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STRATOSPHERIC TURBULENCE AND TEMPERATURE GRADIENTS MEASURED BY AN RB-57F. COLDSCAN FLIGHTS 2 TO 18

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Coldscan Flights 2 to 18

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SUMMARY

In January 1969, the National Aeronautical Establishment instrumented a USAF RB-57F weather reconnaissance aircraft to measure turbulence and temperature gradients encountered on routine flights at altitudes from 40,000 feet to above 60,000 feet. To date 19 data flights covering 30,000 nautical miles of the central and western United States have been flown in a continuing program named "Coldscan". This report summarizes the results of the first 19 flights and presents detailed accounts of a selection of 15 events showing large temperature changes or light to moderate turbulence. These presentations include time histories of the recorded variables, flight tracks showing event positions, and meteorological analyses. Data are presented on the correlation between the measured stratospheric turbulence and horizontal temperature gradients and on the geographical distribution of recorded incidents. Results of these winter and spring flights are most significant for the number of encounters with mountain waves, even at altitudes above 60,000 feet.

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INTRODUCTION

In January 1969, the National Aeronautical Establishment instrumented a USAF RB-57F (Fig. 1) of the 58th Weather Reconnaissance Squadron to measure turbulence and temperature gradients encountered on routine flights at altitudes above 40,000 feet. A full description of the instrumentation and its operation has been reported in Reference 1. The aims of the program are to collect data on atmospheric conditions at altitudes to be flown by the supersonic transports, to attempt to relate the nature and severity of each recorded incident to geographical position and meteorological conditions, and to investigate the relationship between stratospheric turbulence and strong horizontal temperature gradients.

Between January 31 and July 9, the first 19 data flights of the Coldscan program were flown, covering over 30,000 nautical miles of the central and western United States. Part 1 of this report summarizes the results of these 19 flights. Part 2 presents detailed accounts of 15 of the more interesting events, and includes time histories of the recorded parameters, route maps showing event positions, and discussions of the meteorological conditions contributing to the events.

Data Acquisition and Analysis

The NAE instrumentation system is operated by the RB-57F crews on routine operational and training flights above 40,000 feet. It is a highly automated system based on the NRC memory recorder. This 7-channel F. M. magnetic tape recorder has a 2-minute tape loop in addition to its 5-hour reel for permanent storage. Flight data are continuously recorded on the tape loop and simultaneously scanned by exceedance detectors for parameter fluctuations exceeding preset levels. When an exceedance is detected, the tape reels are actuated for the transfer of data from the loop to the storage tape. The two minutes of recorded data prior to the exceedance are retained, along with the exceedance, as long as it persists, plus the two minutes of data following the incident. The recorder reels can be initiated by any or all of the following exceedances:

(i) change in total temperature $\geq$ 2.5°C within a 30-second period;

(ii) change in total temperature $\geq$ 2.5°C in 2 seconds;

(iii) normal acceleration increment $\geq$ 0.35 g;

(iv) rate of change of airspeed $\geq$ 5 knots/sec.

Every stored incident is identified by a coded digital clock time superimposed on one of the recorded signals. For each exceedance the navigator logs the digital clock time, along with geographical position, altitudes, aircraft weight, doppler winds, and his comments concerning autopilot mode, severity of turbulence, and local weather conditions.

Completed tapes with the navigators' data logs and maps are sent to the NAE for analysis. On tape playback, each recorded encounter is assigned a chronological flight and event number based on the coded time pulses and the information written on the data logs. Continuous time records of static (ambient) temperature are calculated by analogue computer, using the airspeed and altitude signals to correct the total temperature for the increment due to kinetic heating. This computation includes corrections to the indicated airspeed for position error and compressibility. The computed static temperature signal is recorded on 14-channel magnetic tape along with the original seven channels of data, all matched low-pass filtered at nine cycles/sec. A voice channel is included on this data storage tape to record flight and event numbers as well as comments from the navigators' logs.

For each event, chart recorder traces are then prepared showing simultaneous time histories of total temperature, static temperature, indicated airspeed, normal acceleration, pitch and roll attitude, and coarse and fine-scale altitude. These are carefully analyzed to determine the nature of each exceedance and to select the more significant events for detailed meteorological analysis. At this stage, many events are eliminated from further serious consideration. Examples are those with g exceedances due to control inputs, or total temperature changes caused by intentional large changes in airspeed. For those events selected for detailed meteorological analysis, copies of the traces and all other data describing each event are sent to the Atmospheric Research Section, Research and Training Division, Meteorological Service of Canada.

PART 1

1.0 SUMMARY OF RESULTS - FLIGHTS 2 TO 18

Table 1 summarizes the flight data for the 19 Coldscan missions flown between January 31 and July 9, 1969. Over 30,000 nautical miles were flown during 88.5 hours of flight, 75.2 of these above 40,000 feet. Figure 2 shows the geographical area covered in these 19 flights, all of which were round trip missions operated from Kirtland A. F. B., New Mexico. Data logs were not received for Flights 10B and 15B, so their exact flight routes are unknown and not included in Figure 2. Route miles for these two flights are estimated from the digital clock times recorded on the data tape and the true airspeed computed from the indicated airspeed and altitude signals.

With the notable exception of Flight 11, all of the flights were routine operational or training missions with no attempt made to intentionally encounter areas of known turbulence. Flight 11 was flown for a Royal Aircraft Establishment mountain wave project, and directed into an area of anticipated lee waves. Several 100-mile legs were flown across the Sangre de Cristo mountain range at altitudes from 40,000 to 62,000 feet. Twenty-seven events were recorded on this flight, most of them with either light to moderate turbulence or significant temperature changes (Table 1). Five events from Flight 11 are detailed in Part 2 of this report.

During cruise portions of the 19 flights, there were 25 events with recorded temperature changes exceeding 2.5°C within 30 seconds, and 26 events with recorded turbulence. Ten of these events contained both temperature change and turbulence. A "turbulence" event was defined to include cases where solution of the gust equation of Reference 1 indicated longer wave length vertical air motion causing aircraft pitching and vertical acceleration, as well as the more usual cases with high-frequency fluctuations in the accelerometer trace.

Of the 99 events recorded to date, more than half had neither turbulence nor the minimum 2.5°C within 30 seconds change of static temperature during level flight. Many of these events (19) were the result of pilot or autopilot control inputs causing g exceedances, another 17 were in climbs or descents with temperature change or g exceedances, seven were the result of total temperature changes due solely to airspeed changes, and three were manual selections to test the instrumentation.

1.1 Duration of Turbulence

In the first 19 flights in the Coldscan program, 74 minutes of turbulence were encountered during cruise at altitudes above 40,000 feet. For this purpose, the duration of turbulence in each case was defined as the period during which there were continuous excursions of the accelerometer trace with at least one spike exceeding 0.35 g. For the RB-57F, this level of vertical acceleration corresponds to a derived gust velocity (Ref. 2) of about 8 ft/sec.

The 74 minutes of turbulence encountered during the 19 flights represent 1.6% of the total time spent above 40,000 feet. Flight 11, however, was directed into an area of anticipated lee wave activity, and accounted for one-third of the recorded turbulence. A more meaningful figure for the frequency of occurrence of stratospheric turbulence should therefore exclude the Flight 11 data. For the remaining 18 flights then, 1.2% of the time above 40,000 feet was flown in turbulence.

1.2 Horizontal Temperature Gradients

Figure 3 shows the changes in static temperature encountered in Flights 2 to 18 versus the distance over which the changes took place. Most of the larger rates of change of temperature in this Figure are from the events shown in Part 2 of this report, and many were concluded to be the result of mountain waves. A few events are represented by more than one point in Figure 3, since each half-cycle of a wave in the temperature contributed a point to the plot. Many of the largest rates of change of temperature were recorded above 60,000 feet. The maximum rate encountered to date was a 5°C change in 2/3 of a nautical mile at 63,000 feet.

The threshold shown in this Figure illustrates the approximate minimum rate of temperature change that will trigger the recorder. This threshold is for a true airspeed of 400 knots, the aircraft's usual speed when above 50,000 feet. It must be remembered that the recorder is activated by a change of 2.5°C within 30 seconds in total temperature, that is, the static temperature plus the dynamic heating effect. At Mach 0.7, this corresponds to the threshold in static temperature shown in the Figure. For the four points lying to the right of the curve, the recorder was initiated, not by temperature change, but by accelerometer and airspeed fluctuations during turbulence.

1.3 Temperature-Turbulence Correlation

Results of the analysis of the correlation between stratospheric turbulence and horizontal temperature gradients are shown in Figure 4. Since only 19 flights have been flown to date, representing just two seasons, the results should be treated with some caution at this stage.

On the left in Figure 4 is shown the percentage of turbulent events that had static temperature changes of 2.5°C or more within 30 seconds. Only 23 of the 26 turbulent events listed in Table 1 are included in this analysis because two had temperature traces off scale and one occurred during a slow climb. Less than half of the 23 events with turbulence showed temperature gradients greater than 2.5°C within 30 seconds, 39% had temperature changes of at least 5°C during the event, and 30% recorded temperature changes exceeding 5°C in one minute.

The reverse correlation, that is the number of events with temperature change that also included turbulence, is illustrated on the right side of Figure 4. For the temperature change categories selected, only 40 to 50% had turbulence. The threshold levels used in this study must be kept in mind, however. A rate of change in temperature of 2.5°C in 30 seconds, for example, represents a change of almost 3/4°C per nautical mile at the speed flown above 50,000 feet.

1.4 Geographical Distribution of Events

In Flights 2 to 18, only 40% of the total miles flown were over or within 30 nautical miles of mountainous terrain. In comparison, of the number of events with known geographical positions, 85% of those with turbulence and 83% of those with the 2.5°C in 30-second temperature change were over or within 30 miles of mountains. Furthermore, turbulence and temperature changes encountered away from the mountains were generally milder than for events near the mountainous terrain. The detailed accounts of Part 2 show that many of the more significant events recorded during the winter and spring flights were the result of mountain waves.

TABLE 1

COLDSCAN FLIGHT AND EVENT SUMMARY - FLIGHTS 2 TO 18

Flight	Date 1969	Cruise Altitudes ft	Flight Hours		Nautical Miles	Total Number of Events	Number of Events During Cruise			Duration of Turbulence min
			Total	Above 40,000 ft			With Static Temp. Change ≥ 2.5°C in 30 sec	With Turbulence	With Both Temp. Change and Turbulence	
2	Jan 31	61 to 64,000	4.35	3.77	1620	5	5	2	2	2.0
3	Feb 3	63,000	3.13	2.64	1240	2	2	2	2	1.6
4	Feb 4	Above 45,000	3.30	2.75	1140	1				
5	Feb 7	55,000	6.36	5.79	2310	4	2	2	2	3.0
6	Feb 10	53 to 55,000	5.60	4.77	1990	3		1		0.8
7	Mar 3	60,000	5.78	5.03	2190	2				
8	Mar 6	50,000	2.45	1.73	770	5	1	1		1.2
9	Mar 10	60 to 62,000	5.00	4.08	1700	5		1		5.4
10	Mar 12	50,000	5.20	4.50	1780	2				
10B	Mar 18	50,000	4.16	3.56	1430*	3				
11	Mar 19	40 to 62,000	6.13	5.02	1700	27	9	6	1	24.6
12	Mar 21	Above 40,000	3.24	2.29	890	0				
13	Mar 27	43,000	6.76	6.19	2340*	5	1			
14	Apr 8	62,000	6.33	5.73*	2350	5	1	1		0.6
15	Apr 10	Above 45,000	5.15	4.48	1800	2				
15B	Apr 11	50,000	4.20*	3.64	1250*	9		5		17.1
16	Apr 15	55 to 61,000	5.57	4.97	2000	10	4	5	3	18.0
17	Jul 8	40,000	1.00	0.13	200	2				
18	Jul 9	50,000	4.75	4.13	1470	7				
TOTALS			88.5	75.2	30170	99	25	26	10	74.3

