NASA TM-80044

NASA Technical Memorandum 80044

NASA-TM-80044 19790017496

METEOROLOGICAL AND OPERATIONAL ASPECTS OF 46 CLEAR AIR TURBULENCE SAMPLING MISSIONS WITH AN INSTRUMENTED B-57B AIRCRAFT

VOLUME I - PROGRAM SUMMARY

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May 1979

National Aeronautics and
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1 Report No TM-80044	2 Government Accession No	3 Recipient's Catalog No
4 Title and Subtitle Meteorological and Operational Aspects of 46 Clear Air Turbulence Sampling Missions with an Instrumented B-57B Aircraft - Volume I- Program Summary		5 Report Date May 1979
		6 Performing Organization Code
7 Author(s) Richard E. Davis, Robert A. Champine and L. J. Ehernberger		8 Performing Organization Report No
9 Performing Organization Name and Address NASA Langley Research Center Hampton, VA 23665		10 Work Unit No 517-53-13-04
		11 Contract or Grant No
12 Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546		13 Type of Report and Period Covered Technical Memorandum
		14 Sponsoring Agency Code
15 Supplementary Notes		

16 Abstract

The results of 46 clear air turbulence (CAT) probing missions conducted with an extensively instrumented B-57B aircraft are summarized from a meteorological viewpoint in a two-volume technical memorandum The missions were part of the NASA Langley Research Center's MAT (Measurement of Atmospheric Turbulence) program, which was conducted from the NASA Langley Research Center (on Langley AFB, VA) and the NASA Dryden Flight Research Center (on Edwards AFB, CA) between March 1974, and September 1975, at altitudes ranging up to 15 km

Turbulence samples were obtained under diverse conditions including mountain waves, jet streams, upper level fronts and troughs, and low altitude mechanical and thermal turbulence. CAT was encountered on 20 flights comprising 77 data runs. In all, approximately 4335 km were flown in light turbulence, 1415 km in moderate turbulence, and 255 km in severe turbulence during the program. The first volume presents the flight planning, operations, and turbulence forecasting aspects of that portion of the MAT program conducted with the B-57B aircraft, as well as the overall results and recommendations for future turbulence sampling programs. In the second volume (Appendix C), 27 MAT flights of particular meteorological interest are each described by narrative summaries, supplemented in some cases by synoptic maps and rawinsonde sounding data. This has been done in a manner to facilitate correlation with the turbulence time histories and power spectra derived in the project. Some photographs of clouds are also included, in order to show some of the cloud patterns which may serve as visual warnings of turbulent conditions.

17 Key Words (Suggested by Author(s)) Atmospheric turbulence, Meteorology, Turbulence forecasting	18 Distribution Statement Unclassified - Unlimited. Subject Category 47

19 Security Classif (of this report) Unclassified	20 Security Classif (of this page) Unclassified	21 No of Pages 77	22 Price* $6.00

* For sale by the National Technical Information Service Springfield Virginia 22161

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SUMMARY

The results of 46 clear air turbulence (CAT) probing missions conducted with an extensively instrumented B-57B aircraft are summarized from a meteorological viewpoint in a two-volume technical memorandum. The missions were part of the NASA-Langley Research Center's MAT (Measurement of Atmospheric Turbulence) program, which was conducted from the NASA Langley Research Center (on Langley AFB, VA) and the NASA Dryden Flight Research Center (on Edwards AFB, CA) between March 1974, and September 1975, at altitudes ranging up to 15 km. The particular emphasis of this program is to extend power spectral measurements of atmospheric turbulence to wavelengths of at least 9,100 m (30,000 ft.) under several meteorological conditions and a range of altitudes of 0-15,240 m (0-50,000 ft.). This is important for design of large, structurally flexible higher speed aircraft in addition to the general research needed for developing a better insight into the relation between turbulence and basic atmospheric phenomena which may cause it.

Turbulence samples were obtained under diverse conditions including mountain waves, jet streams, upper level fronts and troughs, and low altitude mechanical and thermal turbulence. CAT was encountered on 20 flights comprising 77 data runs. In all, approximately 4335 km were flown in light turbulence, 1415 km in moderate turbulence, and 255 km in severe turbulence during the program. A contract project research meteorologist, Mr. David E. Waco of Vought Corporation, filled a unique and key role in this program in that he assisted in formulating the general research plan, forecasted the turbulence, participated as airborne meteorological observer during each of the missions, and conducted the post-flight meteorological analyses. The first volume presents the flight planning, operations, and turbulence forecasting aspects of that portion of the MAT program conducted with the B-57B aircraft, as well as the overall results and recommendations for future turbulence sampling programs. In the second volume (Appendix C), authored by Mr. Waco, 27 MAT flights of particular meteorological interest are each described by narrative summaries, supplemented in some cases by synoptic maps and rawinsonde sounding data. This has been done in a manner to facilitate correlation with the turbulence time histories and power spectra derived in the project. Some photographs of clouds are also included, in order to show some of the cloud patterns which may serve as visual warnings of turbulent conditions.

INTRODUCTION

The NASA Measurement of Atmospheric Turbulence (MAT) program was undertaken primarily to extend turbulence power spectra measurements to wavelengths of at least 9100 m (30,000 ft) under several types of meteorological conditions, and over a wide altitude range, employing the same instrumentation system throughout the entire investigation. The program utilized a B-57B aircraft capable of operation to an altitude of 15 km (50,000 ft); 46 turbulence research flights were conducted from the NASA Langley Research Center (Langley AFB, VA) and the NASA Dryden Flight Research Center (Edwards AFB, CA) between March 1974 and September 1975.

The primary purpose of this two-volume report is to document the operational aspects of the missions and describe each turbulence research flight in terms of the synoptic and mesoscale meteorological situations which accompanied it. The turbulence power spectra obtained will be presented in separate NASA publications (e.g. ref. 1); the goal in the present report is to document the meteorological aspects in sufficient detail that turbulence researchers may be enabled to correlate the spectra with the associated meteorological conditions.

For completeness, the first volume of the present report includes the background and rationale for the MAT program and a brief description of the turbulence-sampling instrumentation. The impact of the B-57B aircraft performance envelope and air traffic control constraints on conducting turbulence search missions is discussed in the section on Flight Operations. A section is devoted to a statistical summary of the sampling experience of the program from various aspects as, e.g., the number of kilometers flown in turbulence of differing intensities under different synoptic conditions. Recommendations for future turbulence sampling programs conclude the main body of the first volume.

Appendix A in the first volume describes the weather support and analysis procedures which were utilized and the role of the project's airborne meteorologist-observer. An evaluation of the turbulence forecasting and sampling results concludes this appendix. Appendix B summarizes the project's experience in mountain wave encounters.

The second volume (Appendix C) documents, by narrative summaries, synoptic maps, rawinsonde plots, and photographs of cloud conditions related to the turbulence, the synoptic and mesoscale meteorological conditions associated with each MAT mission where turbulence was forecast to occur.

SYMBOLS AND ABBREVIATIONS

AFB	Air Force Base
AIRMET	Airmen's Meteorological Advisory
AOA	Angle of Attack
ARTCC	Air Route Traffic Control Center
AWS	Air Weather Service (USAF)
CAT	Clear Air Turbulence
DFRC	Dryden Flight Research Center (NASA)
DME	Distance Measuring Equipment
FAA	Federal Aviation Administration
FAX	Facsimile
g	Acceleration due to gravity, meters second^{-2}
GMT	Greenwich Mean Time
gpdam	Geopotential dekameter (see ref. 11), unit of height for pressure surfaces on charts in Appendix C.
GWC	Global Weather Central (U. S. Air Force)
H	Pressure altitude, kilometers
IAS	Indicated Air Speed, knots or kilometers hour^{-1}
INS	Inertial Navigation System
L	Integral scale value for turbulence, meters.
LaRC	Langley Research Center (NASA)
MAT	Measurement of Atmospheric Turbulence
NMC	National Meteorological Center (National Weather Service)
NWAL	Northwest Air Lines
NWS	National Weather Service
PIREP	Pilot Report
RAOB	Rawinsonde Observation
Ri	Richardson number - a nondimensional number utilized in the study of shearing flows (see, e.g., ref. 11).

SIGMET	Significant meteorological advisory
SMG	Spaceflight Meteorology Group (NWS)
T	Atmospheric temperature, degrees Celsius
TACAN	Tactical air navigation system
TAS	True Air Speed, knots or kilometers hr^{-1}
TP	Turbulence Plot advisory (Northwest Airlines)
U_g	Longitudinal component of gust velocity, meters $second^{-1}$
UHF	Ultra High Frequency
USAF	United States Air Force
VFR	Visual Flight Rules
V_g	Lateral component of gust velocity, meters $second^{-1}$
VHF	Very High Frequency
V_{N-S}	North-south wind component, meters $second^{-1}$ (positive wind from north)
VOR	VHF omnirange
V_{W-E}	West-east wind component, meters $second^{-1}$ (positive wind from west)
W_g	Vertical component of gust velocity, meters $second^{-1}$
$\bar{W}_g$	Mean vertical component of gust velocity, (averaged over 12 seconds), meters $second^{-1}$
α	Angle of attack, degrees
β	Angle of sideslip, degrees
δ	Direction from which wind blows, degrees clockwise from north
ΔV	Incremental change in the longitudinal component of airspeed, meters $second^{-1}$
θ	Potential temperature (see, e.g., ref. 11), kelvins
λ	Wavelength, meters
σ	Root mean square value of turbulence, meters $second^{-1}$
ϕ	Power Spectral density, ($meter^2 second^{-2}$) per (cycle $meter^{-1}$)

BACKGROUND

A model of the spectral properties of atmospheric turbulence is important for design of certain types of aircraft. Measurement techniques and data analysis procedures have been developed by several investigators (e.g., ref. 2) and flight programs have been conducted to investigate the appropriate spectral description for turbulence encountered in the surface layer of the atmosphere (ref. 3), in storm clouds (ref. 4), in jet stream wind shear (ref. 5) and at higher altitudes (ref. 6). In general, the results of most of these sampling programs have indicated that the -5/3 slope of the von Karman power spectrum (see figure 1 (from ref. 7)) is valid above wave numbers on the order of 0.01 rad/m (5×10^{-4} cycles/ft) or below wavelengths of approximately 600 m (2000 ft). Although there is general agreement that the spectral description over these higher frequencies (smaller wavelengths) appears valid, the spectral characteristics obtained at the lower frequencies (longer wavelengths) have exhibited notable disparities among the results from different atmospheric conditions and measurement programs. An example of departures from the von Karman spectrum, obtained in a mountain wave sampling mission on this project, is presented as Figure 2 from ref. 1. The departures may be associated with the atmospheric processes (e.g., wind shear) controlling the generation of the turbulence.

The amount of turbulence or gust energy at the longer wavelengths is of particular importance in the response and design of large, high speed aircraft, such as supersonic transports. Because spectral characteristics of measured turbulence may be influenced by the type of aircraft, the instrumentation used in the measurements, and the

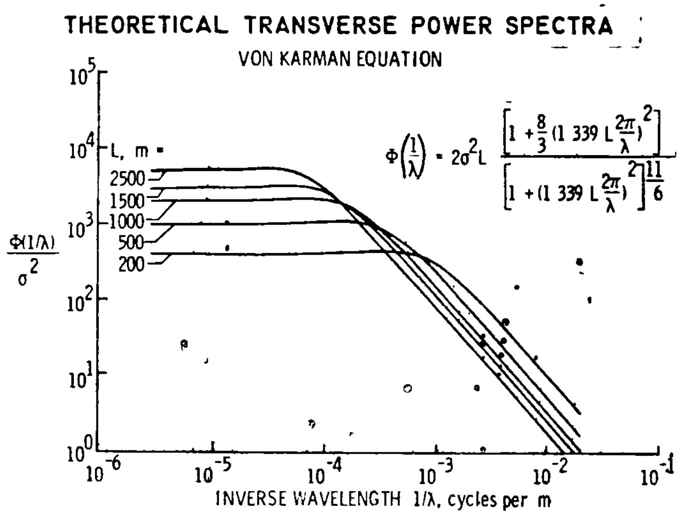

Figure 1.- Von Karman power spectra (transverse components) for various values of the integral scale value L. (Ref. 7).

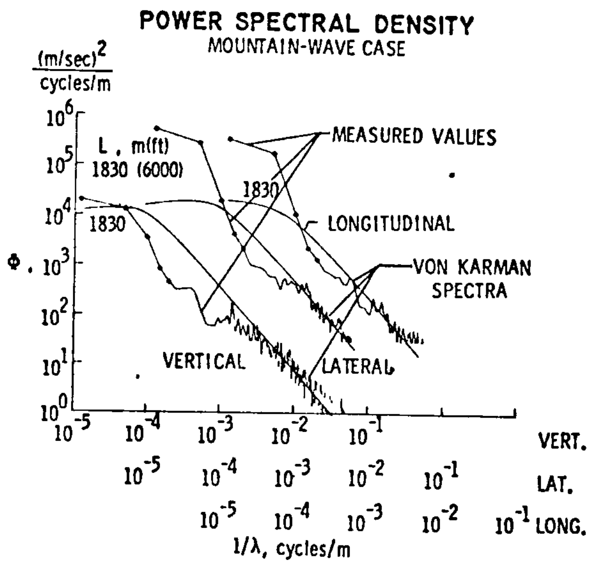

Figure 2.- An example of departures from von Karman power spectra, which may be associated with the atmospheric processes controlling the turbulence (ref. 1).

data reduction and analysis procedures employed, it is not surprising that the spectra resulting from different investigations have not always been comparable. Therefore the MAT program was initiated with the goal of determining whether the von Karman power spectrum is indeed an adequate design model for the longer wavelength turbulence components encountered in a variety of meteorological situations and, if so, defining the appropriate scale lengths (i.e., L values in the equation shown on figure 1) to be employed in the design of future aircraft. To allow valid comparisons of the data from the various meteorological situations, the same instrumentation and data analysis procedures were employed for all MAT missions. Emphasis was placed on searching for turbulence patches of sufficient length (approximately 10 minutes duration) to allow for the determination, with good statistical reliability, of long wavelength components pertaining to various meteorological conditions. It was decided to sample turbulence associated with wind shear regions, jet streams, low altitude orographic layers, convective activity, and mountain wave phenomena. Therefore, flights were made from about 300 m (1000 ft) above sea level up to the 15 km (50,000 ft) ceiling of the sampling aircraft. Aircraft turbulence instrumentation consisted of sensitive airflow direction vanes, an incremental pitot pressure transducer, an inertial platform and a temperature probe (refs. 7 and 8). In addition to providing data for studying gust velocity time histories, these measurements were used in deriving temperature and wind time histories and profiles.

INSTRUMENTATION AND DATA ANALYSIS

The requirements for the measurement and recording system and for the data processing to achieve the goal of providing accurate measurements at long turbulence wavelengths are discussed in ref. 7. The instrumentation system used is described in ref. 8. An assessment of the measurement system, together with the equations utilized for obtaining gust velocity components, is described in ref. 9.

The three primary measurements used in deriving the turbulence structure were the angle of attack (α), the sideslip angle (β), and the incremental change in the longitudinal component of airspeed (ΔV). A Rosemount temperature probe provided measurements of atmospheric temperature. Aircraft motion corrections were applied to the primary measurements to derive the gust velocity components. Meteorological and turbulence data derived from a sampling of particular interest (flight 32) are presented in ref. 10. To provide a more complete understanding of the samples of derived data presented in the present report, some details extracted from refs. 8, 9, and 10 are presented in this section.

The measurements of the aircraft and air motions were used to provide data at meso-meteorological or turbulent scales of the atmospheric flow. The wind velocity was obtained by computing the difference between the measurements of inertial speed (relative to earth-fixed axes) and the airspeed (motion relative to the air mass). Turbulence velocity was similarly determined, but using a more detailed representation of the aircraft motion. The measured data were recorded at a rate of 200 points per second, using a pulse code modulation system. In the analysis, time histories were used from samplings at a rate of 20 per second. Filtering was in general avoided; however, frequencies above the Nyquist value (10 Hz) were attenuated to prevent aliasing effects (see ref. 8). (Electrical filtering could cause phase changes in individual measurements, causing significant errors in deduced gust velocities.)

Examples of Data

An example of gust velocity and meteorological data obtained on the MAT project is presented as figure 3. The time histories shown here were taken from two runs of flight 32 (analyzed in ref. 10) during which moderate turbulence was encountered over Death Valley, CA. The parameters presented on the figure from top to bottom are:

U_G, the longitudinal component of the gust velocity, in meters second^{-1}

V_G, the lateral component of the gust velocity, in meters second^{-1}

W_G, the vertical component of the gust velocity, in meters second^{-1}

$\bar{W}_G$, the mean vertical component of the gust velocity (obtained from a moving average over 12 seconds), in meters second^{-1}

V_{W-E}, the west-east wind component, in meters second^{-1}

V_{N-S}, the north-south wind component, in meters second^{-1}

V, the wind speed, in meters second^{-1}.

