CHAPTER 20

Pressure Differential Techniques

Pressure differential flying, previously known as pressure pattern flying, involves a number of techniques, all of which have one common feature; they are designed to make maximum use of forecast and inflight information relative to the pressure field at the cruising level of the aircraft. Since pressure information is more easily obtained during flight than wind information, and since it is also more accurately forecast than wind information, pressure differential techniques, where applicable, provide the navigator a simple and accurate aid to navigation.

When used in the air, pressure pattern techniques make available two aids to navigation: *Bellamy drift* and the *pressure line of position* (PLOP). Both are obtained by substituting certain inflight information into a basic formula—neither requires any visual reference, special equipment, nor ground equipment.

Bellamy drift supplies net drift over a past period and, hence, information as to the track of the aircraft. It is most useful over water, and particularly during poor visibility and when radio aids are not available. The PLOP is a line of position as valid as any other type of LOP and considerably easier to obtain under difficult flight conditions. It can be combined with another type of LOP for a fix, and can be used to find MPPs. It is advanced and retarded by the usual methods.

CONSTANT PRESSURE SURFACE

Pressure differential navigation is based on the meteorological formula for the geostrophic wind, modified for flying a constant pressure surface. The constant pressure surface is one on which the pressure is the same everywhere, although its height above sea level may vary from point to point as shown in figure 20-1. It is a surface on which a constant reading will be indicated on the pressure altimeter.

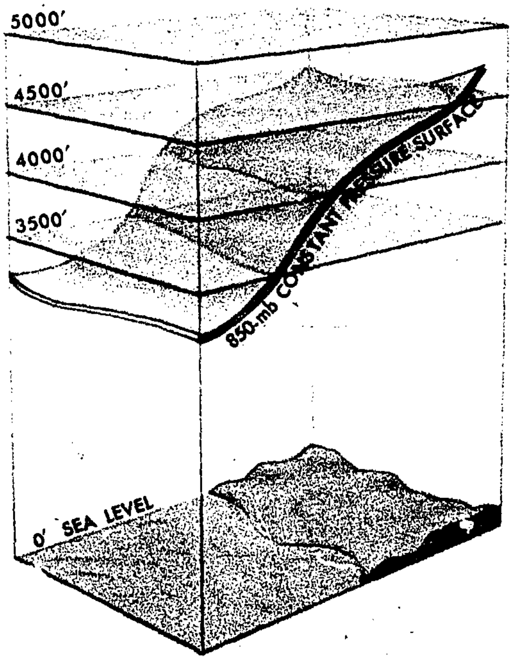
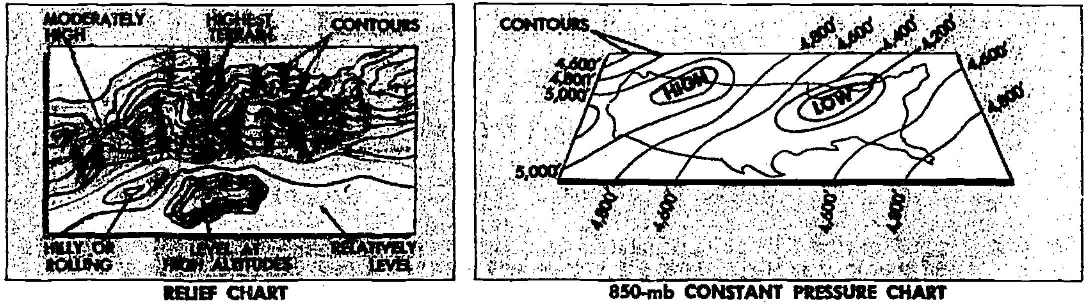


Figure 20-1. Constant Pressure Surface

Constant Pressure Chart

A constant pressure surface is shown on a constant pressure chart on which lines are drawn connecting points of equal height above sea level. These lines have the same significance as contour



RELIEF CHART

850-mb CONSTANT PRESSURE CHART

Figure 20-2. Contours

lines on maps of land areas, and hence, they are also termed *contours* (figure 20-2).

An aircraft flying with a constant indication on the pressure altimeter will automatically follow the configuration of the constant pressure surface, and in so doing, will change its true height as the contours change (figure 20-3).

Areas where the constant pressure surface forms troughs are termed *lows,* and areas where the constant pressure surface is peaked are termed *highs.* These configurations correspond to the highs and lows of the familiar surface chart and their circulation follows the same familiar patterns. Intersections of mean sea level by constant pressure surfaces form *isobars,* and intersections of a constant pressure surface by planes parallel to mean sea level form *contours* (analogous to geographic contours). A comparison of isobars and contours is shown in figure 20-4. The geostrophic wind will blow along the contours of a constant pressure chart just as it blows along the isobars of a constant level chart.

