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SIGNIFICANT EVENTS IN LOW-LEVEL FLOW CONDITIONS HAZARDOUS TO AIRCRAFT

By Margaret B. Alexander and Dennis W. Camp
Space Science Laboratory

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16. ABSTRACT

Atmospheric parameters recorded at the NASA 150-Meter Ground Winds Tower Facility at Kennedy Space Center during high surface winds are analyzed to determine magnitude, frequency, duration, and simultaneity of occurrence of low-level flow conditions known to be hazardous to the ascent and descent of conventional aircraft and the Space Shuttle. Graphic and tabular presentations of mean and extreme values and simultaneous occurrences of turbulence (gustiness and gust factor), wind shear (speed and direction), and vertical motion (updrafts and downdrafts), along with associated temperature inversions are included as a function of tower height, layer and/or distance for six 5-sec intervals (one interval every 100 sec) of parameters sampled simultaneously at the rate of 10 speeds, directions and temperatures per second during an approximately 10-min period (2143 47.0 to 2152 16.9 UT) on July 3, 1973.

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TECHNICAL MEMORANDUM

SIGNIFICANT EVENTS IN LOW-LEVEL FLOW CONDITIONS HAZARDOUS TO AIRCRAFT

INTRODUCTION

Diverse requirements exist for information describing phenomena in the lowest 150 m of the Earth's atmosphere. Particular needs are related to conditions hazardous to the ascent and descent of conventional aircraft and Space Shuttle. But, relatively little high-resolution data from aircraft and/or meteorological towers are available to determine and describe the magnitude, frequency, duration, and simultaneity of occurrence of low-level flow conditions in the vicinity of runways.

Conditions known to be hazardous to aircraft during takeoff/climbout and approach/landing operations are turbulence, wind shear, and vertical motion. Turbulence produces rapid aircraft oscillations such as shaking, pitching, and yawing. Wind shear is a wind change producing an increase or decrease in air speed. Vertical motion, updrafts and downdrafts, produces an increase or decrease in altitude. Wind shear in a zone between relatively calm wind in a temperature inversion and strong horizontal wind above the inversion can cause an abrupt turbulence encounter at low altitude.

All these conditions can and frequently do occur simultaneously. This study was initiated to determine actual occurrences and values for these conditions during strong or gusty surface winds near a runway.

LOW-LEVEL FLOW CONDITIONS

Turbulence, wind shear, and vertical motion effects in terminal operations are all, separately and in combination, serious problems in aviation safety.

Turbulence

A turbulent atmosphere is one in which air currents vary greatly over short distances. These currents range from mild eddies to strong currents. An aircraft moving through these currents undergoes changing accelerations or turbulence [1]. This condition ranges from annoying bumpiness to damaging jolts.

Two measures of turbulence near the Earth are gustiness and gust factor. Gustiness, the difference between maximum and minimum wind speeds during an interval, is reported at one airport if it exceeds 13 ms^{-1} (25 knots) at any level [2]. The dimensionless gust factor represents a maximum wind speed fluctuation about a mean speed during an interval. For operational problems at Kennedy Space Center, Florida, the environmental criteria value for gust factor over a 10-min averaging period for mean wind speed varies with peak speed and height, i.e., for high wind speeds ($\geq$ 10 ms^{-1}) the gust factor varies from 1.7 at 10 m to 1.3 at 150 m [3].

It should be noted that gustiness and gust factor in the literature usually refer to horizontal wind speed. This study includes horizontal wind speed and direction as well as vertical motion.

Wind Shear

The meteorological mechanisms that cause strong wind shears are gust fronts formed by severe thunderstorms, fast-moving frontal zones, and low-level temperature inversions [4]. Wind shear generates eddies between two wind currents of differing velocities. The differences may be in wind speed, wind direction, or in both.

Wind shear may be associated with a wind speed gradient or a wind shift at any level in the atmosphere. Wind speed shears greater than 0.1 s^{-1} in the lowest 100 m are known to be dangerous to large, swept-wing, jet-powered aircraft [5] while large changes in wind direction (>40 deg) are considered hazardous [6].

Wind shear with a low-level temperature inversion can cause an aircraft to abruptly encounter turbulence with a loss of airspeed and possible stall. Temperature normally decreases with increasing altitude throughout the troposphere. This decrease of temperature with altitude is defined as lapse rate. The average lapse rate is 2°C per 300 m. But, temperature sometimes increases with height through a layer. An increase with altitude is defined as an inversion and may occur near the ground-surface inversion – or at any altitude – an inversion aloft. At the Helsinki-Vantaa Aerodome pilots are warned of temperature increases >10°C between any level and the surface [2].

Vertical Motion

The simultaneous occurrence of vertical motion (updrafts and downdrafts) and shear can cause serious problems for approaching and departing aircraft at airports. Describing statistical properties of these occurrences facilitates accuracy in model simulations during adverse conditions. Snyder [5] simulated an aircraft on final approach and subjected it to the events of sudden shear, downdraft, and airspeed drop. Using Snyder's analog computer study and a simple flow model, Kalafus [6] achieved results consistent with Snyder's: that a 0.08 s^{-1} shear is a typical one associated with a 2.57 ms^{-1} downdraft and that a 0.17 s^{-1} shear is a reasonable one for a 5.15 ms^{-1} downdraft. Alexander and Campbell [7] concluded that models for simulating aircraft ascent and descent under adverse conditions should show simultaneously occurring downdrafts and shears to be independent and uncorrelated.

DATA ACQUISITION AND ANALYSIS

The NASA 150-Meter Ground Winds Tower Facility at Kennedy Space Center, Florida, is a unique source of high resolution wind and temperature profile measurements. The 150-m and 18-m towers, depicted in Figure 1 and described by Kaufman and Keene [8], are located on Merritt Island midway between Launch Complex 39B and the Space Shuttle runway. Placement of the meteorological sensors on the towers is shown in Figure 2. The Automatic Data Acquisition System, described by Traver, et al. [9], samples at the rate of 10 each of speeds, directions, and temperatures per second, digitally records, and real-time processes the samples for all sensors on the two towers.

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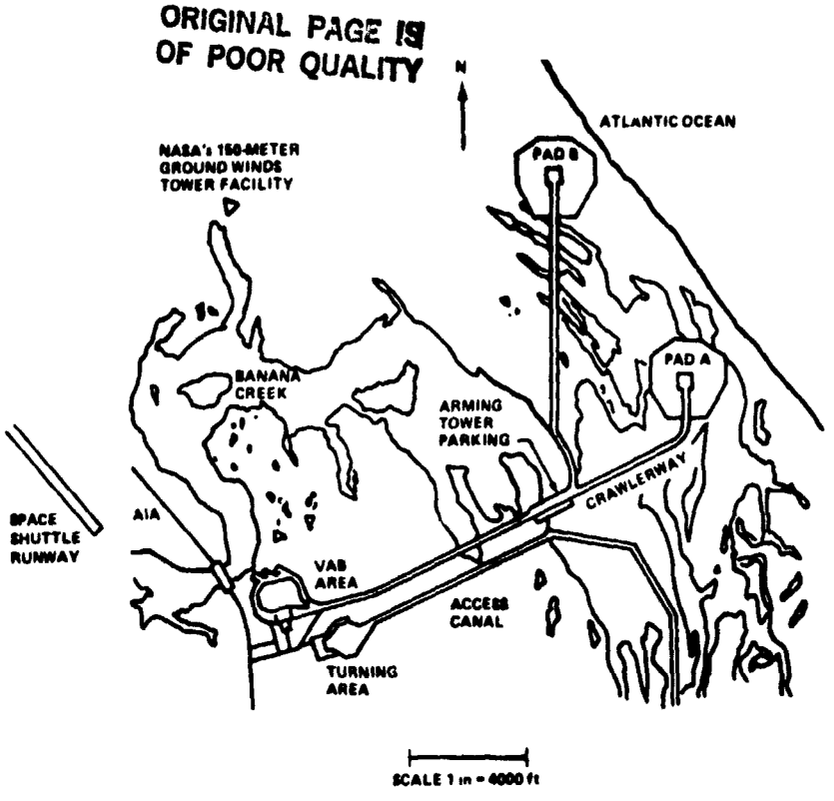

Figure 1. NASA's 150-Meter Ground Winds Tower Facility and Launch Complex 39, Kennedy Space Center, Florida.

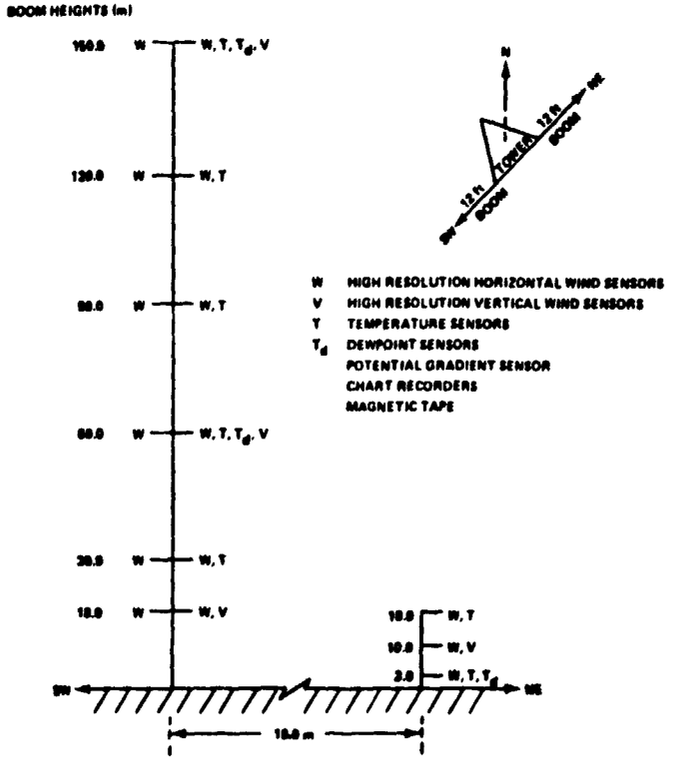

Figure 2. Placement of Sensors on NASA's 150-Meter Ground Winds Tower Facility at Kennedy Space Center, Florida.

This analysis consists of six 5-sec intervals (one interval every 100 sec) from 2143 47.0 to 2152 16.9 UT on July 3, 1973, during high ($10 < 18$ ms^{-1}) to gale-force ($18 < 33$ ms^{-1}) horizontal winds recorded at eight tower heights with associated vertical motion and temperature differences. Associated parameters are defined as those sampled and recorded simultaneously with horizontal wind speed and direction. This analysis is concerned with the WMO-recommended practices [10], viz., that wind-averaging periods for aviation climatology not exceed 10 min, gust-measuring periods be at least 5 sec, and temperature measurements be at 1.25 to 2 m above ground level.

The significant events emphasized in this study of six 5-sec intervals (2143 47.0-51.9, 2145 27.0-31.9, 2147 7.0-11.9, 2148 47.0-51.9, 2150 32.0-36.9, and 2152 12.0-16.9) include the following:

1) Horizontal wind speed and direction gustiness and gust factors for eight heights: 150, 120, 90, 60, 30, 18T[1], 18S[1], and 3 m.

2) Vertical wind speed (updrafts and downdrafts) gustiness and gust factors for four heights: 150, 60, 18T and 10 m.

3) Wind speed shear ≥ 0.1 s^{-1} and wind direction shear ≥ 1.0 deg m^{-1} for six vertical layers: 150-120, 120-90, 90-60, 60-30, 30-18T, and 18S-3 m; and one horizontal distance: 18T-18S m.

4) Updrafts and downdrafts ≥ 1.0 ms^{-1} for four heights: 150, 60, 18T and 10 m.

5) Positive temperature differences for six layers: 150-3, 120-3, 90-3, 60-3, 30-3, and 18S-3 m.

Gustiness is defined to be

$$G = WS_{max} - WS_{min} \quad , \tag{1}$$

where WS_{max} is the wind speed maximum in a 5-sec interval and WS_{min} is the minimum value.

Gust factor is

$$GF = WS_{max}/\overline{WS} \quad , \tag{2}$$

where $\overline{WS}$ is the mean speed for an interval.

Wind direction gustiness and gust factor are similarly determined, i.e.,

$$G = WD_{max} - WD_{min} \quad , \tag{3}$$

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and

$$GF = WD_{max}/\overline{WD} \quad . \tag{4}$$

1. 18T and 18S denote the 18-m level on the tall and short towers, respectively.

Vertical wind shear is the change of wind speed with height and is determined by means of two anemometers mounted at different heights on a single tower. Vertical shear magnitudes were derived by algebraically subtracting the wind speed at the lower level from the speed at the upper and dividing by the distance between levels, i.e.,

$$\frac{WS_U - WS_L}{d_{(U-L)}} = \frac{\Delta WS}{\Delta d} \quad . \tag{5}$$

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Horizontal wind shear is the change of wind speed with horizontal distance and is determined by two anemometers mounted at the same height on different towers. Wind speed shears for one distance (18 m) between the tall and short towers at the 18-m level are presented. Horizontal shear magnitudes were derived by algebraically subtracting the wind speed at the short tower from the speed at the tall and dividing by the distance between towers, i.e.,

$$\frac{WS_T - WS_S}{d_{(T-S)}} = \frac{\Delta WS}{18} \quad . \tag{6}$$

Vertical and horizontal wind direction shears were similarly determined, i.e.,

$$\frac{WD_U - WD_L}{d_{(U-L)}} = \frac{\Delta WD}{\Delta d} \quad . \tag{7}$$

and

$$\frac{WD_T - WD_S}{d_{(T-S)}} = \frac{\Delta WD}{18} \quad . \tag{8}$$

RESULTS

Tabular presentations of the magnitude, frequency, and duration of the significant events by height, layer, and/or distance during strong or gusty surface winds are as follows:

1) Tables 1 through 6 list magnitude, frequency, and duration of significant events for six 5-sec intervals from 2143 to 2152 UT.

2) Table 7 lists extreme values, total frequencies, and maximum continuous durations of significant events for the approximately 10-min data period.

Graphical depictions of the simultaneity of occurrence of significant events for each 0.1 sec of six 5-sec intervals are as follows:

1) Figures 3, 6, 9, 12, 15, and 18 are plots of the occurrences of significant events by heights and layers.

2) Figures 4, 7, 10, 13, 16, and 19 are tallies of the simultaneous occurrence of significant events in combination.

