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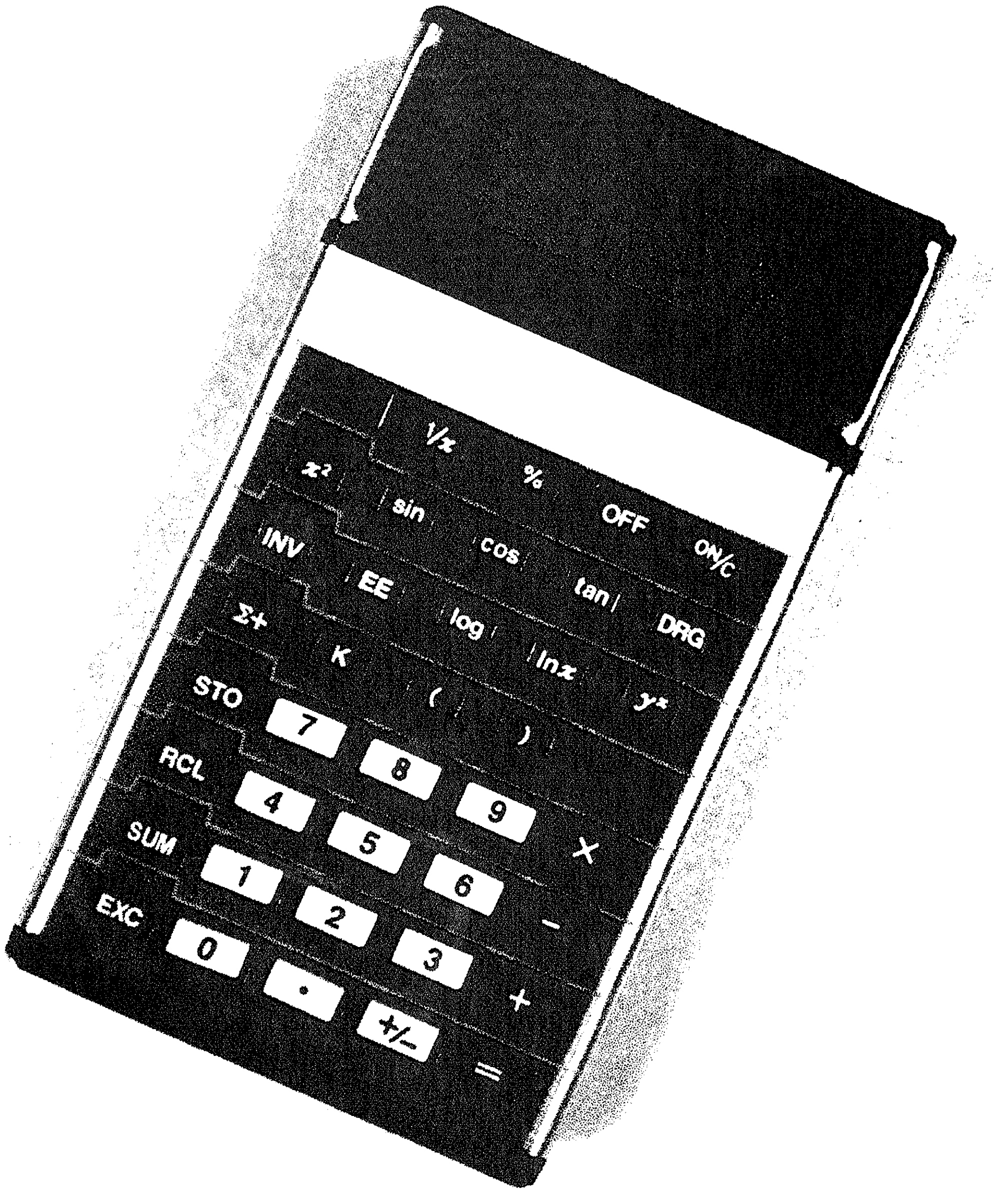
User's Guide to Calculating Rate of Fire Spread

by Hand-Held Calculator

James E. Eenigenburg



North Central Forest Experiment Station
Forest Service—U.S. Department of Agriculture
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St. Paul, Minnesota 55108
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USER'S GUIDE TO CALCULATING RATE OF FIRE SPREAD BY HAND-HELD CALCULATOR

James E. Eenigenburg, *Computer Programmer, East Lansing, Michigan*

The programs in this guide use formulas developed by Simard *et al.*[1] to calculate the rate and direction of fire spread across any triangular or square plot. They can be used in the field with a hand-held Texas Instruments[2] TI-59 calculator. The first program is appropriate for use in a wildfire situation where three landmarks can be sighted and the time when the fire reaches each noted. After the fire passes, the angle and distances between the landmarks can be measured. The second program is best suited for prescribed burns where plot markers can be positioned ahead of time.

