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Navigational errors in pressure pattern flying

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NAVIGATIONAL ERRORS IN PRESSURE PATTERN FLYING

by

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Lieutenant Commander, United States Navy

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Submitted in partial fulfillment
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for the degree of
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PREFACE

This study was made during the first five months of 1949, at the United States Naval Postgraduate School, Monterey, California. A flight to Honolulu, T. H., with VR-2, and one to Kodiak, Alaska, with VR-5, were made to observe air navigation by altimetry as practiced by VR-2 and VR-5. This study was made to evaluate the accuracy of air navigation by altimetry. I wish to acknowledge the guidance of Professor George J. Haltiner and Professor A. Boyd Mewborn, the assistance and advice of Lieutenant Commander E. D. Anderson of Fleet Logistic Support Wings Staff and the generous cooperation of the Naval Transport Squadrons TWO and FIVE.

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LIST OF SYMBOLS AND ABBREVIATIONS

1.	D	Absolute altimeter height minus pressure altimeter height.
2.	ND	Navigator's drift angle.
3.	DD	Drift angle computed from D formula.
4.	$\bar{\phi}$	Average latitude.
5.	θ	Drift angle.
6.	λ	Coriolis parameter, $2\,\omega \sin\phi$.
7.	r	Radius of curvature.
8.	Vn	Wind component normal to heading of aircraft.
9.	g	Acceleration of gravity.
10.	$\doteq$	Equals approximately.
11.	dh/dx	The ratio of the change of height with distance.
12.	$\overline{ND}$	Average over the flight of navigator's drift.
13.	$\overline{DD}$	Average over the flight of drift computed from D formula.
14.	Δt	Fraction of 1 hour.
15.	TAS	True air speed.
16.	Vgs	Geostraphic wind.
17.	Vgr	Gradient wind.

CHAPTER I

INTRODUCTION

The relationship between wind and pressure gradient has been known for many years, but no means of measuring the change in atmospheric pressure while flying in an aircraft was available until absolute altimeters were developed during World War II. Since radar altimeters are now standard equipment in large transport aircraft of the Navy, Air Force, and commercial carriers, the calculation of drift by altimetry has become a valuable navigational aid, especially when visual drifts are not possible.

Taking "D" drifts, as the drift calculated by Bellamy's formula*is called, is standard operating procedure in Naval Transport Squadrons TWO and FIVE. Air Force Weather Reconnaisance planes use "D" drifts in their weather flights from Air Force Field, Fairfield-Suisun, California. No data was available for study of the variation between navigator's drift and "D" drift on the Air Force flights.

The Bellamy formula for wind normal to heading being a modification of the geostrophic wind equation, gives winds, which when translated into drift, agree well with the observed drift. In some cases there has been considerable disagreement between the navigator's drift and "D" drift. In this paper, an attempt is made to evaluate the magnitude of these errors.

* Bellamy, John C. The Use of Pressure Altitude and Altimeter Corrections in Meteorology. Jr. of Meteorology Vol. 2:1, March 1945 page 53.

CHAPTER II

THEORY AND METHOD OF DRIFT COMPUTATION

BY "D" METHOD

The use of the difference between the absolute altimeter height and the pressure altimeter height as a measure of the variation of the atmosphere from standard was suggested by John C. Bellamy in 1943. He defined D as the absolute altimeter height minus pressure altimeter reading with the pressure altimeter set at 29.92" Hg. If a plane flies at a constant pressure altimeter height, it is flying on a constant pressure surface. Along such a surface the geostrophic wind equation may be written

$$V_y = g/\lambda \; dh/dx \, .$$

Taking x as the direction of the true heading, the ratio of change of height to distance in the direction of the true heading is

