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Mr. John Greenewald, Jr.

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PROJECT DUCK FINAL REPORT, VOLUME IV. — EXECUTIVE SUMMARY (U)

A Project Defender Experiment

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ARPA Order Number: -860
Project Code Number: 5910.21.10039.02
Contract: DA-01-021-AMC-14482(Z)
Dated: 19 April 1966
Expires: 15 August 1968
Project Manager: L. C. Edwards
Authors:
L. C. EDWARDS
F. R. ROBERTS

STANFORD RESEARCH INSTITUTE
Menlo Park, California

ARPA Order [redacted] -860
Project Code Number: 5910.21.10039.01
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Authors:
R. C. BOLLEN
D. A. JOHNSON

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ABSTRACT

(U) ~~(S)~~ Project DUCK was jointly undertaken by Stanford Research Institute and the Raytheon Company to study HF reentry phenomenology and to derive empirical and theoretical models to be used by the over-the-horizon (OTH) detection community for system design and data interpretation. The HF launch phenomenology of ABM vehicles as represented by the Sprint was to have been studied; however, no vehicles were successfully launched during the six months of field operations. This report first briefly describes the line-of-sight geometry of the bistatic CW HF network used at White Sands Missile Range (WSMR) and then summarizes the project's results, conclusions, and recommendations.

(U) ~~(S)~~ The energy received from the HF target generated by the Athena payloads had a Doppler frequency that corresponded to the velocity of the reentering vehicle. The target returns were relatively discrete in frequency; however, fine-grain analysis revealed FM sidebands symmetrically displaced around the vehicle Doppler that had a frequency interval between the sidebands equal to the payload's nutation rate. The measured cross sections were orders of magnitude larger than the bare body cross sections of the payloads alone. Different vehicle types showed differences of 10^3 or more in measured cross section. All of the reentry targets were very aspect sensitive. On one vehicle, RR02, the cross section measured with a broadside aspect reached $10^3 m^2$, while that simultaneously measured with a head-on backscatter aspect was $10^{-1} m^2$. The other viewing geometries yielded cross sections that lay between these extremes. Payload returns were enhanced at altitudes as high as 55 km, and somewhere between 23 and 35 km they became suddenly and strongly enhanced at an altitude that depended primarily upon vehicle type and secondarily upon viewing aspect. The target remained strongly enhanced until an

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altitude of approximately 12 km had been reached. This sudden enhancement may have indicated that boundary-layer transition had taken place. The average frequency dependence of the HF target when viewing the same vehicle at the same viewing aspect and altitude was approximately $1/f^2$. Heavily ablating payloads yielded larger cross sections than nonablators; however cross-section dependence on nose-tip radius could not be established. When two identical payloads reentered with a velocity difference of about 3 kft/sec, the faster had a cross section that was approximately a factor of ten larger.

(U) ~~(S)~~ Among the general conclusions reached were that payloads reentering at ICBM velocities have sufficiently large HF cross sections to be detected at OTH distances if favorable viewing geometries are employed. Further, the HF scattering characteristics of a reentering payload were similar to those of a long, thin cylinder moving at the velocity of the payload. Present modeling techniques based on the above principle are probably sufficient to make "optimum" OTH siting predictions, but although some of the vehicles viewed with the line-of-sight network were also detected with quasi-OTH geometries, the ability of the models to predict the behavior of an OTH path could not be confirmed.

(U) ~~(S)~~ Two specific experiments are recommended to fill in present data deficiencies concerning ABM's and larger operational payloads, and also to confirm presently held theories on optimum OTH siting configurations. One experiment would take place at White Sands Missile Range and would be solely concerned with obtaining HF data on the low-altitude intercept Sprint ABM. The other experiment would take place at Kwajalein and would be directed at obtaining data on the high-altitude intercept Spartan and also on large, operational payloads. Both line-of-sight and OTH paths would be employed.

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CONTENTS (U)

ILLUSTRATIONS (U)

TABLES (U)

I INTRODUCTION (U)

A. Background and Objectives (U)

(U) ~~(S)~~ Throughout the history of the over-the-horizon (OTH) detection field, major emphasis has been placed upon understanding the launch phenomenology for major vehicles and upon improving the techniques used to detect them at great distances (1000 to 10,000 km or more). Virtually no effort, however, had been expended on understanding the HF phenomenology involved in either ballistic missile reentry or the launch of high-performance ABM vehicles. Those interested in gathering intelligence information on the activity being undertaken either by the Soviets or Chinese to develop reentry or ABM systems must use HF radars because of the great distances involved. Prior to Project DUCK, however, they would have been forced to plan the installation of their HF detectors with little or no knowledge of target characteristics. In addition, once these radars had been deployed, the operating and using agencies would have had no applicable knowledge of target phenomenology to use in interpreting their results. For these reasons Project DUCK was suggested by Stanford Research Institute (SRI) and undertaken by both SRI and the Raytheon Company with ARPA sponsorship, to pursue the following major objectives:

(1) Establish the HF phenomenology of vehicles reentering the earth's atmosphere at ICBM and IRBM velocities.

(2) Establish the HF launch phenomenology of high-performance antiballistic missile (ABM) vehicles.

(3) Relate the results of the first two major objectives to the gathering of intelligence at over-the-horizon distances on (a) the development of reentry systems and (b) the development of ABM systems and their engagement modes.

~~(S)~~ (U) Phenomenology, as the term applies to Project DUCK objectives, refers to both qualitative descriptions and quantitative measurements of those target parameters required for the development, deployment, and operation of an OTH system. It should be stressed that the objectives of Project DUCK were not oriented toward developing discrimination techniques that could be incorporated into U.S. defense systems; however, it was recognized that information previously unavailable at HF might be provided on the physics of reentry to those groups presently wrestling with U.S. ABM or reentry problems.

