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 acutally 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.

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).

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

where

w = Balloon ascent rate (ft/min)

k_z = Empirical constant = 290.7

m_g = Molecular weight of lifting gas (g/mole)

m = Molecular weight of air - 29.0 g/mole

L = Free lift of balloon package (g)

W_e = Empty mass of balloon (g)

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

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

where

W_e' = 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:

$$w = 589.9 \text{ ft/min} \qquad (3)$$

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:

$$w = 573.3 \text{ ft/min} \qquad (4)$$

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):

- o Increasing w by 20 percent during the first minute of flight,
- o Increasing w by 10 percent during the second and third minutes,
- o Increasing w by 5 percent during the fourth and fifth minutes, and
- o 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.

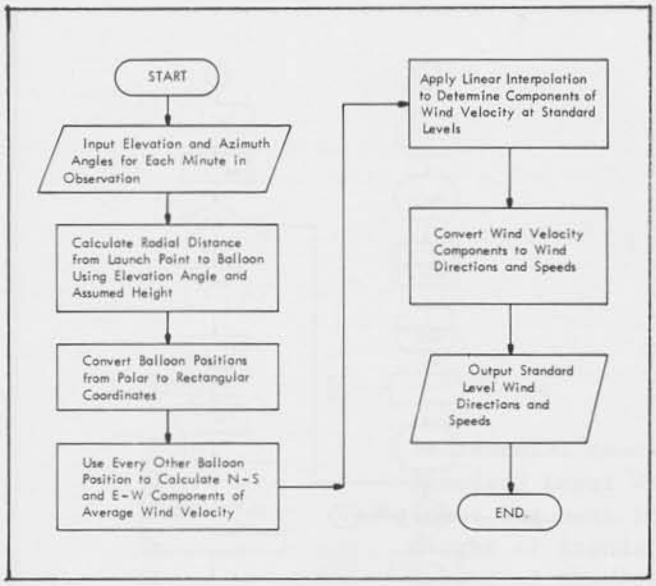

Figure 1. National Weather Service Method of Pilot Balloon Winds Aloft Calculation.

Minute of Flight	Height Above Surface for Daytime Flight (ft)	Height Above Surface for Nighttime Flight (ft)
0	0	0
1	707.9	688.0
2	1356.8	1318.6
3	2005.7	1949.2
4	2625.1	2551.2
5	3244.4	3153.2
6	3834.4	3726.4
7	4424.2	4299.8
8	5014.2	4873.1
9	5604.1	5446.4
10	6194.0	6019.7
11	6783.8	6592.9
12	7373.7	7166.2
13	7963.7	7739.6
14	8553.5	8312.9
15	9143.4	8886.1
Additional minutes	Add 589.9	Add 573.3

Table 1. Balloon height calculated at selected minutes in flight using ascent rates from equations (3) and (4) and the turbulence corrections.

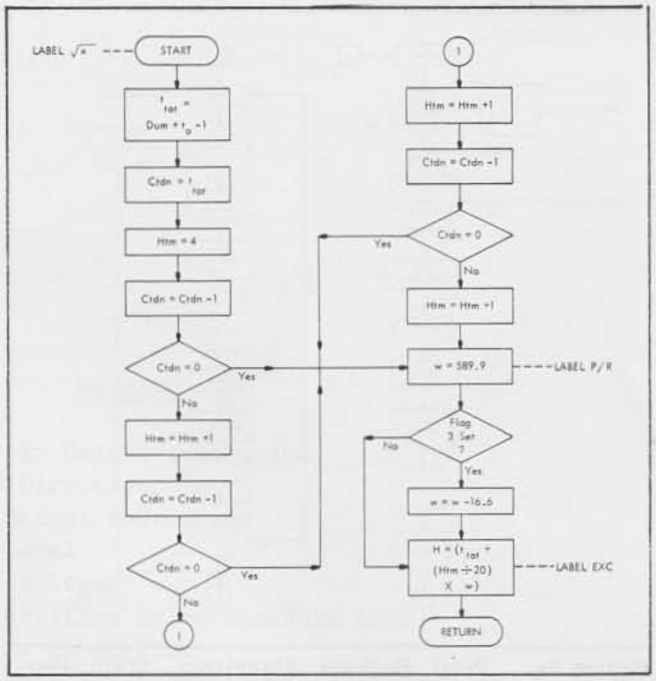

Figure 2. Pilot Balloon Algorithm, Balloon Height Subroutine.