* Estimated

FIG. 1: THE RB-57F

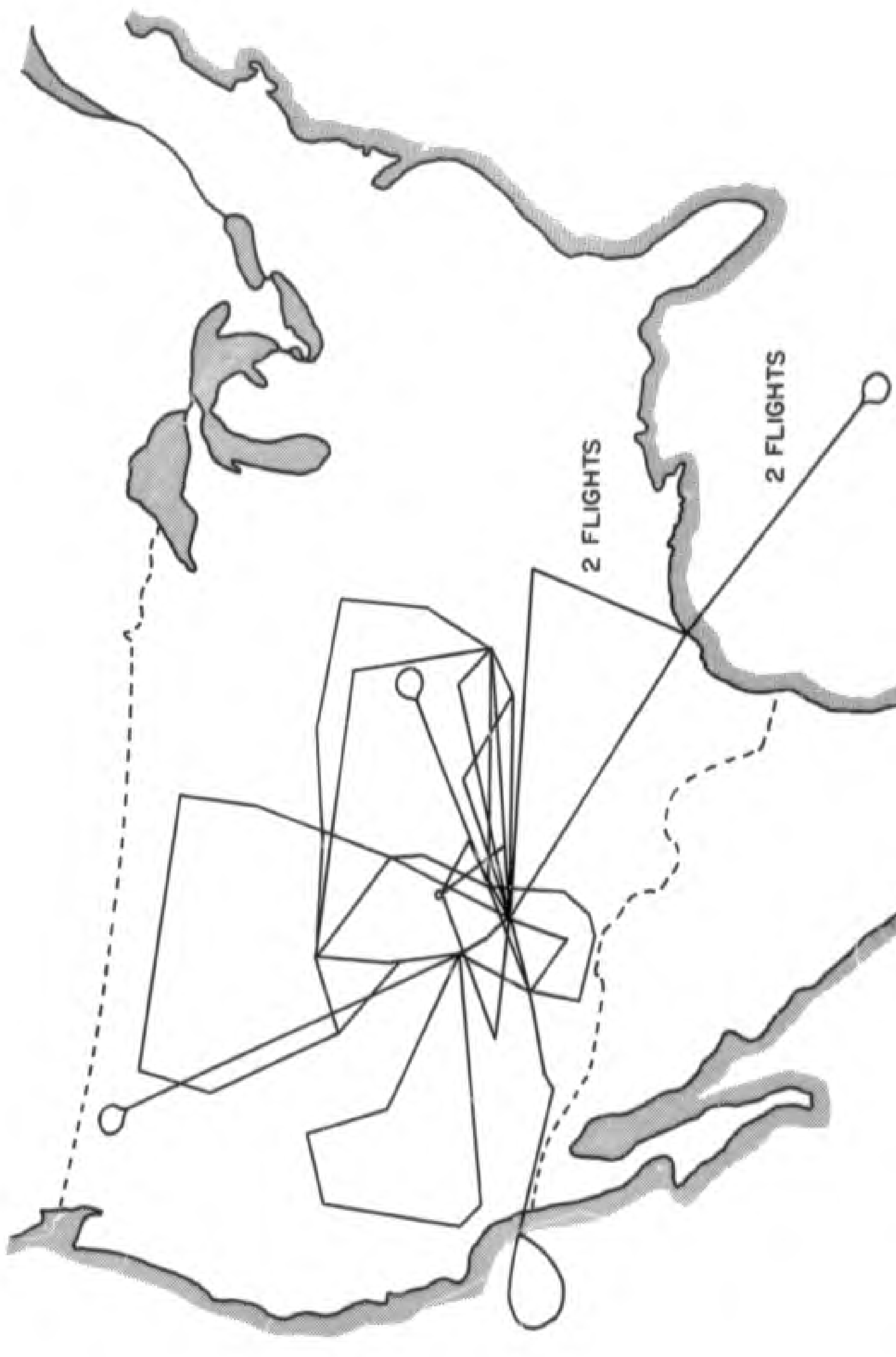

FIG. 2: GEOGRAPHICAL AREA OF COLDSCAN FLIGHTS 2 TO 18, 31 JAN. – 9 JULY 1969

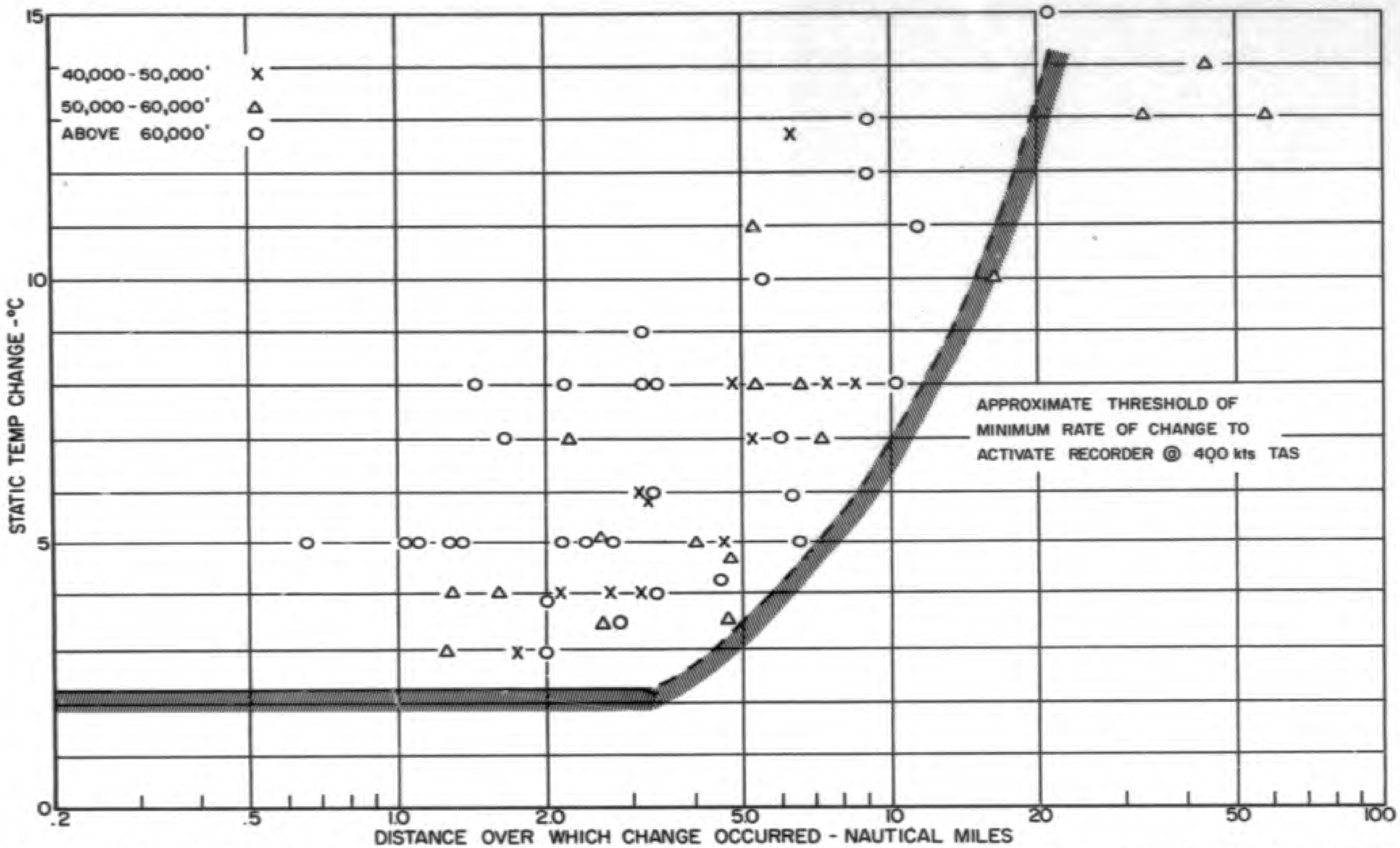

FIG.3: STRATOSPHERIC TEMPERATURE CHANGES ENCOUNTERED ON FLIGHTS 2 TO 18, 31 JAN.—9 JULY 1969

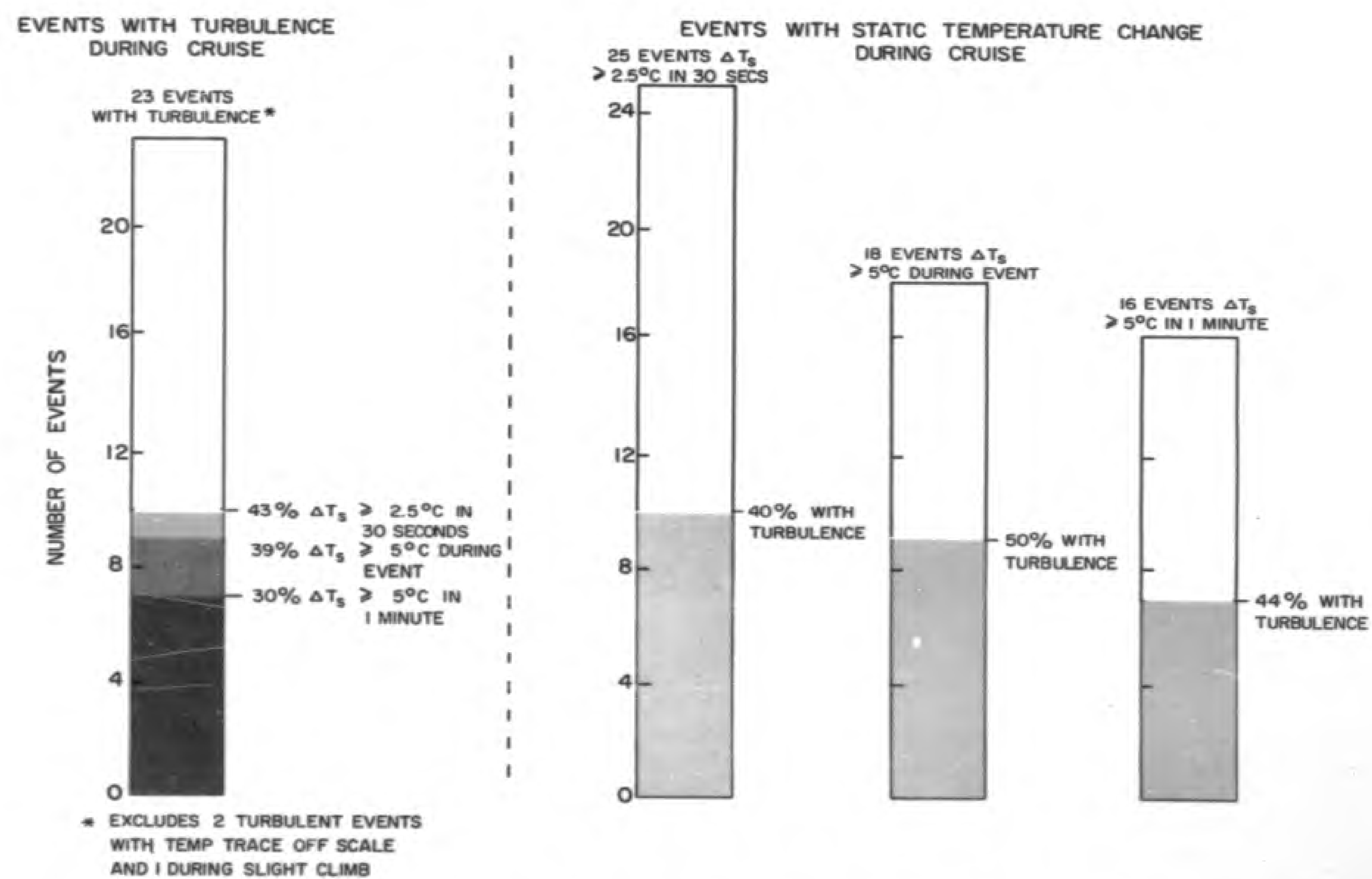

FIG 4: TEMPERATURE - TURBULENCE CORRELATION ABOVE 40,000FT—FLIGHTS 2 TO 18

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PART 2

2.0 SPECIAL EVENTS

From the 99 events recorded to date in Program Coldscan, 15 were selected for a more detailed presentation in this part of the report. The events chosen show the more significant temperature changes and turbulence encountered in the 19 flights previously summarized. Data are presented in six sections, one for each of the six flights from which the 15 events were selected. Each section contains a discussion of the flight data and the meteorological conditions, time histories of the measured parameters for each event, route maps showing event positions, and plotted meteorological data.

The lengths of the selected events vary from a minimum of four minutes to as long as 19 minutes. To show maximum detail, time histories are presented with scales that change from event to event, especially along the time axis. Each spike on the time scale shown below the vertical acceleration trace represents five seconds. Roll attitude is shown only when it is varying significantly. Calibration pulses occurring simultaneously on all channels are identified by "CAL" written on the altitude trace. For Flight 2, the coarse-altitude trace is shown because the fine-scale altitude signal was not recorded.

The continuous time records of static temperature were calculated by analogue computer, using the total temperature and indicated airspeed signals, and the recovery factor of 1.0 for the total temperature probe. Because the response rates for the total temperature and airspeed systems differ, high frequency fluctuations (i.e. greater than 0.5 cycles/sec) appearing on the static temperature trace during turbulence should not be considered real.

Maps accompanying each of the described incidents show the flight track as a dashed line becoming a solid black line at the position of the event. The event commences at the crossbar and ends at the arrowhead. Map scales are indicated by the 60-nautical-mile spacing of the latitudes.

Stratospheric Lee Waves

A number of the static temperature records obtained during the 19 flights contained well organized quasi-sinusoidal variations, all occurring in the vicinity of mountains. It has been postulated in the discussions of the individual events that these temperature fluctuations were caused by lee waves.

Studies have demonstrated that lee waves frequently extend into the stratosphere. All lee waves, stratospheric and tropospheric, are made up of a number of harmonic waves (Ref. 3). According to Palm and Foldvik, there are no observations that suggest the existence of a wave motion consisting only of a fundamental. Stratospheric lee wave components are usually longer than their tropospheric counterparts. This is due to the tendency of the upper troposphere to reflect the short waves downward while allowing the longer waves to pass almost unattenuated into the stratosphere (Eliassen and Palm, Ref. 4). Although the amplitude of stratospheric lee waves is frequently larger than in the troposphere, the amplitude of the vertical velocities is usually smaller. This results from the longer wave lengths and lower horizontal wind speeds in the stratosphere. Because the existence and form of stratospheric lee waves are dependent upon the meteorological conditions throughout the troposphere and stratosphere, they probably tend to change more rapidly with time than those in the troposphere. These changes may be very large and affect the amplitude, wave length, and phase of the component waves.

The static temperature data can be used to obtain an estimate of the amplitude of the lee waves and that of the associated vertical component of wind velocity. Since all of the events discussed in detail below occurred in the stratosphere, it can be assumed that the average undisturbed lapse rate at flight level was near zero in all cases. The actual lapse rate is difficult to estimate from rawinsonde data because of the apparent changes in lapse rate caused by the balloon rising on a slanting path through the lee waves. This effect, discussed by Scorer in Reference 5, is shown schematically in Figure 5. Using the zero undisturbed lapse rate, and assuming that the motion of the air through the wave is adiabatic, the amplitude H of the wave is given by

$$H = \Delta T/\gamma$$

$$= 330\ \Delta T \text{ ft}$$

where γ = adiabatic lapse rate (1°C/330 ft)

ΔT = amplitude of static temperature variation.

If it is further assumed that the wave is sinusoidal, then the amplitude of the vertical wind velocity w is given by

$$w = \frac{2\pi H}{\tau} \doteq 2000 \frac{\Delta T}{\tau} \text{ ft/sec}$$

where τ, the time required for the air parcel to travel through the wave, can be computed from the ground speed, the wind speed, and the time required for the aircraft to traverse the wave.

Because of the assumption of sinusoidal fluctuations of vertical velocity, zero undisturbed lapse rate, and the difficulty in estimating the amplitude and wave length of the various lee wave components, this method cannot be expected to yield an accurate estimate of the vertical wind speed. Nevertheless, in the few cases where it was compared with the gust velocities computed from the aircraft data, the results were in close agreement. The number of cases examined, however, was too small to obtain a reliable estimate of the errors.

2.1 Flight 2, 31 Jan. 1969 - Events 2 and 5/6 (Fig. 6 to 10)

Flight 2 was a 4-1/3-hour flight around New Mexico at altitudes above 60,000 feet. A total of five events were recorded, all initiated by total temperature change, but Events 2 and 5/6 had the largest changes and the only turbulence encountered on the flight (Fig. 6 and 8).

These two events were recorded two hours apart on the same track across the Sangre de Cristo mountain range (Fig. 7 and 9). On the first pass, large-amplitude temperature waves were recorded at 62,000 feet, along with airspeed fluctuations and some aircraft pitching. The navigator reported light turbulence in clear weather and doppler winds from 250 degrees at 75 knots, decreasing to 50 knots downstream of the mountains. The second pass, Event 5/6, was at a slightly higher 63,800 feet, and again showed long-wave temperature changes. This time, however, moderate turbulence was reported, as shown by the ±0.5 g excursions of the accelerometer trace and the high-frequency airspeed fluctuations. One gust measured 15 knots indicated airspeed, corresponding to a true longitudinal gust velocity of over 80 ft/sec. Doppler winds at the flight level were 45 knots from 250 degrees.

The winds and temperatures obtained from the 0000Z, 1 February, 1969, Albuquerque rawinsonde data, are shown in Figure 10. The wind direction at all levels was almost normal to the Sangre de Cristo Mountains. Based on the wind data, the sonde was estimated to have crossed the range at about 100 mb. The variations in temperature data above this level could have been caused by the sonde rising through lee waves (as in Fig. 5). The amplitude of these fluctuations, corrected for the time constant of the thermistor, was about 6°C, similar to that recorded by the aircraft. Assuming an isothermal undisturbed stratosphere, the lee wave amplitude necessary to cause this temperature variation via adiabatic vertical motion is about 2000 feet.

The waves in the aircraft temperature data appear to be made up of two major harmonics. These were estimated to have lengths of 30 and 15 nautical miles for Event 2, and 22 and three nautical miles for Event 5/6, based on the ground speeds and directions given in the navigator's data log. In both cases the longer wave appeared to contribute the major portion of the total amplitude. The times required for the air to traverse the longer waves were estimated to be 1600 seconds for Event 2, and 1800 seconds for Event 5/6. The amplitude of the longer waves was estimated to be 1500 feet so that, for a period of 1700 seconds and assuming sinusoidal motion, the vertical velocity amplitude would have been about 5 ft/sec at this frequency.

The turbulence in Event 5/6 occurred when the temperature was above the local average, that is, in the trough of the longer wave.

2.2 Flight 3, 3 Feb. 1969 - Events 1 and 2 (Fig. 11 to 14)

The only two events of Flight 3 occurred at 63,000 feet over the mountains northwest of Denver (Fig. 13). Traces from Event 1 (Fig. 11) show sudden aircraft pitching and a very rapid climb of 900 feet in 12 seconds. Solution of the gust equation given in Reference 1 indicates that the aircraft encountered ascending and descending air velocities exceeding 20 ft/sec, with increases in static temperature accompanying the descending air. This suggests that wave activity contributed to pilot or autopilot inputs that resulted in the sudden climb and aircraft pitching.

The winds over the area of the events were westerly at all levels, that is, normal to the mountain ranges (Fig. 14). Unlike the events of Flight 2, it was not possible to find a rawinsonde ascent for the immediate area of the events. The closest was from Grand Junction and reached the 63,000-foot level about 90 nautical miles to the southwest of the location of the events.

The aircraft-measured static temperature data indicate the presence of lee waves. In Event 1 there appear to be two waves superimposed, one 5 nautical miles long and the other 19 nautical miles. Both waves had temperature amplitudes close to 3°C, which is equivalent to lee wave amplitudes of about 1000 feet. Using the aircraft wind data and assuming sinusoidal wave forms, the vertical wind components were estimated to have been 20 ft/sec and 5 ft/sec for the five and 19 nautical mile waves respectively.

2.3 Flight 5, 7 Feb. 1969 - Events 2 and 5 (Fig. 15 to 18)

The upper air data (Fig. 18) and flight track (Fig. 17) show that these events occurred in strong west to south-westerly flow in the vicinity of mountains.

Event 2 was recorded at 50,000 feet while outbound from Albuquerque and to the lee of the Jicarilla Mountains. Doppler winds were reported to be from 250 deg at 115 knots. The static temperature trace (Fig. 15) shows 8°C changes occurring with a wave length of about 30 nautical miles. The long wave length can be expected from the theoretical studies discussed by Queney et al. in Reference 6. These studies demonstrated that the shorter lee waves in the stratosphere are subject to large damping, and therefore do not usually occur more than one or two wave lengths downstream of a ridge line.

The temperature trace from Event 5 (Fig. 16) shows a complex wave-form with rapid temperature changes exceeding 10°C. These probably resulted from a combination of two or more large amplitude components of different wave lengths. The event occurred at 55,000 feet between two sets of mountains, the Manzano Range and the Pedernal Hills. This type of terrain can cause considerable amplification of the lee waves if the spacing and shape of the mountains are similar to the resonance waveform in the lower atmosphere (Ref. 7).

The amplitudes of the lee waves were estimated to be 1300 feet for Event 2, and a total of 2000 feet for the sum of both waves of Event 5. For the latter event, the maximum vertical wind speed was probably about 25 ft/sec. This estimate, based on the temperature and doppler wind data and a sinusoidal approximation to the wave, agrees well with solutions of the gust equation using the recorded aircraft acceleration and pitch data.

The navigator reported that the autopilot was disengaged from Mach hold during Event 5, although the precise moment of disengagement was not recorded on the data log. The pitching oscillations during this event suggest over-controlling by the autopilot in an attempt to maintain a constant Mach number in rapidly changing ambient temperatures. This may have caused the pilot to disengage the autopilot.

2.4 Flight 9, 10 Mar. 1969 - Event 2 (Fig. 19 to 21)

Figure 19 is an example of light turbulence encountered at 60,000 feet in the absence of both appreciable temperature change and mountainous terrain. The event was of 14 minutes duration, covering almost 100 nautical miles to the northwest of Houston (Fig. 20).

The 300-mb analysis for 11 March, 0000 GMT (Fig. 21), shows a jet stream just to the north of the event location. The maximum winds occurred at 35,000 feet and were only 35 knots at flight level. There was very little vertical wind shear at 60,000 feet, however the lapse rate given by the Victoria rawinsonde data indicated layers with stability less than usually associated with these levels. It is probable that the turbulence occurred within such a layer. The static temperature trace shows a very slow and small amplitude variation with time.

2.5 Flight 11, 19 Mar. 1969 - Events 4, 14, 16, 22, and 26 (Fig. 22 to 32)

As shown in Part 1 of this report, 27 events were recorded on this flight, the largest number of any flight to date. This mission was flown for a Royal Aircraft Establishment mountain wave project and was therefore directed into an area of anticipated lee wave activity. Several 100-mile legs were flown across the Sangre de Cristo Mountains on the 100° Vortac radial out of Alamosa, Colorado. Upwind and downwind segments were flown at 40,000, 45,000, 50,000, and 59,000 feet, with the last passes flown upwind at 62,000 feet and back at 40,000.

Nine events had level-flight temperature changes exceeding 2.5°C in 30 seconds, with six of these greater than 5°C in one minute. On another six events turbulence was recorded, but only one of these, Event 22, also showed the 2.5°C in 30-second change of temperature. The strongest and most persistent turbulence was encountered during the two passes at 50,000 feet.

The upper air data for Albuquerque and Grand Junction are shown in Figures 31 and 32. The winds over the area were normal to the Sangre de Cristo Mountains, and along the direction of the flight tracks.

The flight data for Events 4 and 22 (Fig. 22 and 28) show rapid increases in temperature. Event 4 occurred at 40,000 feet, almost over the crest of the mountain range (Fig. 23), and Event 22 at 62,000 feet just upwind of the crest (Fig. 30). The static temperature changed 12°C in five nautical miles at 40,000 feet, and 7°C in nine nautical miles at 62,000 feet. Vertical velocity amplitudes were estimated to have been 20 ft/sec and 5 ft/sec respectively. There was no turbulence during Event 4, although two other events at 40,000 feet showed very light turbulence downstream of the mountains. About two minutes of light turbulence were encountered at 62,000, coinciding with the temperature maximum shown in Event 22.

Events 14 and 16 (Fig. 24 and 26) were two long events of 14 and 19 minutes duration, both recorded at 50,000 feet. Event 14 occurred while the aircraft flew upwind towards the Sangre de Cristo range, ending just to the west of the crest (Fig. 25). Event 16 commenced about 10 miles downstream of the crest and continued to the eastern end of the leg and into a climbing turn to the next level (Fig. 27). Both events were marked by light to moderate turbulence, which occurred with the higher recorded temperature. The accelerometer record of Event 14 also showed a period of turbulence coinciding with the slowly increasing temperature. The wave length of these slow 6°C temperature variations was approximately 60 nautical miles. Since most writers suggest that long stratospheric lee waves dissipate slowly, it would seem that the long wave length temperature variations were due to lee waves. The turbulence could have been associated with the dissipation of the shorter components of the waves. The reduction in intensity of the turbulence in the half hour between the two passes would appear to support this conclusion.

Event 26 occurred at 40,000 feet (Fig. 29 and 30). It appears to have been caused by a 14-nautical mile lee wave of about 1500-foot amplitude and with vertical velocities of up to 10 ft/sec. It was the last event encountered during the last leg of this mountain wave flight, and occurred just over hills to the east of the Canadian River. It is possible that these hills amplified the lee waves caused by the main ridge of the Sangre de Cristo Mountains in a manner similar to that suggested for Event 5 of Flight 5.

2.6 Flight 16, 15 Apr. 1969 - Events 2, 6, and 7 (Fig. 33 to 38)

In Event 2 of Flight 16 (Fig. 33), considerable turbulence was encountered while slowly climbing above 52,000 feet. This was accompanied by rapid temperature changes between 53,000 and 55,000 feet. The slow drift in computed static temperature was a result of using a fixed average static pressure in the analogue computation while the aircraft was actually climbing. This produced an error of -3°C at the start and +3°C at the end of the computation.

The 50-mb analysis for 1200 GMT on April 15 (Fig. 38) shows a weak trough orientated north-south across the flight track. This trough extended down through the lower stratosphere and troposphere. The maximum winds occurred between 250 and 300 mb, but none of the rawinsonde stations near the track recorded winds in excess of 100 knots.

There is evidence of some short lee waves (four nautical miles long) in the temperature data for Event 2 during climb-out over the range of mountains to the west of Albuquerque. The amplitude of these waves was about 1200 feet, with vertical velocity variations of approximately 20 ft/sec. The period of oscillation for an air parcel passing through the wave was 300 seconds, which is very close to the Brunt-Viasala period for an isothermal atmosphere at -62°C.

The two turbulence events that occurred at 61,000 feet over the western portion of the flight track were both associated with slight rises in temperature (Fig. 34 and 35). The winds at flight level were low, 35 knots, and the rawinsonde data suggested that there was very little vertical wind shear at this level (Fig. 37). The winds below this level were generally parallel to the main mountain ranges. There were slight increases in static temperature associated with the turbulence, suggesting that it could have been associated with some form of wave action. The amplitude of these temperature variations was about 2°C and the turbulence occurred with the warmer temperatures.

3.0 ACKNOWLEDGEMENTS

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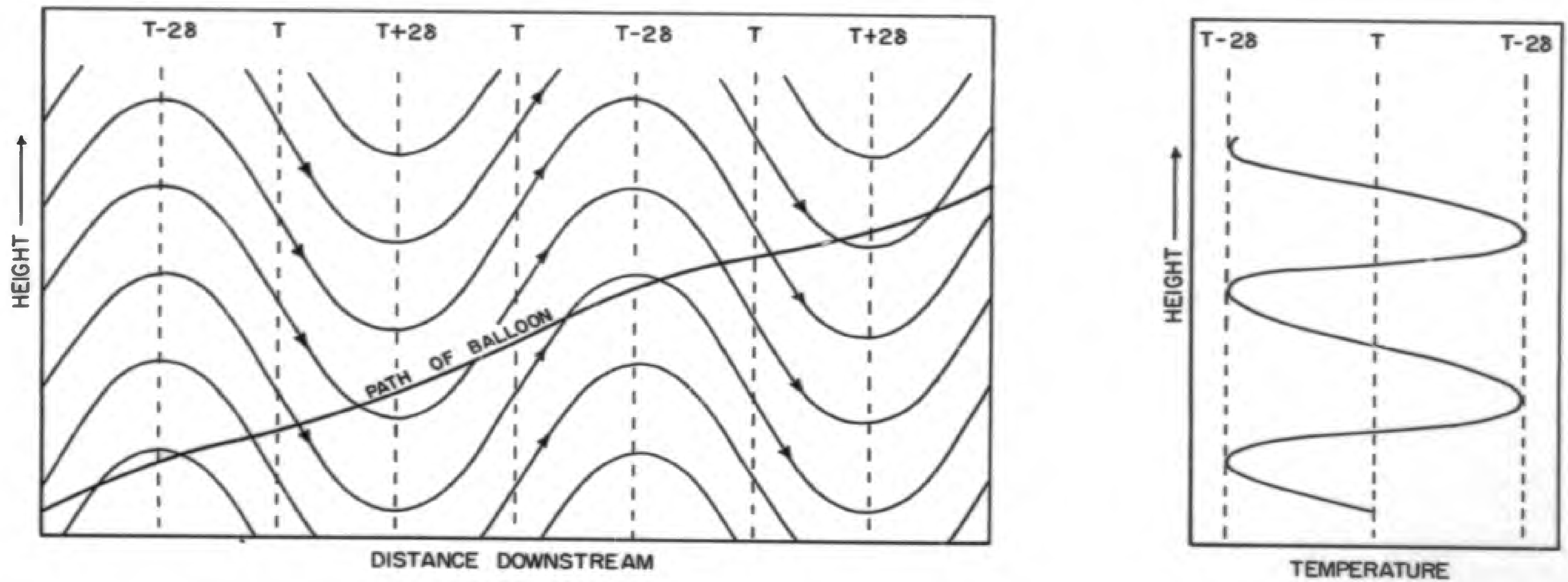

The undisturbed temperature T of the stratosphere is shown on the right together with the temperature vs height profiles recorded by the sonde as it rises along the path shown on the left.

