
</tr>
<tr>
<td></td>
<td>1 Megawatt</td>
<td>10 Megawatts</td>
<td>7.7 db (paramp out)</td>
<td>1 Megawatt</td>
</tr>
<tr>
<td></td>
<td>1.2 degrees</td>
<td>2.8 db (paramp in)</td>
<td>10.7 db (paramp out)</td>
<td>15 Megawatts</td>
</tr>
<tr>
<td>Receiver:</td>
<td>5.4 to 5.9 GC</td>
<td>1215 to 1365 mc</td>
<td>7.7 db (paramp out)</td>
<td>433 to 437 mc</td>
</tr>
<tr>
<td></td>
<td>3 db (paramp in)</td>
<td>130 db</td>
<td>120 db</td>
<td>420 to 440 mc</td>
</tr>
<tr>
<td></td>
<td>9.5 db (paramp out)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Range:</td>
<td>Interval to 32,000 NM</td>
<td>as C-Band</td>
<td>as C-Band</td>
<td>as C-Band</td>
</tr>
</tbody>
</table>

**FIGURE 7. RADAR OPERATING PARAMETERS**

**FIGURE 8. RADAR CALIBRATION AND DATA PROCESSING**
descriptions of:
1) The missile and its configuration
2) The expected trajectory and impact points
3) The sequence of events associated with a particular mission
4) The characteristics of the re-entry vehicle and associated penetration aid.

**Introductory Analytical Theory**

In addition to utilizing pre-test information and the outputs of the various sensing devices, the analyst can expect the missile to respond in a characteristic manner. The response is mostly dependent upon the molecular density of the atmosphere (Figure 9) (3). This figure presents molecular density versus altitude and indicates that at apogee (2.5 million feet) to 500,000 feet, molecular density changes from $10^{+11}$ per cubic foot to $10^{+15}$ per cubic foot: a change by a factor of 10,000 for a 2,000,000 feet change in altitude. Note that from 500,000 feet to 50,000 feet molecular density changes from $10^{+15}$ per cubic foot to $10^{+23}$ per cubic foot, a change by a factor of 100,000,000 in only 450,000 feet. (3) That is, at altitudes above 300,000 feet atmospheric density is so low that the aerodynamics of the vehicle are unaffected and there is no apparent change in target cross-sectional area due to ionization of molecules in the immediate vicinity of the re-entry vehicle. However, as altitude decreases, the effects of the atmosphere are more pronounced, affecting both aerodynamics and cross-sectional area of the re-entry vehicle. Altitudes above 300,000 feet are referred to as exo-atmospheric, and altitudes below 300,000 feet, endo-atmospheric. (Figure 10 summarizes the expected responses for a missile system.) (4)(16)

Since the terms and quantities describing re-entry phenomena embrace a number of sciences, it is felt that a short review at this time will provide a common basis for better understanding the test results. Of particular interest to this discussion are:

1) The generation of the plasma sheath
2) Characteristics of associated wake
3) Changes in REV velocity caused by entry into denser atmosphere
4) Changes in aerodynamic behavior of the REV
5) The use of ablative material

**Generation of the Plasma Sheath:** As previously mentioned, the molecular density of the atmosphere increases inversely as a function of altitude. A re-entry vehicle traveling at hypersonic velocity when entering the atmosphere will cause a system of shock waves to form. These shock waves cause a deceleration of the air flow around the body and will therefore cause the formation of high temperature regions bounded by the shock waves and the re-entering body (the inviscid flow region). (5)

As the temperature increases, the point may be reached where dissociation, ionization and recombination of the gas molecules occur. The result will be to cause layers of concentrated density electrons to form around and behind the re-entering body. The electron density will not be uniform but will vary as a function of the temperature in the inviscid flow region (Figure 11).
FIGURE 9. ATMOSPHERIC CHARACTERISTICS

FIGURE 10. EXPECTED MISSILE SYSTEM PERFORMANCE
The increase in electron density gives rise to the formation of a plasma sheath and associated wake, both of which affect target cross-sectional area. The electron density surrounding the re-entry vehicle, to a large degree, determines the reflectivity of the body at this time. That is, there is a specific relationship between electron density, radar frequency and target reflectivity.

