THE UNIVERSITY OF MICHIGAN

COLLEGE OF ENGINEERING
DEPARTMENT OF ELECTRICAL ENGINEERING
Radiation Laboratory

STUDY OF MICROWAVE RADIOMETRY
DETECTION TECHNIQUES (U)

Final Report
15 April 1958 - 14 August 1961

June 1962

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Contract With: U. S. Army Signal Research and Development Laboratory
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Final Report
15 April 1958 through 14 August 1961

ARPA Order Nr. 120-60
Contract Nr. DA 36-039 SC-75041
Signal Corps Technical Requirement Nr. SCL-5488A, 6 August 1958
Department of the Army Project Nr. 3A99-23-001-01

June 1962

OBJECT

Conduct a Theoretical and Experimental Investigation of
Microwave Radiometry Techniques in Detection of
IRBM and ICBM Targets

Prepared by

B. A. Harrison and R. J. Leite

TABLE OF CONTENTS

1.   (U) PURPOSE

1.1   Original Contract - 15 April 1958 - 14 April 1959

To conduct a study and experimental investigation of microwave radiometry techniques in detection of airborne targets. In accordance with Signal Corps Technical Requirements No. SCL-5488 dated 30 October 1957.

1.2   Modification No. 1

Work statement is amended as follows: "and Signal Corps Technical Requirements No. SCL-5488A dated 6 August 1958, at an intensified rate as hereinbefore indicated."

1.3   Modification No. 2 - 15 April 1959 - 14 April 1960 .

To conduct a study and experimental investigation of radiometry and radar techniques in detection of airborne targets including determination of radiation and reflection characteristics of rockets, in accordance with Signal Corps Technical Requirements SCL-5488A, dated 6 August 1958.

1.4   Modification No. 3 - 15 April 1960 - 14 April 1961

No change in statement of work.

1.5   Modification No. 5 - 15 April 1960 - 14 August 1961

To conduct a study and experimental investigation of radiometry and radar techniques in detection of airborne targets including determination of radiation and reflection characteristics of rockets, in accordance with Signal Corps Technical Requirements No. SCL 5488A dated 6 August 1958, and at an accelerated rate of effort in accordance with University of Michigan Proposal UMRI-60-355-Q1 dated 8 January 1960 and Part A of amendment thereto dated 1 April 1960 to include the following:

        a. Continuation of measurements aboard the American Mariner
            with previously used moderately sensitive 16 and 35 Kmc
            radiometers with essential modification or, if necessary
            replacement equipment of equal sensitivity.

b. Theoretical calculations in plasma dynamics as required to

   help direct the measurement program and to evaluate the results

   of the measurements. Laboratory experiments and/or extensive

   computations to obtain and check optimum parameters and para-

   meter ranges.

c. Analysis of data.

NOTE: Modifications 4 and 6 were administrative changes not affecting the Work Order.

2.   (S) ABSTRACT

A theoretical study and an experimental investigation was conducted of microwave radiometric and radar techniques for the detection of IRBM and ICBM missiles. The theoretical portion of the investigation was concerned with mechanisms which would predict or explain microwave radiation originating in the launch, midcourse or re-entry phase of missile flight. Special attention was paid to the effects produced by missile exhausts, midcourse wake cavities, and re-entry shockwaves and shock layers where partially coherent plasma oscillations might be produced. Microwave radiometric data was obtained with 16 and 35 Kmc equipment installed aboard the USAS American Mariner and operated during its participation at the Atlantic Missile Range in Project DAMP. The data indicated that radiation originating in the vicinity of the re-entry vehicle was being observed, but further test data are needed for positive identification. Bremsstrahlung from a relatively cool plasma was investigated but was found not to provide the mechanism which would explain the experimental data. Observations made at The Ohio State University appeared to support a theoretical model which postulated large increases in radar cross section at the point of closest approach of an object moving at satellite velocities. This effect is due to interaction of the incident electromagnetic wave with the plasma sheath about the satellite and in its wake.

3.   (U) PUBLICATIONS, LECTURES, REPORTS AND CONFERENCES

3.1   "Summary Progress Report on Detection of Missile Exhausts and Ioniza-
tion" by M. L. Barasch, H. Brysk, W. E. Burdick, S. T. Harmon, R. J. Leite
K. M. Siegel, W. E. Vivian, and P. F. Zweifel, 2764-1-P, March 1959
SECRET.

3.2   "Field Measurements of Passive Microwave Radiation" by S. T. Harmon
and W. E. Vivian, 2764-2-T, January 1960, Contract DA 36-039 SC-85403,
SECRET.

3.3   "Studies in Radar Cross Sections XLII - On Microwave Bremsstrahlung
From a Cool Plasma", by M. L. Barasch, 2764-3-T, August 1960,
UNCLASSIFIED.

3.4   "State of the Knowledge of ICBM Midcourse Detection and Discrim-
ination" by K. M. Siegel, 2764-4-T, August 1960, SECRET.

3.5   "Study of Radiometry and Radar Techniques in Detection of Airborne
Targets", First Semi-Annual Report, August 14, 1960 - February 14,
1961, 2764-30-P, SECRET.

3.6   "Photon Transport Theory", by R. K. Osborn and E. H. Klevans,
September 22, 1960, 2764-5-T, UNCLASSIFIED.

3.7   "Plasma Sheath Surrounding a Conducting Spherical Satellite and the
Effect on Radar Cross Sections", by K-M Chen, October 1960,
2764-6-T, UNCLASSIFIED.

3.8   "Report of a Major Event," W. E. Burdick and K. M. Siegel
(Memorandum 2764-7-R, 24 January 1961) DA 36-039 SC-75041.
UNCLASSIFIED.

3.9   "Critical Frequencies in the Stagnation Region of a Shock Layer",
R. J. Leite and N. E. Hawk, Journal of the Aero/Space Sciences,
28, 820-821 (1961).

3.10   "Photon Transport Theory" by E. H. Klevans and R. K. Osborn,
Annals of Physics, 15, 105-140 (1961).

3.11   "A Possible Theoretical Explanation of Observed Signals" by K. M. Siegel and M. L. Barasch, presented at the Symposium on Detection of Missiles, 23-25 September 1958, Washington, D. C. SECRET.

3.12   "On the Change in the Radar Cross Section of a Spherical Satellite Caused by a Plasma Sheath", by C. L. Dolph and H. Weil, presented at the Symposium on the Plasma Sheath 7-9 December 1959, published in Electromagnetic Effects of Reentry, Pergamon Press, London, 123-132 (1961). UNCLASSIFIED.

3.13   "Research Effort on Passive Microwave Radiation and Scattering Matrices", by K. M. Siegel, presented at AMRAC - Waltham, Mass, 29 September 1959; also at AMRAC - San Diego, California, 19-20 January 1961. SECRET

3.14   "Reflecting Properties of Ionized Regions", by K. M. Siegel, presented at Symposium on Detection of Ionospheric Disturbances, Stanford University, 20-22 June 1960. SECRET.

3.15.   "Limit Criteria for Reduction of Radar Cross Sections of Missiles", by K. M. Siegel and H. Weil, presented at Royal Aircraft Establishment Symposium on Echoing Areas of Missiles, England, June 1960. SECRET.

3.16   "State of the Knowledge of ICBM Midcourse Detection and Discrimination" by K. M. Siegel, presented to DDR and E on July 27, 1960. SECRET.

3.17   "On Microwave Bremsstrahlung from a Cool Plasma", by M. L. Barasch, presented at Chalmers Institute and the Royal Institute in Sweden, September 1960. UNCLASSIFIED.