3) Figures 5, 8, 11, 14, 17, and 20 are tallies of the simultaneous occurrence of separated significant events.

Four portrayals for each 5-sec interval illustrate the hazardous low-level flow conditions, e.g., Interval 2143 47.0-51.9 UT: Table 1 and Figures 3, 4, and 5; Interval 2145 27.0-31.9 UT: Table 2 and Figures 6, 7, and 8, etc. Table 1 includes actual values (max, min, mean, and std. dev.), frequencies, and continuous durations of significant events. Figure 3 depicts the occurrence of significant events per tower height, shear layer/distance, and temperature layer. Figures 4 and 5 present a tally of the simultaneous occurrence of the combined and separated, respectively, significant events (maximum horizontal wind speeds and directions, wind speed shears $\geq 0.1\ s^{-1}$, wind direction shears ≥ 1.0 deg m^{-1}, updrafts and downdrafts $\geq 1.0\ ms^{-1}$, and positive delta temperatures emphasized in this period of strong or gusty surface winds.

CONCLUSIONS

Regarding magnitude, frequency, duration, and simultaneity of occurrence of significant events during high ($10 < 18\ ms^{-1}$) and gale-force ($18 < 33\ ms^{-1}$) winds for six 5-sec intervals within a 10-min period:

1) The maximum horizontal wind speed and direction (used to determine gustiness and gust factor as measures of turbulence near the surface) occurred simultaneously infrequently at 3 or more heights and persisted <0.4 sec.

2) Wind speed and direction gustiness and gust factor values increase with decreasing height, i.e., wind speed gustiness of 3.8 ms^{-1} at 150 m to 6.8 ms^{-1} at 3 m and gust factor of 1.083 at 150 m to 1.674 at 3 m, wind direction gustiness of 14 deg at 150 m to 76 deg at 3 m and gust factor of 1.029 at 150 m to 1.226 at 3 m.

3) Vertical wind speed and direction shears increase with decreasing height, persist continuously from 3 to 5 sec and occur simultaneously in four and five layers below 90 m.

4) Occurrence of vertical motion is approximately equal – of 1200 measurements 614 were updrafts and 586 were downdrafts – with updrafts $\geq 1.0\ ms^{-1}$ exceeding downdrafts $\geq 1.0\ ms^{-1}$ by approximately 50 percent (160 to 88).

5) Temperature inversions occurred in layers below 90 m and persisted continuously for 5 sec for five of the six intervals in the lowest layer (18S-3).

6) Total frequency of occurrence of significant events ranged from 4 to 14 events per 0.1 sec and from 360 to 520 per 5.0 sec.

This study certainly lends support to the ideas that information on low-level flow conditions hazardous to aircraft is most important over the lowest 150 m of the Earth's atmosphere and that similar analyses during high vertical motion and strong low-level temperature inversion with associated parameters should be made for information, comparison and flight simulation purposes.

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TABLE 1. MAGNITUDE, FREQUENCY, AND DURATION OF SIGNIFICANT EVENTS FOR INTERVAL 2143 47.0-51.9 UT

Event	Height Layer Distance	Max	Min	Mean	Std Dev	Freq.	Longest Continuous Duration	G	GF
Turbulence Speed	m	ms^{-1}	ms^{-1}	ms^{-1}	ms^{-1}	max ws	max ws	ms^{-1}	non-dim
	150	21.6	19.7	20.700	0.479	3	0.2	1.9	1.043
	120	20.9	18.4	19.890	0.635	3	0.1	2.5	1.051
	90	19.1	16.6	17.940	0.639	1	0.1	2.5	1.064
	60	20.8	13.5	17.250	1.371	1	0.1	7.3	1.206
	30	13.8	10.2	11.990	0.946	1	0.1	3.6	1 151
	18T	15.9	8.9	12.680	1.707	1	0.1	7.0	1.254
	18S	15.1	9.2	12.480	1.654	3	0.3	5.9	1.210
	3	7.6	4.0	5.990	1.021	2	0.1	3.6	1.269
Direction		deg	deg	deg	deg	max wd	max wd	deg	non-dim
	150	227	220	224	1.852	1	0.1	7	1.014
	120	226	215	220	3.052	2	0.1	11	1.025
	90	250	235	243	4.116	1	0.1	15	1.027
	60	213	192	203	4.174	1	0.1	21	1.050
	30	242	217	228	6.128	1	0.1	25	1.063
	18T	236	191	207	8.108	1	0.1	45	1.138
	18S	228	198	210	8.612	1	0.1	30	1.081
	3	235	159	192	19.156	1	0.1	76	1.226
Shear Speed		s^{-1}	s^{-1}	s^{-1}	s^{-1}	$\geq 0.1\ s^{-1}$	s		
	150-120	0.070	0	0.028	0.017	0	0		
	120-90	0.133	0.010	0.066	0.031	7	0.3		
	90-60	0.163	0	0.045	0.039	6	0.4		
	60-30	0.300	0.047	0.175	0.058	46	3.3		
	30-18T	0.300	0	0.122	0.091	27	2.0		
	18S-3	0.653	0.233	0.432	0.107	50	5.0		
	18T-18S	0.322	0	0.125	0.089	29	1.1		
Direction		$deg\ m^{-1}$	$deg\ m^{-1}$	$deg\ m^{-1}$	$deg\ m^{-1}$	$\geq 1.0\ deg\ m^{-1}$	s		
	150-120	0.333	0.013	0.139	0.088	0	0		
	120-90	1.067	0.400	0.763	0.185	6	0.3		
	90-60	1.567	0.867	1.349	0.176	48	3.9		
	60-30	1.633	0.400	0.821	0.272	9	0.8		
	30-18T	4.000	0.417	1.712	0.848	42	1.8		
	18S-3	4.200	0.333	1.785	0.897	40	1.4		
	18T-18S	2.111	0	0.550	0.449	6	0.3		
Vertical Motion									
Up		ms^{-1}	ms^{-1}	ms^{-1}	ms^{-1}	$\geq 1.0\ ms^{-1}$	s	ms^{-1}	non-dim
	150	1.90	0.31	0.828	0.299	14	0.7	1.59	2.292
	60	0.78	0.03	0.369	0.241	0	0	0.75	2.116
	18T	1.43	0.03	0.631	0.419	3	0.2	1.40	2.268
	10	1.38	0.01	0.630	0.456	9	0.8	1.37	2.189
Down									
	150	0.08	0.08	0.080	1.00	0	0	0	1.000
	60	0.94	0.01	0.445	0.304	0	0	0.93	2.112
	18T	0.83	0.01	0.491	0.232	0	0	0.82	1.690
	10	2.22	0.10	0.924	0.618	8	0.6	2.12	2.402
Inversion Delta T		°C	°C	°C	°C	positive	s		
	150-3					0	0		
	120-3					0	0		
	90-3	0.2	0.0	0.150	0.068	50	5.0		
	60-3					0	0		
	30-3	0.4	0.3	0.324	0.043	50	5.0		
	18S-3	0.4	0.3	0.388	0.033	50	5.0		
Amb T	3	21.7	21.5	21.647	0.065				

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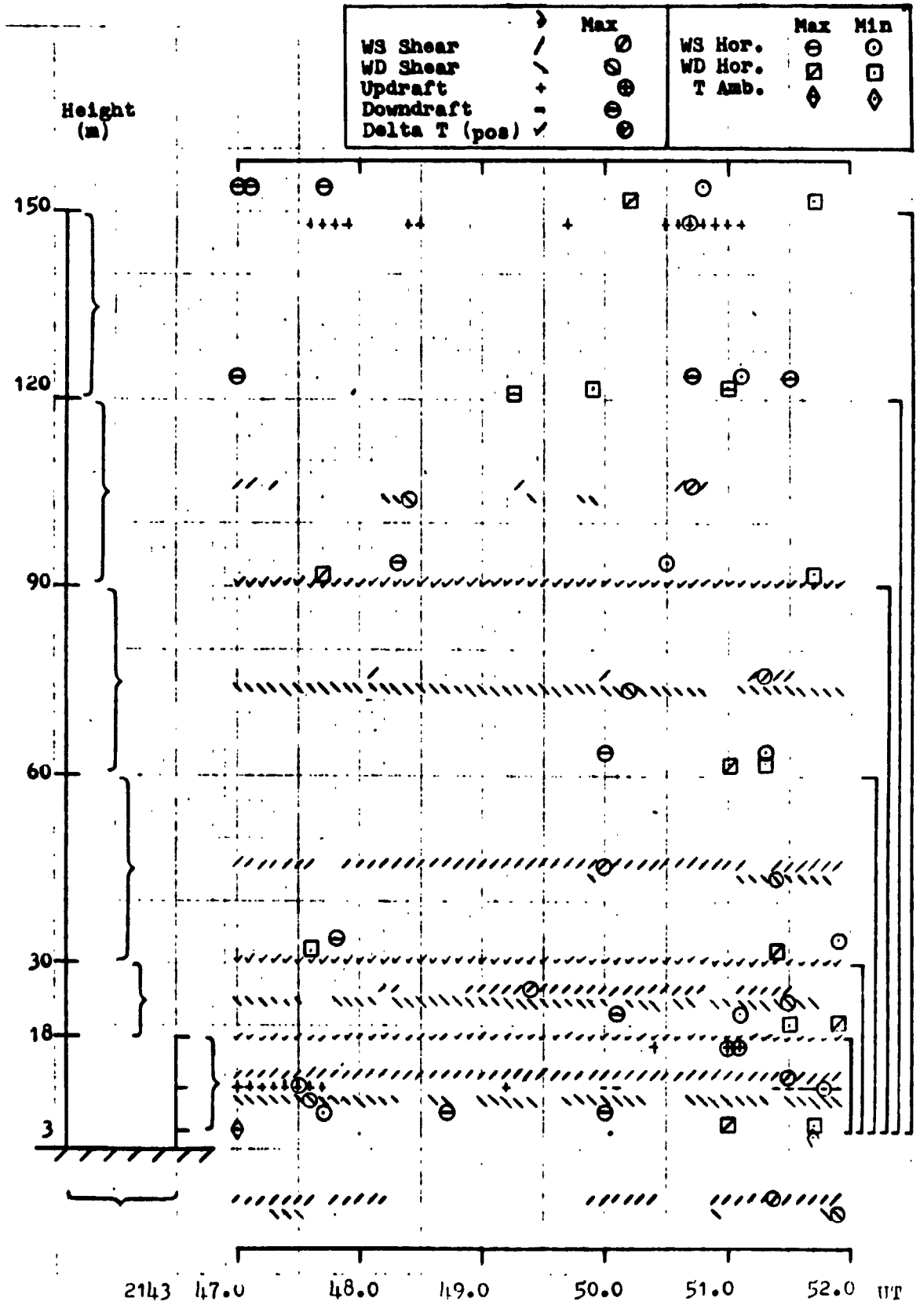

Figure 3. Occurrence of significant events for interval 2143 47.0-51.9 UT.

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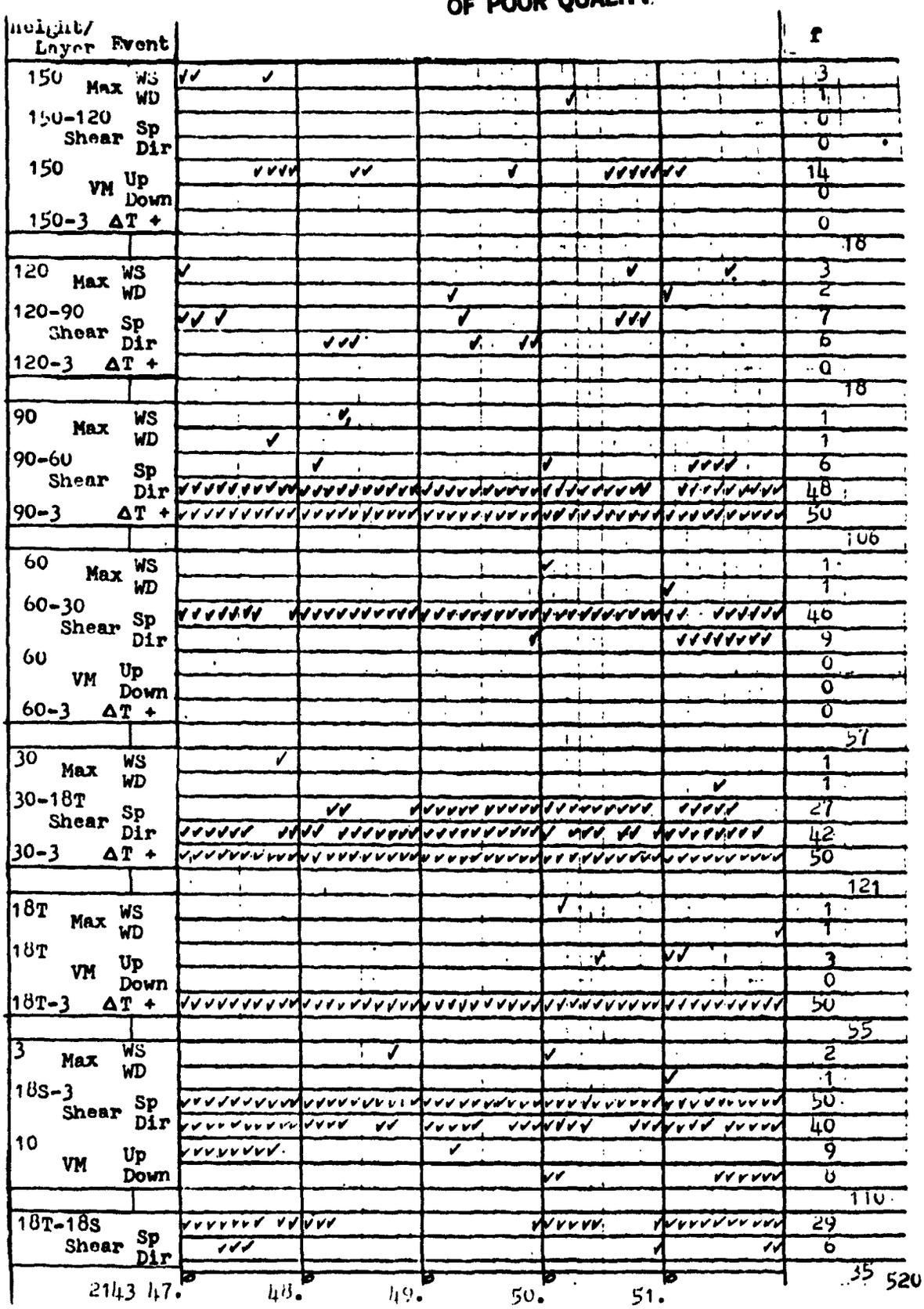

Figure 4. Simultaneous occurrence of combined significant events for interval 2143 47.0-51.9 UT.