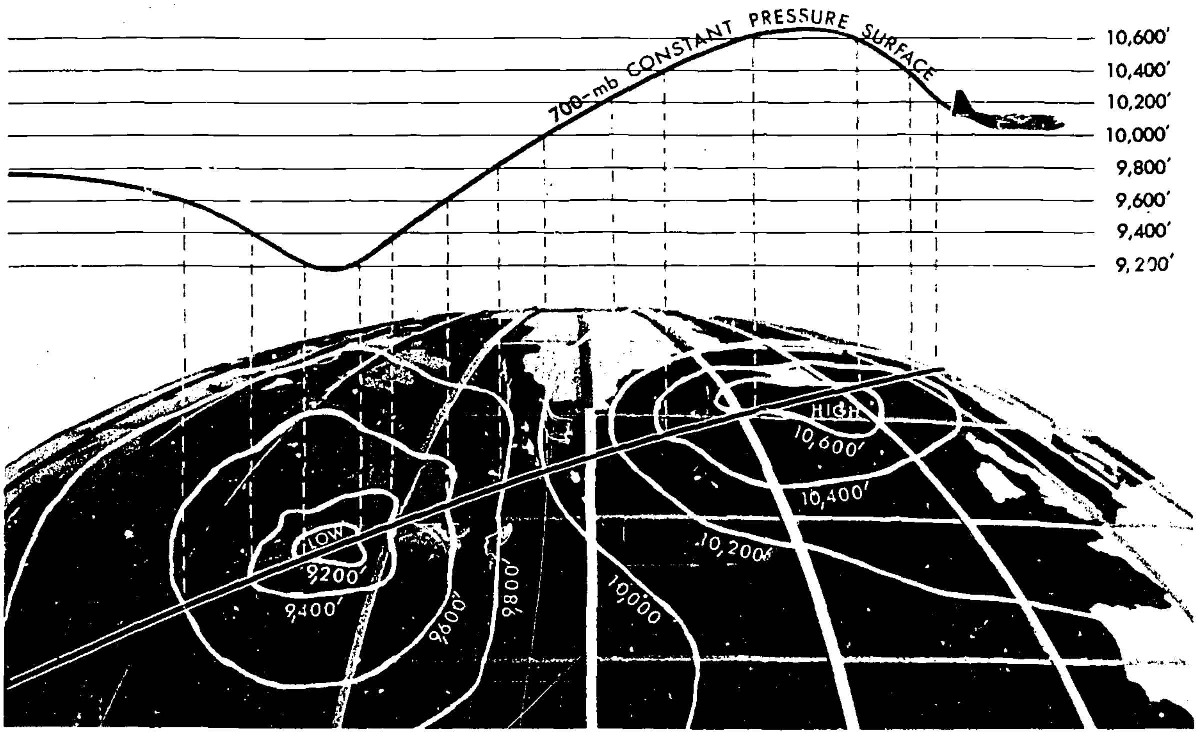


Figure 20-3. Changing Contours of Constant Pressure Surface

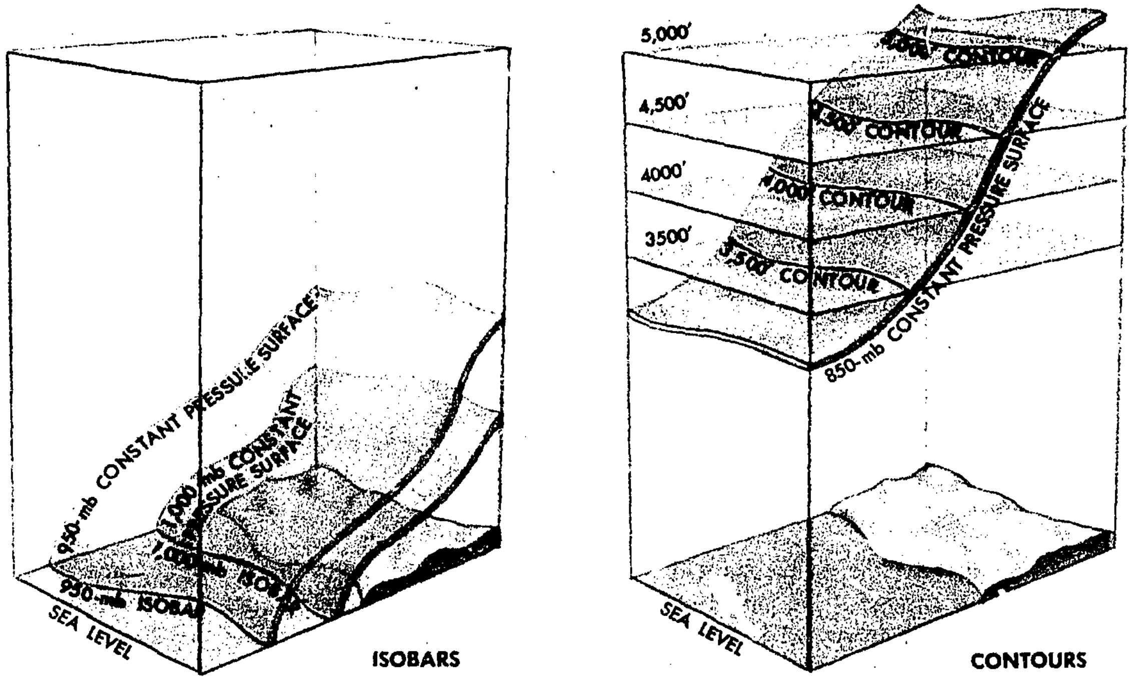


Figure 20-4. Comparison of Isobars and Contours

Geostrophic Wind

The atmosphere will try to regain a balanced condition whenever any disturbing influences are exerted upon it. As the sun's energy acts to bring about an unequal distribution of air mass over the earth's surface, the atmosphere reacts to restore the equal distribution of that air mass. Since the sun's rays are continuously affecting the atmosphere, the state of equilibrium is never reached and atmospheric mass is always unequally distributed over the earth. Atmospheric pressure, therefore, varies from point to point at the surface depending on the mass of air above the area considered. The difference in pressure per unit distance is known as the *pressure gradient* or more commonly as the *slope* of the pressure field (see figure 20-5).

