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FLIGHT TESTS OF A GROUND SPEED INDICATOR OVER MEASURED RUNS

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NAVAL RESEARCH LABORATORY

WASHINGTON, D.C.

N R L REPORT NO. R-3239

FLIGHT TESTS OF A GROUND SPEED INDICATOR OVER MEASURED RUNS

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February 11, 1948

Approved by :

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CONTENTS

ABSTRACT

A series of flight tests have been conducted in order to obtain further information on the problem of ground speed measurement. The equipment used was a continuous-wave Doppler radar, operating at X-band, having a power output of 15 milliwatts, and a single antenna with a gain of about 30 db. The radar was flight-tested in a four-engine Navy bomber, the PB4Y-2.

Following an initial calibration flight over a measured mile at Chesapeake Bay, numerous flights were made between check points off the Atlantic coast. The true average velocity was determined by accurate measurement of the flight time and compared with the record of the ground speed indicator. In only one case did the error exceed 2 percent.

It is concluded, therefore, that with suitable refinement, a ground speed indicator of definite value is entirely practicable over water as well as over land.

PROBLEM STATUS

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

AUTHORIZATION

NRL Problem No. R04-12 (BuAer Problem No.A58.OR-C).

FLIGHT TESTS OF A GROUND SPEED INDICATOR OVER MEASURED RUNS

INTRODUCTION

The tests herein reported were conducted in connection with BuAer Problem A58.OR-C (Reference (a), which requests tne development of an aircraft instrument to indicate true ground speed and drift.

Present efforts are directed towards the development of an instrument which incorporates a continuous-wave Doppler radar. A beam of radio-frequency energy is directed downward from the aircraft so as to make an acute angle with the surface of the earth. The shift in frequency of the receiver signal is then a measure of the velocity of the aircraft.

If an antenna beam of infinitesimal width is assumed, the aircraft velocity can be computed theoretically. A finite beamwidth introduces complications, however, since the Doppler "frequency" now becomes a spread of frequencies. In the expression below, θ refers to the assumed mean value of this spread which is corrected to its true value by the beam factor B. In order to determine the effect of this spread a series of calibration flights was made over a measured mile. The theoretical expression for the aircraft velocity was then modified by the introduction of a "beam factor," the magnitude of which was determined from the calibration flights. The modified expression for ground speed follows:

$$V = \frac{B \Delta f \lambda}{2 \sin \theta} \qquad (1)$$

where B = beam factor,

Δf = assumed mean doppler frequency shift,

λ = wavelength, and

θ = transmission angle measured from the vertical.

DESCRIPTION OF EQUIPMENT

The radar employed for the tests was a low-powered conventional superheterodyne type of Doppler system using a single antenna and "magic tee" duplexer. Since the time of these tests, development has tended toward higher-powered transmitters and zero-frequency superheterodyne receivers. For a description of the high-powered set see Reference (e). As in most c-w duplexers, a 6-db loss occurs due to energy dissipated in the dummy load. The possibility of using a single antenna more than compensates for this loss. The transmitter and local oscillator tubes are 723 A/B klystrons. The receiver incorporates a 30-megacycle intermediate-frequency strip followed by a diode detector and audio amplifiers. In order to suppress low-frequency microphonic noise, a low-pass filter having a cut-off frequency of 1000 cycles per second was employed. The over-all audio-frequency response curve is flat within 1 db over the useful range from 1000 to 2000 cycles per second, but drops off sharply on either side of this range. The radar system has been tested for performance and has been found to compare favorably with standard pulse radars when the differences in power output, antenna gain, etc., are taken into consideration. Figure 1 is a block diagram of the system.