FIG. 5: BALLOON SOUNDINGS IN STRATOSPHERIC LEE WAVES

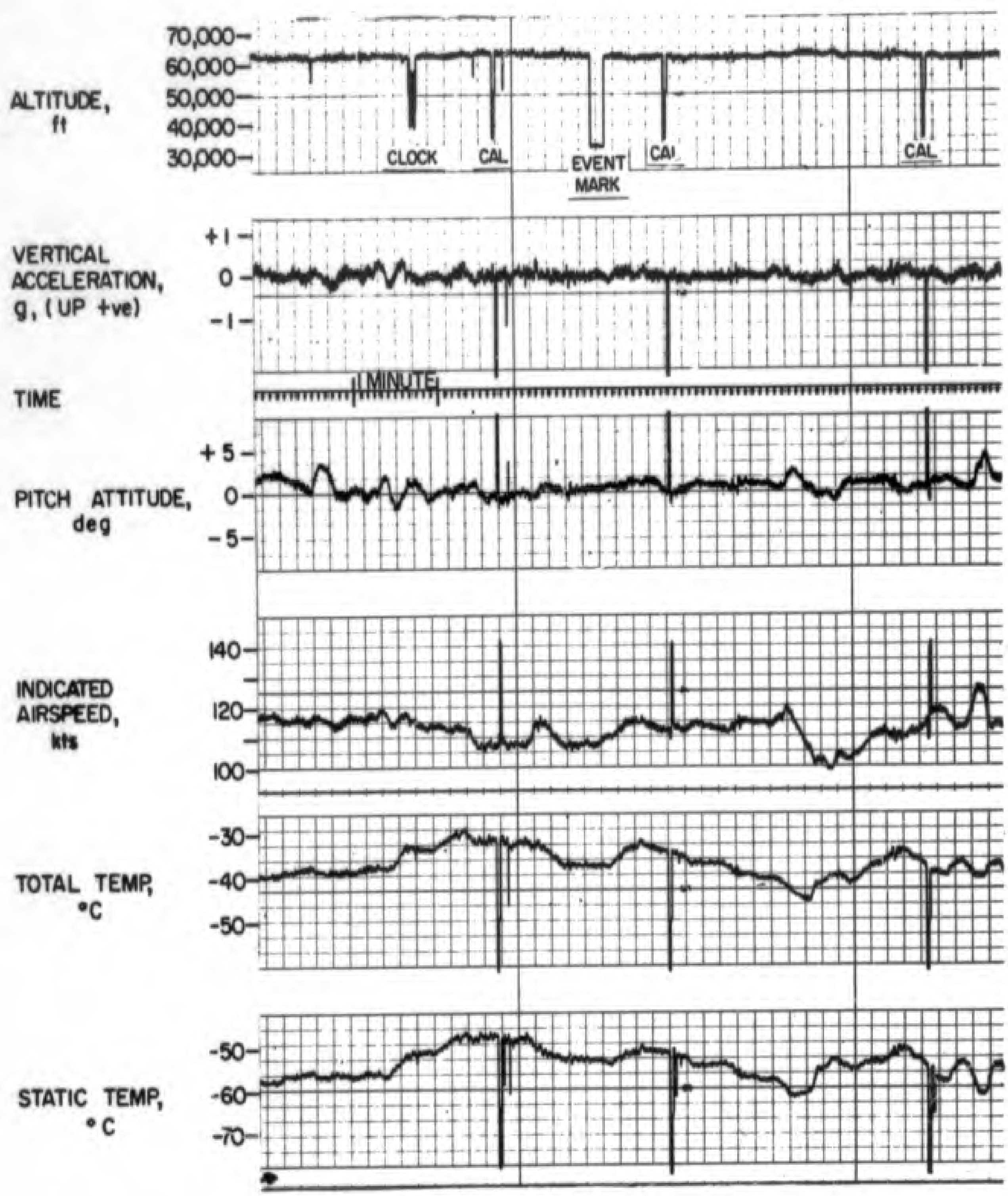

FIG. 6: FLIGHT 2, EVENT 2

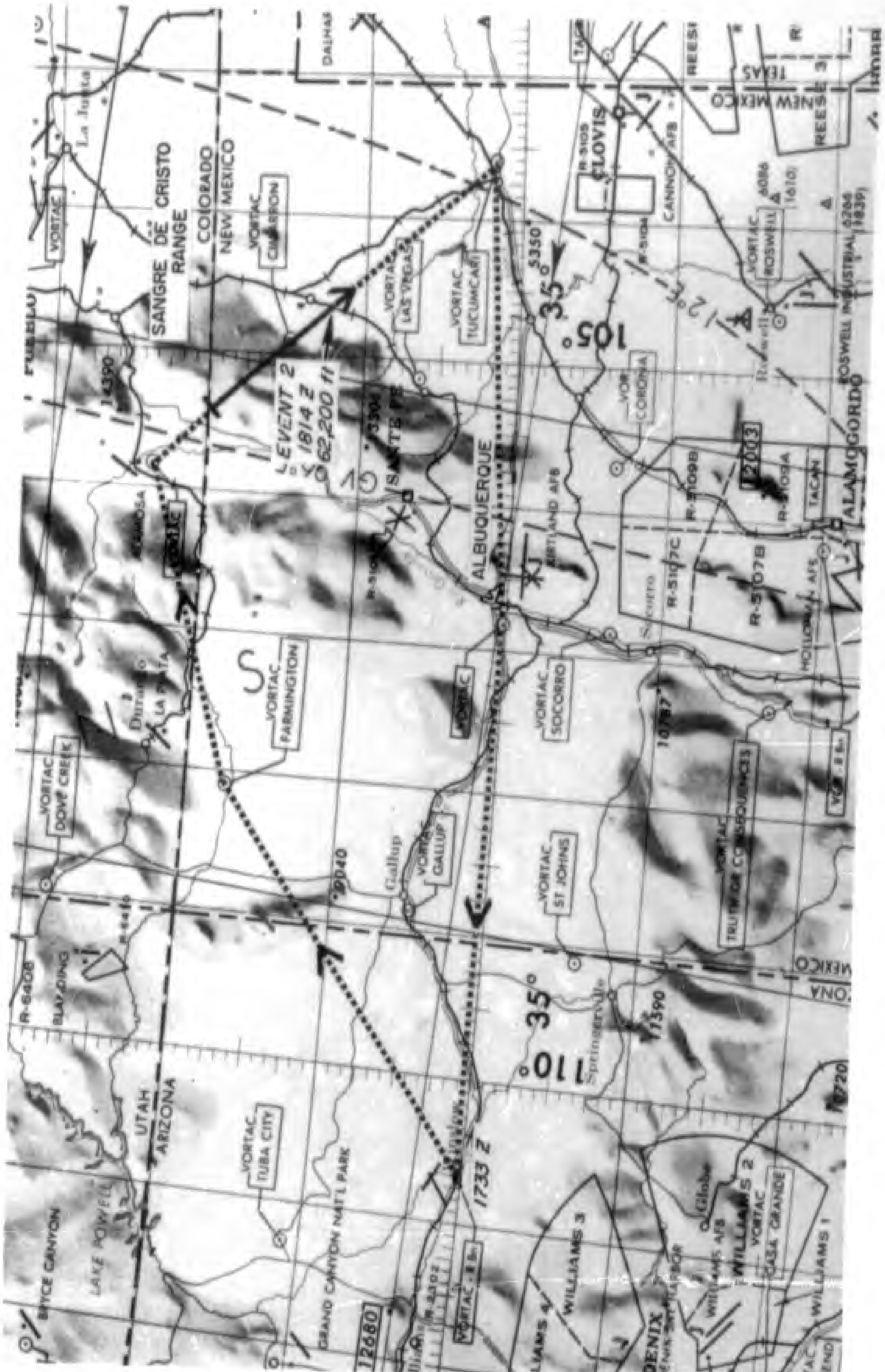

FIG. 7: FLIGHT TRACK SHOWING EVENT 2 OF FLIGHT 2, 31 JAN. 1969

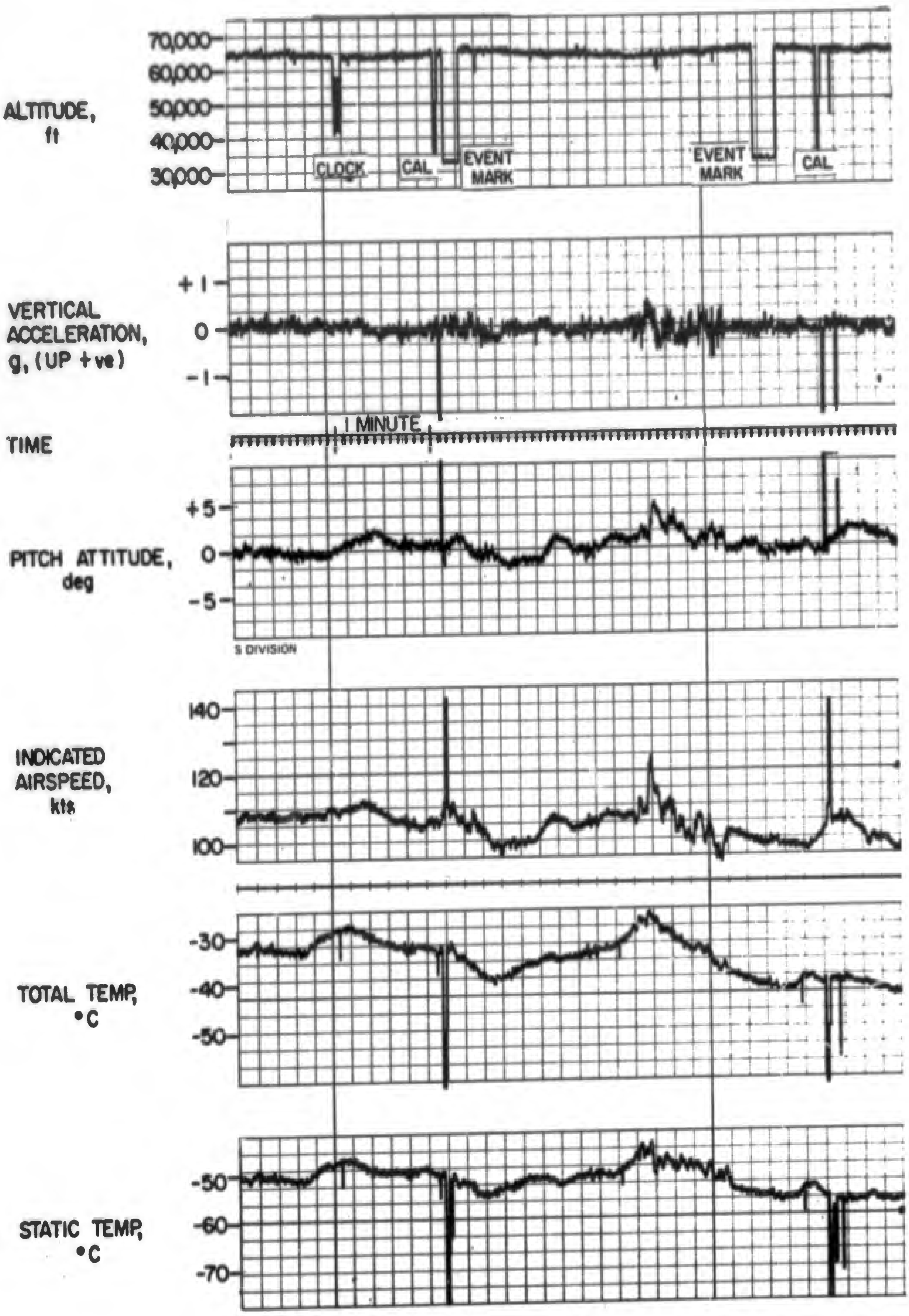

FIG. 8: FLIGHT 2, EVENT 5/6

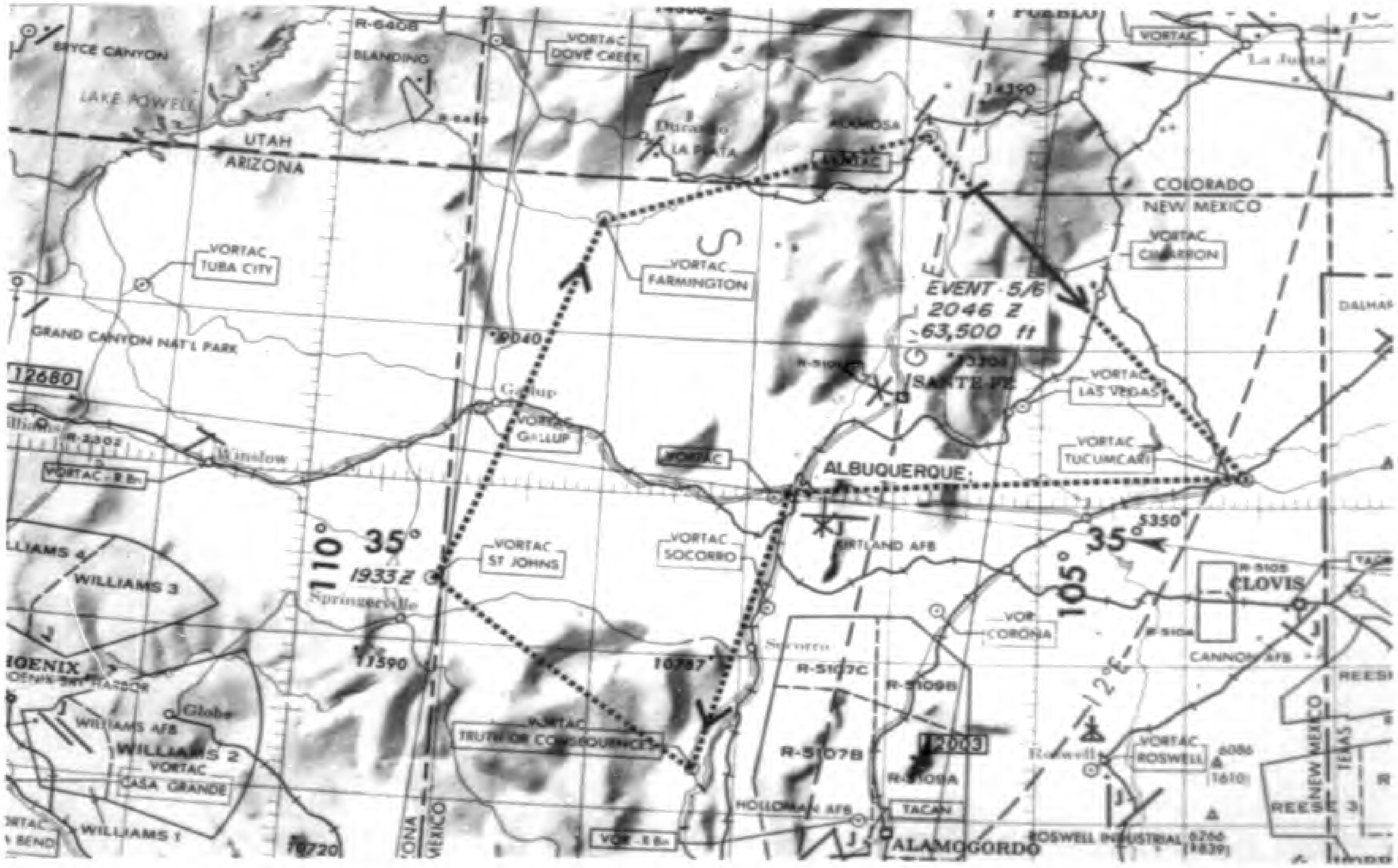

FIG. 9: FLIGHT TRACK SHOWING EVENT 5/6 OF FLIGHT 2, 31 JAN. 1969

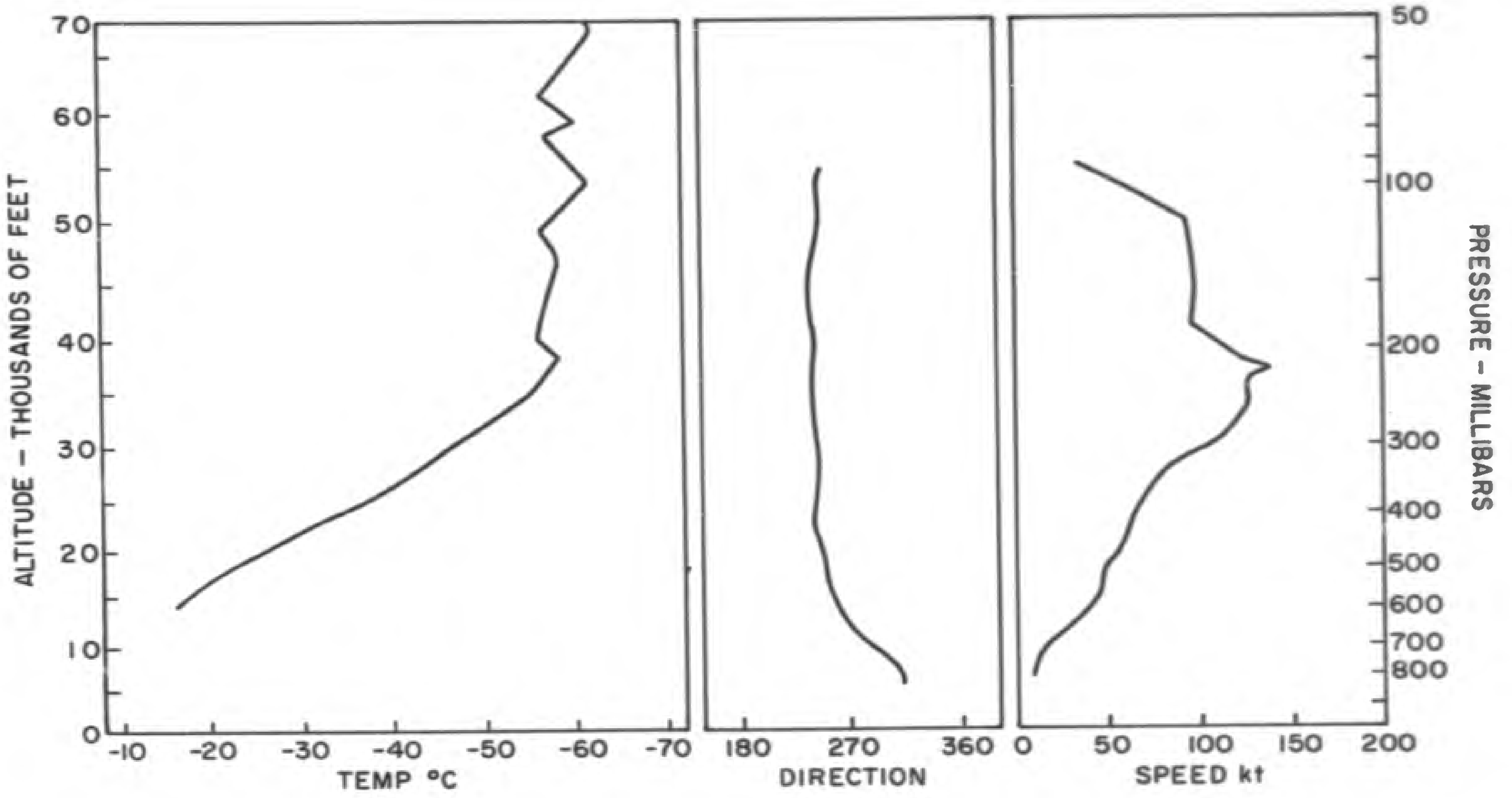

FIG. 10: UPPER AIR DATA

ALBUQUERQUE, N.M.