As the altitude decreases, the concentration of molecules causes the velocity of the vehicle to decrease to a point where there is no longer sufficient temperature to cause dissociation. At this point the plasma sheath and wake will no longer be present.

The plasma sheath begins to form during the very early stages of re-entry but does not usually become observable to the radar until about 250,000 feet.

As the re-entry body passes through the atmosphere, the characteristics of the plasma sheath are continuously changing and, under certain conditions, will cause a drastic modification of the normal radar cross section. The measured radar cross section of the re-entry vehicle may show a significant increase or decrease from the free-space radar cross section. This change is dependent upon the frequency of the incident radar wave and upon the complex interplay between the physical properties of the plasma which, in turn, are related to the re-entry body characteristics (shape, aerodynamics, trajectory, re-entry angle, etc.).

Efforts have been made to interpret the decrease of cross section in terms of 1) absorption of electromagnetic energy due to high electron and
neutral particle collision, 2) a refraction of the incoming rays away or around the body of the vehicle, 3) changes of frontal body shape or material due to heat effects. The increase in cross section has been associated with possible backscattering (coherent and incoherent) from the plasma, sheath, and the turbulent trail or wake.

We shall not attempt here to be explicit as to the exact mechanisms of absorption and enhancement or to discuss all the theories and possibilities that will affect the generation and characteristics of the plasma. Our presentation here is only to point out that deviations from the normal or bare-skin value of cross section might be expected. For purposes of discussion of test results, let us consider a simple model in which the phenomena of refraction and absorption as associated with the terms of plasma frequency and collision frequency are used to describe changes of cross section.

Two quantities which may be used to describe the physical properties of the plasma are plasma frequency and collision frequency. The plasma frequency is a measure of the free-electron density and has the general relationship of:

\[
\frac{\pi}{2} f_p = \left( \frac{N_e e^2}{4\pi\varepsilon_0 m} \right)^{1/2}
\]

where:
- \( f_p \) is the plasma frequency in cps
- \( N_e \) is the electron density
- \( e \) is the electron charge
- \( m \) is the electron mass
- \( \varepsilon_0 \) is the permittivity of free space

The collision frequency is a measure of the rate at which the electrons effectively collide with the heavy particles; furthermore, such collisions can be associated with the absorption of radio waves in the ionized medium. An expression for the collision frequency according to the kinetic gas theory is as follows:

\[
f_c = \frac{N A}{\pi m} \left( \frac{8 k T}{\pi m} \right)^{1/2}
\]

where:
- \( f_c \) is the collision frequency in cps
- \( N \) is the number density of molecules or atoms
- \( A \) is the collision cross section
- \( k \) is Boltzmann's constant
- \( T \) is the temperature in degrees Kelvin
- \( m \) is the electron mass

When the free electron concentration in the plasma is very small, i.e., when the plasma frequency is much less than the radar frequency, an incident wave will penetrate the plasma with little or no change in amplitude or phase. Scattering of the incident wave will be a function of only the body within the plasma sheath.

As the re-entry body enters the denser atmosphere the plasma frequency increases. As the plasma frequency approaches and equals the radar frequency while the collision frequency is much less than the radar frequency, the plasma sheath will tend to refract the electro-magnetic energy around the re-entry body causing a reduction in the radar cross section of the target. As the plasma frequency exceeds the radar frequency, while the collision frequency is much lower than the radar frequency, the plasma sheath will tend to reflect most of the incident wave. The effective radar cross section of the target will be determined by the dimensions of the
plasma sheath. As long as the electron collision frequency is much lower than the radar and plasma frequency the plasma remains reflective. However, as the collision frequency exceeds the radar frequency and approaches the plasma frequency the plasma loses its reflective characteristics and the incident wave will begin to propagate in the plasma. The increasing collision frequency causes the attenuation constant of the plasma to increase. When the collision frequency is equal to the plasma frequency, the attenuation of the plasma will be maximum.