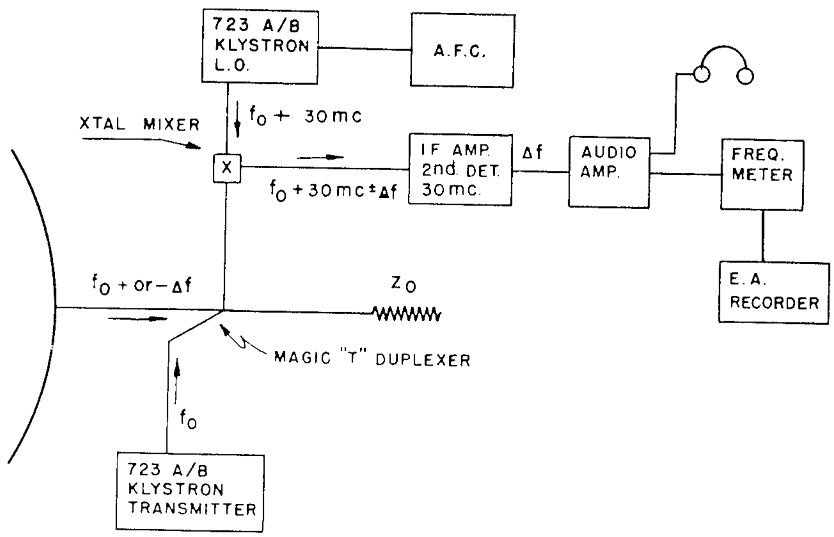

Fig. 1 - Block Diagram of Equipment

METHOD OF RECORDING

In order to obtain accurate data concerning the indicated average velocity of the aircraft, it was deemed necessary to monitor the output of the ground speed indicator throughout the entire flight. During the flight tests described in Reference (c) the signal was recorded on a tape recorder and examined later. In order to eliminate errors due to variations in recording and playback speeds, a new recording method was developed. The Doppler signal, which was normally centered around 1700 cycles per second, was fed into a Model 500-A Hewlett-Packard frequency meter. This meter "squares up" or limits the signal, and then produces a direct current, the magnitude of which depends upon the number of times the limited signal crosses the zero axis per second. This direct current was fed through an Esterline-Angus ink recorder. Recording speeds of 3 to 12 inches of chart per minute were employed.

It has been recognized for some time that a recorder having a long time constant would be beneficial, since the effects of random fluctuations in the signal would be reduced. The frequency meter in conjunction with the ink recorder was very suitable in this respect. The time constant of the entire recording system was determined by alternately switching signals of two different frequencies at the input, and measuring the excursions of the recording pen. From these data the over-all time constant was calculated to be 0.5 second. For calibration purposes a Model-79D Clough-Bringle beat-frequency oscillator was employed. It was found that with frequent zero settings the oscillator could be relied upon to indicate frequency within one percent. Ten-point calibration curves were taken before each run. A sample calibration run is shown in Figure 2. In addition, the oscillator output was wired in such a way that a 2000-cycle-per-second note could be fed to the recording setup by the throw of a switch. The recorder was checked frequently in this manner during the runs, and any drift in calibration was allowed for in the calculations.

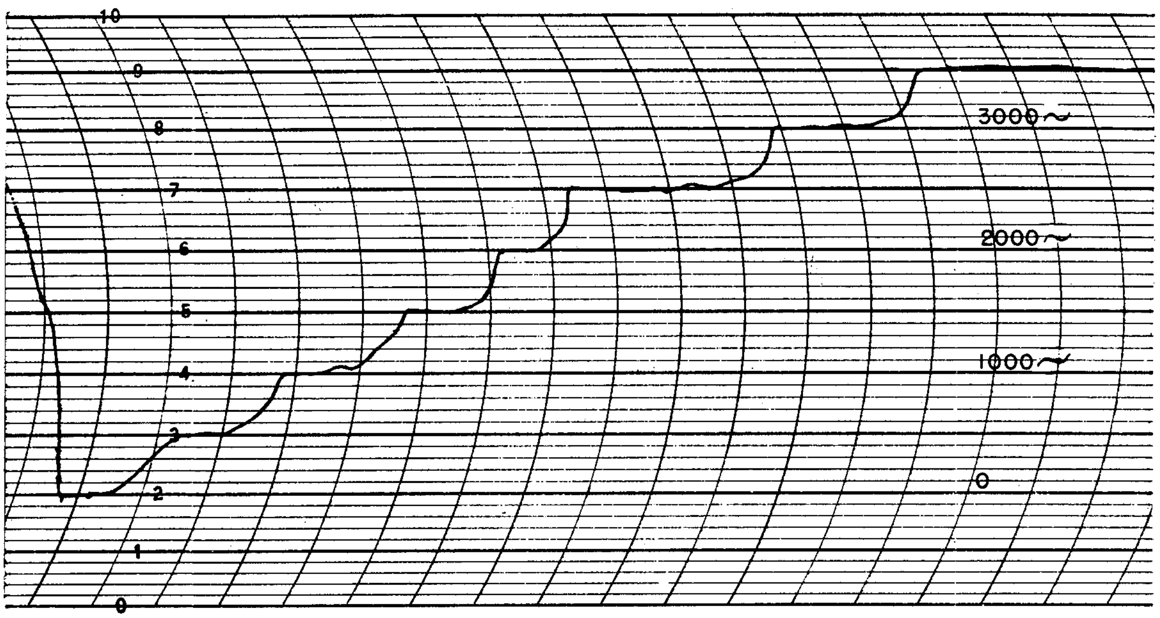

Fig. 2 - Sample Calibration Run

DESCRIPTION OF AIRCRAFT

The PB4Y-2 Privateer was chosen for the tests because it is a large stable aircraft and has an after hatch which is ideal for mounting the ground speed indicator. All equipment was either shock-mounted or mounted on rubber pads. No trouble was encountered with vibration, which is not serious in this type of aircraft. The sound level present was in excess of 100 db and was found to produce a strong interference in the system. In order to maintain high signal-to-noise ratios it was necessary to conduct all tests at altitudes of 1500 feet or less.