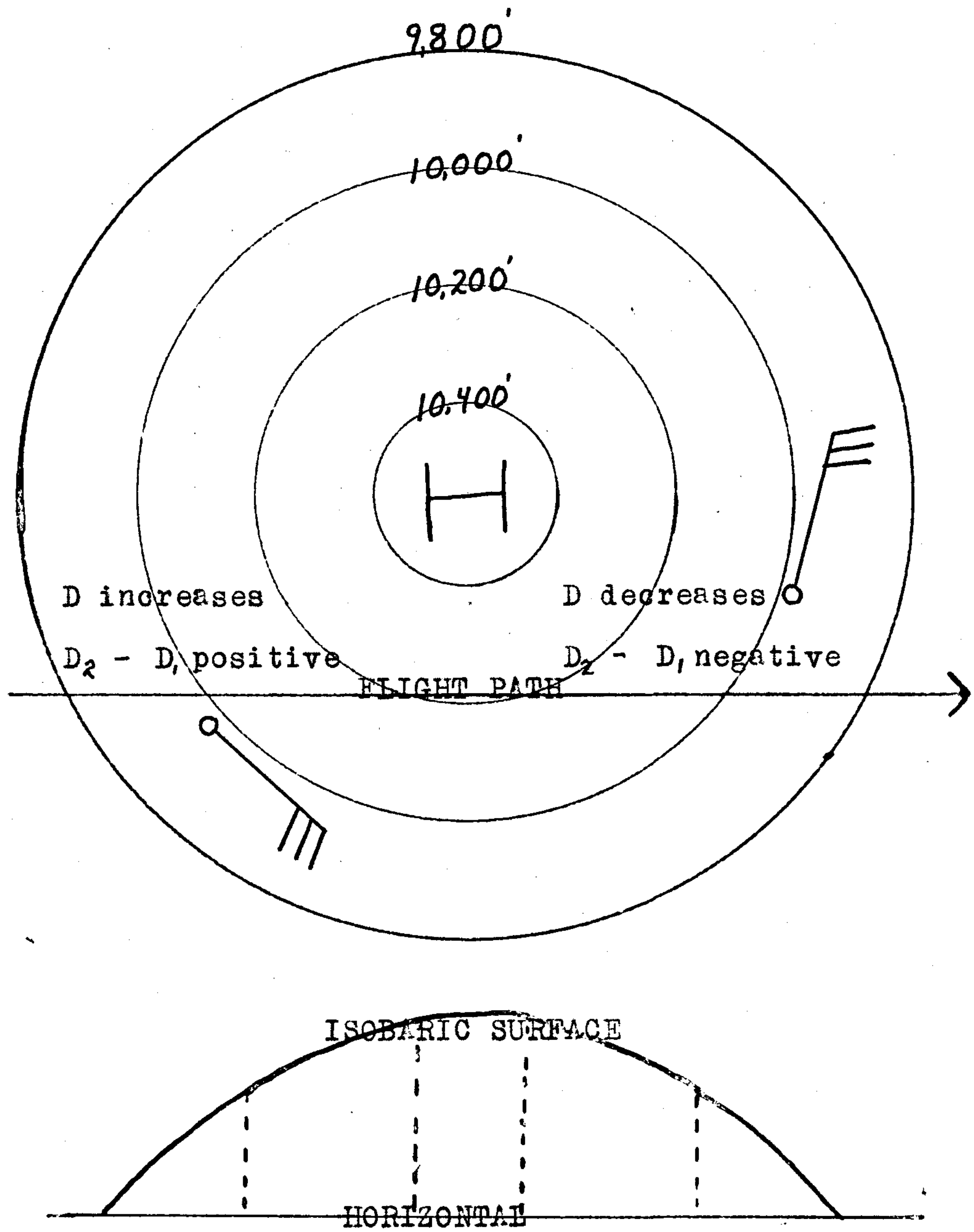
$$\frac{D_2 - D_1}{\Delta t \cdot TAS} \, .$$

Then the component of geostrophic wind normal to the heading is

$$V_n = \frac{K}{\sin \bar{\phi}} \cdot \frac{D_2 - D_1}{\Delta t \cdot TAS}$$

where K equals 21.47 with D in feet, Δt in hours, and true airspeed in knots. Then if a plane flies with a constant pressure altimeter setting and pressure altitude, the change of D with distance really measures the slope of the isobaric surface in the direction of path. This slope is translated into wind normal to the heading through the geostrophic wind equation.

This equation for Vn is accurate when the assumption of geostrophic wind is met; i.e., no pressure change at a point, straight parallel isobars and no friction. These conditions are usually fulfilled nearly enough so



CHANGE OF "D" WHILE FLYING THROUGH A HIGH

CORRESPONDING WIND DIRECTIONS

Figure a

that the geostrophic wind closely approximates the actual wind above 5,000 feet altitude and where the isobars are only slightly curved.

When the aircraft flies toward higher pressure, the values of D increase and $D_2 - D_1$ is positive. (Figure a). In this case Vn is from the right, the drift is to the left, and the drift correction is considered positive. This leads to the simple rule that the sign of the drift correction is the sign of $D_2 - D_1$.

The application of this formula has been made very easy by the Drift Angle Computer L-ch-1 and tables of K and Y (Figure b). The K factor multiplied by $D_2 - D_1$ gives Vn. The Y factor gives the approximate drift by dividing $D_2 - D_1$ by the appropriate value of Y. This Y factor is derived from the original equation and based on the fact that for small angles, the tangent of an angle is approximately equal to the angle measured in radians. Then the drift angle

$$\theta \doteq \tan \theta \doteq \frac{V_n}{TAS}.$$

This drift may be corrected for groundspeed by placing the dot of the Dead Reckoning Computer AN5835-1 over true airspeed, marking the drift, then sliding the dot to the groundspeed and reading the corrected drift. The ease and simplicity of the drift computation by the use of the Y factor outweighs the slight inaccuracy inherent in its derivation.

Even when groundspeed is not known and therefore "D" drift cannot be corrected for groundspeed, Vn and heading give a line of position. Such a line of position may be combined with any other line of position which crosses it to give a fix. Obviously, the accuracy of such a fix depends upon the accuracy of the position at the time the D readings were begun.

