NRL REPORT 4051

THE AN/APN-67 AUTOMATIC NAVIGATOR

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CONTENTS

ABSTRACT

An active research and development program has been pursued at NRL resulting in the realization of an automatic navigator, the AN/APN-67. This is an X-band doppler radar system which will indicate true ground speed and drift of an aircraft, and which may be tied into the autopilot for completely automatic navigation.

The NRL system automatically gives latitude and longitude to an accuracy of one percent in position. The present equipment has an operating altitude of 20,000 feet, and means are at hand for increasing this limit to over 50,000 feet. A contract has been given to Ryan Aeronautical Company by BuAer for building ten similar systems which will be used in evaluation work. The weight of the present equipment is about 200 pounds. An additional contract is being processed by BuAer for two additional miniaturized versions which should weigh about 150 pounds.

PROBLEM STATUS

This is an interim report; work on this problem is continuing.

AUTHORIZATION

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THE AN/APN-67 AUTOMATIC NAVIGATOR

INTRODUCTION

Of all the many factors which are important in the efficient use of aircraft, navigation in its various forms is probably the most basic. Whether the task be the final few minutes in a bombing run, reconnoitering a hostile area, or attempting to reach a distant point on the earth, the primary problem is that of knowing the present position of the airplane and knowing its velocity vector with respect to the ground. Many devices have been designed to solve a part of this problem, but no single device available today can accomplish the entire job satisfactorily. For example, to obtain a solution, a navigator today must use a combination of star fixes, loran fixes, visual fixes, indicated air speed, drift-sight information, and such wind knowledge as he may have available. A part of this information is inaccurate or unobtainable, and part depends on visibility.

A device which could accomplish the complete task has been sought for many years. Since this device, if successful, will be installed in large numbers, it is important to point the design toward an equipment which will be light, compact, reliable in operation, and inexpensive to build.

On 15 June 1933 a problem was established at the Naval Research Laboratory for the development of radio navigational devices; particular emphasis was placed on a ground-speed and drift indicator. Supporting correspondence recommended that a doppler-effect device be used as the ground-speed indicator. Early work on ten-centimeter wavelength used split-anode magnetrons made at the Naval Research Laboratory as transmitters. The equipment was mounted in a searchlight whose reflector had been replaced by a parabolic antenna and was used to track ships traveling up and down the Potomac River. The great bulk and weight of this equipment coupled with its lack of sensitivity precluded its trial in aircraft. This early effort demonstrated the feasibility of the device. It also clearly indicated the necessity for improving the r-f components with the end in view of greatly reducing their size and weight, of reducing the size and weight of the associated power supplies and control devices, and most important of increasing the sensitivity of the device by greatly reducing the inherent noise modulation in the magnetron and by improving the sensitivity of the receiver.

In the course of this program, ten-centimeter klystrons, ten-centimeter triode oscillators, low power three-centimeter klystrons, three-centimeter magnetron oscillators, and finally, higher powered three-centimeter klystrons were successively tried. The three-centimeter klystron is the one presently used. It is characterized by extreme stability of operation and extremely low noise sidebands. In the meantime, the design of point-contact crystal detectors used as the first detector in microwave radio receivers was greatly improved as a consequence of their use in radar receivers during World War II. The system to be described here uses a type X-23 X-band cw klystron and a zero i-f frequency superheterodyne receiver. The transmitter and receiver are connected to a common antenna through a bridge or duplexing network. The operation of the system requires the radiation of two beams so that, in fact, two antennas are used. Each antenna radiates half the power generated by the klystron and each is connected to its own receiver.

During the course of the development program, the objective has always been to obtain a device which will operate satisfactorily over the ocean. Measurements made concurrently with this development have shown that the relationship between the signal reflected by the surface of the sea and the signal returned by land is such that any device which will operate reliably over water should in almost all cases return a more-than-adequate signal over land.

Comparisons between the ultimate sensitivity of a cw radar system and a pulsed radar system have been made, and in general the two types of radar will have approximately the same system sensitivity provided the average radiated power is the same. Such a comparison is predicated on optimum design of the receiver, in particular upon the bandwidth used.

The AN/APN-67 as it is now constituted measures the ground speed of an airplane by use of the doppler principle. An X-band cw radar radiates simultaneously through two antennas producing a pair of beams (referred to as a "V-beam") directed aft and downward from the airplane. The return signals on the two beams are separately received and mixed with a portion of the transmitted signal to derive two doppler notes, one associated with the right-hand beam and the other with the left-hand beam. It is clear that if the aircraft is in straight and level flight with no drift the two doppler notes will be of the same frequency. However, if the plane drifts or has a velocity component at right angles to its longitudinal axis, then the frequency from one beam will differ from that of the other. A solution based on the sum and difference of the two frequencies yields the true ground-track velocity and the drift angle.

GENERAL DESCRIPTION

The Ground Position Indicator and Automatic Navigator AN/APN-67 is a self-contained electronic device proposed to accomplish automatically the dead reckoning necessary to navigate an aircraft, and the instrument continuously indicates position, true ground-track velocity, and heading; it may be tied in to the autopilot to make good a desired course automatically.

The ground speed is obtained by measuring the doppler frequency shift from two signals which have been reflected from the surface of the earth. The AN/APN-67 uses cw transmission. Pulse or cw transmission may be used, but cw was chosen for the AN/APN-67 because of the extreme simplicity of the r-f circuits and the consequent reduction in weight and maintenance.

Ground speed and drift are measured by using two antennas and receivers, one antenna being mounted on each side of the aircraft (Figure 1). These antennas are rigidly fixed to the aircraft so that the beams are pointed diagonally downward to the right and left, making an angle of 20^0 with the plane which is perpendicular to the longitudinal axis of the aircraft and 20^0 with the plane which contains the longitudinal axis of the aircraft and is perpendicular to the lateral axis. This configuration gives an angle of 28^0 between an antenna beam and the vertical axis of the aircraft. The doppler frequencies from the two receivers will be different in the presence of drift so a computer receiving the right- and left-hand signals may be made to yield true ground-track velocity and drift. This information is then fed to a latitude-longitude computer for resolution into latitude and longitude indications and to the autopilot for navigating the aircraft. Information from a stable element (vertical gyro) is used to correct the data supplied the computer, thereby eliminating the need for stabilized antenna platforms.

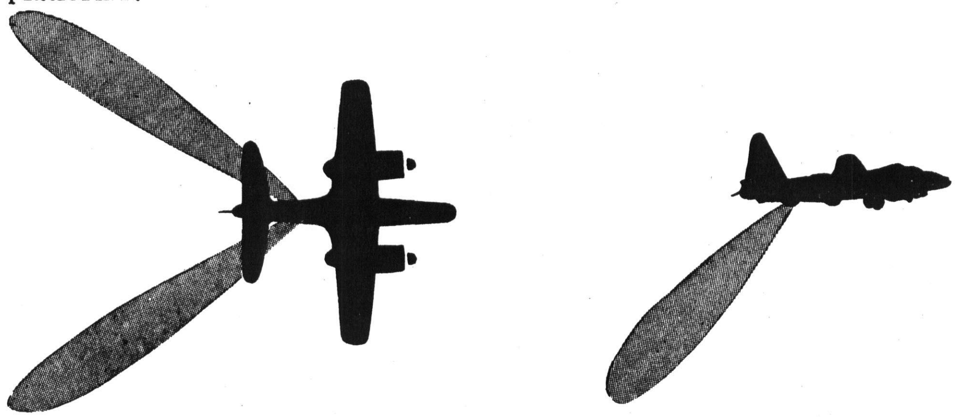

Figure 1 - Manner in which antenna beams are directed with respect to the aircraft

The AN/APN-67 (Figure 2) consists of a radar system, right- and left-hand antennas, a ground-speed and drift computer, a vertical reference system, a G-2 compass system, and the necessary power supplies.

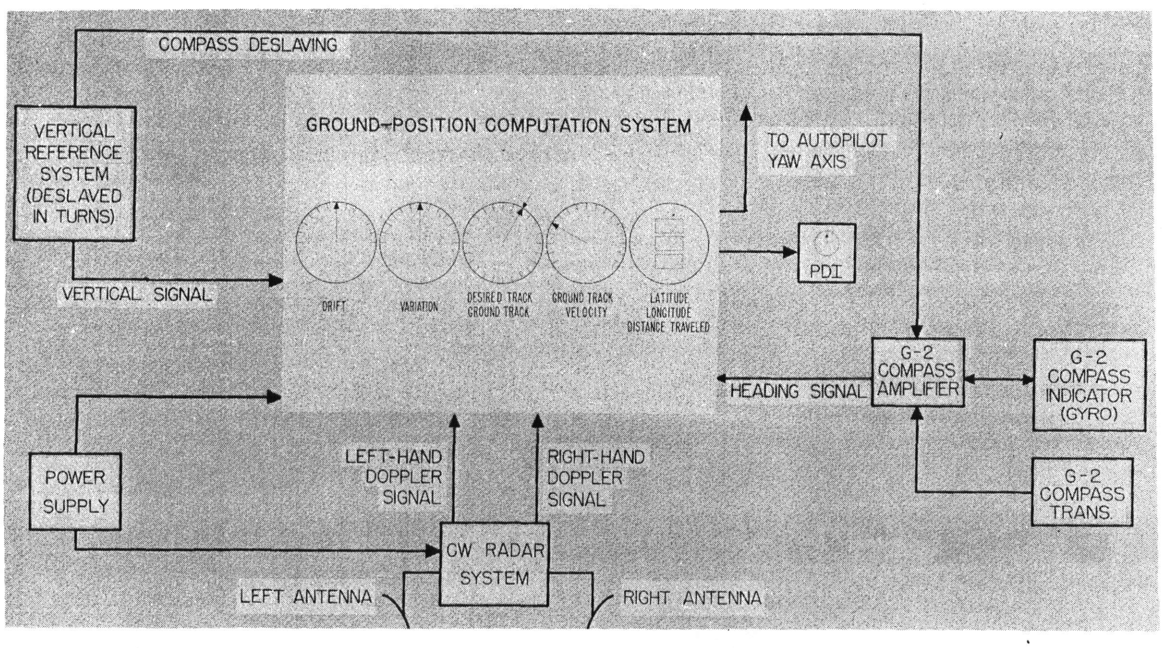

Figure 2 - Block diagram of the equipment

The transmitter is a cw oscillator operating at X-band. The noise sidebands are held to a very low value by means of voltage-stabilization circuits in the power supply and by the inherent mechanical and electrical stability of the tube itself. The transmitter power is between 5 and 10 watts.

The transmitter feeds two hybrid ring duplexers designed for high rigidity and low microphonic vibration. Connected to the duplexers are the antennas and the receiver mixer. The outputs of the right- and left-hand mixers are amplified by AGC audio amplifiers with a bandwidth extending from about 400 to 6,000 cycles. The outputs of these amplifiers are audio signals, the frequencies of which are directly proportional to the components of ground speed resolved on the axis of the antenna beams. In level flight with no drift, the right and left frequencies are the same, but with drift they will be different. The two frequencies are fed to a computer which resolves them into a shaft rotation proportional to ground-track velocity and into a shaft position corresponding to drift angle. These two quantities, ground speed and drift angle, are presented on dials. For manual flight, two other dials are incorporated. One is the desired-track dial, which is set on the desired course by the navigator, and the other is the Pilot Direction Indicator (PDI) dial, which will indicate deviation from the desired course to the pilot. Through a system of differentials and synchros, these two dials are connected to a follow-up on the directional gyro (G-2) compass and to the drift-angle shaft so that the PDI dial will be on zero only when drift has been compensated.

The ground-velocity shaft turns at the rate of 24 revolutions per nautical mile and is connected to the mechanical input of the latitude-longitude computer. The directional gyro signal is followed up in the ground-speed and drift computer and is then modified by a differential-gear system connected to the shaft so that the latitude-longitude computer will properly resolve the ground-velocity vector into latitude and longitude components in the presence of drift.

For automatic flight, this corrected-heading signal is also used for yaw-axis control of the autopilot so that the plane will fly along a desired course rather than merely point in a desired direction. The directional element is a G-2 compass consisting of a magnetically slaved gyro. Roll-and-pitch signals from a Kearfott vertical gyro are used to correct the data supplied the ground-speed computer. This vertical is accurate within six minutes of arc when integrated over a long period of time. The effect of inaccuracy in this device on system errors is discussed in connection with the ground-speed computer.

The accuracy of the over-all system is between one and two percent of range from the last fix.

The antennas are 24-inch parabolas fabricated in sealed units similar to sealed-beam head lamps and are faired into the belly of the plane. They are rigidly mounted to the aircraft. It should be possible to install future models in fighter and reconnaissance aircraft as well as larger planes.

The weight of the present experimental equipment is approximately 207 pounds. Means are at hand for reducing this weight to about 150 pounds in future models. These figures include the weight of the vertical and heading reference units.

Figure 3 shows the complete system, exclusive of the antennas. From left to right in the back row are the following units: ground-position computer, ground-position-computer amplifier unit, vertical reference unit, and complete power supply. In the front row are the altitude transmitter, PDI, G-2 compass transmitter, G-2 compass master indicator, and G-2 compass amplifier. Figure 4 is a view of the antennas as installed in a P2V-2 aircraft.

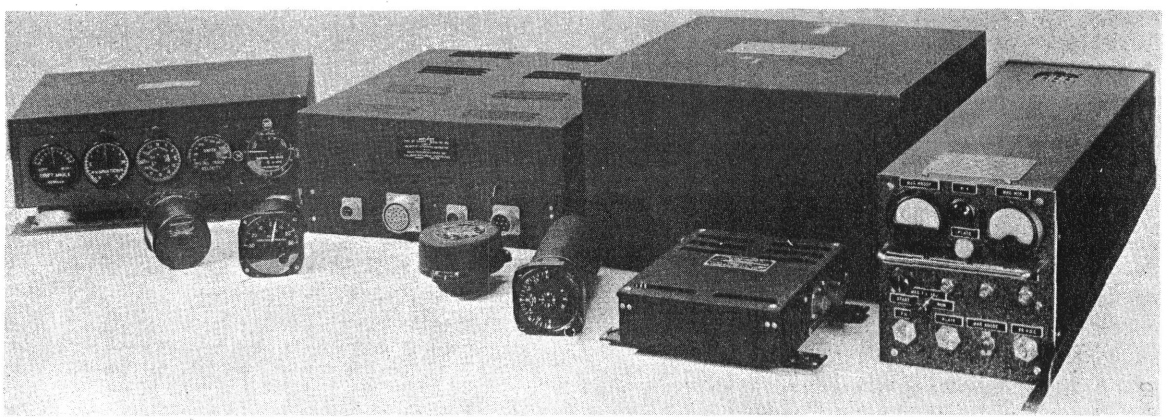

Figure 3 - System components exclusive of antennas

The mounting position is just forward of the tail assembly. Figure 5 is a close-up view of the antenna mounting. Figure 6 is a photograph of one of the sealed-beam antennas removed from the aircraft. Figure 7 shows the plumbing and AGC amplifiers, and Figure 8 is a view of the computation system as installed in the aircraft.

