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REPORT

FLIGHT TESTS
OF A GROUND SPEED INDICATOR

BY

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J. E. GIBSON

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Radio Division-Centimeter Wave Section
Report No. R-2552; Problem No. A58-OR

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NAVAL RESEARCH LABORATORY
WASHINGTON 20, D. C.

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ABSTRACT

Flight tests of an X-band CW radar system, Model AN/PPS-1, were made on board a blimp in order to investigate the performance characteristics of an equipment of this type in obtaining ground speed indications. Flights were made at altitudes from 500 to 3,000 feet on courses both with and against the wind, and the effect of varying the angle of transmission with respect to the earth was investigated.

It was found possible to obtain useful speed indications at altitudes up to about 1,000 feet. At higher altitudes the quality of the speed-indicating signal becomes progressively poorer. An increase in transmitter power to 30 watts should make it possible to obtain reliable signals up to 30,000 feet. The data suggests that the water wave velocity will introduce an error in the indicated ground speed. However, a subsequent investigation of this effect has shown that this error will be small.

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TABLES AND PLATES

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FLIGHT TESTS OF A GROUND SPEED INDICATOR

INTRODUCTION

1. The subject tests were conducted in connection with Problem A58-OR or Reference (a), the purpose of which is the development of an aircraft instrument to indicate true ground speed and drift.

2. The system considered for this purpose makes use of the doppler frequency shift which occurs when radio signals are transmitted over a path of changing length. In this system the radio transmitter and receiver are installed on the aircraft, and a continuous wave transmitted signal is directed downward in such a manner that the axis of the antenna beam makes an acute angle with the surface of the earth. Ground or sea return constitute the received signal. Due to the doppler effect, the received signal has a different frequency from that of the transmitted signal. The frequency difference between the two signals is related to the velocity of the aircraft. With proper orientation of the antenna, ground speed and drift may be determined.

3. Experiments and flight tests with S-band and X-band speed indicator systems have shown the necessity of suppressing microphonic modulation of the transmitter. Since the elimination of vibration is not a simple problem, the subject tests were undertaken aboard a blimp in an effort to gain performance data under conditions of minimized vibration. The primary objectives of these tests were to obtain information on the accuracy of ground speed indications obtainable by this method, and to determine the maximum altitude for satisfactory operation and the optimum angle of transmission with respect to the earth.

DESCRIPTION OF EQUIPMENT

4. A Sperry AN/PPS-1 X-band continuous-wave doppler equipment was used on these tests. This equipment has two antennas, each of which has a beam width of 5 degrees. Type 723 A/B reflex klystrons are used for both transmitter and local oscillator. The transmitter power output is about 30 milliwatts. The receiver is a superheterodyne with a 30 mc IF amplifier having a bandwidth of 300 kc and incorporating automatic frequency control. An audio amplifier raises the level of the signal sufficiently to drive several pairs of headphones. The equipment is divided into three units: the transmitter-receiver unit which houses the RF components and the IF and audio amplifier, and provides a plastic cover for the two 18 inch dishes; the power supply unit; and the battery box unit which contains a six volt storage battery and a two volt booster cell.

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FLIGHT TESTS

5. The equipment was installed aboard a blimp at the Naval Air Station at Patuxent, Maryland. The transmitter-receiver unit was mounted in a slip tank compartment of the blimp on a hinged metal frame-work which enabled the angle of transmission to be varied easily. No additional windows other than the one incorporated in the equipment intercepted the beam. Transmission was to the rear and downward at angles between 0 and 45 degrees from perpendicular. During preliminary flights the doppler beat note was observed by means of headphones, to gain initial information on the operation of the equipment.

6. After a flight plan had been organized, provision was made for signal recording on a magnetic wire recorder. Flights were made at altitudes from 500 to 3,000 feet using various angles of transmission, and on courses both with and against the wind. The ground speed was measured optically (1) by timing the passage of the blimp shadow over a known distance, and (2) by measuring air speed with the blimp ground speed held at zero; then correcting the air speed indicator readings taken in flight. The angles of transmission were measured with an adjustable level during the recorded runs. Upon completion of the flights, the magnetic wire recordings were transcribed to lateral-cut disc records. The signal from a 1,000 cps tuning fork oscillator had been recorded on the original wire at the time the flights were made in order that differences in recording, re-recording and playback speeds could be taken into account.