The ground speed indicator was mounted directly over the hatch on shock-mounts in such a manner that the antenna beam was directed aft; i.e., at a point on the water surface to the rear of the aircraft. The axis of the beam made an angle of approximately 20^0 with the vertical. This angle, which is the compliment of the angle of incidence of the beam at the water surface, will henceforth be referred to as the transmission angle θ .

CALIBRATION RUNS

Four runs were made over the measured mile at Matapeake, Md., on Chesapeake Bay. Run times were measured with stop watches by two observers. The results are tabulated in Table I. The wind was from the south. Thus on the southbound runs the plane was headed

TABLE I

Results of Calibration Runs

Run No.	Run Time (seconds)	Course	True Velocity (knots)	Doppler Frequency (cycles second)	Indicated Velocity (knots)	Error (percent)
1	25.0	SOUTH	144	1640	142	-1.4
2	21.1	NORTH	170	1830	159	-6.5
3	26.6	SOUTH	135	1540	134	-0.7
4	21.8	NORTH	165	1790	155	-6.1

NOTE: Wind was from the south

directly into the wind and on the northbound runs was headed with the wind. It is seen that the ground speed indicator reads low in both directions, but lower when flying with the wind. This is due to the effect of the waves and will be discussed subsequently. As far as is known, waves in the two directions produce errors of very nearly equal magnitude but of opposite sign. Examination of the data reveals that the ground speed indicator readings are 3.7 percent low. The factor B in the expression for ground speed (Equation 1) thus becomes 1.037.

When the indicated ground speeds in Table I are multiplied by the factor 1.037, it is found that the motion of the waves produces an error of 2.6 percent or 4 knots. The Coast and Geodetic Survey "Current Tables" for 1945 were consulted for information concerning possible currents. The table predicts substantially zero current for the time of the run so that the influence of current on the readings was apparently insignificant. As the air speed of the plane was essentially constant during the runs the wind speed may be determined from the data. The wind speed was evidently about 14 knots. In Reference (b) Dr. Hulburt gives a table indicating relationships between wind and waves. For a wind speed of 14 knots, the table indicates a wave speed of 13 knots. The conclusion, that the waves produce an error which is a fraction of the true wave speed, has been previously confirmed both experimentally and theoretically (see References (b) and (d)).

RESULTS OF TEST RUNS

A sample of a portion of a run during calm weather is shown in Figure 3. One of the 2000-cycles-per-second calibration checks is seen in the center of the trace. The nature of the record during bumpy flying is shown in Figure 4. This record was taken on the return trip from Jacksonville, Florida. A record taken during a sharp bank is shown in Figure 5.

The first run was off the Atlantic coast south of Cape May. (See Figure 6.) From the starting point, due east of Cape Henlopen, the pilot was directed to fly south to a point east of Chincoteague. The run distance was 56.0 nautical miles. The indicated velocity, 104 knots, is 0.6 percent lower than the true velocity. During this run the wind was light and from the northwest. One would therefore expect the error on the return run (i.e., northbound run) to be less negative by a small amount. The error on the Chincoteague to Cape Henlopen