0000 GMT 1 FEB. 1969

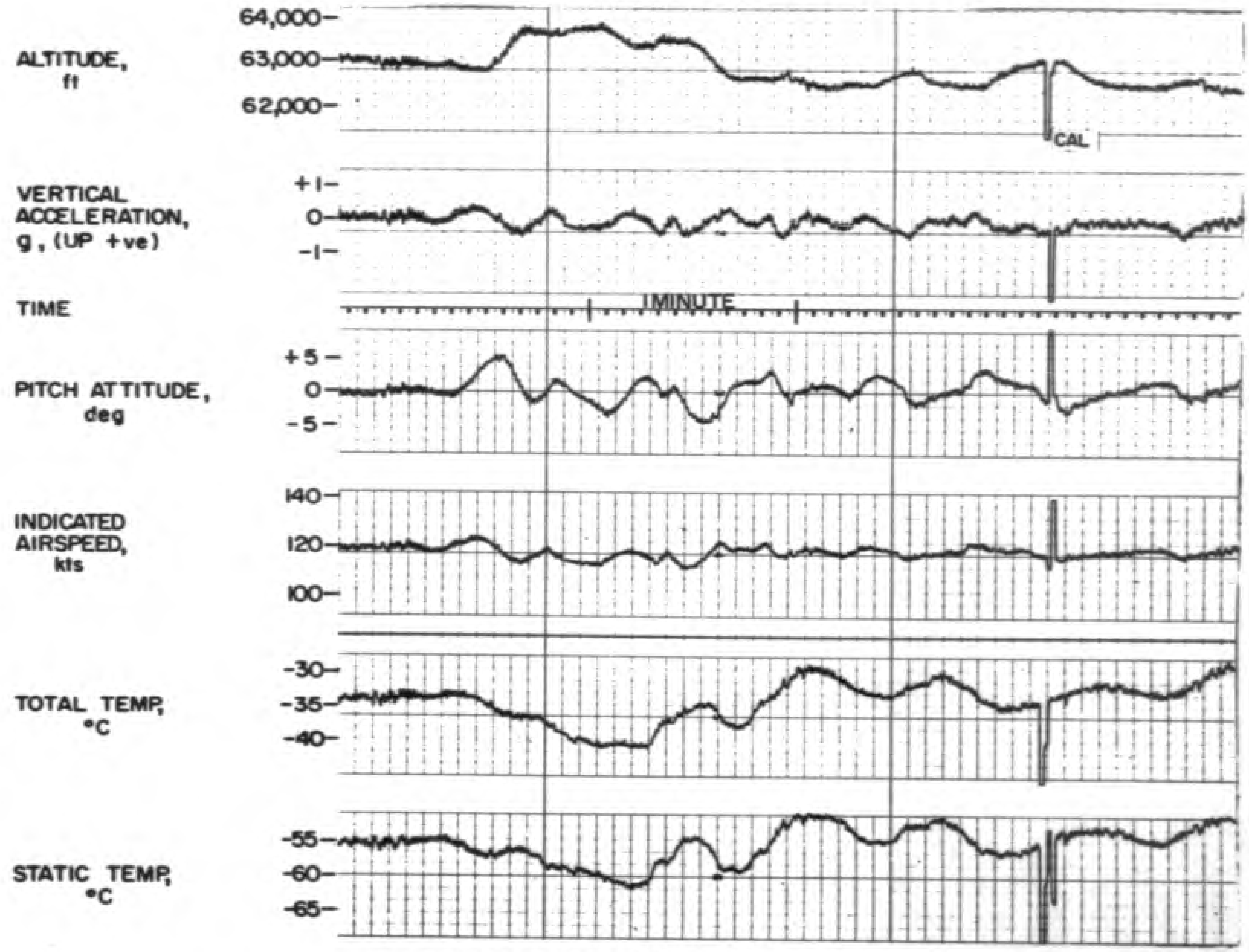

FIG. 11: FLIGHT 3, EVENT 1

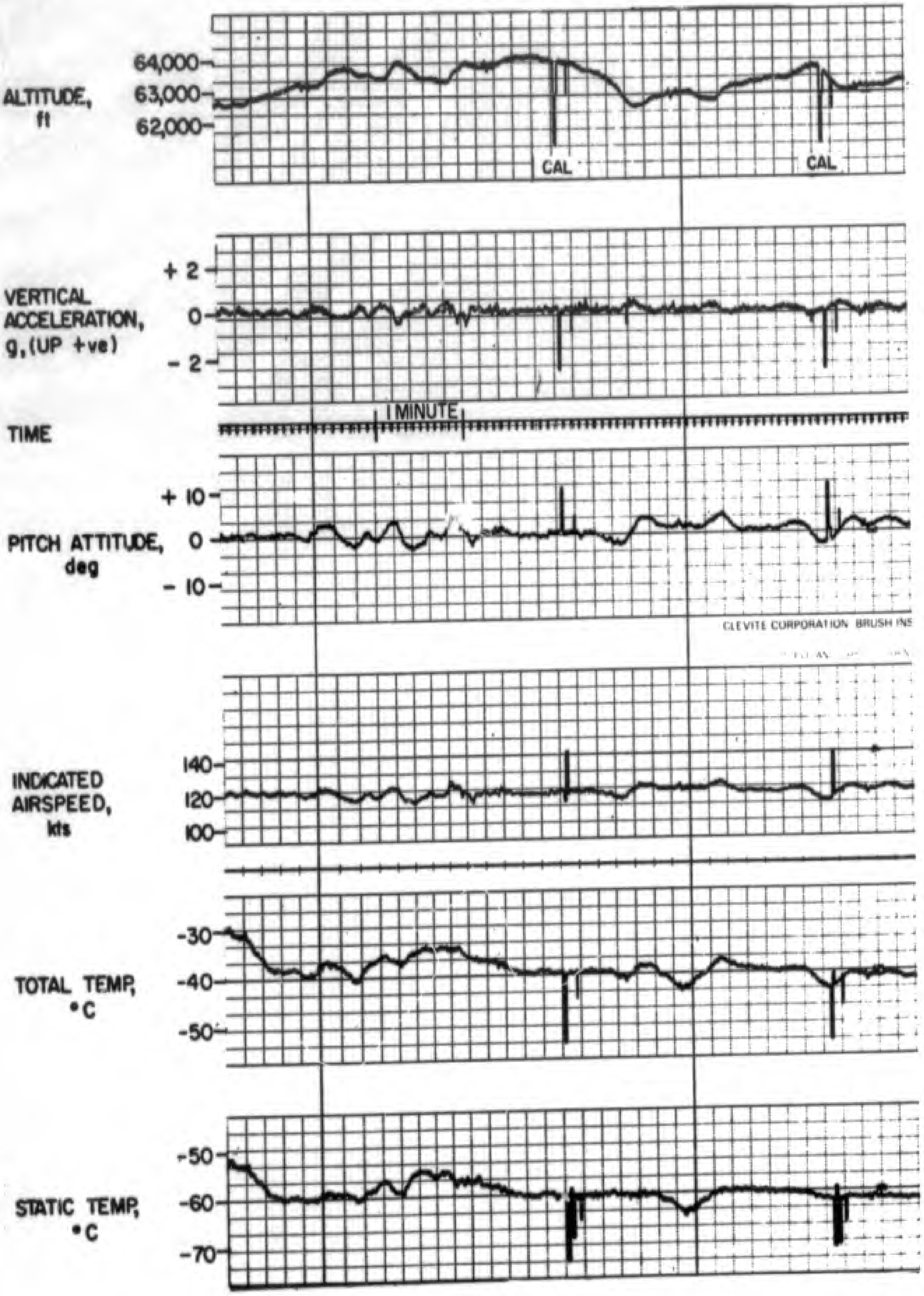

FIG. 12: FLIGHT 3, EVENT 2

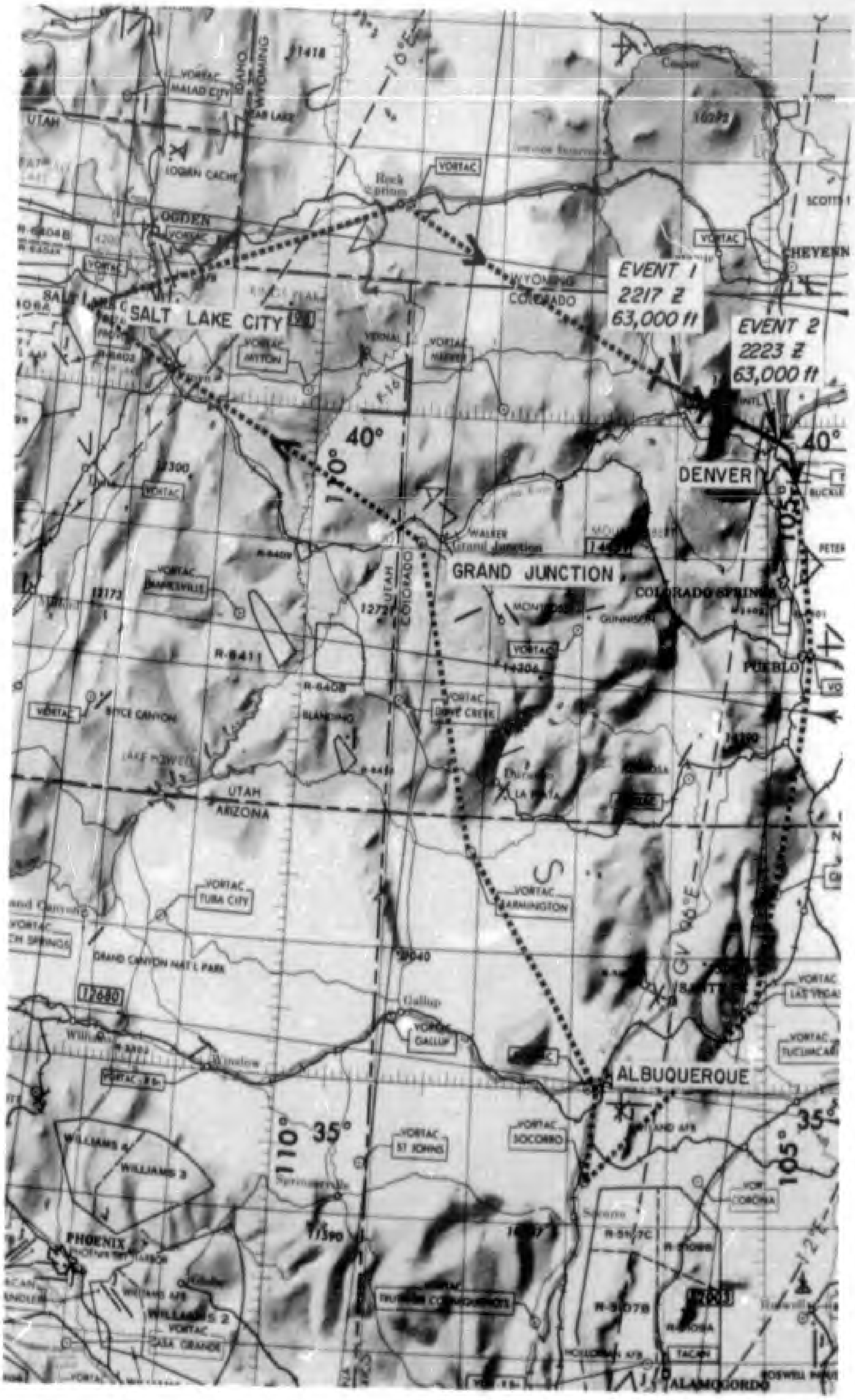

FIG. 13: FLIGHT TRACK SHOWING EVENTS I AND 2 OF FLIGHT 3, 3 FEB.1969

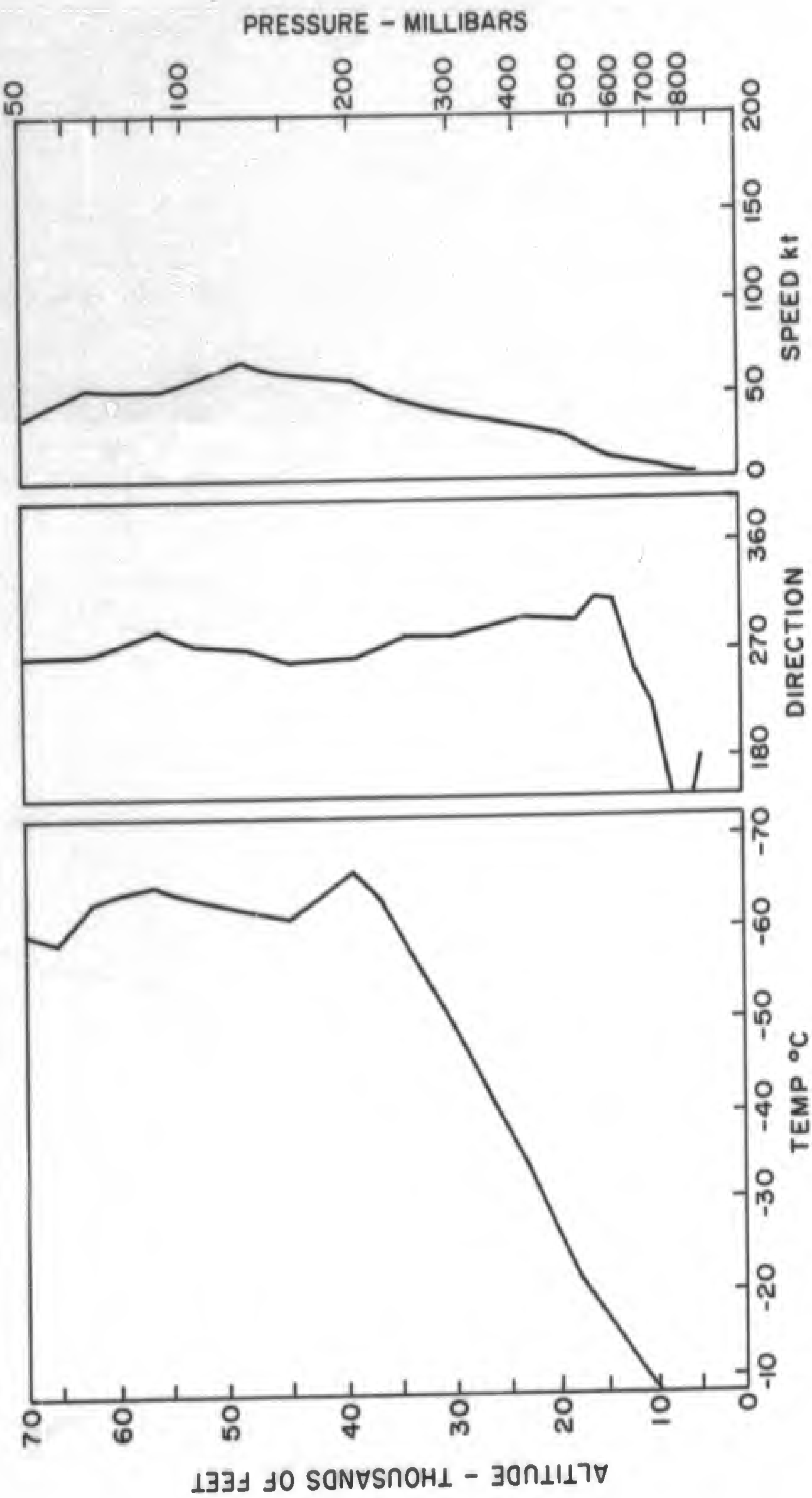

FIG.14: UPPER AIR DATA

GRAND JUNCTION, COLO.