7. The majority of the flights were made over Chesapeake Bay. During most ot the tests the water surface was somewhat choppy, with numerous whitecaps in evidence. The surface was not comparable in roughness to the ocean, in that the wave amplitudes were smaller than those usually present at sea, and the pronounced ocean swells were absent.

8. A condensation of the recordings made on these tests has been prepared for demonstration purposes and is available at the Sound Division, NRL. Reference should be made to recording No. 1091.

ANALYSIS OF SOUND TRACKS

9. The frequency difference between transmitted and return signals is given by

$$\Delta f = N - N' = \frac{2NV \sin \theta}{C + V \sin \theta} \qquad (I)$$

where

N = transmitted frequency
N' = received frequency

[redacted]

V = horizontal velocity of aircraft in direction away from point of reflection on earth
C = velocity of propagation of radio waves
θ = angle of transmission measured from the vertical

Since the velocity of the aircraft is small compared to that of radio waves, Equation (I) may be approximated as

$$\Delta F = \frac{2NV \sin \theta}{C} \qquad \text{(II)}$$

10. Measurements of the frequencies of the recorded signals have been made, using a General Radio electronic frequency meter and a Hewlett-Packard sound analyzer. The former indicates frequency directly, while the latter permits analysis of the energy distribution in a band of frequencies. In the case of the General Radio frequency meter the values for Δf are those values indicated by the meter. On the other hand, the values of Δf obtained with the analyzer are the frequencies indicated by the analyzer to have greatest amplitude within the respective bands for the different runs. The data given in Tables 1 and 2 are the values obtained by averaging the results of a number of measurements for each run. The values given for indicated ground speed were obtained by calculations from Equation (II). In Plates 1, 2, and 3 the results of three test runs are shown. The charts were obtained with the aid of a Hewlett-Packard frequency meter and a recording milliameter.

ACCURACY OF INDICATED SPEEDS

11. Tests to investigate the effect of angle of transmission upon strength and quality of received signal, described more fully in paragraphs 27 and 28, show that, for the conditions of water surface prevailing during these tests, the optimum angle is about 25 degrees. The results of tests made at altitudes from 500 to 3,000 feet at angles from 18 to 27 degrees are given in Table 1.

12. The accuracy of the calculated values of ground speed is limited by several possible sources of experimental error. It is considered that the measured value of θ is accurate to ± 5 degrees only. As a result, the possible error in the calculated ground speed for a measured value of θ of 27 degrees is about 17 percent. Although a 1,000 cycle tone was recorded during the tests for the purpose of record speed calibration, the recording and playback speeds were not absolutely constant, and the resulting possible error is estimated to be of the order of 3 percent. The most accurate frequency measurements are believed to be those obtained with the Hewlett-Packard analyzer,

[redacted]

and the possible error in determining the frequency component of maximum amplitude is estimated to be about 3 percent. Finally, the possible error in the ground speed measured by compensation of air speed indicator readings is considered to be about 5 percent. Thus if all the possible experimental errors add in the same sense, a total error amounting to 25 or 30 percent of the indicated speed may be obtained. Hence the value of the data in Table 1 is qualitative rather than quantitative.

13. Probably the most significant feature of the tabulated data is the fact that the calculated ground speeds tend to be lower than the true speeds when flying with the wind and higher when flying against the wind. It is suspected that this is due to the water wave motion, if the effect is real, since examination of the experimental errors fails to show any other factor capable of introducing a selective error of this nature. However, the volume and accuracy of the data taken is insufficient to preclude the possibility that this effect is only coincidence.

14. One method of recording the output of the ground speed indicator is to display the indications of an electronic frequency meter on a recording milliameter. Three such recordings are shown in Plates 1, 2, and 3. In all three recordings a Hewlett-Packard frequency meter was employed. The frequencies indicated by this meter differ by a few percent from the frequencies as measured with the General Radio frequency meter due to different response characteristics of the two meters. In Plate 1 the altitude of the blimp was 1000 feet and the indicated doppler frequency appears quite steady and reliable. The deterioration of the signal with altitude is clearly shown in Plate 2 where the altitude of the blimp was 3000 feet. The increased buffeting of the blimp by a higher wind together with the lower signal-to-noise ratio are undoubtedly responsible for the unsteadiness of the signal. In Plate 3 the blimp flew a circular course at constant air speed. The expected increase and decrease of the ground speed is shown by the rise and fall of the doppler frequency.