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 mutliplied 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.

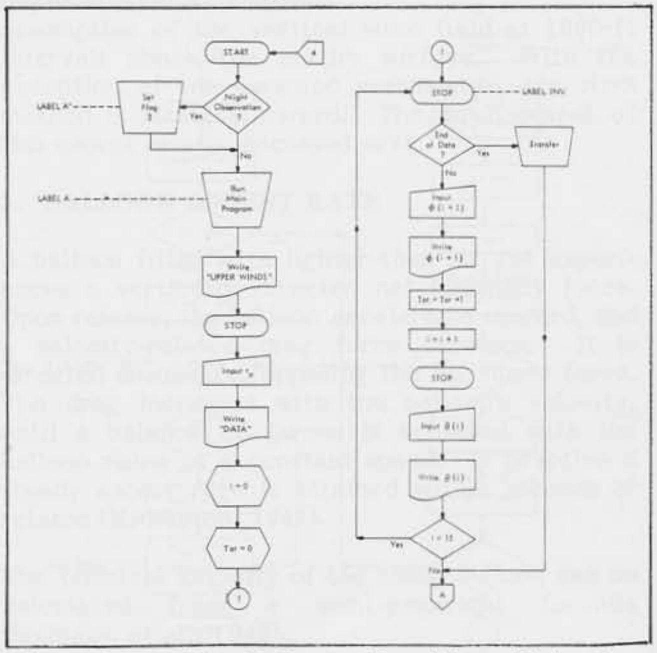

Figure 3a. Pilot Balloon Algorithm, Main Program, Data Entry.

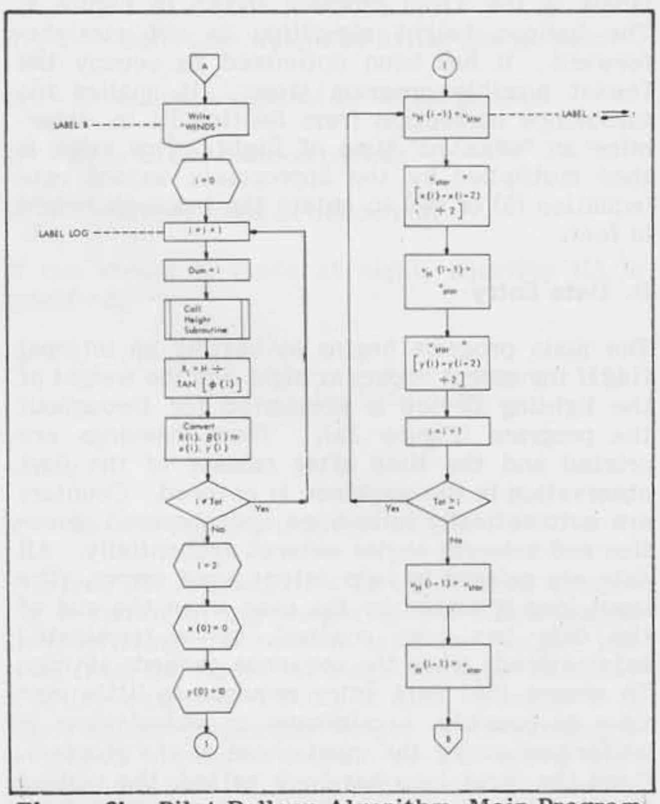

Figure 3b. Pilot Balloon Algorithm, Main Program, Calculation of Balloon Position and Velocity.