Figure 4 - P2V-2 tail section showing antennas mounted below the word Navy

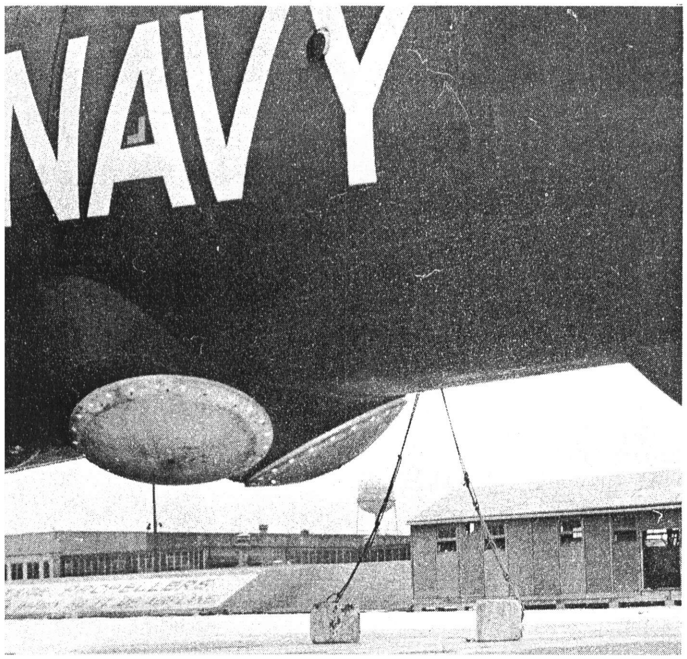

Figure 5 - Close-up view of antennas mounted on P2V-2

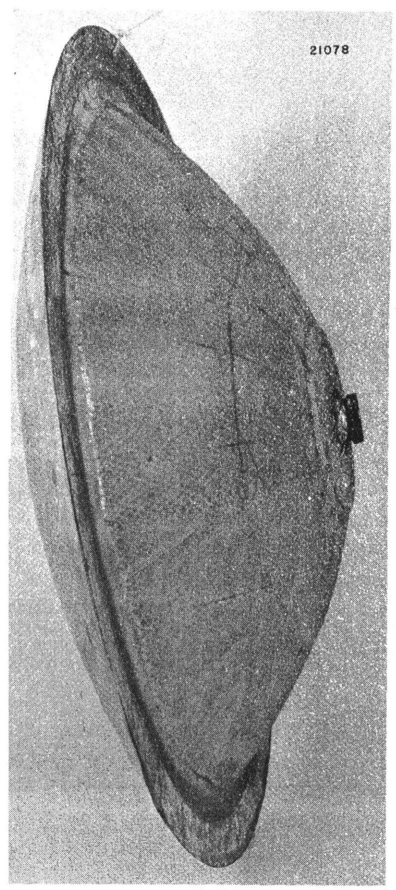

Figure 6 - One of the antennas removed from the aircraft

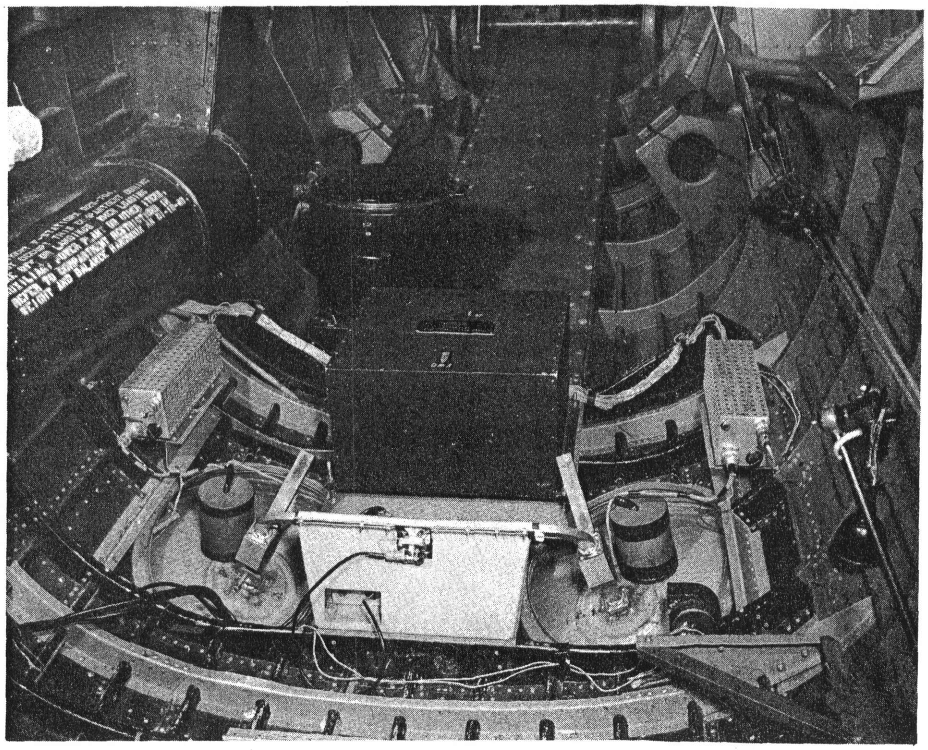

Figure 7 - Interior view of aircraft showing R-F components, AGC amplifiers, and vertical reference unit

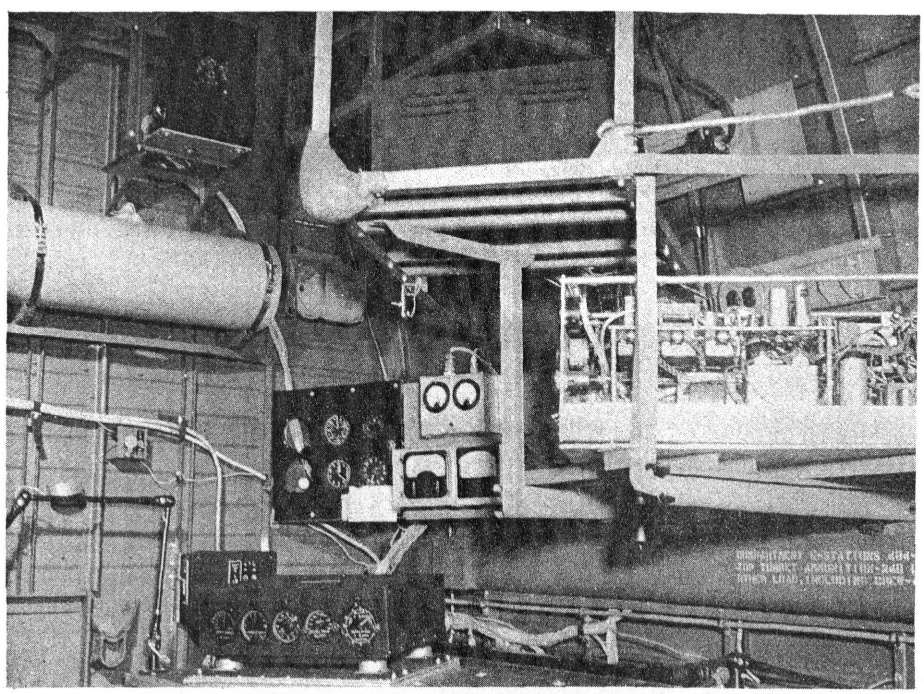

Figure 8 - Interior view of aircraft showing computation system

Since the navigation system which has been flight-tested performed quite well, it is of interest to enumerate the salient aspects of such systems so that they may be compared with other means of navigation. An analysis of performance reveals the following facts:

(a) The theoretical expected accuracy with maximum development is such as to give position error of less than one percent of the distance traveled.

(b) If fixes are available along course, accuracy becomes one percent of the range from the last fix.

(c) The range is unlimited since the system does not depend on ground transmitting stations.

(d) Interpretation of information is unnecessary since ground speed, drift angle, distance, and position are indicated on meters or dials.

(e) Since propagation is line-of-sight at X-band, no propagation errors are anticipated, except possibly during extremely heavy rains.

(f) Immediate indications of failure are available, if desired.

(g) Maximum operating altitude expected is in excess of 100,000 feet with current development. Maximum predicted altitude of present experimental equipment when speed gates are employed is 20,000 feet.

The advantages and disadvantages of this type of navigation system are enumerated below:

Advantages

(a) Accuracy is expected to be one percent of the range from the last fix.

(b) No ground stations are required.

(c) The system is difficult to jam since the entire signal path is confined to a small solid angle and the receiver has a narrow bandpass.

(d) The weight, estimated as less than 150 pounds with maximum development, is low for the job done. The size exclusive of antennas (which will be faired into skin of plane) is estimated at two cubic feet.

(e) R-F circuits are extremely simple and fixed-tuned, thereby requiring a minimum of maintenance.

(f) The weight and size of this unit should permit installation of future models in craft as small as fighter and reconnaissance aircraft.

Disadvantages

(a) Accuracy is a function of range.

(b) Evasive tactics which cause plane to deviate more than 15^0 to 20^0 from normal flight attitudes render equipment temporarily inoperative. Such action, however, does not alter past or future information.

(c) Depending on the speed of the aircraft and the state of the sea, a residual error due to water motion will exist in the computed position of the aircraft.

RADAR SYSTEM

Continuous-wave radar systems may be classed according to their method of duplexing or isolating the transmitter power from the receiving crystal. The two types that have been investigated at NRL are the so-called "space-duplexed" and the "ring-duplexed" systems. The first system uses separate transmitting and receiving antennas, while the second employs a common antenna and a ring-type hybrid junction to provide sufficient isolation between the transmitter and receiver. As an alternative to these two duplexing systems, circular polarization may be employed in a third-type system which is now being investigated.

The sensitivity of a cw radar system may be obtained by determining the equivalent noise-power input of the actual receiver and multiplying this by the required signal-to-noise ratio; this procedure gives the minimum usable signal at the receiver input. The path attenuation which reduces the transmitter power to this level corresponds to a maximum operating altitude.

The noise power at the input terminals of an ideal receiver is given by

$$P_n = KT\Delta f \quad (1)$$

where K = Boltzmann's constant = 1.38×10^{-23},

T = the temperature in degrees Kelvin, and

Δf = the bandwidth in cycles per second.

For the type of system described in this discussion, T is assumed to be 300 and Δf is taken as 5000.

Then $P_n = 2.17 \times 10^{-17}$ watts.

The actual noise factor of the receiver, F, and the desired signal-to-noise ratio, S/N, must be considered in determining the minimum usable power, P_m, at the receiver input terminals;

so $$P_m = (KT\Delta f)\cdot(F)\cdot(S/N). \quad (2)$$

If this type of radar were located above a perfect plane reflector and pointed vertically down, there would be a loss in received power due to the finite beamwidth of the transmitting antenna and the finite capture area of the receiving antenna.

This loss may be calculated as follows

$$\frac{\text{Transmitter power}}{\text{Received power}} = \frac{64R^2}{nGD^2} \quad (3)$$

where R = range or distance to reflector,

n = illumination factor of the receiving antenna,

G = gain of transmitting antenna over an isotropic radiator, and

D = diameter of the receiving antenna.

In addition, there is a loss due to the reflectivity of the sea (Figure 9) which will be of the order of -53 db or 5×10^{-6} in power under an average condition when the beam angle is 28^0. Dividing the transmitted power into two beams accounts for a three-db loss in transmitter power. Duplexer loss must also be considered if there is to be a duplexer in the system under consideration.

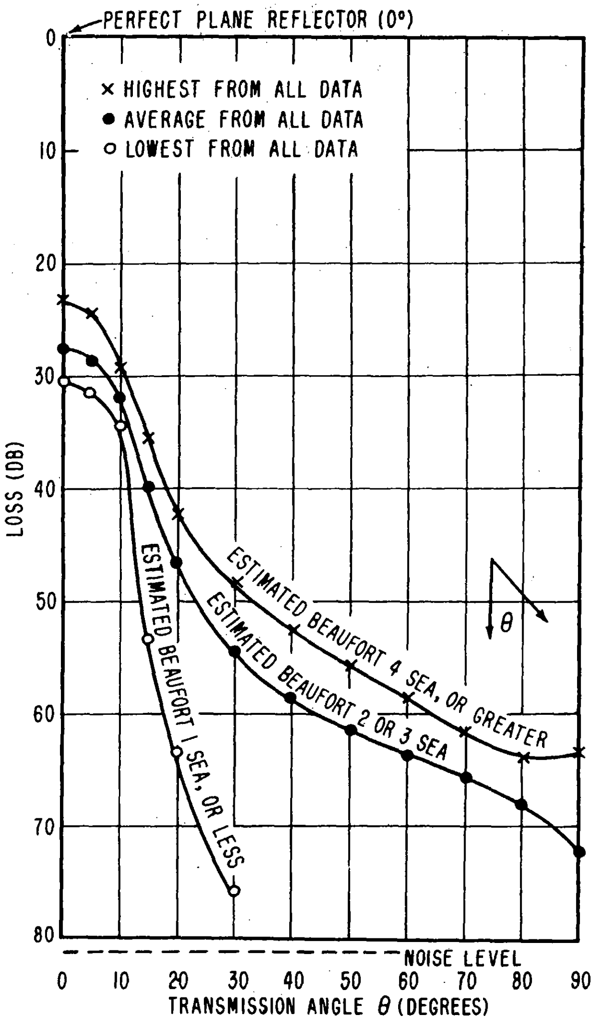

Figure 9 - Reflection loss vs. transmission angle

Solving for range in Equation (3) gives

$$R^2 = \frac{P_t \, n \, G \, D^2 \, L_r \, L_s}{64 \, P_m} \qquad (4)$$

where P_t = transmitter power,

n = illumination factor of antenna (0.65),

G = gain of transmitting antenna over an isotropic radiator,

D = diameter of receiving antenna,

L_r = loss due to reflectivity of the sea,

L_s = loss inherent in system, and

P_m = minimum usable power.

The numerical value of P_m may be obtained by using Equation (2). Experience has shown that noise figures (F) of 30 db or 1×10^3 for the space-duplexed system and 51 db or 1.3×10^5 for the ring-duplexed system are typical. A signal-to-noise ratio (S/N) of 12 db or 15.8 is used in the calculations. Thus, for the space-duplexed system, from Equation (2)

$$P_m = 3.47 \times 10^{-13} \text{ watts.}$$

The values of the other factors in the expres sion for range (Equation 4) are

P_t = 10 watts,

n = 0.65,

G = 3400,

D = 2 feet,

L_r = -53 db = 5×10^{-6}, and

L_s = -3 db = 0.5.

Substituting these values in Equation (4),

$$R = 100{,}000 \text{ feet.}$$

This is the slant range. The altitude in this case would be about 94,000 feet.

For the ring-duplexed case, the noise factor given is 51 db or 1.3×10^5, and

$$P_m = 4.46 \times 10^{-11}.$$

In the range equation, L_s becomes -9 db or 0.126, and

$$R = 4{,}480 \text{ feet.}$$

The altitude for this case would be about 4,200 feet.

The values used in determining the maximum altitudes in this discussion have been obtained by a research program at the Laboratory over a period of years. They have been determined by both bench and field tests.

