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FIELD COMPUTATION OF WINDS-ALOFT VELOCITIES FROM SINGLE THEODOLITE PILOT BALLOON OBSERVATIONS

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The ability to determine wind speeds and directions in the first few thousand meters of the atmosphere is important in many forestry operations such as smoke management, aircraft seeding and spraying, prescribed burning, and wildfire suppression. A hand-held electronic calculator can be used to compute winds aloft as balloon observations are taken. Calculations can be made in the field with any calculator with trigonometric functions, programmable or non-programmable, by the method described.

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Knowledge of wind speeds and directions in the first few thousand meters of the atmosphere is important in many forestry operations such as smoke management, aircraft seeding and spraying, prescribed burning, and wildfire suppression. The ability to determine quickly the velocity of winds aloft over wildfires is important to fire behavior officers. One person can enter data and compute winds from the surface to above 3000 meters in less than 7 minutes with a programmable calculator. This allows winds aloft to be determined as observations are taken. With a non-programmable calculator, winds to above 3000 meters can be computed in approximately 30 minutes or within about 13 minutes after the 3060-meter observation.

Winds aloft can be determined from single theodolite balloon observations with the aid of a graphical calculation kit as described by Hull,[1] but the kit and the plotting of data are cumbersome. They are not necessary if an electronic calculator with trigonometric functions is available. The simplicity of computation with an electronic calculator also decreases the probability of error. If a programmable calculator with at least four storage registers is available, then the solution is very simple. A programmable hand-held calculator will now be used by the Pacific Southwest Station's Fire Behavior Team to compute winds aloft near wildland fires. The programmable calculator routine requires only the entry of the time interval in seconds between observations, balloon height in meters, and elevation and azimuth angles. In the following sections, this routine is first described through an example, as used with or without the rectangular- to polar-coordinate transformation function available on the HP-65 and some other calculators.[2] Then a brief summary of the steps is given, with program user instructions and a program list adaptable to the simplest calculator with trigonometric functions.

USING A PROGRAMMABLE CALCULATOR— AN EXAMPLE

Pilot balloon elevation and azimuth angle observations made at the Coyote Fire at Santa Barbara, California, on September 28, 1964, are good data for an example (*fig. 1*) of winds-aloft calculations made with a hand-held calculator. Observed elevation and azimuth angles are recorded on the computation sheet as shown for every minute after balloon release. Wind speeds and directions in the last three columns are means for the layer between each two observations. For instance, the wind direction and speed recorded at 1.5 minutes are the means between the balloon height at 1 minute and the height at 2 minutes. The means can be computed between any two observations. Calculations with a programmable calculator do not require recording of distance out, east-west distance x, north-south distance y, the east-west distance Δx traveled in the time interval, or the north-south distance traveled Δy. These columns are necessary to record intermediate calculations when nonprogrammable calculators are used.

Record for Computation of Winds Aloft from Single Theodolite Pilot Balloon Observations

Date 9/28/64 Location POTRERO SECO Dry Bulb 77°F Wet Bulb 52°F
Elevation 4692 FT. msl. R.H. 17% Dewpoint 29°F Wind SW 4-6 mi/h
Start Time 1346 PDT Sky Condition CLEAR Visibility UNRESTRICTED
Reason Terminated END OF RUN Observer MUTCH + CHURAK
Remarks AT FIRE CAMP - 6 MILES NE OF FIRE EDGE