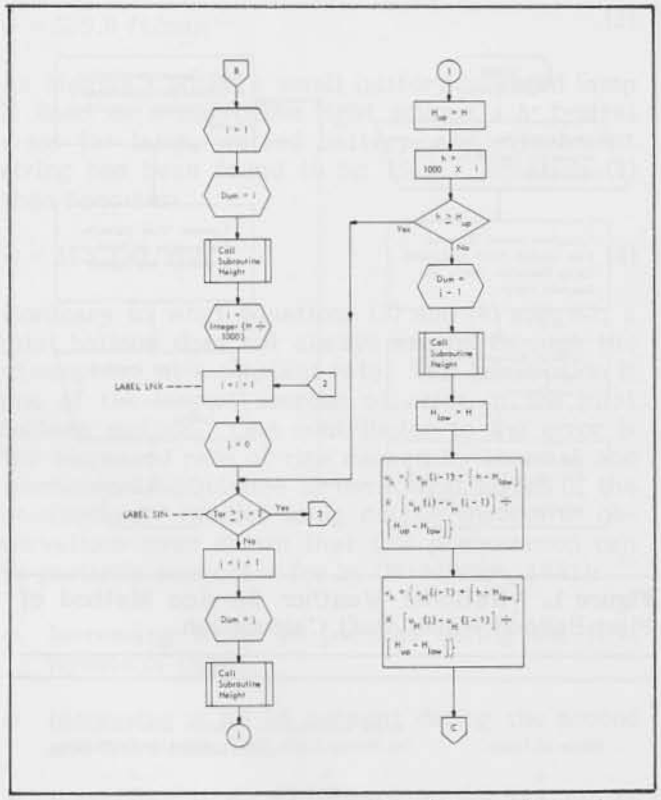

Figure 3c. Pilot Balloon Algorithm, Main Program, Calculation of Standard Level Winds.

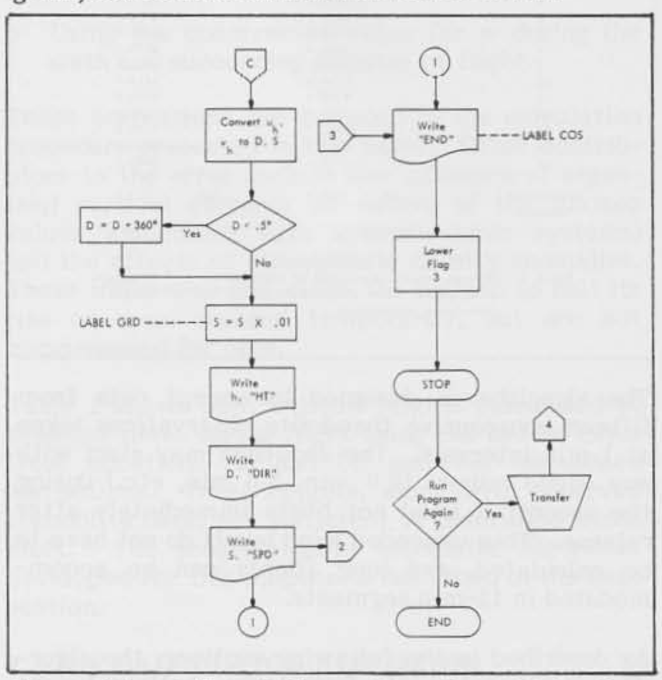

Figure 3d. Pilot Balloon Algorithm, Main Program, Final Conversions and Output.

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

Symbol	Meaning
Ctdn	Decremental counter in Height subroutine
D	Standard Level Wind Direction
Dum	Input Argument for Height Subroutine
h	Height of Standard Level
H	Height of Observation Level
H_{low}	Height of First Observation Below Standard Level
H_{tm}	Accumulator in Height Subroutine
H_{up}	Height of First Observation Above Standard Level
i	Number of Observation
j	Indicator for Linear Interpolation
R	Horizontal Radial Distance from Release Point to Balloon
S	Standard Level Wind Speed
t_o	Time in Flight at First Observation
t_{tot}	Total Time in Flight at Given Observation
Tot	Total number of Observations Entered
u_h	East-West Component of Standard Level Wind Velocity
u_H	East-West Component of Observation Level Wind Velocity
u_{stor}	Holding Storage for u_H Values
v_h	North-South Component of Standard Level Wind Velocity
v_H	North-South Component of Observation Level Wind Velocity
v_{stor}	Holding Storage for v_H Values
w	Balloon Ascent Rate
x	East-West Position of Balloon
y	North-South Position of Balloon
ϕ	Balloon Elevation Angle
θ	Balloon Azimuth Angle

Table 2. Symbol List for Pilot Balloon Algorithm.