It should be emphasized that the computed altitudes correspond to over-water operation with an average sea state. The calculation of the maximum operating altitude of the system using the worst reflection-loss curve of Figure 9 gives values that are 0.1 of those given in the preceding discussion. The reflection loss used in this calculation is 73 db. References to the "Atlas of Climatic Charts of the Oceans," U. S. Weather Bureau, shows that a dead calm corresponding to the worst condition rarely occurs, and when it does, it is in selected areas of the ocean, principally near the equator.

Since the mechanism of reflection for microwave radiation is the same as that for light, it is apparent that a surface must have irregularities; that is, facets and edges set at the proper angle to obtain other than specular reflection, and in particular, to return energy to a receiver located near the transmitter. The strength of the signal received will depend upon the fraction of the total area which is momentarily set at a favorable angle, the distance to the surface, and its reflectivity. Thus, although water is a better reflector than most types of land, the surface may be so smooth that only a small fraction of it will be at a favorable angle, and consequently only a weak signal will be received. Measurements on the reflectivity versus angle of incidence have been made by several groups, and the results are in good agreement considering the wide range of sea states encountered.

The results of the NRL measurements made from the Golden Gate Bridge in San Francisco Bay (1) are given in Figure 9. Compared with the return from a smooth metallic sheet, these data show a 25-db loss by scattering at vertical (normal) incidence. Considerably greater loss is incurred as the angle of incidence departs from normal. These measurements were made with a 3^0 beamwidth for both transmitting and receiving antennas and vertical polarization.

The amplitude of the doppler shift that occurs upon reflection is proportional to the sine of the angle between the beam and the vertical (beam angle). The accuracy of the doppler-shift measurement and therefore the accuracy of the velocity indication increases as the beam angle increases. The allowable aircraft attitudes in both pitch and roll are set by the beam angle. All these factors lead to a large required beam angle. However, the magnitude of the return signal and therefore the maximum altitude is proportional to the cosine of the beam angle. These factors require a compromise, and it has been found experimentally that about 20^0 is a good choice in both the lateral and longitudinal directions.

The accuracy of a doppler ground-velocity indicator system is affected by the motion of the water. Three effects must be considered, the first of which is the motion of the entire body of water resulting from ocean currents. As a consequence, a direct error is present in the indicated velocity, but since the velocity of such currents is ordinarily only one or two knots it is not serious. The other two considerations are the effects of the gravity-wave velocity and the velocity of the ripples or capillary waves. Theoretical (2) and experimental investigations (5, 10) has shown that the doppler frequency does not depend on the velocity of the gravity waves, which move at near wind-speed, but rather on the velocity of the capillary waves, which usually move at less than ten percent of wind-speed. Thus, the error introduced by wave motion, while significant, will not necessarily be serious.

Frequency modulation on the transmitted carrier is quite important in a system of this kind since it appears as frequency modulation on the doppler note. The amount of FM on the doppler note is a function of the transmitter's rate of frequency change and of the altitude or path length of the transmission. The maximum amount of FM which may be present on the doppler note without changing its mean frequency is that deviation which is equal to the doppler frequency. In practice, the tolerable amount is lower because of the circuits which measure the mean frequency. The Naval Research Laboratory has constructed a test set which will draw a continuous plot of frequency deviation versus modulation frequency. Using this test set, it is possible to evaluate a particular transmitter for microphonic FM prior to making flight tests. Presently available developmental tubes indicate operation to maximum altitudes in excess of 100,000 feet.

The amplitude-modulation carrier-to-noise ratio is about 90 db. This loss coupled with a local oscillator isolation of -45 db gives a total sideband power of 135 db below 10 watts or 3.2×10^{-12} watts due to local oscillator energy. In the space-duplexed system, this noise level can be reduced by about 10 db with the use of a balanced mixer.

The crystal detectors available for use in the system show a continuous rise in crystal noise power as the frequency of measurement approaches zero. The crystal noise power at the intermediate frequency (300 - 5000 cycles per second) is of the order of 5×10^{-14} watts. The contributions of these sources of noise determine the noise figure and establish the limit on maximum altitude.

In the ring-duplexed system, the contributions to this noise may be divided into two parts. The noise figure of these receivers under static conditions is 41 db. The vibrations inherent in the airplane installation give a noise-figure rise of about 10 db. A series of tests on the noise rise during flight resulted in the conclusion that the majority of the rise is attributable to the antennas used. An evaluation of the contributions of the various components was impractical since this would have required a long antenna-development program. The major portion of the noise rise occurs in the 300 - 1200 cycles-per-second band of frequencies. An analysis of the air-frame vibrations present showed that both amplitude and frequency were a complicated function of such things as air speed, altitude of flight, motor speed, and the smoothness of the air.

The noise in the audio amplifiers is about 1×10^{-15} watts, which is well below that attributed to other causes.

For the preceding figures to hold, it is necessary for the radar system to be mounted in such a way that the high-frequency vibrations are minimized. This was accomplished by the use of rubber insulating strips at all mounting points. Also, the antennas are of all-welded construction to give strength and to secure perfect electrical contact.

The radar system used in the flight tests, later described, consists of four main parts: a transmitting oscillator, a ring duplexer, a first detector, and an audio amplifier. Taken together, they comprise a cw transmitter and a zero i-f superheterodyne receiver connected to a common antenna. Although the ring-duplexed system is not considered the best method for cw radar investigation, it was used as an expedient in the flight tests and to further research on the duplexers themselves.

The transmitting oscillator is an X-23 klystron manufactured by Varian Associates. Recent developments in klystrons make them more desirable than the cw magnetrons that were used in the early development. The power output with the present tube is about 10 watts, and the AM noise sidebands are down about 90 db. Because of the rigid mechanical design and the use of a good voltage-regulated power supply,the FM noise is quite low. The klystron heater is operated on dc to reduce noise still further. A cathode warm-up time of about one minute is required before applying the anode voltage.

The waveguide system (Figure 10) consists of a power divider, two hybrid ring duplexers with their loads and detectors, and two antennas. Energy from the transmitter enters the duplexers by way of the power divider. In the duplexer, it divides equally between the matched load and the antenna. With perfect mechanical symmetry in the duplexer and with a perfectly matched load and antenna, the isolation between the transmitter and receiver would be infinite. In practice, the VSWR of the antenna and load may be held to about 1.04 over the ± 1-percent frequency band used. In addition, the mechanical symmetry of the duplexers is not perfect so that the coupling between transmitter and receiver is about -45 db. This amount of leakage is of the proper order of magnitude to furnish the required local oscillator signal in the detector. Final adjustment of the amplitude is made by a tuning screw in the antenna arm of the duplexer.

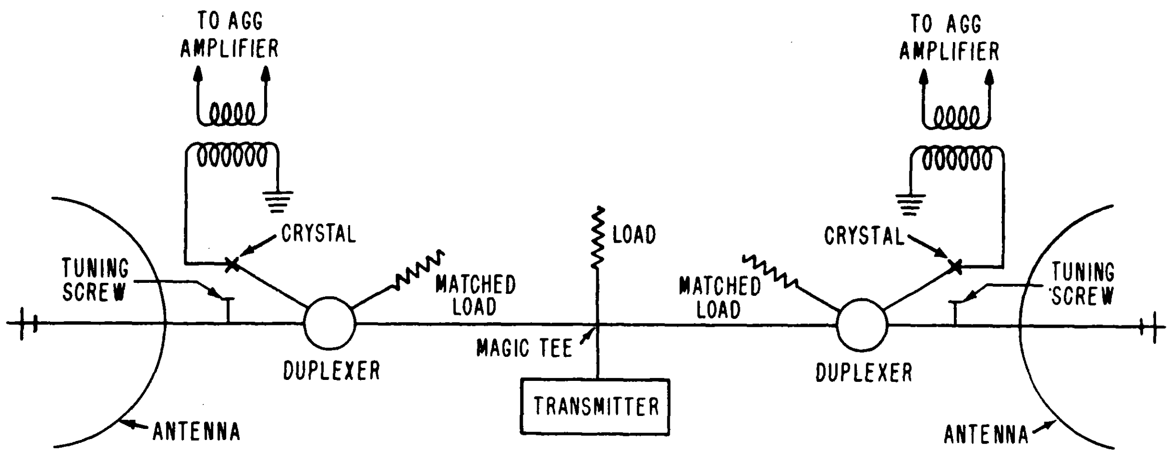

Figure 10 - Schematic of radar system

The signal received from the ground enters the duplexer from the antenna. The field configuration in the duplexer is such that this signal divides equally between the transmitter arm and the detector arm. This three-db loss plus a similar loss on transmission accounts for the six-db duplexer loss. The use of this type duplexer permits the use of a common antenna for simultaneous transmission and reception.

The antennas employed in the system were designed at NRL and constructed at NADC, Johnsville, Pennsylvania. A standard aluminum parabolic reflector is used in conjunction with a double-dipole feed. A vertex plate is employed to obtain the lowest possible VSWR with an antenna of this design. The radome and reflector are rididly joined, and the whole unit is covered with a spun-glass honeycomb to reduce microphonics. The angular deviations of the electrical axes from the mechanical axes of the antennas were measured to an accuracy of ± 0.1 degree. The electrical axes were defined by the ray midway between the half-power points of the antenna beam. The deviation or "squint" angle was obtained by measuring the angular change in the electrical axis with respect to the mechanical axis as the antenna was rotated through an angle of 180 degrees about the mechanical axis. These measurements were made in the four planes containing the mechanical axis of the antenna and making angles of 45 degrees with each other. The calculation of the squint angle obtained in the two sets of planes 90 degrees apart provided a good check on the accuracy of the measurements. A circular shim was used to make the mechanical axis of the antenna coincide with the electrical axis.

The duplexer matched load is made of carbon-filled bakelite surrounded by an electroformed guide.

The detector, a 1N23B crystal in a suitable broadband mount, is connected to the AGC amplifier by an isolation transformer. These amplifiers have a bandpass of from 300 to 5000 cycles per second. Their output is kept approximately constant by a gain-adjusting circuit having a time constant of about 0.1 second. The AGC circuit adjusts the amplifier gain to compensate for changes in amplitude of the doppler signal with changes in terrain and altitude.

Great care must be taken in the waveguide joints, and it was necessary to employ special fingered inserts in all joints to prevent noise and to ensure a low standing-wave ratio. In making a joint, standard flanges are brazed to the waveguides and lapped to a flat surface. Locating holes are then jig-drilled to receive pins which align the two guides. The insert (Figure 11) is placed over the locating pins and the two flanges are bolted together. The VSWR of this type of joint is about 1.002.

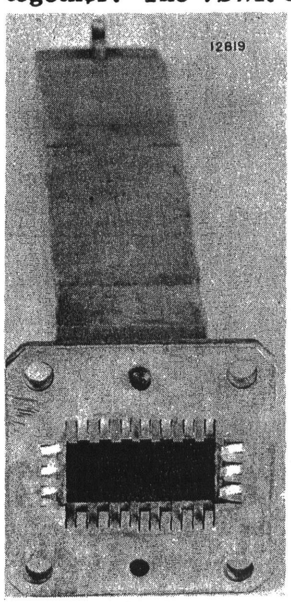

Figure 11 - Fingered washer in place on waveguide flange as used at all wavelength joints

COMPUTATION SYSTEM

Basic Considerations

The AN/APN-67 measures the ground speed of an airplane by use of the doppler principle. In this principle it is stated that a wave from a moving source received at a fixed point will have a frequency which differs from the transmitted frequency by an amount proportional to the radial velocity of the source relative to the receiver. The same principle holds if the transmitter is stationary and the receiver is moving. If transmitter and receiver are fixed together and are moving relative to a reflector, the difference between transmitted and received frequencies will be twice that which would be observed if only one were moving. The principle may be expressed mathematically by

$$\Delta f = \frac{2V}{c} f_0 \qquad (5)$$

where Δf = frequency difference between transmitted and received signals,

V = radial velocity of the transmitter and receiver relative to reflector,

c = velocity of light, and

f_0 = transmitter frequency.

If a cw radio transmitter and receiver were mounted together in an airplane and arranged to transmit and receive energy in a narrow beam pointed directly behind the airplane, the velocity of the aircraft relative to any stationary reflector in the beam could be determined from the preceding expression by measuring Δf (Figure 12a).

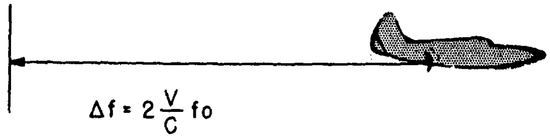

Figure 12a - Situation with target directly behind aircraft

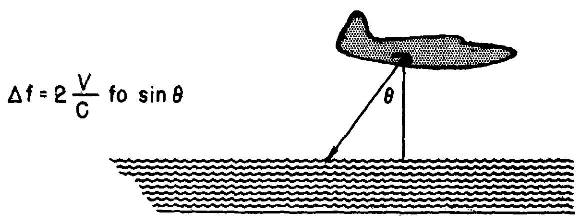

Figure 12b - Situation when target is at an angle other than 90° with respect to the vertical

In practice, of course, the antenna beam must be directed at the earth, at some angle θ from the vertical (Figure 12b). In this case,

$$\Delta f = 2\frac{V}{c}f_o \sin\theta. \qquad (6)$$

As long as the aircraft flies straight and level (i.e., θ constant) with no drift, measurement of Δf gives an accurate measure of the ground speed.

In the presence of drift the situation is changed. Now Δf is no longer proportional to ground speed (or ground-track velocity) but is proportional only to that component of ground speed which lies in the direction of the aircraft heading. Advantage can be taken of this fact to measure both ground-track velocity and drift angle. If the transmitting-receiving antenna were fixed to a rotatable mount, it could be turned until the received frequency equaled the transmitter frequency ($\Delta f = 0$). In this position it would be pointed at right angles to the ground track of the airplane, and the angular difference between the aircraft heading and this ground track would be the drift angle. (In practice, Δf will never be zero because of the finite antenna beamwidth. The direction at which Δf becomes a minimum will be at right angles to the ground track.) Figure 13 illustrates this operation. Here V_H and V_G represent heading and ground-track velocities, respectively, and δ is the drift angle.

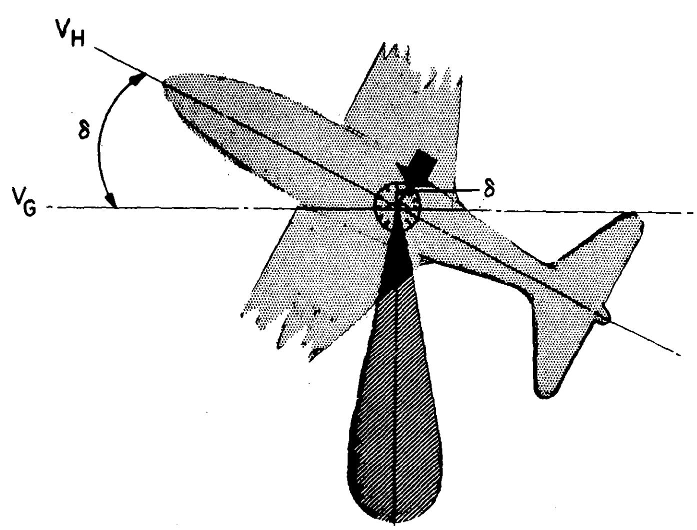

Figure 13 - Method of measuring drift and ground velocity when a single antenna beam is employed

Once the antenna position for minimum frequency has been determined, the antenna can be rotated 90° from this position. If Δf is measured in this new position, V_G can then be calculated. More directly, V_G and Δf can be determined by measuring the angle at which maximum Δf is obtained, but Δf changes slowly with angle around the maximum, and the first or "null" method will be more accurate. The preceding method if properly instrumented can give accurate readings of ground speed and drift. Its disadvantages are that it requires manipulation by an operator and does not give a continuous reading of either variable.