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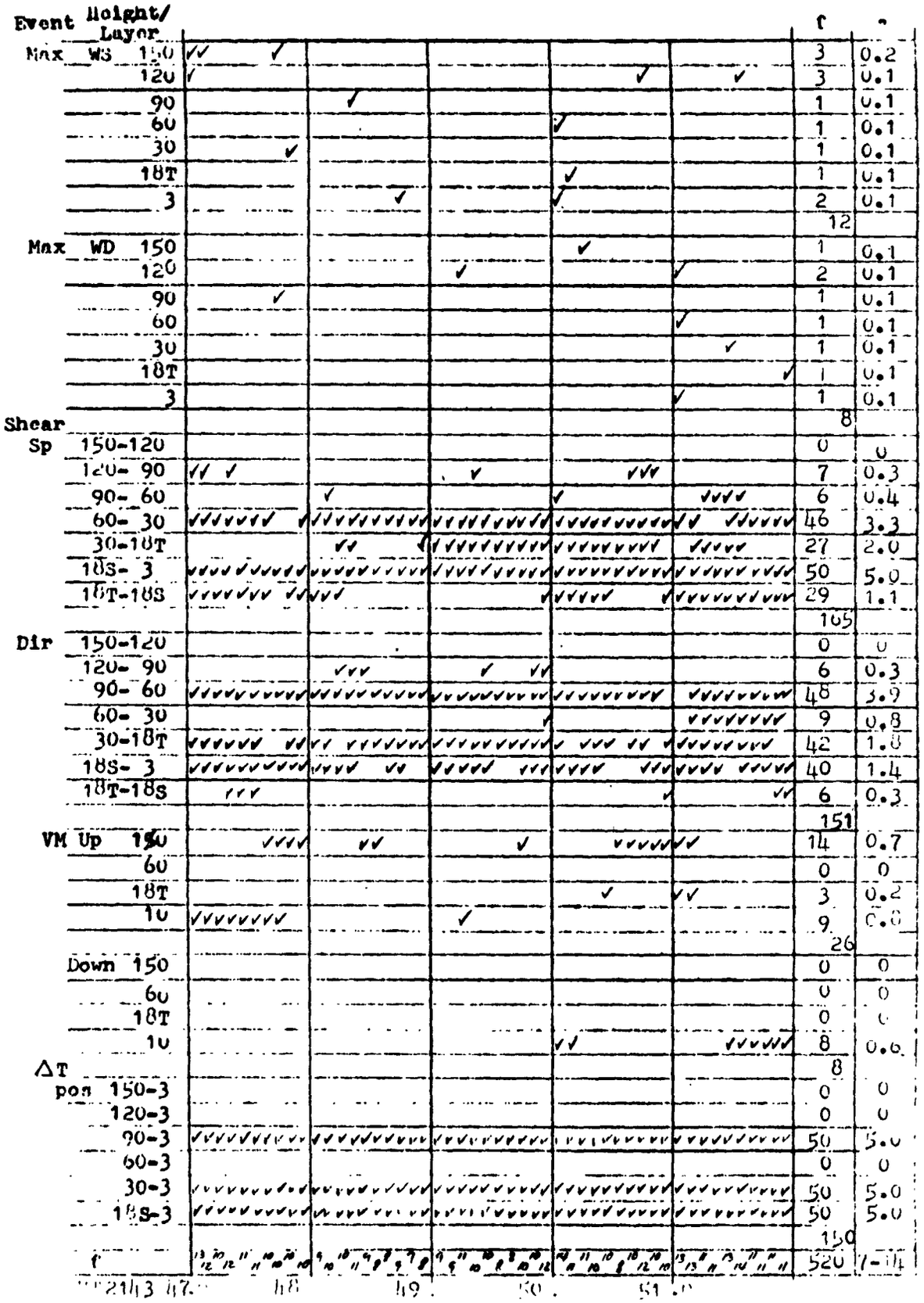

Figure 5. Simultaneous occurrence of separated significant events for interval 2143 47.0-51.9 UT.

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TABLE 2. MAGNITUDE, FREQUENCY, AND DURATION OF SIGNIFICANT EVENTS FOR INTERVAL 2145 27.0-31.9 UT

Event	Height Layer Distance	Max	Min	Mean	Std Dev	Freq.	Longest Continuous Duration	G	GF
Turbulence Speed	m	ms^{-1}	ms^{-1}	ms^{-1}	ms^{-1}	max ws	s max ws	ms^{-1}	non-dim
	150	21.1	17.3	19.476	0.882	1	0.1	3.8	1.083
	120	22.5	18.1	19.954	0.927	1	0.1	4.4	1.128
	90	20.1	16.5	18.690	0.877	1	0.1	3.6	1.073
	60	18.7	13.7	16.212	1.213	1	0.1	5.0	1.153
	30	14.5	9.6	12.056	1.371	1	0.1	4.9	1.203
	18T	11.3	3.6	7.822	2.193	2	0.1	7.7	1.445
	18S	14.8	4.6	8.658	2.739	1	0.1	10.2	1.709
	3	5.8	2.7	4.110	0.742	2	0.2	3.1	1.411
Direction		deg	deg	deg	deg	max wd	max wd	deg	non-dim
	150	224	210	218	4.292	1	0.1	14	1.029
	120	228	207	212	3.002	1	0.1	21	1.077
	90	237	220	229	3.353	1	0.1	17	1.033
	60	221	194	202	6.664	1	0.1	27	1.093
	30	259	216	235	9.928	1	0.1	43	1.100
	18T	259	213	233	9.979	1	0.1	46	1.113
	18S	264	189	235	16.793	1	0.1	75	1.122
	3	227	170	198	17.529		0.1	57	1.147
Shear Speed		s^{-1}	s^{-1}	s^{-1}	s^{-1}	$\geq 0.1\ s^{-1}$	s		
	150-120	0.103	0	0.035	0.029	2	0.1		
	120-90	0.127	0	0.045	0.033	3	0.2		
	90-60	0.190	0.010	0.083	0.047	16	0.9		
	60-30	0.247	0.060	0.139	0.049	39	2.0		
	30-18T	0.783	0.042	0.357	0.201	45	4.5		
	18S-3	0.693	0	0.313	0.169	43	2.9		
	18T-18S	0.356	0.006	0.134	0.104	28	0.9		
Direction		deg m^{-1}	deg m^{-1}	deg m^{-1}	deg m^{-1}	≥ 1.0 deg m^{-1}	s		
	150-120	0.533	0	0.225	0.126	0	0		
	120-90	1.867	0.433	0.737	0.680	0	0		
	90-60	1.233	0.500	0.905	0.176	19	0.6		
	60-30	1.933	0.300	1.097	0.435	30	2.1		
	30-18T	2.667	0.083	0.955	0.759	18	0.8		
	18S-3	5.733	0.067	2.735	1.305	47	4.1		
	18T-18S	3.111	0.111	0.962	0.724	18	0.4		
Vertical Motion Up		ms^{-1}	ms^{-1}	ms^{-1}	ms^{-1}	$\geq 1.0\ ms^{-1}$	s	ms^{-1}	non-dim
	150	1.06	0.03	0.426	0.314	1	0.1	1.03	2.486
	60	1.1[illegible]	0.10	0.694	0.306	6	0.3	1.07	1.685
	18T	2.78	0.03	1.511	0.812	37	3.0	2.75	1.840
	10	[illegible].36	0.03	0.614	0.329	3	0.3	1.33	2.215
Down	150	1.13	0.1	0.461	0.315	2	0.2	1.12	2.453
	60	0.94	0.05	0.451	0.265	0	0	0.89	2.084
	18T					0	0		
	10	0.64	0.05	0.294	0.228	0	0	0.59	2.177
Inversion Delta T		°C	°C	°C	°C	positive	s		
	150-3					0	0		
	120-3					0	0		
	90-3					0	0		
	60-3					0	0		
	30-3					0	0		
	18S-3	0.6	0.5	0.576	0.043	50	5.0		
Amb T	3	20.3	19.9	20.094	0.097				

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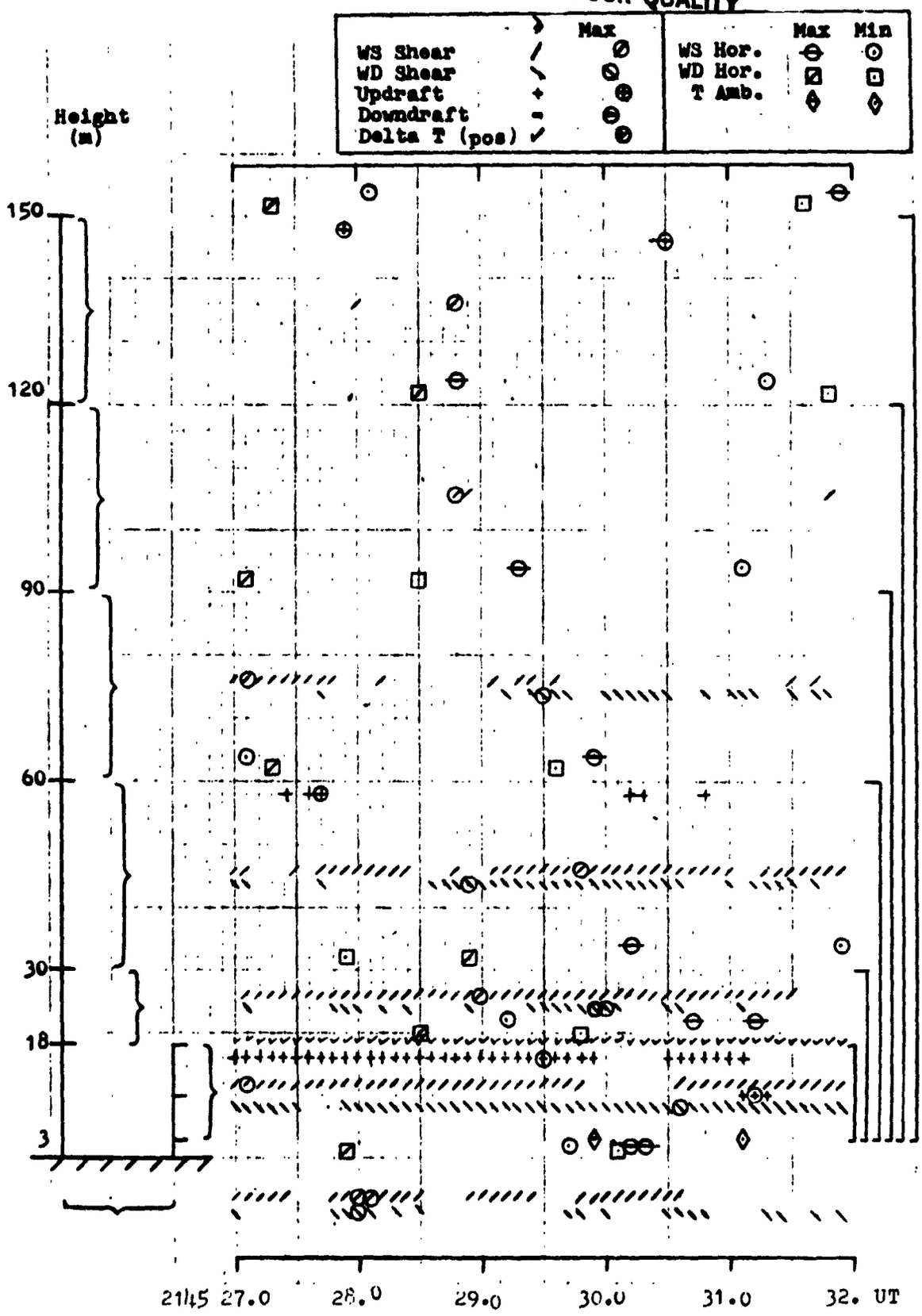

Figure 6. Occurrence of significant events for interval 2145 27.0-31.9 UT.

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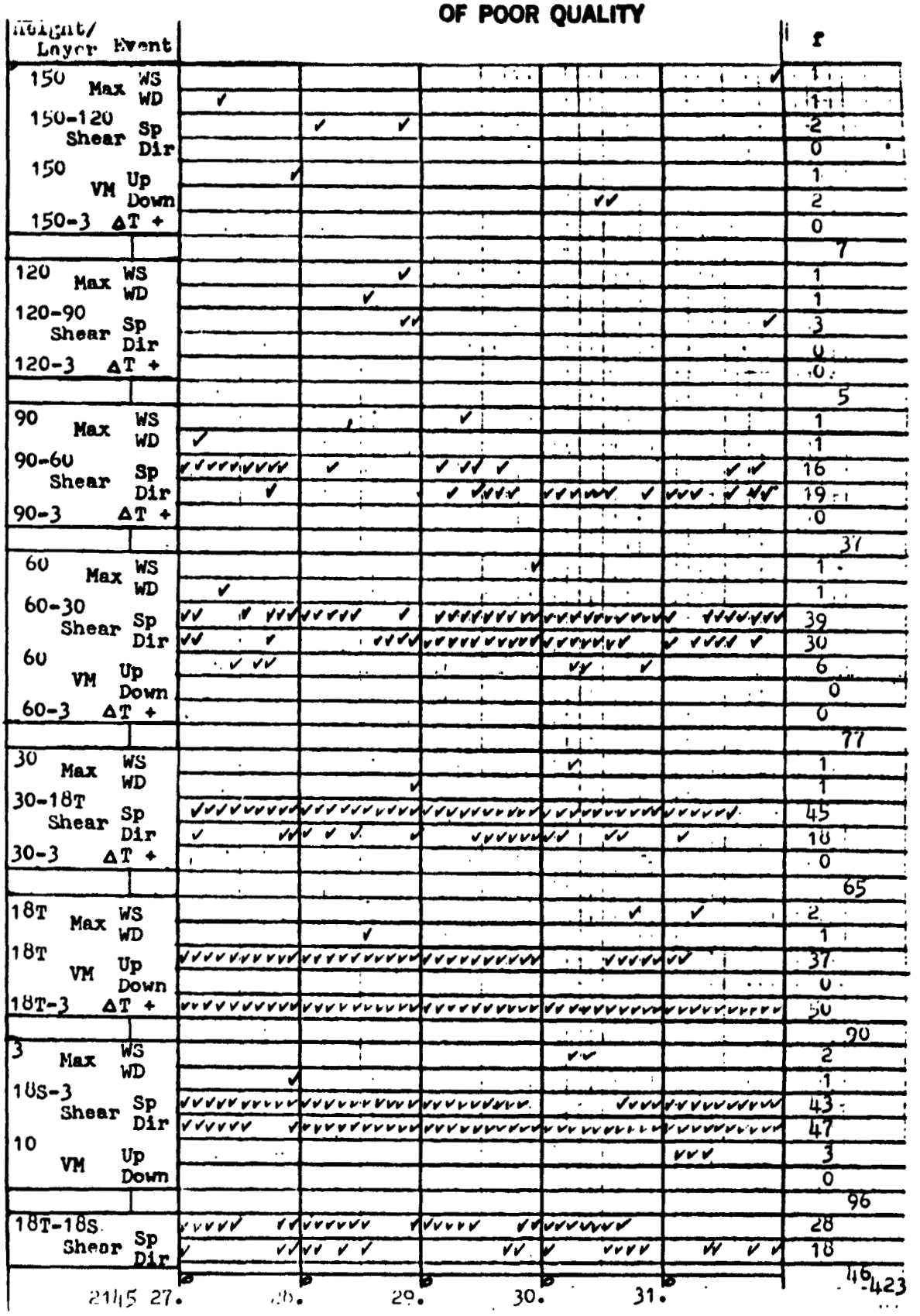

Figure 7. Simultaneous occurrence of combined significant events for interval 2145 27.0-31.9 UT.