δ, direction from which the wind is blowing, in degrees clockwise from north

T, the ambient atmospheric temperature, in degrees Celsius

θ, potential temperature, in kelvins (e.g., ref. 11)

H, the pressure altitude, in kilometers

Note that all quantities are plotted with ground distance in km as the abscissa. Plots similar to this were prepared for significant flights, and analyzed in terms of the variability of the turbulence and meteorological

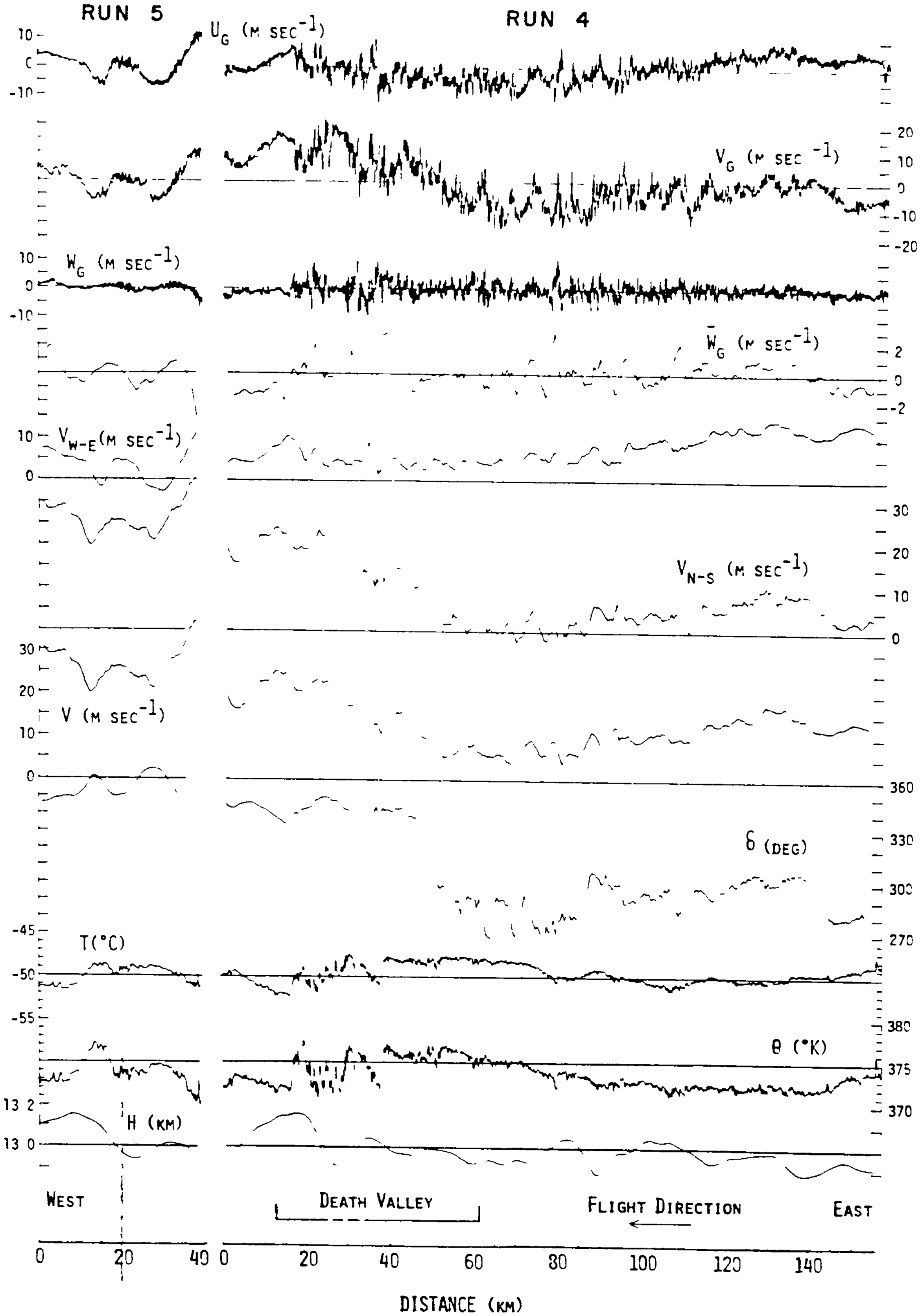

Figure 3.- Example of turbulence and meteorological data obtained in the MAT program. Example is for flight 32, run 4 (March 26, 1975, Death Valley, CA, area). Time histories of longitudinal (U_g), lateral (V_g), and vertical (W_g) and mean vertical ($\bar{W}_g$) turbulence velocities, west-east (V_{W-E}) and north-south (V_{N-S}) wind components, wind speed (V) and direction (δ), temperature (T), potential temperature (θ), and pressure altitude (H) for runs 4 and 5 are shown. The portion of Death Valley below 1 km is indicated at the bottom.

parameters. For example, it may be noted on the figure that the wind direction changed from 340 to 280, and back to 305 degrees during the course of run 4, over a distance of some 155 km, indicating the existence of atmospheric structure at meso- meteorological scales. The record of W_G shows continuous light to moderate turbulence (for definition of intensity, see RESULTS AND DISCUSSION section), with peaks between ± 5 and ± 8 $msec^{-1}$. It should be noted that, although filtering was not applied a priori to the MAT time histories, those presented here in figure 3 have undergone "filtering" in the form of a sliding arithmetic average to provide increased clarity in presentation. Table 1 presents the time averaging periods applied for this particular case, together with the estimated accuracies which apply to all MAT missions. The 12-second averaging applied to derive mean vertical turbulence velocity was arbitrary, but chosen to enhance viewing the record for significant lower frequency components. The 12-second averaging for wind components was used to remove contamination stemming from the aircraft's characteristic 6-second period yaw and sideslip oscillation, excited by the turbulence. (The simplified equations for obtaining steady winds assume that the true airspeed vector is alined with the airplane heading, and do not account for an oscillating sideslip angle.) The 0.5 second averaging period was applied to the temperature mainly to improve the appearance of these particular plots, for which the distance (time) scale was quite compressed. The amplitude of the fluctuations was not affected noticeably. Averaging was not employed for later plots of temperature, which are presented on a more expanded time scale. (See, for example, figure C-17 in Appendix C.) Some relatively high-frequency noise is present on the sensitive static pressure time history used to obtain incremental altitude. This noise results from cross flow over the static ports located in the forward end of the nose boom, and increases with turbulence severity. Twelve-second averaging was therefore applied to the altitude trace to remove these pressure noise-related effects, since they were not indicative of actual altitude changes.

TABLE I.- ESTIMATED ACCURACIES AND TIME AVERAGING PERIODS, OF TURBULENCE AND METEOROLOGICAL DATA

Quantity	Estimated Accuracy	Time Averaging Period (Figure 3)
Turbulence Velocity Components	$\pm$ 0.3 m/s	None
Mean Vertical Turbulence Velocity	$\pm$ 0.3 m/s	12.0 sec.
Wind Components	$\pm$ 2.0 m/s	12.0 sec.
Wind Speed	*	12.0 sec.
Wind Direction	*	12.0 sec.
Temperature Increments	$\pm$ 0.3^{o}C	0.5 sec.
Potential Temperature	$\pm$ 0.5^{o}C	0.5 sec.
Altitude Increments	$\pm$20.0 m	12.0 sec.

*Accuracy depends on wind component values.

In reference 9 an assessment of the quantities comprising the vertical turbulence measurement concluded that it is essentially accurate to zero frequency, but that maximum linear trend errors of 1.5 to 1.8 msec^{-1} over 10 minutes' time could be present in the time histories of the horizontal components. However, these errors would affect only the longest wavelength turbulence components, and are significant as a "noise" source only in cases of low turbulence intensity.

FLIGHT OPERATIONS

Airplane Capabilities and Limitations

A B-57B "Canberra" (NASA aircraft 516) was chosen for this project primarily because of its ruggedness and capability to cruise at altitudes extending to 15 km (50,000 ft) within an acceptable operational range radius. The B-57B was designed as a light bomber capable of withstanding a load factor of 5g at 444 knots IAS (823 km hr^{-1}) and 3.7g at 513 knots IAS (950 km hr^{-1}). This strength provided a large load factor safety margin for recovery from upsets in severe turbulence. The cockpit provided for two crew members, which satisfied the program requirement to carry a meteorologist-observer on-board for all flights. The observer's role is described later in Appendix A. Because the Allegheny Mountains, a prime area for obtaining turbulence in flights out of Langley AFB, VA, are only 460 km away, it was felt that the cruising range without tip tank fuel would be only slightly restrictive for operations in the eastern U.S. Experience gained during the program, however, showed that increased range or endurance would indeed have improved the capability to search and find areas of turbulence. The tip tanks would have allowed an extra 1887 kg of fuel, which would have provided an additional hour of endurance or about 690 km increase in one-way range, at sea level. Since the tip tank system on this aircraft had previously been deactivated as part of a previous research program, it was concluded that the major rework necessary to regain its use was not warranted. Figure 4 shows endurance and one-way range (until fuel is exhausted); this information is based on flying at 300 knots indicated airspeed (556 km hr^{-1}). Basically the airplane is capable of approximately 3 hours' duration or 1500 km at sea level and 2700 km at an altitude of 12 km (40,000 ft). For the

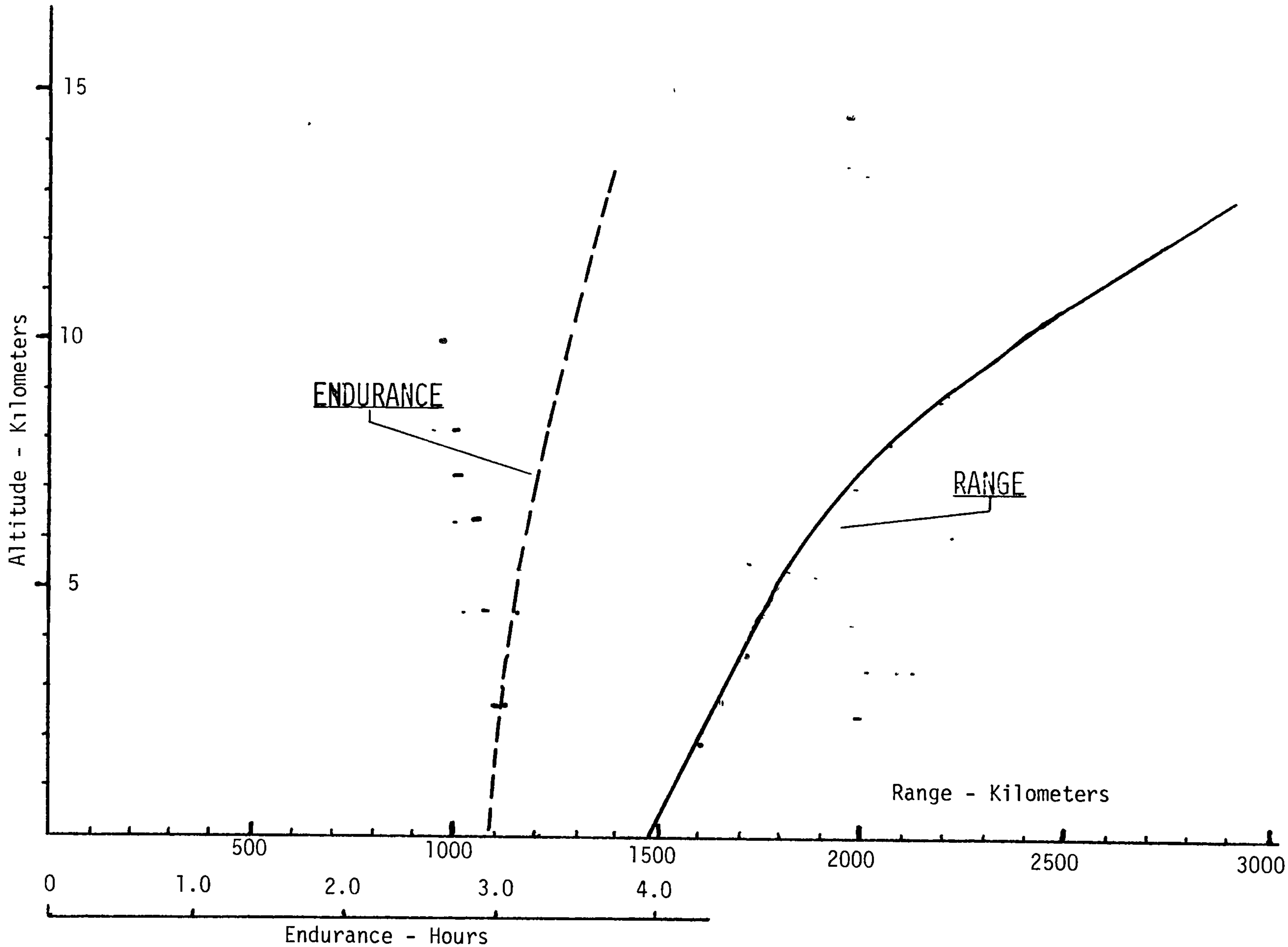

Figure 4.- B-57B endurance and range performance.

altitudes generally probed, the effective sampling radius was about 500 km, allowing sufficient fuel in the aircraft to cruise out to the area of interest and probe for about one hour, then cruise back to the base of operation and have enough reserve fuel for operational safety.

Figures 5(a) and (b) show, respectively, the geographic areas covered in MAT B-57B operations over the eastern and western U.S. The boundaries of the Air Route Traffic Control Center (ARTCC) regions are also shown by the dashed lines. Radii of circles concentric with the bases of operation (Langley AFB, VA, and Edwards AFB, CA) are labeled in kilometers. The principal areas of flights for mountain wave turbulence penetrations were to the northwest of Marion, Roanoke, and Charlottesville, VA, to Charleston, WV, for flights out of Langley AFB and to the east and southeast of the Sierra and Tehachapi mountain ranges for flights from Edwards AFB.

Flight Procedures - Airplane and Experiment

Because of the interest in turbulence sampling penetrations, unusual flight planning and operating problems were encountered in addition to the restrictions imposed by aircraft capabilities. The biggest consideration was the need for non-conformity to ARTCC procedures. It was recognized that coordination with and approval by ARTCCs of the NASA flight plan, and changes thereto while in flight, were mandatory. Therefore, early in the planning stage, discussions were held with the FAA to determine acceptable procedures and, since the first flights were conducted in the eastern U S., an agreement was worked out with the Washington, DC, ARTCC for special attention and support to achieve desired flight patterns, changes in flight

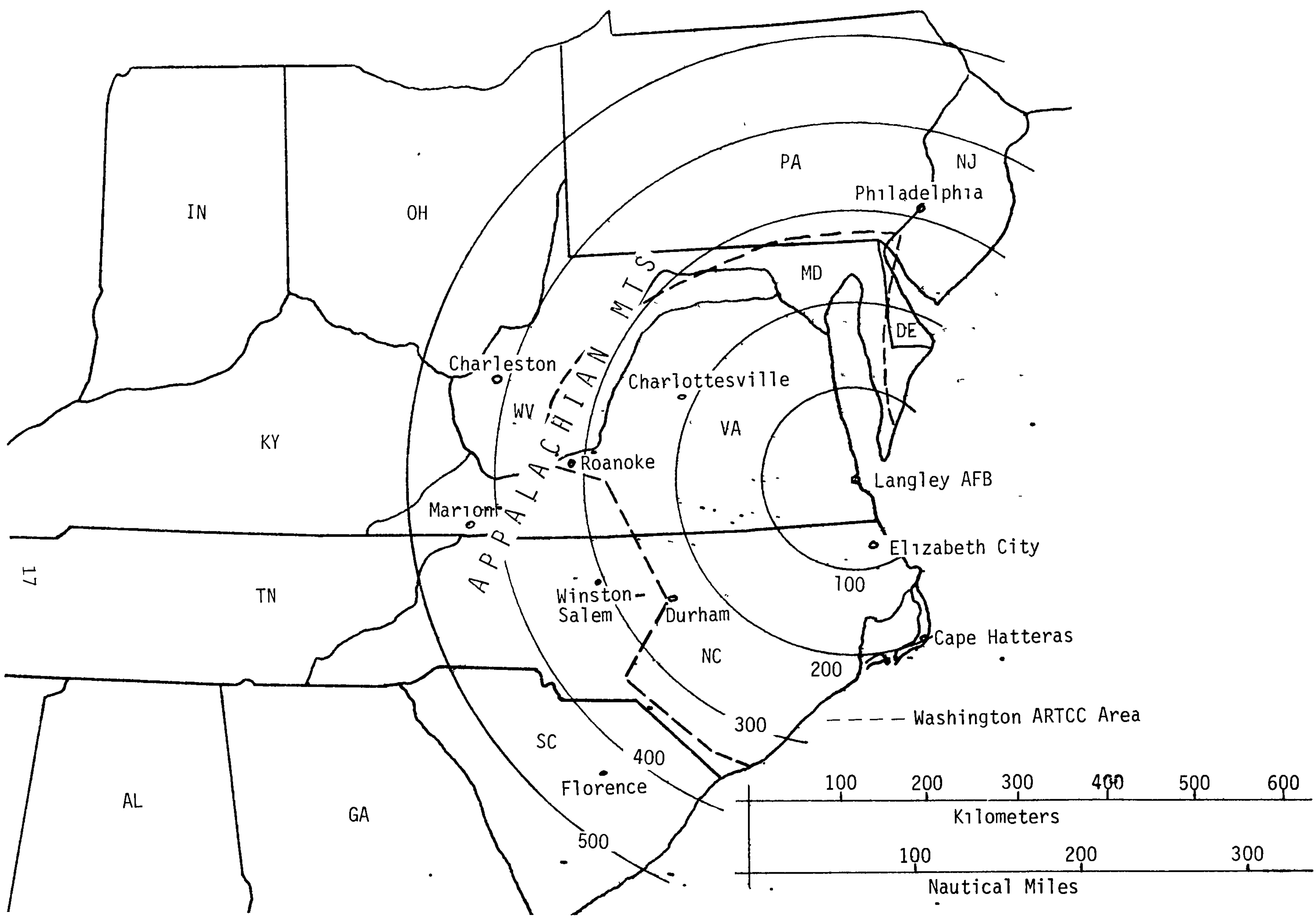

Figure 5.- Geographic Area Covered in MAT B-57B Operations.