To obtain simultaneous and continuous readings of ground speed and drift, it is necessary to use two beams directed to the rear (or forward) and at equal angles to the right and left of the aircraft heading. With this configuration (still assuming straight and level flight), drift to the right (ground track to right of heading) will result in a higher doppler frequency from the left-hand beam for rearward-pointing antennas; conversely, drift to the left will result in a higher frequency from the right-hand beam. For forward-pointing antennas, the situation will be reversed. In either case, right and left doppler frequencies will be equal if there is no drift.

If both right and left antennas are mounted on a rotatable platform, that angular rotation of the platform necessary to equalize the two doppler frequencies is equal to the drift angle, and ground speed is then proportional to this frequency. The rotation required to equalize the doppler frequencies may be accomplished either manually or automatically. In either case, continuous readings of ground speed and drift can be made available (Figure 14). If the two antennas are fixed to the aircraft instead of being rotatable, ground speed and drift may still be calculated from the two doppler frequencies by means of an analog computer.

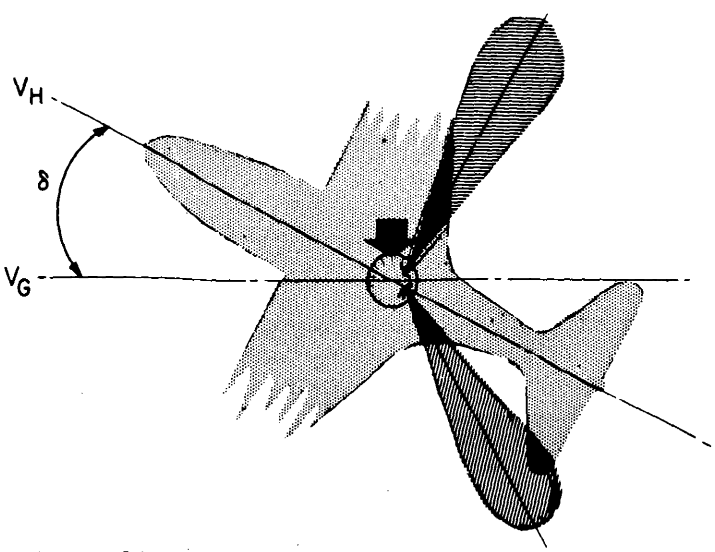

Figure 14 - Method of measuring drift and ground velocity using two antennas mounted on a rotatable platform

The preceding discussion holds only for straight and level flight, i.e., with no pitch or roll of the aircraft. Equation (6) shows that Δf varies directly as the sine of the angle between the r-f beam and the vertical, so that pitch and trim of the aircraft must be considered when calculating V from Δf. Mathematical analysis shows that consideration must also be given to roll, although to a lesser degree. It is necessary then to mount the "V-beam" antennas on a stabilized platform, or if they are to be rigidly mounted, to multiply the two doppler frequencies by a correction factor which takes roll and pitch into account. At NRL the latter system was chosen as the one which could be built to have the smaller size and weight. The computer which performs the necessary operations receives the two doppler frequencies, plus pitch-and-roll information from a vertical-reference gyro, and then solves for ground-track velocity and drift angle. It also combines drift angle with aircraft heading and with ground-track velocity to give continuous readings of latitude and longitude.

Derivation of Equations

In this section will be given the mathematical analysis leading to expressions for heading and drift velocities (V_H and V_D) and showing the dependence of the two doppler frequencies on roll and pitch. In this derivation, the components of the beam vector are transformed to a set of coordinates attached to the ground. These transformation equations are used to find the projection of the ground velocity on the beam vector under conditions of pitch and roll.

Let r_R = right beam vector,

r_L = left beam vector,

x, y, z = a right-handed coordinate system,

i, j, k = unit vectors of the coordinate system,

V_H = heading velocity,

V_D = drift velocity (drift to left taken as positive), and

V_C = climb velocity.

The variables involved are defined in Figures 15, 16, and 17. Primed coordinates refer to aircraft coordinates; unprimed coordinates refer to ground coordinates. Pitch (ϕ) is defined as the angle between the longitudinal axis of the aircraft and a horizontal plane. Roll (ρ) is defined as the angle of rotation about the longitudinal axis of the aircraft. The components of a beam vector in the coordinate system of the aircraft are given by

$$r' = i'x' + j'y' + k'z'. \tag{7}$$

But x′, y′, and z′ are the direction cosines of the beam vector when

$$\left.\begin{aligned} x' &= \cos\alpha' = \sin\psi\cos\theta, \\ y' &= \cos\beta' = \sin\theta, \text{ and} \\ z' &= \cos\gamma' = -\cos\theta\cos\psi. \end{aligned}\right\} \tag{8}$$

By the geometry of Figures 16 and 17,

$$\left.\begin{aligned} i' &= i(\cos\rho) - j(\sin\rho\sin\phi) - k(\sin\rho\cos\phi), \\ j' &= j(\cos\phi) - k(\sin\phi), \text{ and} \\ k' &= k(\sin\rho) + j(\sin\phi\cos\rho) + k(\cos\rho\cos\phi). \end{aligned}\right\} \tag{9}$$

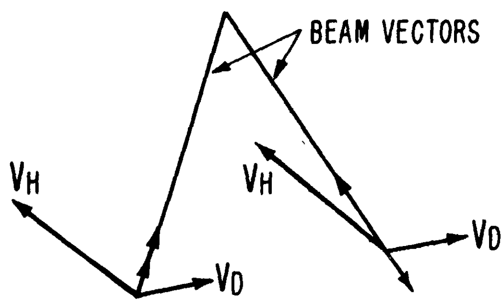

Figure 15 - Projection of heading and drift velocities on antenna beam vectors

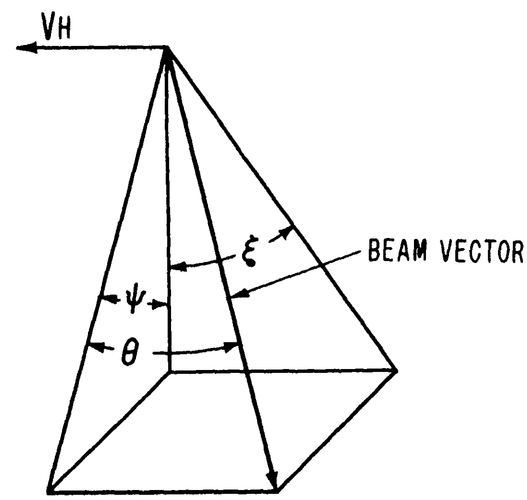

Figure 16 - Sketch showing angles involved in defining the location of beam vectors

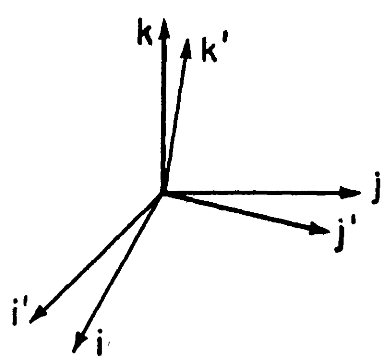

Figure 17 - Sketch of coordinate systems used in derivation of equations

The right and left beam vectors are

$$\left.\begin{aligned} r_R' &= -i'x' + j'y' + k'z' \text{ and} \\ r_L' &= i'x' + j'y' + k'z'. \end{aligned}\right\} \qquad (10)$$

Then, by substitution of Equations (8) and (9) in (10)

$$\left.\begin{aligned} r_R' = {} & -i\,(\cos\rho \sin\psi \cos\theta + \sin\rho \cos\theta \cos\psi) \\ & +j\,(\cos\phi \sin\theta + \sin\rho \sin\phi \sin\psi \cos\theta - \sin\phi \cos\rho \cos\theta \cos\psi) \\ & -k\,(\sin\phi \sin\theta - \sin\rho \cos\phi \sin\psi \cos\theta + \cos\rho \cos\phi \cos\theta \cos\psi) \\ r_L' = {} & i\,(\cos\rho \sin\psi \cos\theta - \sin\rho \cos\theta \cos\psi) \\ & +j\,(\cos\phi \sin\theta - \sin\rho \sin\phi \sin\psi \cos\theta - \sin\phi \cos\rho \cos\theta \cos\psi) \\ & -k\,(\sin\phi \sin\theta + \sin\rho \cos\phi \sin\psi \cos\theta + \cos\rho \cos\phi \cos\theta \cos\psi). \end{aligned}\right\} \qquad (11)$$

Then projection of the ground velocity on each beam vector is, of course, the dot product of the two vectors r′ and V.

$$\left.\begin{aligned} V_R &= r_R \cdot V \text{ and} \\ V_L &= r_L \cdot V. \end{aligned}\right\} \qquad (12)$$

The ground velocity V is

$$V = -iV_D + jV_H = kV_C. \qquad (13)$$

Equation (12) becomes

$$\left.\begin{aligned} V_L = {} & V_D\,(-\cos\rho \sin\psi \cos\theta + \sin\rho \cos\theta \cos\psi) \\ & +V_H\,(\cos\phi \sin\theta - \sin\rho \sin\phi \sin\psi \cos\theta - \sin\phi \cos\rho \cos\theta \cos\psi) \\ & +V_C\,(\sin\phi \sin\theta + \sin\rho \cos\phi \sin\psi \cos\theta + \cos\rho \cos\phi \cos\theta \cos\psi) \\ V_R = {} & V_D\,(\cos\rho \sin\psi \cos\theta + \sin\rho \cos\theta \cos\psi) \\ & +V_H\,(\cos\phi \sin\theta + \sin\rho \sin\phi \sin\psi \cos\theta - \sin\phi \cos\rho \cos\theta \cos\psi) \\ & +V_C\,(\sin\phi \sin\theta - \sin\rho \cos\phi \sin\psi \cos\theta + \cos\rho \cos\phi \cos\theta \cos\psi). \end{aligned}\right\} \qquad (12a)$$

These equations give the apparent ground velocities as seen by the right and left antennas.

The expression for the doppler shift is given in Equation (5). Using the equations for V_R and V_L and letting $\Delta f_R = f_R$ and $\Delta f_L = f_L$, the sum and difference equations are

$$\left.\begin{aligned} (V_R + V_L) = \frac{c}{4 f_o}(f_R + f_L) = {} & V_H\,(\cos\phi \sin\theta - \sin\phi \cos\rho \cos\theta \cos\psi) \\ & +V_D\,(\sin\rho \cos\theta \cos\psi) \\ & +V_C\,(\sin\phi \sin\theta + \cos\rho \cos\phi \cos\theta \cos\psi) \\ (V_R - V_L) = \frac{c}{4 f_o}(f_R - f_L) = {} & V_H\,(\sin\rho \sin\phi \sin\psi \cos\theta) \\ & +V_D\,(\cos\rho \sin\psi \cos\theta) \\ & -V_C\,(\sin\rho \cos\phi \sin\psi \cos\theta). \end{aligned}\right\} \qquad (14)$$

Since there are three unknowns, V_H, V_D, and V_C, and only two equations, one of the velocities must be obtained separately. The altimeter may be used to supply V_C; thus it may be assumed known and, for simplicity, may be set equal to zero in the solution for V_H and V_D. By determinants

$$V_H = \frac{\begin{vmatrix} \frac{c}{4 f_o} (f_R + f_L) & \sin\rho \cos\theta \cos\psi \\ \frac{c}{4 f_o} (f_R - f_L) & \cos\rho \sin\psi \cos\theta \end{vmatrix}}{\begin{vmatrix} (\cos\phi \sin\theta - \sin\phi \cos\rho \cos\theta \cos\psi) & \sin\rho \cos\theta \cos\psi \\ \sin\rho \sin\phi \sin\psi \cos\theta & \cos\rho \sin\psi \cos\theta . \end{vmatrix}} \tag{15}$$

Evaluating the determinant and simplifying,

$$V_H = \frac{c}{4 f_o} \left[\frac{(f_R + f_L) - \frac{B}{C} \tan\rho \, (f_R - f_L)}{A \cos\phi - \frac{B \sin\phi}{\cos\rho}} \right] \tag{16}$$

where $A = \sin\theta$, $B = \cos\theta \cos\psi$, and $C = \cos\theta \sin\psi$.

The equation for $(f_R - f_L)$ when solved for V_D gives

$$V_D = \frac{c}{4 f_o} \left[\frac{(f_R - f_L)}{\cos\rho \sin\psi \cos\theta} \right] - V_H \frac{\sin\rho \sin\phi}{\cos\rho}. \tag{17}$$

Substituting the above constants, V_D becomes

$$V_D = \frac{c}{4 f_o} \left[\frac{(f_R - f_L)}{C \cos\rho} \right] - V_H \sin\phi \tan\rho. \tag{18}$$

This is a solution for V_H and V_D expressed in measured or known quantities. It must be remembered that the terms involving V_C must be removed from $(f_R + f_L)$ and $(f_R - f_L)$ before the equations are exact.

There are conditions of pitch, roll, and drift which make either f_R or f_L pass through a zero value and attain a "negative" frequency (i.e., the aircraft approaching the ground along the beam instead of receding from it). This occurs, however, only at large deviations from straight and level flight, for example, at 12° pitch and 12° roll, with a 4 to 10 ratio between drift and heading velocity.

Design of Computer

The velocity of the airplane may be considered as being made up of two components V_H along the airplane heading, and V_D at right angles to the heading, so that V_G, the ground-track velocity, is the vector sum of V_H and V_D. If δ is the drift angle, $V_D/V_H = \tan\delta$ and $V_G = V_H \sec\delta$, so that once V_D and V_H are known, δ and V_G can be obtained.

It has been shown in the previous section that if V_C, the climb velocity, is neglected

$$V_H = \frac{1}{2K} \frac{(f_R + f_L) - \frac{B}{C}\tan\rho\,(f_R - f_L)}{A\cos\phi - \frac{B\sin\phi}{\cos\rho}} \quad \text{and} \tag{19}$$

$$V_D = \frac{(f_R - f_L)}{2KC\cos\rho} - V_H \sin\phi\tan\rho \tag{20}$$

where $A = \sin\theta$, $B = \cos\theta\cos\psi$, $C = \cos\theta\sin\rho$, and $K = \frac{2}{\lambda}$, $(\lambda = \frac{c}{f_o})$.

To furnish an exact solution for V_H and V_D, any computer must accurately solve the preceding equations using f_R and f_L as supplied by the two halves of the V- beam doppler system and roll-and-pitch angles (ρ and ϕ) obtained from the airplane's autopilot or other vertical reference. A compromise, however, must be made between the size and complexity of the computer and the accuracy of the result desired. A solution to the equations which would be accurate to within ± 1/2 percent was required. Any assumption which would simplify the computer mechanically without introducing a total error larger than ± 1/2 percent was justifiable.