COMNATS Form No. 8

NAVAL AIR TRANSPORT SERVICE COMMAND

FLIGHT LEVEL PRESSURE & ALTIMETER DRIFT

(RCO 8 - 19A)

FROM __________ TO __________ DATE __________ 194__

NAV. __________ ACFT TYPE & NO __________

PLEASE FILL IN COLS. 1-8 FOR WEATHER STATION → | COLS 9-14 WILL COMPUTE DRIFT → | FOR PRESSURE (OPTIONAL FOR NAVIGATOR) →

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
TIME G.C.T.	POSITION LAT.	POSITION LONG.	RADIO ALTITUDE (FEET)	PRESSURE ALTITUDE (29.92) (FEET)	PRESS ALT. SCALE CORR.	TEMP °C INDICATED	TEMP °C TRUE	D 4 - 5	$D_2 - D_1$ (ALGEBRAIC SUBTRACTION)	Y (OR K) TABLES	APPROX DRIFT CORR. 10 + 11 (OR C_n)	GROUND SPEED (KNOTS) (EST)	DRIFT CORR. (SEE NOTE)	REPORTED RADIO ALTITUDE (100'S)	RPTD. MINUS ACT. ALT. 15 - 4	PRES ALT AT RPTD. RADIO ALT 5 + 6 + 16	PRES. AT RPTD RAD. ALT. (TABLE)	PITOT CORR. (MBS)	TRUE PRES. AT RPTD. RAD. ALT. 18 + 19
EXAMPLE 1200	50.5	43.6	8370	8320	+20	- 7	- 9	+50						8400	+30	8370	742	-2	740 EXAMPLE
									-80	10 (27)	-8° (25)	150	- 9°						
EXAMPLE 1230	50.9	40.0	8230	8260	+20	-6	- 8	-30						8200	-30	8250	745	-2	743 EXAMPLE

Figure 6 5

1. ZERO THE RADIO ALTIMETER CAREFULLY. TAP PRESSURE ALTIMETER BEFORE READING. READ THE TWO SIMULTANEOUSLY TO THE NEAREST 10 FEET.
2. THE SIGN OF $D_2 - D_1$ IS THE SIGN OF THE DRIFT CORRECTION. FOR FURTHER INSTRUCTIONS, SEE OTHER SIDE.

LATITUDE:	25°	30°	35°	40°	45°	50°	55°	60°	65°
Y FACTOR:	5	6	7	8	9	10	10	11	11

USE THESE VALUES ONLY FOR HALF-HOUR INTERVALS AT 170-180 KNOTS TAS. FOR OTHER TIME INTERVALS AND AIR SPEEDS SEE TABLE ON REVERSE SIDE.

Fig 6 5

M.I.N.Y.Δ2351

Col. 1 - Recommended time between drift observations: one half hour.

Col. 5 - If pressure altitude changes by more than 300 ft. between consecutive half hourly observations, or 600 feet between consecutive hourly observations, or true heading changes by more than 10°, the drift computation for that time interval is unreliable. Begin a new series of computations at the new altitude or new heading.

Col. 6 - Use correction from calibration card attached to pressure altimeter. If no card, please indicate in column 6.

Col. 7, 8 - From indicated temperature, SUBTRACT correction for dynamic heating depending on true air speed and thermometer type. For 170-180 mph indicated, correction is 3°C. for direct-indicating thermometers, and 2°C. for newer electrical types.

Col. 9 - Subtract column 5 from column 4 algebraically, and enter the proper sign.

Col. 10 - Subtract D at one observation (D_1) from D at a later observation (D_2), and enter the proper sign. If D_2-D_1 is positive, the wind is blowing from right to left; if D_2-D_1 is negative, the wind is blowing from left to right (North Hem.).

Col. 12 - When using Y factors, divide column 10 by column 11 to get column 12. When computing C_n use formula below.

Col. 13, 14 - On E-6B computer, mark intersection of TAS line with computed drift line (Col. 12). Without turning compass rose, slide grid until mark is over line of estimated ground speed (Col. 13). Read true DRIFT CORRECTION under mark.

Col. 15, 16, 17 - Round off radio altitude (column 4) to nearest 100 feet for WAF-2 report. Pressure altitude must be changed by same amount (column 16, 17).

Col. 18 - Use table at bottom of this page. (feet to millibars)

Col. 19 - Pitot correction for C-54 aircraft is usually -2 millibars at 170-180 mph indicated air speed. This value varies with the air speed and the type of aircraft.

****

TO ZERO AND READ THE RADIO ALTIMETER: Adjust Rec. Gain so that reference lobe (the one that does not move with changes in altitude) is 1/4 in. high. Turn Zero Adjustment so that left (counterclockwise) edge of lobe is exactly on zero scale mark. Readjust Rec. Gain so that reflection (reading) lobe has now the same shape and size that the reference lobe did during zeroing (the reference lobe may now be larger and seem not to be zeroed; do not re-zero it at the larger size). Read reflection lobe at left (counterclockwise) edge. Zero the altimeter at altitude at which readings are to be taken; check every hour by turning Rec. Gain down until reference lobe is again 1/4 in. high.