Pressure gradient force and Coriolis combine to produce the geostrophic wind. The geostrophic wind assumes straight and parallel contours and exists above the level of earth-created friction. If centrifugal force due to curved contours is considered, the resultant wind is called the *gradient wind.*

The speed of the geostrophic wind is proportional to the spacing of the contours (or isobars). Closely spaced contours form a steep slope (higher gradient) and produce a stronger wind. Widely spaced contours or isobars produce relatively weak winds.

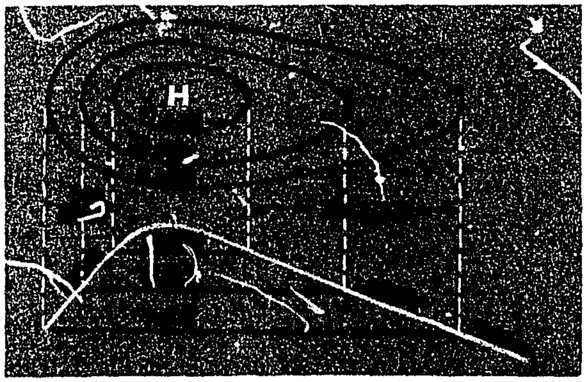


Figure 20-5. Pressure Gradient

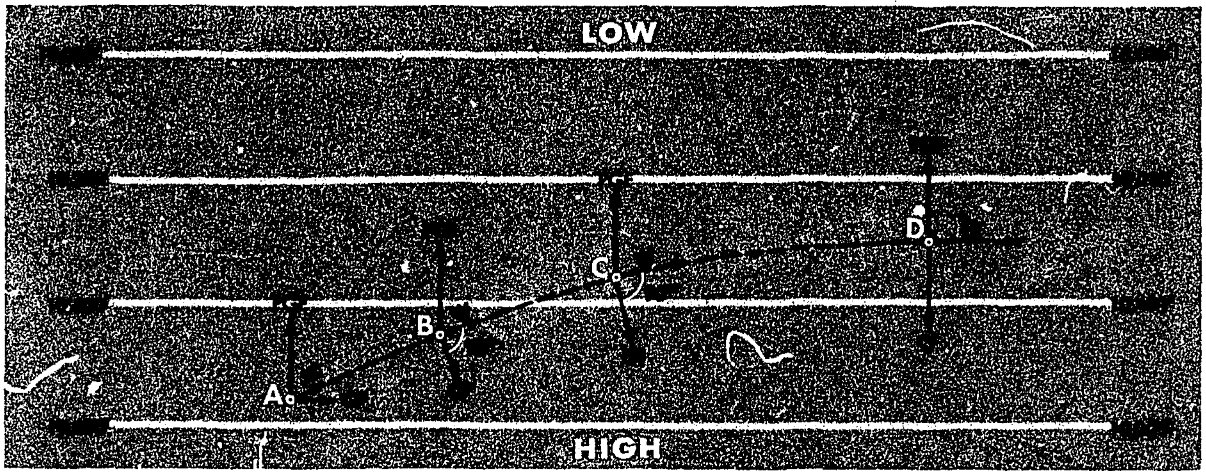


Figure 20-6. Geostrophic Wind

Figure 20-6 illustrates the manner in which the geostrophic wind is produced. A parcel of air at point *A* is being impelled toward lower pressure (*L*) by pressure gradient force (*PGF*). If the parcel were at rest, Coriolis force (*CF*) would be zero. But since the parcel is being initially moved across the contours toward lower pressure, Coriolis force comes into play, deflecting the parcel to the right. The resultant of the two forces is wind (*W*). At point *B*, the parcel continues to move and to accelerate, causing Coriolis force to increase. This action in turn deflects the parcel further to the right. At point *C*, the acceleration of the parcel continues to increase the magnitude of Coriolis force, producing further deflection of the parcel to the right. But at point *D*, pressure gradient force and Coriolis force have become equal in magnitude and opposite in direction. Unless other accelerating forces are introduced from this point on, the parcel continues on indefinitely, travelling parallel to the contours at its attained velocity. At point *D*, it is a portion of the geostrophic wind.

This wind is blowing parallel to the contours with lower pressure to the left of the direction of motion and higher pressure to the right. *Buys-Ballot's Law* states that in the Northern Hemisphere with one's back to the wind, lower pressure is to the left (see figure 20-7). The reverse is true in the Southern Hemisphere, where Coriolis deflection is to the left.