3.18   "Disturbances Due to a Satellite in a Plasma Medium and Its Effect on Radar Return", by K-M. Chen, presented at the Astronautical Society Symposium on Interactions of Space Vehicles with Ionized Atmosphere, Washington, D. C., March 17, 1961. UNCLASSIFIED.

4.   (S) TECHNICAL WORK: SUMMARY

This report summarizes the work conducted under United States Army Signal Corps Contract Number DA 36-039 SC-75041, including Modification Numbers 1 through 6, for the period 15 April 1958 through 14 August 1961. The work described in the report was partially supported by the Advanced Research Projects Agency, ARPA Order Number 120-60, Project Code Number 7700. The objective of the contract was to conduct a theoretical and experimental investigation of micro-wave radiometry and radar techniques in the detection of missiles.

The theoretical portion of the investigation was concerned with mechanisms which would predict or explain microwave radiation originating in launch, midcourse, and terminal phases of missile flight. The effects produced by missile exhausts, the ionization behind the missile at midcourse, and conditions in the shock layer during re-entry were studied. A theoretical model was proposed to explain the presence of radiation believed to originate in the midcourse plasma sheath and the plasma cavity behind the missile. The results of computations concerning shock layer plasma frequencies were compared with data obtained during re-entry of test missiles and the midcourse radar cross section of the wake was related to observations made at The Ohio State University during satellite passages.

In order to obtain experimental data relating to re-entry microwave phenomena, microwave radiometric receiver equipment was installed aboard the test vessel USAS American Mariner. This equipment was operated at the Atlantic Missile Range as part of Project DAMP. Data was obtained during the re-entry phase of several firings. Examination of the data suggested that some type of partially coherent plasma oscillation was being detected. A study was made of the bremsstrahlung from a relatively cool plasma to determine whether this mechanism could be applied to the results of the experimental program to explain the observed power levels.

The results of the above program are summarized in Sections 5, 6 and 7. These sections cover yearly intervals in the program. Considerably more

detail may be found in the technical reports which have been published. A list of these reports is given in Section 3.

5. **TECHNICAL WORK: PERIOD FROM APRIL 15, 1958 TO APRIL 14, 1959.**

5.1 **(U) Introduction**

The first phase of this program, beginning in April 1958 and continuing to April 1959 was concerned with the question of the detection of missile launchings by means of detection of the effects produced by missile exhausts and their interactions with the ionosphere. This phase can be divided into four overlapping areas for the purpose of discussion.

(1) The first of these areas deals with passive detection. Investigation was made of such questions as what processes in the missile exhaust might cause radiation; what would be the spectral distribution of such radiation and whether such radiation would be detected at ranges of practical interest and with equipments representative of the present state-of-art.

(2) The second area deals with ionization behind a missile. Investigation was made of mechanisms by which such ionization could be generated and of the reflection properties of such an ionized region.

(3) The third area deals with environmental effects which might be utilized by active detection schemes. Here the primary interest was in the interaction of radiation from the missile exhaust with the ionosphere.

(4) The fourth area is the preparation to participate in a program of experiments at the Atlantic Missile Range as part of Project DAMP.

The results of the investigation of these questions is given in detail in a University of Michigan report [1]. Subsequent research may have improved upon the assumptions and results of the work described in this report. This section is a summary of that period of investigation.

5.2   Passive Radiometer Detection

5.2.1   (U) Systems Considerations

At the time of this investigation, no reliable estimates of detection or tracking ranges had been published and no analysis of system variants was available, therefore, some of these considerations were given emphasis in this phase of the contract.

Simplifying assumptions were made concerning some of the characteristics of the phenomena encountered in order to make the problem tractable. It was assumed that equilibrium thermal radiation only is emitted by a rocket exhaust although the other possibilities were studied separately. Since the thermal radiation emitted by the flame during launch is the most intense component of the total radiation, it was assumed that the flame acts as a black body radiator over the microwave frequency range and that the temperature and dimensions of the flame are those observed experimentally at optical frequencies. It was also assumed that the flame area for a liquid fueled rocket at high altitudes is of the order of 4500 ft^2. The line-of-sight range of 600 nautical miles, against an 80 km altitude target was used in calculations of detectability.

It was determined that galactic and terrestrial sources might contribute background radiation comparable to thermal radiation at ambient temperatures, or about 300°K.

A system for launch-site monitoring was investigated and it was determined that, for the parameters chosen as reasonable estimates of what might be practical with current technology, reliable detection might be achieved. It was cautioned that these estimates should not be interpreted as proving that such a system is practical but rather to illustrate the potentiality of passive detection systems.

5.2.2 (U) Processes Causing Radiation

Radiation is emitted from molecular transitions, from free electron collisions and perhaps from collective collisions. Prediction of the intensity of the total radiation from a rocket exhaust was felt to be unfeasible due to the lack of information concerning the populations of constituents within the exhaust flame and a lack of tractable models for analyzing an inhomogeneous plasma. Calculations could be made of the intensity of radiation which can be expected from molecular transitions assuming thermodynamic equilibrium in the exhaust. The radiation arising from molecular rotational transitions and from hyperfine structure transitions was studied. The possibility of significant contributions from such molecular transitions was found to be small. The radiation that might arise from spark discharges from the missile was studied by means of analogy with lighting strokes and it was found that the frequency drops off rapidly with increasing altitude and becomes too low to be measured.

5.3 Ionization at the Missile

5.3.1 (U) Processes Within the Exhaust Jet

The shock wave configuration of the exhaust jet of a missile was studied in detail and special attention was given to the Mach disc phenomena since Mach discs are very intense normal shock waves through which the exhaust gases must flow and therefore the constituents may achieve more highly excited states. The chemical problem associated with thermal jets containing Mach discs was found to be extremely complex. The efficiency of combustion inside the combustion chamber and the composition of the exhaust gases themselves were among the more complicated features of the problem. Various fuel-oxidizer combinations were considered but the possibility of constructing a hypothetical model of the exhaust composition was found to be remote.

However, various considerations governing the thermal jet structure and composition did lead to general observations concerning some of the processes occurring within the boundaries of the exhaust jet:

(1) Highly excited states may be generated within shock waves, thereby leading to a large release of energy downstream of each shock wave.

(2) The local temperature within the exhaust jet will decrease with increasing radius. This will result in greatest disassociation near the axis and the greatest recombination at the jet boundary.

(3) The greatest amount of electromagnetic radiation will probably originate in the neighborhood of the axis of the jet. However, some of this radiation will undoubtedly be absorbed in the more greatly expanded, and hence lower temperature, regions in the vicinity of the jet boundary.

(4) Outside the jet boundaries, which can support no pressure differential, expansion of the exhaust gas cloud will take place through the mechanism of diffusion. This region will undoubtedly be an absorbing region, since it is a fairly dense one compared with atmospheric conditions, and relatively large amounts of water vapor will be present.

5.3.2   (U) Radar Scattering by Ionization

In principle, to calculate the electromagnetic scattering from an ionized region one should solve Maxwell's equations for a medium of variable index of refraction. Whenever the dimensions of the region are not large or small compared with the wavelength of the radiation this calculation can be performed only with the use of an electronic computer even when the problem is separable. If the problem is not separable, any attempt at obtaining a solution becomes impractical.

An attempt was made to construct models of low density ionization which could be handled by approximate methods which had been applied to scattering by meteor trails. It was determined that ionization behind a missile could be expected to reach densities well in excess of those for which an independent scatterer approximation used in this model would be justified. It was therefore necessary to explore approaches for the computation of scattering by a super-critical region. The model used consisted of three distinct regimes: the incoming wave, the Compton process, and the outgoing wave. The Compton process was treated as an individual particle effect, just as for the underdense case. The waves, on the other hand were handled from a ray-tracing viewpoint.

