WINDS ALOFT BY PROGRAMMABLE CALCULATOR

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Abstract

Determination of upper level winds is important to many practicing meteorologists. The pilot balloon method of upper winds analysis is discussed. An algorithm is developed to calculate pibal upper winds with a programmable calculator. Program steps and sample results are presented for the Texas Instruments TI-59 calculator.

1. INTRODUCTION

A current knowledge of wind conditions aloft is important to many operational meteorologists. Often this information can be obtained from the regularly scheduled radiosonde ascents of the National Weather Service (NWS). But when no upper air station is close enough to be representative, or when data is required at times other than 0000 GMT or 1200 GMT, winds at upper levels must be observed in the field.

One of the most used methods for determining the vertical windfield is the pilot balloon method, in which a small balloon is manually tracked by theodolite. Periodic observations are made of its position, and the data converted to winds aloft by a graphical plotting procedure. An alternate method uses the same observational data, but employs a digital computer for wind calculations. The numerical technique requires much less time and effort than the manual method; but expenses associated with computer equipment (or the purchase of computer time) can be prohibitive.

Programmable calculators have recently been introduced with the capacity to compute pibal upper winds (one model, the Texas Instruments TI-59 calculator/printer, requires an outlay of under $500.00). A winds calculation procedure has been developed for the TI-59 which should prove valuable to operational meteorologists who need local winds aloft information but hesitate to expend substantial funds for computer equipment.

2. PILOT BALLOON OBSERVATIONS

A small rising balloon will flow freely with the horizontal winds that it encounters. This is the basis for winds aloft observations by pilot balloon. As it ascends, a pilot balloon "samples" the horizontal windfield in successive layers above the release point. Upper level winds can then be closely approximated by analysis of the balloon's course through each layer.

To determine the balloon's path, periodic observations of its azimuth and elevation angles are made using an optical theodolite. Winds aloft do not follow directly, however, because these data alone can not uniquely establish the balloon's position in space. Supplementary information can be obtained by radar ranging, by using two theodolites, or by the tail method (Middleton, 1941; Spilhaus, 1942). A simpler and usually adequate technique locates the pilot balloon in three dimensions by combining the data observed by a single theodolite with an estimated ascension rate (op. cit.) This is the method routinely used by the National Weather Service, and is the one on which this paper is based (Wood, 1973; U.S. Department of Commerce, 1972). Once successive balloon positions are established, upper winds determination is straightforward.

The procedure employs a small thirty-gram balloon which is filled with helium until it can lift a specified weight (its "free lift"). For nighttime ascent a light is attached prior to inflation. Then the balloon is released and its trajectory followed. Observations of azimuth* and elevation angles are made at one-minute intervals. Using the observed data, and balloon heights estimated from the semi-empirical ascent rate, the upper winds calculation proceeds as shown in Figure 1. The result is a

*The angle actually measured is the "co-azimuth," 180° opposite the true azimuth. This compensates for the 180° difference between wind direction and the flow vector, which is actually determined by the calculation procedure.
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description of the vertical wind field at 1000-ft intervals above the earth's surface. With the exception of the assumed ascent rate, the NWS method is straightforward. The development of this ascent rate is discussed next.

3. BALLOON ASCENT RATE

A balloon filled with lighter-than-air gas experiences a vertically directed net buoyancy force. Upon release, the balloon accelerates upward, and a velocity-related drag force develops. It is directed downward, opposing the buoyancy force. The drag increases with the balloon's velocity, until a balance of forces is achieved with the balloon rising at a constant speed. In practice a steady ascent rate is attained within seconds of release (Middleton, 1941).