WORKSHEET FOR EXTRAPOLATING PRESSURES
(for convenience of weather station)

21	22	23	24	25	26	27	28	29	30	31	32
Time GCT Col.1	Position Lat. 2	Long. 3	Rptd. Radio Alt. 15	Press. at Rad. Alt. 20	True Temp. 8	Temp. at ___ ft	Mean Virtual Temp. of Column	Pressure at ___ ft	Temp. at ___ ft	Mean Virt. Temp. of col.	Pressure at ___ ft

TABLE OF Y-FACTORS

Latitude	25°	30°	35°	40°	45°	50°	55°	60°	65°
TAS									
140 knots	7	8	9	10	11	12	13	14	14
160	9	10	12	13	15	16	17	18	19
170	10	12	13	15	16	18	19	20	21
180	11	13	15	17	18	20	21	23	24
190	12	15	17	19	21	22	24	25	26
220	17	20	22	25	28	30	32	34	35

These values are calculated for a ONE-HOUR interval between observations. For smaller intervals, multiply the table value by the fraction of an hour between observations. Example: For 1/2-hour interval at 180 knots and 50°, Y-factor is 10.

TABLE OF K-FACTORS (alternate method)

Latitude Range	K	Latitude Range	K
18° - 20°	66	34° - 38°	36
20° - 22°	60	38° - 43°	33
22° - 25°	54	43° - 50°	30
25° - 28°	48	50° - 55°	27
28° - 31°	44	55° - 70°	25
31° - 34°	40	70° - 90°	22

Basic formula: $C_n = K \frac{D_2 - D_1}{x}$

C_n is component of wind normal to true heading; x is true air distance between observations (= TAS multiplied by fraction of an hour between observations).

FEET TO MILLIBARS USING U. S. STANDARD ATMOSPHERE

Example: For pressure altitude of 8370 feet (Col.17), pressure is 742 millibars (Col.18)

Corrected Pressure Altitude	0	100	200	300	400	500	600	700	800	900
	1013	1009	1006	1002	999	995	992	988	984	981
1,000 ft	977	974	970	966	963	959	956	953	949	945
2,000	942	939	935	932	928	925	921	918	915	911
3,000	908	905	901	898	895	891	888	885	881	878
4,000	875	872	869	865	862	859	856	852	849	846
5,000	843	840	837	833	830	827	824	821	818	815
6,000	812	809	806	803	800	797	794	791	788	785
7,000	782	779	776	773	770	767	764	761	758	756
8,000	752	750	747	744	741	738	736	733	730	727
9,000	724	721	719	716	713	710	708	705	702	700
10.000	697	694	692	689	686	683	681	678	676	673
11,000	670	667	665	662	660	657	655	652	650	647
12,000	644	642	640	637	634	632	629	627	624	622
13,000	619	617	614	612	610	607	604	602	600	597
14,000	595	593	590	588	586	583	581	579	576	574
15,000	572	569	567	565	562	560	558	556	553	551
16,000	549	547	545	543	540	538	536	534	531	529
17,000	527	525	523	520	518	516	514	512	510	508
18,000	506	504	502	499	497	495	493	491	489	487
19,000	485	483	481	479	477	475	473	471	469	467

CHAPTER III

DISCREPANCIES BETWEEN D DRIFT AND NAVIGATOR'S DRIFT

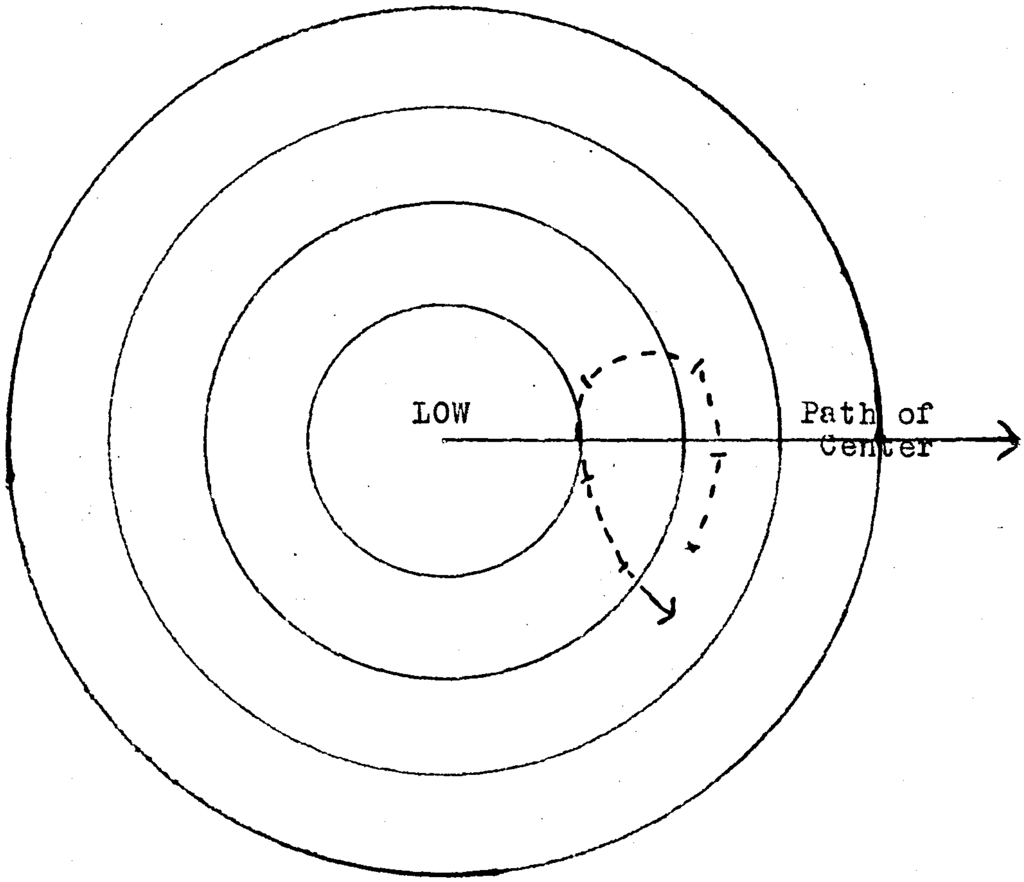
In comparing D drifts to navigator's drifts, it is necessary to remember that D drifts are measurements of the pressure gradient which are converted into wind normal to heading by the adaptation of the geostrophic wind equation. The discrepancies between navigator's drift and D drift then are of three kinds: errors due to non-geostrophic flow, errors due to personnel and equipment failure in the application of the formula and errors due to navigation inaccuracies. The magnitude of these errors for extreme and usual cases will be considered below.