This is related to the phenomenon associated with the formation of a discontinuity in the surface of the plasma sheath caused by a high electron collision frequency. As the incident radar wave impinges upon the plasma field and its associated discontinuities, part of the energy will be directly reflected from the plasma sheath, while part will penetrate the plasma. As the electromagnetic energy propagates through the plasma it will lose energy due to its interaction with the electrons. However, part of this energy will reach the surface of the REV and re-radiate back toward the plasma sheath. Before emerging from the plasma sheath this process may be repeated resulting in substantial losses of energy.

Because of the attenuation within the plasma the power actually reflected from the target is much less than the amount that would be returned by a reflective body. Thus, when the electron collision frequency exceeds the radar frequency and equals the plasma frequency, a diminishment is expected. As the plasma frequency becomes much lower than the radar frequency, the incident wave is reflected by essentially a bare body and the radar cross section becomes a normal free-space value during the terminal portion of the flight.

The upper altitude cross-sectional diminishment is expected to occur between altitudes of 250,000 and 150,000 feet for C-band radar under normal re-entry conditions. Although conditions could theoretically exist where the radar cross section would vanish, the maximum upper altitude diminishment noted to date is about 20 db. The lower altitude diminishment point can occur in the region between 50,000 to 70,000 feet.

Figure 12 summarizes the expected variations of radar cross section with altitude. The re-entry is divided into five events which occur at different altitudes. It should be noted that the altitude at which the different events occur will vary with the type of re-entry vehicle, angle of re-entry, and the frequency of the radar used to observe the event. It is also possible that some of the events may not occur at all or their magnitude may be too small to be observed.

On the left is a theoretical plot of plasma frequency and electron collision frequency versus the frequency of C-band reference. The abscissa represents the frequency of the three functions. The curve on the right shows the variation of radar cross section during re-entry under the frequency conditions illustrated by the curves on the left. The vertical scale for all curves is altitude.

As the body enters the atmosphere the amplitude of the body motions decreases and the frequency increases. In this region the plasma frequency is much less than the radar frequency. The plasma sheath that exists in this region will be transparent to the radar wave. (Figure 12, Area 1)
As the plasma frequency becomes comparable with the radar frequency, and while the collision frequency is much lower than the radar frequency, the plasma sheath appears absorptive and the effective radar cross section is reduced. The reduction in cross-sectional area may be due to the partial refraction of the electromagnetic wave around the body (Area 2).

When the plasma frequency exceeds the radar frequency and the collision frequency is still lower than the radar frequency, the radar cross section is increased and enhancement takes place (Area 3).

When the electron collision frequency exceeds the radar frequency and approaches the plasma frequency, absorption takes place (Area 4). Immediately following the period of absorption the plasma sheath disappears and the measured cross section is the free-space value (Area 5).

Characteristics of Associated Wake: Wake, the ionized field trailing behind the re-entry body, is an area of great interest to the analyst and researcher. In addition to studying the characteristic signal returns during re-entry, attempts have been made to develop theories relating wake length with body size and shape.

Up-to-date field testing has resulted in limited success in validating the above theories, perhaps because of the many uncontrolled variables that can exist during field testing, i.e., the inability to accurately determine the relationship of the velocity vector with the longitudinal axis of the re-entry body, the reflective characteristics of the different types of wake and the effects of contaminants in the wake caused by ablation.
Figure 13 indicates changes in plasma and wake characteristics caused by misalignment of the velocity vector with the longitudinal axis of the re-entry body. At time (1), the longitudinal axis is misaligned with the velocity vector causing a large plasma field to be built up in front of the re-entry body with a small trailing wake. As the longitudinal axis of the re-entry body tends to align itself with the velocity vector, time (2), the plasma starts to "peel off" and wake length increases. Finally, at time (3), the velocity vector and longitudinal axis are aligned, resulting in a minimum plasma field and a maximum wake. Times (4) and (5) are similar to times (1) and (2). The drawings beside the plasma represent A-scope films corresponding to the same times. Note that the maximum wake length corresponds to time (3) when the longitudinal axis is aligned with the velocity vector.(10)