Three cases were considered: a uniform cylinder, a Gaussian cylinder, and two coaxial uniform cylinders. A comparison of the results obtained with the three cases showed that:

(1) For a given line density, the scattering amplitude is less for the two-region case (with inner region more dense) than for the uniform cylinder case and still less for the Gaussian.

(2) The scattering amplitude for the two-region case is in fact just that which would occur if both regions had the density of the outer one.

(3) The scattering amplitude varies as the square root of the line density in the uniform case, as a smaller positive power of the line density in the two-region case, and as its logarithm (still slower) in the Gaussian case.

The implication of these comparisons is that, for a region of radially decreasing high electron density, the scattering characteristics are predominantly determined by the outer portions of the super-critical density region (the core not

being sufficiently penetrated by the radiation). The result of increasing the line density of electrons is primarily to push the effective scattering region outward, rather than to increase its density.

5.4   (S) Environmental Effects of Missile Flight

Another question which was considered was whether the passage of a missile through the atmosphere gives rise to any other effects. Indications were obtained that there is such an effect,* the Thaler effect, which was observed during many missile firings to some degree. A survey of available experimental results led to the following conclusions:

(1)   Where the equipment was operating properly at a frequency suitable for the ionospheric conditions with the antenna beam in the proper location, a disturbance of some sort was almost always observed. This observation coincided in time and range with the firing of the larger missiles.

(2)   The disturbances were largely of two forms:

a. A tightening of the backscatter showing up in the Z-trace from a few seconds to about 5 minutes after launch and lasting perhaps 30 minutes or more. This shows up on the A-scope as a large peak growing out of the backscatter or just in front of the backscatter.

b. A complete disappearance of the backscatter signal.

(3)   Medium and smaller missiles gave returns only occasionally.

(4)   On several smaller missiles, signals coincident with re-entry were observed.

(5)   On daytime firings of the larger missiles, ionosonde records taken at the Cape showed reflections from the E-region which persisted for periods of several to 30 minutes.

———————————

*Perturbation of normal backscatter from the vicinity of the launch area, observed in connection with rocket firings.

At this time, no theory has been postulated to explain the basis for these observations. A possible mechanism was proposed and put forth in a paper [2] which was presented at the ONR Symposium on the Thaler Effect. It was postulated that the exhaust gases act as a catalyst and trigger the formation of local blobs of ionization above the launch site. The signals observed are reflections from these blobs of ionization. It was felt that in the missile propulsion system, when it is above the ozone layer, there is sufficient ultraviolet given off by the trail to increase the excitation above the threshold required to cause sporadic E-layer blobs to form during daylight hours. During these hours the sun is giving off significant excitation and it is felt that only a small increase would cause the E-layer to form. At night when there is a tendency toward equilibrium states, it was felt that photo-detachment might be the mechanism causing the blobs.

It was proposed that an experiment be carried out to obtain information for the evaluation of this postulation. The experiment would include flying a missile on a level flight above the ozone layer and generating ultraviolet to see whether the ultraviolet provided additional excitation and the formation of a blob.

Without further experimental data on the nature of the region above the launch site, any explanation could only be tentative. A tentative explanation was put forth to attempt to explain the characteristics of the observed signals. It considered two situations above the launch site. One situation was that of smooth atmospheric flow conditions and a distinct blob. In this situation a large return could be expected due to reflection from the blob. The second situation was that of turbulent atmospheric conditions which would cause the blob to be diffuse and cover a large area. In this case, there might be considerable absorption and little reflection. Multiple bounces might traverse the indistinct region more than once causing greater absorption and the backscatter signal might completely disappear.

5.5   (U) Preparations for Project DAMP.

A number of experimental tests had been performed prior to this study
to determine what electromagnetic radiation is emitted by rockets during exit and
re-entry. But few experiments had been performed to discover what radiation
is emitted at high altitudes where the plume and gas cap electron plasma frequency
is in the microwave range and where thermalizing collisions are far less dominant.
For this purpose, arrangements had been made for participation in the program
of experiments at the Atlantic Missile Range to be conducted under Project DAMP.
A limited series of experiments were planned to explore whether or not significant
extra-thermal radiation is emitted. A radiometer was installed aboard the
USAS American Mariner. The radiometer operated at 16 Kmc. It was anticipated
that about three exit and three or more re-entry trajectories would be observed.
The equipment was not considered to be an optimum apparatus for this purpose.
It was believed to be adequate for the first exploratory tests.

6.   TECHNICAL WORK: PERIOD FROM APRIL 15, 1959 TO APRIL 14,
       1960.

6.1   (S) Introduction

This period was concerned with the investigation of non-thermal passive
microwave radiation believed to be emitted during the passage of a ballistic mis-
sile through the outer atmosphere at high speed, particularly during that portion
of the flight when the missile is enveloped in a locally generated plasma. Predic-
tions that microwave radiation should occur at midcourse are believed to have
been first made in this Laboratory. A conjectural physical model was developed
and subsequent to this period work was done to investigate its validity. The
frequency and character of the radiation which would be predicted is dependent
upon the parameters and structure of the physical model of the outer atmosphere.
Few experiments had been performed to obtain data on this radiation.

Because of the potential importance of the existence of such radiation, the Radiation Laboratory conducted experimental exploratory tests to determine whether postulated missile-generated microwave radiation could be detected during the latter part of a midcourse flight, prior to and during the initiations of re-entry into the sensible portion of the atmosphere. The measurements were made using two radiometers capable of detecting the radiation received over narrow frequency bands near 16 and 35 Kmc with thermal precision and angular directivity. The radiometers were installed aboard the USAS American Mariner, a ship specially equipped for scientific tests of this nature, stationed in the Atlantic Missile Range. The antennas of the radiometers were servo driven from radar or optical tracking equipment aboard the ship so as to be directed toward the re-entry vehicle.

Test operations began in March 1959 and continued until December 1960. These tests also were associated with the Project DAMP Program. The results of the work during this period are given in detail in $\begin{bmatrix} 3 \end{bmatrix}$.

6.2   (S) Types of Radiation

The types of microwave radiation which could be emitted by the complex system of the re-entry vehicle and the associated plasma were studied. These studies included consideration of the gas cap about the re-entry vehicle, a cavity behind the vehicle, radiation from solid or melting materials during re-entry, radiation reflected or scattered by the missile, and bremsstrahlung. It was determined that the thermal mechanisms were either of such low total intensity as to be of little interest for application to a long range detection system, or to require antennas of larger size than were to be used in the experiment. Particular attention was given to non-thermal radiation from charged particles trapped in and oscillating about the wake cavity. A physical model to describe this type of radiation was developed.

6.2.1   (S) Physical Model of Plasma Oscillation Radiation

A body moving at orbital or suborbital velocity in the ionosphere would have a velocity intermediate to the rms velocities of the ions and the electrons. Therefore a positive particle cap would form in front of it and a partial vacuum behind it. Because of their high thermal velocity, electrons would attempt to fill this cavity behind the body, however, a repulsing coulomb field would be created. The electrons would begin to move out then and an electron oscillation would be initiated. It was felt that this oscillation would produce radiation. It was suggested that this radiation would be partially coherent since the electrons should move outward together (statistically). During this part of the study, the calculation of amplitude and frequency as a function of velocity, altitude, and ballistic coefficient was begun and the exploratory measurement program was undertaken in order to see whether any evidences of non-thermal processes could be found.

6.3   (U) Radiometer Test Instrumentation

A 16 Kmc radiometer was used from March through December 1959 and a 35 Kmc radiometer was used from October through December 1959. Their characteristics are summarized in Table I below.