0000 GMT 4 FEB. 1969

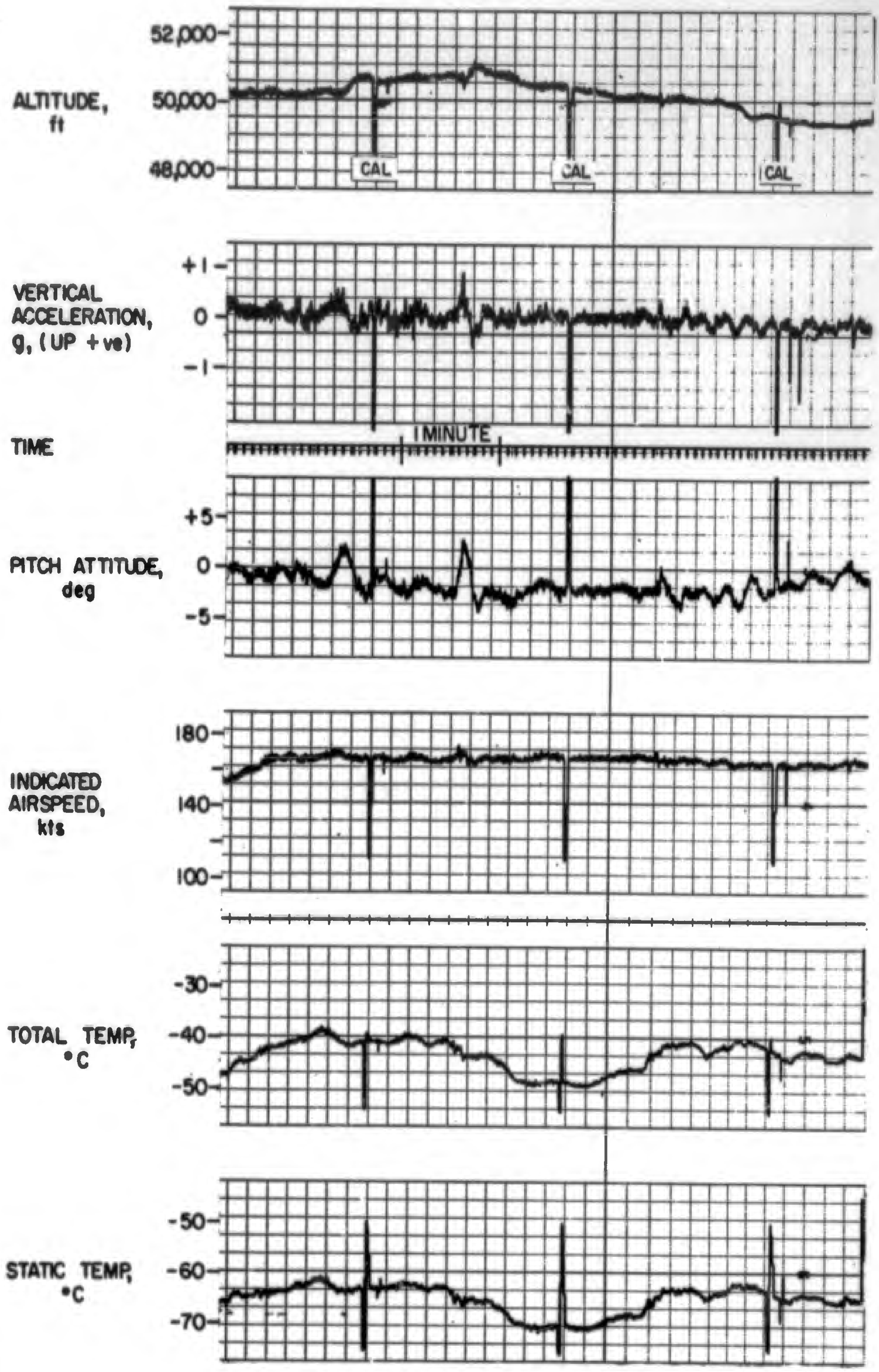

FIG. 15: FLIGHT 5, EVENT 2

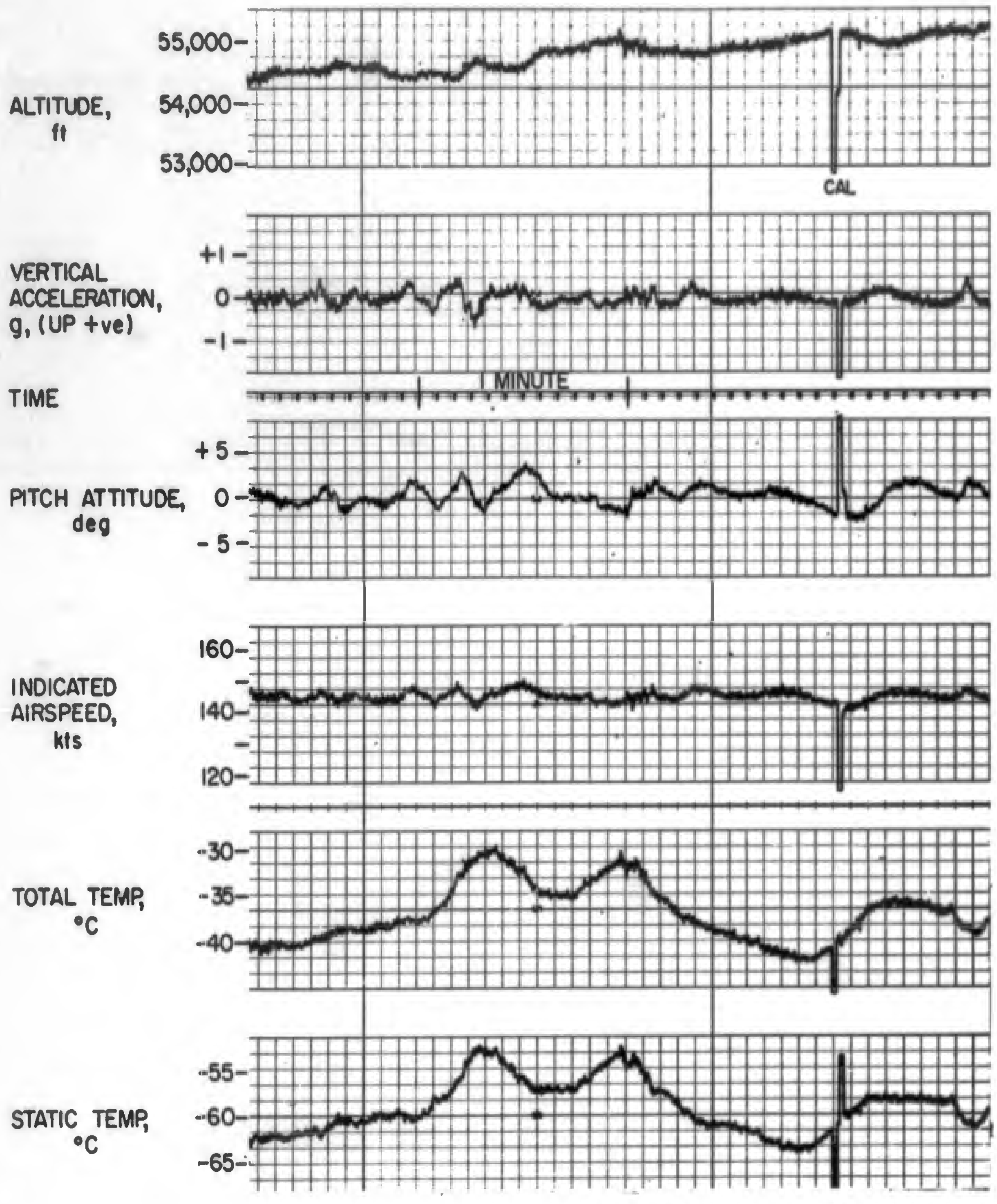

FIG. 16: FLIGHT 5, EVENT 5

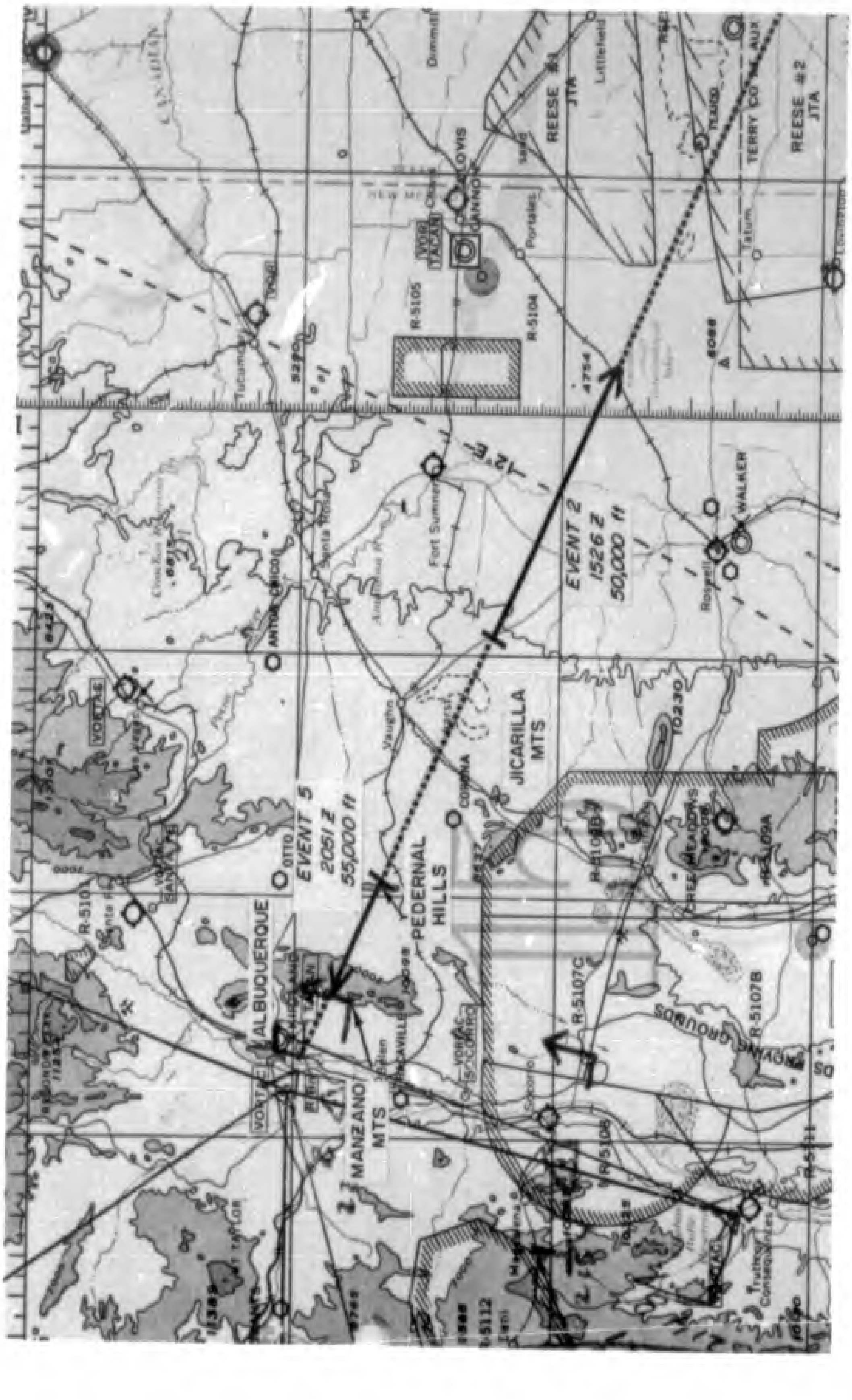

FIG. 17: FLIGHT TRACK SHOWING EVENTS 2 AND 5 OF FLIGHT 5, 7 FEB. 1969

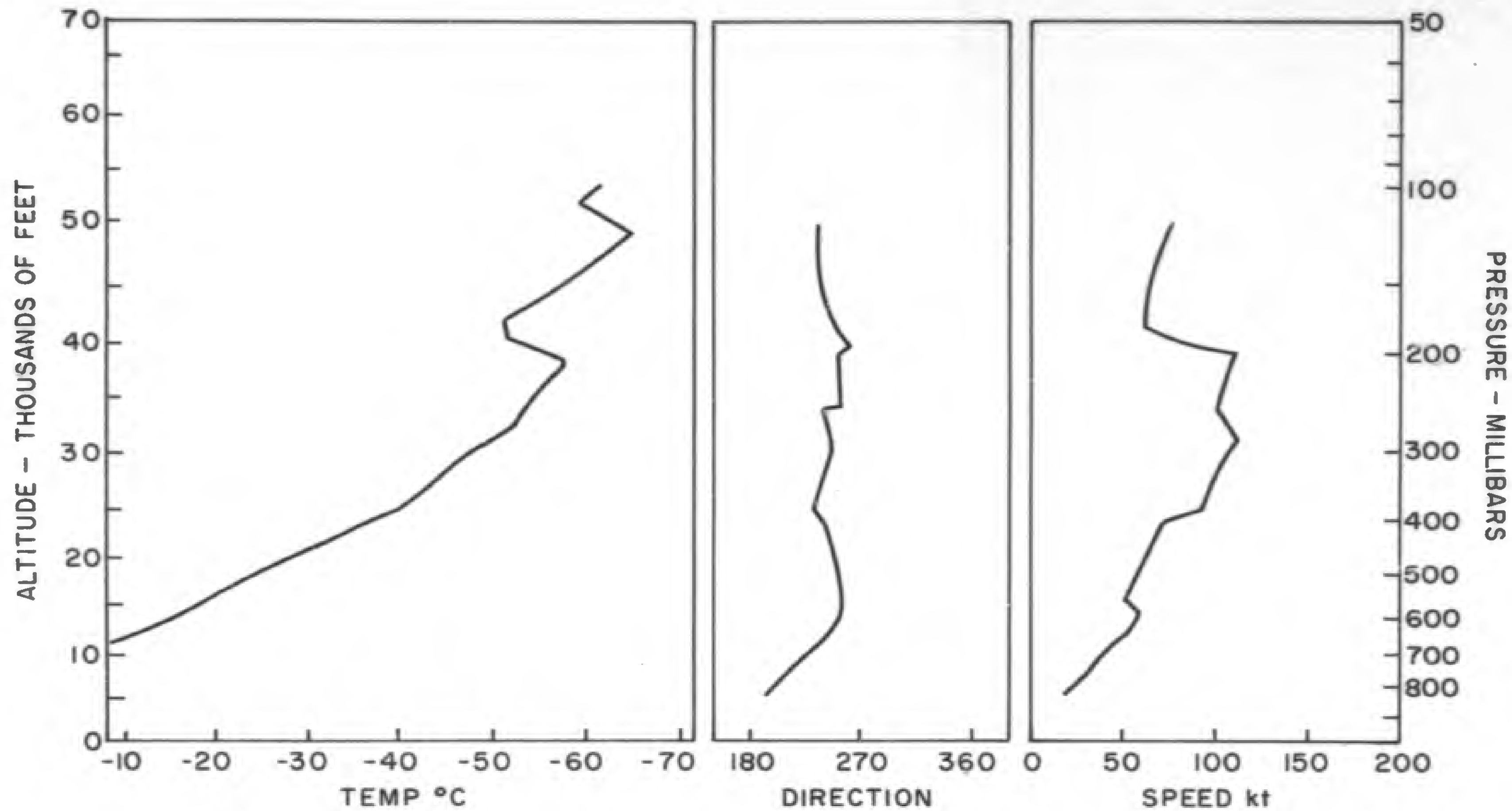

FIG. 18: UPPER AIR DATA

ALBUQUERQUE, N.M.