Another problem encountered involves the reflective characteristics of wake. There are two types of wake, laminar and turbulent, which refer to the characteristics of air flow around a body. (11) For a given body, under certain conditions of density and velocity, the fluid (air) flows around the body in parallel layers (laminar flow). Under such conditions, the flow is smooth and regular (Figure 14a). When these limits of relative velocity and density in a fluid are exceeded, the flow becomes less well-behaved and less stable. The fluid flow becomes more random and whirlpools or "eddies" are generated. This condition is called "turbulence". Figure 14b indicates the establishment of turbulence. Further increases in velocity may create a string or successions of eddies trailing many body lengths behind the vehicle. The turbulent wake is thus a rough surface containing neutral particles (air, ablation products, etc), free electrons, and ionized atoms. Since a rough-surfaced wake provides a better scattering medium than a smooth wake, the turbulent wake presents a better radar reflector than the laminar wake. Signal return magnitudes, however, will depend on the extent and composition of the wake, the aspect angle, and the operating frequency of the radar.

Finally, the return signal, in addition to varying with the aerodynamic characteristic of the vehicle and the type of wake, will also vary as a function of the aspect angle. If the aspect angle of a relatively slender re-entry body is zero, and the longitudinal axis and velocity vector are aligned, the effects of the wake would probably not be noticeable. If there is any increase in target cross sections it can probably be accounted for by the effects of the plasma.

As the aspect angle increases, there is a lengthening of the pulse and a change in signal characteristics corresponding to the type and length of wake.

Figure 15 illustrates the wake length as seen by the radar and viewed on the A-scope. In order to derive the true wake length the following formula is used:

True wake length \( (T_{WL}) = \frac{(T_R - T_t)C}{2 \cos \theta} \)

where: True wake length = wake length in feet
\( T_R \) = length of received pulse in microseconds
\( T_t \) = length of transmitted pulse in microseconds
\( C \) = velocity of light \((10^8 \text{ ft/microsecond})\)
\( \theta \) = aspect angle as viewed from the radar, and
\( \cos \theta = \frac{T_R - T_t}{T_{WL}} \) (\( T_R \) and \( T_t \) in microseconds are derived from the A-scope)
PLASMA STARTS TO PEEL OFF (WAKE ENHANCEMENT)

FIGURE 13. PLASMA AND WAKE CHARACTERISTIC CHANGES

FIGURE 14. TYPES OF FLUID FLOW

(A) LAMINAR FLOW

(B) TURBULENT FLOW
As the aspect angle increases to 90° both the numerator and denominator become zero and there is no indication of wake. However, at this point, a large amplitude specular return caused by apparent change in body length caused by the trailing wake can be expected.

Velocity Changes Caused by Atmospheric Entry: The ballistic coefficient is a measure of the relative efficiency of a missile in overcoming air resistance. Larger magnitudes of the coefficient imply that a vehicle is more efficient. A larger value also implies a faster re-entry, a lower altitude before maximum deceleration is reached, and a better accuracy.

The ballistic coefficient is defined as the ratio of the initial weight of the re-entry body to the drag coefficient and the drag area.

Mathematically it is expressed as

$$\beta = \frac{W}{C_pA}$$

where: $\beta =$ ballistic coefficient (pounds/ft$^2$)
$W =$ weight (pounds)
$A =$ drag area of the body (feet)
$C_p =$ drag coefficient (dimensionless: determined by physical parameters of the body, body dynamics, and the environment in which the body is moving.)
Gravity and aerodynamic drag forces are considered here as the only forces of importance in determining the trajectory and the motion of the re-entering vehicle. The drag force is not measurable directly; however, the ballistic coefficient is measurable and presents one of the most direct connections between the drag forces and its effect upon motion.

