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DOPPLER RADIATION STUDY

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by

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TABLE OF CONTENTS

ABSTRACT

In this, the First Quarterly Report on "Doppler Radiation Study", some preliminary experimental and theoretical investigations are reported.

Antenna pattern data for an AN/APN-153 System collected by The University of Michigan Radiation Laboratory is compared with that obtained at the General Precision Laboratories at Pleasantville, New York. Visits to GPL and the Ryan Aeronautical Corporation of San Diego, California are discussed and the various antenna arrays and doppler systems being developed by these companies are described.

In the theoretical study expressions for the radiation reflected from a smooth perfectly conducting surface are given for a moving and maneuvering aircraft. These variations in the axes of the aircraft with respect to some fixed reference are included in the analysis through a number of matrix transformations on the fixed coordinate system. Geometrical optics is used throughout the analysis.

I INTRODUCTION

This is the First Quarterly Report on Contract N62269-67-C-0545, "Doppler Radiation Study" and covers the period 1 July through 1 October 1967.

The primary objective of this project is to characterize the radiation from airborne doppler navigational radar systems, and to investigate the probability of detecting such radiation. To accomplish this objective, the study is to be carried out in the four phases, listed below:

1. Experimental measurement of the radiation patterns of several antennas that are currently used in doppler navitational systems. These are to be supplied by the sponsor.

2. Based on the measured radiation pattern, the distribution of radiation in space and the effects due to ground reflection, airplane maneuvering and meteorological conditions are to be investigated.

3. From the estimated radiation patterns given in (1), the probability of detecting the radiation at different ranges is to be determined.

4. Finally, the theoretical estimations of (2) will be checked against results obtained from a carefully designed flight test.

During the present research period, the following has been accomplished.

1. The radiation pattern of an AN/APN-153 antenna has been measured in our anechoic chamber. The data is currently being put in digital form suitable for the numerical computation required in phase (2). Also, a study of the available literature on the detectability of doppler radar has been made (Airborne Instruments Laboratory, 1954a, 1954b, 1955). It is our feeling that a more quantitative analysis of the radiation from doppler radar systems would be useful to the present study.

2. Mathematical expressions for the radiation reflected by a smooth, perfectly conducting ground, incorporating the effect of vehicle motion and maneuvering have been formulated. This aspect of the study, based on geometrical optics will be extended to include the effects of unusual propagation conditions, and also reflections from elevated objects and/or clouds. A description of the reflected radiation is also being investigated using physical optics. A survey of the literature on the property of waves reflected by rough surfaces has been made. At present it is considered that calculations based on the assumption of a smooth ground will provide a reasonable estimate of the reflected radiation. Later a more sophisticated model may be called for.

Antenna pattern measurements for the second system of doppler radar will be carried out in the next research period, or when they are made available by NADC. Also during the next period, the theoretical investigation will be continued and numerical results for the reflected radiation from a smooth ground computated for some typical radar systems.

The mathematical formulation will be extended to include the case of a diffuse ground.

II EXPERIMENTAL STUDY

The Radiation Laboratory has received a doppler antenna, AN /APN-153, from the Naval Air Development Center for pattern evaluation. A complete set of three-dimensional radiation patterns have been collected for this antenna so that a contour plot of the data may be constructed. A present this data is being converted to a digital form to facilitate numerical computation.

During a recent visit to the General Precision Laboratories at Pleasantville New York, typical patterns for an AN/APN-153 antenna system were obtained and compared with the data collected by this laboratory. The two sets of data were found to be in good agreement. The gain of the antenna was quoted by GPL personnel to be approximately 18. 5 db above an isotropic source, and was found in experiments conducted at the Radiation Laboratory to be 19 db above an isotropic source. We plan no further experimental work with the present system and are now in a position to collect data for a second system whenever it is made available by NADC.