15. Reference (b) reports the results of tests to determine the possible effect of water wave motion upon the accuracy of ground speed indications. These tests were made with the same radar system used in the subject flight tests, and the equipment was installed in a lighthouse fifty feet above Chesapeake Bay. The tests and also subsequent tests indicate that normal ripple-covered waves contribute only a small error.

16. Comparison of the over-water run of row 14 in Table 1 with the over-land run of row 15 shows that the accuracy for the two cases is about the same, and this may indicate that water wave velocity is not significant.

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FACTORS AFFECTING MAXIMUM ALTITUDE

17. The value for bandwidth of the audio output signal as measured between half power points with the Hewlett-Packard analyzer are given in Table 1. It may be seen that with increasing altitude the bandwidth increases. This deterioration of output signal quality limits the altitude at which the system is effective.

18. The primary cause of this deterioration of signal quality has not been conclusively determined. However, by way of explanation of this effect, it can be pointed out that the actual operation of the ground speed indicator application of CW radar departs from the ideal case outlined in paragraph 2 in several respects, covered in the following paragraphs 19 through 24.

19. Effect of Antenna Beam Width. A single beat frequency is not obtainable in this system for the reason that the antenna beam width, while small, is not zero, and therefore a large area on the earth's surface is illuminated. The angle of transmission varies throughout the beam and thus the return signal consists of a band of frequencies whose width is primarily determined by the antenna beam width.

20. Signal to Noise Ratio. That the signal to noise ratio will decrease with increased altitude is self-evident. However, since the solid angle intercepted by the reflecting area on the earth is not a function of altitude, the power of the return signal in this system can be expected to vary inversely with the square of the altitude (range) rather than with the fourth power of the range as in the case where the target has a fixed cross section. On the basis of the transmitted power of the AN/PPS-1 of 30 milliwatts, the power required for the same signal strength at 30,000 feet as that obtained in the tests at 1000 feet is estimated to be 27 watts. It is expected that tubes delivering this power will be available shortly.

21. Random Transmitter Modulation. It was mentioned in paragraph 3 that these tests were undertaken aboard a blimp to avoid as far as possible microphonic modulation of the transmitter. Analysis of the effect of random amplitude and frequency modulation of the transmitted signal on the quality of the received signal is beyond the scope of this report. However, it can be shown that for amplitude modulation the beat frequency of the received signal (the received signal is that portion of the transmitted signal injected directly into the receiver plus the return signal) will be amplitude modulated at the modulation frequency, and for frequency modulation the doppler audio beat note will be frequency modulated at the modulation frequency.

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In the case of amplitude modulation, the depth of modulation in the received signal at the modulation frequency is dependent upon the modulation percentage in the transmitted signal and upon the degree of coupling between transmitter and receiver. In the case of frequency modulation, the depth of modulation of the output signal (deviation of frequency of doppler audio beat note) is dependent upon frequency deviation in the transmitted signal, modulating frequency and range (or altitude). Thus it is important to suppress random modulation of the transmitted signal.

22. Scintillation of the Sea Surface. The quality of the return signal will also be affected by the nature of the sea surface. It is self-evident that certain portions of the sea will reflect more energy than others at any given instant. The sea surface may be thought of as an aggregation of reflecting elements. These elements, while not necessarily mirror-like, will have directional properties as regards their ability to reflect incident energy.

23. Now, since the sea surface is in continuous motion an individual reflecting element of sea surface exists as such for only a short time. Viewed as a whole, the illuminated area of sea surface appears to the CW radar receiver to glitter or scintillate from many points, and the return signal is actually composed of the sum of many individual wave trains, each of short duration, having a frequency of approximately $N (1 - 2V/C \sin \theta)$, and bearing a random phase relationship with one another.

24. Therefore the resultant return signal can be expected to be modulated in amplitude and phase in a manner determined by a number of factors, including for example the average duration of the individual elemental reflectors, and the number of elemental reflectors existing simultaneously. The extent to which this modulation conflicts with the doppler beat frequency is not known.