PROGRAM #1—THE TRIANGULAR PLOT

Given any triangle, let vertex A be the point the fire reached first (at time t_A), let vertex B be the point the fire reached second (at time t_B), and let vertex C be the point the fire reached last (at time t_C). Such a triangle can be placed on the xy-plane (fig. 1), with point A at the origin and B on the positive x-axis. Note that C can be in any one of the four quadrants.

Inputs needed are the two sides AB and AC, and the included angle A. Also necessary are the three times t_A, t_B, and t_C. The program calculates the rate of spread across the triangle and also gives the angle of spread θ with respect to the positive x-axis. For program listing and documentation, see Appendix I.

[1]*Simard, A. J.; Eenigenburg, J. E.; Adams, K. B.; Nissen, R. L.; Deacon, A. G. A general procedure for sampling and analyzing wildland fire spread. Forest Science (in press).*

[2]*Use of trade name does not constitute endorsement of the product by USDA Forest Service.*

USER INSTRUCTIONS

Step	Enter	Press	Display
1[1]	angle A	A	1/tan A[2]
2	side AB	B	AB
3	side AC	C	AC
4a	t_A	D	$-t_A$
b	t_B	R/S	t_B
c	t_C	R/S	t_C
5		E	rate of spread
6		R/S	angle of spread[3]
		([4])	

[1]Steps 1 through 4 may be entered in any order as long as all are done before step 5. In step 4, the three times must be entered in chronological order.

[2]If angle A equals plus or minus 90°, angle A will be displayed rather than l/tan A.

[3]Relative to a base line between A and B.

[4]If the user wishes to see the rate of spread again after viewing the angle, pressing R/S will cause the program to return to step 5 without reexecuting the entire program. To change one or more of the inputs and rerun the program, only the steps involved need be changed before pressing E again. Changing one of the times of step 4 requires reentering all three times. The display will remain fixed in the decimal configuration of the last output. To return to standard display, enter the sequence INV FIX.

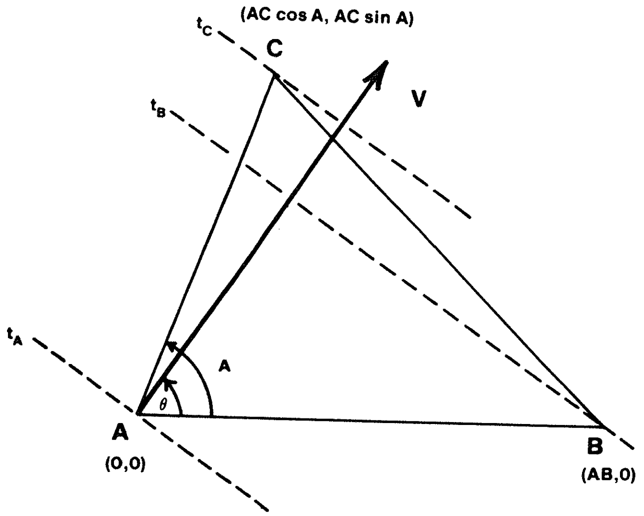

Figure 1.—*The triangular plot.*

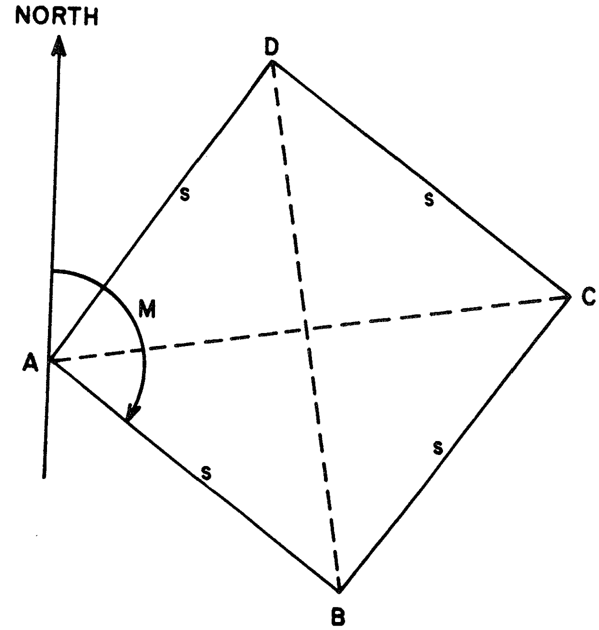

Figure 2.—*The square plot.*

Sample Run

Three landmarks are sighted during a wildfire and the times when the fire reaches each is noted: 2.0 minutes, 3.6 minutes, and 4.2 minutes. The three landmarks are labeled A, B, and C, respectively. The distance between A and B is 45 feet, between A and C, 63 feet, and angle A measures 78°.