Accordingly, an investigation was made of the effects of certain simplifying assumptions. If it is assumed that $\cos\rho = 1$ and $\tan\rho = 0$, the equations become

$$V_H'' = \frac{1}{2K} \frac{(f_R + f_L)}{A\cos\phi - B\sin\phi} \quad \text{and} \tag{21}$$

$$V_D'' = \frac{(f_R - f_L)}{2KC}, \tag{22}$$

letting primed and double-primed quantities indicate approximate values.

Use of the preceding equations leads to unacceptable errors in the presence of small roll-and-pitch angles. As an example, with a pitch of 5° nose-up, roll of 2°, and $\delta = \tan^{-1} 0.1$, the error in V_H is 1.2 percent, in V_D it is 0.6 percent (giving a position error of 1.2 percent). The foregoing conditions of trim are not at all unusual in flight, therefore such a computer was considered unusable.

If it is assumed that $\cos\rho = 1$, but that $\tan\rho$ is given its proper value, a much more accurate solution results. The equations to be solved become

$$V_H' = \frac{1}{2K}\left[\frac{(f_R + f_L) - \frac{B}{C}\tan\rho\,(f_R - f_L)}{A\cos\phi - B\sin\phi}\right] \quad \text{and} \tag{23}$$

$$V_D' = \frac{(f_R - f_L)}{2KC} - V_H'\sin\phi\tan\rho. \tag{24}$$

Obviously, this computer is more complex than the previous one but less intricate than the exact computer would be. For any value of drift angle, the error in V_H' will not exceed the allowable ± 1/2 percent until the product of the pitch-and-roll angles exceeds approximately 55, i.e., 5^0 pitch, 11^0 roll; 7^0 pitch, 8^0 roll; etc. Errors in V_D' are also reduced to small values (Figures 18 through 21).

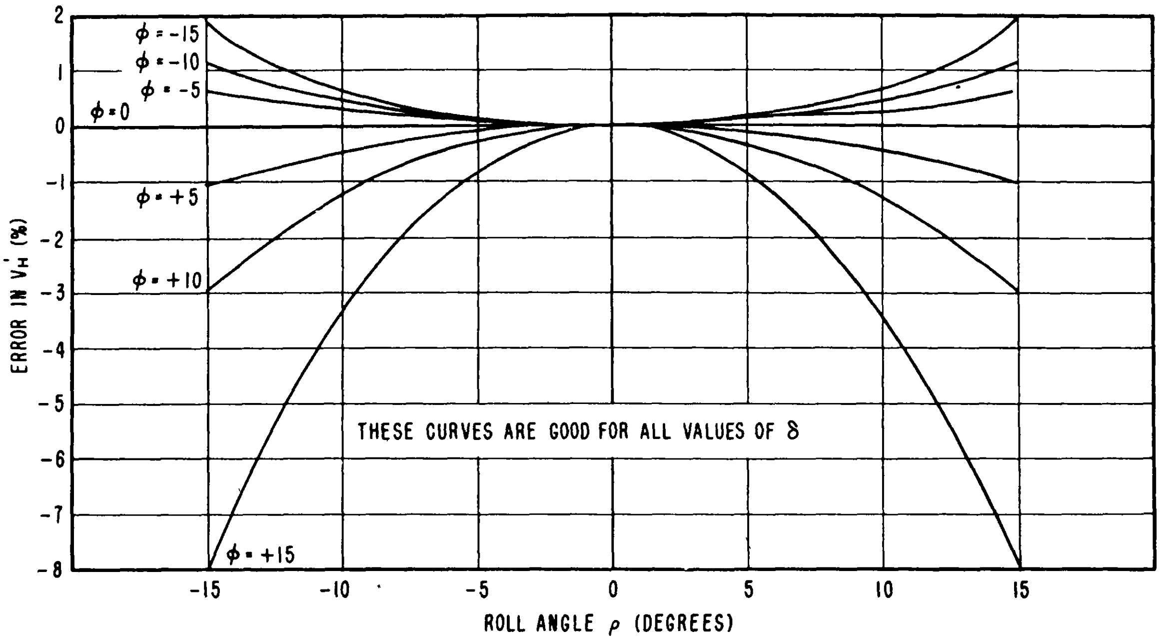

Figure 18 - Percentage error in V_H' for various values of roll and pitch

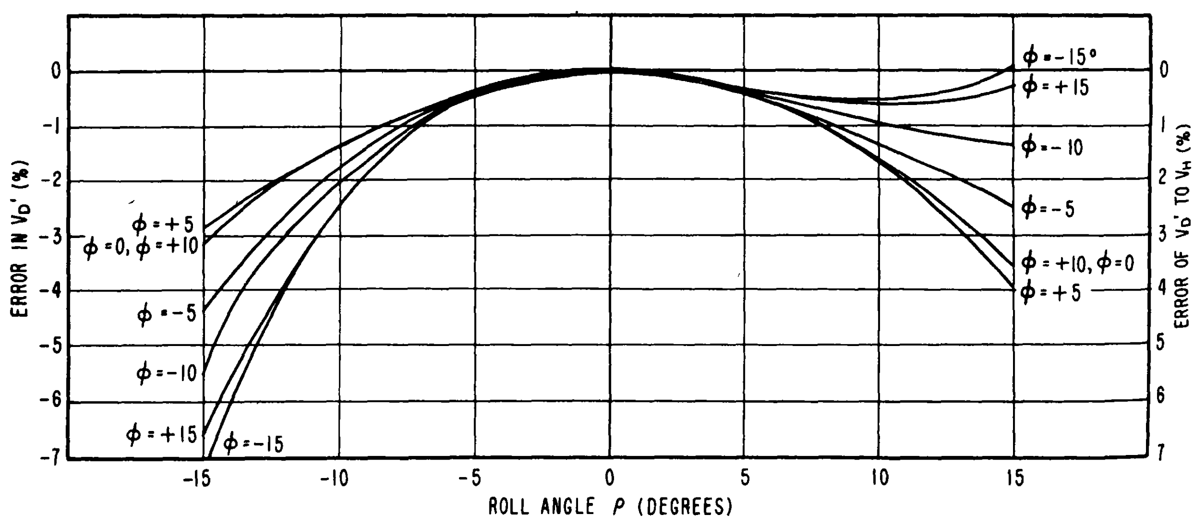

Figure 19 - Percentage error in V_D' for various values of roll and pitch when $\tan\delta = 0.1$

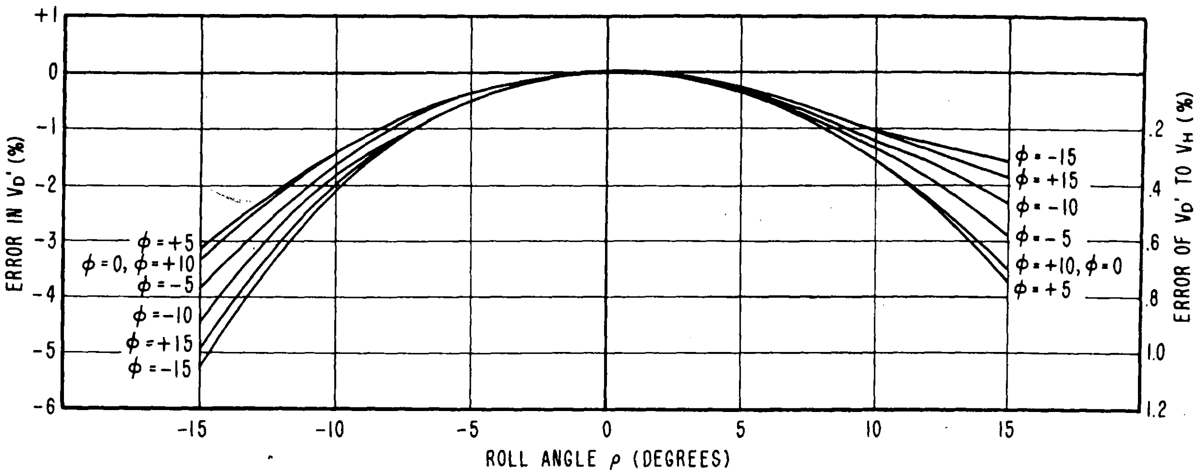

Figure 20 - Percentage error in V_D' for various values of roll and pitch when $\tan\delta = 0.2$

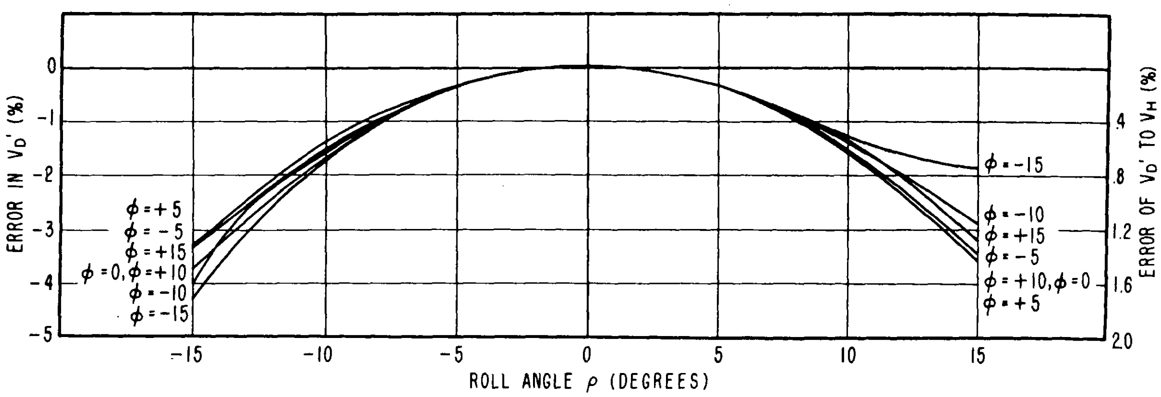

Figure 21 - Percentage error in V_D' for various values of roll and pitch when $\tan\delta = 0.4$

The position error is the vector sum of the errors in V_H' and V_D' and is equal to $\sqrt{(V_H - V_H)^2 + (V_D - V_D')^2}$. The error in δ is equal to $\tan^{-1}(V_D/V_H) - \tan^{-1}(V_D'/V_H')$. Practically, the position error is equal to the error in V_H' for small drift angles (less than 10°). Figure 22 is a plot of position errors for values of ϕ and ρ from -15° to $+15^\circ$ for the case of $\delta = \tan^{-1}0.4$, or about 22°. From this plot it can be seen that a considerable amount of pitch and roll can be tolerated before the allowable error of $\pm 1/2$ percent is exceeded.

Figure 23 is a simplified schematic of the computer designed to solve equations (23) and (24). The inputs to the computer are the doppler frequencies obtained from the right and left beams, an electrical signal obtained from a follow-up servo geared to the altimeter, two electrical signals obtained from follow-up servos attached to the vertical reference which give the roll-and-pitch angles, and a direction signal from the compass.

The computer indications are ground-track velocity (knots), drift angle to left or right of aircraft heading (degrees), nautical ground-miles travelled, latitude, and longitude. Computer outputs are two electrical "desired ground track" signals feeding the Pilot's Direction Indicator and the autopilot (if desired), a shaft rotation proportional to ground-track velocity, and an electrical "true ground track" signal. The latter two outputs were provided for possible future use with auxiliary equipment.

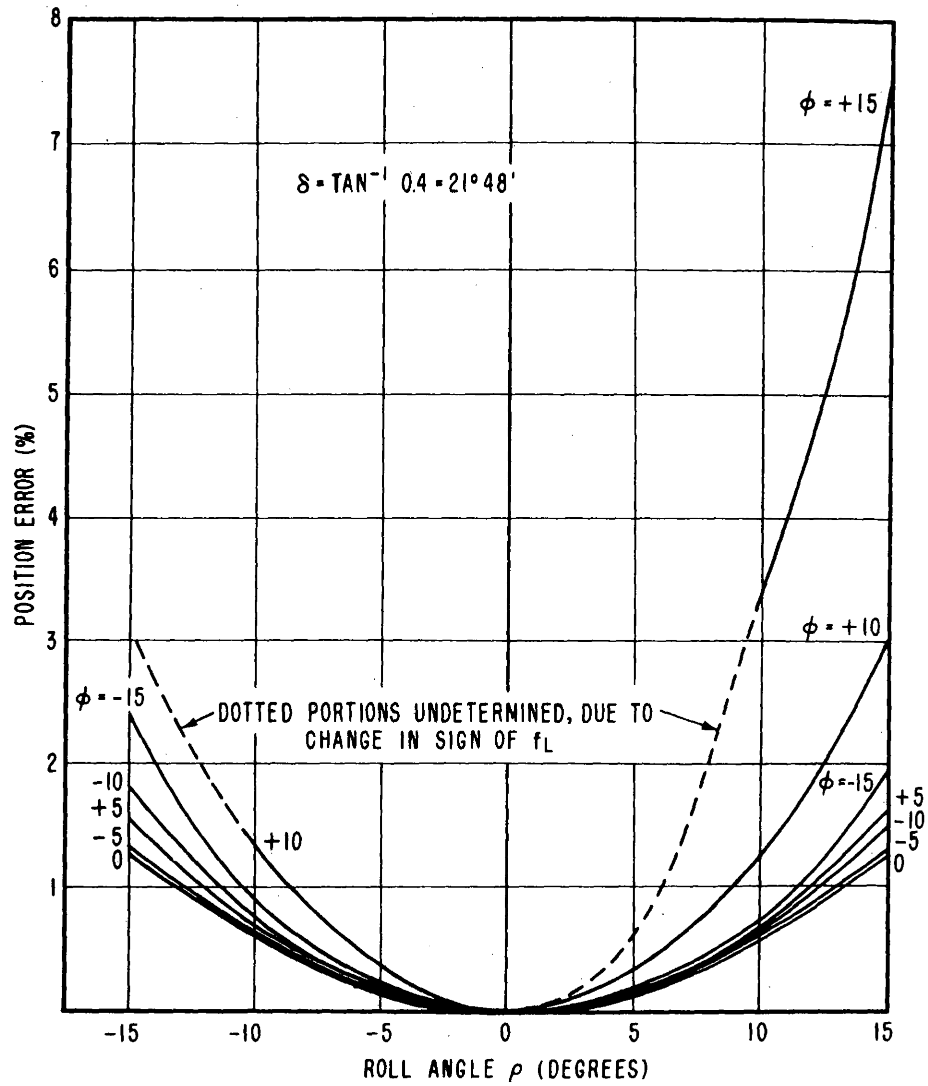

Figure 22 - Position error as percentage of true distance travelled for various values of roll and pitch

The computer schematic is largely self-explanatory. The two doppler frequencies f_R and f_L are fed to electronic frequency dividers which divide them by a factor of 16. The outputs of these dividers, $f_R/16$ and $f_L/16$, are amplified in power and used to run synchronous motors. The motors are geared so that the shaft speed resulting from each is equal to 24 revolutions per nautical mile of distance travelled, projected on the appropriate antenna beam. These shaft rotations are added and subtracted in mechanical differentials No. 1 and No. 2, respectively, and the resulting outputs are shaft speeds proportional to $(f_R + f_L)$ and $(f_R - f_L)$.