Time Min.	Assumed height above ground level (meters)	(feet)	Elevation (deg.)	Azimuth (deg.)	Distance out* (m)	x* (m)	y* (m)	Δx* (m)	Δy* (m)	Direction (deg.)	Speed (m/s)	(mi/h)
0.0	0	0										
0.5	108	354						283	7	269	4.7	11
1.0	216	709	37.3	88.5	284	283	7					
1.5	315	1033						111	76	236	2.2	5
2.0	414	1358	45.8	78.1	403	394	83					
2.5	513	1683						48	130	200	2.3	5
3.0	612	2008	51.3	64.3	490	442	213					
3.5	707	2320						70	135	207	2.5	6
4.0	801	2628	52.3	55.8	619	512	348					
4.5	896	2940						158	87	241	3.0	7
5.0	990	3248	51.1	57.0	799	670	435					
5.5	1080	3543						247	75	253	4.3	10
6.0	1170	3839	48.1	60.9	1050	917	511					
6.5	1260	4134						408	121	253	7.1	16
7.0	1350	4429	42.6	64.5	1468	1325	632					
7.5	1440	4724						482	158	252	8.5	19
8.0	1530	5020	37.8	66.4	1972	1807	790					
8.5	1620	5315						547	152	254	9.5	21
9.0	1710	5610	34.0	68.2	2535	2354	941					
9.5	1800	5906						541	158	254	9.4	21
10.0	1890	6201	31.4	69.2	3096	2895	1100					
10.5	1980	6496						500	143	254	8.7	19
11.0	2070	6791	29.8	69.9	3614	3394	1242					
11.5	2160	7087						493	142	254	8.6	19
12.0	2250	7382	28.6	70.4	4127	3888	1384					
12.5	2340	7677						510	121	257	8.7	20
13.0	2430	7972	27.6	71.1	4648	4398	1506					
13.5	2520	8268						619	144	257	10.6	24
14.0	2610	8563	26.3	71.8	5281	5017	1649					
14.5	2700	8858						549	63	263	9.2	21
15.0	2790	9154	25.6	72.9	5823	5566	1712					
15.5	2880	9449										
16.0	2970	9744										
16.5	3060	10039										
17.0	3150	10335										
17.5	3240	10630										
18.0	3330	10925										

*These columns are not required when programmable calculator is used.

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Figure 1—Example of a form for computing winds aloft from single theodolite pilot balloon observations.

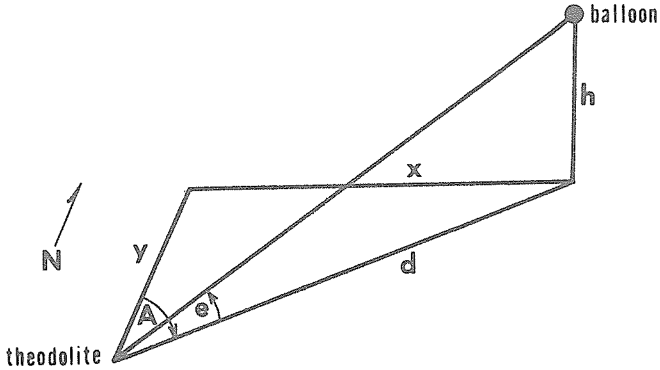

Figure 2— Illustration of distances and angles used to calculate wind velocities from pilot balloon observations.

As the first step in the procedure, mean wind speed and direction between each two observations are calculated. The horizontal component d_t of the distance of the balloon from the theodolite is computed by determining the base of the triangle (*fig. 2*) formed by the theodolite, the balloon at the observation time, and the spot directly below the balloon. Thus,

$$d_t = \frac{h_t}{\tan e_t} \tag{1}$$

where e_t is the elevation angle of the balloon determined by the theodolite observation at time t, and h_t is the standard height of the balloon above the ground at the same time. If the calculator's rectangular- to polar-coordinate transformation function is used, the azimuth angle A_t, the angle of the balloon's position clockwise from north, must be transformed to angle a_t compatible with the calculator's axis orientation, in which 0° is to the east and angles increase counterclockwise. This is accomplished by the transformation

$$a_t = 90 - A_t \tag{2}$$

The distance d_t and the angle a_t can then be used with the polar- to rectangular-coordinate transformation function to determine the east-west x_t and the north-south y_t components. If the transformation function is not built into the calculator then the components are found by determining the opposite and adjacent sides of the triangle (fig. 2) where

$$x_t = d_t \sin A_t \tag{3}$$

and

$$y_t = d_t \cos A_t \tag{4}$$

The east-west distance moved during the time interval is

$$\Delta x_i = x_{(t+1)} - x_t \tag{5}$$

where a positive Δx indicates movement to the east. The north-south distance moved during the same time interval is

$$\Delta y_i = y_{(t+1)} - y_t \tag{6}$$

where a positive Δy indicates movement to the north.