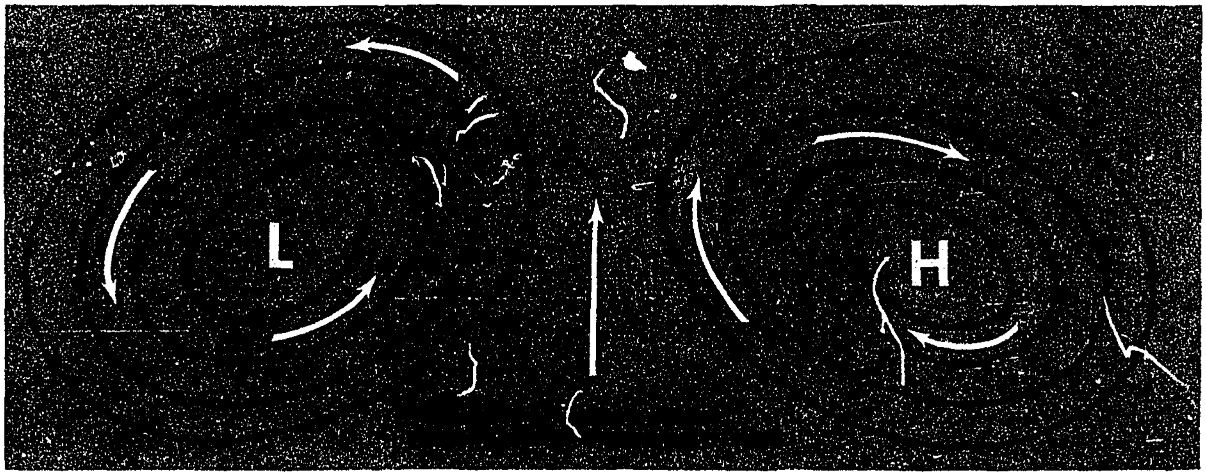


Figure 20-7. Buys-Ballot's Law

If the geostrophic wind is to be an accurate approximation of the actual wind, it is essential that contours be relatively straight and parallel, and that no distortion be introduced through surface friction. A minimum of two to three thousand feet of altitude above the surface usually guarantees an accurate geostrophic wind. In the area of the equator (20° N to 20° S), Coriolis force approaches zero, thereby invalidating the geostrophic wind as a useful factor in navigation; but pressure differential navigation is reliable in midlatitudes and polar areas.

PRESSURE COMPUTATIONS AND PLOTTING

In determining position (PLOP) or drift (Bellamy drift) by pressure differential techniques, the navigator makes use of the crosswind component of the geostrophic wind over a given period of time. The determination of the crosswind component of the geostrophic wind requires specific data for use in a formula, which, when solved, will give the direction and displacement effect of the pressure system through which the aircraft has flown. This resultant is called "ZN." To solve the ZN formula, the navigator must understand how to obtain and apply such special factors as "D" soundings, effective TAS, effective air path, effective air distance, and "K" values.

"D" Soundings

The symbol "D" stands for the difference between the true altitude of the aircraft and the pressure altitude of the aircraft. It is expressed in feet as a plus or minus value. An absolute altimeter is normally used to measure true altitude on overwater flights, and the pressure altimeter is used to measure the pressure altitude. To determine the correct D sounding, assign a plus (+) to true altitude, a minus (—) to pressure altitude, and algebraically add the two. The correct sign can be applied by remembering the key word, TAMPA: True Altitude Minus Pressure Altitude.

The first D sounding is obtained at the fix when the pressure differential navigation leg is started. It is called D_1. The second D sounding, D_2, is obtained at the time of the intended pressure LOP. The value, $D_2—D_1$, is an expression of the slope (pressure gradient) experienced by the aircraft. By algebraically subtracting D_1 from D_2, the navigator determines the change in aircraft true altitude between D_1 and D_2. When this altitude change is compared with the distance flown, the resulting values becomes an expression of the slope. A large value of $D_2—D_1$ indicates a steep slope; a small value of $D_2—D_1$ indicates a gentle slope. The sign of $D_2—D_1$ indicates whether the aircraft has been flying up slope (+) or down slope (—).

The D sounding for the next position is called D_3; the slope experienced between D_2 and D_3 is expressed as $D_3—D_2$. For consecutive positions, it becomes $D_4—D_3$, $D_5—D_4$, etc. If D_2 is believed unreliable, D_3 may be compared with D_1.

To obtain an accurate D sounding, it is advisable to take several readings, obtain the D (difference) for each reading, and arrive at a D sounding for the *midtime* of the readings. This method readily identifies discrepancies in reading. In addition, when any D sounding varies by 40 feet or more from the average of the other soundings, discard it and use the average of the remaining D soundings. It is important to take readings carefully. An erroneous reading of either altimeter will produce an incorrect D sounding and consequently an inaccurate LOP. A gentle tapping of the pressure altimeter before reading it will reduce hysteresis error.

The aircraft should maintain a constant pressure altitude to insure correct D soundings. If it becomes necessary to change altitude enroute, start a new D_1 at the new altitude.

Effective True Airspeed

In determining a pressure line of position, the navigator must compute the *effective true airspeed* (ETAS) from the last D sounding. The ETAS is the true airspeed that the aircraft would have had to make good, had it flown straight from D_1 to D_2. See figure 20-8. If the aircraft has maintained a constant true heading between D soundings, the effective true airspeed equals the average true airspeed. But if the aircraft has altered heading one or more times between the D soundings, the effective true airspeed is derived by drawing a straight line from the fix at the first D sounding to the final air position. This line is called the *effective air path* (EAP). Effective true airspeed is computed by measuring the *effective*