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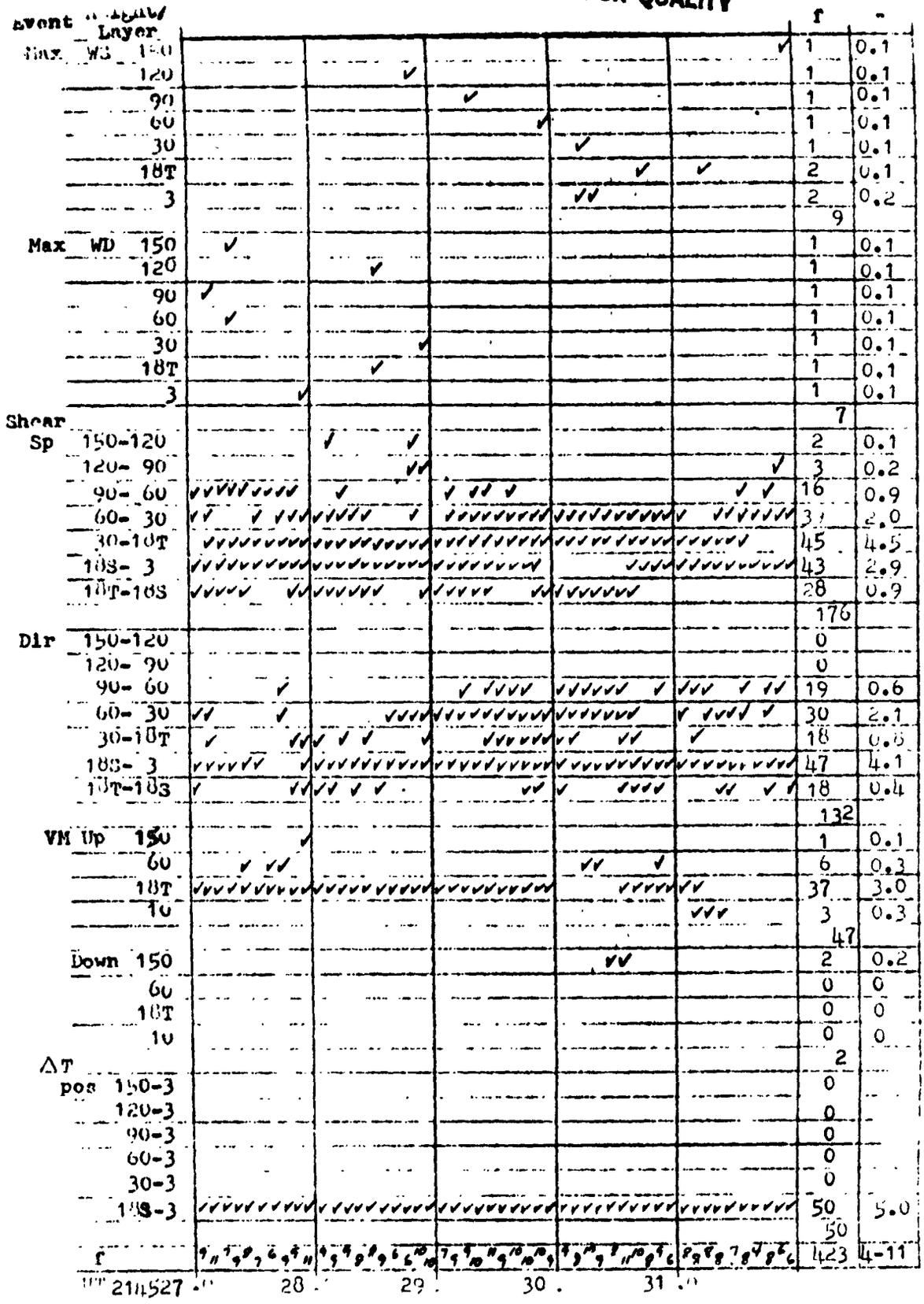

Figure 8. Simultaneous occurrence of separated significant events for interval 2145 27.0-31.9 UT.

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TABLE 3. MAGNITUDE, FREQUENCY, AND DURATION OF SIGNIFICANT EVENTS FOR INTERVAL 2147 7.0-11.9 UT

Event	Height Layer Distance	Max	Min	Mean	Std Dev	Freq.	Longest Continuous Duration	G	GF
Turbulence Speed	m	ms^{-1}	ms^{-1}	ms^{-1}	ms^{-1}	max ws	s max ws	ms^{-1}	non-dim
	150	27.4	24.4	25.668	0.716	1	0.1	3.0	1.067
	120	26.4	23.2	24.946	0.867	1	0.1	3.2	1.058
	90	26.0	21.5	23.556	1.149	1	0.1	4.5	1.104
	60	24.6	19.4	21.998	1.189	1	0.1	5.2	1.118
	30	20.8	11.6	15.944	2.317	1	0.1	9.2	1.305
	18T	18.4	14.5	16.508	1.059	1	0.1	3.9	1.115
	18S	17.2	11.4	13.804	1.396	1	0.1	5.8	1.246
	3	10.6	3.9	6.332	1.542	1	0.1	6.7	1.674
Direction		deg	deg	deg	deg	max wd	max wd	deg	non-dim
	150	226	214	223	2.628	1	0.1	12	1.016
	120	222	211	216	2.589	1	0.1	11	1.025
	90	245	231	238	3.134	1	0.1	14	1.030
	60	221	199	210	4.577	1	0.1	22	1.050
	30	262	208	233	12.329	1	0.1	54	1.125
	18T	228	196	218	7.392	1	0.1	32	1.045
	18S	230	204	220	6.094	1	0.1	26	1.046
	3	233	162	199	15.466	1	0.1	71	1.172
Shear Speed		s^{-1}	s^{-1}	s^{-1}	s^{-1}	$\geq 0.1\ s^{-1}$	s		
	150-120	0.103	0	0.033	0.027	1	0.1		
	120-90	0.117	0.003	0.050	0.030	3	0.1		
	90-60	0.130	0	0.054	0.033	5	0.2		
	60-30	0.387	0.047	0.201	0.093	43	2.5		
	30-18T	0.417	0	0.160	0.132	28	1.6		
	18S-3	0.713	0.240	0.498	0.101	50	5.0		
	18T-18S	0.333	0.011	0.159	0.072	44	2.1		
Direction		deg m^{-1}	deg m^{-1}	deg m^{-1}	deg m^{-1}	≥ 1.0 deg m^{-1}	s		
	150-120	0.400	0.100	0.201	0.067	0	0		
	120-90	1.067	0.500	0.712	0.155	1	0.1		
	90-60	1.400	0.467	0.928	0.220	17	1.3		
	60-30	1.867	0.067	0.764	0.468	12	1.1		
	30-18T	3.583	0	1.352	0.998	28	1.4		
	18S-3	4.400	0.047	1.507	1.087	33	1.9		
	18T-18S	1.667	0.056	0.452	0.349	4	0.3		
Vertical Motion Up		ms^{-1}	ms^{-1}	ms^{-1}	ms^{-1}	$\geq 1.0\ ms^{-1}$	s	ms^{-1}	non-dim
	150	1.62	0.08	0.889	0.336	18	0.3	1.54	1.821
	60	0.41	0.01	0.167	0.129	0	0	0.40	2.460
	18T	0.69	0.03	0.321	0.203	0	0	0.66	2.148
	10	1.06	0.01	0.376	0.297	1	0.1	1.05	2.821
Down	150					0	0		
	60	1.83	0.01	0.573	0.533	10	0.9	1.82	3.194
	18T	1.34	0.01	0.459	0.346	2	0.2	1.33	2.919
	10	1.59	0.01	0.430	0.459	3	0.3	1.58	3.694
Inversion Delta T		°C	°C	°C	°C	positive	s		
	150-3					0	0		
	120-3					0	0		
	90-3					0	0		
	60-3					0	0		
	30-3	0.5	0.2	0.368	0.115	50	5.0		
	18S-3	0.3	0.2	0.244	0.050	50	5.0		
Amb T	3	19.8	19.6	19.642	0.054				

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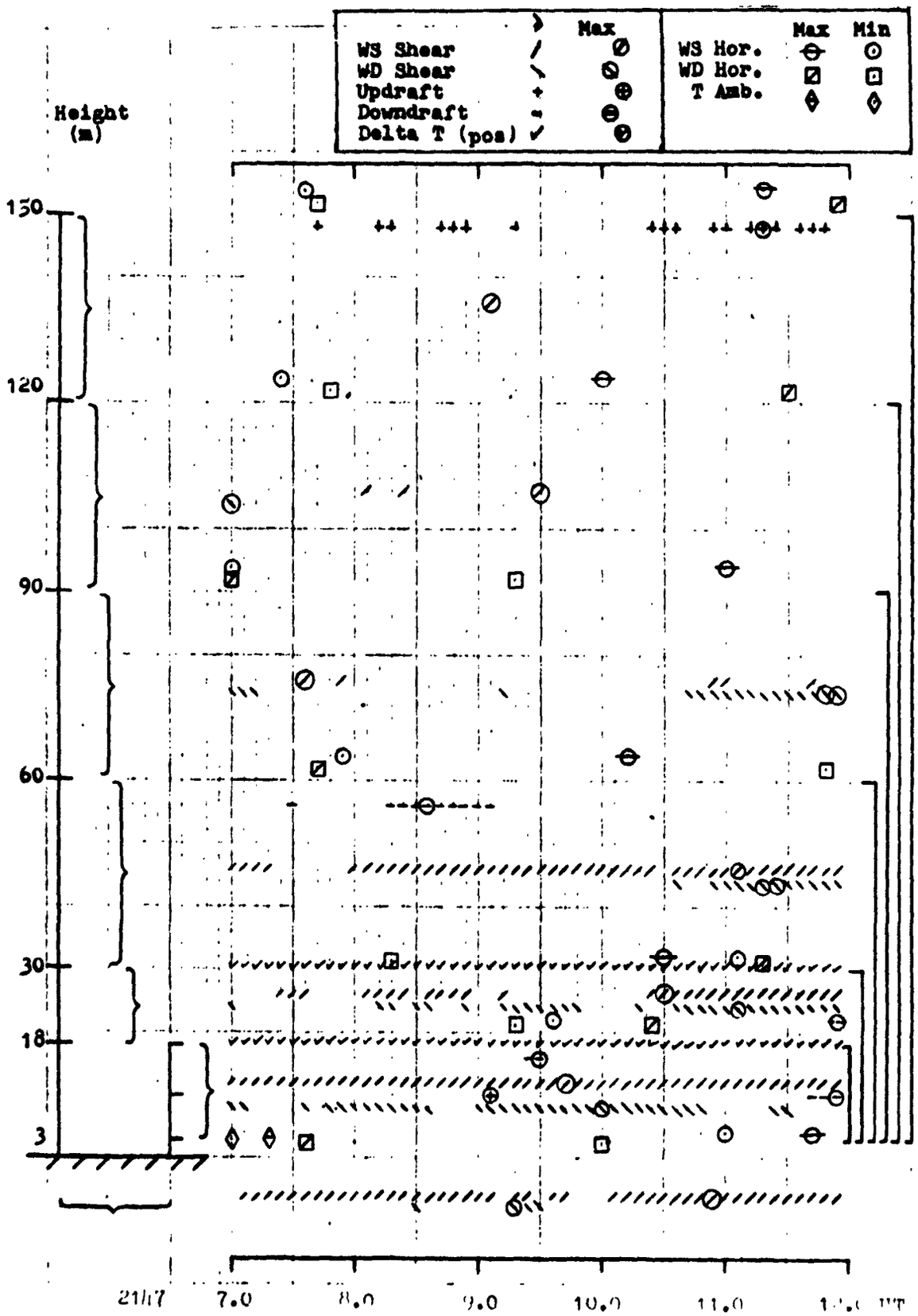

Figure 9. Occurrence of significant events for interval 2147 7.0-11.9 UT.