It will be remembered that in obtaining Equations (19) and (20), and hence Equations (23) and (24), the effect of climb (V_C) has been neglected. In the solution for V_H' (Equation 23), the term involving V_C, hereafter called V_H''', is

$$V_H''' = 2 V_C (A \sin\phi + B \cos\phi \cos\rho) \tag{25}$$

where $A = \sin\theta$ and $B = \cos\theta \cos\psi$.

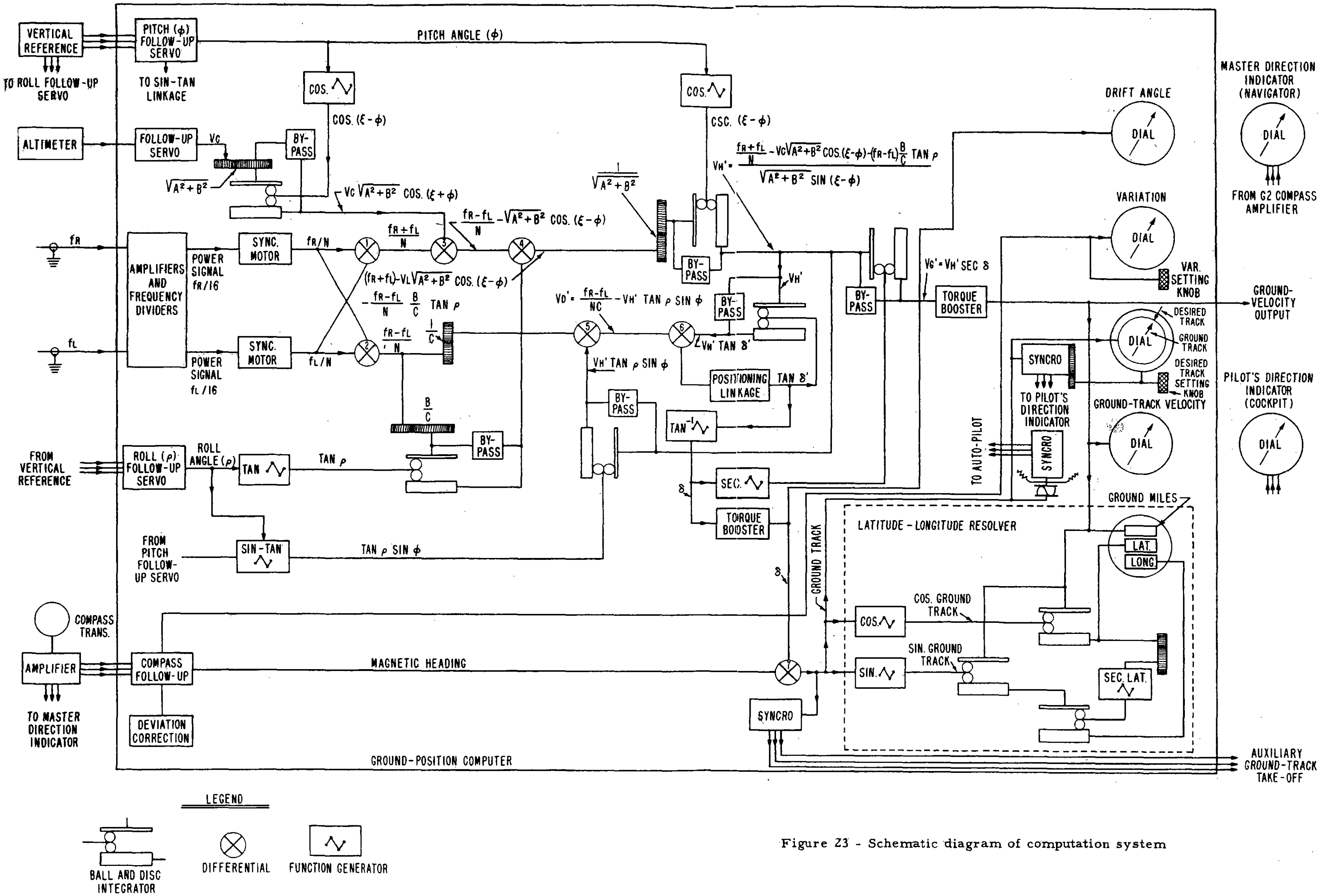

Figure 23 - Schematic diagram of computation system

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In the solution for V_D' (Equation 24), the term hereafter called V_D''' is

$$V_D''' = -2V_C\,(C \sin\rho \cos\phi) \qquad (26)$$

where $C = \cos\theta \sin\psi$.

The values of the foregoing terms are tabulated for a few cases in Table 1.

TABLE 1
Errors in V_H and V_D Contributed by Lack of Pitch Correction on V_C

ϕ	ρ	V_H'''	V_D'''
0	0	$1.76V_C$	0
5	5	$1.82V_C$	$0.056V_C$
10	10	$1.84V_C$	$0.110V_C$
15	15	$1.82V_C$	$0.160V_C$

These errors are considered negligible in V_D' but can become appreciable in V_H'. Any error in $(f_R + f_L)$ caused by the presence of climb is magnified by multiplication in the computer by the secant of the angle between the antenna beam and the vertical. The necessity of correcting V_H' for V_H''' is easily seen.

The correction is accomplished by using a separate altimeter with a follow-up servo whose rotational speed is proportional to that of the shaft of the altimeter pointer, and thus to the rate-of-climb. The altimeter is connected through appropriate gearing to give a shaft rotation of 24 revolutions per nautical mile of ascent.

Assuming that $\cos\rho = 1$ and that A, B, and C have the same values as in Equations (19) and (20), the correction to be applied to (V_H') becomes $2\,V_C(A\sin\phi + B\cos\phi)$. This value may be reduced to a different form by assuming an angle ξ such that

$$\sin\xi = \frac{A}{\sqrt{A^2 + B^2}} \quad \text{and} \qquad (27)$$

$$\cos\xi = \frac{B}{\sqrt{A^2 + B^2}}. \qquad (28)$$

The pitch angle ϕ may be added directly to this angle ξ; then

$$\cos(\xi - \phi) = \cos\xi \cos\phi + \sin\xi \sin\phi \text{ and} \qquad (29)$$

$$A \sin\phi + B \cos\phi = \sqrt{A^2 + B^2}\,\cos(\xi - \phi). \qquad (30)$$

Thus the value of V_C obtained from the shaft rotation must be multiplied by the constant $\sqrt{A^2 + B^2}$ and by $\cos(\xi - \phi)$. The factor 2 is omitted since f_R and f_L have each been divided by this factor before being added together. The corrected V_C is subtracted from (V_H') in a mechanical differential.

In a mechanical computer such as this, multiplication of a shaft rotation by a constant is easily achieved by means of a gear ratio. Multiplication by a variable is accomplished in a so-called "Ball and Disc Integrator" in which a flat disc drives a cylinder by friction, power being transmitted by two steel balls between them. The output-input ratio of this combination depends upon the distance of the balls from the disc center. A push rod is used to vary this distance in any desired manner. Multiplication by a function of an angle requires a linkage to generate the function and apply it to the push rod. Operation of these integrators should be clear from the schematic. To increase accuracy and reduce slippage a refinement of this method uses a by-passing differential, coupled in a way to use the outer portion of the disc, and to give a wider range of ball position for a small range of the variable angle. These by-passes are not fully diagramed on the schematic; they are indicated simply on each assembly by a block labelled "By-pass."

As shown in the computer schematic, $(f_R - f_L)$ is multiplied by the constant B/C and and by $\tan\rho$. This value, $(f_R - f_L)$ B/C $\tan\rho$, is now subtracted from the corrected value of $(f_R + f_L)$ already obtained. The result is a shaft rotation proportional to

$$(f_R + f_L) - V_C \sqrt{A^2 + B^2} \cos(\xi - \phi) - \frac{B}{C} \tan\rho (f_R - f_L),$$

which is the numerator of the right-hand side of Equation (23) after the V_C correction. This must be divided by the denominator, $A \cos\phi - B \sin\phi$. By the same process used in the preceding correction for V_C, $A \cos\phi - B \sin\phi$ can be shown equal to $\sqrt{A^2 + B^2} \sin(\xi - \phi)$ so that the shaft rotation, which is the numerator, is multiplied by a gear ratio $1/\sqrt{A^2 + B^2}$ and then by $\csc(\xi - \phi)$ in a ball-and-disc integrator. The resulting shaft rotation is proportional to V_H' at the rate of 24 revolutions per nautical mile. A torque booster is inserted here to minimize the loading on this cosecant integrator.

By applying Equation (6) to $(f_R - f_L)$, V_D' is obtained. It should be noted that the correction $V_H' \sin\phi \tan\rho$ is a function of V_H' instead of V_H; i.e., the correction is in error in proportion to the error in computed V_H. This fact has been taken into account in computing the graphs showing errors in V_D'.

Next, V_H' and V_D' are combined to give V_G' and δ (ground-track velocity and drift angle). The shaft corresponding to V_H' drives the disc of a ball-and-disc integrator, the ball carriage of which may be in any position to start. The cylinder of this integrator is connected to one input of a differential, and V_D' feeds the other input. The output of this differential is connected to the ball carriage of the integrator in such a way that it changes the position of the balls in accordance with its direction of rotation. If the position of the balls corresponds to $\tan\delta'$, the cylinder rotates at a speed $V_H' \tan\delta' = V_D'$, and the differential output is zero. Any other position of the balls causes a different value of cylinder rotation, which in turn causes the output shaft of the differential to rotate in such a way as to bring the ball carriage back to the $\tan\delta'$ position. A $\tan^{-1}\delta'$ linkage generates δ'' from this $\tan\delta'$ position. A secant linkage then generates $\sec\delta'$ which is applied to V_H' through another integrator to obtain V_G'. A second torque booster is inserted here.

Following this torque booster is a tachometer calibrated in knots; it is mounted on the front panel and furnishes a direct indication of ground speed.

The motion of the shaft corresponding to V_G' is also applied directly to the latitude-longitude resolver. This resolver is part of the Air Position Indicator Computer Type AN5841-1, modified and built directly into the AN/APN-67, and is shown enclosed in dashed lines on the computer schematic. Its operation is self-evident from Figure 23. The drift angle δ' is shown directly on the face of the computer. It is also used to correct the compass heading, as are variation and deviation corrections. Variation is applied through a knob on the front panel; the amount of variation set in is indicated on the "Variation" dial. Deviation correction must first be determined from a compass swing, then set in by means of a 12-screw adjustable cam. Once set, this correction should require no further attention.

Ground track or "true course" representing the actual track of the aircraft over the ground is made up of compass heading, deviation, variation, and drift angle. This ground track is applied to the latitude-longitude resolver as shown in the schematic. It is also applied to the ground-track pointer on the front panel. The dial has another pointer, and the navigator can set this second pointer to any desired ground track by means of the small knob directly above the dial. A "Pilots Direction Indicator" (PDI), mounted in the cockpit, repeats the angular difference between the ground-track and desired-track pointers, and by steering the aircraft so as to keep this indication at zero, the pilot makes good the desired course over the ground.

Provision is also made to connect the PDI information directly to the autopilot if desired.

Figure 24 shows the front panel of the Kollsman KS-10 computer, built for NRL use in the AN/APN-67. From left to right, the dials are: drift angle, up to 25° left or right, variation up to 150° east or west, which may be set in by means of the small knob, ground-track and desired-track pointers, ground-track velocity, 50 to 500 knots, and the latitude-longitude computer. The latitude-longitude knobs are provided for setting in the latitude and longitude of the starting point. The "VAR" knob shown at the top of this dial is not used, its former function (setting in variation) being provided elsewhere. Also presented on this dial is a counter which is connected directly to V_G', and indicates miles travelled. Since the unit was originally part of the Air Position Indicator, this counter reads "Nautical Air Miles," whereas it now indicates nautical ground miles.

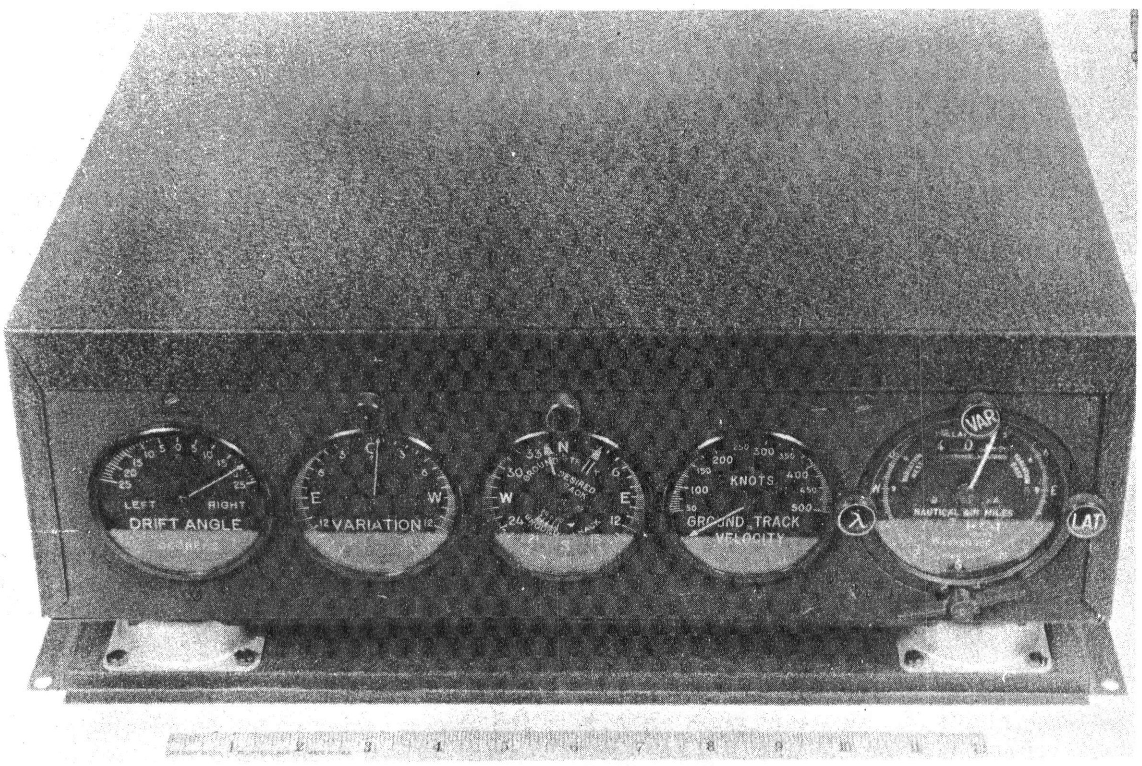

Figure 24 - The Kollsman KS-10 computer

FLIGHT TESTS

The installation was completed in P2V, No. 122463, and the first test flight was made on 3 April 1951. The transmitting tube used in this flight (and in subsequent flights until 22 June) was a QK259 magnetron.

During the early test flights, difficulties noted in the equipment were:

(a) Noisy operation and general unreliability of the QK259 magnetrons,

(b) Excessive vibration of the antenna and r-f portions of the system,

(c) Collection of water in the antenna assemblies, and

(d) Microphonics in the audio amplifiers.

All these factors contributed large amounts of noise to the output signal and had to be corrected before any further steps could be taken. After 22 June 1951, X-21 and later X-23 klystrons, procured from Varian Associates, were substituted for the magnetrons as the r-f source. This substitution necessitated construction of a voltage-regulated power supply to replace the current-regulated supply which had been used to power the magnetron.