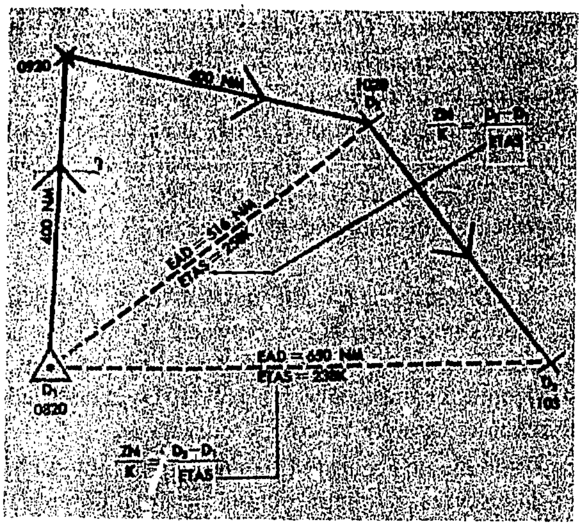


Figure 20-8. Effective True Airspeed

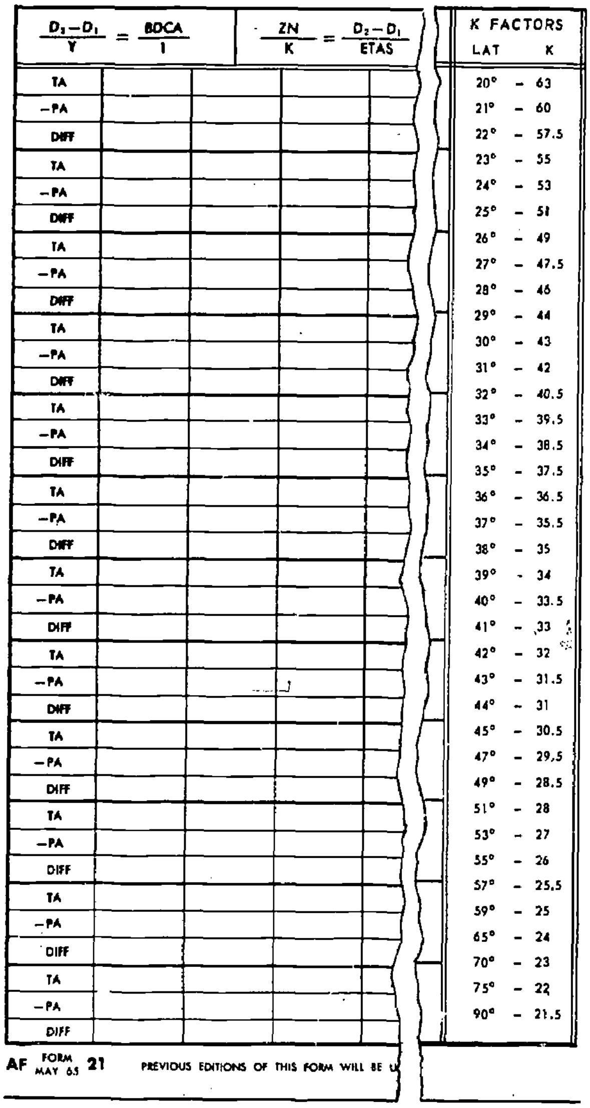
air distance (EAD) and dividing it by the elapsed time (in hours). In figure 20-8, an aircraft flew at 400 knots TAS from the 0820 fix to the 1020 air position via a dog-leg route. The effective air distance is 516 nautical miles; consequently, the effective true airspeed is 258 knots. In the illustration the navigator considered the D_2 sounding unreliable; therefore, he compared D_3 with the D_1 sounding.

K Factor

The constant (K) has been determined by taking into account the values of the Coriolis constant and the gravity constant for particular latitudes. K equals $\frac{21.49}{\sin \text{midlatitude}}$; where midlatitude is the average latitude between D_1 and D_2.

It is put in tabular form for the convenience of the navigator as shown in figure 20-9. In the table, this constant is plotted against latitude since Coriolis force varies with latitude. In using the ZN formula, the table is entered with midlatitude and the corresponding K is extracted.

Slope is properly expressed by vertical and horizontal displacement in the same units; however, the navigator expresses horizontal displacement in nautical miles and vertical displacement in feet. The K factor has been adjusted by a factor so that, with slope expressed in feet and distance in nautical miles, the geostrophic wind speed is computed in knots. Thus, the K factor cannot be used with statute miles to solve for the geostrophic wind in statute miles per hour.



$\frac{D_3-D_1}{Y} = \frac{BDCA}{1}$		$\frac{ZN}{K} = \frac{D_2-D_1}{ETAS}$		
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K FACTORS

LAT	K
20°	63
21°	60
22°	57.5
23°	55
24°	53
25°	51
26°	49
27°	47.5
28°	46
29°	44
30°	43
31°	42
32°	40.5
33°	39.5
34°	38.5
35°	37.5
36°	36.5
37°	35.5
38°	35
39°	34
40°	33.5
41°	33
42°	32
43°	31.5
44°	31
45°	30.5
47°	29.5
49°	28.5
51°	28
53°	27
55°	26
57°	25.5
59°	25
65°	24
70°	23
75°	22
90°	21.5

AF FORM MAY 65 21 PREVIOUS EDITIONS OF THIS FORM WILL BE U

Figure 20-9. K Factors Table from AF Form 21

Crosswind Displacement (ZN)

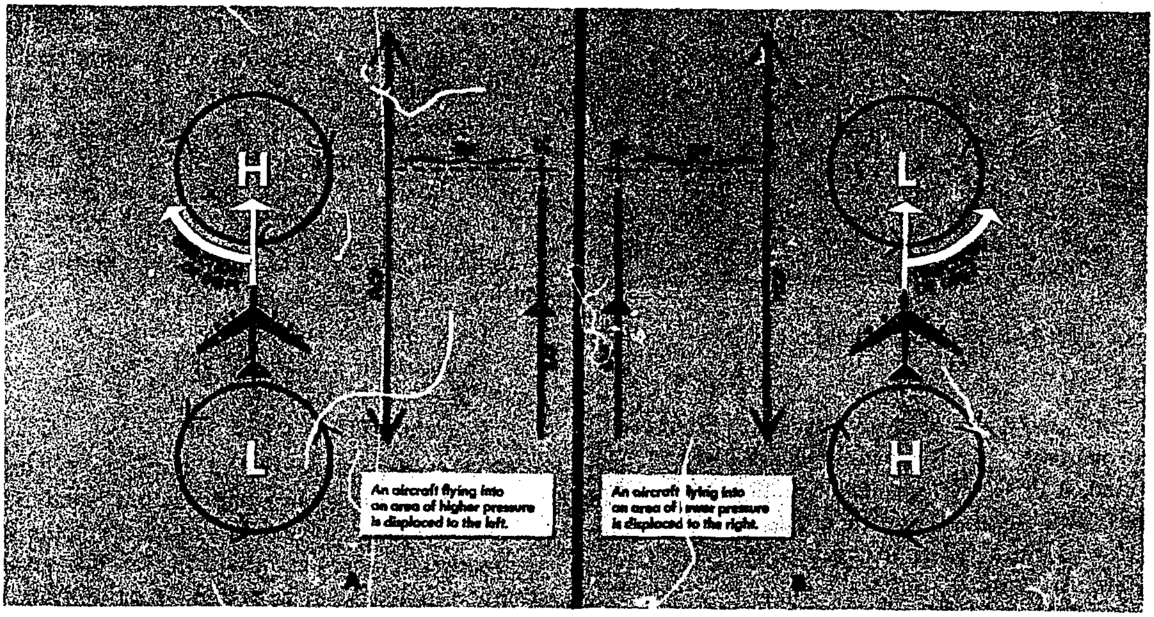
ZN is a displacement value derived from soundings at two air positions. It is the displacement from the straight line air path between the soundings. Therefore a PLOP must be drawn parallel to the effective air path.