(a) Eastern U.S.

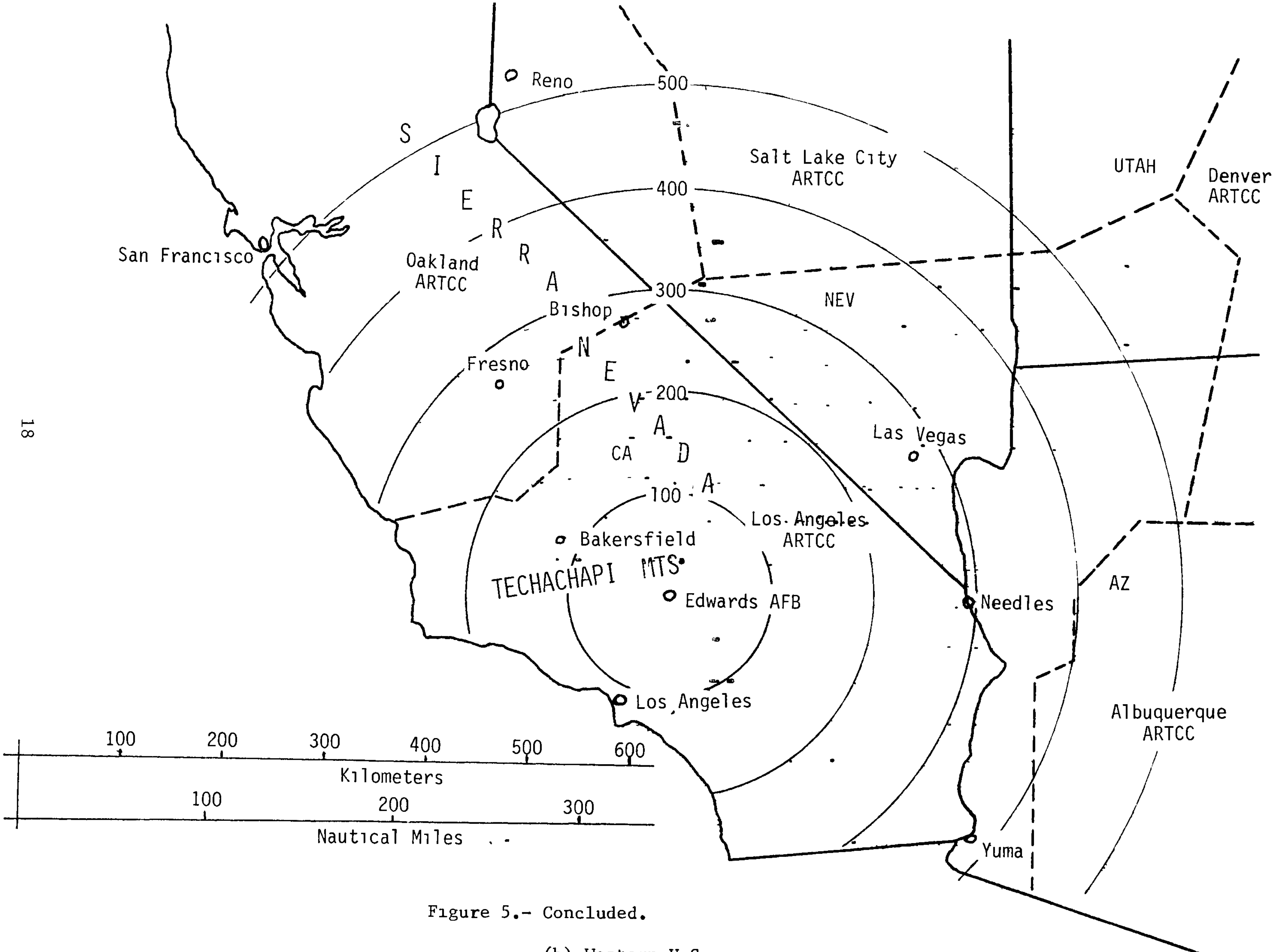

Figure 5.- Concluded.

(b) Western U.S.

directions and altitudes, and transfer to the adjacent ARTCC Centers where appropriate. Standard instrument flight plans were requested, annotated with "remarks" pertaining to the MAT flight requirements, about 30 minutes prior to estimated takeoff time. The NASA pilot would then place a call to the Watch Supervisor at the Washington ARTCC and explain the details of the particular flight. The supervisor in turn would brief the controller on duty; as a result, operations proceeded in a relatively routine manner.

As the airplane proceeded from one sector to another within the Washington Control Center area a radio communication frequency shift was required, and sometimes a transponder code change was also necessary, but these changes did not cause serious problems. Coordination between Centers was generally carried out with no difficulties. These communications were handled on UHF radio; VHF radio was used to keep the project engineers informed on the progress of the flight. While the aircraft was enroute to the designated turbulence search area, minor changes in altitude and/or aircraft heading were sometimes necessary to provide separation from other aircraft. However, during the data - taking runs, where precise, constant headings and altitudes were required, the Center controllers in most cases were able to direct other aircraft to alter their headings or altitudes so that sampling runs could be completed without undue disruption of traffic. Position information was monitored and logged by using the onboard TACAN and VOR/DME equipment to establish instantaneous aircraft position and, over a period of time, the ground track. The observer would log the position data with magnetic heading, pressure altitude, indicated temperature and airspeed, and the time of day. This type of information was used in many cases to estimate winds to within 10 degrees and 2 m sec^{-1} (5 knots) and also to help identify upper air fronts, jet streams, and mountain wave structures. The latter computations were generally made after the flight.

Cockpit Controls and Displays

To reduce the pilot's workload, and assist him in conducting search patterns, modern avionics and pilot panel displays were installed. These improvements permitted flights in most weather conditions, provided for reasonable accuracy in navigation, and facilitated maintaining a more precise heading and trim condition during data taking runs. Note that in order to have high resolution for the various measurements required in determining gust velocity, available recording ranges need to be as small as practical. The final compromise ranges selected for all of the measurements are given in ref. 8. Generally, the airplane motion ranges were such that alert piloting techniques and use of the displays was required to keep the quantities from drifting away from center of the available range, and consequently going off-scale in the rougher turbulence. Variations in piloting technique did not affect the final turbulence time histories, since airplane motion effects are removed in the data reduction. In a few instances, however, an off-scale condition of a motion measurement resulted in momentary loss of one or more turbulence components, i.e. vertical, lateral, or longitudinal. (An off-scale condition for a motion measurement can cause very large errors in the computed turbulence component. For that reason the data reduction was such that the appropriate turbulence component was discarded during the interval of any off-scale condition.)

Figures 6(a), (b), and (c) show the general layouts of the pilot and observer instrument panels, with the turbulence instrumentation controls and displays identified. Figure 6(a) is a photograph of the pilot's instrument panel. The controls for the turbulence recording instrumentation are located on a control panel at the top right of the figure. (This panel was mounted on the instrument panel's glare shield.) Figure 6(b) is an enlargement of the panel. From left to right on the figure is a "failure warning" light located directly above a "record" light, to denote failure of the inertial platform. Next is a "tape quantity" meter. Then follows a readout of the instrumentation time code generator to enable correlation of pilot-observed events with the recorded measurements. This was usually done on the

Figure 6.- MAT B-57B Cockpit Instrumentation

(a) Pilot's Instrument Panel

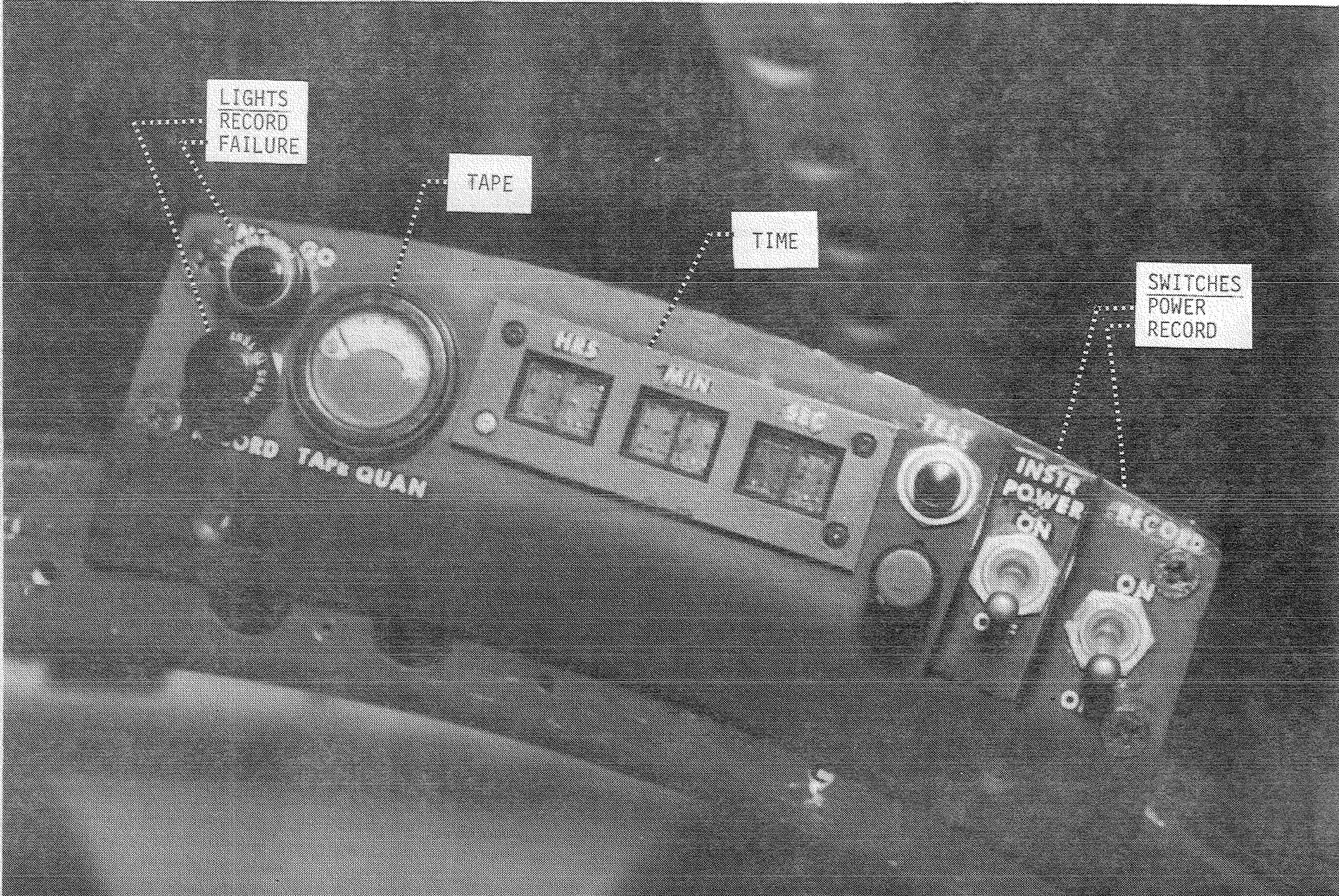

Figure 6.- Continued.

(b) Turbulence Instrumentation Control Panel

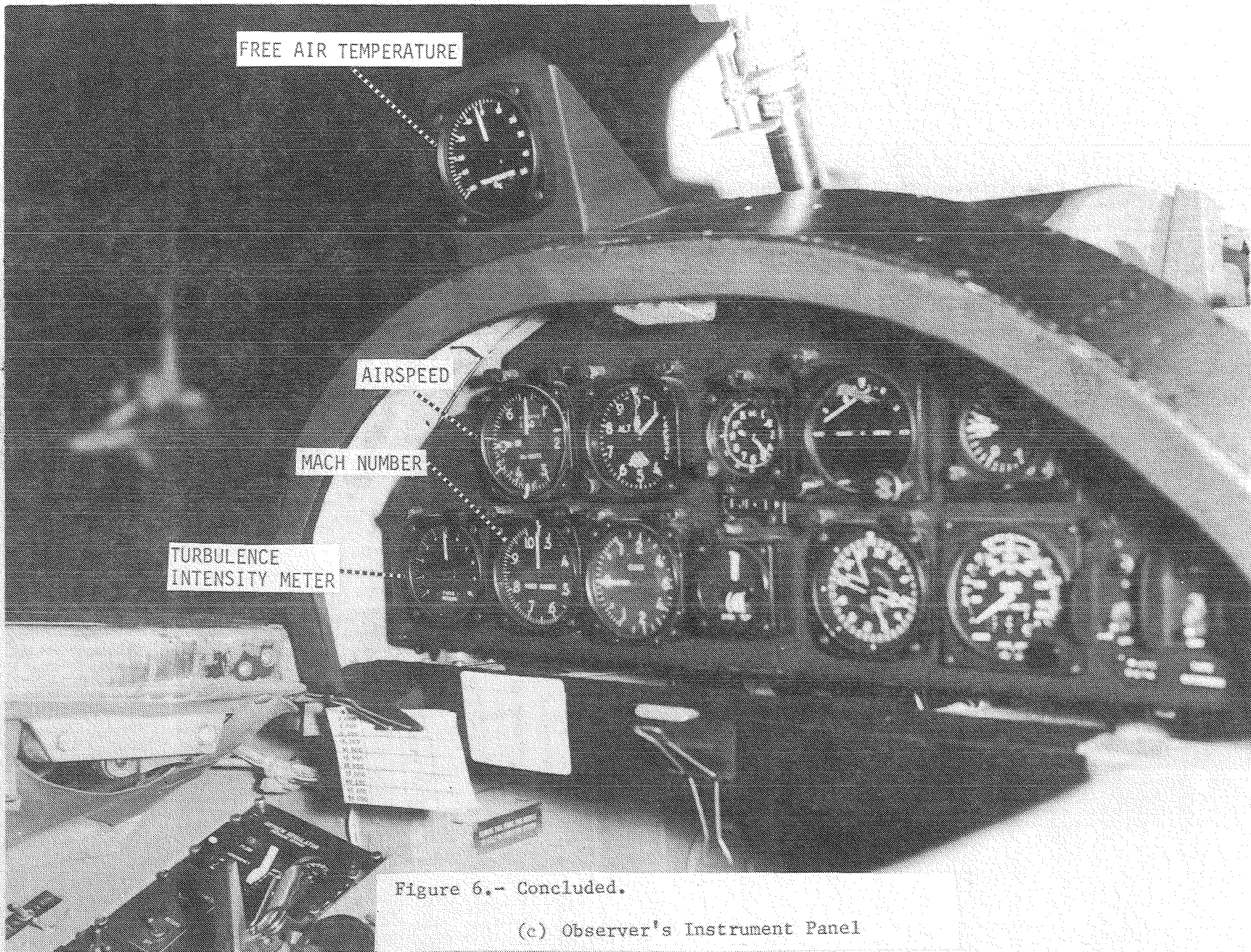

Figure 6.- Concluded.