The terminal velocity of the rising balloon can be calculated from a semi-empirical formula (Spilhaus, et al., 1942).

\[ w = k_z \left(1 - \frac{m_g}{m}\right)^{1/3} \frac{L^{1/2}}{(L + W_e)^{1/3}} \]  

(1)

where

\[ w = \text{Balloon ascent rate (ft/min)} \]
\[ k_z = \text{Empirical constant} = 290.7 \]
\[ m_g = \text{Molecular weight of lifting gas (g/mole)} \]
\[ m = \text{Molecular weight of air - 29.0 g/mole} \]
\[ L = \text{Free lift of balloon package (g)} \]
\[ W_e = \text{Empty mass of balloon (g)} \]

If the ascent is made at night, equation (1) is modified:

\[ w = k_z \left(1 - \frac{m_g}{m}\right)^{1/3} \frac{L^{1/2}}{(L + W_e + W_l)^{1/3}} \]

(2)

where

\[ W_l = \text{Mass of lighting unit (g)} \]

The free lift is usually set at inflation by attaching a known lifting weight to the filler nozzle, then inflating the balloon until the weight just rises from the floor. At Magma Copper Company a lifting weight of 139.0 g is used. Because it is inert, helium (molecular weight of 4.0 g/mole) is employed whenever possible as the lifting gas. Modern methods of manufacture are precise, so that a balloon weight of 30.0 g can be assumed with little loss of accuracy. With these values, equation (1) becomes:

\[ w = 589.9 \text{ ft/min} \]  

(3)

At Magma Copper a small battery-powered lamp is used as a nighttime light source. A typical mass for lamp, wetted battery, and attachment string has been found to be 15 g. Equation (2) then becomes:

\[ w = 573.3 \text{ ft/min} \]  

(4)

Contrary to what equations (3) and (4) suggest, a pilot balloon does not always ascend through the atmosphere at a constant rate. This assumption is one of the largest sources of error in the pilot balloon method. One contributor to the error is the increased rate of rise caused by thermal and mechanical turbulence in the lowest layers of the atmosphere. Studies using double theodolite observations have shown that this phenomenon can be partially accounted for by (Middleton, 1941):

- Increasing \( w \) by 20 percent during the first minute of flight,
- Increasing \( w \) by 10 percent during the second and third minutes,
- Increasing \( w \) by 5 percent during the fourth and fifth minutes, and
- Using the uncorrected value for \( w \) during the sixth and succeeding minutes of flight.

These corrections are included in the calculation procedure presented in this paper. Other contributors to the error include the influence of organized vertical currents (in excess of the cm/sec values associated with synoptic-scale systems) and the effects of atmospheric density anomalies. These influences can cause the balloon to halt its rise or even descend temporarily, but are not compensated for here.

Table 1 shows pilot balloon heights calculated at selected times during flight using the ascent rates from equations (3) and (4) and the turbulence corrections. These heights, along with observed theodolite data, are sufficient to determine winds aloft. The programmable calculator algorithm developed for this purpose is described in the next section.

4. THE CALCULATOR ALGORITHM

The pibal algorithm (Figures 2 and 3) is designed for use with a programmable calculator of capacity similar to the Texas Instruments TI-59 calculator/PC-100A printer combination. As developed for the TI-59, it requires 50 memory locations and 515 program steps. Table 2 lists the symbols used in the algorithm. For clarity, the program uses variable names, a function beyond the capability of the TI-59. In practice, the variable names represent calculator memory locations.
The algorithm is designed to accept data from fifteen consecutive theodolite observations taken at 1-min intervals. The sequence may start with any whole minute (2.0 min, 3.0 min, etc.) during the ascent; it need not begin immediately after release. Thus unneeded wind levels do not have to be calculated, and long flights can be accommodated in 15-min segments.

As described in the following sections, the algorithm is separated into four parts: balloon height determination, data input, balloon position and velocity calculation, and determination of standard level winds.

**A. Balloon Height Determination**

The pilot balloon height procedure used in the algorithm is based on the discussion in Section II. Because it is used at several points in the program, the height computation is treated as a subroutine to be called when necessary. Figure 2 presents a flow chart of the height calculation procedure. Comments on the chart indicate labels in the TI-59 program shown in Figure 4. The balloon height algorithm is not straightforward. It has been optimized to occupy the fewest possible program steps. It applies the turbulence correction from Section III to determine an "adjusted" time of flight. This value is then multiplied by the appropriate ascent rate (equation (3) or (4)) to obtain the balloon's height in feet.