OPTIMUM ANGLE OF TRANSMISSION

25. Tests to determine the optimum angle of transmission were made at angles from three to forty-one degrees with the vertical. The data for these runs are given in Table 2.

26. It was found that the best quality of beat note was obtained at an angle of about 25 degrees. At small angles the strength of the return signal was high, but the quality was so poor that an analysis of its band width with the analyzer was impossible. At angles approaching 45 degrees the return signal intensity decreased sharply.

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CONCLUSIONS

27. Flight tests of a CW radar system on board a blimp show that a useful beat frequency can be obtained at low altitudes. The accuracy of the speed indications obtained is highly dependent upon the maintenance of a known angle of transmission, and the measurements of speed obtained in flights with and against the wind suggest that the motion of the water produces an error in the indicated ground speed, although this error is probably small.

28. The quality of the beat frequency was found to deteriorate with altitude. Possible causes are:

(a) Insufficient transmitter power
(b) Inadequate transmitter frequency constancy
(c) Modulation of the return signal by the water surface.

29. The optimum angle of transmission was found to be about 25 degrees, from the standpoint of signal strength and quality of the return signal.

REFERENCES

(a) BuAer ltr Aer-E-339-IDS F31-1(12) NP14 of 21 August 1943 to Dir NRL (SRPPB)

(b) NRL ltr to BuAer C-S42-5(390JGM) Ser C-390-307 of 20 October 1944

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SPEED INDICATIONS AT VARIOUS ALTITUDES

					GR Breq. Meter			H-P Analyzer			
Run No.	Altitude (ft)	*	Angle (θ) degrees	True Gnd. Speed	Beat Freq. (cps)	Indicated Speed	% Error	Dominant Freq.	Freq. Spread	Indicated Speed	% Error
1.	500	W	22	60	741	62	+ 3.3	760	150	63	+ 5
2.	500	a	22	34	459	38	+ 11.8	480	155	40	+ 17.7
3.	500	W	27	60	855	58	-3.3	900	180	62	+ 3.3
4.	500	circle	27	60-34	855-475	58-33	-3.5-2.9				
					- - -	- - -	- - -	- - -	- - -		
5.	1000	W	27	60	840	57	-5.0	900	180	62	+ 3.3
6.	1000	a	27	34	500	34	0	560	135	38	+ 11.8
					- - -	- - -	- - -	- - -	- - -		
7.	2000	W	18	75	670	67	-10.7	646	250	65	-13.3
8.	2000	a	18	28	310	31	+ 10.7	300	200	30	+ 7.2
9.	2000	W.	22	75	740	61	-18.7	760	345	63	-16.0

[redacted]

TABLE 1 (page 1)

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					GR Freq. Meter			H-P Analyzer			
Run No.	Altitude (ft)	*	Angle (θ) degrees	True Gnd. Speed	Beat freq. (cps)	Indi-cated Speed	% Error	Domi-nant Freq.	Freq. Spread	Indi-cated Speed	% Error
10.	2000	a	27	20	380	26	+ 30	400	200	27	+ 35.0
11.	3000	W	22	85	710	59	-30.6	925	425	77	-9.4
12.	3000	a	22	15	250	21	+ 40	not measurable			
13.	500	cross wind	22	45	510	42	-6.6	525	90	44	-2.2
14.	500	W (water)	22	63	700	58	-7.9	700	105	58	-7.9
15.	500	W (land)	22	63	744	62	-1.6	712	140	59	-6.3

* "W" signifies flying with wind, "a" against wind.
θ Angle of Transmission with respect to vertical.
All speeds given in knots.