The mean wind speed

$$V_i = [(\Delta x_i)^2 + (\Delta y_i)^2]^{½} / \Delta t_i \tag{7}$$

where Δt_i is the time interval in seconds between balloon observations.

If the calculator's rectangular- to polar-coordinate function is used, the angle β obtained must be transformed from the computer axis orientation, in which 0° is to the east and azimuth increases counterclockwise, to the wind direction axis orientation, with 0° to the north and azimuth increasing clockwise. To accomplish this transformation and obtain the direction θ_i from which the wind is coming, the relationship

$$\theta_i = 270 - \beta_i \tag{8}$$

where if $\theta_i > 360$, $\theta_i = \theta_i - 360$, is used. If a rectangular- to polar-coordinate transformation is not a built-in function, the angle ϕ_i where $\phi_i = \arctan(\Delta y_i/\Delta x_i)$ must be determined and ϕ_i transformed based on analysis of the signs of Δx_i and Δy_i as shown in *table 1*.

Table 1—*Conversion of calculator output angles to wind direction*

	–	+	Δ	
		–	Δx_i	+
Δy_i	+	$\theta_i = 90 - \phi_i$		$\theta_i = 270 - \phi_i$
	–	$\theta_i = 90 - \phi_i$		$\theta_i = 270 - \phi_i$

USING OTHER CALCULATORS

The program user instructions (*table 2*) and the program list (*table 3*) for computation with an HP-65 can be adapted easily for a nonprogrammable calculator or other programmable type of calculator. The following checklist of steps describes how winds aloft can be determined by the simplest calculator with trigonometric functions.

1. Compute and record distance out.

   $d_t = h_t/\tan e_t$

2. Compute and record x_t and y_t.
   a. If polar- to rectangular-coordinate function is available,
      (1) input d_t and $90 - A_t$;
      (2) employ polar- to rectangular-coordinate function;
      (3) read and record x_t and y_t.
   b. If polar- to rectangular-coordinate function is not available,
      (1) find $x_t = d_t \sin A_t$ and record;
      (2) find $y_t = d_t \cos A_t$ and record.
3. Determine Δx_i and Δy_i
   a. find $\Delta x_i = x_{(t+1)} - x_t$ and record;
   b. find $\Delta y_i = y_{(t+1)} - y_t$ and record.
4. Compute mean speeds and directions for each layer.
   a. If rectangular- to polar-coordinate function is available,
      (1) input Δx_i and Δy_i
      (2) employ rectangular to polar function
      (3) read speed and vector direction, β_i
      (4) transform vector direction β_i to wind direction θ_i:

      $\theta_i = 270 - \beta_i$;

      if $\theta_i > 360$, $\theta_i = \theta_i - 360$.

   b. If rectangular to polar function is not available,
      (1) find speed

      $= [(\Delta x_i)^2 + (\Delta y_i)^2]^{1/2} / \Delta t_i$

      (2) find direction
         (a) first find $\phi = \arctan(\Delta y_i/\Delta x_i)$ then
         (b) determine wind direction θ_i by analysis of signs of Δy_i and Δx_i as shown in *table 1.*

Table 2—*User instructions for HP-65 calculator*

Instructions	Input data	Key	Output data
1. Key in program or load card if program is recorded.			
2. Initialize program.		A	
3. Enter time interval, Δt, between observations.	Δt in seconds	R/S	
4. Enter constant to convert calculated wind speed to miles per hour or knots.	To obtain mi/h: K = 2.24 To obtain knots: K = 1.94	R/S	
5. Enter first height (usually 0 for surface).	h in meters above surface	R/S	
6. Enter first elevation angle (usually 0 for surface).	e in degrees above level	R/S	
7. Enter first azimuth angle (0 for surface).	A in degrees clockwise from north	R/S	
8. Enter next height.	h in meters above surface	R/S	
9. Enter next elevation angle.	e in degrees	R/S	
10. Enter next azimuth angle.	A in degrees	R/S	Direction in degrees clockwise from north
11.		R/S	Speed in (m/s)
12.		R/S	Speed in units determined by K
13. For speed and direction in next layer, go to step 8.		B	
14. If different time interval is encountered, go to step 2.			