TI - 59 PROGRAM STEPS

Step #	Statement
000	76 LBL
001	34 ΓX
002	42 STO
003	38 38
004	42 STO
005	42 42
006	53 (
007	43 RCL
008	43 43
009	75 -
010	01 1
011	54)
012	44 SUM
013	38 38
014	44 SUM
015	42 42
016	29 CP
017	04 4
018	42 STO
019	41 41
020	01 1
021	22 INV
022	44 SUM
023	38 38
024	43 RCL
025	38 38
026	67 EQ
027	37 P/R
028	02 2
029	44 SUM
030	41 41
031	01 1
032	22 INV
033	44 SUM
034	38 38
035	43 RCL
036	38 38
037	67 EQ
038	37 P/R
039	02 2
040	44 SUM
041	41 41
042	01 1
043	22 INV
044	44 SUM
045	38 38
046	43 RCL
047	38 38
048	67 EQ
049	37 P/R
050	01 1
051	44 SUM
052	41 41
053	01 1
054	22 INV
055	44 SUM
056	38 38
057	43 RCL
058	38 38
059	67 EQ
060	37 P/R
061	01 1
062	44 SUM
063	41 41
064	76 LBL
065	37 P/R
066	05 5
067	08 8
068	09 9
069	93 .
070	09 9
071	42 STO
072	38 38
073	22 INV
074	87 IFF
075	03 03
076	48 EXC
077	01 1
078	06 6
079	93 .
080	06 6
081	22 INV
082	44 SUM
083	38 38
084	76 LBL
085	48 EXC
086	53 (
087	53 (
088	43 RCL
089	42 42
090	85 +
091	43 RCL
092	41 41
093	55 ÷
094	02 2
095	00 0
096	54)
097	65 ×
098	43 RCL
099	38 38
100	54)
101	92 RTN

Step #	Statement
102	76 LBL
103	69 OP
104	42 STO
105	34 34
106	73 RC*
107	34 34
108	42 STO
109	37 37
110	02 2
111	22 INV
112	44 SUM
113	34 34
114	03 3
115	05 5
116	44 SUM
117	40 40
118	53 (
119	53 (
120	43 RCL
121	37 37
122	75 -
123	73 RC*
124	34 34
125	54)
126	55 ÷
127	02 2
128	54)
129	63 EX*
130	40 40
131	72 ST*
132	34 34
133	92 RTN
134	76 LBL
135	70 RAD
136	53 (
137	73 RC*
138	37 37
139	85 +
140	53 (
141	43 RCL
142	33 33
143	65 ×
144	01 1
145	00 0
146	00 0
147	00 0
148	75 -
149	53 (
150	43 RCL
151	39 39
152	54)
153	54)
154	65 ×
155	53 (
156	73 RC*
157	34 34
158	75 -
159	73 RC*
160	37 37
161	54)
162	55 ÷
163	53 (
164	53 (
165	43 RCL
166	40 40
167	54)
168	75 -
169	53 (
170	43 RCL
171	39 39
172	54)
173	54)
174	54)
175	92 RTN
176	76 LBL
177	16 A'
178	86 STF
179	03 03
180	76 LBL
181	11 A
182	22 INV
183	58 FIX
184	69 OP
185	00 00
186	43 RCL
187	48 48
188	69 OP
189	01 01
190	43 RCL
191	49 49
192	69 OP
193	03 03
194	69 OP
195	05 05
196	98 ADV
197	91 R/S
198	99 PRT
199	42 STO
200	43 43
201	98 ADV
202	69 OP
203	00 00
204	43 RCL
205	47 47