[redacted]

TABLE 1 (page 2)

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EFFECT OF ANGLE OF TRANSMISSION

True Ground Speed 63 Knots
Altitude 500 ft.
Flying with wind over water

		GR Freq. Meter			H-P Analyzer			
Run No.	∅ (degrees)	Beat Freq. (cps)	Indicated Speed	% Error	Dominant Freq.	Freq. Spread	Indicated Speed	% Error
1.	3	175	104	+63.0	not measurable			
2.	12	330	49	-22.2	325	140	49	-22.0
3.	22	600	50	-20.6	575	150	48	-24.0
4.	27	800	55	-12.7	760	90	52	-7.5
5.	31	900	54	-14.3	1000	220	60	-4.8
6.	38	not measured			1150	200	58	-7.9
7.	41	1000	47	-25.4	1305	170	62	-1.6

[redacted]

TABLE 2

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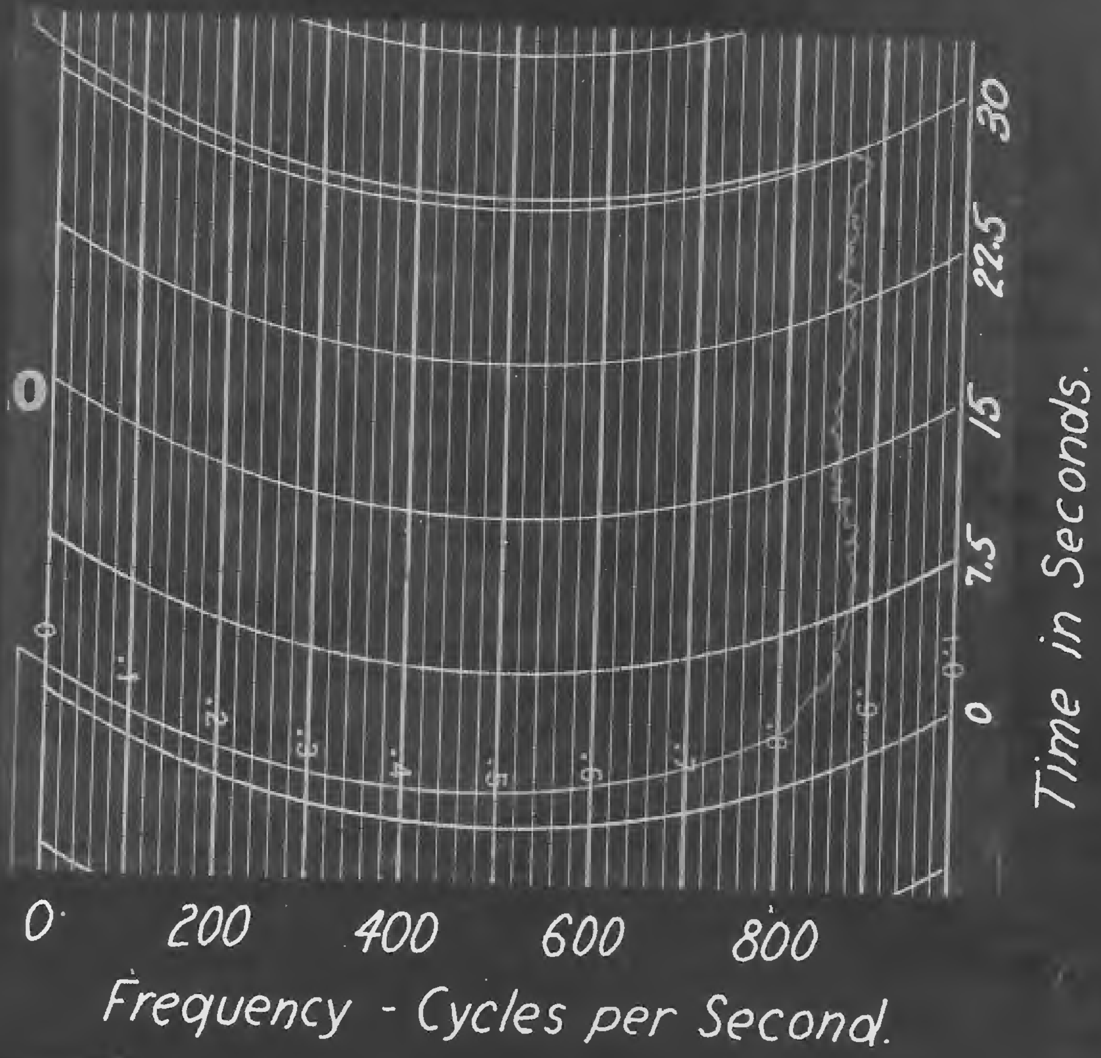

Plate I - Sample record of test run - Altitude 1000 Feet.

Ground Speed measured by pilot 60 Knots.