The ZN equation

$$ZN = \frac{K(D_2-D_1)}{ETAS}$$

can be rearranged for convenient solution on the DR computer as follows:

$$\frac{ZN}{K} = \frac{D_2-D_1}{ETAS}$$



An aircraft flying into an area of higher pressure is displaced to the left.

An aircraft flying into an area of lower pressure is displaced to the right.

Figure 20-10. ZN Displacement in Northern Hemisphere

On newer DR computers, such as the MB-4, a subscale of latitude has been constructed opposite the values for K factors on the minutes scale. A table of K factors is not needed when these computers are used. Printed instructions on the face of these computers specify that, to compute crosswind component, set air miles flown (effective air distance) on the minutes scale opposite $D_2—D_1$ on the miles scale. The crosswind component (V_n) is not to be confused with crosswind displacement (ZN). The crosswind component (V_n) is crosswind velocity in knots. This component (V_n) must then be multiplied by the elapsed time between D_2 and D_1, in order to compute the crosswind displacement (ZN). If effective true airspeed is substituted for air miles flown (effective air distance) on the MB-4 computer, the ZN can be read over the K factor (or latitude on the subscale).

PRESSURE LINE OF POSITION (PLOP)

Once ZN is determined, it can be plotted to obtain a *pressure line of position* (PLOP).

The direction of this displacement must also be determined; that is, the navigator must determine whether the aircraft has drifted right or left of the effective air path. Recall that wind circulation is clockwise around a high and counterclockwise around a low in the northern Hemisphere; the opposite is true in the Southern Hemisphere. Thus, in the Northern Hemisphere, when the value of D *increases* (a positive $D_2—D_1$), the aircraft is flying into an area of higher pressure and the drift is left (see figure 20-10A). When the value of D *decreases* (a negative $D_2—D_1$), the aircraft is flying into an area of lower pressure and the drift is right (see figure 20-10B).

Always plot the PLOP *parallel to the effective*

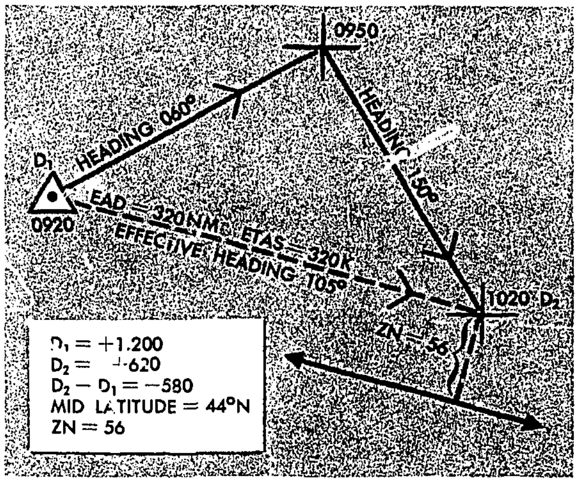


Figure 20-11. Plotting the PLOP

air path, and not necessarily parallel to the present true heading. This is shown in figure 20-11. Once plotted, a PLOP is used in the same manner that any LOP is used. It can be crossed with another LOP to form a fix or it can be used with a DR position to construct an MPP.

BELLAMY DRIFT

Bellamy drift is a mean drift angle calculated for a past period of time. It is named for Dr. John Bellamy who first demonstrated that drift could be obtained from the use of pressure differential information. Bellamy drift is used in the same way as any other drift reading.

The primary advantage of Bellamy drift is its independence from external sources. An undercast, overcast, or poor radio transmission will not adversely affect the drift. The accuracy of Bellamy drift is comparable to other drifts and depends largely on the skill of the navigator.

Bellamy drift can be determined from a ZN ground distance triangle without the intermediate step of the PLOP, but it is easier to understand if it is constructed graphically using a PLOP.

In figure 20-12, a PLOP has been plotted from the following information:

D_1 at a fix at 1000
D_2 at an air position at 1045
ZN = − 20 NM
Constant TH of 090°

Next, construct an MPP on the PLOP. This is done by swinging an arc, with a radius equal to the ground distance traveled, from the fix at the first D-reading to intersect the PLOP. The ground distance traveled can be found by multiplying the best known groundspeed (groundspeed by timing, metro groundspeed, etc.) by the time interval between readings. The mean track is shown by the line joining D_1 and the MPP. The mean drift is the angle between true heading and the mean track (8°R). Thus, the Bellamy drift is 8° right.