Step #	Statement
206	69 OP
207	02 02
208	69 OP
209	05 05
210	98 ADV
211	01 1
212	06 6
213	42 STO
214	34 34
215	00 0
216	42 STO
217	32 32
218	76 LBL
219	22 INV
220	98 ADV
221	91 R/S
222	99 PRT
223	32 X:T
224	01 1
225	44 SUM
226	32 32
227	44 SUM
228	34 34
229	32 X:T
230	72 ST*
231	34 34
232	91 R/S
233	99 PRT
234	72 ST*
235	32 32
236	01 1
237	05 5
238	32 X:T
239	43 RCL
240	32 32
241	22 INV
242	77 GE
243	22 INV
244	76 LBL
245	12 B
246	58 FIX
247	00 00
248	98 ADV
249	69 OP
250	00 00
251	43 RCL
252	49 49
253	69 OP
254	02 02
255	69 OP
256	05 05
257	98 ADV
258	01 1
259	06 6
260	42 STO
261	34 34
262	00 0
263	42 STO
264	33 33
265	76 LBL
266	28 LOG
267	01 1
268	44 SUM
269	33 33
270	44 SUM
271	34 34
272	43 RCL
273	33 33
274	71 SBR
275	34 ΓX
276	55 ÷
277	53 (
278	73 RC*
279	34 34
280	30 TAN
281	54)
282	95 =
283	32 X:T
284	73 RC*
285	33 33
286	37 P/R
287	72 ST*
288	34 34
289	32 X:T
290	72 ST*
291	33 33
292	43 RCL
293	32 32
294	32 X:T
295	43 RCL
296	33 33
297	22 INV
298	67 EQ
299	28 LOG
300	02 2
301	42 STO
302	33 33
303	00 0
304	42 STO
305	00 00
306	42 STO
307	16 16

Step #	Statement
308	76 LBL
309	32 X:T
310	00 0
311	42 STO
312	40 40
313	43 RCL
314	33 33
315	71 SBR
316	69 OP
317	01 1
318	42 STO
319	40 40
320	43 RCL
321	33 33
322	85 +
323	01 1
324	06 6
325	95 =
326	71 SBR
327	69 OP
328	01 1
329	44 SUM
330	33 33
331	43 RCL
332	33 33
333	32 X:T
334	43 RCL
335	32 32
336	77 GE
337	32 X:T
338	01 1
339	44 SUM
340	34 34
341	43 RCL
342	36 36
343	72 ST*
344	34 34
345	01 1
346	06 6
347	22 INV
348	44 SUM
349	34 34
350	43 RCL
351	35 35
352	72 ST*
353	34 34
354	01 1
355	71 SBR
356	34 ΓX
357	55 ÷
358	01 1
359	00 0
360	00 0
361	00 0
362	95 =
363	59 INT
364	42 STO
365	33 33
366	76 LBL
367	23 LNX
368	01 1
369	44 SUM
370	33 33
371	00 0
372	42 STO
373	35 35
374	76 LBL
375	38 SIN
376	43 RCL
377	35 35
378	85 +
379	02 2
380	95 =
381	32 X:T
382	43 RCL
383	32 32
384	22 INV
385	77 GE
386	39 COS
387	01 1
388	44 SUM
389	35 35
390	43 RCL
391	35 35
392	71 SBR
393	34 ΓX
394	42 STO
395	40 40
396	32 X:T
397	43 RCL
398	33 33
399	65 ×
400	01 1
401	00 0
402	00 0
403	00 0
404	95 =
405	77 GE
406	38 SIN
407	43 RCL
408	35 35
409	42 STO
410	34 34
411	75 -
412	01 1
413	95 =

Step #	Statement
414	42 STO
415	37 37
416	71 SBR
417	34 ΓX
418	42 STO
419	39 39
420	71 SBR
421	70 RAD
422	42 STO
423	36 36
424	01 1
425	06 6
426	44 SUM
427	34 34
428	44 SUM
429	37 37
430	43 RCL
431	36 36
432	32 X:T
433	71 SBR
434	70 RAD
435	22 INV
436	37 P/R
437	42 STO
438	36 36
439	32 X:T
440	42 STO
441	37 37
442	93 .
443	05 5
444	22 INV
445	77 GE
446	80 GRD
447	32 X:T
448	85 +
449	03 3
450	06 6
451	00 0
452	95 =
453	42 STO
454	36 36
455	76 LBL
456	80 GRD
457	93 .
458	00 0
459	01 1
460	49 PRD
461	37 37
462	43 RCL
463	44 44
464	69 OP
465	04 04
466	43 RCL
467	33 33
468	65 ×
469	01 1
470	00 0
471	00 0
472	00 0
473	95 =
474	69 OP
475	06 06
476	43 RCL
477	45 45
478	69 OP
479	04 04
480	43 RCL
481	36 36
482	69 OP
483	06 06
484	43 RCL
485	46 46
486	69 OP
487	04 04
488	43 RCL
489	37 37
490	69 OP
491	06 06
492	98 ADV
493	61 GTO
494	23 LNX
495	76 LBL
496	39 COS
497	69 OP
498	00 00
499	01 1
500	07 7
501	03 3
502	01 1
503	01 1
504	06 6
505	69 OP
506	02 02
507	69 OP
508	05 05
509	98 ADV
510	98 ADV
511	22 INV
512	86 STF
513	03 03
514	91 R/S