TABLE I - RADIOMETER CHARACTERISTICS

FREQUENCY	16	34.8	KMC
I-F FREQUENCY	30	60	MC
I-F BANDWIDTH	10	10	MC
RCVR NOISE TEMP	3000	9000	DEG. K
ANTENNA BEAMWIDTH	2.5	2.0	DEGREES
REFERENCE TEMP	300	300	DEG. K
INTEGRATION TIME	1-25	1-25	SECONDS
RMS NOISE (1.5 SEC)	5	9	DEGREES

6.3.1   (U) 16 Kmc Radiometer

6.3.1.1 Receiver

A mixer-I. F. receiver with Dicke-type resistive disc input modulator and ferrite directional isolator was used. Radiation within two (image) bands each 10 Mc wide, separated by 60 Mc, and centered at about 16 Kmc, was detected. The noise temperature of the receiver, during an initial period up to 1 June 1959, was about 8000°K. New receiver components were installed at that time. The receiver noise then dropped to about 3000°K.

During the tests the apparent temperature output was smoothed through a filter (single-pole low-pass) with time constant of approximately 2 seconds. The thermal resolution of the instrument, estimated from examination of experimental records, was about 5°K standard deviation. For comparison, the thermal resolution calculated from theory using receiver parameters was 2°K.

6.3.1.2 Antenna

A vertically-polarized parabolic dish antenna 0.75 meters in diameter providing a pencil beam of half-power beamwidth of approximately 40 milliradians had been employed. The side and back lobes were sufficiently low that residual thermal radiation from the surrounding ship's structure was of no evident consequence over the angular field of concern. Measurements of apparent sky temperature indicated that the combination of feed emission, side-lobe radiation and atmospheric emission induced an apparent antenna temperature, at the zenith, of about 120°K. Day-to-day weather changes were observed to affect this profile very little, provided no heavy rain occurred.

6.3.1.3 Recorder

An oscillographic strip-chart pen recorder was used to record the radiometer output. Timing signals derived from the Atlantic Missile Range master-timing network were recorded on the chart to provide a precision time reference for correlation of other information.

6.3.2   (U) 35 Kmc Radiometer

The 35 Kmc radiometer configuration was the same as that of the 16 Kmc radiometer. It also employed a mixer-I. F. receiver with a Dicke-type input modulator. The noise temperature of this receiver was about 9000°K., yielding a thermal resolution of 9°K. The antenna reflector diameter was 0.3 meters providing a pencil beam of 35 mils beamwidth.

6.3.3   (U) Tests for Spurious Responses

Careful tests had been performed to determine if any spurious signals of a magnitude sufficient to detract from meaningful observations were likely to have occurred in either radiometer. Particular attention has been paid to checking for potential artifacts which would correlate with re-entry events, particularly those caused by activation of the ship's equipment. Efforts to isolate and eliminate such interference proved only partly successful; however, all known sources of interference has been isolated and were known to be inoperative during tests.

6.4   (S) Test Environment and Procedure

The measurements were made on Jupiter and Thor IRBM's and Atlas ICBM's. The observation ship was located 15 n. m. down range from the impact point during IRBM Tests (AMR 1001, 1003 and 4200) and 28 n. m. down range during ICBM Tests (AMR 2120 and 2344). At these locations the azimuth and elevation of the incoming missile remain relatively constant, with a fairly predict-able elevation and azimuth, during most of the re-entry period (until the last few seconds).   Conversely, during IRBM Tests (AMR 2005 and 2347), the observation ship was located about 100 n. m. up range from the impact point and about 20 n. m. west of the flight line. At this location the azimuth and elevation change radically during the reentry period.

A comprehensive radar and optical tracking system was installed aboard the USAS American Mariner capable of tracking a reentering missile over a large

fraction of its re-entry trajectory. The tracking system served for direction of radiation-measuring instruments mounted on servo-driven slave pedestals. This system, and the ship itself, were operated by RCA. The radiometers were mounted on one of these pedestals. Early in the terminal phase the tracking system was predirected from trajectory data transmitted to the ship from the missile launch area at Cape Canaveral. As soon as radar tracking could be established, accuracy improved from 20 milliradians to better than one milliradian. On some occasions when radar acquisition was not accomplished, optical tracking was obtained for the brief period when the re-entering objects were clearly visible to an optical tracker operator. To establish the actual performance of this directing system, boresight cameras were mounted on the radar and radiometer antenna pedestals.

6.5   (S) Radiometric Test Data

Reasonably reliable radiometer and tracking system operation over significant portions of the terminal phase of the trajectory was attained on AMR Tests 2005, 2347, 4200 and 2344. During two IRBM tests, AMR 1001 and 1003, the tracking system worked well but the radiometer was excessively noisy. Photocopies of original records are included for the five tests on which pertinent signals are evident. These are for AMR Tests 2344, 2347, 1001, 2005 and 4200 and are shown in Figures 1 through 5. The strip-chart records present, vs. time, the measured microwave radiation intensity, scaled in terms of apparent antenna input temperature. Time is indicated both by a superimposed numerical scale giving time after lift-off (T-time), and also by the original AMR timing signal imprint (coded relative to GMT). Nose-cone altitutde, when known, is overprinted above. Where two apparent temperature traces are shown, the upper trace is the output of the 35 Kmc radiometer, the lower the output of the 16 Kmc radiometer.
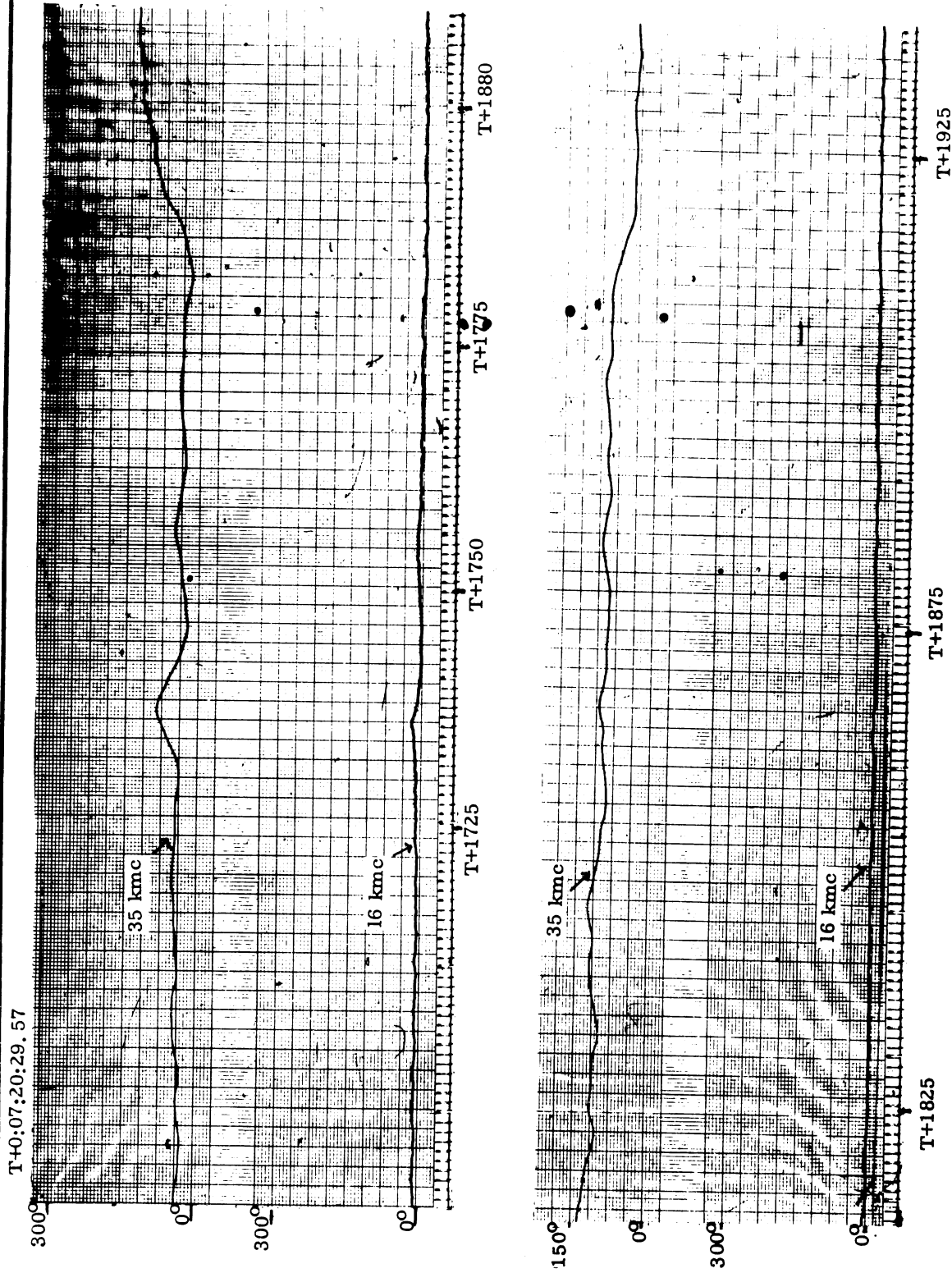
FIGURE 1: (S) AMR TEST 2344 – ATLAS, 29 OCTOBER 1959