(U) ~~(C)~~ As examples of qualitative parameters useful in the OTH field, it is necessary to consider such things as the general form of the return signal and whether the majority of the returned energy is spectrally clean (indicating a coherent target) or spread in frequency space (as with a diffuse target). On the other hand, the most meaningful quantitative measurement in this type of experiment is radar cross section. For cross section to be a useful parameter in the OTH sense it should be known as a function of distribution in Doppler space, viewing aspect angle, radar operating frequency, altitude, and vehicle type or configuration.

(U) ~~(S)~~ Once the OTH phenomenology relating to U.S. reentry and ABM activities is known, and the assumption is made that the country under observation is not taking a drastically different approach in the problem areas, it should be possible to derive a great deal of useful intelligence information. Boosted reentry tests should be distinguishable from simple ballistic reentry testing. Diagnostic information on the type of reentry system being developed and whether or not penetration aids are being used might be available. A multiple reentry system, a maneuverable reentry system, or a fractional orbit reentry (FOB) system would be characterized by distinctively different OTH energy returns. Simply establishing that one of these systems was being developed, how it was being configured, or what level of effort was being employed in its development would be useful to members of the intelligence community.

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(U) ~~(S)~~ The OTH phenomenology obtained on U.S. ABM's could be used to determine the other country's approach to the problem of missile defense. For instance: it should be possible to ascertain whether a low-altitude intercept, high-acceleration vehicle such as the Sprint, or a high-altitude intercept, long-range vehicle such as the Spartan, or both, are being developed, since these vehicles should yield distinctively different signatures. It is possible that more specific information on the acceleration, maximum velocity, approximate altitude of intercept, or approximate miss distance for either type of vehicle could also be obtained.

B. Purpose and Organization of Report (U)

(U) ~~(C)~~ This report is intended to give the reader a concise summary of the Project DUCK objectives and an understanding of the degree to which the objectives have or have not been obtained. The implications of the Project's results to the design, deployment, and use of OTH radar systems are presented throughout the text. Where objectives have not been achieved, the implications have been assessed and recommendations are presented where appropriate.

(U) The project's major objectives are summarized in this section. Section II very briefly describes the experiment. Section III gives a summary of the target characteristics acquired with line-of-sight geometries, discusses the models derived from these measurements, and presents a summary of the results obtained with the OTH paths. Sections IV and V give the conclusions and recommendations, respectively.

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II EXPERIMENT (U)

(U) ~~(S)~~ Between 1 September 1966 and 1 March 1967 the Project DUCK CW bistatic HF network shown in Fig. 1 was operated at White Sands Missile Range (WSMR) to view the 15 reentry experiments of the Athena program flown during this period. The Athena is a solid-fuel workhorse vehicle which, after being lofted from Green River, Utah by the first two rocket stages, is accelerated downward with either a third stage (in the case of the B and E vehicle configurations) or a third and fourth stage (in the case of the C and D vehicle configurations). The third and/or fourth stage boosted the payload to IRBM or ICBM velocities, when the payload begins its test at about 90 km. altitude. The bistatic HF network was thus able to view not only the P/L reentry but also the third and fourth stages while they were performing their boost function and when they reentered as dead tankage. The CW HF radar system was designed to provide data on targets as small as 0.1 square meters at a range of 200 kms.

(U) ~~(S)~~ Each of the two transmitter sites operated its two spectrally pure 10-kW transmitters in a frequency ratio of approximately 2 to 1. The corresponding frequencies of the two transmitter sites were set in close proximity. With this operating mode, the six channels of high-frequency bistatic data (and the six channels of low-frequency data) acquired by the three receiver sites could be compared to determine target frequency characteristics over the net's frequency range of 8 to 26 MHz.

(U) ~~(S)~~ All of the transmitters and most of the receivers were synthesized to derive a very stable unmodulated carrier. In order to relax the two-tone-dynamic-range requirements placed on the analog tape recorders and spectral processing equipment, a deep notch was used at the output of each receiver to suppress the strong carrier without disturbing the Doppler-shifted returns. The radiation patterns for all the CW antennas were flown and calibrated.

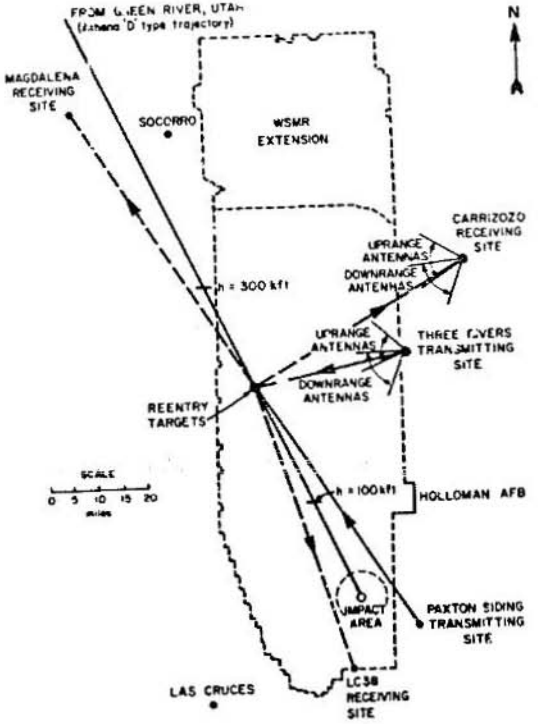

FIG. 1 GEOMETRICAL CONFIGURATION OF PROJECT DUCK (U)

(U) The preliminary analog data analysis and interpretation was performed in the field by project personnel to produce cross-section data for field reports and to allow effective on-the-spot evaluation of project operations. Of course, the long-term analysis carried out since the termination of the field activities has been performed at Raytheon and SRI.