During the visit to GPL, the operational characteristics of the AN/APN-153 antenna, antenna patterns, and the techniques employed by GPL to obtain these were discussed. It should be noted that GPL collect patterns only in the two principal planes of the antenna. A total of 8 patterns were obtained for evaluation purposes. Several three-dimensional patterns were collected at The University of Michigan during the earlier part of the program. These, however, are no longer available.

General Precision Laboratories described the antenna as follows. The antenna consists of two resonant slot arrays employing broadwall slots spaced a half guide wavelength apart. The wide spacing that is observed in the array comes about because of the narrow-wall guide that is used for the slot array. The slots are all arranged on the same side of the center line to achieve 180^0 phase reversal between adjacent slots. This generates the dual beam characteristics that are required for the GPL doppler system. The slots are of the dumbbell configuration. The dumbbell was chosen to simplify the manufacturing process rather than for electrical reasons.

An additional purpose for the visit was to obtain an understanding as to the manner in which the velocity vector is resolved into components. It was learned that when the forward beam and the rear beam are simultaneously present, the signal output of the magic tee (of the doppler antenna system) is an electrical addition of these two beams and that this yields the doppler frequency. When the electromechanical switch (located in the waveguide plumbing of the doppler antenna system) is activated the beams appear in the forward right and left rear. The doppler signal is again obtained at the output of the tee. The two doppler frequencies are compared (electronically) and if identical, the antenna is oriented along the true line of flight. However, when the two doppler frequencies differ the servo system is activated and the antenna rotates to align its longitudinal axis with the line of flight of the aircraft. Servo information, available from the antenna, gives the angular difference between the aircraft centerline and the line of flight. This data is compared to compass data, measured relative to the aircraft center line. Compass information, doppler data, and the velocity data are fed into a small computer where the velocity vector is reduced into the two ground velocity vector components.

Future systems will have the ability to reduce the velocity vector into three velocity components and will provide information from which the rate of climb may be found. This is of use in high-speed supersonic aircraft and in helicopters. In these systems, a new antenna concept is to be employed. Rather than having a small array similar to the AN/APN-153 a larger two-dimensional planar array is to be used. In the receiving sense a total of eight beams will be required, but in the transmitting mode only four beams will be needed. Basically, the receiving array consists of one large array with four input ports. Each input can be switched to the on-mode alternately to generate the required eight beams. When a signal is introduced into the input of one port, two beams are generated by the array giving a total of eight beams.

The new doppler systems will employ varactor multipliers for transmitters rather than magnetrons or klystrons. Further, much of the circuitry is to be built using solid state components. It is hoped that this will result in a higher degree of reliability from the doppler system than hereto achieved.

The Ryan Aeronautical Corporation in San Diego California was also visisted during this period. Their Model 533 Doppler system was discussed. The system consists of two waveguide slot arrays, one for transmitting and the other for receiving. The transmitting array is of particular relevance to the present study.

It consists of hybrids and solid state diode switches and is designed in such a manner that two beams looking forward are first transmitted and then through the operation of the solid state switch, the array is caused to generate two beams in the rear direction. A typical gain figure for the transmitter array is 29 db with a side lobe level of 25 db below the main lobe. When the beamwidths of the array are very narrow (in the neighborhood of 1^{o}) and are symmetrical, the beams point approximately 20.5^{o} and 11.5^{o} to either side of the aircraft. When switched to the rear direction, the beams are 20.5^{o} to the rear and 11.5^{o} to either side of the local vertical. The technique used by Ryan requires that only one beam be interrogated at a time. To accomplish this the receiving array is designed employing 3 db hybrids and double throw solid state switches. This time, however, as the switch is activated from one position to the other, the array is caused to generate two beams first to one side of the aircraft then to the other. By proper programming of the switch it is possible to interrogate one beam at a time. For example, if the transmitting array is transmitting two beams forward and the receiving array is transmitting two beams to the left of the aircraft, the only beam that would simultaneously have a transmitting and receiving beam present would be the one in the forward left quadrant.

After the data has been collected by the antenna, it is routed through mixing stages into a computer. There, the data is analyzed for the required velocity components.