Table 3–*Program to compute winds aloft velocities from single theodolite balloon observations*

Program	Code	Comments	Registers
LBL A	2311		R1 Δt
f CLR REG	3143		R2 x
f^{-1} SF1	3251		R3 y
R/S	84	Enter Δt; $\Delta t = t_2 - t_1$	R4 K
STO 1	3301	Δt into register 1, R1	
R/S	84	Enter constant, K, if units of speed in addition to m/s are desired (for mi/h, K = 2.24; for knots, K = 1.94)	
STO 4	3304	K into register 4, R4	
LBL B	2312		
R/S	84	Enter balloon height h in meters	
R/S	84	Enter elevation angle e in meters	
R/S	84	Enter azimuth angle A in degrees clockwise of north	
gx=y	3523	If e = A = 0 then continue; if not, skip 2 steps	
GTO	22		
2	02		
g R↓	3508	e into X register	
f TAN	3106	tan e	
÷	81	h/tan e	
g R↑	3509	A into X register	
CHS	42	−A in X register	
9	09		
0	00	90 into X register, −A into Y	
+	61	90 − A = α into X register	
gx↔y	3507	d into X, α into Y register	
f^{-1} R→P	3201	Change distance and direction to x and y components	
LBL 2	2302		
f TF 1	3161		
GTO	22		
3	03		
f SF 1	3151	Allows 1st and 2nd sets of	
STO 2	3302	data to be entered before	
gx↔y	3507	speed and direction are	
STO 3	3303	calculated	
GTO B	2212		
LBL 3	2303		
RCL 2	3402	x_1 into X register	

Program	Code	Comments
RCL 3	3403	y_1 into X register; x_1 into Y
g R↑	3509	y_2 into X register
STO 3	3303	y_2 stored in register 3, R3
g R↑	3509	x_2 into X register
STO 2	3302	x_2 stored in register 2, R2
g R↓	3508	y_2 into X register; y_1 into Y register
−	51	$y_1 - y_2 = -\Delta y$ into X register
CHS	42	Δy into X register
g R↓	3508	x_1 into X register, x_2 into Y
−	51	Δx into X register
gx↔y	3507	x_2 into X register
g R↓	3508	Δx into X register, Δy into Y register
f R→P	3101	Δx and Δy changed to distance D and angle β
RCL 1	3401	Δt into X register
÷	81	$D/\Delta t$ = speed (m/s) in X register
gx↔y	3507	β into X register, speed into Y
CHS	42	$-\beta$ into X register
2	02	
7	07	
0	00	
+	61	Transforms β in
3	03	mathematical coordinate
6	06	system to wind direction θ
0	00	
gx≤y	3522	
−	51	
g R↑	3509	
g R↓	3508	Wind direction in X register, speed into Y register
R/S	84	Display wind direction
gx↔y	3507	Speed into X register, direction in Y
R/S	84	Display speed (m/s)
RCL 4	3404	K into X register, speed into Y
X	71	Speed in units determined by K
RTN	24	

CONCLUSIONS

The hand-held calculator makes it possible to compute winds aloft without tables or the plotting of data. Although programmable calculators are easier to use and faster, nonprogrammable types are not difficult to use and the time to complete calculations is less than that required if tables are used. The decrease in cost of calculators and the ease with which they can be employed certainly warrants their use for winds-aloft calculations.

Acknowledgment: I acknowledge the help of Vincent L. Salgado in writing the calculator routine.

NOTES

[1] Hull, Melvin K. 1966. **Evaluating winds aloft by a simplified field technique.** USDA Forest Serv. Res. Note PSW-110, 10 p. Pacific Southwest Forest and Range Exp. Stn., Berkeley, Calif.

[2] Manufactured by Hewlett-Packard, Loveland, Colorado. Trade names and commercial enterprises or products are mentioned solely for information. No endorsement by the U.S. Department of Agriculture is implied.

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