(c) Observer's Instrument Panel

voice track of the data tape. An instrumentation power on/off switch and a record on/off switch are located to the right of the readout.

To assist the pilot in evaluating the intensity of the turbulence level, a "turbulence intensity" meter (RMS meter) was developed and placed on both the pilot's and observer's instrument panels, as shown on figures 6(a) and (c), respectively. This meter displays the root-mean square value of the output of a normal axis ±4g accelerometer located near the airplane's c.g.. The rms output is averaged over a pilot-selectable period of from 2 to 20 seconds, and has a range of 0 to 1g (rms average).

A pilot's "alpha-beta" display (fig. 7) was developed (ref. 8) and mounted on the panel just below the turbulence intensity meter. This combined display portrays the position of the nose boom angle-of-attack (AOA) and sideslip vanes, and the pitch attitude angle (derived from the inertial system). To facilitate keeping the heading near the center of the data scale, a very sensitive incremental heading display was also developed and mounted in the glare shield at top center. The display, driven by a signal from the inertial platform, has a ±7.5° limit of heading change. A monitor for the temperature probe output is mounted atop the observer's panel glare shield. This was provided to enable the observer to record the temperature changes associated with turbulence phenomena, and was especially valuable in mountain wave samplings.

Piloting Techniques

The piloting technique, developed to keep the data within acceptable limits by using the displays described in the previous section, was as follows: First, one or more minutes of straight and level flight were maintained to establish the proper engine power settings for a true

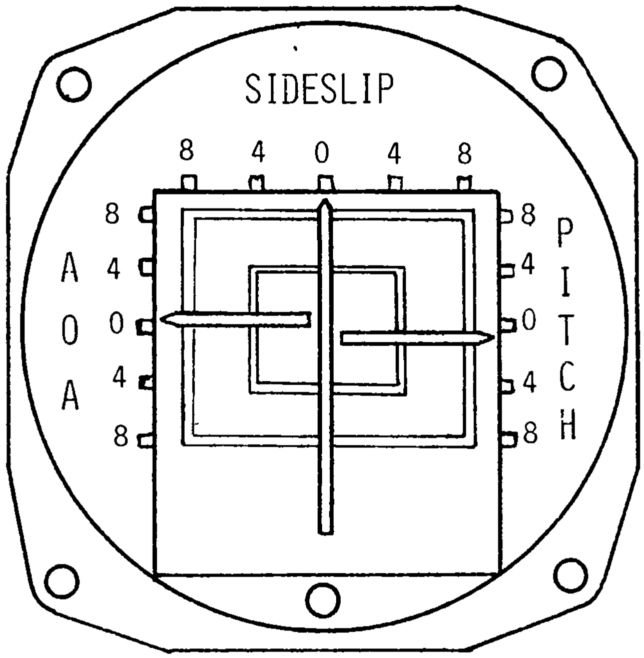

Figure 7.- Alpha-beta attitude indicator used in MAT B-57B turbulence missions (ref. 8).

airspeed of approximately 695 km hr^{-1} (375 knots); then, the data recording systems were turned on. Particular attention was then given to the incremental heading, airspeed, and altitude indicators. Adjustments to the throttles were acceptable to maintain indicated airspeed within the scale limits, which varied from $\pm$12 kt (6m sec^{-1}) at sea level to $\pm$33 kt (17m sec^{-1}) at 15 km (50,000 ft). The observer assisted the pilot by monitoring altitude and speed and would remind the pilot of any appreciable changes from the values existing at the start of the run. Maintaining motions within the accepted limits became more difficult, especially in severe turbulence, while talking to ATC or changing radio or transponder frequencies. At these times, the observer's assistance was particularly valuable.

Turbulence Sampling Patterns

Three types of sampling patterns were proposed in the early stages of the program. Patterns were derived for penetrating mountain wave phenomena, high velocity wind regions (i.e. jet streams) and isolated turbulence patches, as shown in figures 8, 9, and 10 respectively. On these figures, turbulence data-gathering runs are denoted by the heavy straight line segments lying between the solid dots. The primary consideration in deriving the pattern lengths was that each data run be long enough to provide statistically reliable data for power spectral estimates on wavelengths of 9000m or greater. As indicated in reference 7, continuous turbulence samples of about 10 minutes' duration at 375 knots TAS (395 km hr^{-1}) were desired. Therefore, data runs approximately 111 km in length are found in each of the search patterns. The various relative orientations of flight paths within each pattern were chosen to enable an assessment of the sizes of the turbulent areas, and to provide information on possible differences in the turbulence attributable to mean wind or wave orientation. The "start"

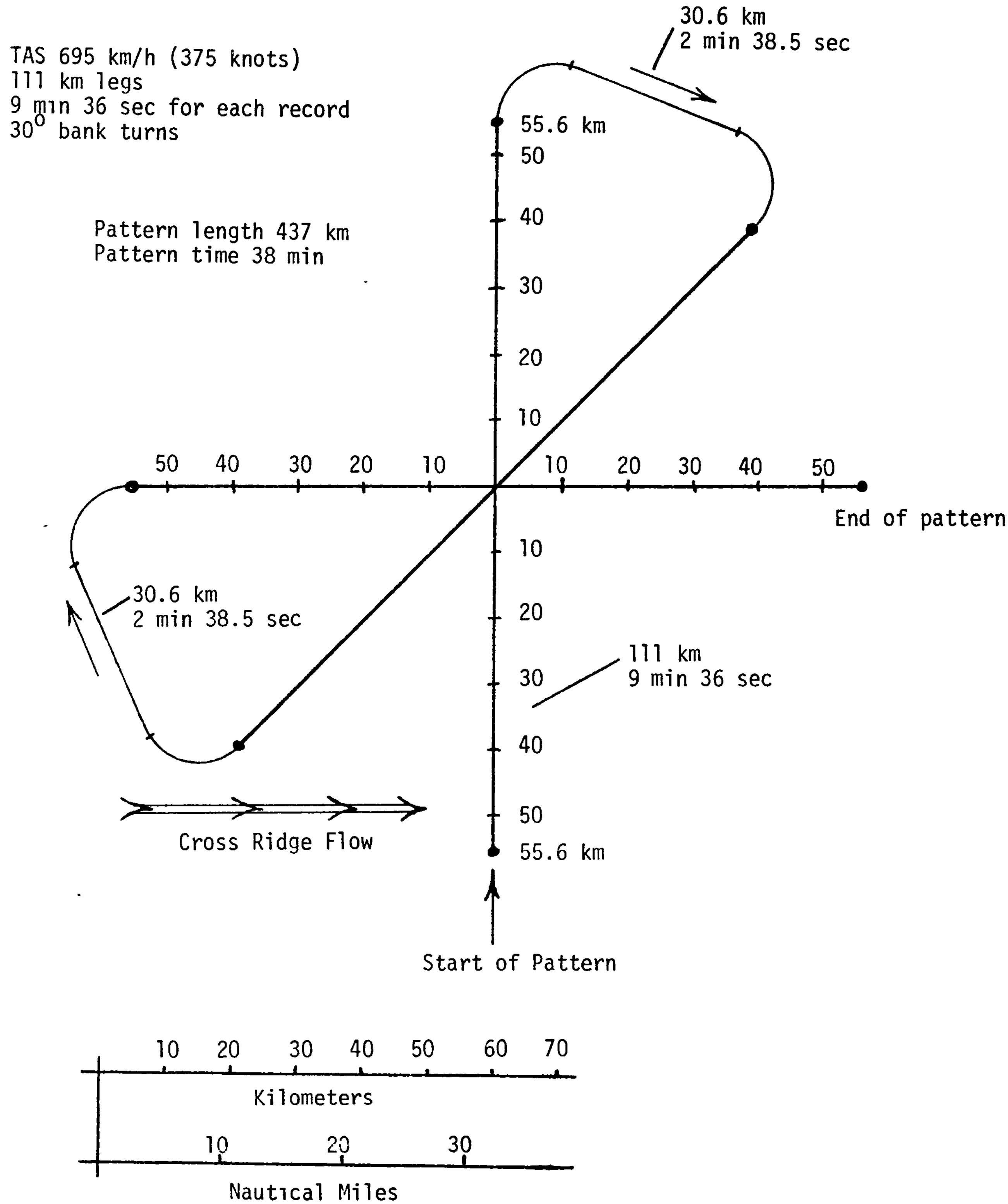

Figure 8.- Sampling pattern for investigation of wave phenomena.

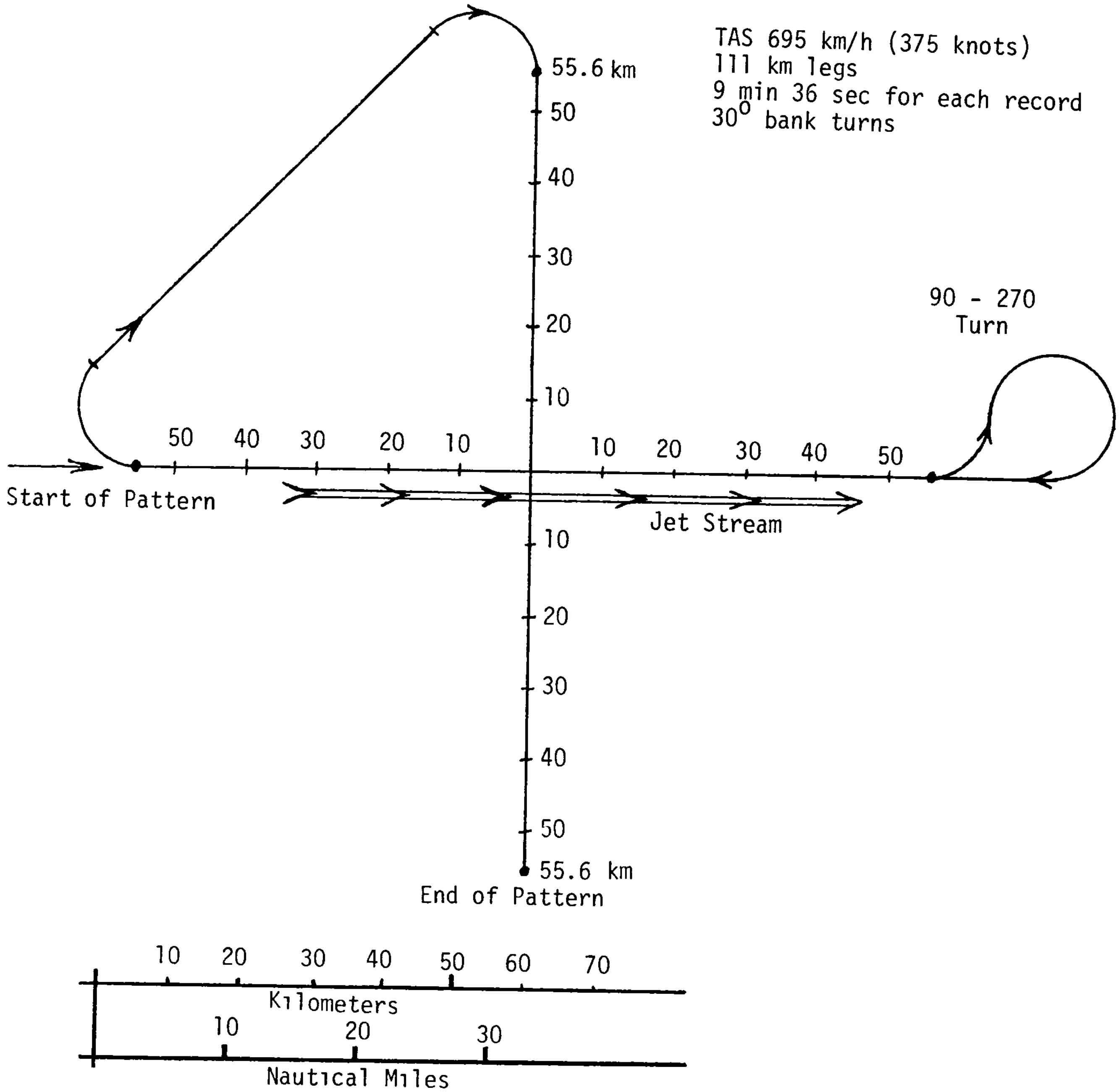

Figure 9.- Sampling pattern for investigating jet stream turbulence.

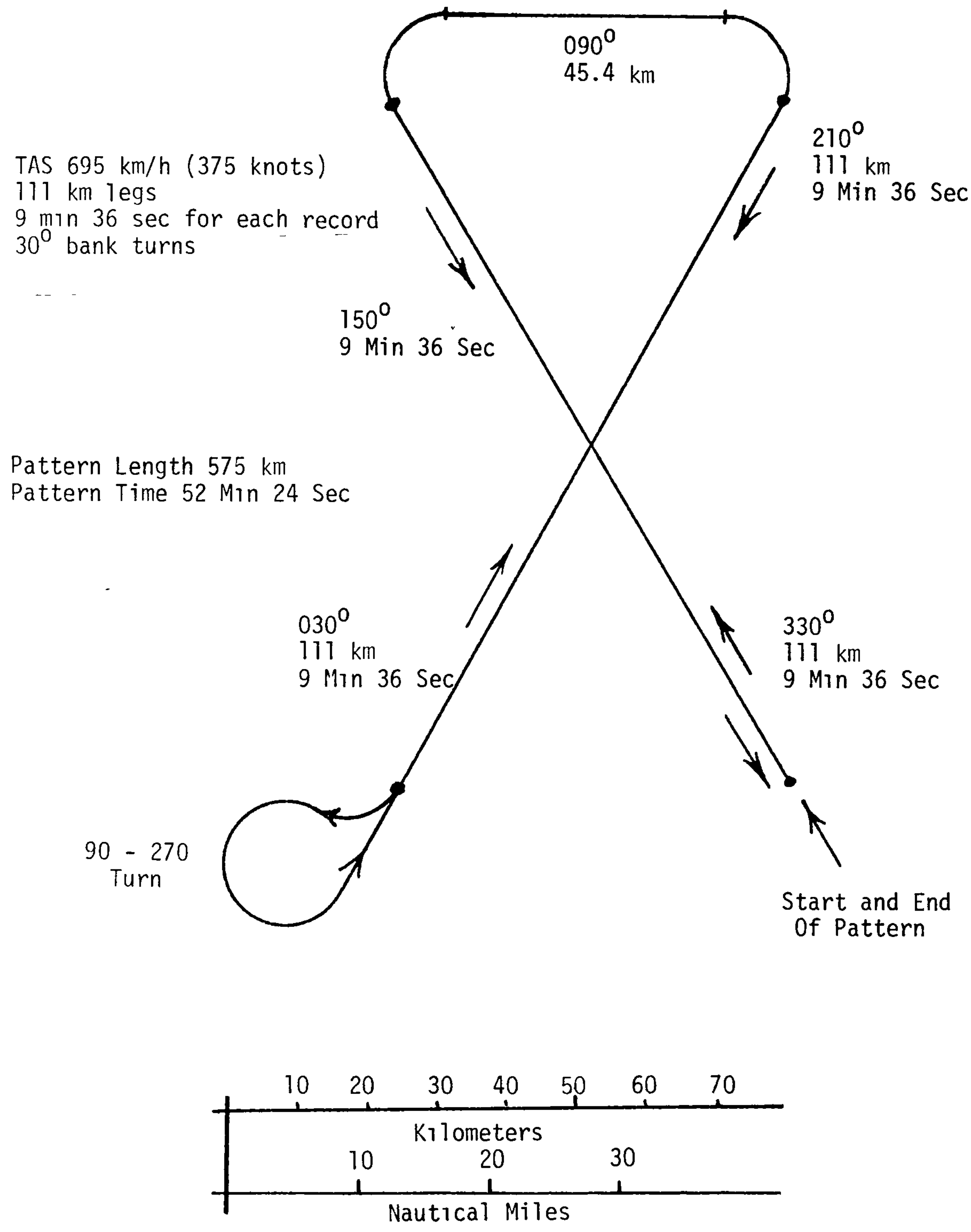

Figure 10.- Sampling pattern for investigating isolated turbulence patches.

headings were often oriented into the air mass or local wind so that two runs would have a minimum of drift angle and the cross legs would have maximum drift. Therefore, the figure for the isolated turbulence patch investigation pattern (fig. 10) is the only one with arbitrary track directions (030, 150, 210 and 330 degrees in the example on the figure for the four turbulence investigation legs), chosen for convenience in a given sampling. For the other two patterns, the track directions were chosen to fit the alignment of the meteorological or terrain features. For example, in the case of the jet stream (fig. 9), the first turbulence sampling run parallels the jet stream in a downwind direction, the second run parallels it heading upwind, and the final run is made perpendicular to the jet flow. The wave pattern (fig. 8) has its first run parallel to the mountain ridge. The wave is then sampled, heading upwind, at an angle of approximately 45 degrees to the ridge. The final run is made heading downwind, perpendicular to the ridge. All these patterns were idealized, and good for guidance, but seldom exactly followed in practice due to numerous constraints which will be elaborated on in the results section of the report. The no-wind time to fly the patterns varied, according to the pattern type, from 40 to 60 minutes. Other types of data runs not involving the above patterns were often flown. These were generally straight-line runs, as, for example, those passing along thunderstorms in clear air, or through their tops.