Step	Enter	Press	Display
1	78	A	.2125565617
2	45	B	45.
3	63	C	63.
4a	2	D	-2.
b	3.6	R/S	3.6
c	4.2	R/S	4.2
5		E	22.05
6		R/S	38.

Output from the program shows the fire spreading at 22 ft/in at an angle of 38° with respect to side AB.

PROGRAM #2—THE SQUARE PLOT

The four corners of the square are labeled A through D (fig. 2). It does not matter which vertex is labeled A, as long as the order is counterclockwise. Angle M is the azimuth of B as viewed from A.

Inputs needed are the time when the fire reaches each corner of the square, the length of a side of the square s, and the azimuth M.

Define triangle A as that formed by ABC, triangle B by BCD, triangle C by CDA, and triangle D by DAB.

The program calculates the rate of spread ROS and compass direction for each triangle and averages them to produce a rate and compass direction for the square. Standard deviations of the rate and direction of spread may also be obtained.

The program also calculates a vector average to test variability. Here the rate and direction of spread for each triangle is treated as a vector. The four vectors are added and the resultant vector divided by four. The vector average gives the rate of spread in the indicated direction. The closer this number is to the arithmetic average, the less variable the direction and/or rate of spread.

For program listing and documentation, see Appendix II.

USER INSTRUCTIONS

Step	Enter	Press	Display
1[1]	time at point A	A	t_A
2	time at point B	B	t_B
3	time at point C	C	t_C
4	time at point D	D	t_D
5	side of square	E	s
6	azimuth M	R/S[2]	average ROS across square
7		R/S	average direction across square
8		R/S	standard deviation of ROS
9		R/S	standard deviation of direction
-		([3])	
10a[4]		A'	ROS across triangle A
b		R/S	direction across triangle A
11a		B'	ROS across triangle B
b		R/S	direction across triangle B
12a		C'	ROS across triangle C
b		R/S	direction across triangle C
13a		D'	ROS across triangle D
b		R/S	direction across triangle D
14a		E'	vector ROS across square
b		R/S	vector direction across square
-		([5])	

[1]Steps 1 through 4 may be entered in any order as long as all are done before step 5.

[2]The program makes all calculations at this point before displaying the arithmetic average rate of spread. This takes approximately 45 seconds.

[3]Pressing R/S at this point will cause a jump to step 14.

[4]Steps 10 through 14 may be executed in any order and repeated at will.

[5]Pressing R/S at this point will cause a jump to the output of step 6 without reexecuting the entire program. This may be followed by step 7, etc., if the user so wishes. The user can rerun the program with new data or restart the program from any point merely by returning to step 1. Unlike the triangular plot program, all inputs (even if they are the same as the previous run) must be reentered. The display will remain fixed in the decimal configuration of the last output. To return to standard display, enter the sequence INV FIX.

Sample Run

A square plot, 10 feet on each side, is laid out prior to a prescribed burn. Each corner is labeled counterclockwise, A to D, with the azimuth of side AB equal to 135°. The fire reaches point B first at a time of 5.0 minutes, point C at 5.3 minutes, point A at 5.33 minutes, and point D at 5.54 minutes.

Step	Enter	Press	Display
1	5.33	A	5.33
2	5	B	5.
3	5.3	C	5.3
4	5.54	D	5.54
5	10	E	10.
6	135	R/S	26.34
7		R/S	357.
8		R/S	3.71
9		R/S	8.
10a		A'	22.42
b		R/S	357.
11a		B'	26.03
b		R/S	6.
12a		C'	31.36
b		R/S	356.
13a		D'	25.57
b		R/S	347.
14a		E'	26.17
b		R/S	357.

The output from this sample run is as follows:

	Rate of spread	Compass direction of spread
	Ft/min	*Degrees*
Square		
Arithmetic	26	357
Vector	26	357
Triangle		
ABC	22	357
BCD	26	6
CDA	31	356
DAB	26	347
STANDARD DEVIATION	4	8

APPENDIX I

The Triangular Plot Program

```
000   76 LBL
001   11   A
002   42 STO
003   11   11
004   29 CP
005   32 X⇌T
006   42 STO
007   00   00
008   09   9
009   00   0
010   67   EQ
011   30 TAN
012   94 +/-
013   67   EQ
014   30 TAN
015   32 X⇌T
016   30 TAN
017   35 1/X
018   42 STO
019   00   00
020   76 LBL
021   30 TAN
022   91 R/S
```