TI - 59 PRE - PROGRAMMED MEMORY STORAGE

Stored Value	Memory #
0.	00
0.	01
0.	02
0.	03
0.	04
0.	05
0.	06
0.	07
0.	08
0.	09
0.	10
0.	11
0.	12
0.	13
0.	14
0.	15
0.	16
0.	17
0.	18
0.	19
0.	20
0.	21
0.	22
0.	23
0.	24
0.	25
0.	26
0.	27
0.	28
0.	29
0.	30
0.	31
0.	32
0.	33
0.	34
0.	35
0.	36
0.	37
0.	38
0.	39
0.	40
0.	41
0.	42
0.	43
23370000.	44
16243540.	45
36331600.	46
16133713.	47
4133331735.	48
4324311636.	49

Figure 4. The TI-59 Pilot Balloon Program and Pre-Programmed Memory Contents.

(Figure 3b). Next, the algorithm converts the positions from polar (r, θ) to rectangular (x, y) coordinates with origin at the release point. Average wind velocities are then determined for each minute of the sequence (except the first and last for which data are insufficient). This is done by computing the balloon's change of position during the 2-min interval surrounding each observation. For example, the x position (ft) at Minute 1 is subtracted from the x position at Minute 3, and the result divided by two. This produces an average u wind velocity (ft/min) which is assigned as the value for Minute 2. A similar process is used to determine a v velocity from appropriate y positions. This procedure is repeated until velocity components have been calculated for the entire sequence. The program utilizes temporary storage so that component wind speeds can replace already used values of x and y positions. This allows a savings of 15 memory locations, but results in the loss of balloon position data.

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 1^{o} to 360^{o}, 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 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 wnds 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.

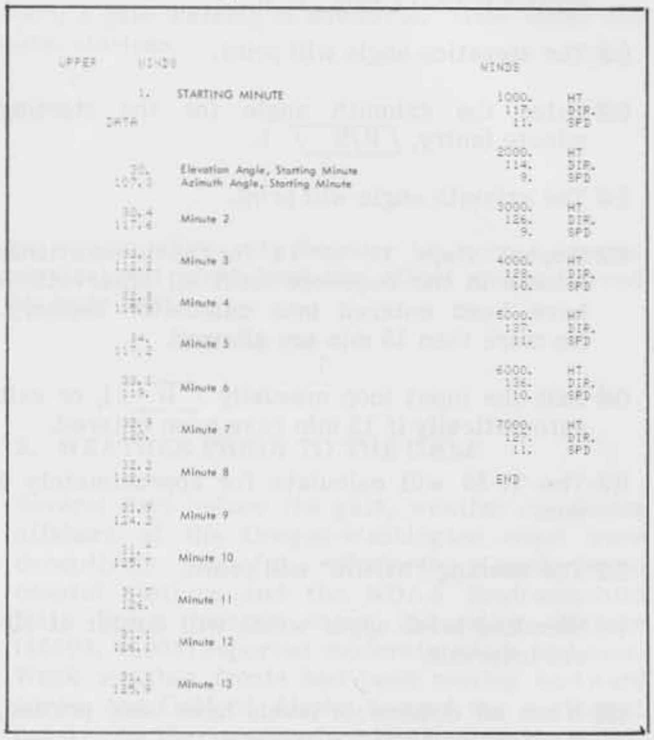

Figure 5. Example Output from the TI-59 Pilot Balloon Program Shown in Figure 4.

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 (/ 5 / / 2nd / / OP / / 1 / / 6 /).

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

(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 nightime flight / 2nd / / A' /).

(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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