(U) ~~(S)~~ A short-pulse radar (SPAGAR) operating with a peak pulse power of 10 MW at 23.5 MHz and a pulse width of 1/2 μs was also installed and operated as part of the line-of-sight network. Since the radar, as well as subsequent test and development work, is described elsewhere,* it is sufficient to state here that while the device worked as designed, it has insufficient sensitivity for the job at hand.

(U) ~~(S)~~ In addition to the direct-look (line-of-sight) network, CW HF transmitters at Pahoa, Hawaii, and Ava, New York were monitored by some of the projects "on range" receiving sites to establish paths with OTH illumination. OTH receiving sites, one near Mount Hamilton, California and the other at Stockbridge, N.Y., monitored the project transmitters on the range.

(U) ~~(S)~~ Provisions to monitor the expected Sprint firings on the range were incorporated into the network with antennas oriented to view the vehicle directly and with vertical-incidence phase-path sounders to sense perturbations in the ionosphere.

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*G. Oetzel, I- Shakelman, & R. Todd, "Short-Pulse Radar Development (U)", Final Report, SRI Project 5993, Contract DA-01-021-AMC-14483 (Z), Stanford Research Institute, Menlo Park, Calif., ~~Aug. 1968~~, SECRET.
Jan 69

AD 15,659
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III SUMMARY OF PROJECT RESULTS (U)

A. Results of Line-of-Sight Measurements (U)

1. Payload Reentry Targets (U)

(U) ~~(S)~~ Bistatic cross sections were derived for several different classes of payloads varying from the small to the relatively large (for White Sands) RR and SS vehicles whose base diameters and lengths are 13 and approximately 30 inches, respectively. The magnitudes of the cross sections observed for different classes of payloads had major differences. For the smaller vehicles, the cross sections at some aspect angles often lay below the sensitivity of the system, and this alone indicates that variations of radar cross section between different types of vehicles can be three or more orders of magnitude. Positive results were always obtained on most paths for the RR and SS vehicles; hence virtually all of the quantitative analysis work of the project has been directed toward these vehicles.

(U) ~~(S)~~ It should be emphasized that all of the Project DUCK results summarized in this report characterize the target presented to a coherent HF radar and do not necessarily apply to the target presented to an incoherent radar or to a radar operating in the VHF or higher-frequency ranges.

(U) ~~(S)~~ With the CW network, the energy returned from the reentry target always lay at the Doppler frequency corresponding to the payload velocity and usually had very little frequency spread. However, on some vehicles, fine-grain analysis of this energy showed the presence of symmetrical FM sidebands around the Doppler frequency. In one case these sidebands were separated from the vehicle Doppler and from each other by 5 to 10 Hz and the separation correlated exactly with the nutation rate or rate of oscillatory change in the vehicle's angle of attack as determined by on-board instrumentation. No discrete or

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diffuse echoes near zero Doppler have been observed for the payloads; however, a discrete return would have to be very large to be sensed in the presence of the carrier.

(U) ~~(S)~~ The magnitude of the cross section derived from the energy at the payload Doppler frequency is much larger than would be predicted or measured for the bare-body cross section of the payload alone. The wake contributes by far the major portion of the CW cross section and has the "apparent" velocity of the payload. Note that this does not imply that the wake material is moving at the vehicle velocity. The bare-body cross sections of the vehicles viewed are well into the Rayleigh scattering region and are calculated to be on the order of 10^{-4} to 10^{-5} m^2 or less. However, the cross sections measured at some aspects were seven or more orders of magnitude greater. A maximum cross section value of 10^3 m^2 was observed with a broadside viewing geometry. At the same altitude for the same vehicle, a cross section of 10^{-1} m^2 or less was observed from a "head-on" viewing aspect. In between these two extremes of viewing aspects, intermediate values of cross section were observed.

(U) ~~(S)~~ Because the reentering vehicle's cross section can vary as much as four or five orders of magnitude with viewing aspect angle, any HF radar that is to detect the reentering vehicle must be placed very carefully. If it is not, its chances of seeing an ABM's target and thereby deriving any information about the intercept mode will be greatly reduced.

(U) ~~(S)~~ In general, the lower-frequency observations on Project DUCK yielded cross sections 3 to 6 dB (and on occasion as much as 20 dB) larger than those simultaneously obtained with the same viewing aspect at higher frequencies. This characteristic also indicates that the HF reentry target is not in the Rayleigh scattering region where the frequency dependence would be reversed.

(U) ~~(S)~~ The altitudes at which the payloads viewed at WSMR were first enhanced above bare-body cross section could not be determined

~~(S)~~ (U)

due to insufficient system sensitivity and/or contamination by returns from the reentering fourth-stage tankage. Nevertheless, cross-section enhancement has been observed as high as 50 to 60 km. It should be noted that this high-altitude enhancement could be observed only with a quasi-frontal aspect since the network was configured to obtain side-aspect data at lower altitudes.

(U) ~~(S)~~ Characteristically the cross sections became strongly enhanced when the payloads had reached altitudes between 35 and 23 km, and remained strongly enhanced until the vehicle had flown to an altitude of approximately 12 km. The particular altitude of cross-section brightening depended primarily upon vehicle type and configuration, and to some extent upon viewing aspect.

(U) ~~(S)~~ Variations in cross section were observed as a function of velocity on identical payloads. A difference in velocity of approximately 3000 ft/s caused an order-of-magnitude larger HF cross section in the case of the payload having the higher velocity.