Missile Altitude 85 km
Slant Range 135 km
Time T + 859 Seconds

Degrees Kelvin

210

140

70

0
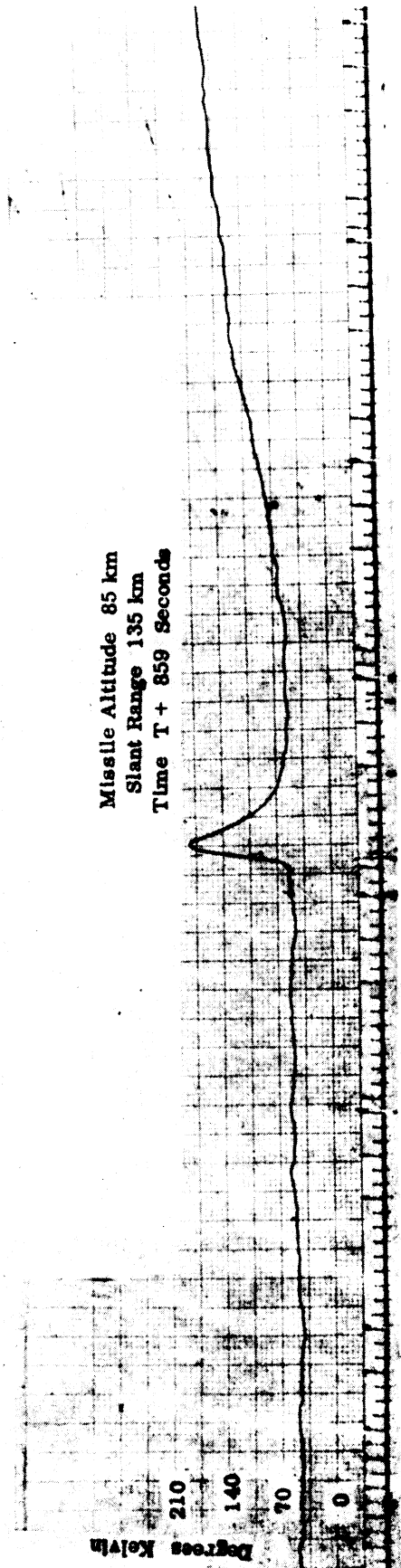
FIGURE 2: (S) AMR TEST 2347 - THOR, 27 AUGUST 1959
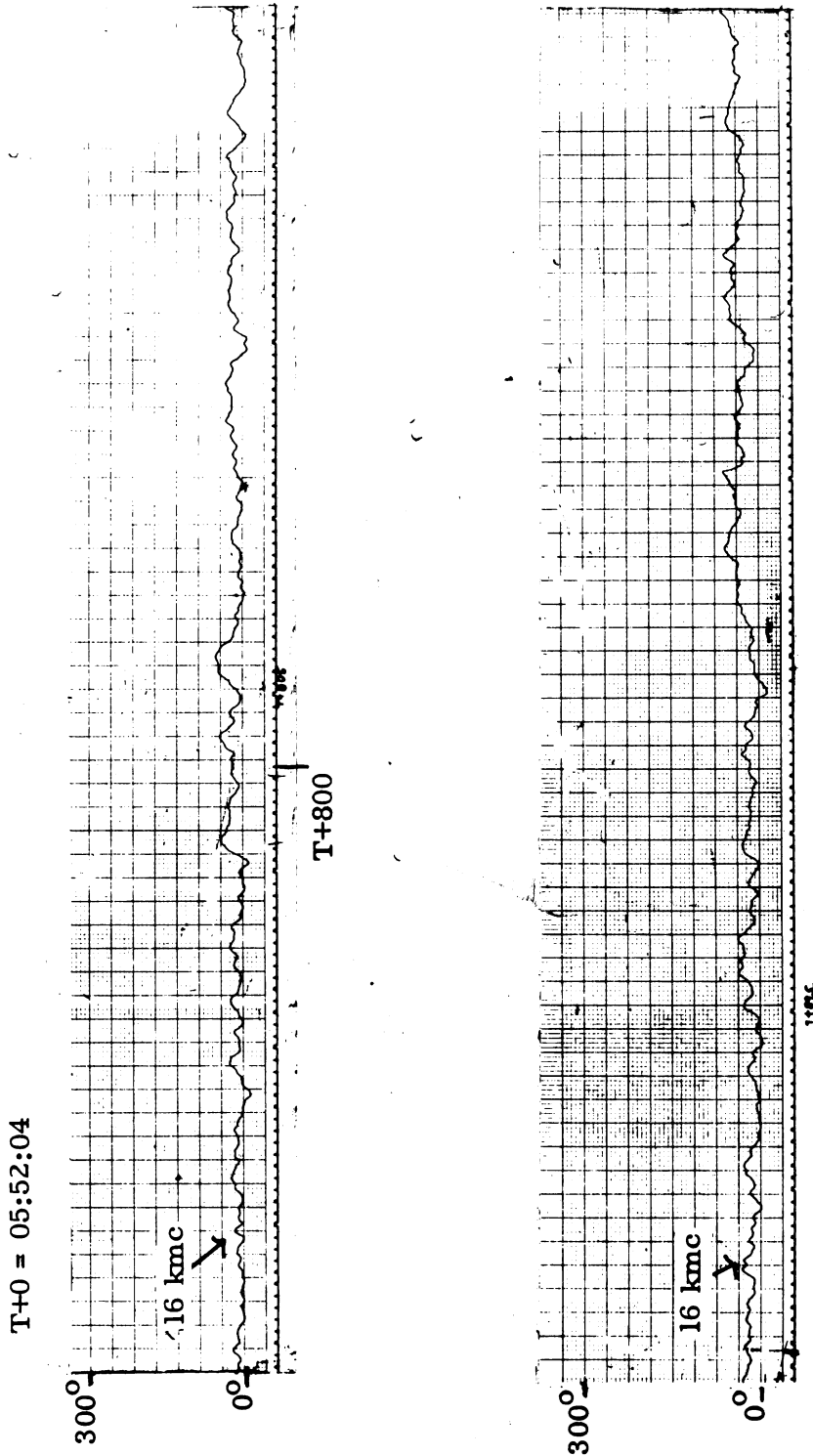
FIGURE 3: (S) AMR TEST 1001 – JUPITER, 14 MAY 1959

1. End of computer operation
2. Missile became visible
3. Switched to optical director
4. End of optical track
5. Beginning of Barnes photometer response
6. Beginning of boresight camera response
7. End of photographic response
8. Spike in photometer response

T+0 : 03:20:16

FIGURE 4: (S) AMR TEST 2005 – THOR, 25 JUNE 1959

FIGURE 5: (S) AMR TEST 4200 – JUPITER, 9 DECEMBER 1959

AMR Test 2344 is discussed here in some detail because the data obtained from it was the most encouraging. Detail about the other test data may be found in $\boxed{3}$.