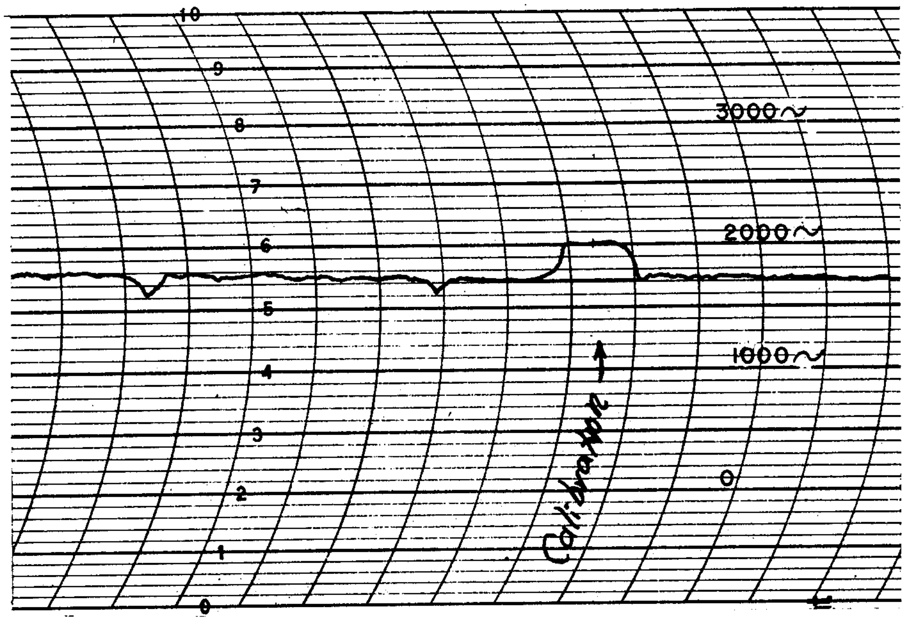

Fig. 3 - Sample Record with Calibration Check - Air Calm

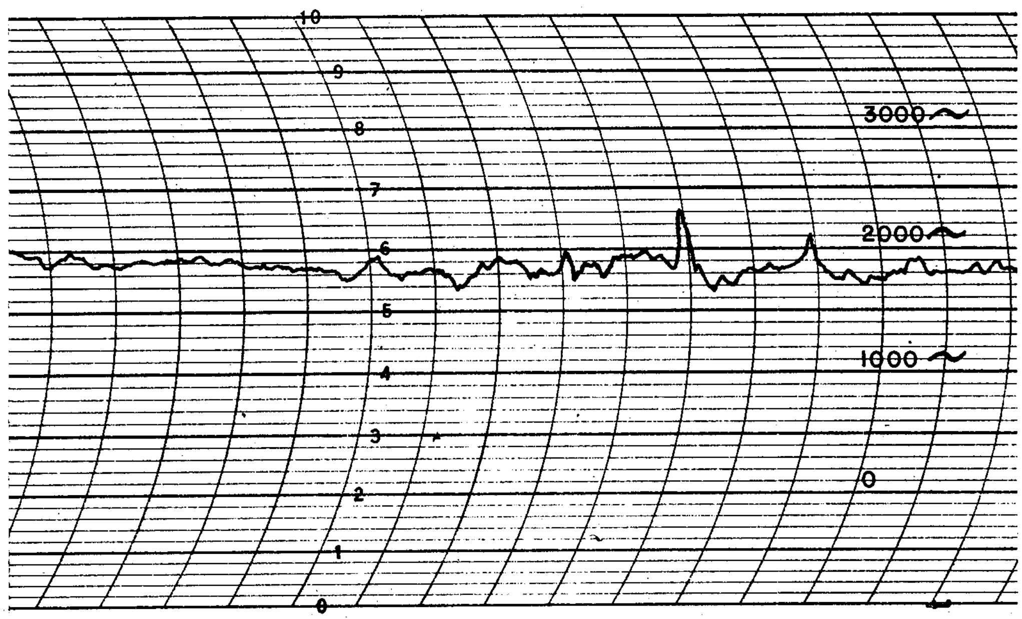

Fig. 4 - Sample Record - Air Rough

run, however, was -2.6 percent. The discrepancy is evidently due to experimental error. It must be emphasized that there is greater possibility for error in a long run of this nature than in a short run. Three main sources of error which are more serious in the longer runs are: (a) changes in transmission angle caused by crew members walking around and by the decreasing gasoline load, (b) drifts in the recorded calibration, and (c) deviations in flight from the charted course. The calibration runs all took place in a few minutes time, and the absence of errors in the afore-mentioned character is made evident by the consistency of the data.