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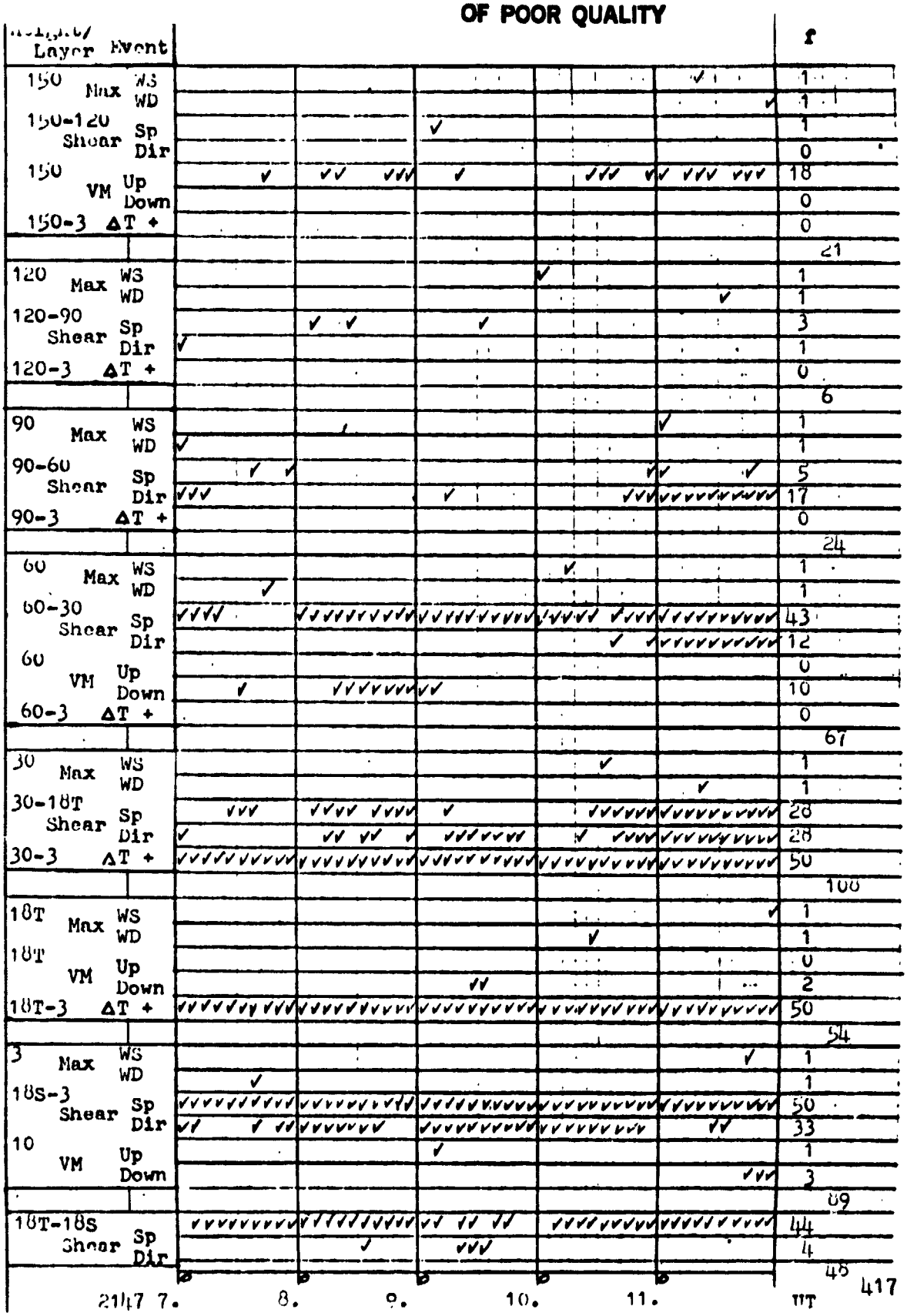

Figure 10. Simultaneous occurrence of combined significant events for interval 2147 7.0-11.9 UT.

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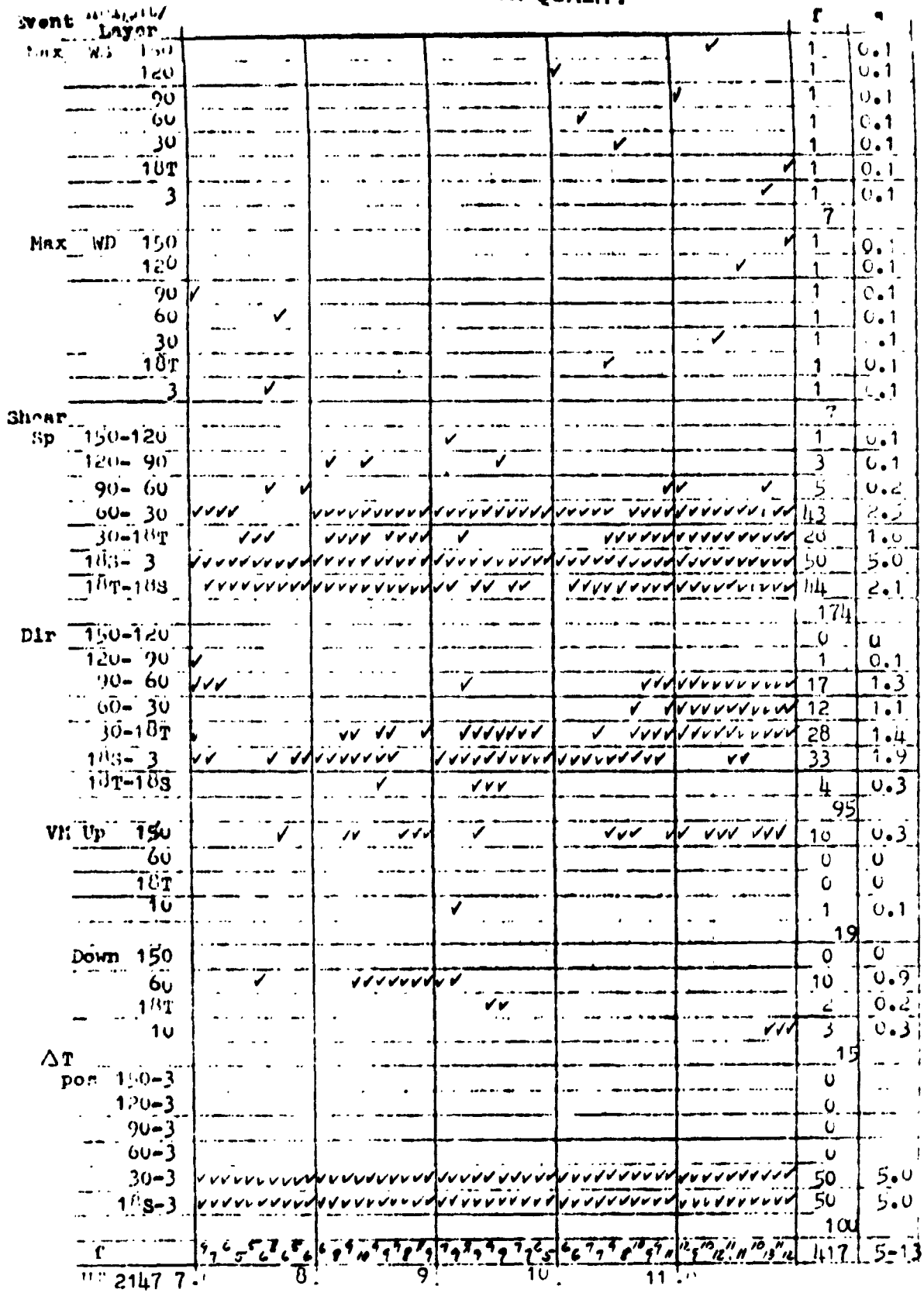

Figure 11. Simultaneous occurrence of separated significant events for interval 2147 7.0-11.9 UT.

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TABLE 4. MAGNITUDE, FREQUENCY, AND DURATION OF SIGNIFICANT EVENTS FOR INTERVAL 2148 47.0-51.9 UT

Event	Height Layer Distance	Max	Min	Mean	Std Dev	Freq.	Longest Continuous Duration	G	GF
							s		
Turbulence Speed	m	ms^{-1}	ms^{-1}	ms^{-1}	ms^{-1}	max ws	max ws	ms^{-1}	non-dim
	150	25.6	23.7	24.670	0.400	2	0.2	1 9	1.038
	120	26.0	23.6	24.980	0.530	2	0.1	2 4	1.041
	90	25.1	23.5	24.290	0.420	1	0.1	1.5	1.033
	60	24.0	19.3	21.934	1.201	1	0.1	4.7	1.094
	30	19.0	12.1	16.242	1.974	2	0.2	6.9	1.170
	18T	20.1	11.0	16.660	2.294	2	0.1	9.1	1.206
	18S	17.6	11.4	15.090	1.596	1	0.1	6.2	1.166
	3	13.5	6.7	9.588	1.562	1	0.1		1.408
Direction		deg	deg	deg	deg	max wd	max wd		non-dim
	150	231	225	227	1.360	1	0.1		1.017
	120	223	219	221	1.074	1	0.1		1.011
	90	245	238	242	1.755	1	0.1	7	1.012
	60	219	206	211	3.610	2	0.2	13	1.036
	30	264	238	250	5.487	1	0.1	26	1.057
	18T	249	225	232	4.256	1	0.1	24	1.072
	18S	257	221	237	9.804	1	0.1	36	1.084
	3	225	178	206	10.875	1	0.1	47	1.091
Shear Speed		s^{-1}	s^{-1}	s^{-1}	s^{-1}	$\geq 0.1\ s^{-1}$	s		
	150-120	0.063	0	0.019	0.016	0	0		
	120-90	0.057	0	0.026	0.015	0	0		
	90-60	0.177	0.003	0.079	0.037	14	1.3		
	60-30	0.303	0.060	0.190	0.059	49	4.9		
	30-18T	0.550	0	0.107	0.105	20	0.5		
	18S-3	0.680	0.040	0.367	0.160	47	3.8		
	18T-18S	0.256	0	0.092	0.073	22	1.1		
Direction		deg m^{-1}	deg m^{-1}	deg m^{-1}	deg m^{-1}	≥ 1.0 deg m^{-1}	s		
	150-120	0.333	0.133	0.233	0.041	0	0		
	120-90	0.833	0.533	0.716	0.072	0	0		
	90-60	1.267	0.700	1.023	0.134	35	1.6		
	60-30	1.633	0.733	1.284	0.190	46	3.5		
	30-18T	2.417	0.083	1.422	0.551	39	1.4		
	18S-3	4.400	0.400	2.064	1.008	42	3.2		
	18T-18S	1.611	0.017	0.529	0.410	8	0.7		
Vertical Motion Up		ms^{-1}	ms^{-1}	ms^{-1}	ms^{-1}	$\geq 1.0\ ms^{-1}$	s	ms^{-1}	non-dim
	150	1.85	0.41	1.040	0.305	27	1.3	1.44	1.779
	60	0.48	0.01	0.152	0.147	0	0	0.47	3.158
	18T	0.55	0.01	0.171	0.166	0	0	0.54	3.216
	10	1.92	0.08	0.945	0.600	8	0.7	1.84	2.031
Down	150					0	0		
	60	1.22	0.01	0.621	0.337	7	0.5	1.21	1.965
	18T	1.55	0.01	0.619	0.378	4	0.4	1.54	2.503
	10	1.69	0.01	0.786	0.458	11	0.5	1.68	2.151
Inversion Delta T		°C	°C	°C	°C	positive	s		
	150-3					0	0		
	120-3					0	0		
	90-3					0	0		
	60-3					0	0		
	30-3					0	0		
	18S-3	0.1	0.0	0.008	0.027	50	5.0		
Amb T	3	19.0	18.9	18.982	0.039				

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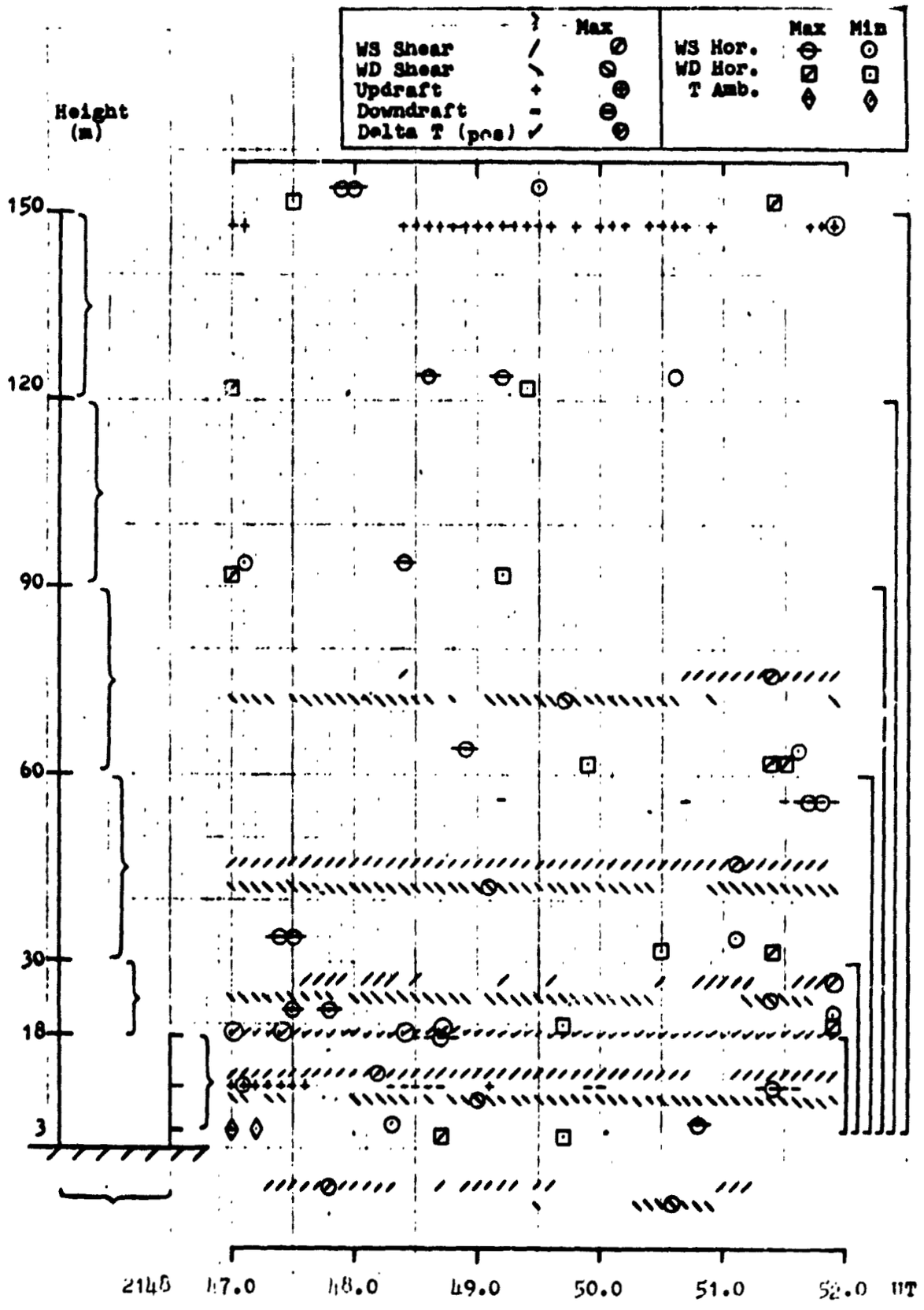

Figure 12. Occurrence of significant events for interval 2148 47.0-51.9 UT.