The effect of non-geostrophic flow on D drifts is due to curvature of trajectories, change of pressure at a point, and friction. The effect of friction is difficult to assess but is generally considered negligible above the friction layer next to the surface. The curvature of trajectory of air particles results in deviation of the wind from geostrophic according to the formula for gradient wind.

$$V_{gr} = \frac{\lambda r}{2}\left(1 - \sqrt{1 - \frac{4V_{gs}}{\lambda r}}\right) \quad \text{anti cyclonic}$$

$$V_{gr} = \frac{\lambda r}{2}\left(\sqrt{1 + \frac{4V_{ga}}{\lambda r}} - 1\right) \quad \text{cyclonic}$$

The curvature of trajectories of air particles in fast moving systems may vary considerably from the curvature of the isobars (Figure c). In extreme cases the radius of curvature may be as small as 200 nautical miles. Table I gives values of the gradient wind for stated values of geostrophic wind, latitude, and radius of curvature, where the curvature is cyclonic.



TRAJECTORY OF AN AIR PARTICLE

Figure c

TABLE I

Vgs, Vgr, and TAS are measured in knots
r is measured in nautical miles

D drift – actual drift

Vgs	Lat.	Radius of Curvature	Vgr	TAS	Drift Difference
40	45	200	29	180	$3\frac{1}{2}^\circ$
60	45	200	39	180	$6\frac{1}{2}^\circ$
30	45	500	26	180	$1\frac{1}{4}^\circ$
30	45	1000	28	180	$\frac{1}{2}^\circ$

Since Vn is calculated on the basis of geostrophic wind, the D drifts would be larger than actual drift, but since the direction of the wind is unchanged, the direction of the drift would be the same. The column in Table I headed Drift Difference was computed on the assumption that Vn was the total wind.

The effect of anticyclonic curvature is to increase the actual wind over the geostrophic wind. Since the radius of curvature in anticyclones is generally of greater magnitude than in cyclones, the deviation of the gradient wind from geostrophic is small. The radii of curvature of trajectories in anticyclones are seldom less than 400 nautical miles. At 45 degrees latitude, for geostrophic wind of 30 knots, and radius of curvature of 400 nautical miles, the gradient wind is 42 knots.

The areas where cyclonic curvature is great are located near the center and to the left of the path of the center of closed low pressure areas. In this region the curvature of the trajectory is greater than the curvature of the isobars.

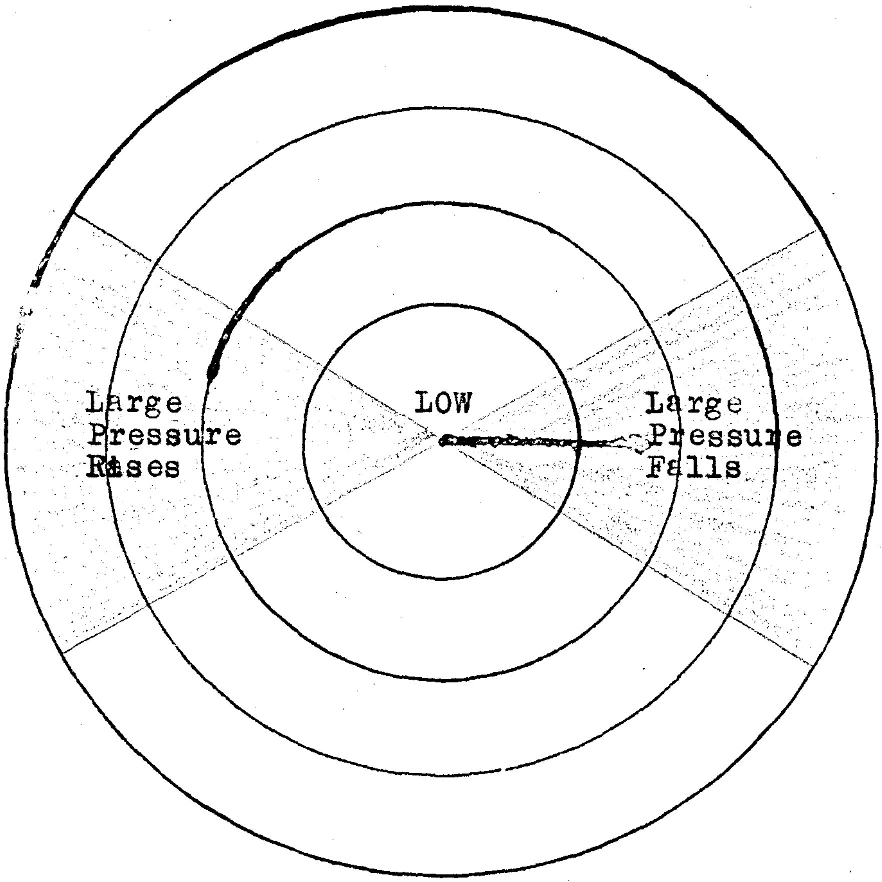
The difference between geostrophic and gradient winds which were discussed above will be reflected as errors in the value of Vn as calculated from the Bellamy formula. Vn will differ from the actual wind proportionately depending on the angle between the aircraft's heading and the isohyptic contours, assuming no compensating factors. Translated into drift these differences are large, but the areas in which such large curvatures occur are so small in comparison to an aircraft's speed that it is very improbable that more than one hour of flight could be influenced.