Rearranging terms for computational convenience, the formula for the angle of spread θ given by Simard *et al.* is:

$$\theta = \tan^{-1}\left[\left(\frac{AB}{t_B - t_A}\right)\left(\frac{t_C - t_A}{AC \sin A}\right) - \left(\frac{1}{\tan A}\right)\right],\ t_B \neq t_A.$$

The program first checks to see if angle A equals 90° (step 010) or −90° (step 013). If so, then 1/tan A equals 0. A zero is stored in memory register 00 R00 at steps 006-007 for this purpose. If angle A does not equal ±90°, then 1/tan A is calculated and stored in R00 (steps 015-019).

```
023   76 LBL
024   12   B
025   42 STO
026   12   12
027   91 R/S
028   76 LBL
029   13   C
030   42 STO
031   13   13
032   91 R/S
```

Sides AB and AC are read in with labels B and C and stored in R12 and R13 respectively.

```
033  76 LBL
034  14  D
035  94 +/-
036  42 STO
037  22  22
038  42 STO
039  23  23
040  91 R/S
041  44 SUM
042  22  22
043  91 R/S
044  44 SUM
045  23  23
046  91 R/S
```

Since we need t_B - t_A and t_C - t_A, first a negative t_A is stored in R22 and R23, then t_B is added to R22 and t_C to R23.

```
047  76 LBL
048  15  E
049  43 RCL
050  13  13
051  32 X:T
052  43 RCL
053  11  11
054  37 P/R
055  55  ÷
056  43 RCL
057  23  23
058  95  =
059  42 STO
060  30  30
```

At this point all inputs have been entered into the calculator. Placing side AC in the t-register and angle A in the display permits taking advantage of the calculator's built-in vector feature. P/R at step 054 calculates the y-coordinate of this vector, which equals AC sin A. Dividing by t_C - t_A (steps 055-057) gives us the reciprocal of (t_C - t_A)/(AC sin A), which is stored in R30.

```
061  29 CP
062  43 RCL
063  22  22
064  67  EQ
065  38 SIN
066  35 1/X
067  65  ×
068  43 RCL
069  12  12
070  55  ÷
071  42 STO
072  21  21
073  43 RCL
074  30  30
075  75  -
076  43 RCL
077  00  00
078  95  =
079  22 INV
080  30 TAN
081  42 STO
082  31  31
083  39 COS
084  65  ×
085  43 RCL
086  21  21
087  95  =
088  42 STO
089  30  30
090  61 GTO
091  16 A'
```

The next section of the program evaluates AB/(t_B - t_A). First, a check is made to see if $t_B = t_A$. If so, a special case exists and a jump is made to label SIN.

Otherwise, AB/(t_B - t_A) is calculated. Since this is also an intermediate value of the spread rate calculation, it is stored in R21 before continuing. This value is then divided by (AC sin A)/(t_C - t_A) which has been stored in R30, and finally (1/tan A) from R00 is subtracted. Taking the arctan in steps 079-080 yields θ, which is stored in R31.

The rate of spread of a fire across a triangular plot given by Simard *et al.* is:

$$r = \frac{AB \cos \theta}{(t_B - t_A)}, \; t_B \neq t_A.$$

Cos θ is taken at step 083 and multiplied by AB/(t_B-t_A) from R21. This is stored in R30 before jumping to label A', where the output is displayed.

```
092  76 LBL
093  38 SIN
094  09  9
095  00  0
096  42 STO
097  31  31
098  43 RCL
099  30  30
100  77  GE
101  16 A'
102  50 I×I
103  42 STO
104  30  30
105  09  9
106  00  0
107  94 +/-
108  42 STO
109  31  31
```

If t_B equals t_A, the fire is spreading perpendicular to the x-axis. In this case, θ equals $\pm 90°$ and the rate of spread equals the absolute value of (AC sin A)/(t_C - t_A).

The latter value had previously been calculated in steps 049-058 and stored in R30. A positive 90° is first stored in R31. The rate is checked at step 100 to see if it is positive. If not, its absolute value is taken at step 102 and stored in R30, and the angle -90° is stored in R31.

```
110  76 LBL
111  16 A'
112  43 RCL
113  30  30
114  58 FIX
115  02  02
116  91 R/S
117  43 RCL
118  31  31
119  58 FIX
120  00  00
121  91 R/S
122  61 GTO
123  16 A'
```

The output is displayed in the same units that the inputs were given in. Two decimal places are allowed for the user working in chains/hour. The user working in feet/minute should round to the nearest whole foot. The angles are output to the nearest degree. Steps 122-123 are added so that the output sequence can be repeated.