The following calculations indicate how the drag force parameters, ballistic coefficient, and radar parameters may be related. (12)

The drag force \( F_D \) has been empirically determined for a wide range of speeds to be equal to:

\[
F_D = \frac{C_D \rho AV^2}{2}
\]

where:
- \( \rho \) = air density = slugs = LB Sec\(^2\) FT\(^3\) FT\(^{-4}\)
- \( A \) = drag area (FT)
- \( C_D \) = drag coefficient (dimensionless)
- \( V \) = velocity measured (FT/Sec)

From Newton's 2nd Law of Motion \( F = ma \)

\[
F_D = m_B a_D
\]

where:
- \( m_B \) = body mass = \( \frac{W}{g} \) (grams)
- \( a_D \) = acceleration due to drag

or,

\[
F_D = \frac{W a_D}{g}
\]

Equating (1) and (2b):

\[
\frac{C_D \rho AV^2}{2} = \frac{W a_D}{g}
\]

Rearranging:

\[
\frac{W}{C_DA} = \frac{\rho g V^2}{2a_D}
\]

This final expression contains quantities that may be measured with the radar or programmed from empirical tables or mathematical models.

Figure 16 is a graph of \( \frac{W}{C_DA} \) with mach number. Note that in the region of interest the ballistic \( \frac{W}{C_DA} \) coefficient does not vary appreciably and falls within certain boundaries.
Change in REV Aerodynamics Behavior: Normally the REV is spin-stabilized at separation from the powered stage and maintains the same orientation throughout the trajectory. When the vehicle is attitude-stabilized there is a tendency for the re-entry vehicle to go into precessional motion (Figure 17).

For most REV's during the exo-atmospheric phase the precessional frequency and $\beta$, the coning angle, will remain constant. However, upon re-entry there are marked changes in these parameters brought about by the denser atmosphere. Usually there is a decrease in the coning angle $\beta$ and an increase in the frequency of precession.

Use of Ablative Material: During re-entry there is a need to protect the re-entry vehicle from the tremendous heat generated during this period. The missile designer has a number of techniques available, such as heat exchangers, radiant shields, heat sinks, etc., with the most successful being the ablative technique. Ablation is simply the dissipating of excessive heat by the wearing away or melting of a specially prepared protective covering. (4) (13). The effects of ablation on the characteristics of radar cross section and wake are usually apparent and readily observed.

Hypothetical Test Report

Operational Directives

For the hypothetical test it was assumed that the General H.H. Arnold was stationed forty nautical miles uprange and 140 nautical miles cross-range (north of trajectory). (Figure 18). The assumed operational mode for the C-band radar as planned was:

1) to acquire beacon track of the re-entry body as soon as it rose above the horizon
2) to switch to skin angle track if beacon blackout occurred during re-entry
3) to lock-on ancillary trackers to any target of opportunity that may appear in the C-band beam while tracking the re-entry body and to perform chaff mapping twenty minutes after impact. (14) (15)

All above and previously stated objectives will be considered as satisfied for the hypothetical test.
Analysis

An analysis of the signature data, chaff mapping and trajectory was performed using the reduced data from three tests.

During testing an attempt is made to have a continuous film record of the entire test. The record is in the form of a deflection (A-scope) and intensity modulated films, and covers a selected range segment of 32 miles.