6.5.1 (S) AMR Test 2344 (Atlas, 29 October 1959, end-on aspect, 16 Kmc and 35 Kmc Radiometers Operated).

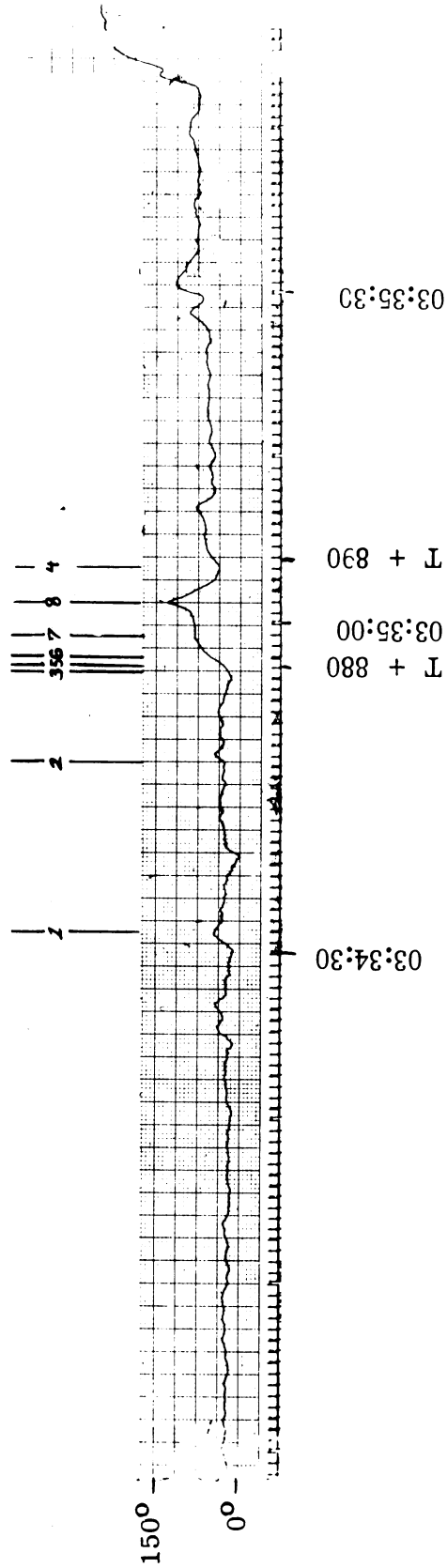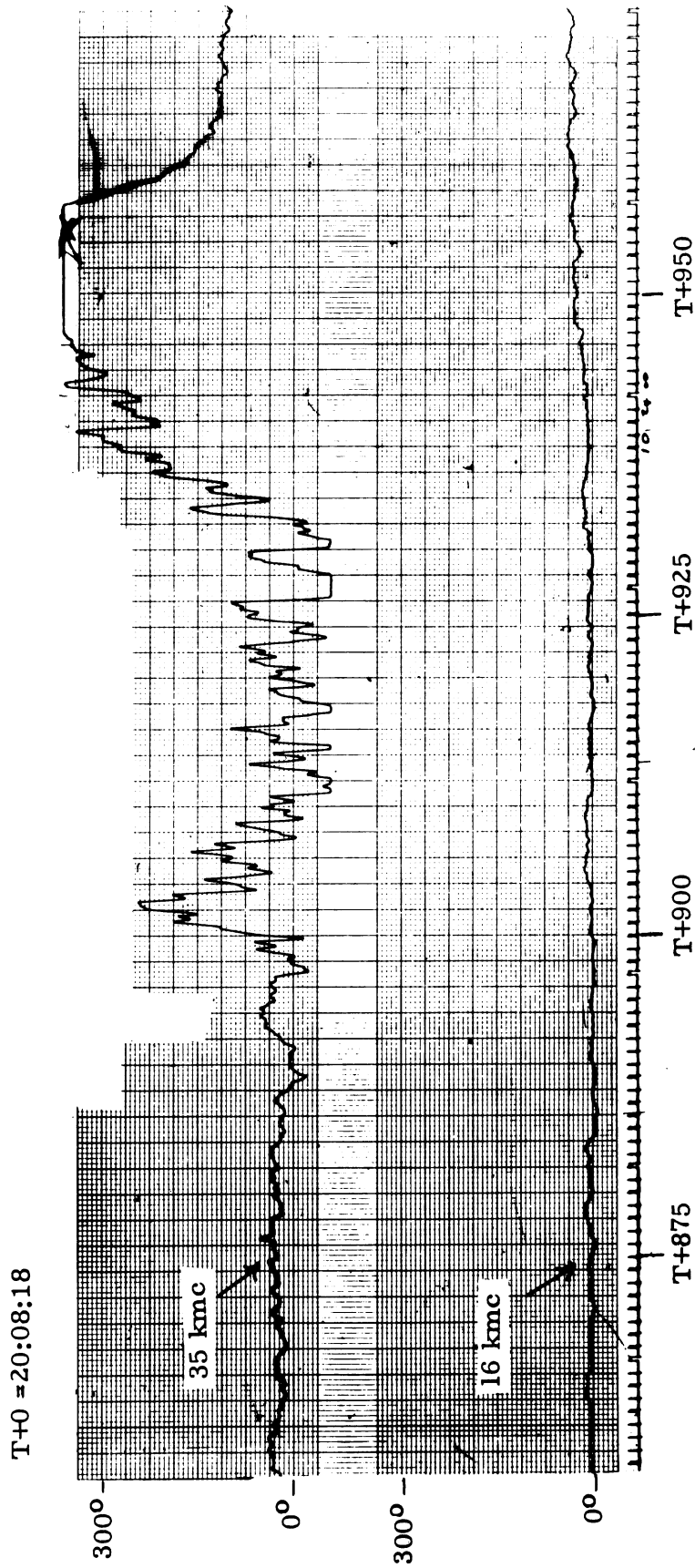For this test the nose cone was a high-performance, ablative type carrying a C-band beacon; it was followed by fourteen-thousand carbon rods, ejected for penetration-aid tests. The radar directing the slaved pedestals tracked the beacon, first from T + 1655 until T + 1675 and again from T + 1713 until T + 1728, at which time the beacon signal abruptly ceased. There was no subsequent lock-on. From this time until T + 1730, the radar trackers remained fixed at the elevation (14 degrees) and azimuth of the last beacon observation. At T + 1730 the radar elevation dropped slowly to 9 degrees and then at T + 1735 rose abruptly to 17 degrees and remained there throughout the next few minutes.

Since the observation point was chosen to make the azimuth rate zero and the elevation rate small over most of the terminal phase of the trajectory, it is likely that even though there was no radar lock-on between T + 1728 and the nose cone splash time, parts of missile complex were in the radiometer beam for a fraction of this period if the missile followed its nominal trajectory. The relationship of the actual flight path to the nominal flight path has not been finally established by those organizations responsible for such data[+].