Meteorological Support and Analysis

The approach adopted in this program was to conduct turbulence sampling missions only when conditions were highly favorable for encountering turbulence. Such conditions were both identified from the pilot reports and forecasted on the basis of specific meteorological patterns apparent on weather analyses and prognoses. (This turbulence sampling approach is in contrast to that of many other programs (e.g. ref. 3) which accumulated flight miles in order to determine the percent of time spent in turbulence of a given intensity). A unique feature of the sampling operations was the requirement that a meteorologist participate not only in the traditional forecasting activities of meteorologists in weather stations but also act as an airborne observer on all turbulence sampling missions.

An attempt was made to utilize, as much as possible, the outputs of other agencies and organizations, involved with CAT — forecasting and reporting, in the conduct of the MAT B-57B sampling operations. Advice was solicited from other government agencies and commercial airlines on forecast procedures and acquisition of real time reports of turbulence encounters. The U.S. Air Force (USAF), the National Weather Service (NWS), the Federal Aviation Administration (FAA), and Northwest Air Lines (NWAL) all participated in the program.

It is the authors' opinion that this approach (i.e. utilization of a flying observer, plus obtaining the active cooperation of all agencies) enhanced the accomplishment of a series of successful turbulence encounters, resulting in significant acquisition of turbulence data. In the belief that this planning experience may be useful in the planning of possible future turbulence investigation programs, further details on the turbulence forecasting experience is presented in Appendix A. The role of the project meteorologist/airborne observer, the merging of the forecast products of the various agencies into the MAT forecast, the maps and analyses used, and the forecasting procedure employed are all included.

RESULTS AND DISCUSSION

A detailed description of each of the turbulence-significant flights is provided in the second volume (Appendix C). Each of these descriptions comprises (a) a narrative flight summary, with emphasis on the turbulence obtained along with a flight track, (b) a meteorological summary, supported by synoptic analyses, rawinsonde plots, etc., and (c) a discussion which includes the most likely explanation for the turbulence encountered (or for its absence). The turbulence encounter experience will be summarized in this section of the report. Five tables are presented which summarize the experience from several aspects. The first of these, Table II, gives a complete chronology of the 48 missions in the MAT B-57B program. (Two missions, numbers 4 and 5, were not flights, but ground taxi runs for checking the instrumentation; thus 46 flights were made during the program). The table lists flight number, date, Greenwich Mean Time, the geographic area searched, the altitude range searched, the type of mission (either instrument calibration or meteorological condition related to turbulence), a subjective assessment of the maximum turbulence intensity encountered, and the assessed likelihood (preflight) of encountering turbulence. The table is divided into three parts, reflecting the three phases of the program, which were:

1. Phase 1: 25 Flights conducted from the NASA Langley Research Center (on Langley AFB, VA) over the Eastern US from March 1974 to February 1975
2. Phase 2: 16 Flights conducted from the NASA Dryden Flight Research Center (Edwards AFB, CA) over the southwestern US during February - June 1975.

TABLE II.- A COMPLETE CHRONOLOGY OF MAT MISSIONS WITH THE B-57B AIRCRAFT

(a) PHASE 1 (EASTERN U.S.,3/18/74 TO 1/30/75)

NO	DATE	TIME (GMT)	SEARCH AREA (DIST IN km)	SEARCH ALTITUDE (km)	PURPOSE	MAX TURBULENCE ENCOUNTERED	FORECAST LIKELIHOOD OF TURBULENCE
1	3/1?/74	17?0-193?	Langley AFB Local Area	4 5,4 8	Instrumentation Checkout	None	P
2	4/10/74	15?0-170?	S of Norfolk, VA	4 [illegible]	Instrumentation Checkout	None	F
3	4/10/74	1555-1705	SE of Wallops FC, VA	to [illegible]	Instrumentation Checkout (aborted)	VL above 11 6 km	P
4	N/A	N/A	N/A	N/A	Ground Taxi of Instrumentation	N/A	N/A
5	N/A	N/A	N/A	N/A	Ground Taxi of Instrumentation	N/A	N/A
6	5/10/74	1?5?-1750	SE of Wallops FC, VA	1 [illegible]-13 7	Instrumentation Checkout	None	P
7	6/ 5/74	17?4-1901	Wallops FC, VA	4 [illegible]	Computer Calibration	None	P
8	6/19/74	1609-193?	Franklin, VA - Roxboro NC	0 5	Low Altitude Thermal Turbulence	Continuous L	F
9	6/20/74	1?07-200?	Franklin, VA - Wilmington, NC	0 5 [illegible]	Low Altitude Thermal Turbulence	Continuous L	F
10	10/11/74	1517-1708	E of Cape Charles, VA	4 9	Inertial Platform Check	None	P
11	10/22/74	1537-1721	Gordonsville, VA	10 4	Inertial Platform Check [illegible] Turbo Pattern [illegible]	None	P
12	10/25/74	1538-1745	Roanoke, VA	6 7	[illegible] Surface Patterns	VL	P-F
13	11/ 5/74	1646-1900	90 radius Staunton, VA	9 4	Inst Checkout Jet Stream Turbc	None	P-F
14	11/ 7/74	1549-1817	180 radius Richmond, VA	6-[illegible]	Inst Checkout, Jet Stream Wind Shear	Brief VL	VG
15	11/ 8/74	1643-1927	190 E and ENE to 220 SW of Norfolk, VA	8-11	Trough Wind Shear	Patchy L	F
16	11/12/74	1730-192?	200 radius Gordonsville, VA	3 4-4 9	Inertial Platform Check	M (in clouds)	F
17	11/21/74	1553-1707	0-330 E Norfolk, VA	7 5-9 5	Jet Stream and Trough Wind Shear	None	P
18	11/21/74	1930-2040	93 N Lynchburg-Richmond, VA	9 0	Mountain-Wave Turbo, Low-High Alts	Continuous L-M (in cirrus)	G
19	11/26/74	1630-1837	3?-330 E, 109 ESE Langley AFB, VA	1-9	Jet Stream and Trough Wind Shear	Brief L-M in Patches	G
20	12/ 3/74	164?-18?9	0-125 [illegible], ?00 N and 110 NE Lynchburg, VA	1-5,5	Mountain wave	S	EX 1-2 km, G > 2 km
21	12/ 9/74	1621-1739	Langley AFB, - [illegible] to Gordonsville, VA	0-12 +	Instrumentation Checkout	Brief L	G
22	12/10/74	1623-1756	Langley AFB - Wallops FC, VA	N/A	Instrumentation Checkout	None	P
23	12/11/74	1623-1756	50 radius Charlottesville, VA	12 5	Inst Checkout, Jet Stream	None	P
24	12/17/74	16?2-1804	60 radius Richmond, VA	6 1	Vertical and Horizontal Wind Shear	Patchy L	G
25	12/31/74	1654-1840	140 SE to 90 NW Rocky Mount, NC	9 8-12 5	Vertical Wind Shear near Jet Stream	Patchy VL	F
26	1/14/75	1712-1946	0-90 E, 80 S, and 9-10 SW Richmond, VA	9-10	Jet Stream and Trough Wind Shear	L-M	VG
27	1/30/75	1548-1807	65 SSW Langley AFB - 55 NE New York City, NY	4 5-11 5	Jet stream and Vertical Wind Shear	L-M	F-G

KEY

Turbulence	Forecast Likelihood
L - Light	P - Poor
M - Moderate	F - Fair
S - Severe	G - Good
E - Extreme	VG - Very Good
VL - Very light	EX - Excellent

TABLE II.-ACOMPLETE CHRONOLOGY OF MAT MISSIONS WITH THE B-57B AIRCRAFT (CONTINUED)

(b) PHASE 2(SOUTHWESTERN U.S.,2/14/75 TO 6/17/75)

NO	DATE	TIME (GMT)	SEARCH AREA (DIST IN km)	SEARCH ALTITUDE (km)	PURPOSE	MAX TURBULENCE ENCOUNTERED	FORECAST LIKELIHOOD OF TURBULENCE
28	2/14/75	2122-233[illegible]	Owens Valley, 0-50 W, E, E Palmdale, CA	1-3 6-12 5	Mountain Wave and Orographic	S	EX 1-3 km, P-F 6-12 5 km
29	2/20/75	1909-2130	E Sierra, 0-75 W 90 [illegible], 150 E Palmdale, CA	1 2 6-12	Mountain Wave and Orographic	S	EX 1-3 km, P-F 6-12 km
30	3/ 7/75	2142-0047	Owens Valley, 90 radius Edwards AFB	[illegible]-[illegible]5	Mountain wave and Vertical Wind Shear	Patchy L	P (Mtn Wave), G (Shear)
31	3/25/75	153[illegible]-2118	E-central CA to central-southern NV	8 5-13 5	Mountain Wave	Patchy VL	P-F
32	3/26/75	194[illegible]-2219	Lone Pine CA to Las Vegas, NV	12-13 5	Trough Wind Shear, Vertical Shear above Jet Stream	M	G-VG
33	3/28/75	1847-2048	0-160 [illegible] E, and SE Edwards AFB	2-14	[illegible] and Trough Wind Shear	M	G
34	4/ 4/75	18[illegible]-2130	Coaldale, NV - Fresno, CA - 300 SE Bishop, CA	4-4 5, 6-1[illegible]	Mountain wave	E	EX 4-4 5 km, G 6-13 km
35	4/ 5/75	1753-1946	Edwards AFB - Coaldale - Reno, NV	[illegible] 7-13 7	Mountain wave	Patchy VL	F
36	4/14/75	1907-2[illegible]41	Lone Pine - Antelope Valley - Mojave Desert	5-6, 10 5-	Mountain Wave, Vertical Wind Shear	None	F-G
37	4/17/75	1144-1301	Edwards AFB - [illegible], CA - Boulder City, NV	5 5-[illegible] 5	Trough Wind Shear	None	G
38	4/24/75	2210-00[illegible]4	Owens Valley, 200 radius Coaldale, NV	6-13 5	Mountain Wave	Patchy L	F-G
39	5/20/75	1813-2026	0-100 [illegible] Tehachap Mts	3-4 5	Mountain Wave	E	VG
40	5/20/75	2349-0153	Edwards AFB - Hector - Ontario - Bakersfield, CA	9 5-13	Mountain Wave and Vertical Wind Shear	Patchy L	F-G
41	5/21/75	2150-0034	Owens Valley, N to NE Edwards AFB	7-13	Trough Wind Shear	M	G
42	6/13/75	1811-2017	Clark Peak Range - 70 SW Las Vegas, NV - 55-90 E and SE Edwards AFB	1-4 5	Thermal Convection, Sea Breeze Convergence	S	EX
43	6/17/75	1903-2135	0-75 E of Sierra	7 5-10 5	Mountain Wave	Patchy L	F

KEY

Turbulence	Forecast Likelihood
L - Light	P - Poor
M - Moderate	F - Fair
S - Severe	G - Good
E - Extreme	VG - Very Good
VL - Very light	EX - Excellent

TABLE II. -A COMPLETE CHRONOLOGY OF MAT MISSIONS WITH THE B-57B AIRCRAFT (CONCLUDED)

(c) PHASE 3 (EASTERN U.S.,-THUNDERSTORM FLIGHTS, 8/5/75 TO 9/26/75)

NO	DATE	TIME (GMT)	SEARCH AREA (DIST IN km)	SEARCH ALTITUDE (km)	PURPOSE	MAT TURBULENCE ENCOUNTERED	FORECAST LIKELIHOOD OF TURBULENCE
44	8/ 5/75	1843-2135	150 SE Langley AFB, VA	12 2	Near Thunderstorms	None	VG
45	9/12/75	1416-1607	0-120 W Roanoke, VA	12 2	Near Thunderstorms	None	VG
46	9/23/75	1829-2043	Langley AFB, VA - Wilmington, NC	12 5-15	Near Thunderstorms	Patchy VL	VG
47	9/25/75	1642-1922	60-160 radius Langley AFB, VA	12 5-14	Near Thunderstorms	Patchy L	VG
48	9/26/75	1746-2005	0-55 E, 90 S, 135 W Langley AFB, VA	12-13 5	Near Thunderstorms	Patchy M	VG

KEY

Turbulence	Forecast Likelihood
L - Light	P - Poor
M - Moderate	F - Fair
S - Severe	G - Good
E - Extreme	VG - Very Good
VL - Very light	EX - Excellent

3. Phase 3: 5 Flights conducted from the NASA Langley Research Center over the eastern US, with emphasis on thunderstorm - related turbulence, during August - September 1975.

The classification of turbulence utilized in this report has been based upon observations of the normal acceleration records for the center of gravity in the following manner:

Lignt turbulence - frequently occurring peak c.g. accelerations of ± .10 to .25 g.

Moderate turbulence - frequently occurring peak c.g. accelerations of ± .25 to .60 g.

Severe turbulence - peak c.g. accelerations exceeding ± .6 g.

Although these critical values agree closely with the criteria mentioned for classifying turbulence in reference 12, the relatively low wing loading of the B-57B may have resulted in some overclassification of intensities in this report.

Table III is a summary of those missions which actually encountered and measured turbulence that could be classified as falling generally within the "clear air" category. (Low altitude mechanical turbulence, and thermal convective turbulence, not usually regarded as CAT, are included along with turbulence categories normally considered as CAT, such as jet stream wind shear turbulence, the turbulence measured on missions 47 and 48, which occurred entirely within the tops of cumulonimbus clouds, is excluded from further discussion.) The table classified turbulence by duration of encounter and altitude band. The duration of encounter is described as being patchy (i.e., non-continuous) or extended (i.e., more long-lasting). Three bands: (a) less than 3 km, (b) 3-6 km, and (c) greater than 6 km are used to describe the altitude of the turbulence.

TABLE III.- SUMMARY OF FLIGHTS ENCOUNTERING TURBULENCE BY DURATION OF ENCOUNTER AND ALTITUDE BAND

Altitude Band / Duration of Encounter	<10,000 ft. (3 km)	10-20,000 ft. (3-6 km)	>20,000 ft. (6 km)
PATCHY TURBULENCE ENCOUNTERS 15 Flights (40 runs)	Flight - Turbulence Extent	Flight - Turbulence Extent	Flight - Turbulence Extent
	28 - one run 2.5 min	19 - one run 2 min; one 4 min 34 - one run 4 sec, one 56 sec 42 - one run 51 sec	15 - three runs 30 sec-1 min 24 - four runs 1-3.5 min 29 - two runs 1-2 min 30 - one run 1.3 min; one 2.5 min 34 - one run 34 sec; one 2 min 38 - three runs 1-2 min; one 18 sec 40 - two runs with brief patches 41 - two runs brief patches 43 - two runs brief patches
	TOTAL: 1 Flight/1 run	TOTAL: 3 Flights/5 runs	TOTAL: 9 Flights/23 runs
EXTENDED TURBULENCE ENCOUNTERS 14 flights (48 runs)	Flight - Turbulence Extent	Flight - Turbulence Extent	Flight - Turbulence Extent
	8 - two runs 21-24 min 9 - two runs 20-22 min 20 - five runs 6-9 min 28 - three runs 9-15 min 29 - one run 13.5 min 33 - one run 9.5 min; one run 3.5 min	27 - one run 15 min; one 12 min 34 - one run 8 min - two runs 4.5 min 39 - three runs 8-9 min - three runs 3.5-5 min 42 - three runs 7-9 min - three runs 4.5-5 min	26 - one run 13 min - one run 6.5 min - three runs 2-4 min 30 - one run 5 min 32 - two runs 10-11 min - two runs 4-5 min 41 - one run 7.5 min - one run 3.3 min - four runs 1.5-3 min
	TOTAL: 6 flights/15 runs	TOTAL: 4 Flights/17 runs	TOTAL: 4 Flights/16 runs

It may be noted from the table that turbulence was encountered and measured on twenty flights. (Some flights are included in more than one category). Thirteen flights had patchy turbulence, comprising 29 distinct turbulence data-taking runs; extended turbulence encounters occurred on 14 flights (48 data runs). The encounters with patchy turbulence comprised one flight (1 data run) in the lowest altitude band, three flights (5 runs) in the middle band, and nine flights (23 runs) in the highest band. The extended turbulence encounters included six flights (15 runs) in the lowest, four flights (17 runs) in the middle, and four flights (16 runs) in the upper altitude categories.