APPENDIX II

The Square Plot Program

```
000  76 LBL
001  16 A'
002  43 RCL
003  22  22
004  58 FIX
005  02  02
006  91 R/S
007  43 RCL
008  23  23
009  58 FIX
010  00  00
011  91 R/S
012  76 LBL
013  17 B'
014  43 RCL
015  24  24
016  58 FIX
017  02  02
018  91 R/S
019  43 RCL
020  25  25
021  58 FIX
022  00  00
023  91 R/S
024  76 LBL
025  18 C'
026  43 RCL
027  26  26
028  58 FIX
029  02  02
030  91 R/S
031  43 RCL
032  27  27
033  58 FIX
034  00  00
035  91 R/S
036  76 LBL
037  19 D'
038  43 RCL
039  28  28
040  58 FIX
041  02  02
042  91 R/S
043  43 RCL
044  29  29
045  58 FIX
046  00  00
047  91 R/S
```

The first part of the program is actually used last. Since the program pointer always starts at location 000 when searching for a label, all user-defined labels are found within the first 100 steps. To further reduce execution time, absolute addressing is used rather than labels for all branching operations.

The code at left outputs the final results. The rates of spread for triangles A through D are stored in even-numbered registers 22 through 28 and are output to two decimal places to satisfy users working in chains/hour. Users working in feet/minute should round to the nearest foot. The angles are stored in odd-numbered registers 23 to 29 and are output to the nearest degree.

```
048  76 LBL
049  10 E'
050  43 RCL
051  30  30
052  58 FIX
053  02  02
054  91 R/S
055  43 RCL
056  31  31
057  58 FIX
058  00  00
059  91 R/S
060  61 GTO
061  04  04
062  57  57
063  76 LBL
064  11  A
```

R30 and R31 contain the vector averages for the rate and direction. Steps 060-062 show a jump to location 457, where the mean and standard deviation for both the rate and direction of spread are output.

```
065  42 STO
066  01  01
067  42 STO
068  05  05
069  42 STO
070  12  12
071  91 R/S
072  76 LBL
073  12  B
```

The input labels come next. As each time is entered, it is stored in three different registers because each corner of the square is associated with three different triangles.

```
074  42 STO
075  02  02
076  42 STO
077  09  09
078  42 STO
079  10  10
080  91 R/S
```

The program pages through the registers in reverse order, starting with R12. R12, R11, and R10 contain times for points A, C, and B, respectively, indicating that triangle A is processed first.

```
081  76 LBL
082  13  C
083  42 STO
084  06  06
085  42 STO
086  07  07
087  42 STO
088  11  11
089  91 R/S
090  76 LBL
091  14  D
092  42 STO
093  03  03
094  42 STO
095  04  04
096  42 STO
097  08  08
098  91 R/S
099  76 LBL
```

R09, R08, and R07, containing times for triangle B, are processed next. Triangle C is third, followed by triangle D.

```
100  15  E
101  42 STO
102  13  13
103  91 R/S
104  42 STO
105  14  14
106  02  2
107  02  2
```

Label E stores the length of one side of the square in R13, and the azimuth in R14.

```
108  42 STO
109  15  15
110  01  1
111  02  2
112  42 STO
113  00  00
114  00  0
```

R15 is used for indirect addressing. Whenever a rate of spread or a direction is calculated, R15 contains the address where it should be stored. It is originally set to 22.

```
115  42 STO
116  30  30
117  42 STO
118  31  31
119  42 STO
120  32  32
121  42 STO
122  33  33
```

R00 is also used for indirect addressing. It is originally set at 12 and is intended to input the correct triangle to the program as noted above. R30 to R33 are cleared for later summations.

The main loop of the program (steps 123-352) is executed four times, once for each triangle. Since the process is the same on each, for clarity this discussion will use the notation of the first triangle. As noted above, the times for the first triangle are brought into the loop in the order t_A, t_C, t_B. The notation $\min(t_A,t_C)$ is used to indicate the lesser of t_A and t_C, while $\max(t_A,t_C)$ is used to indicate the greater of the two.

The general formula for the angle of spread across a right isosceles triangle (Simard *et al.*) is:

$$\theta = \tan^{-1}\left[\alpha\left(\frac{t_3 - t_1}{t_2 - t_1}\right) - \beta\right],\ t_2 \neq t_1, \text{ where}$$

t_1, t_2 and t_3 are the three times in chronological order, and α and β are constants dependent on the specific case involved (fig. 3).

Each case can have a subcase consisting of its mirror image. To differentiate between the two, the first group is called a and the reflected group b. Steps 123-188 identify the particular case and subcase as well as place $(t_3 - t_1)$ in R19 and $(t_2 - t_1)$ in R20.