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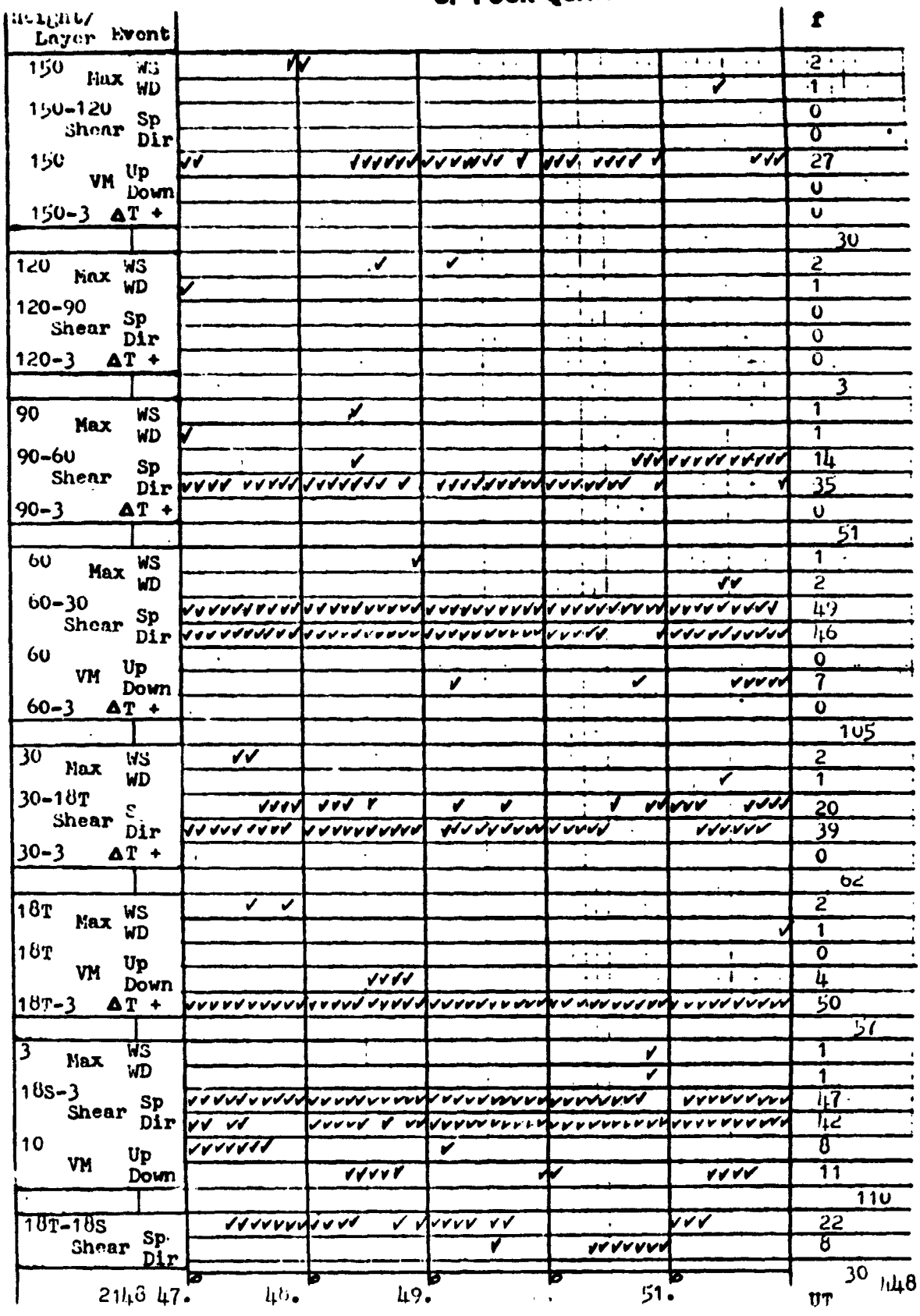

Figure 13. Simultaneous occurrence of combined significant events for interval 2148 47.0-51.9 UT.

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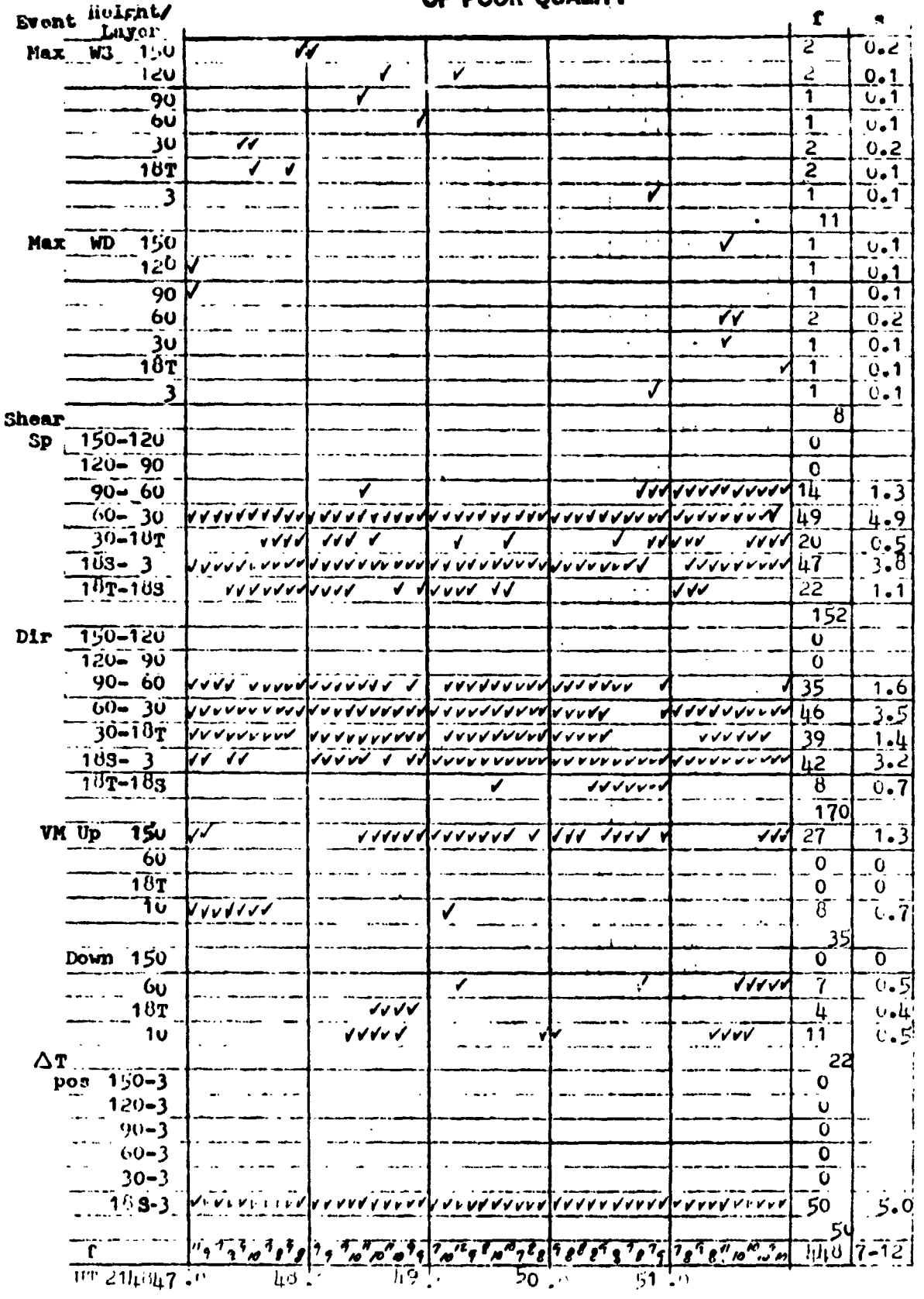

Figure 14. Simultaneous occurrence of separated significant events for interval 2148 47.0-51.9 UT.

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TABLE 5. MAGNITUDE, FREQUENCY, AND DURATION OF SIGNIFICANT EVENTS FOR INTERVAL 2150 32.0-36.9 UT

Event	Height Layer Distance	Max	Min	Mean	Std Dev	Freq.	Longest Continuous Duration	G	GF
Turbulence Speed	m	ms^{-1}	ms^{-1}	ms^{-1}	ms^{-1}	max ws	max ws	ms^{-1}	non-dim
	150	23.9	20.5	22.590	0.740	1	0.1	3.4	1.058
	120	24.6	19.8	21.920	1.380	1	0.1	4.8	1.122
	90	23.3	20.1	21.450	0.800	1	0.1	3.2	1.086
	60	21.6	17.6	20.232	0.861	1	0.1	4.0	1.068
	30	21.5	12.3	17.706	2.215	1	0.1	9.2	1.214
	18T	20.7	7.9	14.406	3.609	1	0.1	12.8	1.437
	18S	16.6	5.7	11.346	3.241	1	0.1	10.9	1.463
	3	9.6	3.4	6.250	2.105	1	0.1	6.2	1.536
Direction		deg	deg	deg	deg	max wd	max wd	deg	non-dim
	150	238	225	232	2.287	1	0.1	13	1.028
	120	225	214	220	2.548	1	0.1	11	1.022
	90	248	236	240	2.893	1	0.1	12	1.032
	60	220	202	210	4.444	1	0.1	18	1.049
	30	265	228	240	6.926	1	0.1	37	1.104
	18T	243	214	231	6.881	1	0.1	29	1.050
	18S	252	212	231	11.594	2	0.1	40	1.089
	3	238	186	217	13.439	1	0.1	52	1.097
Shear Speed		s^{-1}	s^{-1}	s^{-1}	s^{-1}	$\geq 0.1\ s^{-1}$	s		
	150-120	0.130	0.003	0.043	0.032	3	0.3		
	120-90	0.113	0	0.033	0.027	2	0.1		
	90-60	0.130	0	0.043	0.032	2	0.1		
	60-30	0.307	0	0.092	0.081	15	1.1		
	30-18T	0.792	0	0.292	0.245	34	2.0		
	18S-3	0.553	0.120	0.340	0.103	50	5.0		
	18T-18S	0.678	0.028	0.354	0.156	47	2.9		
Direction		$deg\ m^{-1}$	$deg\ m^{-1}$	$deg\ m^{-1}$	$deg\ m^{-1}$	$\geq 1.0\ deg\ m^{-1}$	s		
	150-120	0.633	0.100	0.374	0.132	0	0		
	120-90	0.967	0.400	0.671	0.143	0	0		
	90-60	1.333	0.667	1.011	0.175	30	1.7		
	60-30	1.933	0.533	1.007	0.278	22	0.8		
	30-18T	3.167	0	0.811	0.720	15	0.5		
	18S-3	2.600	0.067	1.113	0.683	26	0.6		
	18T-18S	1.833	0	0.719	0.463	12	0.7		
Vertical Motion Up		ms^{-1}	ms^{-1}	ms^{-1}	ms^{-1}	$\geq 1.0\ ms^{-1}$	s	ms^{-1}	non-dim
	150	1.17	0.03	0.448	0.316	3	0.3	1.14	2.612
	60	0.27	0.03	0.142	0.076	0	0	0.24	1.906
	18T	3.50	0.03	1.137	0.884	16	0.9	3.47	3.078
	10	2.97	0.03	0.990	0.866	13	1.3	2.94	3.001
Down									
	150	0.59	0.01	0.202	0.179	0	0	0.58	2.927
	60	1.50	0.01	0.656	0.456	9	0.8	1.49	2.286
	18T	1.04	0.24	0.546	0.253	1	0.1	0.80	1.903
	10	2.22	0.15	0.715	0.605	4	0.3	2.06	3.106
Inversion Delta T		°C	°C	°C	°C	positive	s		
	150-3					0	0		
	120-3	0.02	0.02	0.020	0.000	2	0.1		
	90-3	0.2	0	0.068	0.075	19	1.8		
	60-3					0	0		
	30-3	0.3	0	0.120	0.095	20	1.9		
	18S-3	0.02	0.02	0.020	0.000	1	0.1		
Amb T	3	18.9	18.7	18.778	0.051				