Assuming that the height of an isobaric surface does not change with time over a point is the other major cause for deviation of the wind from geostrophic. A study of the height changes of the 700 m.b. surface in middle latitudes during the three months between December 15, 1948 to March 15, 1949 over the northern United States and Southern Canada showed only one instance where a station actually changed 600 feet in 12 hours. That is 50 feet in one hour if the change of height is uniform. To find a possibly better approximation to the maximum change in one hour, an isohyptic low with large gradient of contour lines and rapid movement of the center was chosen. Multiplying the height change per degree of latitude by the number of degrees of latitude which the center moved in one hour gave a height change due solely to movement. To this amount was added one twelfth the deepening of the center which occurred in the 12 hour period. This gave 70 feet height change in one hour and was the largest found in 60 maps.

If a Y factor determined for 180 knots air speed and 45 degrees latitude is applied to 70 feet ($D_2 - D_1$), the drift is 3.9 degrees. If the pressure change were negative the fictitious drift would be right drift.

Except in rare cases an aircraft will not be in areas of such pressure changes. Usually the amount of height change will be in the neighborhood of 10 feet per hour. This would give approximately $\frac{1}{2}$ degree of fictitious drift using the same Y factor as earlier.

These actual errors of drift computed by the D formula may be qualitatively known from the forecast map, but, for practical use, the formula should be applied with no attempt at correction.



AREAS OF LARGE PRESSURE CHANGES

Figure d

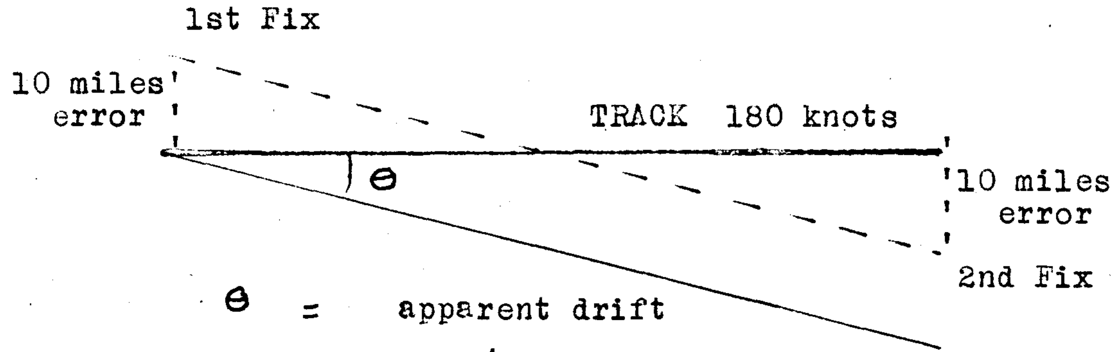
There are other causes for inaccurate D drifts. The absolute altimeter in use in the Mars and R5D aircraft of the Navy is graduated in increments of 50 feet. It can be read to at least 25 feet accuracy. The reference lobe is not a sharp line, but the fuzzy, fluctuating trace on a radar scope. The pressure altimeter is graduated in 10's of feet and is easy to read, but for an accurate reading the instrument should be tapped with the finger to remove lag. The readings of the two instruments might conceivably give rise to errors of $D_2 - D_1$ of 60 feet. This is unlikely because the process of subtraction ~~will~~ may cancel a constant error. For example:

Actual Readings			Navigator's Readings		
1200			1200		
	A.A.	10,000 ft.		A.A.	10,025 ft.
	P.A.	9,800 ft.		P.A.	9,800 ft.
D_1		200 ft.	D_1		225 ft.
1300			1300		
	A.A.	10,200 ft.		A.A.	10,225 ft.
	P.A.	9,800 ft.		P.A.	9,800 ft.
D_2		400 ft.	D_2		425 ft.
$D_2 - D_1$		200 ft.	$D_2 - D_1$		200 ft.