Ground Speed calculated from record 59 Knots.

Error 2 per cent.

[redacted]

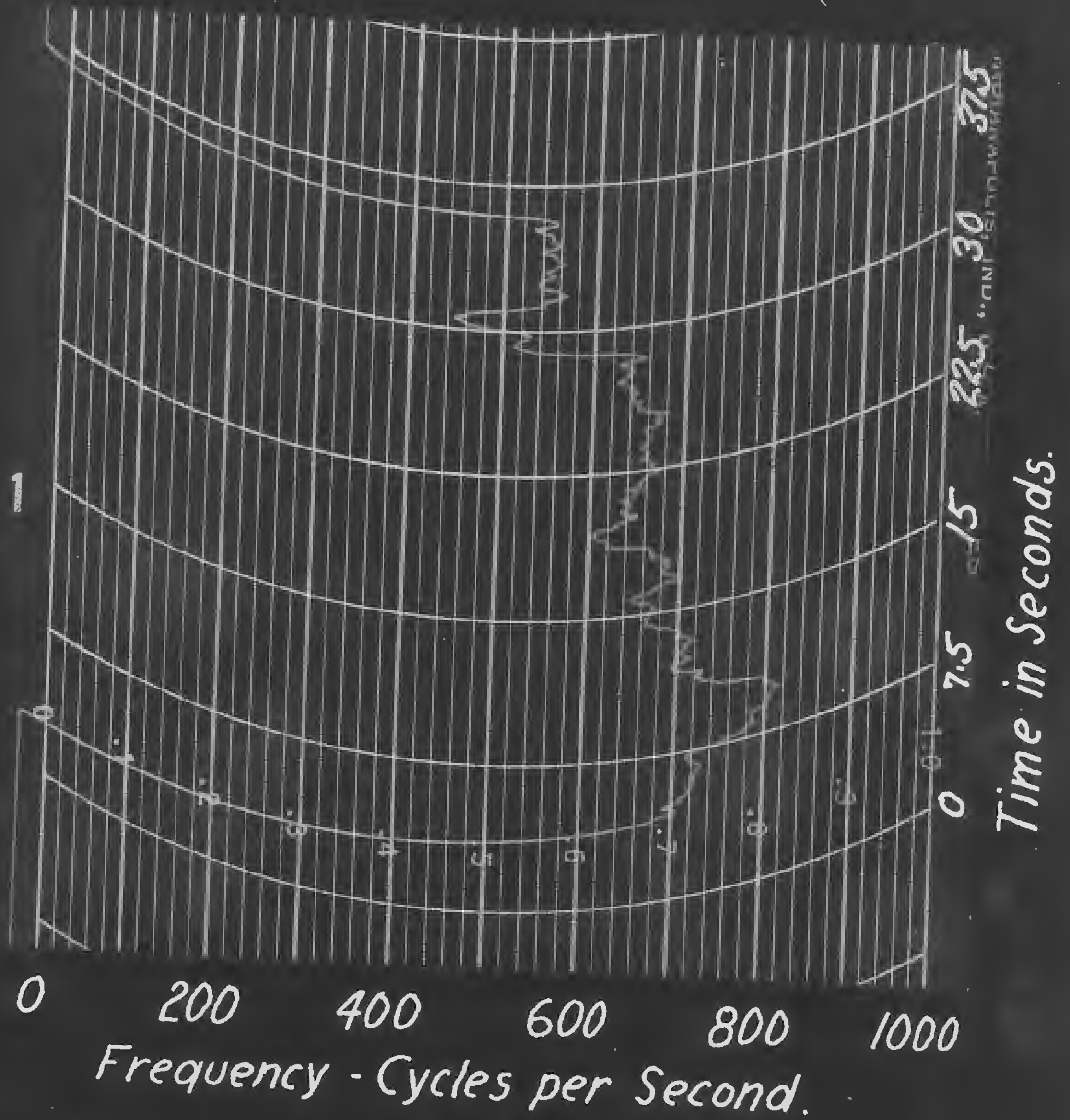

Plate 2 Sample record of test run - Altitude 3000 Ft.
Ground Speed measured by pilot - 85 Knots.
Ground Speed calculated from record - 54 Knots
Error 36 per cent.