The intensity modulated film presents a running record of the entire test and can be used to identify the prime targets, target relation to the prime target, important chronological events and for chaff mapping. The amplitude modulated film is used primarily to measure cross-sectional areas of targets other than those being tracked, yet falling within the beam coverage. It can also be used to measure depth and cross-sectional area of chaff. (14)(15)

The intensity modulated scope film shown in Figure 19 provides a chronological record of three tests during exo- and endo-atmospheric flight. Corresponding critical time segments were selected from the upper three film strips of Figure 19, enlarged, and presented in the lower three film strips of the figure. Tests 1 and 2 employed only decoys, while test 3 employed a combination of chaff and decoys. At initial acquisition the decoys and chaff had already been released and assumed spatial separation. There was little change in the spatial distribution until re-entry. At this time, the decoys and re-entry vehicle separate from the chaff. This is a result of the denser atmosphere which causes a rapid change in velocity between the chaff and the heavier REV and decoy. In effect, the chaff compresses or flattens out when it impinges upon the denser atmosphere.
while the REV and decoy, because of their greater weight, continue to travel at higher velocities.\textsuperscript{16}

At an altitude of around 240,000 feet (Figure 19) there is the first indication of the effects of the atmosphere. It is evidenced by a change in the spatial distribution of the chaff (test 3). Simultaneously, or near simultaneously, there is an apparent broadening of the signal in tests 1 and 2, possibly caused by a combination of wake and improved aspect angle.

At around 157,000 feet it appears that the REV and decoys have separated from the chaff (test 3). There is no apparent change until around 80,000 feet when a sudden decrease in signal occurs, probably caused by absorption. At around 35,000 feet there is no longer any indication of decoys.

Figure 20 represents periods of chaff mapping following completion of the test. Each of the blobs represents signal returns from chaff. The subsequent paragraphs will discuss this in greater detail.

In performing a more detailed analysis, the previous chronological records are correlated with characteristic exo- and endo-atmospheric performance. In the exo-atmosphere we looked for:

1) Separation of stages
2) Stabilization of REV (pitch and spin rates)
3) Initial release velocities and spatial distribution of interference package, and
4) Size, shape and movement of REV, third stage or any unexplained debris.

Because of acquisition late in the trajectory, the separation of stages, initial stabilization of re-entry body, and the initial release velocities of the interference package were not observed. However, by comparing the actual spatial separation of the interference package at a given altitude with the theoretical, one can extrapolate backward and conclude that the decoys and chaff were released with the proper velocity and assumed a satisfactory spatial distribution. Other techniques involved comparison of actual and theoretical trajectories.

The sizes, shapes and movements of the REV and decoys were determined by a detailed analysis of the signature plots.

Several types of body motion can be expected in the exo-atmosphere as spin, tumble, precession, or nutation (oscillating precession). A means of determining the approximate physical size of the object by study of the variations or cyclic patterns in the cross section measurements has been developed. By analysis and the use of developed formulae involving the width and number of lobes and body parameters, the length and radius of such general configurations as cylinders, cones and ellipsoids can be determined. For instance, Figure 21, which is exo-atmospheric signature of the same object as obtained on C- and L-bands, illustrates this point. The four major lobes that are indicated in each band may be identified with a form of body tumble having a cyclic period of approximately 24 seconds. Upon establishing the period, the length of the cylinder-like object can be determined by using the following formula and assuming the object to be tumbling in a plane containing the radar line-of-sight.\textsuperscript{17}
FIGURE 19. RANGE INTENSITY MODULATED FILM
FIGURE 20. RANGE INTENSITY MODULATED FILM

FIGURE 21. L-BAND & C-BAND SIGNATURE—EXOATMOSPHERE
The number of lobes contained in one period of the C- and L-bands were 262 and 62 respectively. Inserting these values into the above formula, it was found that the length of the cylinder for C-band was approximately 1.76 meters (5.77 feet) and the length for L-band was approximately 1.9 meters (6.23 feet).

In like manner, a radius may be established using the following formula:

\[ R_{\text{meters}} = \frac{\sigma_{\text{max}} \lambda}{2\pi L} \]

where
- \( R \) = radius in meters
- \( \sigma_{\text{max}} \) = maximum cross section in square meters
- \( \lambda \) = operating wavelength
- \( L \) = length of cylinder

The radius was determined to be 0.173 meters (0.568 feet) and 0.166 meters (0.544 feet) for the C- and L-bands respectively. These values were obtained for the C-band radar using \( \sigma_{\text{max}} \) of 18 dbsm (63.1 square meters), \( \lambda = 0.053 \) meters, and an \( L \) of 1.76 meters. For the L-band, \( \sigma_{\text{max}} \) was 12 dbsm (15.8 square meters), and \( \lambda = 0.238 \) meters, while the \( L \) was 1.90 meters.