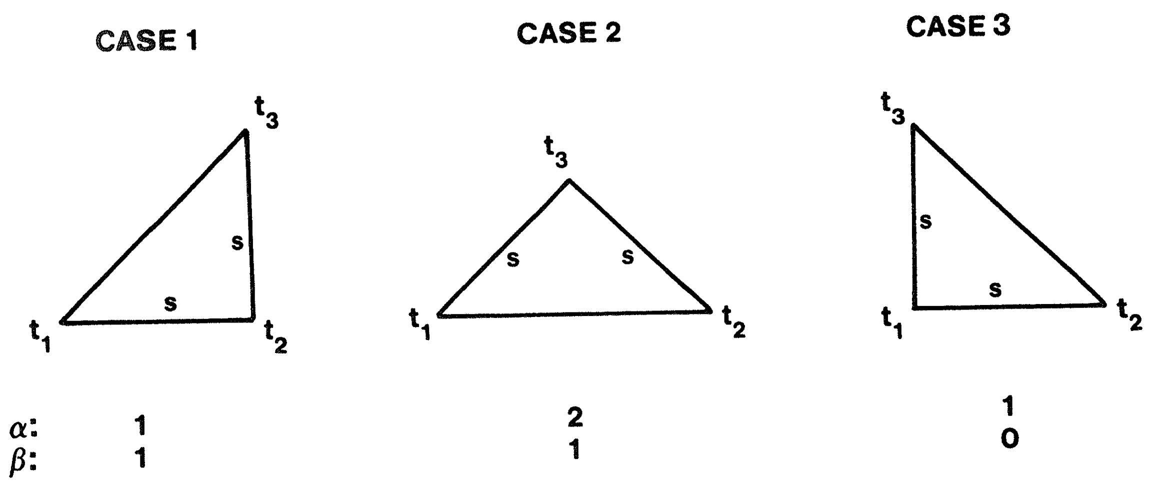

Figure 3.—*The three right isosceles triangles.*

```
123  86  STF
124  01   01
125  01   1
126  42  STO
127  17   17
128  42  STO
129  18   18
130  73  RC*
131  00   00
132  32  X:T
133  01   1
134  94  +/-
135  44  SUM
136  00   00
137  73  RC*
138  00   00
139  42  STO
140  19   19
141  77   GE
142  01   01
143  50   50
144  32  X:T
145  42  STO
146  19   19
147  22  INV
148  86  STF
149  01   01
150  01   1
151  94  +/-
152  44  SUM
153  00   00
154  73  RC*
155  00   00
156  42  STO
157  20   20
158  77   GE
159  01   01
160  70   70
161  00   0
162  42  STO
163  17   17
164  32  X:T
165  48  EXC
166  20   20
167  61  GTO
168  01   01
169  84   84
```

The sequence begins by setting flag 1, which is used to separate case a from b. A one is then stored in R17 and R18, indicating β and α respectively.

Next t_A is recalled (steps 130-131) and entered into the t-register. RC* at step 130 does not appear on the calculator's keyboard. It is achieved by entering the sequence RCL IND.

The program then recalls t_C (steps 133-138), stores it in R19, and tests it against t_A (step 141). If t_C is less than t_A, their locations (t-register and R19) are switched (steps 144-146) and flag 1 is reset (steps 147-149), indicating case 1b, 2a, or 3a.

Then t_B is recalled (steps 150-155) and stored in R20. If it is less than the time currently in the t-register, $\min(t_A,t_C)$, then the triangle is case 3 and β (R17) is set equal to zero (steps 161-163), $\min(t_A,t_C)$ is moved to R20, and t_B is placed in the display (steps 164-166) before jumping to step 184.

```
170  32  X:T
171  48  EXC
172  19   19
173  77   GE
174  01   01
175  82   82
176  42  STO
177  20   20
178  02   2
179  42  STO
180  18   18
181  32  X:T
182  48  EXC
183  19   19
184  94  +/-
185  44  SUM
186  19   19
187  44  SUM
188  20   20
```

If, on the other hand, t_B is greater than $\min(t_A,t_C)$, it passes the test at step 158, causing a jump to step 170. The program moves t_B to the t-register, $\min(t_A,t_C)$ to R19, and $\max(t_A,t_C)$ to the display (steps 170-172).

A test is made at step 173, and if $\max(t_A,t_C)$ is greater than t_B, the triangle is case 1, and a jump is made to step 182.

If $\max(t_A,t_C)$ is less than t_B, the triangle is case 2, $\max(t_A,t_C)$ is placed in R20, α (R18) is set equal to two, and t_B is moved to the display (steps 176-181).