A second system, the Ryan Model 537 was also discussed. This system is similar to the one seen by University of Michigan personnel during their recent visit to the NADC facilities. It consists of a transmitting waveguide array which generates four beams simultaneously and three receiving antennas, each connected to a separate receiver. Thus the system does not require switching and collects data continuously. The gain of the antenna is approximately 27 db above an isotropic source. The receiving antenna consists of two parabolic torus antennas. (A parabolid torus is parabolic in one plane and circular in the orthogonal plane. It is discussed by Kelleher and Hibbs, 1953.) Through the use of such an antenna configuration, a number of antennas may be placed at the focus of the reflector. For the Ryan Model 537, one of the parabolic torus' has a single feed and the second employs two feeds located on the focal circle of the antenna. In this way three of the transmitting beams are interroguated by the receiving antenna, the fourth beam being generated to simplify the antenna design. Data, received by the receiving antenna is processed by the computer and the coordinate components of the velocity vector resolved.

Insofar as new systems are concerned, Ryan will continue to make improvements in the 533 system. They are giving consideration to modulation techniques that may be employed to effect rain rejection, near zone rejection and to provide altitude information about the aircraft. They are also considering techniques of simultaneous lobing to help minimize the effects of varying sea states.

III THEORETICAL STUDY

The radiation from a doppler radar transmission observed at a point in space may exhibit complicated temporal and spatial variations because the vehicle carrying the radar is moving, the orientation of the antenna beam is changing due to stabilization and the aircraft itself is maneuvering. In the investigation of the possibility of detection of the doppler signal, our preliminary investigation is focused on characterizing radiation reflected from a smooth, perfectly conducting ground. The theory is developed for a moving and maneuvering aircraft.

3.1 Radiation Pattern

From the radiation pattern measurement of the antenna, we represent the field due to the direct signal by the following expression,

$$E(\underline{r}, t) = \frac{p\left(t - \frac{\omega}{c} R\right)}{R} \, f'(\theta', \phi') \, e^{-i\omega t} \, e^{+i \frac{\omega}{c} R} \qquad (3.1)$$

where

ω = the carrier frequency

$\underline{r}$ = the coordinate of the observation point

R = distance between the transmitter and point of observation

$f'(\theta', \phi')$ = the field pattern of the radiation referred to a reference system fixed relative to the antenna

$p(t)$ = a function related to the power of the transmitter and the modulation of the transmitted signal, which is assumed to be a slowly varying function of t. [*]

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[*] The function $p(t)$ may be easily shown to be related to the gain of the antenna G, and the instantaneous transmitted power $P(t)$ by:

$$p(t) = \sqrt{60 \, G \, P(t)} \quad .$$

To a fixed observer the distance R is a function of time because the vehicle is moving. In addition, since it is maneuvering, the angles θ' and ϕ' must also be considered time dependent.

3.2 Coordinate System

To account for the time variation of the airplane's coordinate system, let us choose a system fixed with respect to normal, level flight as illustrated in Figure 3-1. The ground is chosen as the plane $z = 0$, the longitudinal axis of the airplane as x-axis and the transverse axis as the y-axis. Referred to as an arbitrary origin, the coordinate of the transmitter may be given by

$$x_a(t), \qquad y_a(t), \qquad z_a(t)$$

respectively. These coordinates are functions of time to account for the motion of the vehicle.

Actually, of course, the orientation of the airplane may not be along the $\hat{x}, \hat{y}, \hat{z}$ axis. We shall in general assume that the longitudinal, transverse and vertical axes of the airplane are along the direction $\hat{x}', \hat{y}', \hat{z}'$ respectively as indicated in Fig. 3-1. Mathematically, the directions $\hat{x}'$, $\hat{y}'$, $\hat{z}'$ may be related to the fixed directions $\hat{x}$, $\hat{y}$, and $\hat{z}$ through a rotation of axes. In terms of the Eulers angles (e.g. Goldstein, 1956) α, β, ψ, specifying the rotation, the directions along the primed and the unprimed axes may be related by;