(U) ~~(S)~~ Several vehicle parameters were examined for the purpose of relating them to differences in HF-cross-section magnitude. The first of these was the material used in the nose tip or heat shield of the vehicle. A substantial difference (as much as 20 dB) in HF cross section was observed on the same vehicle configuration when different nose-tip materials were used, with the more ablative nose-tip materials yielding the larger cross sections.

(U) ~~(S)~~ The second parameter examined was nose-tip radius and its relationship to cross-section magnitude. Here the results were rather inconclusive. Although the sharper (small nose-tip radius) vehicles generally showed smaller (on the order of 10 dB) HF cross sections than the blunt vehicles, there were, in addition to differences in the nose-tip radius, differences in materials used on the nose tips and heat shields of the vehicles compared. Theoretical considerations indicate that the blunter vehicles should have higher cross sections;

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however, it is impossible, on the basis of the data, to say whether the smaller cross section measured with the sharper vehicles was caused by the vehicle being sharp or by differences in materials used. One can only say that the data are not inconsistent with expectations.

(U) ~~(S)~~ Sudden enhancements in cross sections were noted for both the sharp SS and the blunt RR vehicles. In the case of the RR's the enhancement occurred between 29 and 35 km, and in the case of the SS vehicles between 23 and 26 km. Fortunately, GE and AVCO reports giving optical results acquired with the TRAP aircraft were available for the SS vehicle series (unfortunately not available for the RR series). A comparison of the HF and optical results shows that optical brightening and the sudden HF enhancement occur at the same altitude. The optical brightening has been interpreted by the two groups as boundary layer transition. (GE also states that base pressure sensors confirm the optical interpretation.)

(U) ~~(S)~~ Radar-derived curves of $\beta = w/C_d A$ for the RR and SS vehicles viewed by Project DUCK show a peak that has also been interpreted as corresponding to the interval associated with boundary-layer transition. The times that these peaks in β occur correlate with the sudden enhancement in HF cross sections.

(U) ~~(S)~~ Except from the frontal backscatter aspect, the energy returned at the payload Doppler during the period of enhancement for some of the vehicles was characterized by slow, well-defined and pronounced "fades." Since the depth and position of the peaks and nulls were dependent upon both the viewing aspect angle and the frequency of the observation, they could not be attributed to a mechanical motion or blooming or withering of the target. In addition, the cross sections characteristically built up to high values at the specular (i.e., zero Doppler frequency) point on the trajectory. These facts suggested that the target had a well-defined length and consequently scattering characteristics similar to Fraunhofer

~~(S)~~ (U)

diffraction. Indeed, one is hard pressed to explain the fading characteristics without invoking an effective length and diffraction. Techniques were developed in which the uniquely identifiable peaks or nulls on some individual paths were used to determine a curve of length versus altitude for a given payload. The target length determined with this simple one-dimensional model was then "flown" by computer on the appropriate trajectory to obtain predictions of relative cross section for each path geometry and frequency of operation. The agreement between the predictions and the data was in general excellent. The lengths associated with the payloads where this type of modeling was employed were found to decrease with decreasing altitude, varying from approximately 100 meters at 40 km to 10 meters at 15 km.

(U) ~~(S)~~ Because the application of the simple Fraunhofer Diffraction Model can yield no more than relative cross sections and the variation of effective target length with altitude, a more sophisticated model was pursued. A generalization of the Chu formula for electromagnetic scattering from cylindrical bodies was assumed to derive such things as target polarization dependence and the absolute value of cross section. This model assumed forced currents and TM waves. When values of the target length and reflectivity taper deduced from the diffraction analysis were incorporated into this scattering model, it was possible to perform calculations of the target cross section that provided reasonable matches to observations. This model, then, not only accounts for major elements of the aspect dependence, but also explains the observed frequency dependence, incorporates polarization dependence, and provides magnitudes of cross section.

(U) ~~(S)~~ The "sudden brightening" of the HF cross section tends to indicate that a more severe aspect dependence of reflectivity exists for lossy than for lossless targets. Extending the scattering theory to include lossy targets has tended to verify this hypothesis theoretically and may provide the basis for a model of more general applicability, especially when front-to-front backscatter viewing aspects are employed.

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(U) ~~(S)~~ A one-dimensional study of wake scattering has shown theoretically that the effects of wake velocity, varying vehicle velocity, systematic variation of wake length, periodic variations in wake intensity, and periodic variations of wake length are qualitatively entirely consistent with the data.

2. ABM Launch Phonomenology (U)

(U) ~~(S)~~ One of the major objectives of Project DUCK could not be attained in any degree. Since firings of the high-performance Sprint terminal-defense missile had been planned for the period of project operations at WSMR, the transmitting and receiving sites were placed to view these firings as well as the Athena reentries. Antennas were directed towards the expected trajectories. Unfortunately, all of the scheduled firings were canceled or aborted; hence, there still remains little or no information on the phenomenology of ABM launch. This, then, must become the major objective of some future program if the information required for gathering and interpreting data on Russian or Chinese ABM development is to be obtained.

3. Associated Reentry-System Targets (U)

(U) ~~(S)~~ The Project DUCK direct-look network necessarily observed the burning third and fourth stages, retrofire, and the reentering third- and fourth-stage tankage. Typical cross-section values derived with a near frontal aspect and with an analysis bandwidth of 8 Hz are given in Table I. With the information gained and sufficient sensitivity, it should be possible to sense and identify a boosted reentry testbed. Incidentally, the frontal-aspect measurements of the burning engines are unique in HF launch phenomenology.