Table IV presents the data for the 20 flights yielding significant measured clear air turbulence from the view points of the distances flown in turbulence of various intensities (light, moderate, severe), and the meteorological features most probably related to the turbulence occurrence. The table presents the flight number, date, altitude (km) of turbulence encounter (not search altitude as in Table III), the number of kilometers flown in turbulence intensities greater or equal to light, moderate, and severe, and the meteorological features most probably related to the turbulence. The turbulence encounter experience of the MAT B-57B project can be summarized from the TOTALS row at the bottom of the table. Over a 15 month period, 20 flights (out of 46 total) encountered significant turbulence; its intensity was measured on 77 runs. A summation of the distances flown in turbulence shows that approximately 4335 km of turbulence data in the "light" category, 1416 km in the "moderate", and 255 km in the "severe" category were recorded. If the 375 kt TAS (695 km/hr^{-1}) baseline airspeed typical of nearly all MAT missions (see FLIGHT OPERATIONS section) is assumed to apply for all turbulence encounters, these distances translate

TABLE IV.- SUMMARY OF NAT B57B MISSIONS ENCOUNTERING SIGNIFICANT TURBULENCE LENGTHS BY DISTANCE (km) FLOWN IN TURBULENCE OF VARIOUS INTENSITIES, AND MOST PROBABLE CLEAR AIR RELATED METEOROLOGICAL CONDITION

FLIGHT NO.	DATE	ALTITUDE OF TURBULENCE ENCOUNTER(S) (km)	NO. OF RUNS ENCOUNTERING TURBULENCE	TOTAL DISTANCE (km) IN TURBULENCE			MOST PROBABLE RELATED METEOROLOGICAL CONDITION(S)
				LIGHT	MODERATE	SEVERE	
8	6/19/74	0.5 - 1.1	2	300	0	0	Low Altitude Convection
9	6/20/74	0.5 - 1.1	2	480	0	0	Low Altitude Convection
15	11/8/74	6.2 - 9.1	3	47	0	0	Upper Trough and Jet Stream
19	11/26/74	5 - 6	2	71	0	0	Low Level Jet Stream with Vertical Wind Shear and Strong Horizontal Temperature Gradient
20	12/3/74	1 - 5.5	5	293	111	14	Appalachian Mountain Wave
24	12/17/74	5.9	4	112	1	0	Strong Vertical and Horizontal Wind Shears below Jet Stream
26	1/14/75	9.1 - 9.5	5	324	75	0	Upper Trough and Jet Stream
27	1/30/75	4.7	2	147	4	0	Low Level Jet Stream with Vertical Wind Shear Below
28	2/14/75	1.3 - 2.6	4	305	168	52	Low Altitude Wind Shear and Orographic Effects
29	2/20/75	1.2	1	108	66	20	Low Level Orographic Effects, Rotor Zone
		7.4	1	200	0	0	Mountain Wave
		10.7	1	15	0	0	Mountain Wave
30	3/7/75	14.3 - 14.5	3	77	0	0	Mountain Wave
32	3/26/75	12.0 - 13.5	6	331	177	0	Complex Orographic Effects in Death Valley, Vertical Wind Shear, Jet Stream
33	3/28/75	1.8 - 2.8	2	112	44	0	Low level Orographic Effects
34	4/4/75	4.0 - 4.4	5	168	161	70	Low Level Mountain Wave
38	4/24/75	10.8 - 11.6	4	58	0	0	Short Wave Trough and Orographic Effects
39	5/20/75	3 - 4.5	6	453	176	52	Mountain Wave and Intense Upper Front
40	5/20/75	12.1 - 12.4	2	16	0	0	Frontal Passage and Orographic Effects
41	5/21/75	7.3 - 7.6	8	230	105	0	Fast Moving Short Wave Trough with Vertical, Horizontal Wind Shears
42	6/13/75	1.6 - 4.5	7	464	317	47	Low Altitude Convection and Sea Breeze Convergence
43	6/17/75	8.8	2	24	11	0	Dissipating Mountain Wave
TOTALS			77	4335	1416	255	

to roughly 6.3 hrs. spent in light, some 2.1 hrs. in moderate, and some 0.5 hr. in severe turbulence during the program. In the research program, the B-57B was airborne for a total of 93.5 hrs. Thus, the aircraft was in light turbulence 6.7 percent, moderate turbulence 2.2 percent, and severe turbulence 0.5 percent of the time. The overall ratios of severe/light and moderate/light turbulence experienced in this program are larger than the average amounts found over the same altitude bands in reference 12. This probably reflects the fact that the MAT program actively sought turbulence, and thereby encountered more of the intense categories, than did the other turbulence search programs, which passively recorded turbulence encounters during routine operations.

Partitioning the lengths (or time intervals) of turbulence encountered according to probable meteorological cause is difficult because, as may be seen from Table IV, on several flights a combination of conditions was probably acting to contribute to the observed turbulence. Nevertheless, an approximate distribution based on the predominant conditions is presented in Table V. For each condition or combination, the table lists the number of flights (and associated data runs), the distances (km) flown in the three intensity categories, and the total distance flown in turbulence for each category. Table V shows that more low-level orographic turbulence was sampled during the program than that of any other category, and turbulence from low altitude convection was the second-ranked category.

Tables VI and VII present the MAT turbulence encounter data in a form which should assist investigations of the connections between the turbulence spectra to be derived from this project and the meteorological situation existing at the time of each flight. In this connection, it is recommended that the investigator utilize these two tables, along

TABLE V.- A RANKING OF MAT B-57B CLEAR AIR TURBULENCE ENCOUNTERS BY METEOROLOGICAL CONDITION

PREDOMINANT METEOROLOGICAL CONDITION	NUMBER OF FLIGHTS (DATA RUNS)	DISTANCE (km) IN TURBULENCE INTENSITY			
		LIGHT	MODERATE	SEVERE	TOTAL
LOW-ALTITUDE OROGRAPHIC	4 (17)	916	550	122	1588
LOW-ALTITUDE CONVECTION	3 (9)	1132	234	21	1387
MOUNTAIN WAVE, IN ASSOCIATION WITH INTENSE UPPER FRONT	1 (6)	453	176	52	681
HIGH ALTITUDE JET STREAM AND WIND SHEAR	3 (12)	483	76	0	559
MOUNTAIN WAVE	3 (10)	394	122	14	530
LOW ALTITUDE OROGRAPHIC, TOGETHER WITH MOUNTAIN WAVE	1 (3)	323	66	20	409
UPPER TROUGH OR UPPER FRONT	3 (14)	304	105	0	409
LOW ALTITUDE JET STREAM AND WIND SHEAR	2 (11)	218	4	0	222
SEA BREEZE CONVERGENCE	1 (2)	112	83	26	221
TOTALS	20 (77)	4335	1416	255	6016

with the applicable synoptic analyses, flight tracks, rawin soundings, etc. presented in Volume II (Appendix C), to gain an understanding of the micro, meso, and synoptic scales of meteorological variability accompanying the turbulence encounter(s) under study. Table VI summarizes individual turbulence runs for the 20 MAT B-57B flights where significant turbulence was encountered and measured. For each turbulence run, the start and finish points are given in terms of latitude and longitude, as well as the true heading (ground track) of the run in degrees. Then, as in Tables IV and V, the number of kilometers spent in turbulence of various intensities is tabulated. Table VII describes the temperature and wind variability encountered along the run, and gives additional details such as cloud cover. Using the results of these tables, and referring to Volume II (Appendix C), correlations can be made of the turbulence observed to the positions of mountain ranges, and weather fronts, jet streams and temperature gradients, etc. Reference 10 is an example of a flight analyzed in such a manner (Flight 32).

TABLE VI.- A LISTING OF MAT B-57B TURBULENCE ENCOUNTERS, BY DATA RUN

(a) Flights 8-24, positional data

Flight (date)	Data run/ altitude (km)	End points of data run				Run heading (deg. true)	Distance in turbulence (km)		
		Start		Finish					
		Lat. (N)	Long. (W)	Lat. (N)	Long. (W)		≥ Light	≥ Moderate	≥ Severe
8 (6/19/74)	1/0.46	37°05'	76°21'	36°06'	79°57'	240	130	0	0
	2/0.46	36°06'	79°57'	37°05'	76°21'	060	170	0	0
9 (6/20/74)	1/0.46	37°05'	76°21'	36°06'	79°57'	240	240	0	0
	2/0.46	36°06'	79°57'	37°05'	76°21'	060	240	0	0
15 (11/8/74)	1/8.2	36°48'	73°13'	38°39'	74°19'	020	12	0	0
	2/8.2	38°24'	73°38'	36°53'	76°11'	201	4	0	0
	6/9.1	36°53'	75°56'	34°57'	76°48'	211	31	0	0
	7/9.4	35°20'	76°45'	36°09'	76°12'	032	0	0	0
19 (11/26/74)	1/5.9	37°37'	72°39'	37°27'	72°36'	109	40	0	0
	2/5.9	37°27'	72°36'	37°41'	75°59'	287	1	0	0
	3/5.1	37°41'	74°53'	37°40'	74°57'	301	30	0	0
	4/5.1	37°35'	74°56'	36°52'	75°59'	141	0	0	0
	5/5.5	37°17'	74°41'	37°18'	75°28'	275	0	0	0
20 (12/3/74)	3/2.0	37°44'	78°55'	38°18'	71°46'	305	65	32	2
	5/2.0	38°15'	79°47'	37°44'	79°04'	125	53	0	0
	6/2.0	37°34'	79°13'	38°16'	79°32'	347	73	19	1
	7/2.0	38°13'	79°28'	37°38'	79°57'	223	49	31	3
	8/2.0	37°43'	79°51'	38°14'	79°18'	029	53	29	8
24 (12/17/74)	6/6.0	37°30'	77°19'	36°39'	77°46'	233	34	0	0
	7/7.0	36°52'	77°54'	37°57'	76°12'	068	39	0	0
	8/6.0	36°33'	77°20'	37°10'	77°55'	242	13	0	0
	9/6.0	37°10'	77°44'	36°03'	77°06'	092	26	1	0

TABLE VI.- Continued

(b) Flights 26-30, positional data

Flight (date)	Data run/ altitude (km)	End points of data run				Run heading (deg. true)	Distance in turbulence (km)		
		Start		Finish					
		Lat. (N)	Long. (W)	Lat. (N)	Long. (W)		≥ Light	≥ Moderate	≥ Severe
26 (1/14/75)	5/9.5	36°27'	78°45'	35°56'	80°22'	249	121	31	0
	6/9.6	35°51'	80°06'	36°03'	78°40'	070	54	22	0
	8/9.0	36°57'	79°57'	36°03'	77°15'	327	27	0	0
	9/9.1	37°51'	79°58'	37°03'	79°58'	237	59	22	0
	10/9.1	37°49'	79°58'	37°04'	77°09'	084	63	0	0
27 (1/30/75)	10/10.7	40°00'	73°45'	40°10'	73°31'	022	0	0	0
	13/10.7	40°39'	73°46'	39°07'	74°23'	222	0	0	0
	17/4.7	37°59'	74°41'	36°33'	76°31'	222	87	0	0
	18/4.8	36°36'	76°17'	35°10'	75°28'	022	60	4	0
28 (2/14/75)	4/1.6	34°44'	117°14'	34°36'	116°45'	102	84	42	6
	6/2.0	34°34'	116°51'	34°38'	117°59'	275	76	7	1
	7/2.6	34°55'	117°59'	34°39'	117°14'	061	21	4	0
	8/1.3	35°14'	117°28'	34°48'	118°05'	250	124	115	45
29 (2/20/75)	6/10.7	36°49'	118°21'	36°21'	117°05'	120	15	0	0
	7/7.4	36°11'	116°36'	36°49'	118°21'	300	20	0	0
	8/1.2	37°47'	118°38'	35°17'	117°39'	052	108	66	20
30 (3/7/75)	2/14.3	34°45'	118°34'	35°05'	117°25'	075	0	0	0
	3/14.8	35°46'	117°52'	34°19'	117°33'	174	0	0	0
	4/14.6	35°14'	117°14'	34°39'	117°47'	268	15	0	0
	5/14.4	35°12'	117°51'	35°08'	118°06'	247	7	0	0
	6/14.2	35°07'	118°21'	35°06'	117°42'	255	0	0	0
	8/14.5	34°39'	117°14'	34°39'	120°48'	255	55	0	0
	9/14.5	35°28'	117°46'	35°03'	117°31'	150	0	0	0

TABLE VI.- Continued

(c) Flights 32-38, positional data

Flight (date)	Data run/ altitude (km)	End points of data run				Run heading (deg. true)	Distance in turbulence (km)		
		Start		Finish					
		Lat. (N)	Long. (W)	Lat. (N)	Long. (W)		≥ Light	≥ Moderate	≥ Severe
32 (3/26/75)	2/13.2	36°36'	117°50'	36°48'	116°28'	075	44	39	0
	3/13.2	36°48'	116°04'	36°24'	115°41'	105	47	5	0
	4/13.2	36°17'	115°43'	36°48'	117°27'	284	110	78	0
	5/13.1	36°35'	117°31'	36°36'	117°57'	283	5	0	0
	7/13.1	36°29'	117°45'	35°57'	116°11'	105	20	5	0
	9/13.2	36°20'	115°52'	36°38'	117°25'	294	105	50	0
33 (3/28/75)	2/2.8	34°01'	116°42'	33°48'	116°36'	099	84	37	0
	3/1.8	34°05'	115°46'	34°06'	115°16'	096	28	7	0
34 (4/4/75)	2/4.4	37°21'	117°59'	37°21'	118°00'	340	1	1	1
	3/4.4	36°33'	118°03'	37°04'	117°34'	340	36	34	7
	5/4.0	36°49'	118°11'	37°31'	117°58'	160	50	49	9
	6/4.0	36°17'	117°34'	36°14'	117°59'	185	8	4	0
	7/4.0	36°40'	118°03'	37°05'	118°21'	336	73	73	53
38 (4/24/75)	3/11.6	37°53'	117°47'	38°11'	117°45'	071	3	0	0
	5/10.8	38°20'	116°59'	38°00'	117°46'	241	13	0	0
	6/10.8	38°07'	117°29'	38°48'	115°48'	061	19	0	0
	7/10.8	38°09'	115°58'	39°16'	116°41'	322	23	0	0
	8/10.8	38°59'	117°08'	38°49'	117°14'	215	0	0	0

TABLE VI.- Continued

(d) Flights 39-41, positional data

Flight (date)	Data run/ altitude (km)	End points of data run				Run heading (deg. true)	Distance in turbulence (km)		
		Start		Finish					
		Lat. (N)	Long. (W)	Lat. (N)	Long. (W)		≥ Light	≥ Moderate	≥ Severe
39 (5/20/75)	2/3.2	34°54'	118°07'	34°33'	117°42'	118	47	11	0
	3/4.1	34°29'	117°33'	34°55'	118°20'	301	39	15	0
	5/4.1	34°54'	118°07'	34°11'	116°53'	127	63	17	0
	7/4.2	34°24'	116°50'	35°10'	118°06'	304	100	42	2
	9/4.2	35°06'	116°38'	33°51'	118°04'	229	107	65	31
	10/4.2	33°58'	117°56'	35°14'	117°54'	357	97	26	19
40 (5/20/75)	3/12.4	34°23'	117°53'	34°48'	117°17'	149	7	0	0
	5/12.1	34°48'	116°21'	34°25'	115°36'	296	9	0	0
41 (5/21/75)	5/7.4	36°53'	119°42'	36°41'	118°18'	092	0	0	0
	6/7.4	35°24'	118°09'	34°51'	118°07'	178	3	0	0
	7/7.5	35°17'	117°45'	34°59'	117°05'	113	5	0	0
	8/7.5	35°14'	117°35'	35°46'	117°33'	358	34	5	0
	10/7.5	35°44'	118°04'	34°50'	117°50'	181	38	15	0
	12/7.5	34°59'	117°11'	35°03'	116°52'	078	86	44	0
	13/7.5	34°59'	117°11'	35°03'	116°52'	078	23	16	0
	14/7.5	35°10'	116°43'	35°09'	117°07'	266	17	17	0
	15/7.5	35°04'	116°58'	34°49'	117°54'	260	24	8	0