$$\left.\begin{matrix}\hat{x}'\\ \hat{y}'\\ \hat{z}'\end{matrix}\right] = \left[\begin{bmatrix} \cos\alpha\cos\beta\cos\gamma-\sin\beta\sin\gamma & \cos\alpha\sin\beta\cos\gamma+\cos\beta\sin\gamma & -\sin\alpha\cos\gamma \\ -\cos\alpha\cos\beta\sin\gamma-\sin\beta\cos\gamma & -\cos\alpha\sin\beta\sin\gamma+\cos\beta\cos\gamma & \sin\alpha\sin\gamma \\ \sin\alpha\cos\beta & \sin\alpha\sin\beta & \cos\alpha \end{bmatrix} \begin{matrix}\hat{x}\\ \hat{y}\\ \hat{z}\end{matrix}\right] \tag{3.2}$$

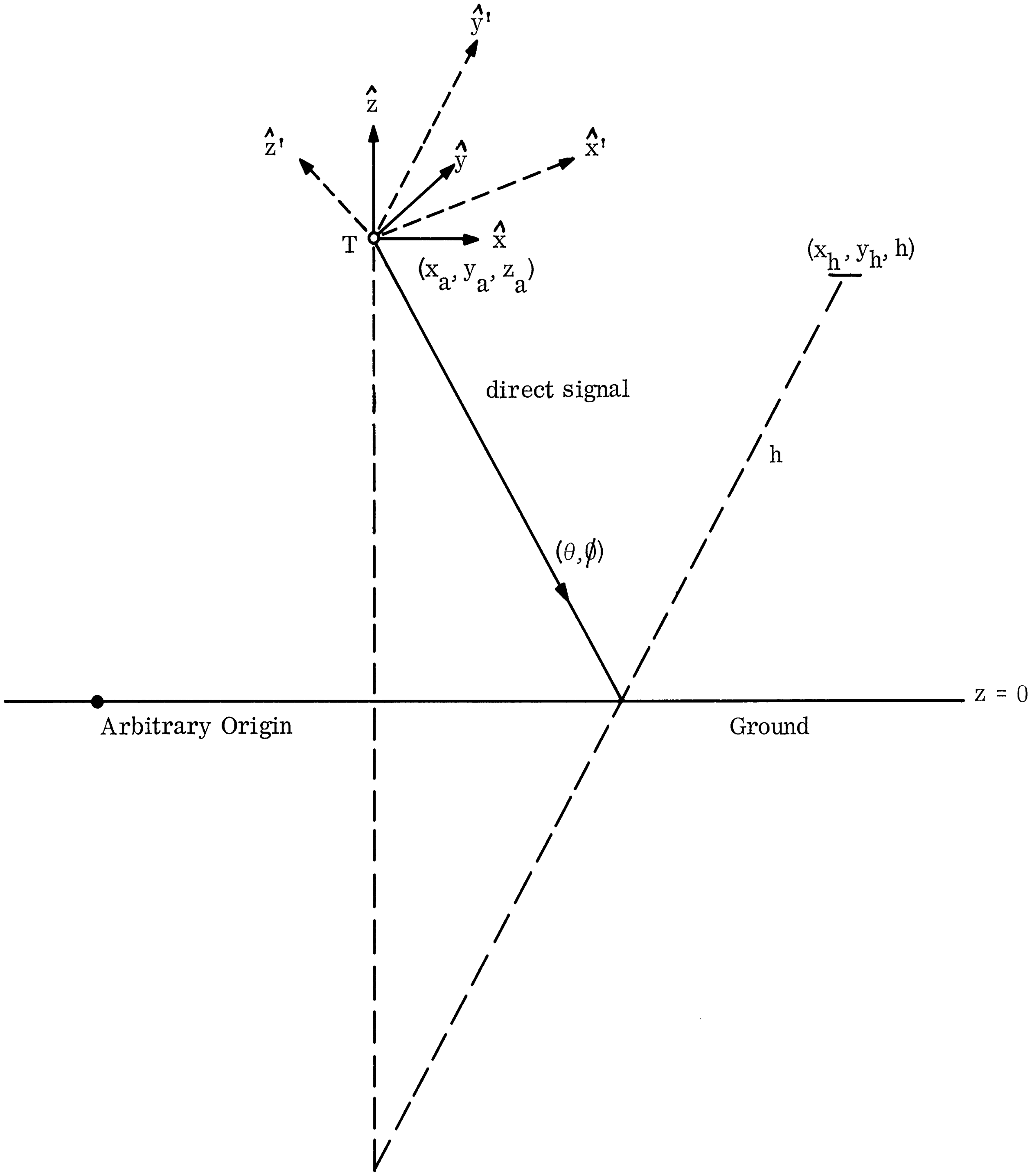

FIG. 3-1: COORDINATE SYSTEMS OF AIRPLANE WITH RESPECT TO AN ARBITRARY, FIXED REFERENCE SYSTEM.

Physically, we may show that if the airplane maneuvering consists of a rotation given a yaw angle δ_y, then a pitch angle δ_p and then a roll angle δ_r, the relation between α, β, γ and the angles δ_y, δ_p and δ_r by

$$\cos \alpha = \cos \delta_r \cos \delta_p \tag{3.3}$$

$$\sin \alpha = \sqrt{1 - \cos \delta_r^2 \cos^2 \delta_p} \tag{3.4}$$

$$\cos \beta = \frac{\cos \delta_r \sin \delta_p \cos \delta_y + \sin \delta_r \sin \delta_y}{\sqrt{1-\cos^2 \delta_r \cos^2 \delta_p}} \tag{3.5}$$

$$\sin\beta = \frac{\cos \delta_r \sin \delta_p \sin \delta_y - \sin\delta_r \cos\delta_y}{\sqrt{1-\cos^2 \delta_r \cos^2 \delta_p}} \tag{3.6}$$

$$\sin \gamma = \frac{\sin \delta_r \cos \delta_p}{\sqrt{1-\cos^2 \delta_r \cos^2 \delta_p}} \tag{3.7}$$

and

$$\cos \gamma = \frac{\sin \delta_p}{\sqrt{1-\cos^2 \delta_r \cos^2 \delta_p}} \quad . \tag{3.8}$$