Both case 1 and case 2 execute steps 182-183 and succeed in placing the maximum time, t_3, in R19, and the minimum time, t_1, in the display. All three cases come together at step 184, where t_1 is made negative and added to t_3 in R19 and t_2 in R20 (steps 185-188).

```
189   29  CP
190   43  RCL
191   20   20
192   67   EQ
193   02   02
194   22   22
195   43  RCL
196   18   18
197   65   ×
198   43  RCL
199   19   19
200   55   ÷
201   43  RCL
202   20   20
203   75   -
204   43  RCL
205   17   17
206   95   =
207   22  INV
208   30  TAN
209   42  STO
210   21   21
211   39  COS
212   65   ×
213   43  RCL
214   13   13
215   55   ÷
216   43  RCL
217   20   20
218   65   ×
219   61  GTO
220   02   02
221   32   32
```

The program now calculates θ. If $t_2 = t_1$, $\theta = 90°$. This special case is processed with a test at step 192 and a jump to 222, where 90° is stored as the angle. All other cases are handled with steps 195-210.

The formula for the rate of spread (Simard *et al.)* is:

$$\text{ROS} = \frac{s \cos \theta \sqrt{\alpha}}{(t_2 - t_1)}, \; t_2 \neq t_1,$$

where s is the length of a side of the square. ROS is calculated in steps 211-221 and 232-235.

```
222   09   9
223   00   0
224   42  STO
225   21   21
226   43  RCL
227   13   13
228   55   ÷
229   43  RCL
230   19   19
231   55   ÷
232   43  RCL
233   18   18
234   34  √X
235   95   =
236   72  ST*
237   15   15
238   42  STO
239   34   34
240   44  SUM
241   32   32
242   33  X²
243   44  SUM
244   33   33
245   01   1
246   44  SUM
247   15   15
```

If we are dealing with the special case where t_2 equals t_1, the formula for the rate of spread is:

$$\text{ROS} = \frac{s}{(t_3 - t_1)\sqrt{\alpha}},$$

which is calculated in steps 226-235.

ROS is stored indirectly in the register indicated by R15. ST* at step 236 does not appear on the calculator's keyboard. It is achieved by entering the sequence STO IND. ROS is also stored in R34 for later vector calculations and summed in R32, with its square summed in R33 for later standard deviation calculations.

θ is stored in R21 for subsequent azimuth calculations.

```
248  32  X:T
249  43  RCL
250  17   17
251  67   EQ
252  02   02
253  72   72
254  87  IFF
255  01   01
256  02   02
257  65   65
258  09   9
259  00   0
260  94  +/-
261  75   -
262  61  GTO
263  03   03
264  07   07
265  01   1
266  08   8
267  00   0
268  85   +
269  61  GTO
270  03   03
271  07   07
272  43  RCL
273  18   18
274  67   EQ
275  02   02
276  95   95
277  87  IFF
278  01   01
279  02   02
280  88   88
281  01   1
282  03   3
283  05   5
284  75   -
285  61  GTO
286  03   03
287  07   07
288  04   4
289  05   5
290  94  +/-
291  85   +
292  61  GTO
293  03   03
294  07   07
```

The general formula for finding the compass direction of spread DOS is: DOS = $N \pm \theta$ + M, where $N \pm \theta$ is dependent on the case involved. Steps 248-306 begin the calculation with N + or N -, followed by a jump to 307 for θ + M.

Cases 1 and 2 pass the test at step 251 and jump to 272. Steps 258-264 are for case 3a and 265-271 for case 3b.

Case 3a: DOS = $-90° - \theta$ + M.

Case 3b: DOS = $180° + \theta$ + M.

Cases 1 and 2 are tested again at step 274. Case 1 passes and jumps to 295. Case 2a is handled in steps 281-287 and case 2b in steps 288-294.

Case 2a: DOS = $135° - \theta$ + M.

Case 2b: DOS = $-45° + \theta$ + M.

```
295  87  IFF
296  01   01
297  03   03
298  05   05
299  09   9
300  00   0
301  85   +
302  61  GTO
303  03   03
304  07   07
305  00   0
306  75   -
307  43  RCL
308  21   21
309  85   +
310  43  RCL
311  14   14
312  95   =
313  32  X:T
314  43  RCL
315  34   34
316  32  X:T
317  37  P/R
318  44  SUM
319  30   30
320  32  X:T
321  44  SUM
322  31   31
323  32  X:T
324  22  INV
325  37  P/R
326  32  X:T
327  93   .
328  05   5
329  94  +/-
330  32  X:T
331  77   GE
332  03   03
333  39   39
334  85   +
335  03   3
336  06   6
337  00   0
338  95   =
```

Case 1b is processed in steps 299-304 and case 1a in 305-306.

Case 1b: DOS $= 90° + \theta + M$.