TABLE VI.- Concluded

(c) Flights 42 and 43, positional data

Flight (date)	Data run/ altitude (km)	End points of data run				Run heading (deg. true)	Distance in turbulence (km)		
		Start		Finish					
		Lat. (N)	Long. (W)	Lat. (N)	Long. (W)		≥ Light	≥ Moderage	≥ Severe
42 (6/13/75)	2/4.5	35°42'	115°48'	35°06'	115°13'	140	88	68	20
	3/4.5	35°59'	116°03'	35°10'	115°13'	322	103	69	0
	4/4.5	35°29'	115°59'	35°48'	115°27'	056	47	14	0
	6/1.6	36°00'	115°54'	36°20'	115°33'	161	104	83	0
	7/1.8	35°14'	115°31'	35°10'	115°27'	152	10	0	1
	8/3.3	34°25'	116°50'	34°39'	117°26'	295	47	26	8
	9/3.3	34°24'	117°05'	34°58'	117°16'	347	65	57	18
43 (6/17/75)	2/9.1	36°30'	118°27'	37°05'	118°19'	355	0	0	0
	3/8.8	39°24'	118°00'	38°46'	115°51'	105	8	0	0
	4/7.6	38°50'	115°52'	39°14'	116°36'	307	16	11	0
	7/10.7	38°03'	117°11'	39°48'	117°49'	298	0	0	0
	9/10.7	37°05'	117°44'	36°30'	118°11'	241	Patchy VL	0	0

TABLE VII.- A LISTING OF MAT B-57B ENCOUNTERS, BY DATA RUN

(a) Flights 8-24, meteorological data

Flight (date)	Data run/ altitude (km)	Average wind (deg/msec^{-1})	Significant variability on run				Remarks (cloud conditions, etc.)
			Temperature (°C)		Wind (deg/msec^{-1})		
			Gradient	Small scale	Gradient	Small scale	
8 (6/19/74)	1/0.46	Not available	Not available (data recording problems)				Scattered Cu at 1 km
	2/0.46	Not available	Not available (data recording problems)				Scattered Cu at 1 km
9 (6/20/74)	1/0.46	Not available	Not available (data recording problems)				Broken Cu at 1 km
	2/0.46	Not available	Not available (data recording problems)				
15 (11/8/74)	1/8.2	331/25	-37.5 → -40	±1	---	20° dir. changes	Cs 60 m below a/c
	2/8.2	337/35	-40 → -36	-1.5/2 km	35 → 38 → 28 msec^{-1}		Cs 60 m below a/c
	6/9.1	290/16	~0	-1.5/2 km	20 → 13 msec^{-1}		In thick Cs
	7/9.4	241/22	~0	~0	19 → 24 msec^{-1}	235-235°	In and out of thick Cs tops
19 (11/26/74)	1/5.9	246/60	Not available		Not available		(Overcast with tops at 2 km on all runs)
	2/5.9		Not available		Not available		
	3/5.1		Not available		Not available		
	4/5.1	242/34	Not available		Not available		
	5/5.5		Not available		Not available		
20 (12/3/74)	3/2.0	326/27	Waves of 6-8° amplitude		10 msec^{-1} higher in warm zones		(Large variations in turbulence intensity on all runs on this flight)
	5/2.0	318/28	Wavelengths 12 km		10 msec^{-1} higher in warm zones		
	6/2.0	328/25	Wavelengths 12 km		10 msec^{-1} higher in warm zones		
	7/2.0	330/28	4>5°	No waves	Min. speed 25 msec^{-1}		
	8/2.0	315/23	30 km wave, 7° amplitude		Min. speed 25 msec^{-1}		
24 (12/17/74)	6/6.0	234/18	-3.0	±1° in turbc.	8° dir. changes		Run parallel to As 3 km below a/c
	7/7.0	227/55	+4.5	±2° in turbc.	Direction constant		Cs at end of run
	8/6.0	243/37	-4.4	±1° in 1-2 km	Steady change of 14°		Ac bands 3 km below a/c
	9/6.0	227/61	+5.3	±1° in 2-3 km	223-220°		Cs at end of run

TABLE VII.- Continued

(b) Flights 26-30, meteorological data.

Flight (date)	Data run/ altitude (km)	Average wind (deg/msec^{-1})	Significant variability on run: Temperature (°C)		Significant variability on run: Wind (deg/msec^{-1})		Remarks (cloud conditions, etc.)
			Gradient	Small scale	Gradient	Small scale	
26 (1/14/75)	5/9.5	245/36	+2°C warming in middle of run		-13 msec^{-1}	235 → 260°	Scattered Cu on all runs, at 1.4 km altitude
	6/9.6	244/50	+1.2°C increase at end of run		+16 msec^{-1}	250 → 240°	
	8/9.0	229/62	+1-2°C in 2 → 6 km		-18 msec^{-1}, dir. constant		
	9/9.1	241/41	+1°C in 150 → 300 m		-8 msec^{-1}, dir. constant		
	10/9.1	237/50	None	None	+18 msec^{-1}	245 → 230°	
27 (1/30/75)	10/10.7	290/79	None	None	+8 msec^{-1} at end		Scattered Ci 300 m above a/c with patchy VL turbc. Occasional L-M turbc, As 90-150 m above a/c
	13/10.7	296/76	+1° in last 35 km		-8 msec^{-1} at end		
	17/4.7	303/42	-8.4	(±2-3 in	+5 msec^{-1} in middle		
	18/4.8	291/41	-8.8	2 → 3 km)	±5° direction changes		
28 (2/14/75)	4/1.6	277/21	-1.5	±1	±20° direction changes		Scattered Cu at 1.2 km, turbc. intensity variable on all four runs
	6/2.0	279/13	0	-2.5 mid run	±40° direction changes		
	7/2.6	283/16	±6 → 8 in 14-28 km waves		±4 msec^{-1}, dir. constant		
	8/1.3	285/18	±6 → 8 in 14-28 km waves		12 → 30 msec^{-1} shear in 70 km		
29 (2/20/75)	6/10.7	247/57	+4.5 wave in 34 km		+5-7 msec^{-1}, dir. constant		A/c 1.3 km above edge of Cs
	7/7.4	292/40	None	None	+5 msec^{-1}, dir. constant		At base of thick Cs
	8/1.2	259/13	11 → 13 in 32 km		2 → 23 msec^{-1}, 30° variation		(Clear)
30 (3/7/75)	2/14.3	Unknown	None	None	None	None	Large Cs layer 6 km below a/c (Turbulence along edge of Cs on runs 3-9, with cloud tops at 8.2 km)
	3/14.8	249/34	None	None	Speed varies	25 → 40 msec^{-1}	
	4/14.6	244/20	None	±1	4 msec^{-1} decrease		
	5/14.4	244/20	None	±1	None	None	
	6/14.2	244/20	None	±1	None	None	
	8/14.5	244/20	None	±1-3/20 km	10 msec^{-1} increase		
	9/14.5	240/35	None	+15/2 km	±5 msec^{-1}/2 km		

TABLE VII.- Continued

(c) Flights 32-38, meteorological data.

Flight (date)	Data run/ altitude (km)	Average wind (deg/msec^{-1})	Significant variability on run				Remarks (cloud conditions, etc.)
			Temperature (°C)		Wind (deg/msec^{-1})		
			Gradient	Small scale	Gradient	Small scale	
32 (3/26/75)	2/13.2 3/13.2 4/13.2 5/13.1 7/13.1 9/13.2	355/26 314/24 304/12 353/27 344/36 326/15	(See appendix C, text, and figure C-59, also see reference 10)				
33 (3/28/75)	2/2.8 3/1.8	030/7 030/7	One 2.2 cooling at end of run Not available		Speed decreases from 10 → 1 msec^{-1}		(Clear)
34 (4/4/75)	2/4.4 3/4.4 5/4.0 6/4.0 7/4.0	Not available 235/17 279/11 Not available 250/13	None ~0 -1.0 1.5/2 km waves Two warm zones (4°C), 5 km long	None ±1/3 sec 2/5 sec	None ±5 msec^{-1} in 5 sec 240 → 320°, 5 → 10 msec^{-1} Not available 5 → 20 msec^{-1}	None	(As rotor clouds observed 5 → 15 km windward of all runs)
38 (4/24/75)	3/11.6 5/10.8 6/10.8 7/10.8 8/10.8	240/47 242/35 240/45 230/45 245/38	None +.4 -2 <1.0 None	±.5 ±.2 ±.2 +1/2 sec None	240/45 → 230/50 236/38 → 246/33 230-240,/42-47 msec^{-1} 234/52 → 227/38 None	None	Some Cu over mountains Some Cu over mountains Overcast, tops 4.6 km Overcast, tops 4.6 km Overcast, tope 4.6 km

TABLE VII.- Continued

(d) Flights 39-41, meteorological data

Flight (date)	Data run/ altitude (km)	Average wind (deg/msec^{-1})	Significant variability on run: Temperature (°C), Gradient	Significant variability on run: Temperature (°C), Small scale	Significant variability on run: Wind (deg/msec^{-1}), Gradient	Significant variability on run: Wind (deg/msec^{-1}), Small scale	Remarks (cloud conditions, etc.)
39 (5/20/75)	2/3.2	(270-290/ 28-38 on all runs)	None	4 → 5/2-3 km	Backing 270-250° during run		Overcast Cu 300-900 m below flight level on all runs
	3/4.1		Sharp gradients -4/10 km, +6/4 km		Wind decrease in turbulence		
	5/4.1		Short waves, +4/2 km		Wind decrease in turbulence		
	7/4.2		15	+5/2 km waves	±7° dir. changes/km		
	9/4.2		+4	+10/2 km	±10°, ±5 msec^{-1}/km changes		
	10/4.2		-10	Two 2.5/4 km waves	±20-30° dir. changes in 2 km		
40 (5/20/75)	3/12.4	(270-290/ 28-38)	None	±2	None	None	Scattered-broken Cu, tops 4 km
	5/12.1		None	None	None	None	
41 (5/21/75)	5/7.4	010/30	None	None	None	None	Overcast Cu, with buildups to 4.6 km
	6/7.4	360/27	None	1/1 km	360/27 → 345/20		Cs to north, base 7.3 km
	7/7.5	350/25	<-1°	Two patches ±0.3	360/27 → 342/21		Cs to north, base 7.3 km
	8/7.5	010/17	None	±0.2	20° dir. changes in .5-4 km waves		Scattered Cu near 3 km
	10/7.5	035/26	None	±0.3	20° dir. changes in 1-2 km		(See runs 5-8)
	12/7.5	025/20	None	±0.3			(See runs 5-8)
	13/7.5	355/15	None	±.2 → .3/.5 km	±5 → 2 msec^{-1}, and 30° dir. changes in 2 km		(See runs 5-8)
	14/7.5	020/15-20	None	+2/4 km	±4 msec^{-1}, ±5°		(See runs 5-8)
	15/7.5	010-020/20	+1.4	±.1	±4 msec^{-1} → ±1 msec^{-1}		(See runs 5-8)

TABLE VII.- Concluded

(e) Flights 42 and 43, meteorological data

Flight (date)	Data run/ altitude (km)	Average wind (deg/msec^{-1})	Significant variability on run				Remarks (cloud conditions, etc.)
			Temperature (°C)		Wind (deg/msec^{-1})		
			Gradient	Small scale	Gradient	Small scale	
42 (6/13/75)	2/4.5	(Direction highly variable on all runs, speeds 2-10 msec^{-1})	None	±0.4	120 → 270°	±2 msec^{-1}	In low altitude convective turbulence
	3/4.5		None	±2/2 km	070 → 230°	±2 msec^{-1}	In low altitude convective turbulence
	4/4.5		None	Two +1.5/2 km	127 → 265°	±2 msec^{-1}	In low altitude convective turbulence
	6/1.6		None	Two +1/.6 km	020 → 350°	±1 msec^{-1}	In low altitude convective turbulence
	7/1.8		None	+1/km	100 → 180°	±2 msec^{-1}	In "dust devil"
	8/3.3		None	1.5/.3 km	140 → 040°	±2 msec^{-1}	In sea-breeze convergence area
	9/3.3		None	+2/.5 km	140 → 040°	±2 msec^{-1}	In sea-breeze convergence area
43 (6/17/75)	2/9.1	(Not available)	None	None	None	None	Lenticulars near flight level
	3/8.8	↓	None	None	Not available		Lenticulars imbedded in Cu
	4/7.6	↓	None	±1	Not available		Lenticulars imbedded in Cu
	7/10.7	↓	None	None	Not available		Lenticulars dissipating
	9/10.7	↓	None	None	Not available		Lenticulars dissipating

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ref. 8). The procedure required that electrical power be maintained on the inertial navigation system (INS) during the Schuler check, and the use of special ground equipment. In addition to the requirement for special ground equipment, refueling at a forward base to expand the turbulence search radius would have required shutting off power to the instrumentation. Before the mission could have continued, in such a case, the above-mentioned 1 1/2 hour checkout procedure would have been required. Due to these constraints, therefore, operations were limited to a single base (i.e., Langley AFB, VA, or Edwards AFB, CA) during each phase of the program. There were several occasions wherein operations from a forward base would have allowed sampling jet streams, etc., which otherwise lay outside the operational radius of the aircraft. The mentioned difficulties attendance to such operations, however, lead to the conclusions that having tip tanks on the aircraft, or using a longer range aircraft, would be preferred to staging from forward bases with the existing instrumentation system.

At Langley AFB delays in takeoff of up to 20 minutes occasionally occurred due to heavy military air traffic. In operations from each base, three or four missions had delays between 15 and 30 minutes during climbouts because of heavy commercial and military traffic. In some instances the meteorological conditions appeared highly favorable for mountain wave turbulence over Baja California (Mexico) however, no missions were flown out of Edwards AFB to northern Mexico, although this was within the operational radius of the project aircraft, because of the extensive delays that are usually necessary in order to obtain clearance to fly over Mexico. Occasionally, turbulence runs were prematurely terminated because a continuation would have resulted in the aircraft entering a restricted area.

The initial program sampling objectives called for the measurement of turbulence associated with jet streams, low altitude flow and

Appalachian Mountain waves in the late winter of 1973-4 while the B-57B was based at LaRC. Then, the airplane was to be based at DFRC to sample mountain wave turbulence during the seasonal peak of the Sierra mountain wave activity from late February through April 1975. Turbulence associated with dry thermal convective activity was also to be sampled from DFRC during the May – June 1975 period. A delay of approximately four months in preparing the aircraft resulted in initation of sampling missions in June 1974. This delay ordinarily would have had little impact on the sampling obtained during the program. During late 1974, however, the frequency of strong jet stream activity within range of LaRC was significantly less than normal, this resulted in a reduced amount of jet stream turbulence samplings.

Based on the MAT B-57B experience, it is believed that future clear air turbulence investigations should consider the following recommendations.

Aircraft Operations

1. Utilize an aircraft with a long operational radius, both for increasing the size of the search area or for increasing the on-station sampling time.

2. Operate from a base which has a high percentage of VFR weather and is within range of a variety of meteorological conditions such as mountain waves, jet streams, thermal convection, sea breeze convergence and terrain-related low altitude turbulence (e.g. Edwards AFB).

3. When practicable, schedule flight times to interface with the upper-air analysis and forecasting schedule as closely as possible.

Turbulence Instrumentation

1. Configure the airborne instrumentation system to be capable of independent operations from forward bases. The system should be capable of a rapid start-up time to allow launching the aircraft to become airborne quickly for investigating transient turbulence phenomena, such as those found in thunderstorms and rapidly moving upper air fronts.

2. Minimize pilot workload by locating displays and switches in the observer's compartment, such as·

a. On-off data switch

b. Primary digital clock

c. More sensitive altitude readout

d. INS displays, enabling the observer to determine ground tracks more easily and accurately, and read out winds directly.

Turbulence Sampling

1. Utilize the full-time project-dedicated flying meteorologist/observer concept.

2. Solicit reports from other search aircraft (or dedicated "probe" aircraft) on turbulent conditions. Request that probe-type aircraft remain in the turbulent area long enough to evaluate it for the data sampling aircraft.

3. Photograph clouds as appropriate for documenting turbulent situations. (See examples in the second volume.)

4. Obtain aircraft temperature soundings upstream and downstream, as well as in the turbulent area, utilizing a high rate of descent to discern local atmospheric structure in the vertical.

5. Obtain special rawinsonde ascents in dynamic situations, utilizing a network where practicable (e.g. ref. 13).

6. Maintain liaison with FAA Air Traffic Control on mission needs, to enable achieving as much turbulence pattern time as practicable.

Turbulence Forecasting

1. Actively seek PIREPs from aircraft operating within the operational radius of the research aircraft through Air Traffic Control communications. Make best use of reports from military and/or other civilian research aircraft, when operating from bases such as Langley or Edwards.

2. Employ mesoscale analyses giving the altitude(s) and magnitudes of maximum wind shear, both in the horizontal and the vertical directions (either manual (as, e.g., in ref. 13) or automated analyses could be used).

3 Qualitative considerations and nomograph techniques (ref. 14) should be used to isolate mountain-wave CAT and eliminate some non-promising CAT situations.