During the actual readings the altitude must be as nearly constant as possible for the pressure altimeter lag will result in a false reading during changing altitude. The aircraft should not alter heading by more than 10 degrees or the altitude more than 200 feet during a time interval over which $D_2 - D_1$ is taken.

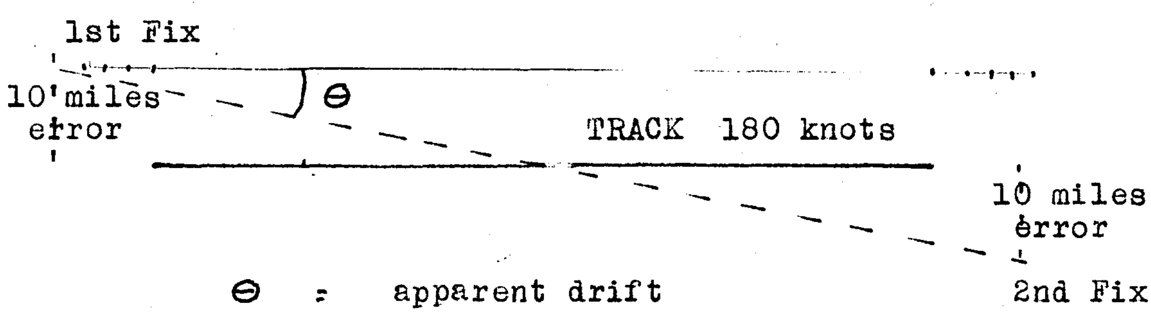
The errors discussed to this point have been errors of the drift computed from the D formula. Navigational and instrument errors lead to discrepancies between navigator's drift and D drift. Figure e, page 12, shows