1200 GMT 7 FEB. 1969

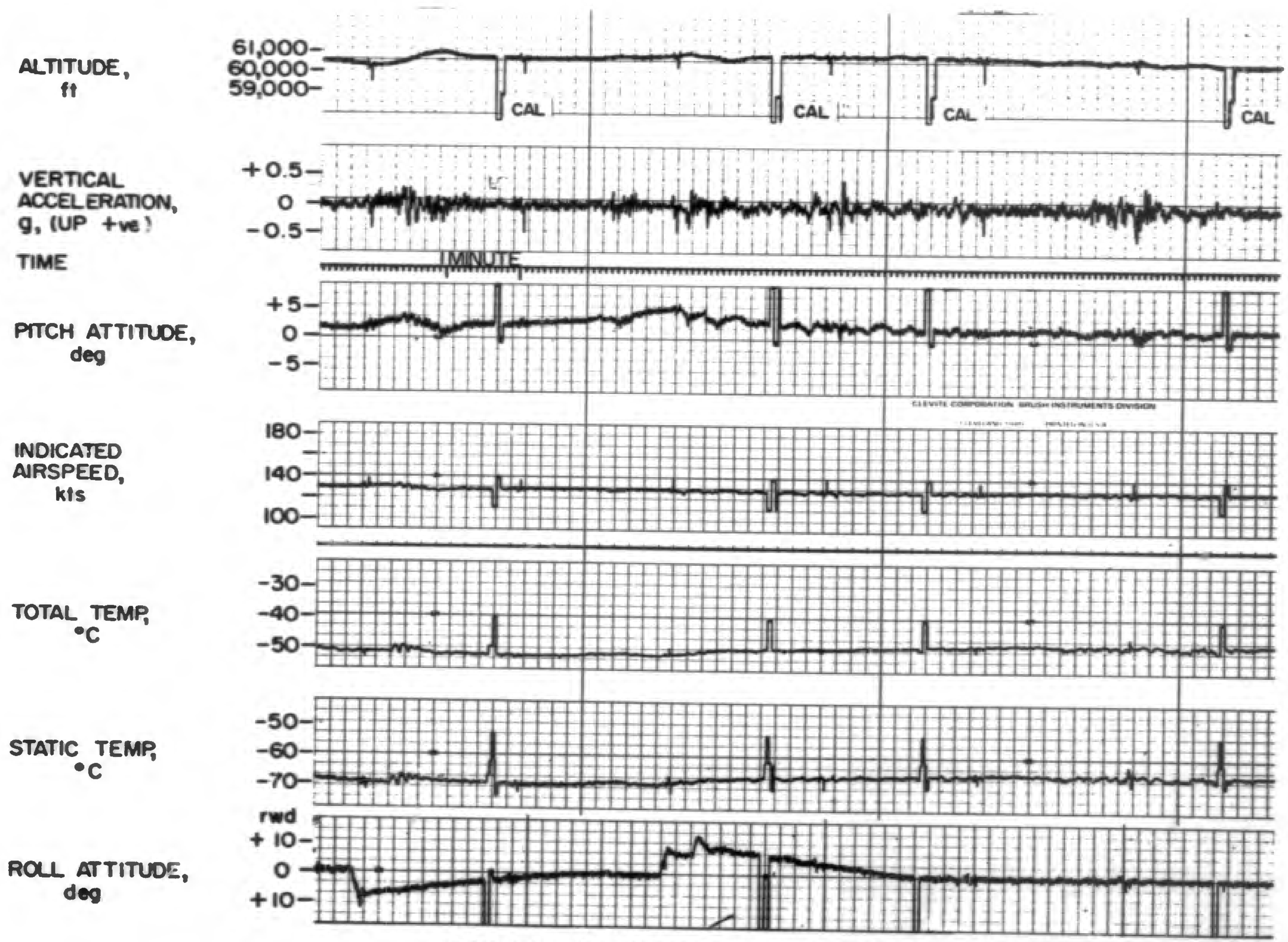

FIG. 19: FLIGHT 9, EVENT 2

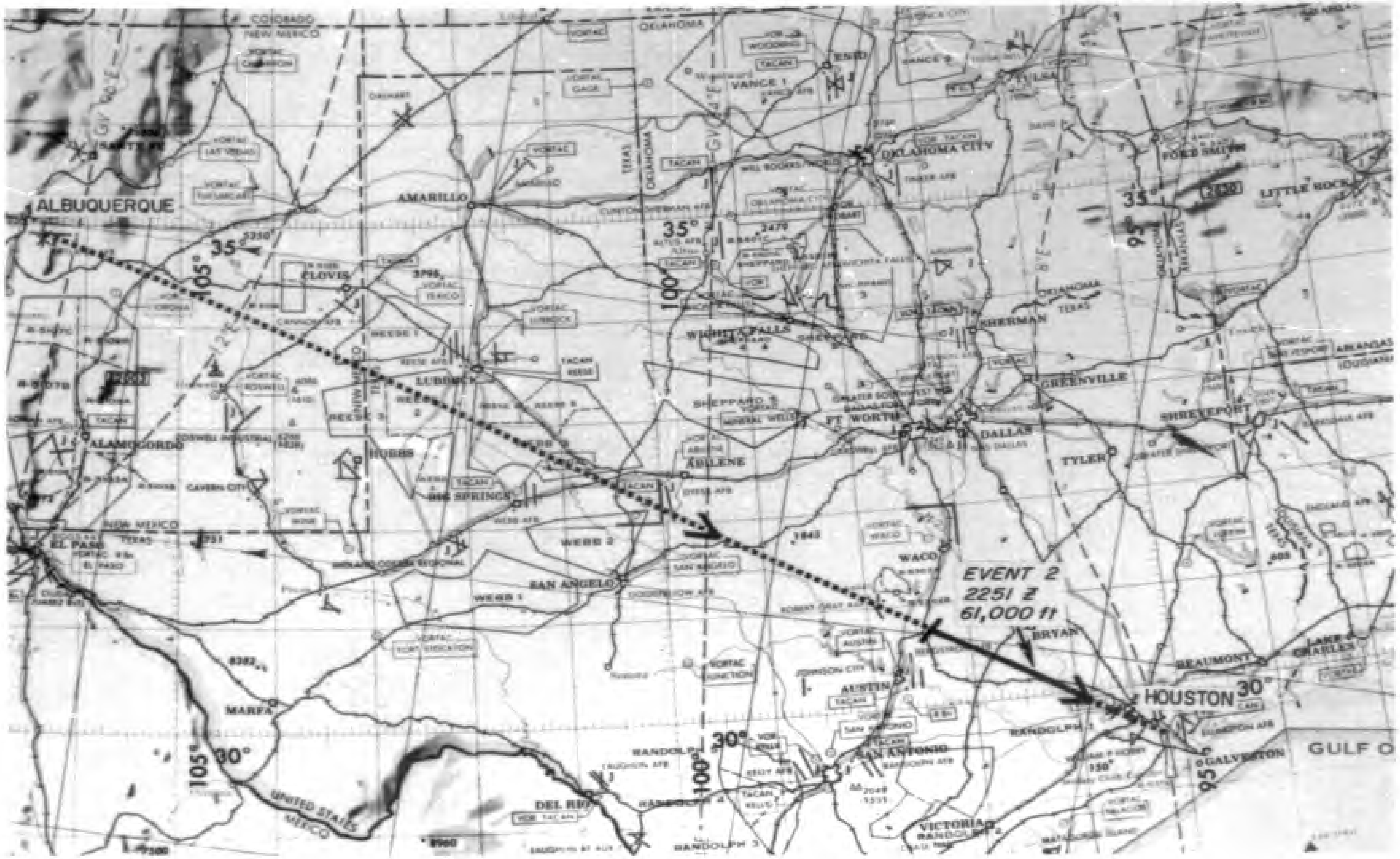

FIG. 20: FLIGHT TRACK SHOWING EVENT 2 OF FLIGHT 9, 10 MAR. 1969

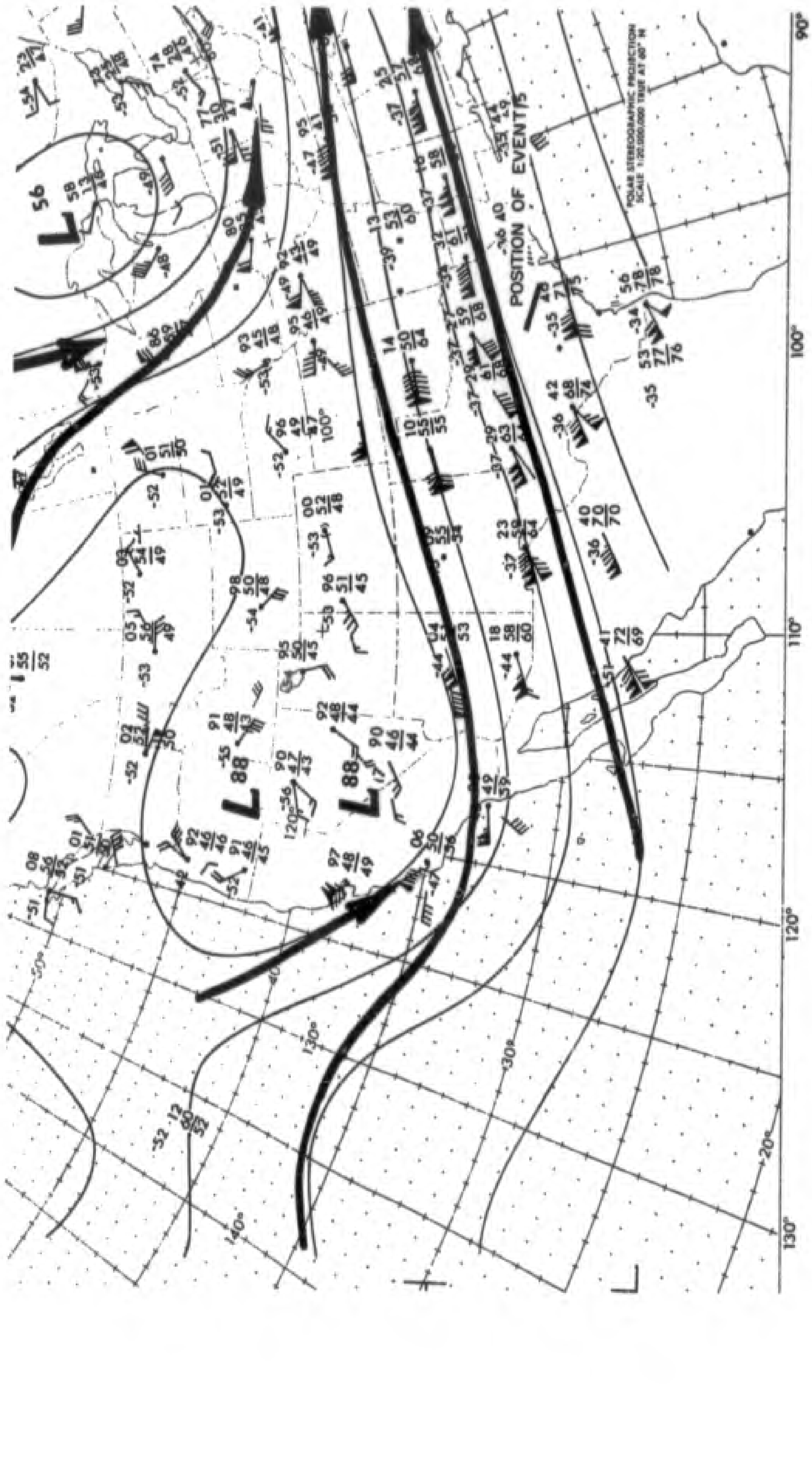

FIG. 21: 300-mb ANALYSIS, 0000 GMT, 11 MAR. 1969

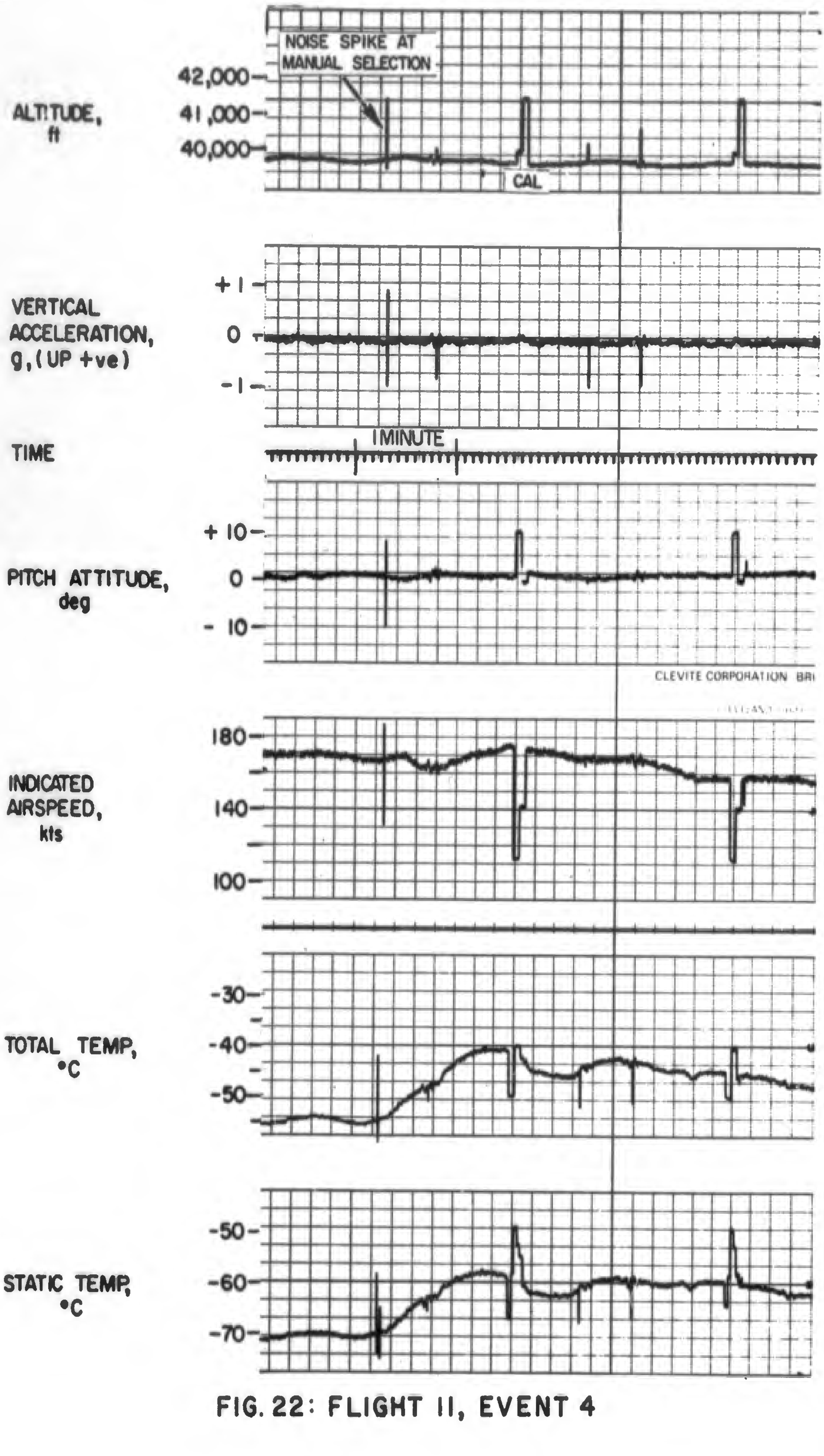

FIG. 22: FLIGHT 11, EVENT 4

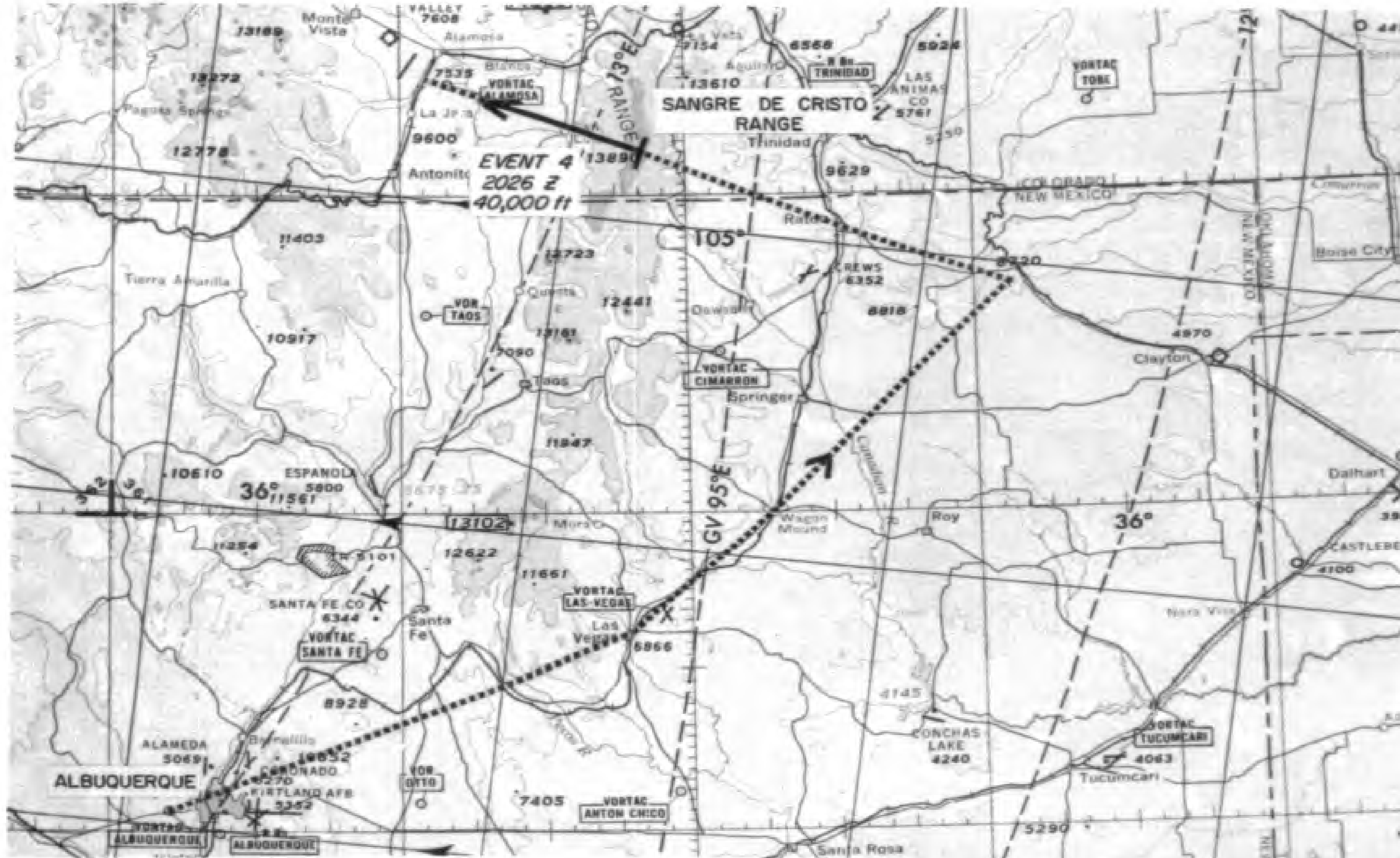

FIG. 23: FLIGHT TRACK SHOWING EVENT 4 OF FLIGHT 11, 19 MAR. 1969

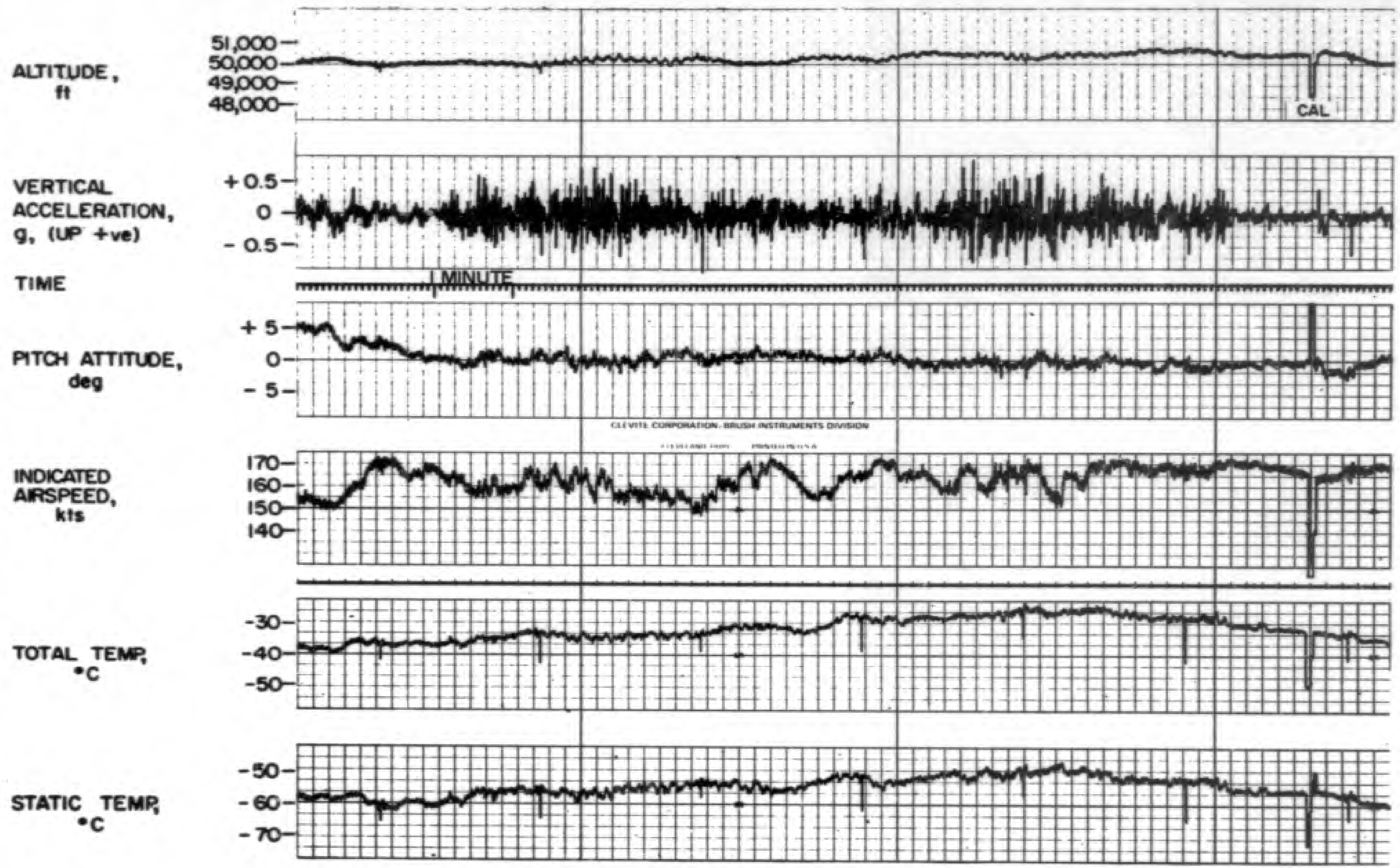

FIG. 24: FLIGHT 11, EVENT 14

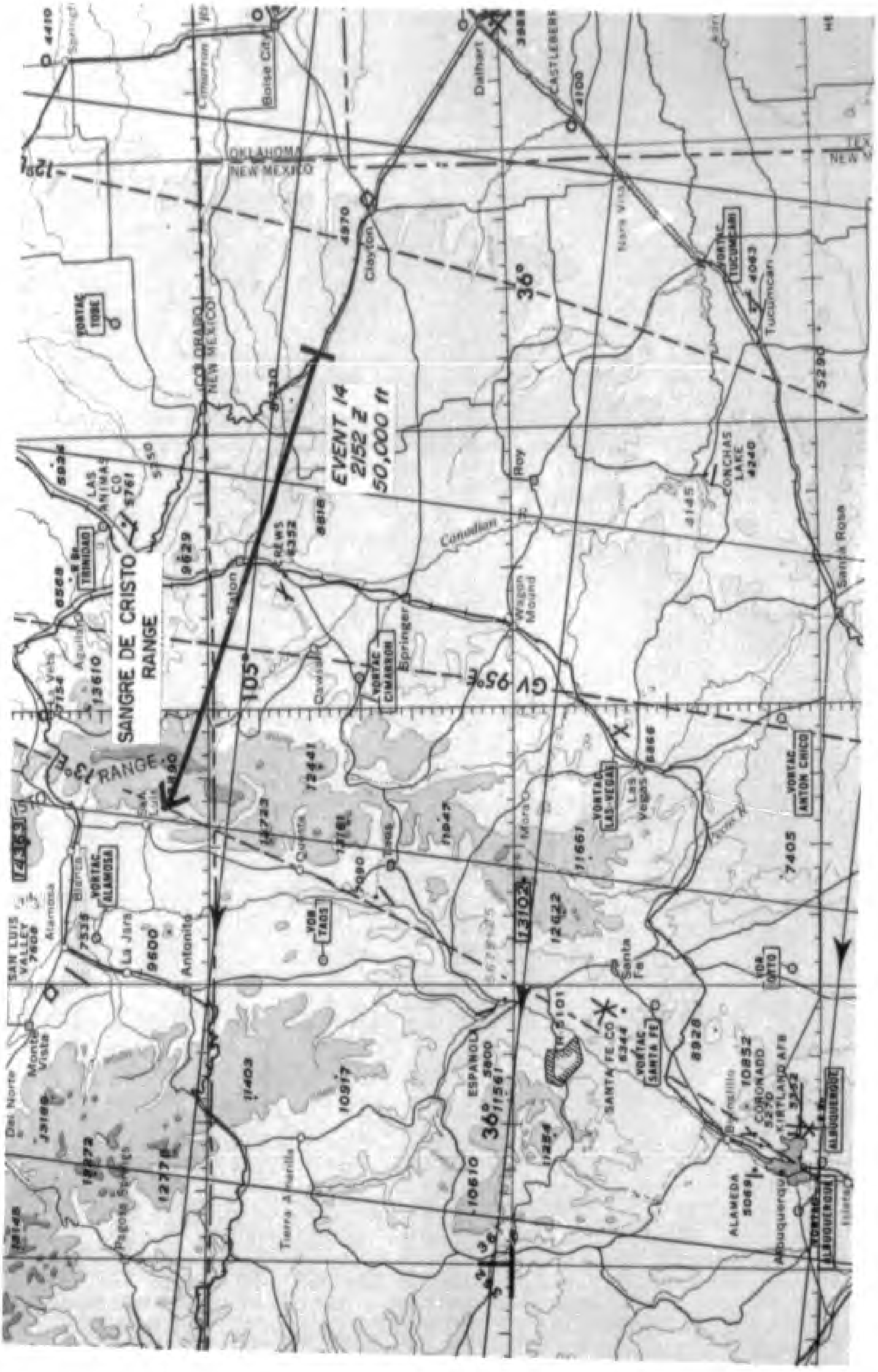