Table I

(U) ~~(S)~~ HF RADAR CHARACTERISTICS FOR SOME ATHENA REENTRY-SYSTEM COMPONENTS (S)

Event	Type of Echo	Altitude (km)	Cross Section (m^2)	
			21.6 MHz	11.6 MHz
3rd-stage burn	Enhanced skin echo	195 - 165 km	10^2	10^3
4th-stage burn	Enhanced skin echo	140 - 115 km	10^0	$5x10^2$
	Exhaust echo	140 - 115 km	Not available	10^4 to 10^5
Retrofire	Diffuse	110 km	Not available	10^5 to 10^6
2nd-stage reentry	Discrete	80 - 40 km	$5x10^{-1}$	$5x10^1$
3rd-stage reentry	Discrete until breakup	Not available	10^{-1}	10^1
4th-stage reentry	Discrete until breakup	80 - 50 km	10^{-1}	10^0

4. Targets of Opportunity (U)

a. Pre-Stage Launch (U)

(U) ~~(S)~~ Two pre-stage test vehicles flown at WSMR were observed as targets of opportunity. A Nike booster provided the upward acceleration while a Tomahawk second stage propelled the pre-stage downward for its test during the last few seconds before impact. The cross section of the passive second stage was approximately 10^{-3} to 10^{-2} m^2 and was enhanced by approximately 10 dB, to 10^{-2} to 10^{-1} m^2 during its burn. Although the vertical-incidence phase-path soundings of the ionosphere were made, the results were negative.

b. Pershing Reentry (U)

(U) ~~(S)~~ The low-velocity reentries of three Pershing vehicles were monitored during one evening by the network with front-to-front and front-to-side viewing aspects. The reentry of the second stages was observed; however, no returns from the warhead were seen in the spectral analysis records made in the field. The reentry velocity was approximately 2.4 km/sec.

b. Results of OTH Observations (U)

(U) ~~(S)~~ Several semi-OTH paths (where one leg is OTH and the other is line-of-sight) were operated during DUCK, demonstrating the feasibility of detecting reentering bodies at OTH ranges. Positive detections were achieved over paths that would be judged favorable on the basis of aspect dependence deduced from the direct-look results.

(U) ~~(S)~~ The OTH records contained many of the signature components observed at line-of-sight ranges. These included, as separately identifiable elements, the events listed in Table II. A comparison of Tables I and II shows that there are large discrepancies in the observed cross-sections. These differences are probably attributable to dissimilar geometries, viewing aspects, and altitudes that existed while the measurements were being made, as well as to the different analysis bandwidths and methods used in deriving the cross-sections for the two sets of data. Although the gathering of OTH data was not emphasized in Project DUCK, care should be taken in a future HF reentry experiment to ensure that line-of-sight and OTH cross-section data can be compared directly.

Table II

(U) ~~(S)~~ OTH RADAR CHARACTERISTICS FOR SOME ATHENA REENTRY-SYSTEM COMPONENTS ~~(S)~~ (U)

Event	Altitude (km)	Cross-Section (m^2)
Boost engine (4th Stage) enhanced skin exhaust	140 - 115	$10^4 - 10^5$
Tankage reentry (near specular aspect)	60	$10^6 - 10^7$
Payload reentry	35 to 18	$10^2 - 10^3$ (max)
Retrofire	115	$> 10^6$

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(U) ~~(S)~~ It is significant, in view of possible intelligence applications, that each of the signature components could be related, by Doppler frequency, to the responsible event.

(U) ~~(S)~~ The large values of cross-section observed for the tankage at near-specular aspect on OHD paths at 60 km altitude, together with the associated incoherent (near-zero Doppler frequency) return observed in the same altitude regime with line-of-sight geometry, are interpreted as implying a target of appreciable length, perhaps of the order of a kilometer. A more direct demonstration of this would be desirable inasmuch as other factors, such as ionospheric focusing, could also be responsible for large OHD cross sections.

(U) ~~(S)~~ This apparently long length of the target associated with the tankage implies extreme aspect sensitivity yielding high cross section values only in the very near vicinity of zero cps--i.e., in the center of the ambient clutter and/or notch filter of a CW system. The fact that multihop tankage echoes failed to exhibit narrow peaks but, rather, displayed high cross sections well away from 0 cps suggests that these long targets can be easily detected with multihop CW paths. This might be interpreted as evidence that the diffuse (i.e., somewhat non-specular) ground scattering broadened the inherently narrow scattering patterns of the long targets.

(U) ~~(S)~~ The Chu model for electromagnetic scattering by payload wakes has been extended from the original line-of-sight formulation to one suitable for calculation for arbitrary OTH configurations. Due to an insufficient number of OTH detections of payload against which to check this calculation, it must be considered not yet experimentally validated. On the basis of both models and experimental observations, criteria have been established for optimally configuring OTH paths. These criteria have been applied to the design of new OTH experiments.

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IV CONCLUSIONS (U)

A. Target Characteristics (U)

(U) ~~(S)~~ The significant conclusions of Project DUCK rest upon the determination of target characteristics for a vehicle reentering the earth's atmosphere at IRBM or ICBM velocities. The HF reentry phenomenology of those vehicles viewed with the Project DUCK line-of-sight CW network at WSMR is summarized by the following:

(1) The HF CW returns have the reentering vehicle's Doppler frequency and spectrally are relatively discrete.

(2) The HF CW cross sections measured for reentry targets strongly depend upon viewing aspect angle. The cross sections measured at frontal aspect are as much as five orders of magnitude less than those obtained when viewing with a side aspect where the cross section reached 10^3 m^2.