Thus, the maneuvering of the aircraft may be represented by a matrix A relating the directions of the axes by,

$$\left.\begin{matrix} \hat{x}' \\ \hat{y}' \\ \hat{z}' \end{matrix}\right] = [A] \left.\begin{matrix} \hat{x} \\ \hat{y} \\ \hat{z} \end{matrix}\right] \quad . \tag{3.9}$$

For an unstabilized system, the antenna is fixed to the airplane, therefore, any direction represented by angle θ', ϕ' relative to the airplane may be represented by θ, ϕ relative to the fixed system through the transformation

$$\begin{bmatrix} \sin\theta'\cos\phi' \\ \sin\theta'\sin\phi' \\ \cos\theta' \end{bmatrix} = \left[A\right]^T \begin{bmatrix} \sin\theta\cos\phi \\ \sin\theta\sin\phi \\ \cos\theta \end{bmatrix} \tag{3.10}$$

where $\left[A\right]^T$ is the transpose of $\left[A\right]$.

For stabilized systems, the antenna is usually rotated so that the radiation from the forward and backward lobes have their return signals with the same doppler frequency shift. If the horizontal component of the aircraft velocity is inclined at an angle θ_V to the x-axis, then the direction of radiation with respect to the fixed system may be represented by making the following transformation.

$$\begin{bmatrix} \sin\theta\cos\phi \\ \sin\theta\sin\phi \\ \cos\theta \end{bmatrix} \rightarrow \begin{bmatrix} \cos\theta_V & -\sin\theta_V & 0 \\ \sin\theta_V & \cos\theta_V & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \sin\theta\cos\phi \\ \sin\theta\sin\phi \\ \cos\theta \end{bmatrix} \tag{3.11}$$