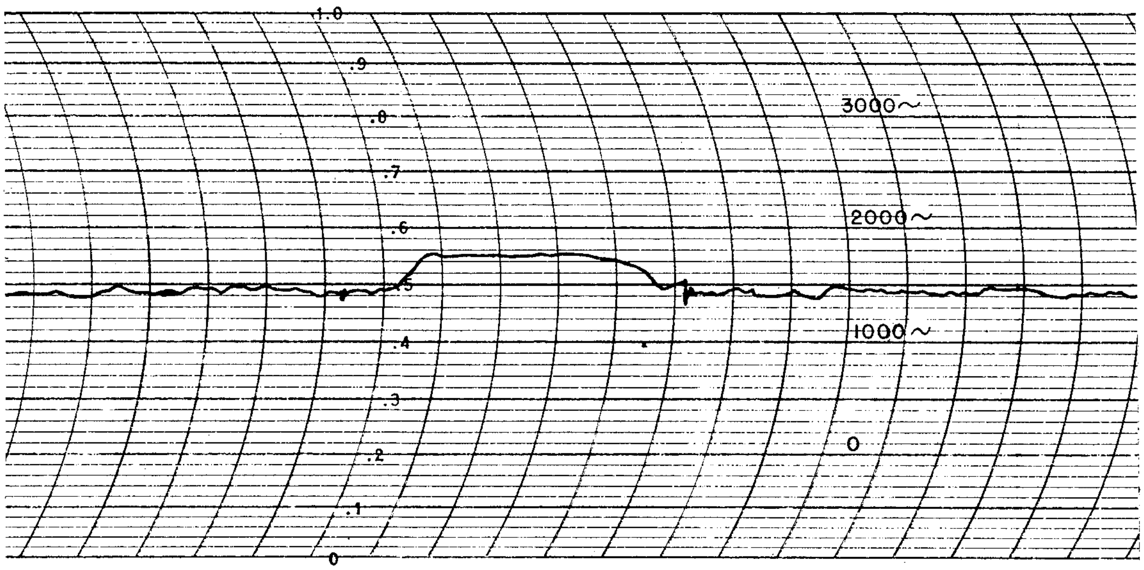

Fig. 5 - Sample Record During Bank

Following the Cape Henlopen-Chincoteague runs it was decided to make additional runs over greater distances. For this purpose a run between Cape Hatteras and Jacksonville was decided on (see Figure 7). This run, a distance in excess of 400 nautical miles, provided an opportunity for a good check on the reliability of the ground speed indicator under varying conditions of sea and weather. During the southbound run the weather was generally fair, and the wind moderate from a direction approximately at right angles to the ground track. The over-all error for the run was -1.3 percent.

During the return run the wind was light at the start but increased as the plane approached Cape Fear. Wind directions varied. Numerous whitecaps were visible. Flying was very "bumpy" and on several occasions a light rain was encountered. The rain did not appear to interfere with the operation of the equipment although it is possible that a heavy rain would. Owing to misjudgment of the wind on the part of the pilot, the plane was blown considerably off its course, passing directly over Cape Fear. This was a graphic illustration of the need for a ground speed indicator equipped to measure both speed and drift. The error for this run was +1.6 percent.

As the plane passed over Cape Fear the pilot was directed to change course and head for Cape Hatteras. The error for the Cape Fear to Cape Hatteras run was +0.8 percent. The over-all error for the return run from Jacksonville to Cape Hatteras was calculated independently from the data and found to be +1.5 percent. The results of the above runs are tabulated in Table II on page 9 of this report.

ACCURACY OF MEASUREMENTS

There are numerous sources of error in the present method of measuring ground speed and these will be considered in detail.