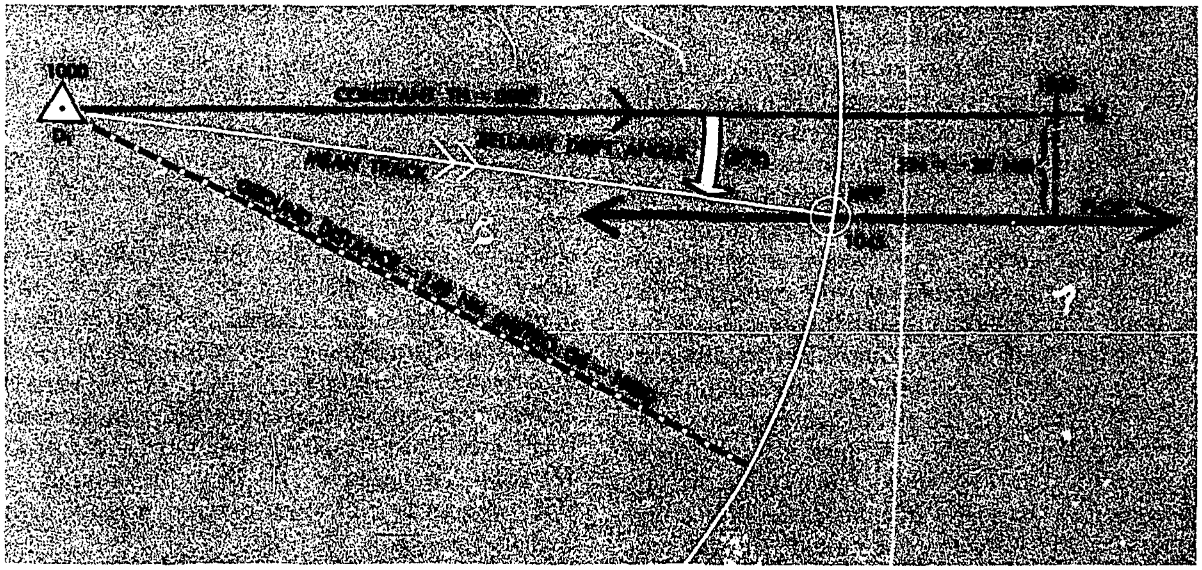


Figure 20-12. Solution of Bellamy Drift Using PLOP

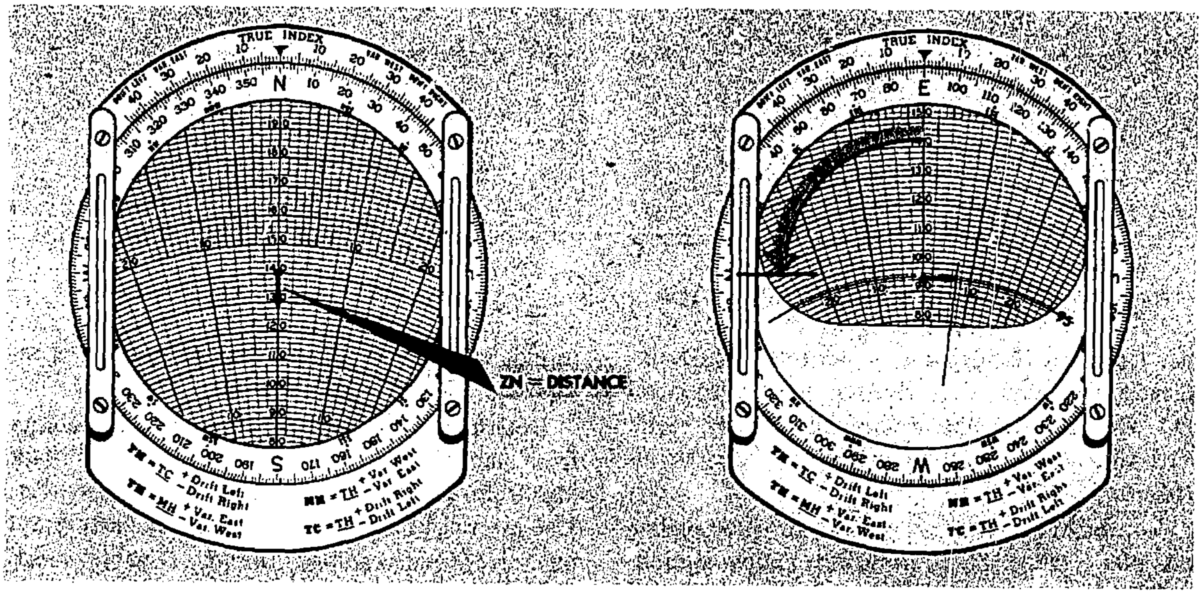


Figure 20-13. Computer Solution of Bellamy Drift

Computer Solution of Bellamy Drift

Solving the Bellamy drift angle on the DR computer is a relatively simple process. The center vertical line on the slide represents true heading. The ZN must be plotted at right angles to the true heading. This can be done by drawing the ZN vector down from the grommet and rotating the transparent face 90°. For convenience, one of the cardinal headings is placed under the true index when the ZN is drawn in to make it simple to rotate the face through 90°.

It makes no difference whether the face is turned to the right or left, as the sense of the drift is not taken from the DR computer. The sense is determined by the same considerations governing the plotting of the PLOP ($D_2—D_1$ negative, Northern Hemisphere, drift right).

The slide is then positioned so that the ground distance is under the end of the ZN vector and the drift angle is read at the end of the ZN vector.