(3) The cross sections of the reentry payload are enhanced, at least below 55 km, when viewed from some aspects. Somewhere between 35 and 23 km altitude, the cross sections become suddenly and very strongly enhanced, and this enhancement remains until the vehicle has reached an altitude of at least 12 km. Significantly, the bare-body cross sections were well below the Project DUCK threshold of sensitivity. The very strong target enhancements occurring between 35 and 23 km altitude may indicate that boundary-layer transition has taken place.

(4) On the average, the HF reentry target exhibits a $1/f^2$ frequency dependency.

(5) The HF cross section will increase with an increase in payload velocity.

(6) Heavily ablating payloads appear to yield larger HF cross sections than nonablating vehicles when the payloads have similar configurations.

~~(S)~~ (U)

(7) Payload nutation during reentry can be sensed with CW HF radars and manifests itself by FM sidebands appearing around the target Doppler. The frequency separation between sidebands is equal to the nutation rate.

(8) Reentries at WSMR of both payloads and tankage were detected with paths having OTH illumination and line-of-sight receivers. The OTH returns were successfully related, on the basis of Doppler, with those obtained with the line-of-sight network.

B. Modeling Results (U)

(U) ~~(S)~~ The characteristics of the HF reentry target have been used in developing mathematical models to describe the HF reentry phenomenology. They assume that the electromagnetic scattering is that of a long, thin cylinder moving at the payload velocity. Modeling results are summarized as follows:

(1) Given data from a single viewing geometry and a single frequency, the models can be successfully used to predict the magnitude and fading characteristics of the observed cross sections acquired with other viewing geometries and frequencies. The predictions computed with the models apply at least over the 10-to-25 MHz frequency range and 35-to-12 km altitude range.

(2) The HF target generated by a reentering payload has an effective scattering length that varies from approximately 100 m at 40 km to nothing at 12 km. The sudden enhancement in cross section between 35 and 23 km can be interpreted as an abrupt increase in scattering coefficient; however, the target's length at this time is not affected.

(3) Steep axial gradients in the HF scattering coefficient exist in the wake.

(4) The modeling concepts employed imply nothing of the actual physical motion of the wake material.

(5) The modeling techniques are sufficiently well developed that they can be extended to OTH applications.

C. General Conclusions (U)

(U) ~~(S)~~ The general and major conclusions of Project DUCK are the following:

(1) The cross sections of reentry vehicles are sufficiently large that they can be detected with over-the-horizon detection techniques when favorable viewing aspects are employed.

(2) The phenomenological models and their engineering approximations have been developed to the point where they can be used for OTH system design, evaluation, and optimization, and for interpreting data acquired by existing OTH systems. With the existing models a single HF line-of-sight observation made on an arbitrary vehicle and with a given geometry may be sufficient to make accurate predictions of what would be observed with OTH geometries. In addition, with a priori trajectory information, the most favorable OTH siting geometry can probably be determined or, given a list of already existing sites, the best detection geometry can probably be chosen. This conclusion should be confirmed with further testing.

(3) The present HF reentry data base is inadequate and includes only a portion of the relatively small vehicles flown at WSMR. Data are needed on larger payloads and should be acquired with different geometries and wider frequency ranges than those employed at WSMR.

(4) One concept for discriminating payloads from decoys is based upon deriving the size of the vehicle from its HF radar cross section. The radar cross section of a vehicle lying in the Rayleigh scattering region is proportional to the square of the volume of the vehicle, and further, is not to any degree aspect-sensitive. The tacit assumption in this type of discrimination system is that the only observable at the Doppler frequency of the vehicle will be the payload itself. The observations of Project DUCK, where the wavelengths employed were sufficient to put the payload in the Rayleigh region, clearly demonstrate that over the altitude regime of at least 40 to 10 km such a system will have problems. There is some evidence

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in the data that there may be problems associated with such a system up to altitudes as great as 55 km. The only aspect where it might be successful is the directly head-on "backscatter situation."

(S) ABM vehicles were not launched at WSMR during Project DUCK operations; hence one of the program's major objectives could not be attained. An understanding of ABM launch phenomenology is still required and should be established for both low-altitude (Sprint) and high-altitude (Spartan) intercept vehicles with experiments that simultaneously utilize line-of-sight and OTh paths.

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V RECOMMENDATIONS (U)

(U) ~~(S)~~ In Sec. IV, Conclusions, note is taken of several areas where information on HF reentry phenomenology is still lacking. No data could be acquired at WSMR on the larger operational payloads. The reentry target characteristics at the higher altitudes could not be established at WSMR since above 40 km the payload returns were contaminated by echoes from the fourth-stage tankage and debris. The target's functional dependence upon frequency has been tested only to approximately 25 MHz. Additional data at higher frequencies are needed to ensure that target behavior is consistent and is understood over the entire frequency range of interest to the OTH community. Finally, there has been no reasonable test of the applicability of the models derived with line-of-sight measurements to OTH geometries. We therefore recommend that an experiment be conducted with the reentries occurring in the Kwajalein area. This experiment will widen the present data base and should overcome the deficiencies remaining at the conclusion of Project DUCK.

(U) ~~(S)~~ Perhaps the single most important objective of Project DUCK could not be achieved--namely, determining the HF phenomenology of ABM vehicle launch. Low-altitude ABM's (represented by Sprint) and high-altitude long-range ABM's (such as Spartan) have very different performance characteristics; hence their HF radar target characteristics such as cross section, energy spread in frequency space, and accompanying ionospheric perturbations will probably be very different. The HF launch phenomenology for both types of vehicles should be established.

(U) ~~(S)~~ Apparently the Spartan test series now being flown at Kwajalein will continue for at least two years. Fortunately the data needed on the Spartan vehicle can be obtained with the instrumentation installed around Kwajalein to study further the HF reentry target.