Case 1a: DOS $= 0° - \theta + M$.

All cases come to step 307, where θ is either added to or subtracted from the previous calculation and added to the original azimuth M.

Steps 313 to 322 change polar to rectangular coordinates. The y-values are summed in R30 and the x-values in R31.

Steps 323-325 return the angle to polar within the field $-90° \leq \text{DOS} < 270°$.

Angles which are negative have 360° added to them in steps 326-338.

```
339  72 ST*
340  15  15
341  01  1
342  44 SUM
343  15  15
344  09  9
345  00  0
346  94 +/-
347  44 SUM
348  14  14
349  97 DSZ
350  00  00
351  01  01
352  23  23
353  43 RCL
354  31  31
355  55  ÷
356  04  4
357  95  =
358  32 X:T
359  43 RCL
360  30  30
361  55  ÷
362  04  4
363  95  =
364  22 INV
365  37 P/R
366  32 X:T
367  42 STO
368  30  30
369  93  .
370  05  5
371  94 +/-
372  32 X:T
373  77  GE
374  03  03
375  81  81
376  85  +
377  03  3
378  06  6
379  00  0
380  95  =
381  42 STO
382  31  31
```

The angle is stored indirectly to the location address that is stored in R15.

Because triangle B is rotated 90° from triangle A, and C is rotated 90° from B, etc., 90° is subtracted from the azimuth M at this point before returning to the beginning of the main loop at step 123.

Finally, after the main loop is executed four times, once for each triangle, the program arrives at step 353.

The vector averages are calculated in steps 353-382, with the rate of spread stored in R30 and the angle of spread, after converting to positive degrees, stored in R31.

383	75	-
384	01	1
385	08	8
386	00	0
387	95	=
388	42	STO
389	11	11
390	85	+
391	03	3
392	06	6
393	00	0
394	95	=
395	42	STO
396	12	12
397	04	4
398	42	STO
399	00	00
400	42	STO
401	03	03
402	00	0
403	42	STO
404	04	04
405	42	STO
406	05	05

A problem may arise when calculating standard deviations, if the angles are close to 0°. For example, 355° and 0° are only 5° apart, yet their magnitudes are 355° apart. To avoid this problem, 180° is subtracted from the vector average for a lower bound and stored in R11. Then 180° is added to the vector average as an upper bound and stored in R12.

After preparing R00 to R05 for statistics calculations, each angle is checked to see if they lie within the bounds.

407	02	2
408	03	3
409	42	STO
410	15	15
411	43	RCL
412	11	11
413	32	X:T
414	73	RC*
415	15	15
416	77	GE
417	04	04
418	24	24
419	85	+
420	03	3
421	06	6
422	00	0
423	95	=
424	32	X:T
425	43	RCL
426	12	12
427	32	X:T
428	22	INV
429	77	GE
430	04	04
431	37	37
432	75	-
433	03	3
434	06	6
435	00	0
436	95	=
437	44	SUM
438	04	04
439	33	X²
440	44	SUM
441	05	05
442	02	2
443	44	SUM
444	15	15
445	97	DSZ
446	00	00
447	04	04
448	11	11

If outside the bounds, 360° is either added to or subtracted from the angle before summing. However, the original angle stored in registers 23 to 29 remains unchanged.

Each of the four angles of spread ±360°, are summed in R04 and their squares summed in R05.

```
449  43 RCL
450  32  32
451  42 STO
452  01  01
453  43 RCL
454  33  33
455  42 STO
456  02  02
457  79  x̄
458  58 FIX
459  02  02
460  91 R/S
461  32 X:T
462  58 FIX
463  00  00
464  91 R/S
465  22 INV
466  79  x̄
467  58 FIX
468  02  02
469  91 R/S
470  32 X:T
471  58 FIX
472  00  00
473  91 R/S
474  61 GTO
475  10 E'
```

Each of the four rates of spread and their squares previously summed in steps 240-244 are now entered into R01 and R02.

Using the calculator's built-in functions for calculating the mean and standard deviation, each can be displayed by repeatedly pressing the R/S key. First is the mean of the rates, then the mean of the directions, then the standard deviation of the rates, and finally the standard deviation of the directions.

Pressing R/S once more causes a jump to label E', where the vector averages are output. Although pressing label E' accomplishes the same thing, this feature was added to eliminate one keystroke for user convenience.

Eenigenburg, James E.
User's guide to calculating rate of fire spread by hand-held calculator. Gen. Tech. Rep. NC-89. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station; 1983. 16p.

Presents TI-59 programs that use fire arrival times to calculate the rate and direction of spread of a fire across a triangular or square plot.

KEY WORDS: Programs, plot, vector, wildfire, prescribed burn.

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