Mechanical braces were installed to minimize vibration of the plumbing components. The antenna units were opened, cleaned, resealed, bore-sighted, and then reinstalled with new shims to compensate for slight changes in squint angle which had occurred during the cleaning process.

Even with the mechanical bracing, low-frequency noise voltages were still excessive. It was necessary to install 400-cycle high-pass filters between the receiver crystals and the audio-amplifier inputs to minimize this difficulty.

The audio amplifiers were found to be too microphonic for airborne use even though the amplifiers were shock-mounted. The high level of acoustic noise in the tail section where these amplifiers were installed caused considerable microphonic noise to be generated in the first audio tube. This tube, a 6BJ6, was replaced by an RCA 5879, a specially-built low-microphonic tube. This substitution reduced the microphonics, but it was found that the gain of the 5879 was not sufficient for reliable operation. Hence it was eventually necessary to rebuild the amplifiers completely, adding an additional 5879 stage to increase the gain. Experience in early flight tests indicated that an AGC time constant of about 1/10 second was the proper value to use, and this value was incorporated in the new design.

These modifications required about four months, during which time 13 flights were made. On 31 July 1951, the complete system, including computer, was flown for the first time. A second flight was made on 8 August. On both flights it was apparent that the computer was not operating properly. The doppler drive motors were erratic, moving in jerks rather than smoothly, and obviously were not following the input signals quantitatively. An investigation of this fault resulted in a complete rebuilding of both right- and left-hand frequency-dividing circuits and the associated squaring preamplifiers.

The type of counting circuit used in the AN/APN-67 is basically an axis-crossing frequency meter in which each positive or negative axis crossing of the doppler note is converted into a pulse. The pulses are fed to a string of four multivibrators, each of which puts out one pulse for two input pulses. The resulting pulse frequency is thus 1/16 of the input frequency. The pulses are converted into triangular waves and used to drive the synchronous motors in the computer, so that each motor runs at a speed proportional to the doppler frequency of its particular channel.

To form the initial pulses from the doppler signal, it must be amplified and clipped so that each wave is made approximately square. The pulses are then formed by differentiation.

The nature of the doppler signal places unusual requirements on the squaring-clipping amplifier. Because of the finite beamwidth of the radiated energy, there will usually be several targets from which energy is reflected simultaneously, and the frequency of this reflected energy will depend upon the position in the beam of the particular target from which the energy is reflected. Thus the received signal is usually made up of several components of slightly different frequency and widely varying amplitude. Beats between these frequencies give a resulting voltage wave which varies rapidly in amplitude. In the design of the squaring amplifiers, this variation must be carefully considered.

Squaring a sine wave or a voltage wave whose envelope varies slowly with respect to its period is a simple matter if it is not necessary to retain the original direct current axis of the wave. However, if small-amplitude waves are lifted off the dc axis when the doppler signal is used, subsequent clipping is liable to remove them entirely, resulting in a loss of information. In the KS-10 computer amplifier as originally designed, the squaring was done by overdriving cascaded RC amplifier stages. The overdriving resulted in drawing considerable grid current with consequent negative biasing of the amplifier grids during strong signals. Because of the low-frequency requirements of the amplifier, the time constants of the coupling networks could not be made sufficiently small to keep up with the envelope variation of the doppler signal; as a result, "holes" appeared in the squared-up output.

The circuit was rebuilt with a clamping network consisting of two biased diodes in each grid to limit the excursion of the input signal to $\pm$ 2 volts. Since this voltage was slightly less than that of the negative grid bias, no grid current could be drawn. Bias was obtained from the B^+ supply through a voltage divider.

After this modification, the motors followed the doppler signals satisfactorily as far as could be determined on the bench. The next flight was made on 14 September for qualitative tests of the complete equipment. Operation appeared to be satisfactory, but quantitative tests could not be made since the vertical reference had not been leveled and the compass-deviation correction had not been put into the computer. Completion of these adjustments was expected before the next test flight. A compass swing, however, could not be performed by AIL Philadelphia until 25 September. As a result, it was decided to make a flight for the purpose of taking distance measurements without regard to heading accuracy.

The procedure for leveling the vertical reference was quite simple. The synchros in the computer were previously adjusted to null at the zero pitch-and-roll positions when the gyro was leveled. These zero positions were determined by lining up small holes in the gears of the pitch-and-roll trains with a similar hole in the mounting plate. The antenna angles $\theta = 20^\circ$, $\psi = 20^\circ$ were set in with the airplane in a 2° nose-up position. On the basis of expert opinions, this angle was chosen as that angle which is obtained in flight at the cruising speed of 180 knots. Accordingly, the airplane was brought to this position by means of jacks; the leveling screws on the vertical reference were then adjusted until a pin could be dropped through the three aligning holes. This procedure assured correspondence between the antenna angles and the vertical reference.

For the test flight it was necessary to fly a perfectly defined course between two easily identified end points. The course selected, one previously used by the Air Force in testing the AN/APN-66, was a straight railroad track approximately 45 miles long running between Petersburg and Suffolk, Virginia. Highway crossings furnished the end points. The pilot was instructed to keep the airplane over the railroad track, and to change heading as necessary for wind compensation. End points were observed through a gyro-stabilized drift sight.

On 24 September 1951, two runs were made over this course in each direction at an altitude of 2000 feet. Distance readings were obtained from the "Nautical Air Miles" counter on the computer at the start and finish of each run. The distance-traveled display unit built into the Kollsman KS-10 computer consists of three dials showing miles in units, tens, and hundreds; they are visible through small holes in the dial plate. Neither indexing marks nor fractional markers are on the dials, and it is felt that readings are accurate to no better than ± 0.1 mile. This figure corresponds to approximately ± 0.25 perce for the 45-mile railroad track. Results were uniformly and surprisingly good (Table 2).

TABLE 2
Results of Test Flights on 24 September 1951

Run	Course	Indicated Nautical Miles Travelled
1	Petersburg-Suffolk	44.3
2	Suffolk-Petersburg	44.5
3	Petersburg-Suffolk	44.5
4	Suffolk-Petersburg	44.2

It will be noted that there is a maximum discrepancy of only 0.3 nautical mile or approximately 0.7 percent between these readings.

The highway crossing which had been used on the Petersburg end of the runs could not be accurately located on the map, so no figure could be established for the absolute accuracy of this series of runs. However, the repeatability of the distance measured was quite encouraging.

Drift on these runs was practically negligible. Generally, a drift of about 1° (and occasionally as high as 3°) to the right was indicated on the Petersburg-Suffolk runs; the same degree of drift to the left was noted on the Suffolk-Petersburg runs.

On 25, 26, and 27 September, the compass was swung at Aircraft Instruments Laboratory Mustin Field, Philadelphia. Data were recorded for later use in compensating the deviation cam in the computer. Readings were taken every fifteen degrees around the compass, and deviations as high as 9° were noted on some headings. Since deviations in a normal installation rarely run higher than 3°, it was felt that this high deviation indicated some serious trouble in the compass system. Accordingly, AIL spent the next few days investigating the installation and finally replaced several of the units with new parts. The repair and final swing were completed on 12 October. It was arranged to have the Kollsman representative come to Johnsville on 17 October to put the deviation corrections in the computer, using data taken by AIL on the repaired system.

Meanwhile another test flight was made on 15 October. This time two end points were chosen whose distance apart was carefully measured on the map at 43.125 nautical miles. Results are tabulated in Table 3.

TABLE 3
Results of Test Flights on 15 October 1951

Run	Course	Measured Distance (naut. mi)	Measured Drift (degrees)
1	Petersburg-Suffolk	42.2	4-1/2° to 6° Right
2	Suffolk-Petersburg	42.7	4-1/2° Left
3	Petersburg-Suffolk	42.6	5° Right
4	Suffolk-Petersburg	42.6	4° to 5° Left

This time the maximum disagreement between readings was 1.2 percent; the absolute accuracy of the average reading (42.5 nautical miles) was 1.4 percent. No attempt was made to check heading accuracy.

On 22 October, after the deviation corrections had been set in, another series of runs was made using a different end point at Petersburg. The new end point was more easily identified from the air, and made the course a mile longer, or 44.125 nautical miles.

Because of an intermittent low overcast, the first four runs were made at an altitude of 1000 feet. Two different air speeds were used to check the dependence (if any) of the indication on speed. Actual ground speed was calculated from the elapsed time of each run, which was taken by a stop watch. Results are given in Table 4.

TABLE 4
Results of Test Flights on 22 October 1951

Run	Course	Ground Speed (knots)	Measured Distance (naut. mi)
5	Petersburg-Suffolk	175	43.6
6	Suffolk-Petersburg	186	43.5
7	Petersburg-Suffolk	118	43.4
8	Suffolk-Petersburg	125	43.5

In the runs in Table 4 the true distance was 44.125 nautical miles, and the average indicated distance was 43.5 nautical miles. The absolute error of the average distance on these runs was 1.4 percent.

These readings agree with each other more closely than those taken in the preceding flight. This improved consistency may possibly be attributed to the fact that lower altitude made the end markers easier to locate or that the engineers were becoming more familiar with the equipment and were establishing a standard technique. The agreement demonstrates that the distance indication is independent of ground speed at least within the limits of 118 to 186 knots. The agreement of these figures with those of the previous flights (15 October) seems to show that it is also independent of altitude from 1000 to 2000 feet.

After these four runs, two more were attempted at a 3000-foot altitude, but the overcast prevented positive identification of the end points, and no significant data were taken.

During the 1000-foot runs on this date, the heading accuracy was checked by means of latitude and longitude readings. At the beginning of each run, latitude and longitude of the starting point were set in, and the readings taken at the end point were checked with the actual values taken from a map. Agreement was fairly good, but the distance travelled was too short for accurate determination of angular errors.

On 25 October a series of runs was made to determine the maximum operating altitude of the equipment. The results are shown in Table 5.

TABLE 5
Results of Test Flights on 25 October 1951

Run	Altitude (ft.)	Calculated Ground Speed (knots)	Distance Measured (naut. mi.)	Calculated Doppler Frequency (cps)
9	2000	180	43.4	2140
10	5000	174	43.1	2065
11	5000	198	42.5	2360
12	5000	126	43.5	1495

These runs in Table 5 were made over the 44.125-mile course. Runs 10 and 11 may indicate a slight deterioration in accuracy at 5000 feet although the data are not sufficient to be conclusive. A possible reason for such deterioration could be the presence of large noise components in the doppler signal between 500 and 1500 cycles. When the amplitude of any noise component approaches to within about 10 db of the signal component, the count begins to move in the direction of the mean noise frequency, and the amount of shift depends upon the relative amplitudes of noise and signal and the frequency difference between them. Thus a low-frequency noise component might be expected to cause more error at high ground speed than at low ground speed. Measurements on the equipment indicate that some deterioration should occur at 5000 feet.

The noise components in the 500-1500 cycle range are quite large, as is evident from spectrum analysis of the recorded signal, and they begin to affect the doppler count at the 5000-foot altitude. Table 5 gives values of Δf for the various ground speeds attained. It has been demonstrated that distance measured is independent of ground speed at lower altitudes, but the effect of the noise at 5000 feet can be seen in Table 5. For example, at 198 knots where $\Delta f = 2360$ cps, there is an error of approximately two percent; at 126 knots where $\Delta f = 1495$ cps (very little greater than the mean noise frequency), the error is not discernible.

The preceding runs are summarized in Table 6. Here the most significant fact is the rms deviation of ± 0.39 percent about the mean. This indicates that the equipment may be expected to perform well within the specification limit of ± 2 percent. The mean deviation of - 1.5 percent represents a calibration constant or difference from true miles which was later taken out by means of adjustments provided in the computer. The deviation is almost

TABLE 6
Summary of 12 Runs over Railroad Course

Run	Deviation from True Miles (%)	Deviation from Mean (%)
1	-1.99	-0.49
2	-1.55	-0.05
3	-1.55	-0.05
4	-2.21	-0.71
5	-2.08	-0.58
6	-0.93	+0.57
7	-1.16	+0.34
8	-1.16	+0.34
9	-1.13	+0.37
10	-1.36	+0.14
11	-1.58	-0.08
12	-1.36	+0.14
Mean deviation	-1.50	
RMS deviation from mean		±0.39

completely accounted for by the shift which occurs in the effective electrical axes of the antenna beams due to the change in reflectivity of the earth with the change in the angle of incidence. For the angle at which the beams are set (28 degrees from the vertical), the amplitude of signal return is a fairly steep function of angle. When this function is combined with the antenna beam pattern, the angle at which maximum return occurs is 0.35 degrees less than would be the case if the beam pattern alone were considered. Because of this, the frequency of the return signal for a given ground speed is lower by 1.2 percent, and this same figure is applied directly to the "miles travelled" indication. Calibration adjustments for the antenna angles were made in the computer before any navigational flights were made.

On 5 November a flight was made to check the vertical reference and altitude correction. Two runs were made over the course at 2000 feet to determine whether or not the equipment was operating properly. On the third run, the airplane passed over the end point at 2000 feet, and then immediately climbed to 3000 feet, then down to 500 feet, up to 3000, down to 500, etc., as fast as it could maneuver, all the while remaining over the railroad track. During this run, the aircraft altitudes varied from 7^{0} nose up to 1^{0} nose down. The normal attitude was 1-1/2^{0} nose up. Results of these runs are given in Table 7, and the agreement between the level runs and the variable altitude run is obvious.

TABLE 7
Results of Level vs. Variable Altitude Tests

Course	Altitude (ft.)	Measured Distance (naut. mi.)
Petersburg-Suffolk (level)	2000	47.0
Suffolk-Petersburg (level)	2000	47.2
Petersburg-Suffolk (var. alt.)	500-3000	47.2

Since the equipment consistently recorded a distance of 43.1 to 43.6 miles for runs made over the same 44.125-mile distance previously used, it was evident that something had changed the absolute accuracy but not the consistency of the equipment. The sudden change to 47 miles represented roughly an eight-percent discrepancy. Investigation showed that a gear in the pitch synchro train of the computer had slipped on its shaft causing the follow-up to null at a point nearly two degrees away from its proper position. Ordinarily, there is no strain on this gear since it drives nothing but the follow-up synchro. However, the stops which limit the pitch-cam excursion to $\pm 15^{\circ}$ are placed on this shaft, and when either of these stops is contacted, there is a resultant strain between shaft and gear. Even this is not sufficient to cause slippage if the extreme position is approached slowly, since the pitch motor drives through a friction clutch which will slip before any damage is done. However, if power is suddenly applied to the motor at a time when there is considerable discrepancy between the pitch transmitter and its follow-up, the gear train develops appreciable speed in the process of nulling. If at the same time the null position is beyond one of the stops, the inertia of the gear train is enough to cause slippage provided there is a weak point in the train. This weak point was a press fit between the gear in question and its shaft. The root cause of the trouble was the practice of energizing the complete equipment before the vertical gyro had erected to closer than 15° from the vertical.

With the assistance of the Kollsman representative, the gear was repositioned and cemented in place. Proper procedure would have been to pin or clamp the gear to the shaft, but this would have been a time-consuming process resulting in the loss of valuable flight time. It was felt by both Kollsman and NRL personnel that the gear was sufficiently tight on the shaft to work properly if care were taken to allow the gyro to erect before energizing the follow-up.