The compressing of the chaff and the separation of decoys from the more efficient re-entry body were illustrated in Figure 19. Were \( \beta \) to be computed for the chaff, decoys, and re-entry body, responses as shown in Figure 22 would result. The relatively short penetration time of the re-entry body is represented by a high \( \beta \). The lower \( \beta \) represents the decoys and the very low, the chaff."

Figure 23 illustrates the results of plasma field and associated wake for three tests. The altitudes covered range from about 180,000 feet down to 50,000 feet, and the aspect angles varied from 87° to 104°. It is interesting to note the characteristic changes in the signature data. At an altitude slightly below 170,000 feet there was a marked increase in signal amplitude characterized by rapid fluctuations. This continued until around 85,000 feet when the rapid fluctuations ceased and there was a sudden decrease in signal level. The increase in signal amplitude (approximately 15 db) and rapid fluctuations could be attributed to reflections from a turbulent wake, the rapid decrease in signal amplitude to absorption, and the reduction in signal fluctuation to the decay of the plasma and resumption of bare body returns.

Figure 24 is a composite overlay of the three shots showing the resultant correlation. Although the data from this series of shots did not show the upper altitude absorption period, an example of this phenomenon taken from another test is shown in Figure 25. Interestingly, this particular shot, which was viewed from a zero aspect angle, exhibits no appreciable signal enhancement due to plasma and wake effects.
FIGURE 23. POSSIBLE RESULTS OF PLASMA FIELD AND ASSOCIATED WAKE

FIGURE 24. L-BAND CROSS SECTION
AVERAGE 'BARE' SKIN

FIGURE 25. RADAR CROSS SECTION VS. ALTITUDE

FIGURE 26. RE-ENTRY BODY ASPECT ANGLE CHANGES
The signature data for this series of tests did not produce evidence of stabilization of the re-entry body during re-entry, i.e., a reduction in the coning angle and increase in frequency of precession. The probable reason for this can be related to the re-entry body’s radical change in aspect between the exo- and endo-atmosphere (Figure 26). Early in the flight a head-on or near-head-on view of the re-entry body was presented, and during re-entry, a 90° 'side view of the vehicle was seen. After re-entry, with the aspect angle in excess of 100°, a tail-on view is presented to the radar. Since the signature is substantially different when viewed from this aspect angle, correlation of signature and body motions is very difficult.

Figure 20 presents periods of chaff mapping; the objective was to determine size, shape, radar cross section, and dispersion rates of the chaff cloud following impact in each of the tests. (2)

Chaff mapping is essentially obtained by "dissecting" the space volume containing the chaff cloud (18). It is accomplished by programming the antenna through a basic coverage pattern. Figure 27 presents the primary timing and dimensional aspects associated with chaff mapping and intensity modulated film. The antenna began scanning at T + 0. At T + 1-1/2 seconds, the beam began to intercept the chaff cloud and at T + 1-3/4 seconds scanned completely through it. During this period, the film recorder ran for 1/4 second. If the cloud had a greater dimension in the elevated plane, a longer time would have been required for the antenna to pass through it thereby allowing the film to run for a longer time, resulting in an increased dimension A. The time base for the return data is essentially a measure of chaff coverage in an elevated plane. This is presented in Figure 27 as dimension A. The depth or thickness of the cloud will appear as a range function to the radar and will appear on the film as a dimension in range, dimension B.

Figure 28 is presented to outline the radar hardware action in obtaining a chaff map. The radar is made to dissect the cloud into five or six segments of 0 to 8° in elevation and approximately 2° in azimuth. Approximately 11 seconds are required to complete one cloud map cycle. Figure 29 is the expected film results.