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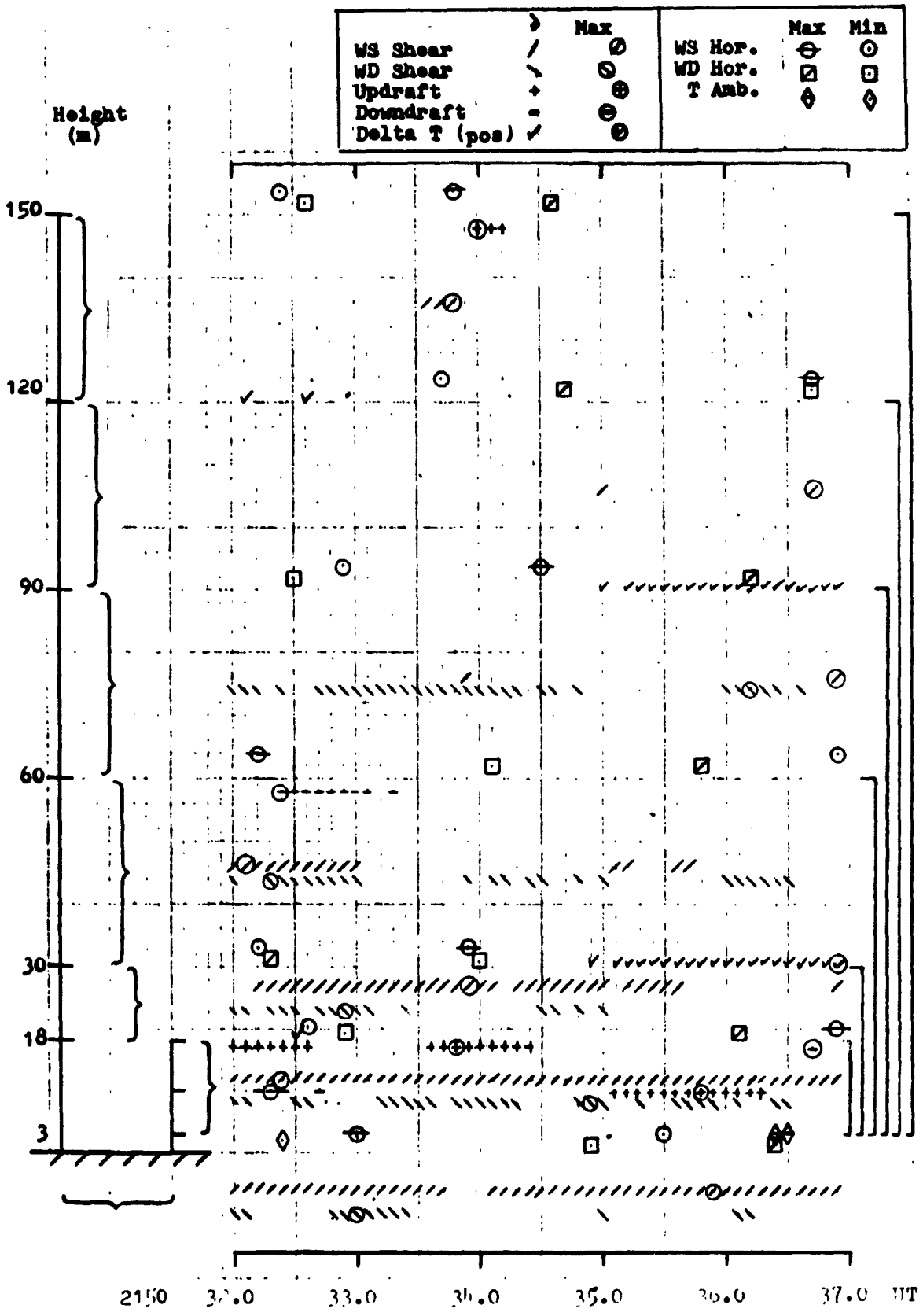

Figure 15. Occurrence of significant events for interval 2150 32.0-36.9 UT.

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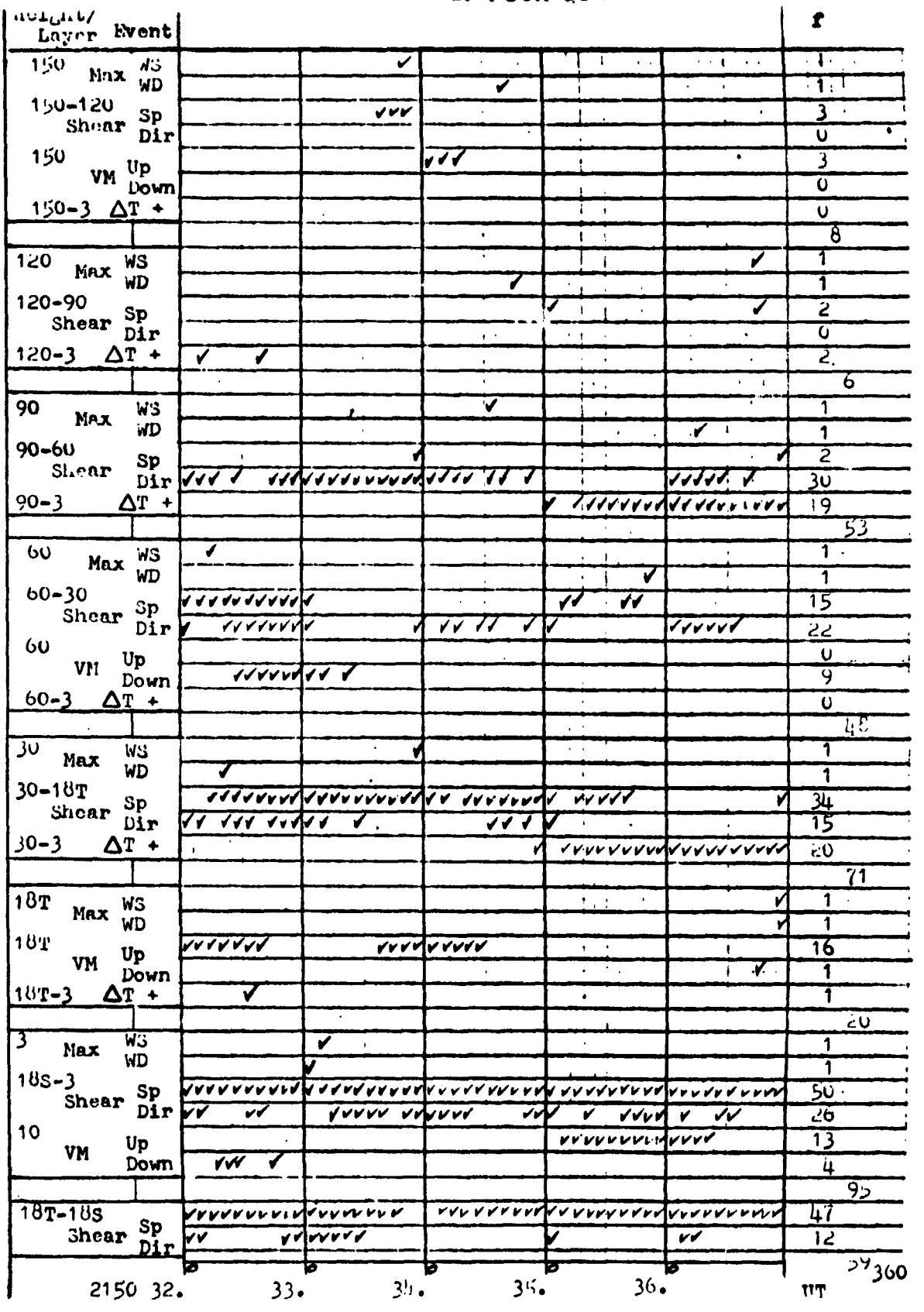

Figure 16. Simultaneous occurrence of combined significant events for interval 2150 32.0-36.9 UT.

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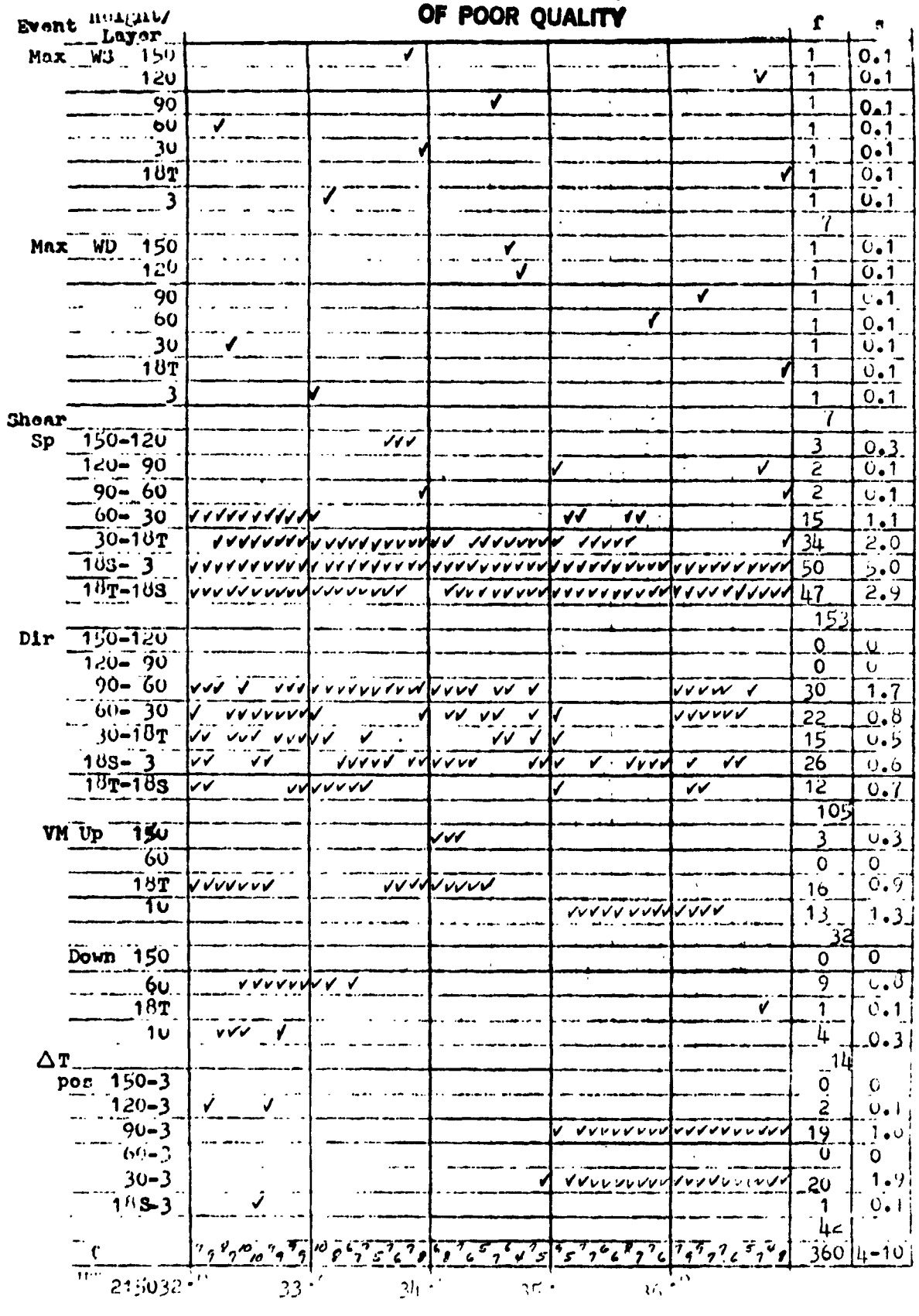

Figure 17. Simultaneous occurrence of separated significant events for interval 2150 32.0-36.9 UT.

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TABLE 6. MAGNITUDE, FREQUENCY, AND DURATION OF SIGNIFICANT EVENTS FOR INTERVAL 2152 12.0-16.9 UT

Event	Height Layer Distance	Max	Min	Mean	Std Dev	Freq.	Longest Continuous Duration	G	GF
							s		
Turbulence Speed	m	ms^{-1}	ms^{-1}	ms^{-1}	ms^{-1}	max ws	max ws	ms^{-1}	non-dim
	150	20.5	18.4	19.460	0.510	1	0.1	2.1	1.053
	120	20.5	18.7	19.600	0.390	1	0.1	1.8	1.046
	90	20.5	17.3	19.270	0.660	1	0.1	3.2	1.064
	60	18.7	14.4	16.450	1.068	1	0.1	4.3	1.137
	30	16.6	10.6	14.122	1.378	1	0.1	6.0	1.175
	18T	14.5	11.4	13.432	0.836	4	0.2	3.1	1.080
	18S	13.4	10.3	11.996	0.722	1	0.1	3.1	1.117
	3	8.9	3.2	6.508	1.506	1	0.1	5.7	1.368
Direction		deg	deg	deg	deg	max wd	max wd	deg	non-dim
	150	231	222	224	1.741	1	0.1	9	1.029
	120	218	214	216	0.718	1	0.1	4	1.009
	90	240	234	237	1.750	1	0.1	6	1.012
	60	215	200	206	3.166	1	0.1	15	1.045
	30	250	224	238	5.929	2	0.2	26	1.051
	18T	221	208	215	2.900	1	0.1	13	1.029
	18S	232	214	221	3.881	1	0.1	18	1.052
	3	250	183	214	17.651	1	0.1	67	1.166
Shear Speed		s^{-1}	s^{-1}	s^{-1}	s^{-1}	$\geq 0.1\ s^{-1}$	s		
	150-120	0.047	0	0.016	0.012	0	0		
	120-90	0.083	0	0.020	0.021	0	0		
	90-60	0.157	0.010	0.094	0.033	27	1.0		
	60-30	0.143	0	0.079	0.042	22	1.1		
	30-18T	0.308	0	0.124	0.074	29	0.8		
	18S-3	0.640	0.167	0.366	0.126	50	5.0		
	18T-18S	0.183	0	0.094	0.049	26	1.5		
Direction		$deg\ m^{-1}$	$deg\ m^{-1}$	$deg\ m^{-1}$	$deg\ m^{-1}$	$\geq 1.0\ deg\ m^{-1}$	s		
	150-120	0.500	0.200	0.308	0.155	0	0		
	120-90	0.833	0.400	0.695	0.076	0	0		
	90-60	1.267	0.733	1.049	0.109	39	1.4		
	60-30	1.533	0.500	1.072	0.251	33	1.3		
	30-18T	3.167	0.667	1.933	0.555	47	1.8		
	18S-3	2.667	0.020	1.006	0.683	25	0.9		
	18T-18S	0.889	0	0.335	0.222	0	0		
Vertical Motion Up		ms^{-1}	ms^{-1}	ms^{-1}	ms^{-1}	$\geq 1.0\ ms^{-1}$	s	ms^{-1}	non-dim
	150	1.01	0.03	0.624	0.239	1	0.1	0.98	1.620
	60					0	0		
	18T	0.31	0.27	0.290	0.028	0	0	0.04	1.069
	10	0.29	0.03	0.177	0.090	0	0	0.26	1.642
Down	150					0	0		
	60	1.57	0.01	0.643	0.375	7	0.5	1.56	2.44
	18T	1.59	0.03	0.665	0.405	12	0.9	1.56	2.39
	10	1.43	0.01	0.690	0.351	8	0.5	1.42	2.07
Inversion Delta T		°C	°C	°C	°C	positive	s		
	150-3	0.01	0.0	0.010	0.0	2	0.1		
	120-3					0	0		
	90-3					0	0		
	60-3					0	0		
	30-3					0	0		
	18S-3	0.2	0.0	0.036	0.056	50	5.0		
Amb T	3	18.7	18.5	18.610	0.036				