Since the time of the first slippage of this nature was unknown, the absolute accuracy of the equipment as a distance-measuring device could not be determined from the runs made. The absolute reading is primarily a function of antenna angles and transmitter frequency. Adjustments to compensate for both of these have been built into the computer. At this stage, it was felt that repeatability of measurements was much more significant than absolute accuracy, so long as the average error was within range of the calibration adjustments. As is evident from the preceding results, the measurements made over the railroad track were always repeatable to an accuracy better than one percent, and usually an accuracy of one-half percent could be maintained. Consequently, it seemed reasonable to expect that absolute accuracy should be as good once a proper calibration was made.

On 9 November, two runs were made over the railroad track(the 43.125 nautical-mile course) at a 2000-foot altitude, and distance readings of 41.8 and 41.6 miles were obtained. Using the average of 41.7 miles, the reading is 3-1/4 percent lower than the actual value. A correction of this amount in the reverse direction was then entered in the cosecant (pitch) cam of the computer. A third run over the course gave a distance reading of 43.0 miles. This figure was still about one-quarter percent low, but was considered close enough to justify a trial over a longer course.

A triangular course from Washington to Pittsburgh to Roanoke to Washington was flown on the same date. Without the guidance of the railroad track it was impossible to fly an absolutely straight course between any two of these points; as a result, accuracy was determined from latitude and longitude indications, which are a function of heading as well as distance. Consequently, it is difficult to separate a position error into its components. An estimate of the contributions of distance and heading errors to the final position error can be made by plotting the course made good as shown by the latitude and longitude dials, and comparing with a straight line between the end points. If the course is reasonably straight, position error at right angles to it may be taken as heading error.

Results of this trial are given in Table 8.

TABLE 8
Results of Washington-Pittsburgh Run

Course	Straight-Line Distance from Map (naut. mi.)	Distance Measured by APN-67 (naut. mi.)	Position Error from Lat. & Long. (naut. mi.)	Pos. Error (%)
Washington-Pittsburgh	159.8	161.8	3.8 (rt. angle)	2.4
Pittsburgh-Roanoke	183.6	182.3	4.6 (short)	2.5
Roanoke-Washington*	——	——	——	——

*Run of little value; heading follow-up erratic.

, During these runs latitude and longitude readings taken from the computer were used to plot position on a chart for every few miles. The final position was plotted from readings taken when the pilot indicated he was passing over a selected range station or homing beacon. Position error is the distance between the point represented by these final readings and the actual location of the end point. After the final readings were taken, the airplane circled until the actual readings of the new end point were set in, and a fresh start was made for the next leg. Thus, errors incurred in one leg of the course do not carry over to the next.

The position error in the first leg appears to be due almost entirely to heading error. The indicated end point is 3.8 miles from the actual end point, in a direction almost at right angles to the course. Its straight-line distance from the starting point is 0.8 mile less than the distance from starting point to actual end point. The right-angle error is 3.7 miles. The error thus breaks down into a 0.5-percent distance and a 1.3-degree heading error to the right.

On the second leg, however, the error appears to be due almost entirely to distance measurement. The right-angle error is negligible, but the distance as plotted from latitude and longitude is 4.6 miles short. In this connection, it should be pointed out that the distance measured on the Nautical Ground Miles dial is of no particular significance since the course was not a straight line. The reason for this short measurement is unknown, although it may possibly be due to rapid changes in effective altitude caused by the rugged terrain over which most of the leg was flown. The pilot was holding a 2000-foot terrain clearance where possible, but in many places deep valleys may have caused loss of signal strength and thus a lower distance reading.

The Roanoke to Washington leg was aborted because of erratic operation of the heading follow-up. At times the Master Direction Indicator followed the compass transmitter, and at other times it would not.

The next operation was a series of calibration runs made on 19 November in preparation for a long over-water flight. Four runs were made at 2000 feet over the 43.125-mile railroad course, and distance readings of 43.0, 43.5, 43.0, 43.0 nautical miles were obtained. The heading follow-up, however, would not operate at all. After this flight a ground check of the equipment disclosed a faulty tube in the compass amplifier which was replaced.

The next day (20 November) a flight was made at 2000 feet from Washington to Guantanamo Bay, Cuba. Position was checked and reset at Wilmington, N. C., West Palm Beach, Miami, and Guantanamo. Results are given in Table 9.

TABLE 9
Results of Washington-Guantanamo Run

Course	Scale Distance (naut. mi)	Position Error (naut. mi.)	Distance Error (naut. mi.)	Distance Error* (%)	Angular Error (naut. mi.)	Angular Error (degrees)
Washington-Wilmington	274	13.1	3.0	1.1	12.0	2.5 right
Wilmington-W. Palm Beach	470	41	6.5	1.4	40.0	4.9 right
W. Palm Beach-Miami	56.2	3.8	0.3	0.5	3.8	3.9 right
Miami-Guantanamo	452	13.9	0	0	13.9	1.7 left

* Distance was short in each case

Distance accuracy on these runs, although in general not as good as had been hoped for, is still well within the ±2 percent specification. Heading accuracy, however, is another matter. Any consistent error could have had a simple cause and might have been easily corrected, but random errors were puzzling at the time.

As far as navigational data were concerned, the return flight from Guantanamo to Washington was aborted at the start when the pitch gear train ran into one of the stops. This mishap was caused by an insufficient gyro speed-up time together with the extreme maneuvers of the aircraft. That the loose gear had been slipped was immediately apparent from ground-speed readings. It was decided that the time during this flight should be used to investigate the heading follow-up difficulties.

The G-2 compass system consists of a magnetic element and a gyro Master Direction Indicator which is slaved to it through an amplifier. A faulty tube previously found in this amplifier had once caused complete failure of the slaving. This unit, however seemed to be operating properly. In the AN/APN-67, the G-2 Master Direction Indicator transmits a synchro signal to the heading pointer of the latitude-longitude resolver. This heading signal is modified by drift, variation, and any deviation correction which may have been inserted. The system was previously corrected for deviation so that if all equipment was working properly the Master Direction Indicator reading plus drift plus variation should equal latitude-longitude resolver reading. If variation and drift are arbitrarily set at zero, then the latitude-longitude resolver should follow the Master Direction Indicator exactly. In this instance, the resolver did not follow exactly, and such behavior indicated that trouble existed somewhere in the heading mechanism of the computer.

Before any further test flights it was essential that the slipped gear be repositioned and that the heading follow-up be corrected insofar as possible. Repositioning the gear was a simple matter of leveling the airplane and realigning the three calibrating holes. It was realized, however, that lack of time prevented any extensive work on the computer. The Guantanamo flight was completed on 21 November, and the airplane had to be turned back for a major overhaul on 1 December.

Consequently, it was decided to determine just what errors existed between the Master Direction Indicator and the latitude-longitude resolver; it was also necessary to plot a graph from which essential corrections could be determined and then set in manually by means of the variation knob. In flight, this procedure would require a new correction whenever heading changed significantly. The graph plotted from data taken on 23 November showed a cyclic variation with a difference of slightly over 13 degrees between positive and negative peaks. The most probable cause for this variation was the deviation correction cam; it is not accessible without disassembly of the computer. It was hoped, however, that the error could be compensated in flight by means of the proposed manual correction.

During the week of 26-30 November, a flight was made from Washington to the West Indies. Numerous accuracy runs were made; most were taken at a 2000 foot altitude. Results are given in Table 10.

TABLE 10
Results of Washington-San Juan Flight

Course	Scale Distance (naut. mi.)	Position Error (naut. mi.)	Position Error (%)	Distance Error (naut. mi.)	Distance Error (%)	Angular Error (naut. mi.)	Angular Error (degrees)
Petersburg-Cherry Point via Suffolk	151	5.0	3.3	-0.9	0.6	5	1.9 right
Wilmington-Miami*	- -	- -	- -	- -	- -	- -	- -
Miami-Crooked Island†	- -	- -	- -	- -	- -	- -	- -
Crooked Island-San Juan, P.R.	526	7.6	1.4	6.5	1.2	4	0.4 left
San Juan-Port-au-Prince, Haiti§	415	3.5 4.4‡	0.85 1.1‡	- -	- -	- -	- -
Alta Vela Island-San Juan	323	7.9 6.8‡	2.5 2.1‡	4.5 0.8‡	1.4 0.6‡	6.5	1.2 right
San Juan-Miami*	- -	- -	- -	- -	- -	- -	- -
West Palm Beach-Jacksonville	229	10.1	4.4	-1.6	0.7	10	2.5 right
Brunswick-Raleigh	311-1/2	6.4	2.1	-0.5	0.2	6.4	1.2 right
Raleigh-Washington**	- -	- -	- -	- -	- -	- -	- -

* No results, ocean very smooth
† Defective equipment
§ Circuitous source, impossible to separate distance and heading
** No significant data, heading erratic
‡ With correction for ocean current

Several features of these runs deserve amplification. In general, the heading accuracy was much increased over its previous performance. This improvement can no doubt be ascribed to the manual corrections set in for each heading. It should be noted that the amount of correction necessary did not remain constant with time. This correction was replotted twice during the week of testing, and each time it was found to have changed. The cyclic nature and positions for maxima and minima of the curve did not change significantly, but differences in magnitude of correction varied as much as four degrees.

On the basis of wave charts, it was previously assumed that smooth water in the open ocean was a rarity, but several instances of water being nearly Beaufort zero were noted.

At these times the water showed no ripples at all, and only slight swells kept it from having a true mirror surface. The signal return under these conditions was not sufficient to operate the computer even at altitudes as low as 800 ft, which was as low as the pilot considered it safe to fly. Consequently, the Wilmington-Miami and San Juan-Miami runs did not produce any usable data.

During the run from Miami to Crooked Island, the klystron power supply blew a fuse. About ten minutes were spent in locating the trouble; the fuse was then replaced and operation resumed, but as a result of the interruption data for this run are meaningless.

It is easily seen that ocean currents, which are an actual movement of the reference medium with respect to which the AN/APN-67 measures speed, will cause a direct error in results. Accordingly, corrections for ocean currents must be applied to any over-water flights. Through information obtained from the Navy Hydrographic Office, it was determined that as far as these test results were concerned this current was significant in only one locality. The current just south of the islands of Hispaniola and Puerto Rico runs due west and averages two knots. Other currents (i.e., Miami to San Juan) are negligible. On the runs from San Juan to Port-au-Prince and return, the equipment would be subject to this current for approximately 240 miles or about 1-1/3 hours. Thus, a correction of 2-2/3 miles west should be entered on both these runs. This correction gives a value for distance error of +0.6 percent on the run from Alta Vela to San Juan. The position error on the San Juan to Port-au-Prince run becomes 1.1 percent.

For the five runs in which it is possible to separate errors, there is a spread ranging from +1.2 to -0.7 percent in distance and from 0.4° left to 2.5° right in heading. The equipment seems to be well within the accuracy specifications for measuring distance, but still does not measure up in heading accuracy even with the manual correction as applied during these latter flights. The average heading error is about 1.5° right, but this may possibly be attributed to misalignment of the antennas. If the angles ψ and θ are not exactly equal for both antennas, a false drift component will be introduced which would consistently give an error to one side. Drift-angle readings taken during flight and compared with those taken with the gyro drift sight frequently showed a one- to two-degree discrepancy to right or left, but it was difficult to obtain accurate drift-sight readings under most conditions. Consequently, too much weight should not be given to these observations.

The flights were completed and the airplane was returned to Johnsville on 30 November 1952. This was the last day on which the plane was allowed to fly, i.e., the last day of its fourth 3-month extension for a major overhaul. Consequently, no further flight-testing, which might have helped to clarify this heading error, could be performed. It is expected that the cause will be found and corrected during a forthcoming overhaul of the computer.

FUTURE PLANS

Work during the last several years has culminated in the successful operation of a doppler radar type of automatic navigator. Throughout the flight tests reported, research was conducted on the doppler radar portion of the system. Although operation was entirely satisfactory at an altitude of 5000 feet, experience with space-duplexed systems during 1948 and 1949 indicated satisfactory operation at approximately 50,000 feet.

In view of these results, NRL proposes a further development and flight-test program designed to provide reliable operation up to altitudes of 50,000 feet. This program would encompass the design and construction of space-duplexed antenna systems on 10,100 Mc and a series of flight tests using these antennas with the KS10 computer. Apparently, 13,500-Mc tubes will not be available for some months; as a result, no work is planned on this frequency for the present. In an effort to reduce the effect of crystal noise on receiver sensitivity, NRL proposes to do research on receivers throughout this program.

On the strength of the results at NRL, the Bureau of Aeronautics let a contract with Ryan Aeronautical Corporation for ten equipments. The first of these should be delivered during the latter part of 1952. The Ryan equipment will use a circularly polarized type radar system which, while offering certain advantages, is similar to the recently tested NRL system in its sensitivity to vibration and microphonics.

It is felt that additional NRL work on space-duplexed systems is necessary to compare the three types of duplexing systems and to make a proper choice for production equipments.

CONCLUSIONS

The AN/APN-67 Automatic Navigator, developed by the Naval Research Laboratory, consists of a pair of cw doppler radar systems rigidly mounted to the aircraft and compensated for pitch and roll by a mechanical analog computer actuated from the airplane's compass and vertical reference. Of several types of radar systems investigated, the space-duplexed zero intermediate-frequency system with some type of speed gate has shown the best performance. The system is capable of operation up to 100,000 feet with a nominal 20-watt cw output at X-band or some slightly higher frequency. Over-water accuracy of one percent or better has been demonstrated and should be expected under most conditions of flight. The reliability of the AN/APN-67 is comparable with any radar and could be improved still further by incorporating some type of memory system to carry over during occasional brief signal fade-outs occasioned by smooth water. If presently available components were used, the estimated over-all weight of the model under consideration would be about 150 pounds; the weight could be further reduced with specifically designed parts.

The system should be extremely difficult to jam because of the narrow, nonscanning radar beams and the high speed of the aircraft. Because of the inherent simplicity of the system, the production cost should be low. Furthermore, no unproved components, such as complex vacuum tubes, are required.

In addition to the dead-reckoning use for which the AN/APN-67 was primarily designed, it also has an obvious use in connection with ground stabilization for search radar, strip mapping, and photo reconnaissance. Since the short-time accuracy is of a high degree, it can also be used in connection with precision bombing runs. In answer to specific requests for some of these functions, several special outputs have been incorporated in the computer. The unit is unusually flexible in this respect, and modifications for special uses can be made at any time without impairing the other functions by the attachment of follow-up devices.

Without help from many outside organizations and assistance from within the Laboratory, this equipment could not have been successfully completed. The authors wish to express their appreciation to the Antenna Research Branch of Radio Division I for their work on the design of antennas. Special acknowledgment is also due to the Kollsman Instrument Company for work on the design and fabrication of the computation system, to NADC, Johnsville for flight services, assistance in the fabrication of antennas, and the installation of equipment, and to AIL, Philadelphia for the design and construction of the vertical and heading reference system. In addition, the Bureau of Aeronautics, Code AE-9, is to be commended for their work as coordinators between NRL and the various other activities. This organization provided the necessary financial support.

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