The C-band radar was employed to provide chaff mapping after the primary vehicle had impacted. The following analysis deals with periods of chaff mapping following the completion of the test. (2)

The values for reconstructing the chaff cloud were obtained from the C-band range intensity film by approximating the range depth, by establishing amplitudes relative to the largest target, and by reading the film time code (Figure 20). It is assumed that the first and sixth targets did not show on film because of reduced amplitude.

Figure 30 is then an extension of this data into a three-dimensional cloud shape approximating the pattern observed by the radar at C-band. At fixed increments of time the same procedure is followed thereby acquiring additional information from which dispersion rates and changes in cloud shapes could be determined.

Another technique that was used in determining exo-atmospheric performance of chaff during this test was to analyze a film record of an amplitude modulated scope (A-scope). (2)
The "A" Dimension is a function of time on target in the elevation plane.

The "B" Dimension is a function of the cloud range thickness during the time on target.

**FIGURE 27. TIME VS. DIMENSION ASPECT CHAFF MAPPING**

**FIGURE 28. RADAR SCAN PATTERNS DURING CHAFF MAPPING**
Amplitude modulated film is usually used to obtain cross-sectional areas of secondary targets, chaff and chaff depth. The general procedure for converting film data to cross-sectional area is accomplished by use of a film reader, which derives relative amplitude and range directly from the film data. The relative amplitudes and ranges are then converted to absolute cross-sectional areas and range differences (for chaff) by use of appropriate computer programs.

Figure 31 presents selected A-scope frames covering a 70-second period which was used to derive chaff characteristics, i.e., amplitude changes and range depth. The illustration points out the relative change in chaff amplitude and depth as a function of time. By comparing the chaff amplitude and range depth at T + 0 with the conditions at T + 70, the relative dispersion rates can be determined.

Conclusion

This then, is the way in which a signature report is generated. Although not specifically stated in the previous discussion the report will include all data to substantiate the analysis. The data will also be presented in a format that is readily amenable for any depth analysis. These reports have been favorably received by various range users. We welcome the opportunity to discuss matters of interest to you and are open at any time to be of service. For those seeking a more formal complete program of re-entry data collection, reduction, and analysis, the following provides an outline of the structure established to expedite such programs.
FIGURE 31. A-SCOPE FRAMES
Figure 32 presents the program and support responsibilities. As noted in the figure, the ETR is, in general, functionally oriented into three principal divisions: (1) Range Operations, (2) Range Engineering, and (3) Plans and Requirements.

Under Range Engineering is the Directorate of Re-Entry Systems and the appropriate other directorates which provide support. Of concern here is the channels of the Directorate of Re-Entry Systems under the Range Engineering Directorate. Figure 32 also indicates the two divisions under the Director of Re-Entry Systems. Finally, it is one of those divisions, the Re-Entry Systems Operations Division, that acts as a single point of control for the convenience of all re-entry program Range Users. It analyzes requirements, evaluates deficiencies, schedules and deploys re-entry ships and integrates and evaluates ETR support planning and performance.

A simplified documentation system cycle is shown in Figure 33. This figure illustrates the sequence in the generation of documents and requirements by continual cooperation and communication between Test Planning and the Range Users.

The formal documentation includes (1) Program Requirements documents and (2) the Program Support Plan which responds to it; (3) the Operation Requirements, and (4) the Operations Directive which responds to it; (5) the Test Instructions to the ship; and finally (6) the mission improvement information which is a result of a joint discussion between the Range User and the Test Planning.

In addition, mandatory meetings are held during the planning of a test and afterwards. Such an exchange is maintained from time of the Program Support plan meetings until the final critique meeting and helps to assure that no data is lost.

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FIGURE 32. PROGRAM AND SUPPORT RESPONSIBILITIES
FIGURE 33. DOCUMENTATION SYSTEM CYCLE
REFERENCES


15. AVCO/RAD Document: Data Reduction for Chaff Test 137F (Unclassified), AFMTC 575.