From the measured antenna pattern $f'(\theta', \phi')$, we may obtain numerically the actual direction of radiation by substituting θ', ϕ' for θ, ϕ. Denote

$$f'(\theta', \phi') \triangleq f(\theta, \phi \quad . \tag{3.12}$$

The distribution of direct radiation may be calculated from (3. 1) which is now written in the form:

$$E(\underline{r}, t) = \frac{p(t - \frac{\omega}{c} R)}{R} f(\theta, \phi)\, e^{-i\omega t}\, e^{-\frac{\omega}{c} R} \quad . \tag{3.13}$$

3. 3 The Ground and Reflected Signal.

Corresponding to each direction θ, ϕ, the direct signal would reach the ground at

$$x_o(\theta, \phi) = -z_a \tan\theta \cos\phi + x_a \tag{3.14}$$

$$y_o(\theta, \phi) = -z_a \tan\theta \sin\phi + y_a \tag{3.15}$$

and the electric field strength is given by

$$E_o(x_o, y_o) = \frac{p(t)}{-z_a \sec\theta} f(\theta,\phi) e^{-i\omega t} e^{-i\frac{\omega}{c} z_a \sec\theta} \quad . \tag{3.16}$$

For fixed x_o, z_o, ince z_a, z_a, y_a may be functions of t, we may evaluate from (3.14) and (3.15) θ and ϕ as a function of time. Equation (3.16) then yields the temporal variation of the field observed at any point on the ground.

If the ground is smooth, and perfectly conducting, a ray originated from the antenna in the direction (θ, ϕ) would be reflected by the ground and reaching a point (x_h, y_h, h) at height h. By simple geometry, we have

$$\left.\begin{aligned} x_a(\theta,\phi) &= -(z_a+h)\tan\theta\cos\phi + x_a \\ y_h(\theta,\phi) &= -(z_a+h)\tan\theta\sin\phi + y_a \end{aligned}\right\} \quad . \tag{3.17}$$

The reflected field observed at that point is, by geometric optics, given by

$$E_h(x_h, y_h) = \frac{p(t)}{-(z_a+h)\tan\theta} f(\theta,\phi) e^{-i\omega t} e^{-i\frac{\omega}{c}(z_a+h)\sec\theta} \quad . \tag{3.18}$$

Again for a fixed point (x_h, y_h, h), due to the motion of the aircraft, θ, ϕ are functions of time, so that (3.18) yields the temporal variation of the field at a height h .

We intend to choose several typical cases, and using the digitalized form of the measured radiation pattern, make numerical calculations to display the essential features of the spatial and temporal variations of the field strength. A scheme for obtaining and presenting the numerical computations will receive much attention during the next research period. Modification of the scheme for diffuse ground reflection and other meteorological effects will also be considered.

IV TRIPS AND CONFERENCES

The following personnel, C-M Chu, R. E. Hiatt, J. E. Ferris and D. L. Sengupta of The University of Michigan Radiation Laboratory visited the Naval Air Development Center facilities on 18 and 19 July 1967 to discuss the status of the contract with Mr. E. Rickner, Mr. Miles Greenland and Dr. Trawick. It was suggested at that meeting that The University of Michigan Radiation Laboratory make arrangements to visit two or three manufacturers of doppler systems.

Mr. Joseph E. Ferris of the Radiation Laboratory visited GPL (General Precision Laboratory) at Pleasantville New York on 12 September 1067 and discussed with Mr. John Rolfs of the Antenna Department, and Mr. Donald Hough, the doppler systems being developed and fabricated by their organization. Mr. Ferris also visited the Ryan Aeronautical Corporation in San Diego, California on 20 September 1967, and while there he met with the following personnel. Mr. Ray Fredsti, Tom Lund, Galin Mitchell, Phil Parker, Ron Naylor and Jim Farrar . Discussion concerned the doppler systems presently being designed and fabricated by Ryan.

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