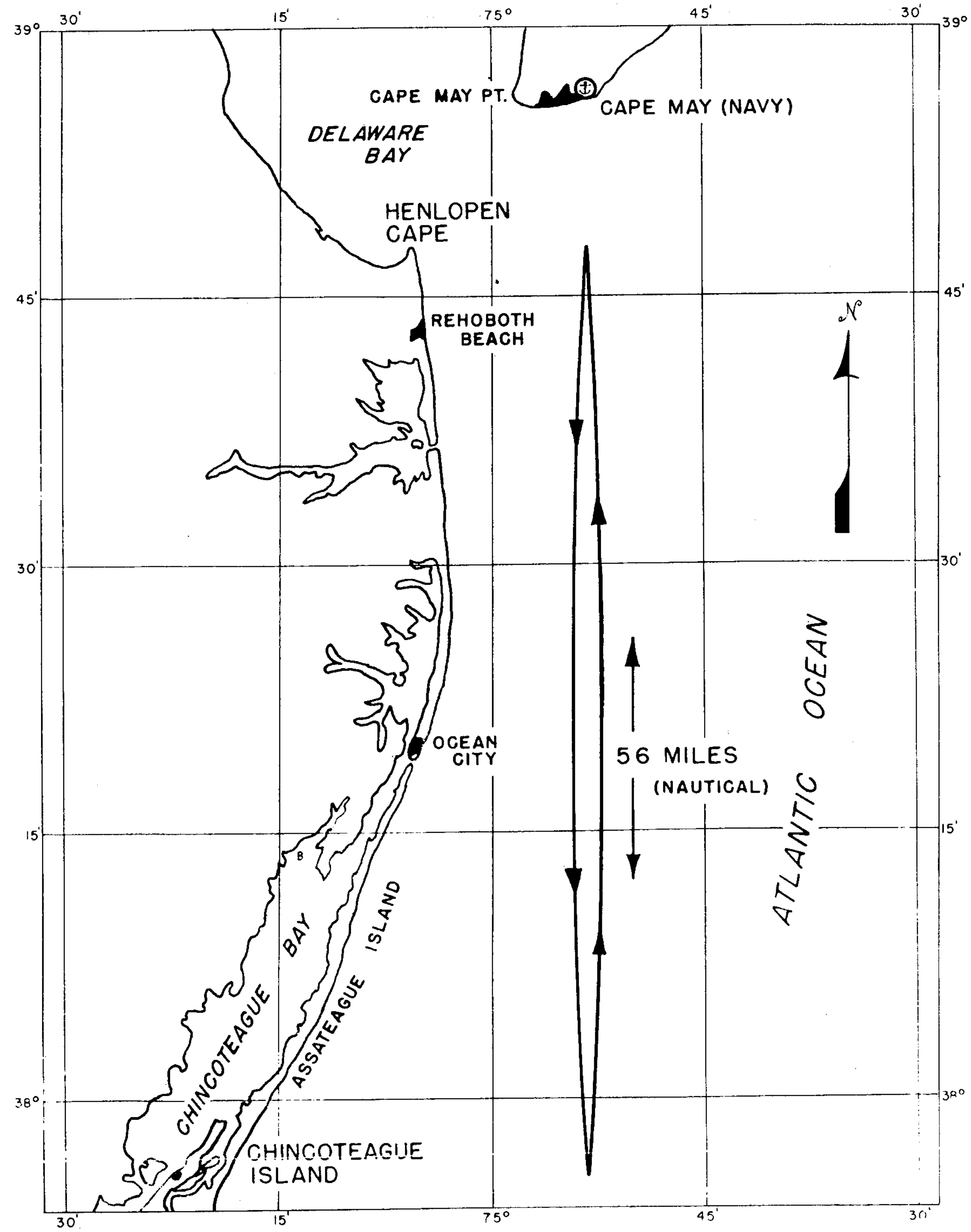

Fig. 6 - Cape Henlopen - Chincoteague Run

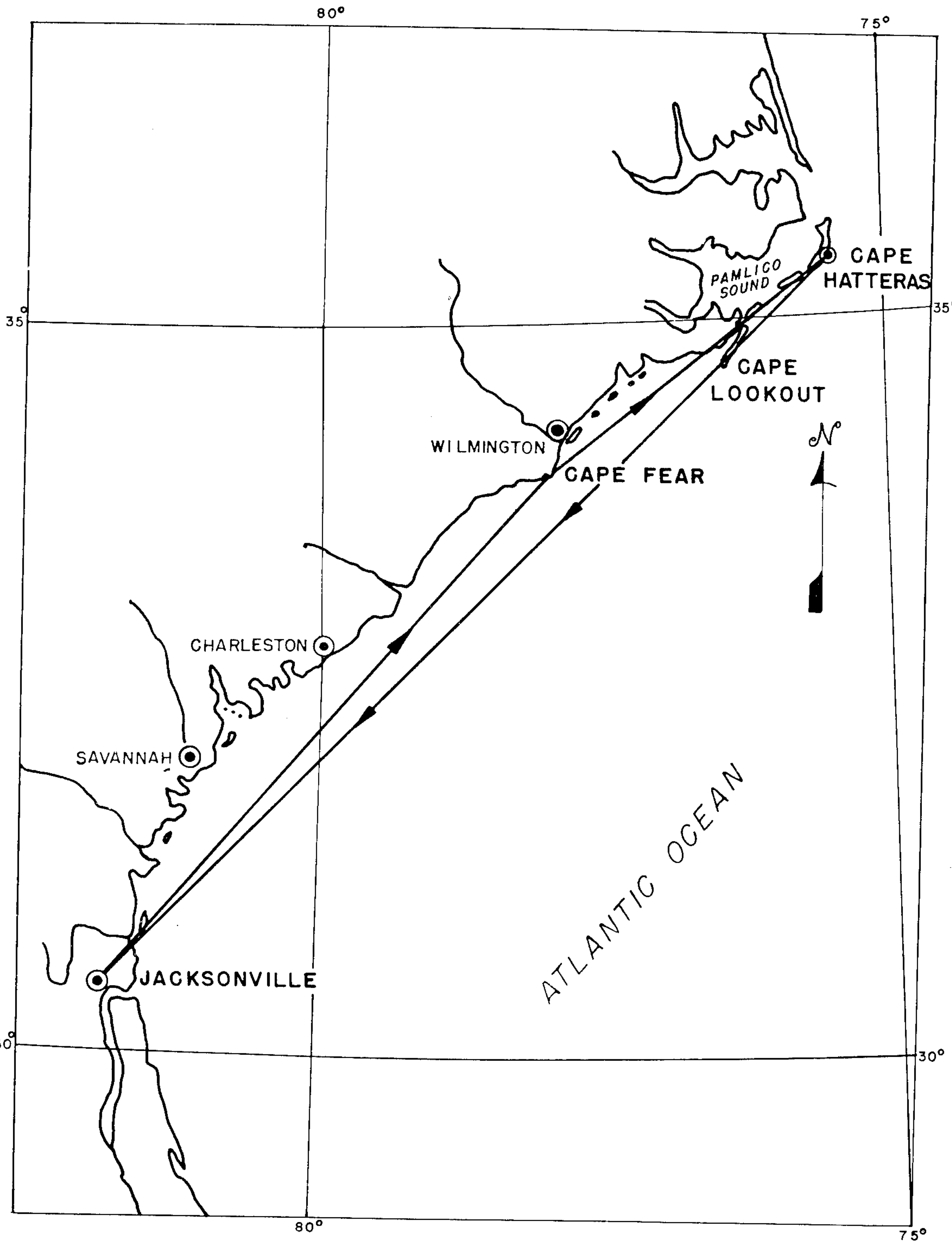

Fig. 7 - Cape Hatteras - Jacksonville Run

TABLE II

Results of Test Runs

Starting Point	Destination	Distance (miles)	True Velocity (knots)	Doppler Frequency (cycles/sec.)	Transmission Angle (degrees)	Indicated Velocity (knots)	Error (Percent)
Cape Henlopen	Chincoteague	56.0	165	1820	21.0	164	-0.6
Chincoteague	Cape Henlopen	56.0	149	1610	21.0	145	-2.8
Cape Hatteras	Jacksonville	408.1	153.2	1620	20.3	150	-1.3
Jacksonville	Cape Fear	263.6	173.3	1870	20.0	176	+1.6
Cape Fear	Cape Hatteras	147.9	168.5	1810	20.0	170	+0.8
Jacksonville	Cape Hatteras	411.5	171.5	1850	20.0	174	+1.5

(a) Transmission angle from the vertical, θ – The calculated ground speed is inversely proportional to the sine of the transmission angle:

$$V = \frac{K}{\sin\theta} \qquad \text{where K is a constant} \tag{2}$$

Differentiating (2),

$$\frac{dV}{d\theta} = \frac{-K\cos\theta}{\sin^2\theta} = \frac{-K}{\sin\theta\tan\theta} \tag{3}$$

For small changes in θ the fractional error may be written:

$$\frac{\Delta V}{V} = \frac{-\Delta\theta}{\tan\theta} \tag{4}$$

Let us now assume $\theta = 20^0$, and that the error is 1 percent.

$$\Delta\theta = -\left(\frac{\Delta V}{V}\right)\tan\theta = 0.00364 \text{ radian} \tag{5}$$

$$= 12.5 \text{ minutes.}$$

It is thus seen that an error of only 12.5 minutes in the transmission angle will produce an error of 1 percent in the indicated ground speed. Although the transmission angle was estimated to the nearest tenth of a degree, or 6 minutes, it is doubtful if the readings were accurate to within less than 20 minutes or a little less than 2 percent. One obvious answer to this problem is to have an antenna which can be rotated about a vertical axis. If the readings obtained with the antenna first in its normal position and then rotated 180^0 are averaged, any error in θ will be very nearly eliminated.

(b) Plane heading – When the direction of the wind is such as to produce drift, the plane heading will not coincide with the ground track. The ground speed indicator will then measure the true ground speed along the ground track multiplied by the cosine of the angle between the plane heading and the ground track. It is estimated that a wind of about 20 knots at right angles to the ground track would produce an error of 1 percent in the indicated ground speed. This error may, of course, be eliminated by orienting the antenna until it is directed along the ground track. Means of accomplishing this have been investigated.

(c) Plane navigation - Navigation errors and random variations in the heading of the plane undoubtedly introduced errors, but these errors are thought to be very small.