**B. Data Entry**

The main program begins by setting an internal flag if the ascent occurs at night and the weight of the lighting device is accounted for throughout the program (Figure 3a). Then, headings are printed and the time after release of the first observation in the sequence is entered. Counters are automatically initialized and observed elevation and azimuth angles entered sequentially. All data are printed to help detect input errors. The input loop is exited by the user when the end of the data has been reached, or is terminated automatically when the sequence exceeds 15 min. To ensure that data entry requires as little user time as possible, a minimum of calculations is performed during the input phase of the program. Once the input loop has been exited, the rest of the algorithm is executed with no attention from the user.
C. Calculation of Balloon Position and Velocity

The first step in the computation of upper level winds is the calculation of balloon position at the beginning of each minute of flight. These are calculated from input data and the estimated balloon heights by using trigonometric formulas...
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Meaning</th>
</tr>
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<tbody>
<tr>
<td>Ctdn</td>
<td>Decremental counter in Height subroutine</td>
</tr>
<tr>
<td>D</td>
<td>Standard Level Wind Direction</td>
</tr>
<tr>
<td>Dum</td>
<td>Input Argument for Height Subroutine</td>
</tr>
<tr>
<td>h</td>
<td>Height of Standard Level</td>
</tr>
<tr>
<td>H</td>
<td>Height of Observation Level</td>
</tr>
<tr>
<td>Hlow</td>
<td>Height of First Observation Below Standard Level</td>
</tr>
<tr>
<td>Htm</td>
<td>Accumulator in Height Subroutine</td>
</tr>
<tr>
<td>Hup</td>
<td>Height of First Observation Above Standard Level</td>
</tr>
<tr>
<td>i</td>
<td>Number of Observation</td>
</tr>
<tr>
<td>j</td>
<td>Indicator for Linear Interpolation</td>
</tr>
<tr>
<td>R</td>
<td>Horizontal Radial Distance from Release Point to Balloon</td>
</tr>
<tr>
<td>S</td>
<td>Standard Level Wind Speed</td>
</tr>
<tr>
<td>t₀</td>
<td>Time in Flight at First Observation</td>
</tr>
<tr>
<td>tₜₜ₀</td>
<td>Total Time in Flight at Given Observation</td>
</tr>
<tr>
<td>Tot</td>
<td>Total number of Observations Entered</td>
</tr>
<tr>
<td>uₓ</td>
<td>East-West Component of Standard Level Wind Velocity</td>
</tr>
<tr>
<td>uₓH</td>
<td>East-West Component of Observation Level Wind Velocity</td>
</tr>
<tr>
<td>vᵧ</td>
<td>North-South Component of Standard Level Wind Velocity</td>
</tr>
<tr>
<td>vᵧH</td>
<td>North-South Component of Observation Level Wind Velocity</td>
</tr>
<tr>
<td>vᵧstor</td>
<td>Holding Storage for vᵧH Values</td>
</tr>
<tr>
<td>w</td>
<td>Balloon Ascent Rate</td>
</tr>
<tr>
<td>x</td>
<td>East-West Position of Balloon</td>
</tr>
<tr>
<td>y</td>
<td>North-South Position of Balloon</td>
</tr>
<tr>
<td>φ</td>
<td>Balloon Elevation Angle</td>
</tr>
<tr>
<td>θ</td>
<td>Balloon Azimuth Angle</td>
</tr>
</tbody>
</table>

Table 2. Symbol List for Pilot Balloon Algorithm.
Figure 4. The TI-59 Pilot Balloon Program and Pre-Programmed Memory Contents.
application of the program using a specific calculator - the Texas Instruments TI-59.

5. THE TI-59 PROGRAM

Figure 4 shows the program used in the TI-59 version of the pibal algorithm. It lists both the program steps and the pre-programmed memory contents needed to compute winds aloft. The program is lengthy, but does not have to be re-entered for each use. The TI-59 is equipped with magnetic recording cards which allow program storage much like a full sized computer. The entire pibal program can be recorded on two cards of two tracks each, and then read into the calculator whenever needed.