FIG. 25 : FLIGHT TRACK SHOWING EVENT 14 OF FLIGHT 11, 19 MAR.1969

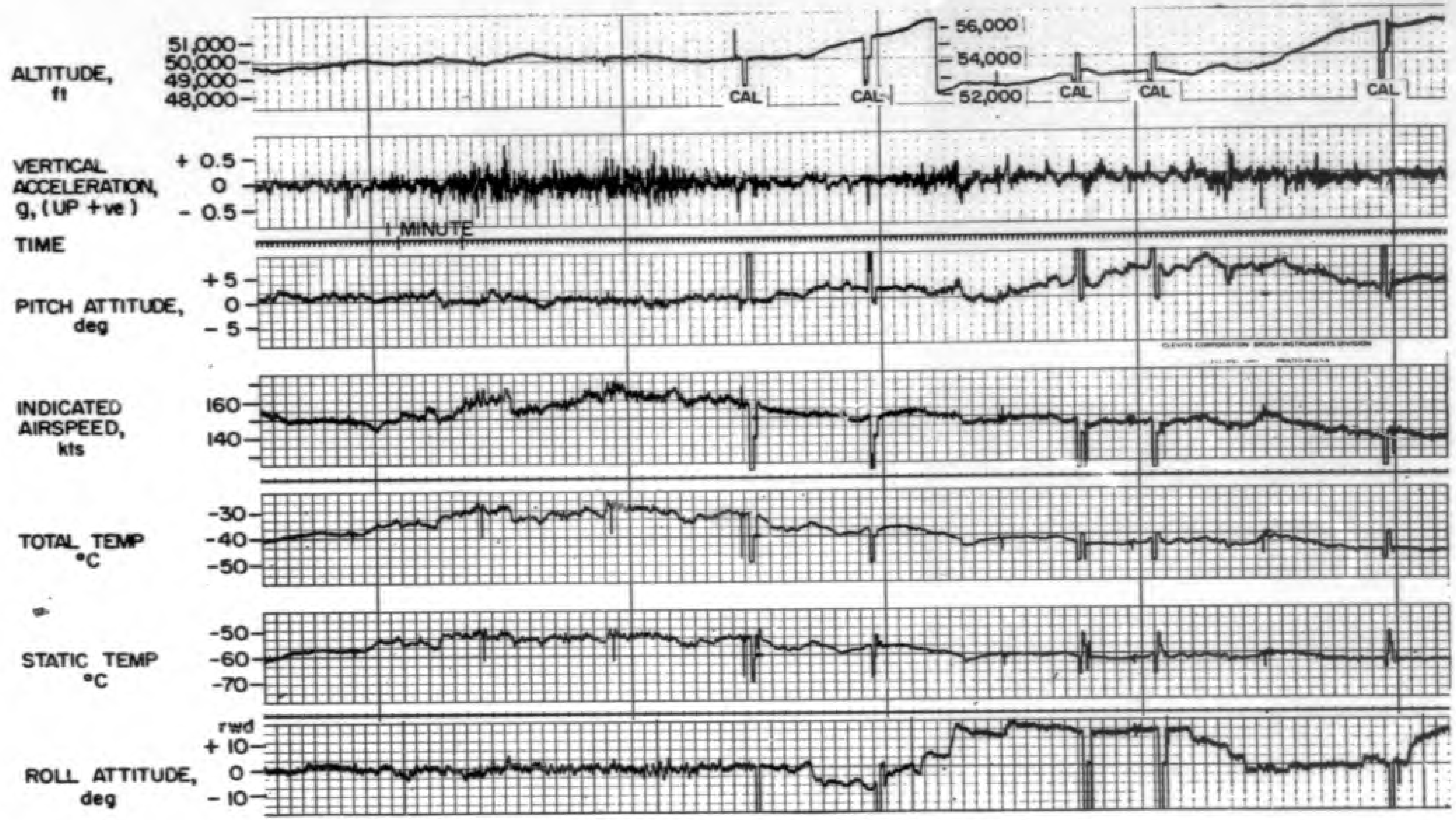

FIG. 26: FLIGHT 11, EVENT 16

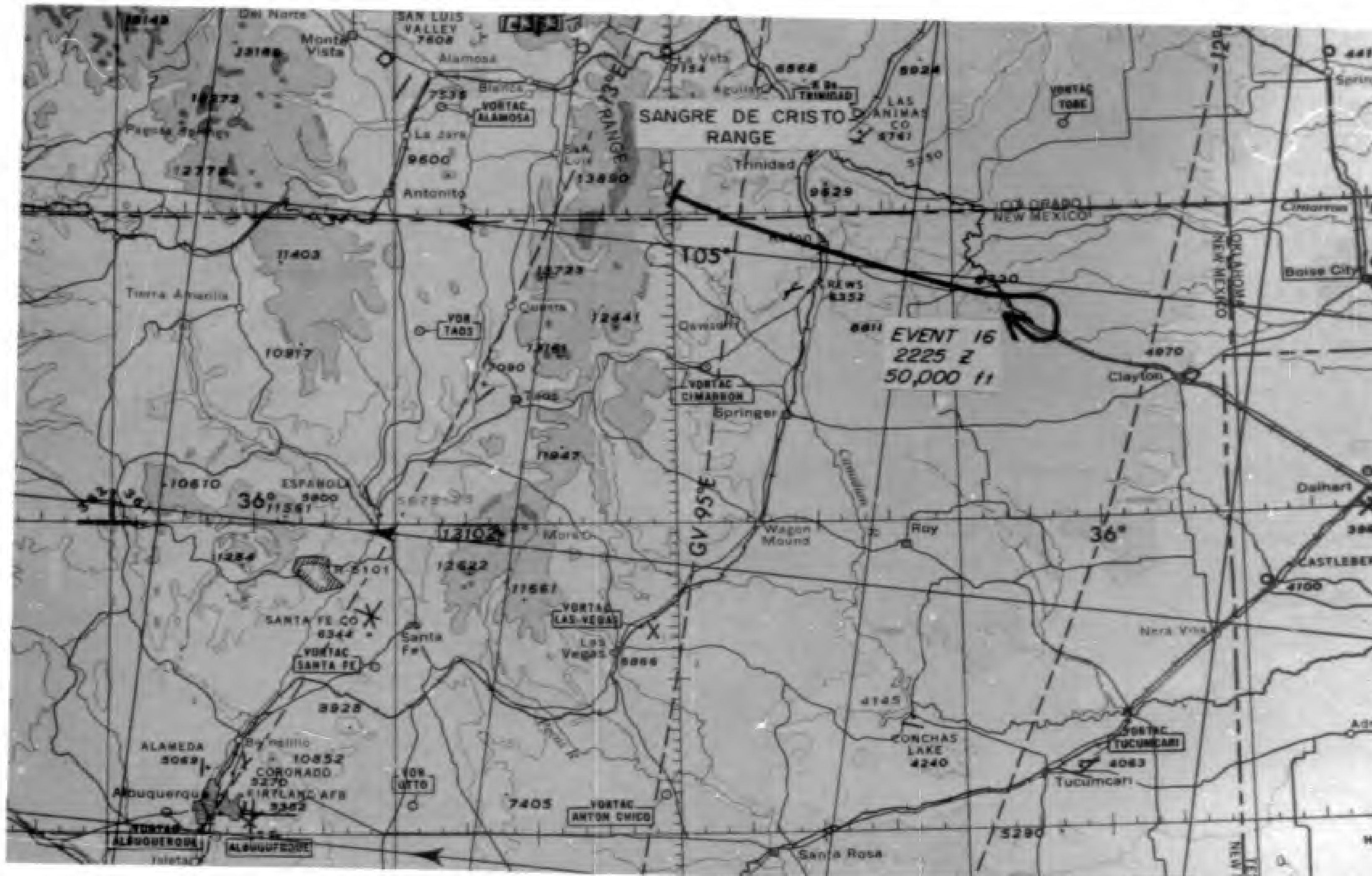

FIG. 27 : FLIGHT TRACK SHOWING EVENT 16 OF FLIGHT II, 19 MAR.1969

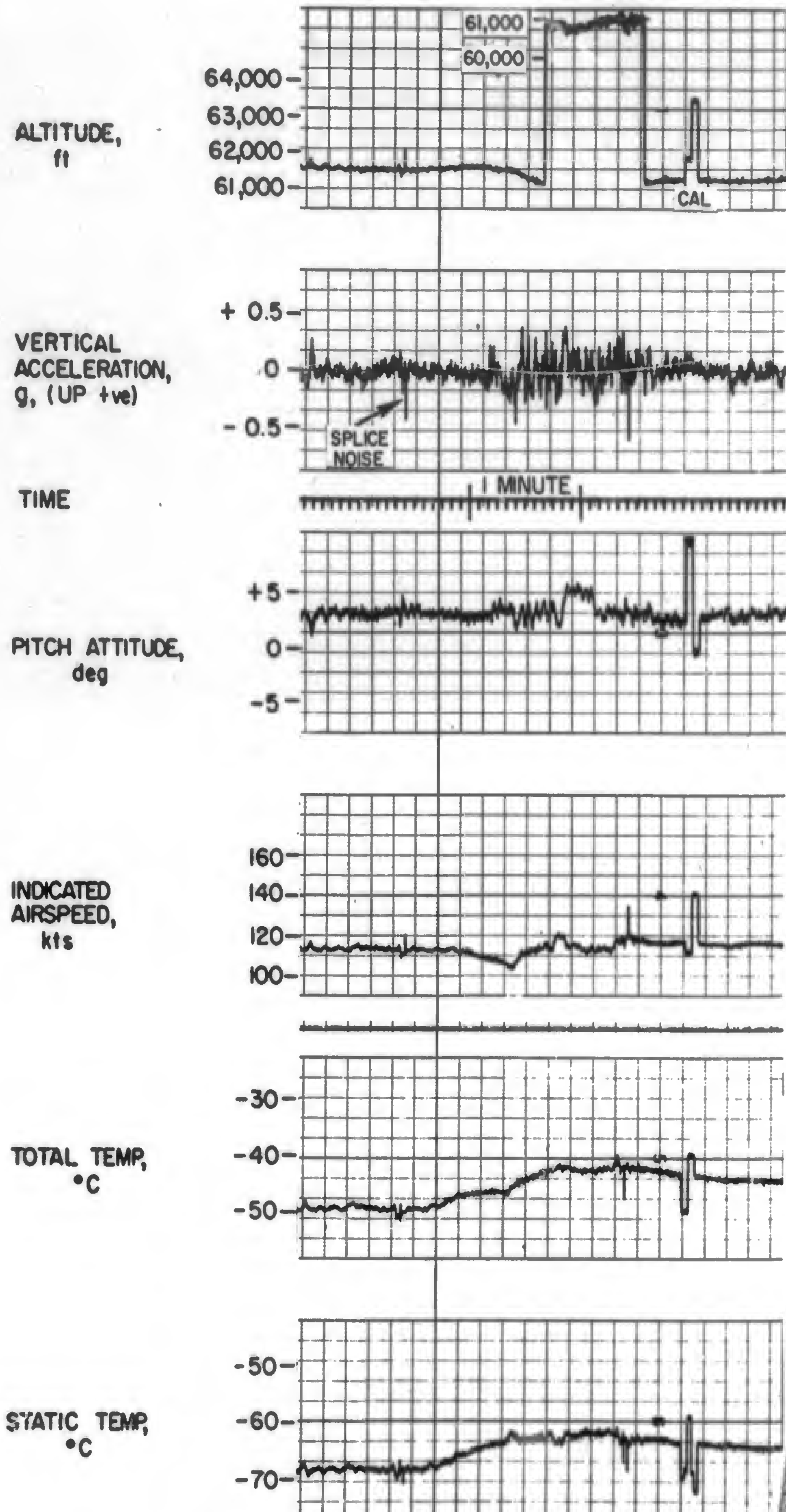

FIG. 28: FLIGHT 11, EVENT 22

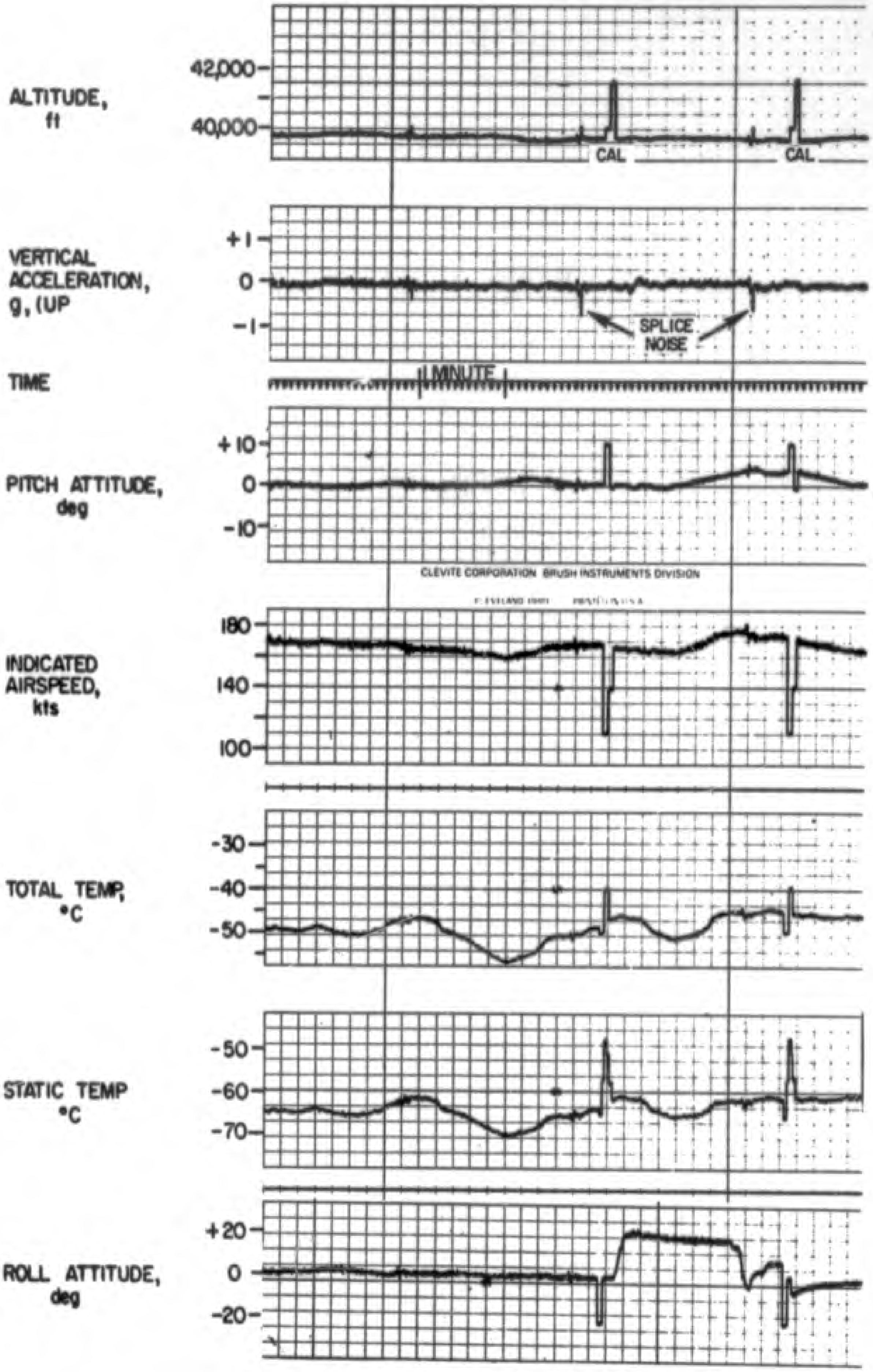

FIG. 29: FLIGHT II, EVENT 26

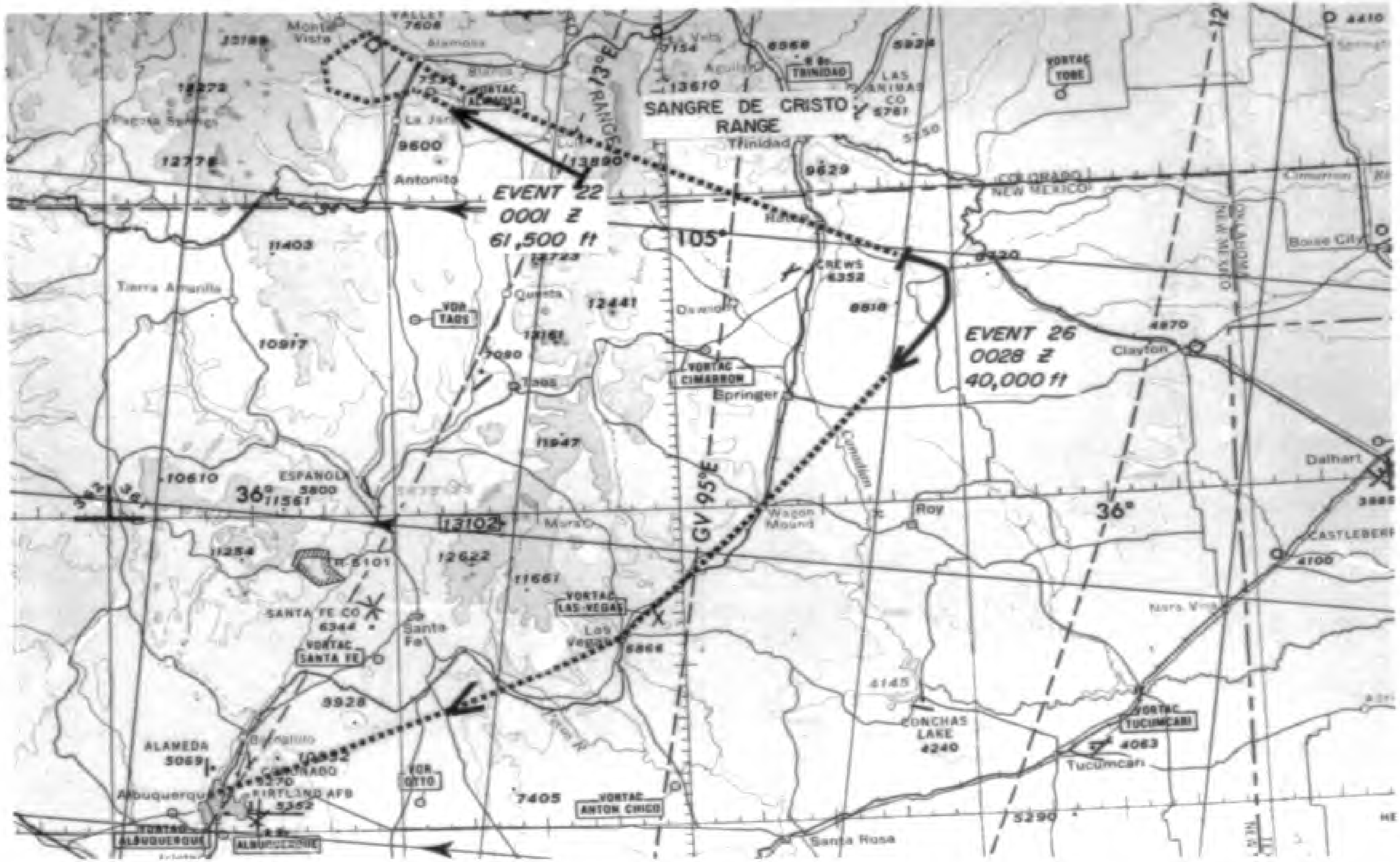

FIG.30: FLIGHT TRACK OF EVENTS 22 AND 26 ON LAST PORTION OF FLIGHT II, 19 MAR.1969

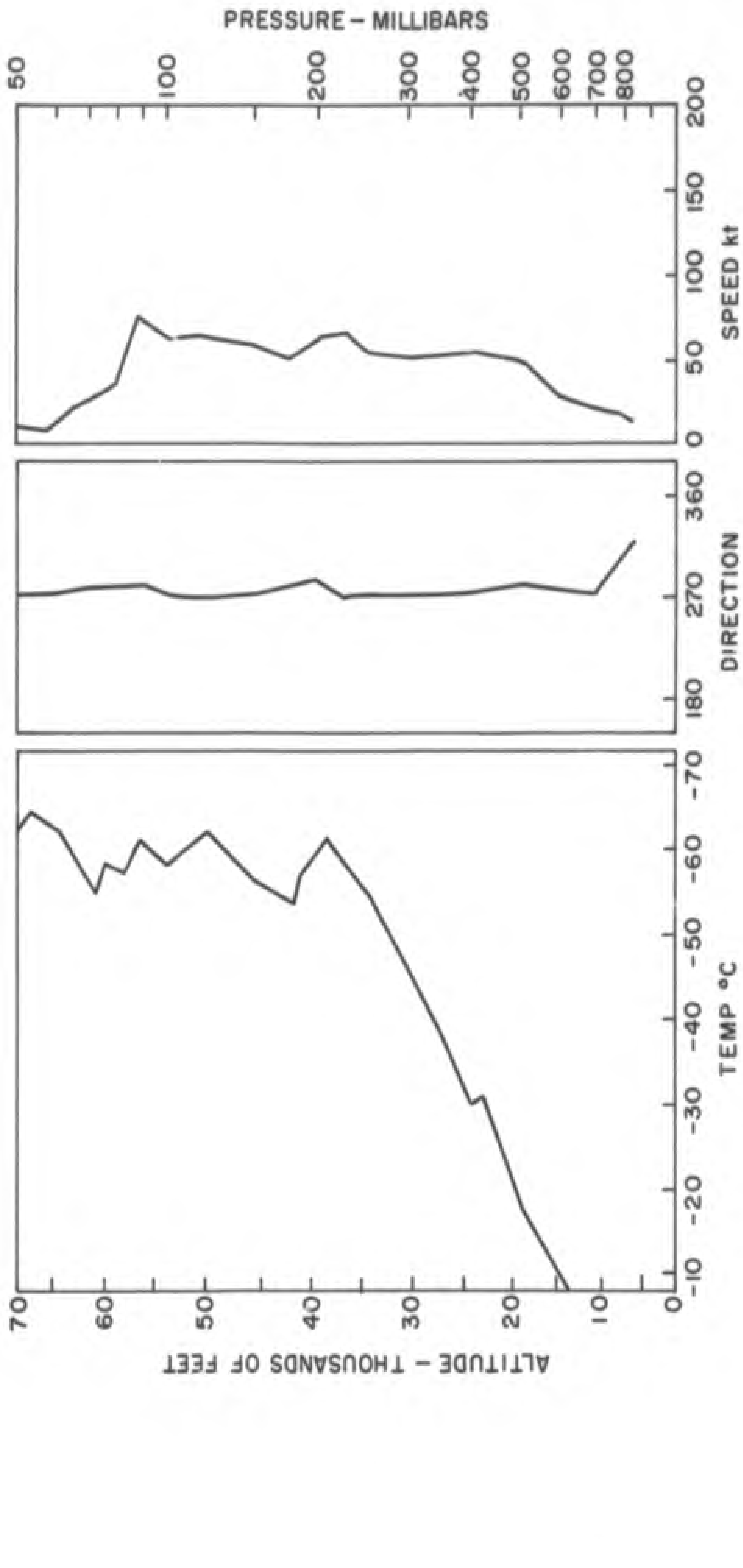

FIG.31: UPPER AIR DATA

ALBUQUERQUE, N. M.