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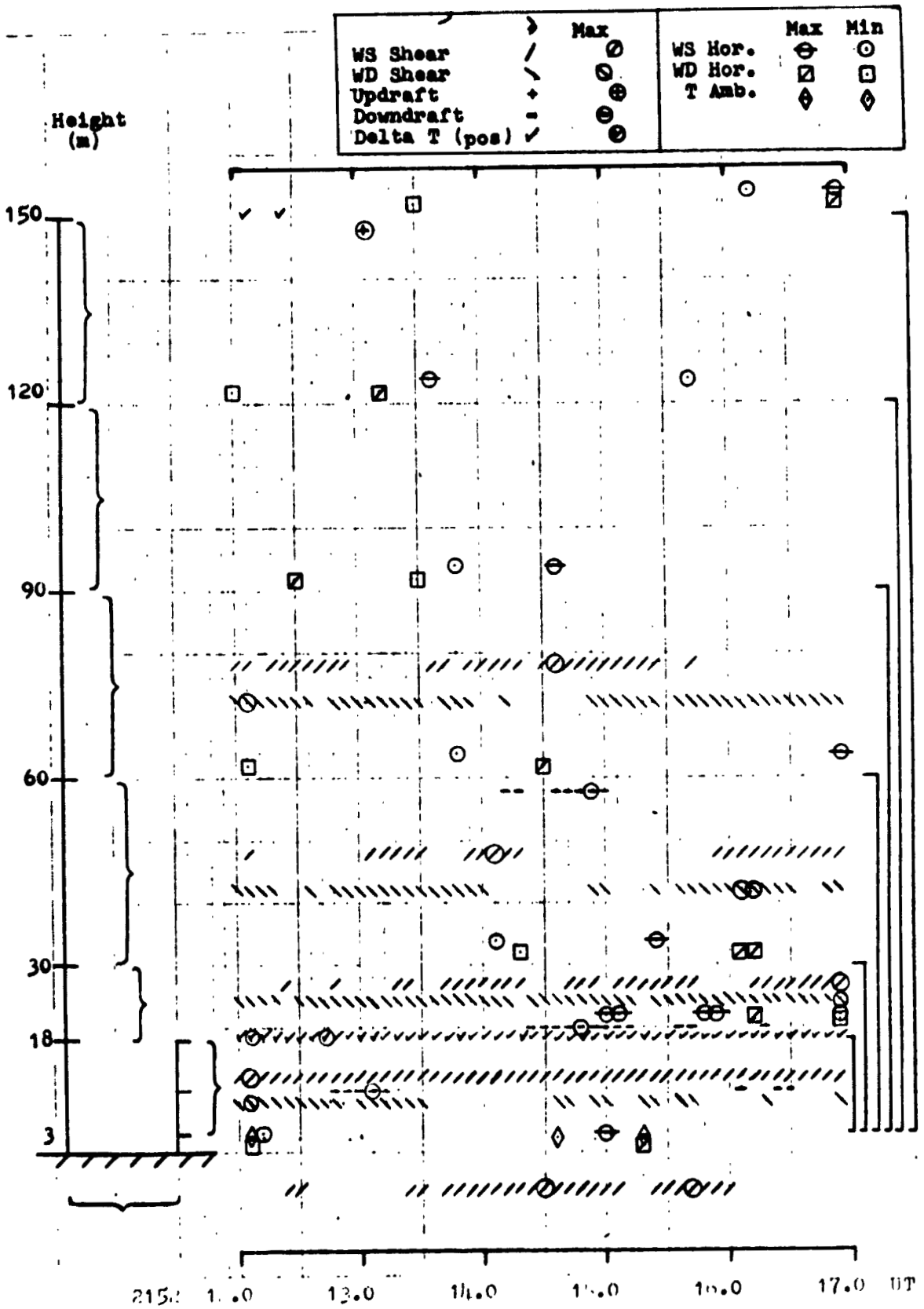

Figure 18. Occurrence of significant events for interval 2152 12.0-16.9 UT.

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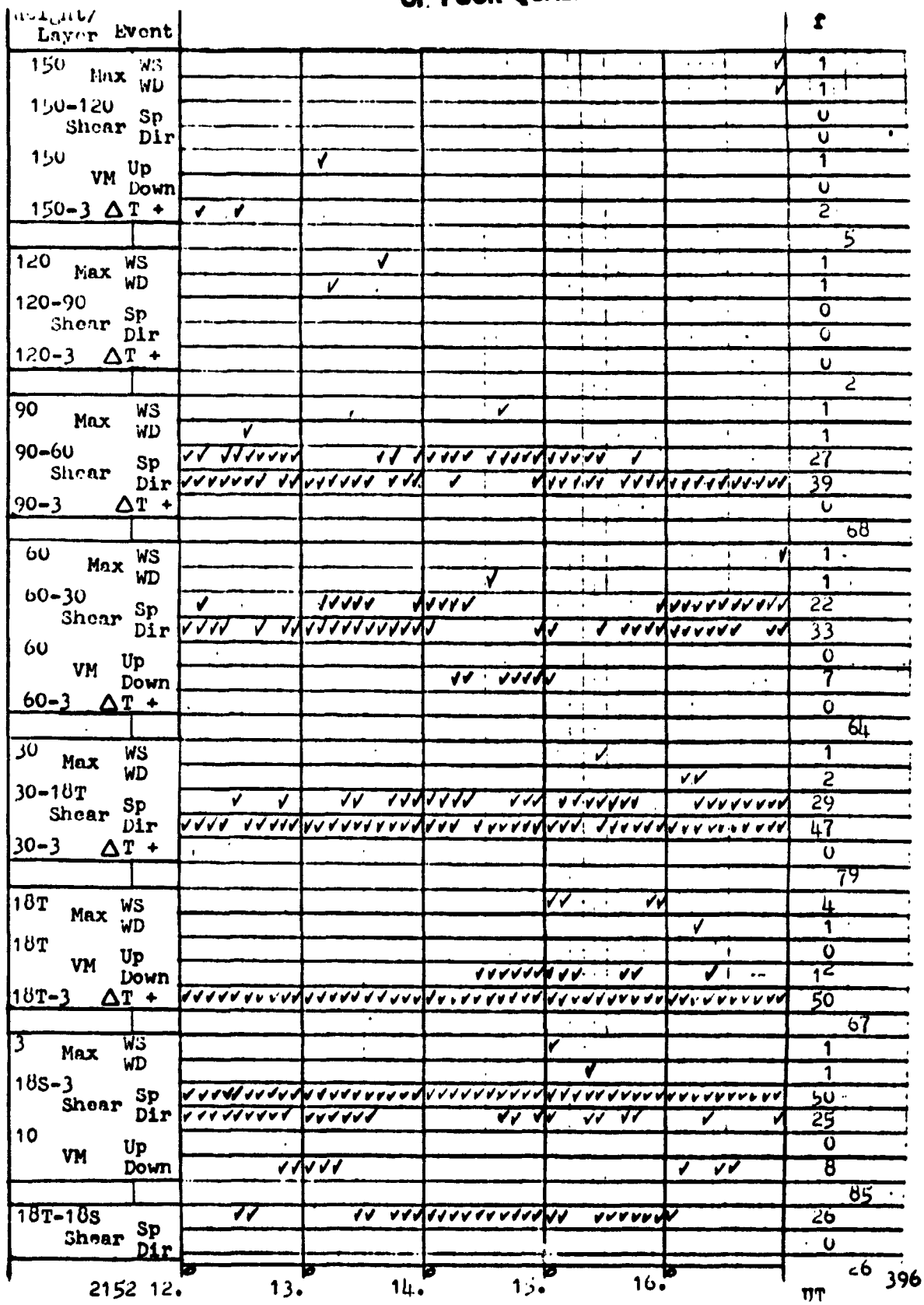

Figure 19. Simultaneous occurrence of combined significant events for interval 2152 12.0-16.9 UT.

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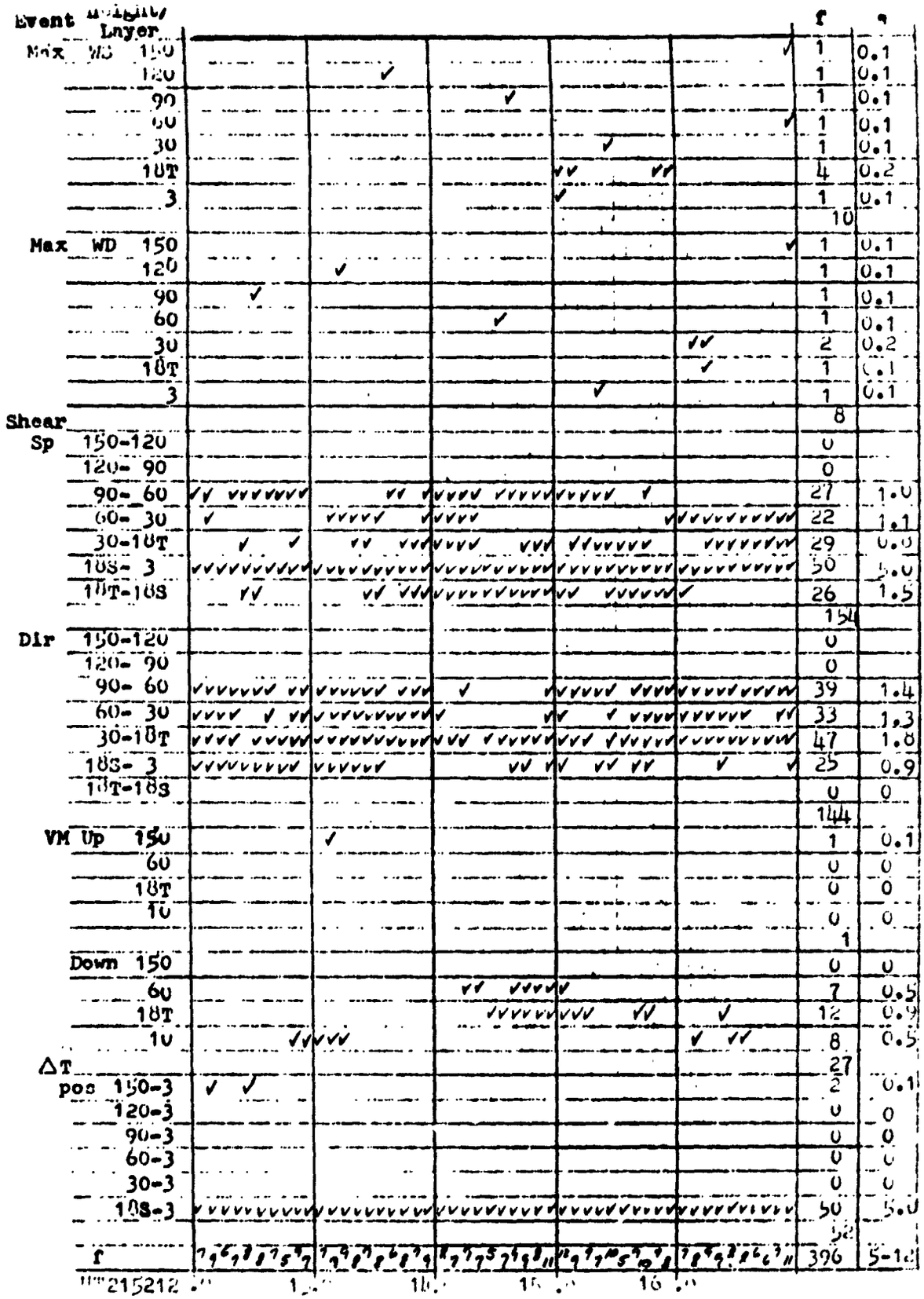

Figure 20. Simultaneous occurrence of separated significant events for interval 2152 12.0-16.9 UT.

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TABLE 7. EXTREME VALUES, TOTAL FREQUENCIES, AND MAXIMUM CONTINUOUS DURATIONS OF SIGNIFICANT EVENTS FOR 2143 47.0-2152 16.9 UT

Event	Height Layer Distance	Max G	Max GF				Max WS/WD	Max Duration
Turbulence	m							
Speed		ms^{-1}	non-dim				ms^{-1}	s
	150	3.8	1.083				27.4	0.2
	120	4.8	1.128				26.4	0.1
	90	4.5	1.104				26.0	0.1
	60	7.3	1.206				24.6	0.1
	30	9.2	1.305				21.5	0.2
	18T	12.8	1.445				20.7	0.2
	18S	10.9	1.709				17.6	0.3
	3	6.8	1.674				13.5	0.2
Direction		deg	non-dim				deg	s
	150	14	1.029				238	0.1
	120	21	1.077				228	0.1
	90	17	1.033				250	0.1
	60	27	1.093				221	0.2
	30	54	1.125				265	0.2
	18T	46	1.138				259	0.1
	18S	75	1.122				264	0.1
	3	76	1.226				250	0.1
Shear								
Speed		s^{-1}		$\geq 0.1\ s^{-1}$	f	%		s
	150-120	0.130			6	2.00		0.3
	120-90	0.133			15	5.00		0.3
	90-60	0.190			70	23.33		1.3
	60-30	0.387			214	71.33		4.9
	30-18T	0.792			183	61.00		4.5
	18S-3	0.713			290	96.67		5.0
	18T-18S	0.678			196	65.33		2.9
Direction		$deg\ m^{-1}$		$\geq 1.0\ deg\ m^{-1}$	f	%		s
	150-120	0.633			0	0		0
	120-90	1.067			7	2.33		0.3
	90-60	1.567			188	62.67		3.9
	60-30	1.933			152	50.67		3.5
	30-18T	4.000			189	63.00		1.8
	18S-3	5.733			213	71.00		4.1
	18T-18S	3.111			48	16.00		0.7
Vertical Motion								
Up		ms^{-1}		$\geq 1.0\ ms^{-1}$	f	%		s
	150	1.90			64	25.91		1.3
	60	1.17			6	7.23		0.2
	18T	3.50			56	40.88		3.0
	10	2.97			34	23.13		1.3
Down								
	150	1.13			2	3.77		0.2
	60	1.83			33	15.21		0.9
	18T	1.59			19	11.66		0.9
	10	2.22			34	22.22		0.6
Inversion								
Delta T		°C		positive	f	%		s
	150-3	0.01			2	0.67		0.1
	120-3	0.01			2	0.67		0.1
	90-3	0.20			69	23.00		5.0
	60-3	0			0	0		0
	30-3	0.50			120	40.00		5.0
	18S-3	0.60			251	83.67		5.0
Amb T	3	21.7						

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APPROVAL

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By Margaret B. Alexander and Dennis W. Camp

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

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