EFFECT OF NAVIGATION ERRORS ON DRIFT



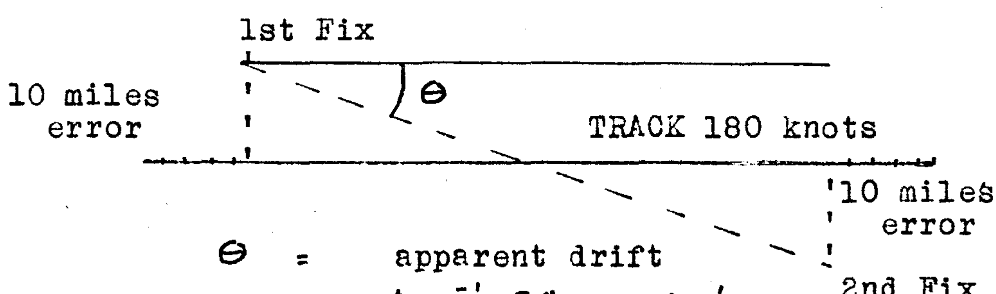
θ = apparent drift

$= \tan^{-1} \frac{20}{180} = 6° 21'$



θ = apparent drift

$= \tan^{-1} \frac{20}{200} = 5° 43'$



θ = apparent drift

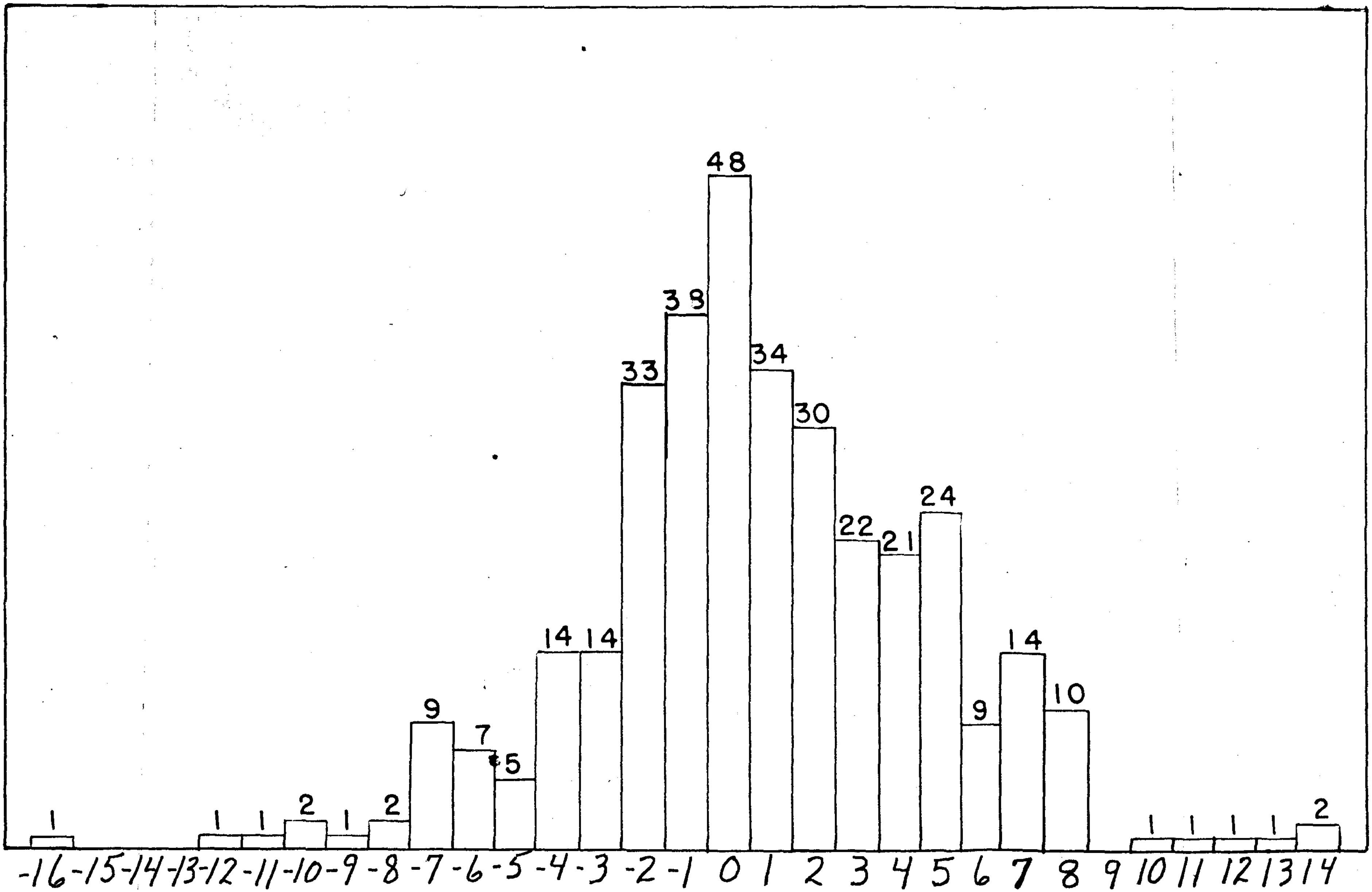
$= \tan^{-1} \frac{20}{160} = 7° 7'$

Figure e

the apparent drift resulting from errors in navigational fixes within generally accepted standards of celestial air navigation. Inaccurate deviation calibration of a magnetic compass results in flying off course, and to fly on track a drift correction would be made which is equal to the compass deviation error. Failure to fly the correct course gives rise to a similar error.

Comparing navigator's drift to D drift for 33 flights made by VR-2 between NAS, Alameda, California and Honolulu, T. H., gave the frequency distribution shown in Figure f. The mean of the difference (navigator's drift - D drift) of the 346 observations is .73 degrees and the standard deviation is 4.21 degrees. The 50% probability interval is from 3.55 degrees to -2.09 degrees. Four observations are more than three standard deviations from the mean. The probability that these observations are chance variations is less than .027 or about one in 400. Since there were only ~~400~~ 346 observations, these four observations probably are not the result of chance occurrence of several of the errors discussed earlier. Due to the large magnitude, it seems likely that the altimeters were read incorrectly or that one of the instruments was not operating accurately for that one reading.

The average over each of the 33 flights of the navigator's drift and D drift was computed. The difference (ND average - DD average) is then a variate. This distribution is given in Table II.



FREQUENCY DISTRIBUTION OF ND - DD

Figure f

TABLE II

$\overline{ND}-\overline{DD}$	Frequency
5.0	1
4.5	0
4.0	0
3.5	0
3.0	3
2.5	1
2.0	3
1.5	1
1.0	5
0.5	4
0.0	1
- 0.5	9
- 1.0	1
- 1.5	2
- 2.0	0
- 2.5	2

The mean of this distribution is .52 degrees and the standard deviation is 1.73 degrees. No frequency polygon is presented due to the relatively small number of observations, 33, of this variate.

Since the expected value of the variate ND-DD is zero if there are no errors, the fact that the mean is positive in both cases is significant. From San Francisco to Honolulu, the circulation is mostly anticyclonic due to the subtropic high. If the average curvature of the trajectory of air particles is 1000 nautical miles, geostrophic wind is 30 knots, average latitude is 30 degrees, then the gradient wind exceeds the geostrophic wind by 4.8 knots. The true air speed of the aircraft from which the observations were made is about 160 knots, and if we take the average angle between the heading of the aircraft and the wind to be 45 degrees forward or aft of the beam, the normal component of the 4.8 knots is 3.4 knots. Since the wind is greater than geostrophic, this would result in a positive difference of navigator's drift - D drift of approximately one degree, comparing very favorably with the observed mean of .73.

CHAPTER IV

CONCLUSIONS

Errors in drift computed from the D formula are to be expected, especially where curvature is great or near the centers of fast moving pressure systems. Since the areas of large curvature and great pressure changes are small in relation to the whole map and the speed of an aircraft the errors will be of significant magnitude over a short time interval when flying in the area. To make a check of the correspondence of actual drift with D drift required some method of finding the actual drift accurately. A flight from Seattle to Kodiak and return was made in which over a considerable period the water was visible. Comparison of the D drifts with the drift sights made on a B-3 Drift Meter showed good agreement. The maximum difference was $5\frac{1}{2}$ degrees and average difference was 1.6 degrees. Unfortunately, the wind at the surface was so light that the whitecaps were small and too far apart for accurate drifts with the drift sight from 9000 feet altitude.

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