0000 GMT 20 MAR. 1969

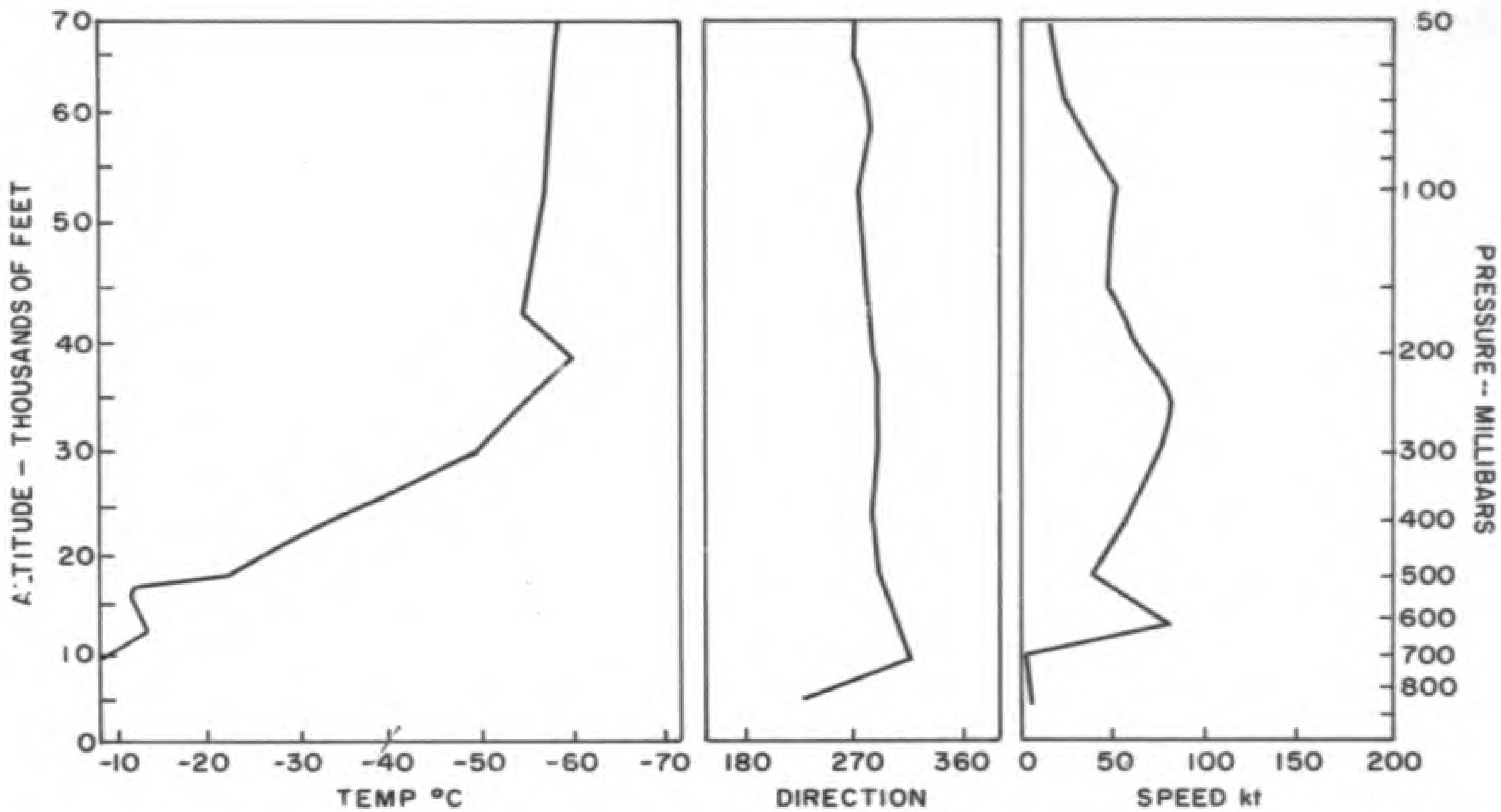

FIG.32: UPPER AIR DATA

GRAND JUNCTION, COLO.

0000 GMT 20 MAR. 1969

FIG. 33 : FLIGHT 16, EVENT 2

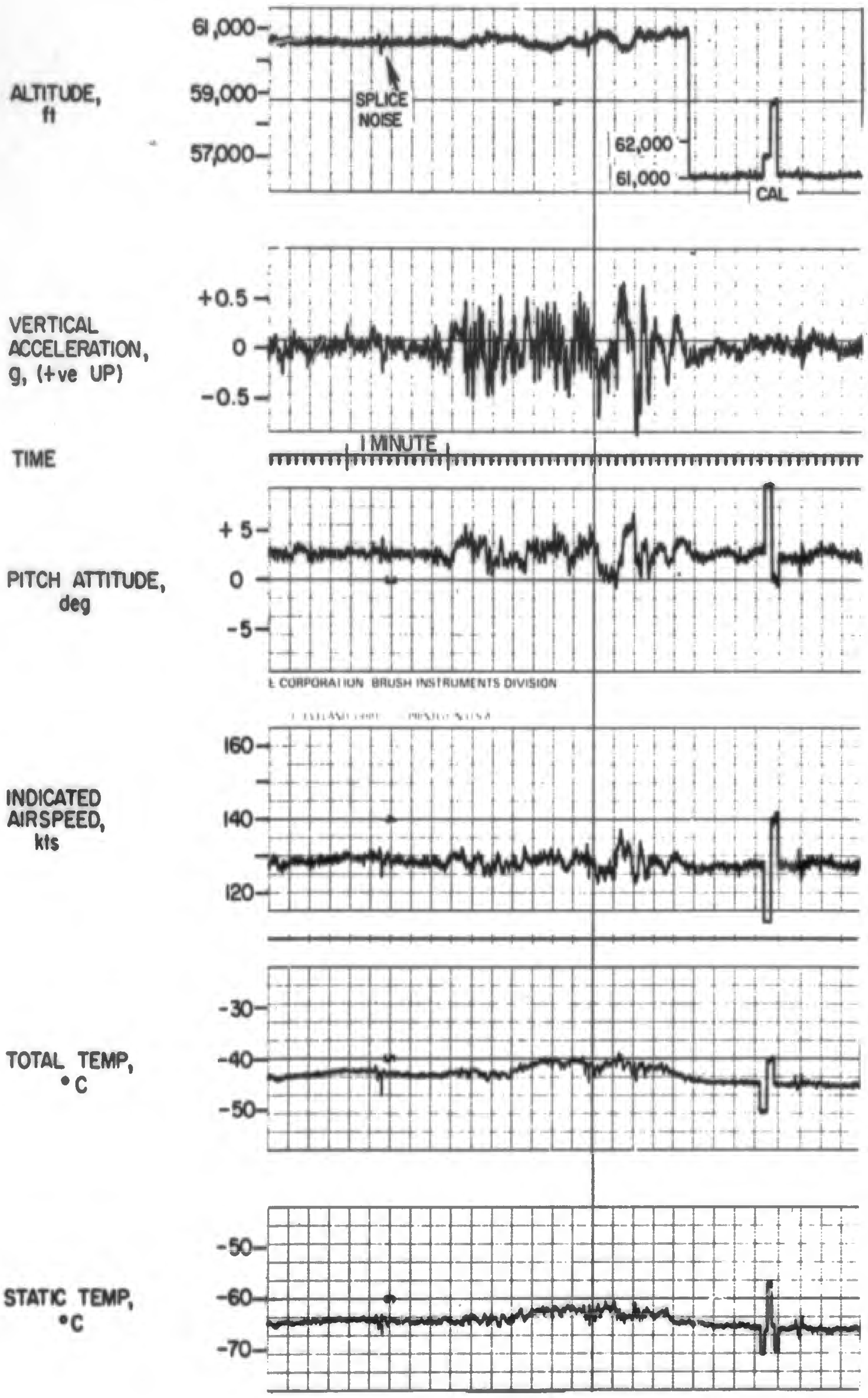

FIG. 34: FLIGHT 16, EVENT 6

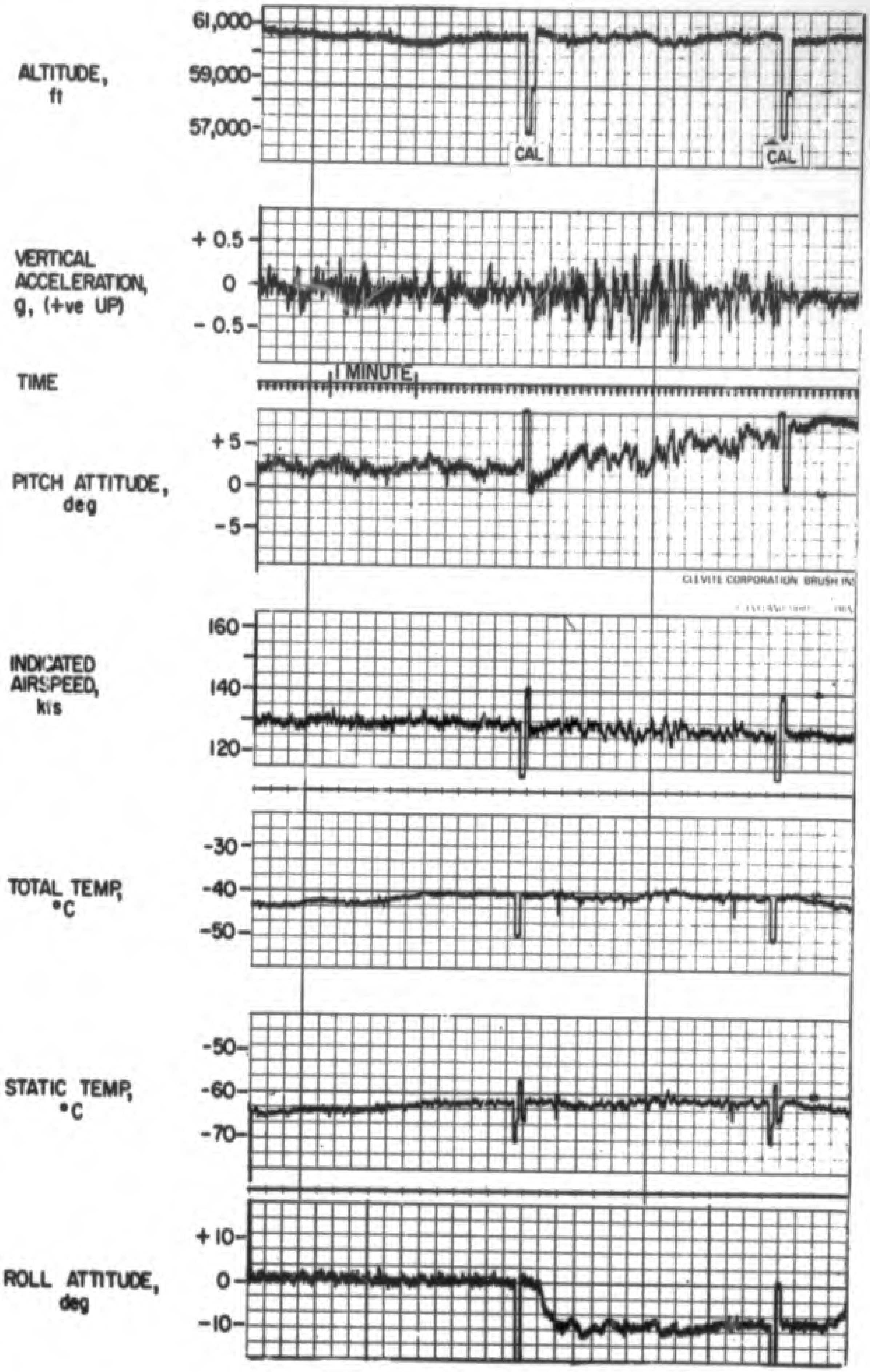

FIG. 35: FLIGHT 16, EVENT 7

FIG.36: AIRCRAFT TRACK — FLIGHT 16, 15 APR. 1969

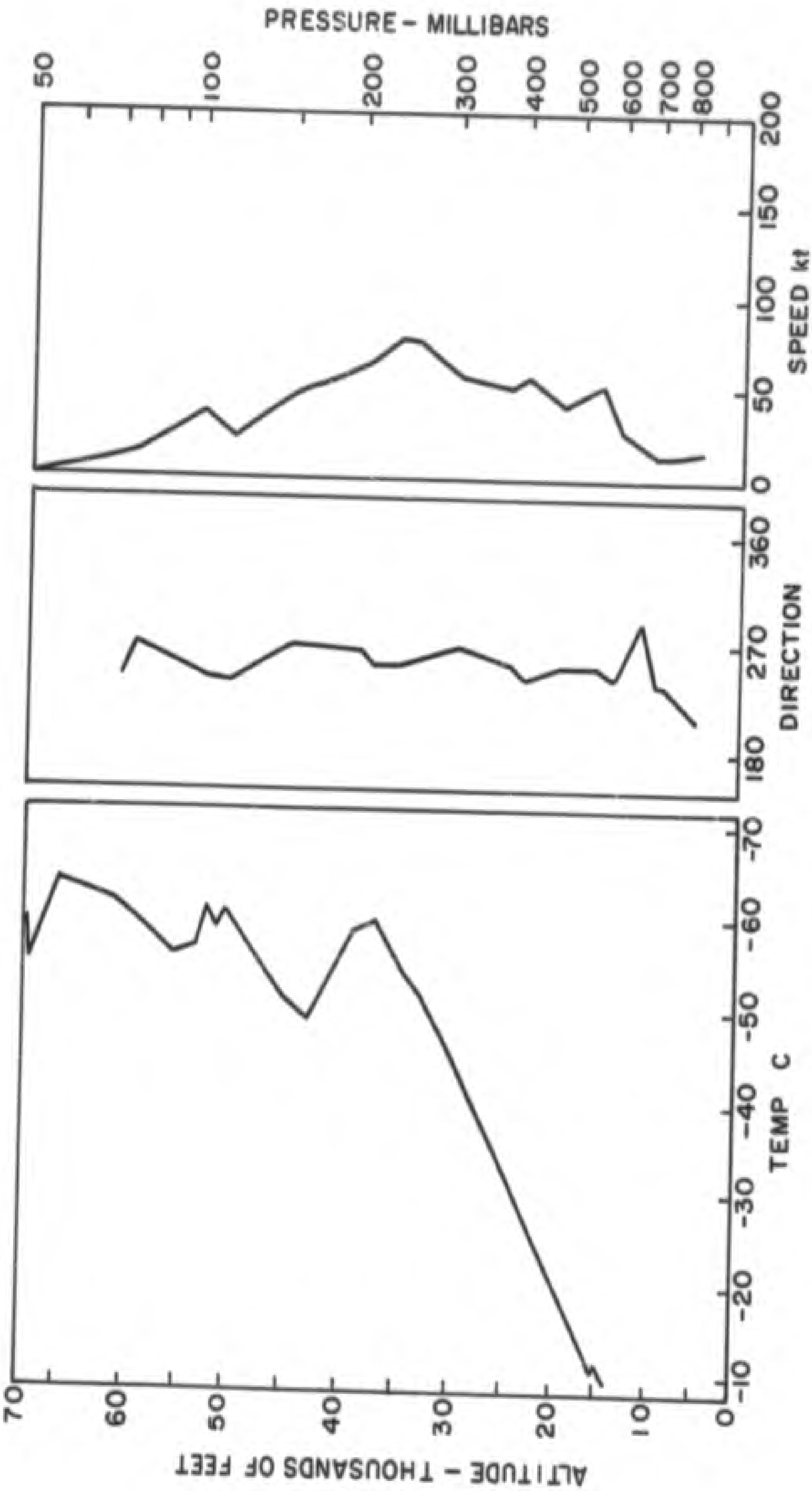

FIG.37: UPPER AIR DATA

1200 GMT 15 APR. 1969

ALBUQUERQUE, N.M.

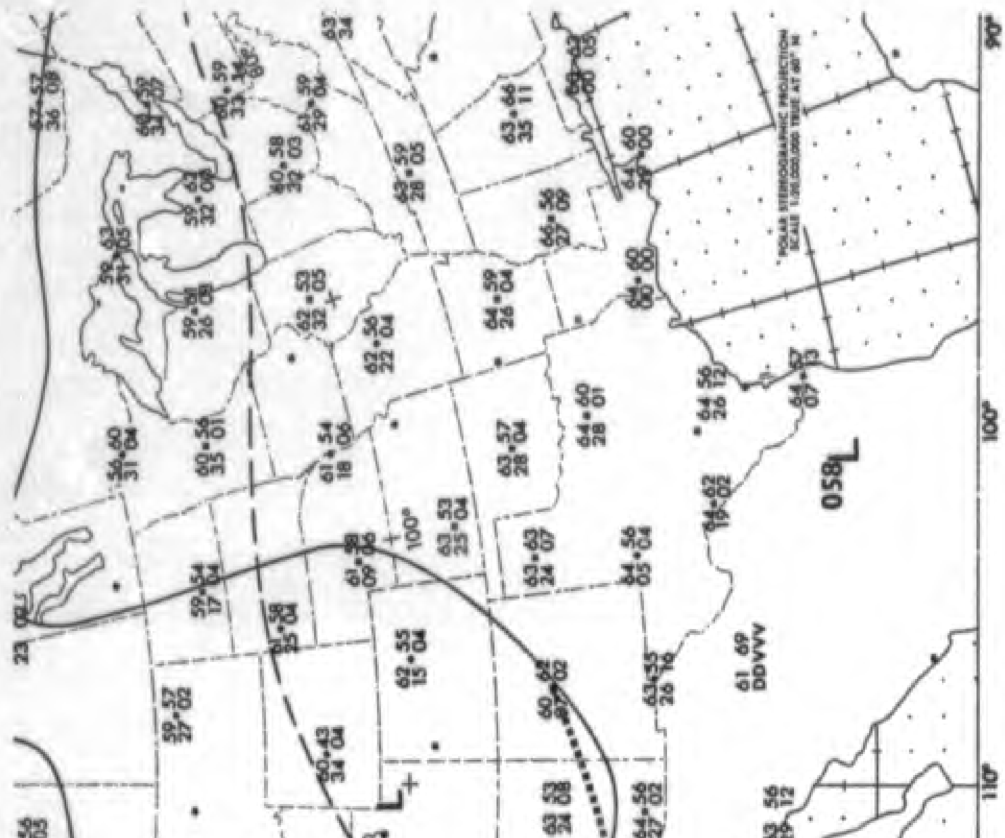

FIG.38: 50-mb ANALYSIS, 1200 GMT, 15 APR. 1969

4.0 REFERENCES

1. MacPherson, J.I.; Lum, K. — Instrumentation of an RB-57F to Measure High Altitude Turbulence Encounters. NRC, NAE Aero. Report LR-522, National Research Council of Canada, Ottawa, March 1969.

2. Pratt, K.G.; Walker, W.G. — A Revised Gust Load Formula and a Re-Evaluation of V-G Data Taken on Civil Transport Airplanes from 1933 to 1950. NACA Report 1206, Langley Aeronautical Laboratory, 1954.

3. Palm, E.; Foldvik, A. — Contribution to the Theory of Two-Dimensional Mountain Waves. Geofysiske Publikasjoner, Geophysica Norvegica, Vol. 21, No. 6, 1960.

4. Eliassen, A.; Palm, E. — On the Transfer of Energy in Stationary Mountain Waves. Geofysiske Publikasjoner, Geophysica Norvegica, Vol. 22, No. 3, 1961.

5. Scorer, R.S. — Airflow over Mountains: II -- The Flow over a Ridge. Quarterly Journal of the Royal Meteorological Society, Vol. 79, No. 1, 1953.

6. Queney, P. et al. — The Airflow over Mountains. World Meteorological Organization, Technical Note 34, Geneva, 1960.

7. Gerbier, N.; Berenger, M. — Experimental Studies of Lee Waves in the French Alps. Quarterly Journal of the Royal Meteorological Society, Vol. 87, 1961.

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