Figure 5 shows an example of the output from a run of the program shown in Figure 4. It involves a 13-min observation sequence starting with the first minute after balloon release. Standard level winds have been calculated for heights from 1000 to 7000 ft above ground level.

Once the pibal program is stored on magnetic cards, upper level winds can be computed using the steps below. Appropriate keystrokes are indicated in parentheses after each step.

(1) Set the TI-59 internal storage allocation to 50 memories and 560 program steps (1550 5).

(2) Read magnetic card 1, track 1 CLR input card).

D. Calculation of Standard Level Winds

At this point in the pilot balloon algorithm, average wind velocities have been calculated at successive 1-min intervals in the balloon's ascent. However, it is usually more meaningful to specify the winds at equal intervals of height above the earth's surface. This is done in the algorithm by applying linear interpolation to the computed 1-min velocities (Figure 3c). Winds are determined at standard 1000-ft intervals.

The process begins by identifying the lowest standard level for which winds can be computed; this will be 1000 ft above the surface if the observation sequence begins with the balloon release. Then, using the average velocities (calculated above for each minute) which bracket this height, the standard level velocity components are interpolated. As the flow diagram in Figure 3d shows, the vector wind components for this level are then converted to the polar coordinates of wind direction and speed. Two additional conversions follow, placing any negative wind direction in the range of 10° to 360°, and converting the speed from ft/min to knots. No attempt is made to remove the direction from a calm wind. The results for this 1000-ft interval are now in final form, and are printed out along with appropriate labels. The algorithm then loops back and repeats the process for the next standard level. Iterations continue until higher levels can no longer be computed from the available data. The program then signals the user that all possible standard level winds have been determined, and prepares to receive new input data for another run.

The algorithm described above has been generalized for use with any programmable calculator of suitable capacity. The next section details the
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(3) Read magnetic card 1, track 2 / CLR / input card).
(4) Read magnetic card 2, track 1 / CLR / input card).
(5) Read magnetic card 2, track 2 / CLR / input card).
(6) Prepare the program for daytime flight / A / or nighttime flight / 2nd A / input card).
(7) The heading "UPPER WINDS" will print.
(8) Enter the starting minute of the observation sequence (entry, / R/S / ).
(9) The starting minute will print.
(10) The heading "DATA" will print.
(11) Enter the elevation angle for the starting minute (entry, / R/S / ).
(12) The elevation angle will print.
(13) Enter the azimuth angle for the starting minute (entry, / R/S / ).
(14) The azimuth angle will print.
(15) Repeat steps 11 to 14 for each additional minute in the sequence until all observations have been entered into calculator memory. No more than 15 min are allowed.
(16) Exit the input loop manually / B /, or exit automatically if 15 min have been entered.
(17) The TI-59 will calculate for approximately 8 min.
(18) The heading "WINDS" will print.
(19) Standard level upper winds will output at 30-sec intervals.
(20) When all obtainable levels have been printed, the heading "END" will output.
(21) The program can be re-run with new data by repeating steps 6 to 20.

A complete run of the program for a 15-min pibal observation takes approximately 12 min. The calculation time can be significantly shortened by removing the internal labels (e.g., label P/R) and using numbered program steps for internal transfers.

A variation of the TI-59 pibal program has been routinely used in several hundred pilot balloon ascents made in support of the operational air quality forecasting program at Magma Copper Company. The data from many of these ascents were also analyzed by the graphical plotting method in order to validate the program. Results from the two methods were nearly identical (within 2 knots and 5 degrees) for releases under a wide range of meteorological conditions.

6. SUGGESTIONS FOR FURTHER DEVELOPMENT

The pibal program presented in this paper can be adapted to a variety of special needs. For instance, winds can be calculated for standard heights above mean sea level, instead of above ground level. Provisions can be made to input data for intervals shorter or longer than the 1-min segments used here, or even for variable times. Winds can be calculated at increments greater or smaller than 1000 ft. The algorithm can easily be adapted for use without the printer, making the TI-59 ideally suited to remote field use.

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