(U) ~~(S)~~ The Sprint is now being flown at WSMR and may start tests at Kwajalein about one year. From the experimenter's point of view, WSMR

(U) ~~S~~

has important advantages over Kwajalein. Line-of-sight instrumentation can be easily and quickly placed virtually anywhere on or around WSMR. On the other hand, in the Kwajalein area the experimenter is constrained to employing islands that may not be located in a desirable area. Furthermore, negotiating the use of these islands may require considerable time. Another advantage is that there are several high-power OTH CW and pulse radars operating on the East Coast that can monitor WSMR launches and take data simultaneously with a line-of-sight experiment. At this time there are no OTH radars that can effectively illuminate the Kwajalein area. We therefore recommend that a second experiment be conducted as soon as feasible at WSMR to study the HF launch phenomenology of the Sprint vehicle.

(U) The two recommended experiments are very briefly described below.

A The White Sands Missile Range Experiment (U)

(U) ~~(S)~~ To obtain the phenomenology of the launch of the Sprint-type missiles, an experiment should be mounted at WSMR that would encompass observations of both the Sprint vehicle itself and the ionosphere overhead.

(U) ~~(S)~~ The measurements to be performed on the vehicle would use HF CW, line-of-sight paths to observe both the burning and passive phases of the flight. The information sought will include cross-section as a function of viewing aspect, HF operating frequency, and the specifics of flight trajectory such as high acceleration maneuvers. The experiment will require use of the Project DUCK CW instrumentation at WSMR configured to provide coverage with side-side, side-back, and side-front viewing aspects. Sites will be carefully selected to yield the required aspects, to provide illumination at the appropriate altitudes unobstructed by terrain, and to be logistically supportable.

(U) ~~(S)~~ Simultaneously with the direct-look observations of the vehicle, the overhead ionosphere should be probed by pulsed phase-path sounders as planned at the outset of Project DUCK. At least one short-

~~(S)~~(U)

base-line oblique CW path should also be incorporated into the experiment to provide sensitive probes for the detection of interaction of the iono sphere with either acoustic waves or some other as yet undetermined phenomenon associated with the Sprint launches.

(U)~~(S)~~ It is expected that other investigators at NRL, ITT-EPL, and/or RADC will simultaneously view the Sprint launches using existing OTH paths and equipment.

B. The Pacific Kwajalein Experiment (U)

(U)~~(S)~~ The Pacific experiment should be centered on the Kwajalein Test Range where line-of-sight paths would define target phenomenology, and distant stations would establish forward scatter, backscatter, and semi-OTH (where either the receiver or transmitter is line-of-site) detection paths. Figures 2 and 3 show the line-of-sight paths for the Kwajalein HF experiment. These paths will provide needed information on the reentry of large operational payloads, reentry of multiple payload systems, and the launch of Spartan and Sprint ABM's. In addition it should be possible to obtain HF reentry data at higher altitudes without contamination by other stages, a problem that had previously been experienced at WSMR.

(U)~~(S)~~ The objectives of the line-of-sight experiment include providing calibration for the long-range OTH paths and acquiring phenomenological information that could not be acquired during Project DUCK. Experience gained at WSMR has indicated that the line-of-sight data can be used with the models developed on Project DUCK to predict the signal strengths observed on OTH paths.

(U)~~(S)~~ The three CW transmissions originating at Kotje Island will be received at Likiep and Roi-Namur Island to establish the line-of-sight network. The frequencies of operation will be approximately 10 MHz, 20 MHz, and 40 MHz, so that the resulting data can be used to test the HF reentry modeling techniques over the entire frequency range of interest to the OTH community. To ensure an adequate signal-to-noise ratio, a 20-kW transmitter is required at each frequency.

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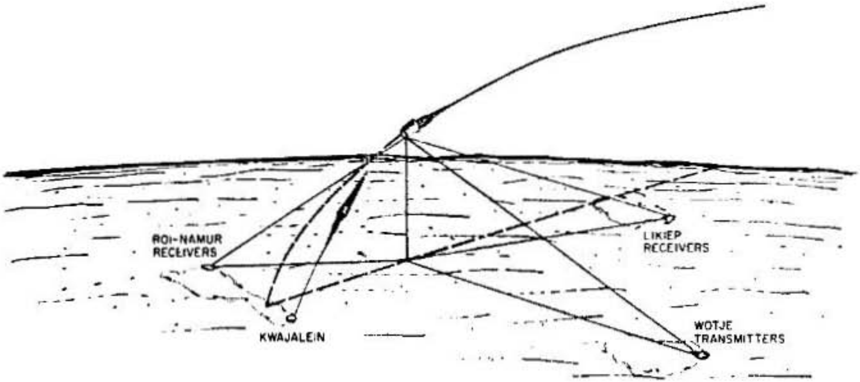

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FIG. 2 LINE-OF-SIGHT GEOMETRY FOR PACIFIC EXPERIMENT
(Shading indicates plane of illumination and reflected rays) (U)