(d) Time measurement - During the calibration runs the observers were able to determine accurately the start and finish points with the aid of the double sighting towers provided by the Navy. When the two towers on shore appear to coincide, the observer is exactly on the starting line of the measured mile. The finishing line is determined similarly. The timing errors on the Cape Henlopen-Chincoteague runs were appreciable owing to the lack of well-defined start and finish points. On the Cape Hatteras-Jacksonville runs the timing errors were undoubtedly negligible.

(e) Rolling and pitching - Theoretical considerations show that, for a pencil beam, pure rolling will not affect the indications of a ground speed indicator. As a first approximation to pitching, let it be assumed that the plane pitches in a sinusoidal manner about a fixed angle and that the horizontal velocity remains constant during the pitch. How valid these assumptions are is not yet known, but they should serve as a rough approximation. The transmission angle then becomes

$$\theta = \theta_0 + \Delta\theta \sin \omega_p t$$

where θ_0 = transmission angle in absence of pitch,

$\Delta\theta$ = angular amplitude of pitch, and

ω_p = angular frequency of pitch.

The Doppler frequency shift is then

$$f = \frac{2v}{\lambda} \sin (\theta_0 + \Delta\theta \sin \omega_p t). \qquad \text{.....(6)}$$

If the expression is averaged the average frequency $\bar{f}$ becomes:

$$\bar{f} = f_0 \cdot J_0 \ (\Delta\theta) \qquad \text{.....(7)}$$

where J_0 is the zero order Bessel function of the first kind.

Calculations show that $\Delta\theta$ must become equal to 11.5 degrees before an error of 1 percent results. During most of the flights the magnitude of pitch, as far as could be determined by observing the excursions of the bubble in a level, was less than 2 degrees. It is therefore concluded that errors due to pitching and rolling were insignificant except during rough weather. It should be realized, however, that a change in the average attitude of the aircraft will cause serious errors. As an example, if the transmission angle is 15^0 a change to $15^0\ 10'$ will cause an error of 1 percent. This makes a stabilized antenna, or stabilization of data, a necessity.

(f) Frequency determination - The calibrating oscillator was found to be accurate within 1 percent. In averaging the trace on the chart, a planimeter was used except where the trace was so constant that the average could be estimated accurately by eye. The error involved in reading the charts was probably less than 2 percent.

(g) <u>Over-all error</u> - If all of the errors discussed were to add in the same sense, the over-all error would be less than 5 percent. This error is exclusive of the effects of wave motion and current, which appear capable of increasing the error by a few more percent. That the over-all error was less than this total is indicated by the data.

PROPOSED IMPROVEMENTS

Two main improvements are under consideration: (a) an increase in power output, and (b) a method of drift determination. The use of continuous-wave magnetrons has resulted in a large increase in the output power and has made a substantial increase in the altitude from which useable signals have been received.

Several methods of drift determination have been proposed. Of these, two have been considered. The first method, the V-beam method, employs two antennas so oriented as to direct beams a few degrees to port and to starboard of the plane heading. The frequencies of the signals from the two beams will differ; the receiver pointing in the direction of drift will receive a higher Doppler note. From this process the drift angle and ground speed can be determined simultaneously. This method has the disadvantage of necessitating the use of two antennas.

In the other system, a single antenna is rotated until minimum Doppler frequency is obtained. The bearing of the antenna is then at right angles to the ground track, and the drift angle may be determined. This system has the disadvantage that the antenna must be rotated 90^0 between the drift angle and ground speed measurements.

CONCLUSIONS

It is concluded that with increased power output and suitable refinements a ground speed indicator capable of indicating speed with an error of less than 5 percent and capable of indicating drift angle is well within the realm of possibility. Although a large volume of data will be necessary before the true effect of wave motion can be determined, preliminary indications are that the error produced will be small.

* * *

REFERENCES

(a) BuAer ltr Aer-E-339-IDS F31-1 (12) NP 14 of 21 August 1943 to Dir. NRL (SRPPB).
(b) E. O. Hulburt, NRL Report H-2422, "Report on the Doppler Frequency Change in Radiation Reflected from the Waves of the Sea," 19 December 1944.
(c) C. L. Estes and J. E. Gibson, NRL Report R-2552, "Flight Test of a Ground Speed Indicator," 5 June 1945.
(d) NRL ltr report C-F42-5(390Ga) Ser. C-390-305/45 to Chief BuAer dated 9 August 1945.
(e) NRL ltr report C-1390-106/47 (1392/wd) to BuAer dated 14 July 1947.
(f) NRL ltr report C-1390-211/47 (1391/wd) to BuAer dated 2 January 1948.

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