The apparent-temperature vs. time recordings of the 16 and 35 Kmc radiometers are shown in Figure 1. Until T + 1731 no signals were recorded on

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[+] The uncertainty centers about the nose-cone altitude vs. time during the terminal phase of its flight. Initial shipboard estimates placed the altitude at approximately 250 km at T + 1725. Later estimates placed it at approximately 100 km at this same time. In each case there was cause for doubt.

either radiometer. At this time the 35 Kmc record shows an increasing output, reaching a peak at T + 1737 and then decaying to ambient. It shows a second strong radiation lasting from about T + 1790 until T + 1910. The 16 Kmc radiometer record shows a slow rise beginning at about T + 1731, reaching a maximum at T + 1736 and then decaying to ambient.

Attention is called to the fact that the time of occurrence of the 16 Kmc radiometer response and the first of the 35 Kmc responses correspond roughly to the period when the antenna elevation was changing. At low elevation angles the apparent antenna temperature of both radiometers increases as the elevation angle decreases. Therefore, some, if not all, of the radiation recorded during this interval undoubtedly was due to this cause.

Since the angular excursion is known, it is possible to estimate the expected temperature rise for both radiometers. The 16 Kmc antenna temperature should have increased by 15 degrees Kelvin as the elevation angle decreased from 14 to 9 degrees. The measured temperature rise was 12 degrees. Thus the elevation-predicted value differed from the measured by less than the amplitude of the rms noise fluctuation. Therefore, the rise on the 16 Kmc radiometer is highly likely to have been caused in total by the antenna angular depression.

Similarly, during this same interval, the 35 Kmc antenna temperature should have increased 15 degrees Kelvin because of the antenna excursion. By comparison, the measured radiation rise of 50 degrees Kelvin far exceeds this predicted rise, and in addition, exceeds the background radiation by about six times the noise fluctuation. It is noted that the time of maximum response at 35 Kmc is one second later than the time of the similar event on the 16 Kmc radiometer*. Each of these considerations suggests that a non-environmental source

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* Between 3/4 and 1 second.

of radiation at 35 Kmc may have been present in the radiometer antenna beam near T + 1737 in addition to the undoubted atmospheric radiation. However, because the radar was not tracking at the time, and because other pertinent facts about the missile's actual flight path are unknown, it is not possible to relate any of the radiometer events to missile phenomena.

The 35 Kmc radiometer shows a second strong response beginning at T + 1790; the response lasted until T + 1910, or at least a minute beyond nose cone impact time. Thus the nose cone was not likely to have caused this signal. However, as previously stated, the missile was accompanied by 14,000 carbon rods, ejected from the missile capsule for penetration-aid tests. On the average, the rods had a lower weight-to-drag ratio than did the nose cone and should, therefore, have been in flight for a longer time, possibly on a flight path through the radiometer beam. Since there was no radar contact with the rods nor any other data on their re-entry (the test took place during completely overcast skies), there is no evidence to support or deny this conjecture. All known sources of radiation interference were known to have been inoperative during the test.

6.6   (S) Evaluation

The records indicate the occurrence of several interesting radiation signals at times when missiles were known to have been, or were likely to have been, in the radiometer beam. But virtually none of the signals observed in the above records can be labelled with certainty as being missile-generated, as opposed to environmental radiation. The ancillary data accumulated on test conditions and events was too incomplete to permit a conclusive, quantitative evaluation. However, the records - particularly from AMR Test 2344 - did encourage continued theoretical and experimental effort.

6.7   (S) Theoretical Models for Radiation Sources

Some of the possible mechanisms to explain the radiation which could be responsible for the signals observed were investigated. It was assumed that the signals did arise from missile-generated radiation. Strong signals were received during the visible portion of the re-entry of tests AMR 2005 and 2347 as the IRBM's were viewed from a side aspect, and from AMR 2344 at a time when the beacon failed.

Thermal processes were studied since the signals could conceivably be thermal bremsstrahlung radiation from the large diffusing superheated plasma wake occurring during the visible portion of re-entry. Bremsstrahlung is a process in which a free electron is scattered by a potential into a free state of lower energy, the energy difference appearing as a radiated photon. In the inverse process, free-free absorption, a free electron in a potential absorbs a photon and makes a transition to a free state of higher energy. The results of this study showed that the model, while not impossible, was not promising since it would be surprising to have the radial diffusion which was encountered and still retain a high enough temperature required for this process.

Bremsstrahlung radiation in the shock layer was investigated as a possible source for this radiation. Because the thermal velocities of the ambient gas electrons are much larger than the vehicle velocity, surface scattering of the incident electron flow at the missile boundary layer or shock front cannot produce important radiation enhancement. The thermal radiation from the surrounding gas environment would overwhelm such surface radiation.

The transient-like character of the signal during AMR Test 2005 lends support to the suggestion that upon re-entry some type of coherent, non-equilibrium plasma oscillation is occurring. The signal observed in Test 2344 also has the

character of a plasma-like oscillation. This type of oscillation was believed to be the most likely source for the signals.

6.8   (U) Associated Studies

Of direct concern to the work on this program was the study, under separate funding,[+] of the plasma sheath and the plasma cavity occurring when a spherical body moves at ICBM or orbital velocities through the ionosphere and the atmosphere. A program was undertaken to formulate a mathematical description of the physical situation and to compute the electron density distribution about the sphere. The results of this investigation are given in a University of Michigan report [4].

The research reported in [3] and listed in Section 3.2 was an integral part of the program. However, it should be noted that the work was funded under a separate contract (DA 36-039 SC-85403, ARPA Order Nr. 120-60, Project Code Nr. 7700) with USASRDL.

7.   TECHNICAL WORK: PERIOD APRIL 15, 1960 to AUGUST 14, 1961

7.1   (S) Introduction

In this period, further attempts were made to obtain data on passive microwave detection of re-entry vehicles. The experimental equipment which was used included a modified 35 Kmc radiometer. The theoretical work continued in an effort to explain the phenomena encountered in midcourse and re-entry of ballistic missiles and to predict the frequency of the microwave energy thought to originate in the wake of the re-entry body.

+ Air Force Contract No. AF 30(602)-1853 sponsored by the Rome Air Development Center.

7.2   (S) Passive Microwave Measurement Experiments

An improved 35 Kmc radiometer was designed and a subcontract let to the Strand Engineering Company to modify and rebuild the equipment which had been used in the first series of tests. The radiometer was to have the following general specifications:

Frequency Range	34-36 Kmc
Overall Noise Figure	11-13 db
IF Frequency	30 Mc
Bandwidth	10 Mc minimum

The equipment which was obtained by this modification had a larger antenna for increased sensitivity. It had a built-in calibration system to simplify and shorten calibration procedures.

The equipment was installed aboard the USAS American Mariner in August 1960, but the check-out was hampered by lack of AC power while the ship was in drydock at Dakar, Senegal. The work was limited to the mounting of the antenna and the r-f and receiver housing and to the alignment of the antenna boresight scope axis with the pedestal axis. The electronic installation and check-out were done while enroute to Ascension Island.

The USAS American Mariner arrived at Ascension Island on 28 August 1960. At that time, three firings were scheduled, with impacts planned in the Ascension Island area in the following two week period. However, only one, AMR 2819 was successfully launched. The radars aboard the USAS American Mariner attempted acquisition and tracking but the beacon tracking radar to which the radiometer was slaved did not track any part of the re-entry complex. Thus no data was obtained on that firing.