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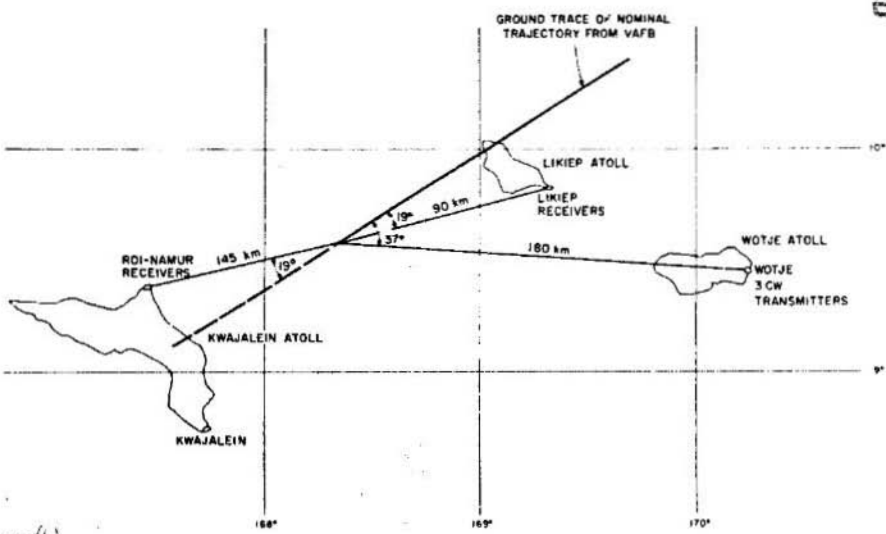

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FIG. 3 PLAN VIEW OF LINE-OF-SIGHT GEOMETRY FOR PACIFIC EXPERIMENT (U)

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(U) ~~(S)~~ The OTH paths shown in Fig. 4 and 5 have been chosen on the basis of Project DUCK results. Geometries yielding Dopplers that slowly approach zero frequency in the altitude range of interest will also yield the highest radar cross-section for the longest period of time. These paths are defined as being optimum from the OTH sense in that they will give the highest possibility of detection, and their data will yield a maximum amount of information. It is on this basis that the paths from Johnston to reentry area to Roi-Namur and Likiep, and from Johnston to reentry area to Brisbane, Australia were chosen. The first is a simulation of an optimum semi-OTH detection path with the receiver being line-of-sight. The second is a long but still optimum forward-scatter path. The geometry of the third path from Johnston Island to reentry area to Midway Island established with a 120-kW transmitter on Johnston was chosen for somewhat different reasons. It gives an approximation of the scatter angles, and therefore the Doppler, of the Sentinel Shoe system which is constrained to illuminating its target by 1-1/4 hops. This path, however, will also allow the vehicle to be illuminated by a 3/4-hop mode. The returns simultaneously obtained with these two illumination modes will be separable in Doppler space; hence, the experimental results derived from each should be of use not only to the operators and analysts of the Sentinel Shoe system but also to any others who might establish an HF radar that would illuminate its targest with a 3/4-hop mode.

(U) ~~(S)~~ Russian reentries have occurred in the general area of Johnston and Midway Islands, and the x's shown in Fig. 5 represent the impact points for several. If the Russians should conduct more of these tests during the period in which the Pacific experiment is operating, it is probable that valuable HF line-of-sight or OTH data can be acquired on their reentry vehicles.

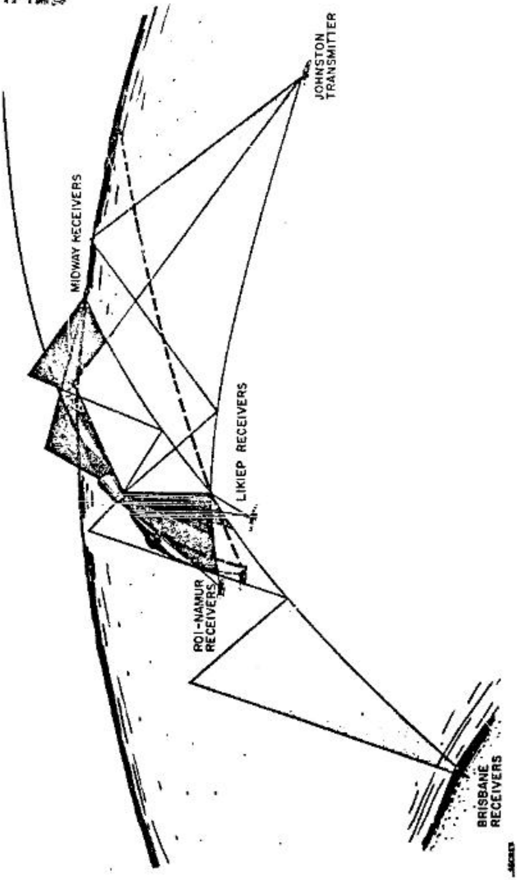

FIG. 4 OTH GEOMETRY FOR PACIFIC EXPERIMENT
(Shading indicates plane of illumination and reflected rays) ~~(S)~~ (U)

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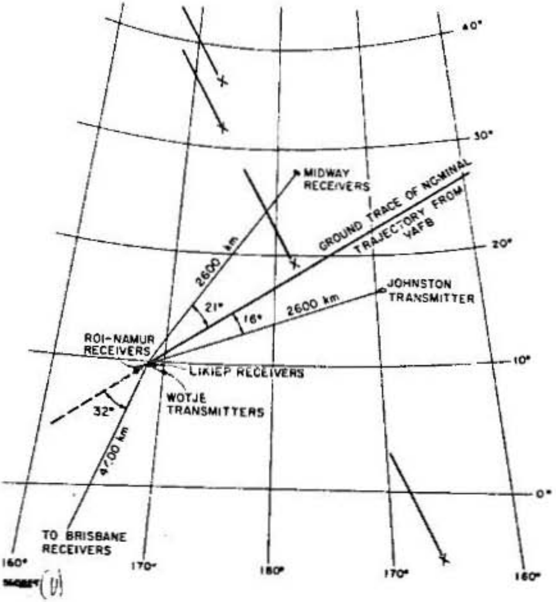

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FIG. 5 PLAN VIEW OF OTH GEOMETRY FOR PACIFIC EXPERIMENT
(Crosses indicate impact points for some Russian Reentries) ~~(S)~~ (U)

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