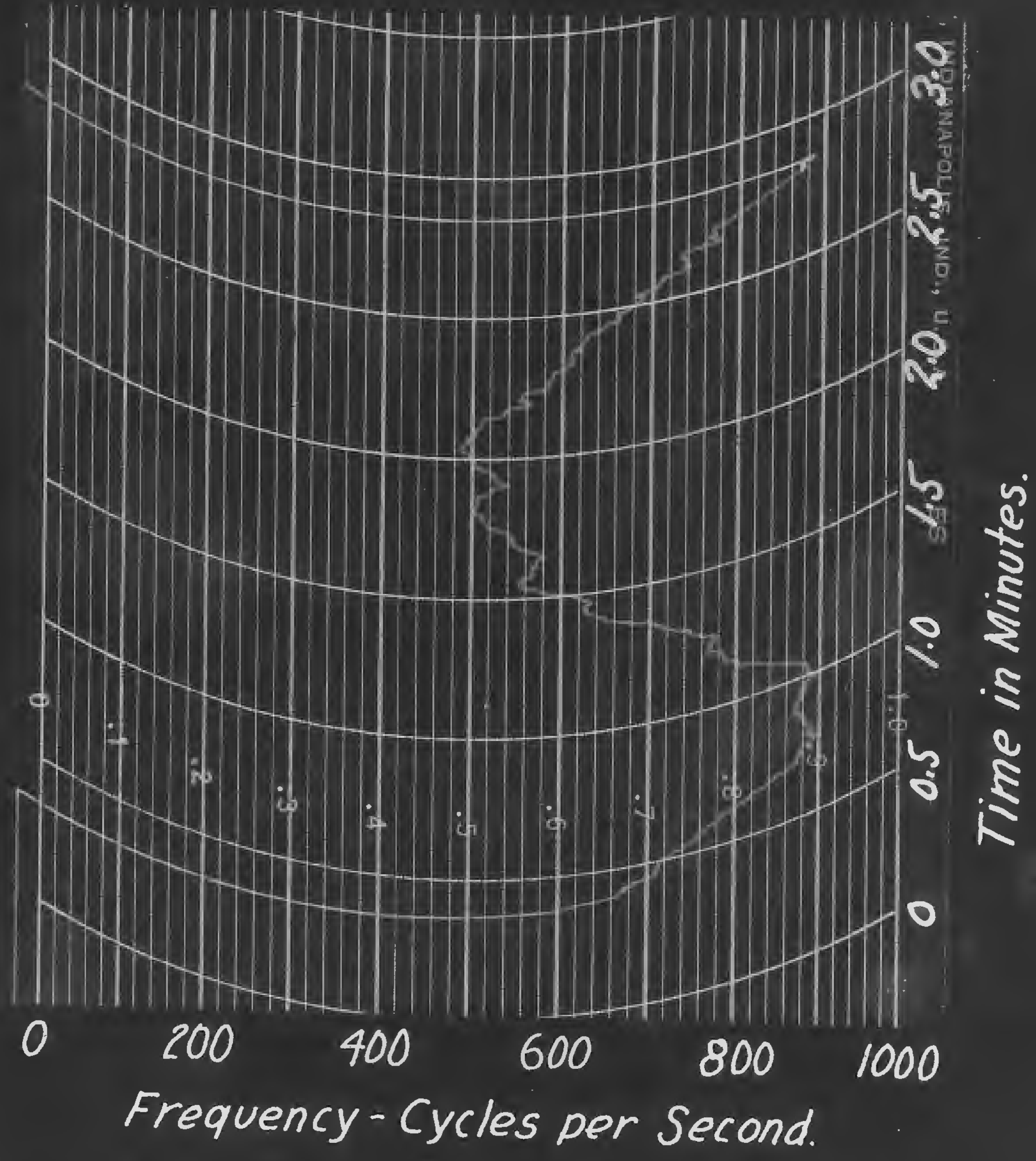

Plate 3 - Record of Blimp flying Circular Course

Air Speed of Blimp - 47 Knots.

Wind Speed - 13 Knots.

Maximum Calculated Ground Speed - 60 Knots.

Error - 0 Per Cent.

Minimum Calculated Ground Speed - 34 Knots

Error - 0 Per Cent.