After putting into Monrovia, Liberia for supplies and fuel, the American Mariner was again in position for further tests a month later. On one test during the renewed firings, the ship's radars tracked well and twenty seconds of radio-metric data were obtained. Unfortunately, the equipment did not function well and the results were considered to be ambiguous and inconclusive. A detailed check of the data and the equipment showed that much of the recorded data was atmospheric. There was an initial boresight error of several mils. The antenna beamwidth is 6 mils. The receiver sensitivity was low and the total loss of sensitivity was about 6 db. With this loss of sensitivity no signals were observed which could be ascribed to missile effects.

In the remainder of the test series, only one missile reached the target area of the USAS American Mariner. On this test, No. 3506, radar lock-on was not maintained and the radiometer pedestal was under the control of the optical tracker during the measurement period. A check of the boresight film from the pedestal showed that during the time the missile appears on the film, there are only six very brief periods totaling about 0.9 seconds, less than 3 per cent of the total time, in which the target was within the antenna beam. Under these conditions, no meaningful data was obtained. The equipment was removed from the ship and returned to the laboratory.

7.3   (S) Theoretical Studies

A study was made of the bremsstrahlung from a relatively cool plasma in order to see whether this mechanism could be applied to the experimental program's measurements to explain the observed power levels. The theoretical approach is given considerable detail in $\left[\,5\,\right]$.

Microwave bremsstrahlung from, and free-free absorption in, a cool, partially-ionized plasma was treated in this study. Electron-ion encounters were treated by the Born approximation and the classical impulse approximation, a

Debye-shielded potential being used. Bremsstrahlung from electron-neutral collisions was treated by the Born approximation. The potential was obtained by fitting a shielded Coulomb form to the Thomas-Fermi potential for distances less than about 7 atomic radii.

For the plasma parameters chosen (T = 5000°K, n_e = 10^{13}/cm^3, Z = 8) and microwave frequencies of the order of 50 Kmc, it would appear that at the correspondingly low degree of ionization, the neutrals are most significant. An effective Z for the oxygen atoms is determined by matching the free-free absorption to Kramers' law. Its value, Z = .17, compares reasonably with the results of previous investigators.

The conclusions of the study were applied to the practical case of the stagnation region conditions for a Thor re-entry at 50 Km. The bremsstrahlung power was computed under the assumption that the bremsstrahlung from molecules would not change the power from neutrals significantly. The bremsstrahlung power was found to be several orders of magnitude below the thermal power. Since the USAS American Mariner radiometer results were several orders of magnitude above thermal, they cannot be explained by bremsstrahlung, on the basis of this computation. The results obtained in this portion of the study were extended to cover a larger frequency range. The additional frequencies considered were 15 Kmc, 35 Kmc, and 125 Kmc. Computations showed that the ion bremsstrahlung power varied only slowly with frequency and that from the neutrals was frequency-dependent in the range considered.

7.4   (U) Report of a "Major Event"

Under the requirements of ARPA Order 120-60, a significant theoretical result was reported as a "Major Event" [6] when experimental data obtained by The Ohio State University seemed to confirm the theory. In a University of Michigan report [7] it was shown theoretically that the cross section of an object

travelling at satellite altitudes and velocities is enhanced by several orders of magnitude by the presence of the plasma sheath about the vehicle and in its wake and that it is very aspect sensitive.

The predictions of this theory for the radar cross section of a spherical satellite of 1 meter radius moving with a velocity of 8 Km/sec. at an altitude of 500 Km are that it would have a return at 20 Mcs as shown in Table II below,

θ	Cross Section (m^2)
90°	3.6×10^5
60°	5.4×10°
45°	2.7×10°

where θ is the angle between the observer and the tangent to the satellite path. Thus this theory predicts that such a satellite would have a large enhancement in radar cross section over a narrow range of aspect near its point of closest approach to an observing radar. J. D. Kraus and his associates at The Ohio State University had reported data [8] on observations of the 20 Mcs WWV signal transmitted by a station near Washington, D. C. The measurements show that large bursts of signal coincide with the passage of a satellite when the satellite is at or very near its point of closest approach to the receiver. In one instance the satellite at its closest approach passed through the center of the antenna beam. The burst pattern was very symmetric in form and Kraus was able to calculate the radar cross section of the satellite as approximately $10^6 m^2$. The magnitude and aspect sensitivity of the return appear to support the theory and it is felt that this study will contribute to the understanding of the physics of the plasma sheath surrounding bodies moving at satellite velocities.

8.   (S) OVERALL CONCLUSIONS

8.1   Although system considerations indicate the use of passive micro-
      wave techniques to detect rocket launchings may be feasible, none of
      the physical processes considered satisfactorily predict the genera-
      tion of detectable electromagnetic emissions within the exhaust
      plume.

8.2   Use of active detection methods in the launch phase might prove
      more successful. The fact that the exhaust is very weakly
      ionized and is quite dense, compared to the surrounding iono-
      sphere indicates that, in effect, a tunnel of essentially neutral
      exhaust products is formed along the missile trajectory and,
      because of the slow mixing, it will persist for a relatively long
      time. Forward or backward scattering of HF electromagnetic
      waves such as Thaler used, might be very useful assuming the
      above model is correct.

8.3   Huge quantities of essentially neutral gases are injected into the
      ionosphere at supersonic velocities and will produce pressure
      disturbances which will propagate through the ionosphere at
      velocities near the local acoustical velocity. Detection of
      these disturbances may prove to be beneficial.

8.4   The fluid mechanical characteristics of terminal phase flow fields
      are not understood well enough to predict the presence of microwave
      emission. The use of passive microwave detection schemes for
      terminal phase detection cannot be recommended on the basis of
      present day knowledge.

8.5   Continuation of terminal phase observations at 16 and 32 Kmc

aboard the USAS American Mariner was deemed impractical

because of an inability of the ships tracking equipment to acquire

the target at high altitude and the low probability of detectable emissions

originating within and propagating through the re-entry shock layer.

8.6   Passive microwave detection may be possible during the mid-

course phase of the flight and at the onset of re-entry. The

electron density gradients associated with the vacuum cavity

behind a body moving through the ionosphere at satellite

velocities and the gradual density increase associated with

the generation of the bow shockwave could provide the proper

environment for a physical mechanism for generating electro-

magnetic waves having frequencies well above the local plasma

frequency.

9.   RECOMMENDATIONS

9.1   (S) General

In view of the preceding general conclusions, the following recommenda-

tions are made for a continuation of investigations concerning passive microwave

detection techniques to be used in defense against ICBM targets. Since a theoretical

basis for the use of such techniques for launch and terminal phase detection has not

been developable at the present time, the following recommendations will refer to

the transition region between the midcourse and terminal phases of flight.

9.2   (U) Specific

9.2.1   Initiate a theoretical investigation to develop a physical model which

would predict the emission of electromagnetic waves at frequencies

well above the plasma frequency.

9.2.2   **Perform experimental investigations to determine whether detectable microwave emissions from the wake of a vehicle** moving through the ionosphere at satellite velocities are generated. Since the bandwidth and power level of such emissions are unknown, use of microwaves radiometers within the re-entry vehicle may be more **satisfactory than land-based** sites.

9.2.3   **Theoretically** investigate the possibility of microwave electro-magnetic waves being generated when the bow shockwave begins to form in the transition region between the midcourse and terminal phases of flight. Examination of the structure of a shockwave may reveal the existence of a physical mechanism which will produce such emissions.

9.2.4   Perform experimental investigations to provide data which may be used to establish guide lines and boundary conditions for the theoretical investigation of the formation of the bow shockwave. The use of Langmuir probe techniques in a full scale flight test program might provide such valuable data.

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