Example (figure 20-13)

Given: Northern Hemisphere
ZN = + 12.1
Time = 0:30
GS = 190 Knots

Find: Ground Distance = 95 NM
Drift = 7° left

Bellamy drift may also be determined on the slide rule side of the DR computer by placing the ZN over the ground distance and reading the Bellamy drift angle opposite 57.3. This can be set up in a formula as follows:

$$\frac{\text{BD}}{57.3} = \frac{\text{ZN}}{\text{Ground Dist. NM}}$$

The previous example would be set up as shown in figure 20-14. The answer 7.3 can be read over 57.3 on the minutes scale or under the index of the DRIFT CORR window.

The direction of Bellamy drift is determined in the same way that ZN direction is determined. In

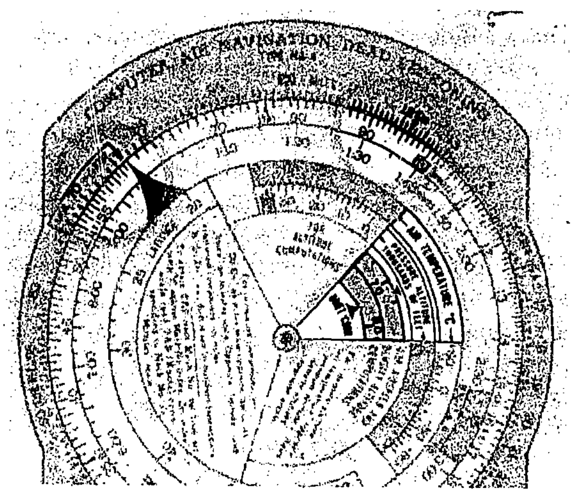


Figure 20-14. Mathematical Solution of Bellamy Drift

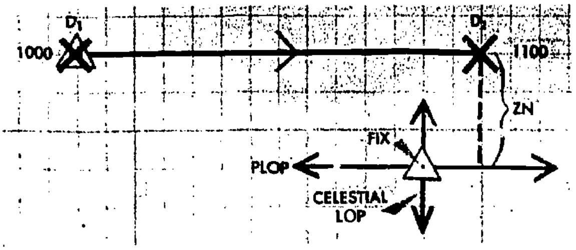


Figure 20-15. Fix Using PLOP and Celestial LOP

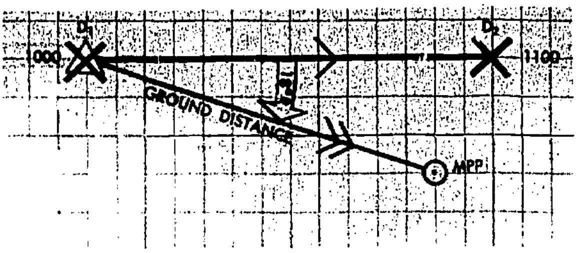


Figure 20-16. MPP by Bellamy Drift

the Northern Hemisphere, a positive D_2-D_1 indicates the aircraft is drifting left; a negative D_2-D_1 indicates the aircraft is drifting right. The situation is reversed in the Southern Hemisphere.

To obtain an MPP, apply BD to true heading and plot a DR position, using best known groundspeed.

Errors and Limitations of Pressure Differential Techniques

GROUND DISTANCE ERROR. In plotting an MPP from a PLOP, an error in ground distance will cause an error in the MPP and, hence, an error in the mean track. However, an error in the MPP will not substantially affect the accuracy of the drift angle.

TACTICAL LIMITATIONS. Bellamy drift has one main limitation. For drift to be determined on each leg of a flight by the Bellamy method, the heading taken up by the aircraft must be maintained long enough to permit a pair of soundings with a time separation of at least 20 minutes.

Some economy of effort will result if a sounding is taken immediately before or after a turn. This sounding may be used, with negligible error, as reference for determining drifts on both legs. Some error will be caused by the difference between the height of the constant pressure surface at the sounding position and the height at the turning point. If not more than a minute or two elapses between turn and sounding, however, the ZN is unlikely to be in error by more than a mile (assuming crosswind is less than 60 knots), and the effect on drift will be correspondingly small, especially if TAS is high.

SUMMARY

ZN is a displacement in nautical miles perpendicular to the effective air path. This means that airplot must be used and a known position is required at the time of D_1.

Determine the D-value by computing readings from the radio altimeter with simultaneous readings from the pressure altimeter, $D = TA - PA$. Use a series of comparisons to aid in picking out any erroneous readings. If any D-value varies by 40 feet or more from the average of the series, discard it and average the remaining values. Consistent errors in the altitudes will not affect the accuracy of the ZN, but changing the setting of either altimeter after the first D-reading will cause inaccuracy. Check the reference blip of the radio altimeter before each reading.

The ZN is obtained by using the equation

$$ZN = \frac{K(D_2-D_1)}{ETAS}$$

which can be rearranged for convenience in using the DR computer,

$$\frac{ZN}{K} = \frac{D_2-D_1}{ETAS}$$

Determine effective true airpseed by using the effective air distance and time. Measure effective air distance along a straight line between the two points in question. After the value of ZN is determined, plot the PLOP parallel to the effective air path. In the Northern Hemisphere, the sign of ZN is the sign of drift correction, and in the Southern Hemisphere, the sign of ZN is the sign of drift. Once the PLOP is plotted, treat it like any other LOP.

Though a PLOP is often preferred to BD, there are two main uses for Bellamy drift:

1. It is often computed to crosscheck the drift that is determined from a fix.
2. Bellamy drift may be plotted as an LOP and then crossed with an LOP from another fixing aid. Figure 20-15 shows a fix determined by use of a PLOP and a celestial LOP; figure 20-16 shows an MPP determined by Bellamy drift.