4. Refine techniques for forecasting and analyzing the location of turbulence near moving upper level mesoscale troughs (these troughs provided the best cases of continuous, high-intensity turbulence encountered in the program).

5. Employ and evaluate automated forecast aids, such as the parametric approach of reference 15 and the construction of isentropic cross sections, as, e.g., in references 16 and 17, for narrowing the areas to be probed for turbulence.

CONCLUDING REMARKS

The results of forty-six clear air turbulence-sampling missions performed with an instrumented B-57B aircraft have been documented from a meteorological viewpoint. The data have been presented in a manner designed to allow correlation of the turbulence spectra derived from the project with the synoptic and mesoscale conditions associated with the turbulence.

In the program, clear air turbulence samples were obtained under a variety of weather conditions including mountain waves, jet streams, upper fronts and troughs, strong low-level winds, and thermal convection. CAT was encountered and measured on 20 flights comprising 77 data runs. In all, approximately 4335 km were flown in light, 1416 km in moderate, and 255 km in severe turbulence during the program.

The flight planning, operational and weather forecasting aspects of the MAT program have been discussed. It was concluded that the practice of engaging the full-time services of a project meteorologist - airborne observer was particularly productive in obtaining a high frequency of turbulence encounters and conserving project resources. Suggestions for planning future turbulence forecasting/sampling efforts were also presented.

APPENDIX A

WEATHER FORECASTING FOR OPERATIONS

Overall Activities of the MAT Meteorologist-Airborne Observer

For MAT operations staged from the NASA Langley Research Center (LaRC), the NASA Flight Services Office meteorologists were responsible for the flight clearance weather briefings. In the operations from the NASA Dryden Flight Research Center (DFRC), USAF Air Weather Service personnel at the Edwards AFB Weather Station had this responsibility. However, the MAT project meteorologist-observer had responsibility for planning the turbulence sampling missions on a day-to-day basis. His concerns included the areas of pre-flight forecasting, consultation on flight planning, in-flight observations and pilot assistance, and post-flight analysis.

In general, the pre-flight forecasting task comprised giving an advanced outlook, a daily alert forecast, and a detailed flight-planning forecast. In the advanced outlook, the development of the general weather situation was monitored and preliminary turbulence outlook forecasts were issued one or two days in advance of a possible research flight. These outlooks were useful primarily in scheduling activities of ground support personnel and conserving project resources. In the daily alert procedure an updated forecast was prepared as early as possible in the day. This was used to alert ground support personnel and the pilot. If the outlook for turbulence was low, these personnel could be released to other duties. If it was fair or better, support operations were initiated in preparation for a flight. Meteorological analyses (mainly for levels of 500 mb and above) were prepared where required, utilizing weather teletype data. For example 500 and 300 or 250 mb charts were prepared from teletype data, to identify regions of strong horizontal wind shears, upper air fronts (i.e. fronts not extending to the surface), sharp tropopauses, etc. (In most cases the flight time was at such an hour that the latest NMC analyses were not yet available in the weather station, so the hand drawn analysis was necessary.) For flight planning purposes, the project meteorologist briefed the research pilot on the areas and altitude bands where turbulence might be expected on the day of operation and on the likely movement and intensification/dissipation of any turbulence activity. The two crew members worked out a flight plan compatible with the forecast situation, the sampling priorities, and aircraft range and ATC constraints.

The project meteorologist was able to assist the pilot by sharing portions of pilot workload other than controlling the airplane such as aiding in navigation to and within the search areas, apprising the pilot of headings and altitudes to be maintained while penetrating the turbulence patches, monitoring turbulence-related instrumentation, switching recording instrumentation on and off to obtain wind and temperature soundings, recording significant events (e.g. blowing dust, sharp temperature changes, roll clouds) and their locations on a voice tape cassette, taking cloud photographs and advising the pilot of the desirability to modify the original flight plan while airborne after turbulence reports from other aircraft were received or after a promising area was found to be without sufficient turbulence for data sampling.

On nearly all flights aircraft soundings of temperature and wind were recorded on magnetic tape from takeoff to some arbitrary altitude (usually above 10 km), and especially in areas of significant turbulence. In addition, temperature readings and other data were voice-recorded on cassettes both during takeoff and landing and periodically during periods of flight where the aircraft changed altitude. Aircraft positions and related data were voice-recorded each minute during turbulence-sampling runs, to be used later in wind calculations. Turbulence meter indications were recorded during turbulence runs. Aircraft positions and headings were noted before and after turns, in order to reconstruct flight tracks. Cloud observations included cloud type, altitude and coverage, cloud photographs were taken whenever the cloud form (e.g. rotor or lenticular clouds) was indicative of turbulence, wave activity or other air movement-related phenomena. (Photographs taken on MAT missions appear in the second volume.)

After each flight the project meteorologist participated in the debriefing and, utilizing his notes and recollections, documented the significant events of the flight. Information, such as winds, temperatures and cloud cover, recorded on the tape cassette located in the observer's compartment, was extracted, documented, and analyzed, usually on the day following the flight.

Forecast Inputs

The inputs utilized in making the day-to-day turbulence forecasts for MAT missions were as follows.

(1) Standard NWS Products. (As posted in the NASA Langley Research Center Flight Services or the Edwards AFB Weather offices.)

These included facsimile (FAX) analyses and forecast charts of constant pressure surfaces, significant weather, as well as teletype data (rawinsonde, PIREPs, AIRMETs, SIGMETs, etc.). A complete listing of the products utilized is found in the section on forecasting procedures.

(2) USAF Forecasts

The Air Weather Service's (AWS) Fifth Weather Wing is co-located at LAFB. Arrangements were made permitting consultation with USAF AWS personnel concerning forecasts or reports of significant turbulence within the operational range of the B57B. As anticipated, the turbulence forecasts from the NASA Flight Services Office, NWS and USAF were similar in the majority of cases. This gave added confidence for planning MAT operations. Also, the availability of FAX and TWX data from both NWS and USAF provided backup when weather teletype outages occurred.

In the operations from the NASA Dryden Flight Research Center (DRFC) both NWS and USAF FAX and TWX data were again available, but all data, and assistance in forecasting, were provided by USAF Base Weather Station personnel. Their assistance also included hand-plotted and analyzed upper air charts, and plotting of rawinsonde data.

(3) Northwest Airlines Turbulence Plot Advisories

Since NWAL employs a somewhat different analysis procedure for forecasting CAT, an additional teletype was installed in the LaRC Flight Services Office for the receipt of NWAL TP (Turbulence Plot) Advisories. These TP advisories were utilized in operations from LaRC, since some TPs applied to areas within the B-57B operational radius.

(4) Special NWS Support

During the first phase of the program, the Spaceflight Meteorology Group (SMG) of NWS provided consulting support to the MAT project under a contract. Discussions with SMG were usually for the assessment of likelihood of turbulent conditions on flight day or one-two days in advance of a MAT operation.

(5) Regular Pilot Reports (PIREPs)

Checking the PIREPs available in the Weather Stations was a vital part of the mission planning procedure. NASA pilots engaged in research and pilot proficiency missions from either LaRC or DRFC were requested to radio in the presence or absence of turbulence so that such information could be used in planning the search patterns for the day's MAT operations (see (c)). Similarly, fighter and transport squadrons operating out of Langley AFB were briefed on MAT operations and requested to make additional efforts to report significant turbulence encounters to the Langley AFB Weather Station. Excellent cooperation was obtained from Air Traffic Control Center personnel who promptly forwarded PIREPs of turbulence to the MAT aircraft in flight.

(6) Special Aircraft and Rawinsonde Observations

On several occasions pilots who were engaged in pilot proficiency or other missions at LaRC or DFRC were able to probe areas of reported turbulence. This source of data had the following advantages:

a. Conservation of program resources - in situations where the synoptic condition suggested that previously reported turbulence should be dissipating, checking with an aircraft already flying in the area of interest could verify this fact. In this manner some unproductive missions were avoided.

b. Where more than one turbulent area was thought possible on a given day, reports from other aircraft helped decide which area(s) to probe.

c. Monitoring the movement of previously reported areas of CAT helped to maximize the probability of encountering CAT and aided in defining the turbulence search patterns at an early stage for coordination with ATC. The most useful missions from both LaRC and DFRC were those in which two PIREPs were obtained, one which located turbulence 1-2 hours prior to the sampling flight, and another very close in time to the B-57B takeoff. This procedure served as a check on the persistence and movement of the turbulent region.

Rawinsondes

In synoptic situations which appeared to be especially promising for the development of turbulence, additional sounding data were sought through the use of special rawinsonde releases. During the program 10 rawinsondes were released from east coast sites to support operations out of LaRC, these were handled by NWS-SMG under the consulting contract mentioned above in (4). Five special rawinsonde releases were made from Edwards AFB, and coordinated by the USAF Flight Test Center. These releases were utilized in post-flight analyses.

Forecasting Procedure

As distinct from the forecast inputs just described, the forecasting procedure for a given day's operation usually involved using the following briefing materials, in the approximate order and in the manner indicated.

(1) Rawinsonde Teletype Data

As mentioned previously, temperature soundings for several stations were hand-plotted to estimate the atmospheric stability and the tropopause characteristics over the flight area. Values were extracted for wind speed and wind direction and vertical wind shears were calculated.

(2) 500 mb FAX Charts and Progs

The FAX charts were used to make the same evaluations as in the hand-drawn charts and the prognostic charts (progs) when flights were scheduled later in the day.

(3) Turbulence Progs/SIGMETs

The FAX low and high level significant weather progs were used as an aid in forecasting turbulence location and intensity and cloud height. Updated teletype forecasts of turbulence were perused.

(4) PIREPs (Teletype pilot reports)

Teletype pilot reports were scanned for the presence or absence of turbulence.

(5) 850 and 700 mb charts

Ridge-level wind speeds and directions were studied to discern possible mountain wave turbulence conditions, in accordance with established criteria, as, e.g. in ref. 18.

(6) Standard Level Winds Aloft Plots

These charts were used to give an indication of wind speeds and directions as well as horizontal wind shear regions.

(7) 500 mb vorticity charts and progs

Their primary use was for locating areas of maximum wind curvature, horizontal wind shear, temperature advection, and trough movement.

(8) Radar Summary Charts

Echo heights were used as estimates of cloud tops in squall lines or isolated thunderstorm situations and the speed of the squall line movement was used to forecast the movement of the associated turbulence.

(9) Surface Map

The general synoptic situation was viewed for occurrences of turbulence-generating situations (e.g., thunderstorms, cold fronts, etc).

(10) Tropopause heights and maximum wind forecasts

Tropopause discontinuities or dropoffs (steep gradients in the height of the tropopause) were suspected areas of turbulence. Maximum wind forecasts gave locations of jet streams and, at times, indicated zones of strong horizontal shear.

(11) Other Products:

NWAL turbulence plot advisories and USAF GWC turbulence forecasts were also utilized.

Merging of briefing materials into the MAT forecast

All the briefing materials described here were not used in a highly objective manner but rather in a flexible way to try to exploit each weather situation to the best advantage. This was necessarily the case, for no method of forecasting CAT with complete reliability is known to exist. Rather, the attempt was to study all readily available information for synoptic or mesoscale patterns suggesting the existence of turbulence. The array of briefing materials listed here was not fully adequate, some recommendations for additional analyses and forecast aids are listed in the section on Recommendations for Future Programs. Of the present list, pilot reports (PIREPs), especially those derived from other NASA aircraft, were probably the most helpful in successfully pinpointing areas of turbulence. However, this does not mean that PIREPs of turbulence are, by themselves, sufficiently reliable indicators of persistent turbulence to warrant disregarding the other briefing aids. Indeed, the most valuable PIREPs were those resulting from a NASA aircraft's probing a particular area, based on the project meteorologist's forecast of possible turbulence therein. For turbulence associated with clouds or topographic features such as rotor activity and convection, either PIREPs or meteorological analysis alone may have been adequate for mission planning purposes. However, in the case of clear air turbulence associated with moving trough lines or shear layers, the analyses and judgement of a project-dedicated meteorologist was vital in identifying the turbulence condition reported in PIREPs and forecasting the movements and persistence of the turbulence, so that the probability of sampling it could be maximized, both by other NASA aircraft and the MAT aircraft itself.

Forecasting Vs. Turbulence Encounters — An Overview

The MAT B-57B program, comprising 46 flights, did not constitute a sample large enough to allow a valid statistical evaluation of the turbulence forecasting techniques employed. In addition, other factors made such an evaluation inappropriate. First, one aircraft is very limited in its ability to sample a sufficiently large atmospheric volume to thoroughly verify a forecast of turbulence. Second, project sampling priorities sometimes resulted in the aircraft flying to areas other than those most likely to be associated with turbulence. This was because samples of turbulence were desired from a variety of synoptic or mesoscale conditions, and if the data needs in one category (e.g., jet stream turbulence) had been met through previous missions, the decision was made to seek data from another category where more data was needed (e.g., mountain wave). Also, it sometimes was desirable to schedule a mission even when the assessed likelihood of encountering turbulence was not particularly high, in order to obtain data from a particular meteorological condition. Third, the forecasting basis is mixed, with many of the missions being directed to locations where turbulence had already been reported by PIREPs or probe aircraft, rather than to areas that appeared favorable for turbulence on the basis of weather map considerations alone. With this influence on the turbulence forecasts, it is impossible to evaluate them with complete objectivity. The summary of turbulence encounter experience, presented in Table A-1, is discussed in the paragraphs below.

Of the 46 MAT missions, 37 were predicted by the MAT forecaster to have a fair or better (i.e., more than 1/3) chance of encountering measurable turbulence. On two of the 37, the turbulence instrumentation was not operational, but they are included here because any encounter with forecasted turbulence, whether recorded by the instrumentation or not, is, of course, regarded as a forecast success. During one of the 37 flights (No. 2), the area where turbulence was expected was deliberately avoided, to allow instrumentation checkout in smooth air. On another two flights (No. 18 and 21) the missions were aborted before the suspected turbulent areas could be probed. Thus, for 34 missions in which turbulence was expected, and the turbulence search was actually carried out, the turbulence encounter experience may be discussed.

Twenty-three (23) of the 34 missions encountered forecasted turbulence. (This agrees with the discussions for Table III through VI, which were based on the 22 flights with measured turbulence (20 in CAT, and 2 in cumulonimbus clouds), and also on flight 3, during which high altitude jet stream turbulence was encountered, but not measured. This constitutes an overall encounter success of 70.6 percent. If the turbulence encounter success is studied with respect to the predominant meteorological conditions of Table V, the results are as ranked in Table A-1. It will be noted that 24 successes are listed in the Table. This is because Flight 42 had two successes--one in encountering

TABLE A-1.- AN ASSESSMENT OF TURBULENCE ENCOUNTER SUCCESS IN THE MAT B-57B PROJECT, VERSUS PREDOMINANT METEOROLOGICAL CONDITION

PREDOMINANT METEOROLOGICAL CONDITION	NUMBER OF ENCOUNTERS FORECAST	NUMBER OF SUCCESSES	SCORE (%)	ENCOUNTERS WITH/WITHOUT PIREPS		MISSES WITH/WITHOUT PIREPS	
OROGRAPHIC	4	4	100	3	1	0	0
THERMAL, CONVECTIVE	3	3	100	0	3	0	0
MOUNTAIN WAVE, PLUS INTENSE UPPER FRONT	1	1	100	1	0	0	0
HIGH ALTITUDE JET STREAM AND WIND SHEAR	5	4	80	3	1	0	1
MOUNTAIN WAVE	6	3	50	2	1	2	1
OROGRAPHIC, PLUS MOUNTAIN WAVE	1	1	100	0	1	0	0
UPPER TROUGH OR UPPER FRONT	5	3	60	3	0	2	0
LOW ALTITUDE JET STREAM, AND WIND SHEAR	3	2	66	1	1	1	0
SEA BREEZE CONVERGENCE	1	1	100	0	1	0	0
NEAR THUNDERSTORMS	5	2	40	0	2	1	2
TOTALS	34	24	70.6	13	11	6	4

sea breeze convergence aloft; the other in encountering low altitude thermal convection. The table shows that very good results (100 percent forecast accuracy) were obtained in encountering low altitude orographic and sea breeze related turbulence, mountain-wave turbulence in connection with other conditions (upper fronts and low altitude orographic turbulence), and thermal (convective) turbulence. Moderate success was obtained in encountering turbulence predicted for jet streams of both low-and high-altitude categories, and turbulence associated with upper troughs and fronts. A success percentage of 50 was obtained in connection with pure mountain wave situations, and one of 40 percent in clear air near thunderstorms.

The high success categories were not unexpected, due to the relative abundance (from surface weather stations) of wind and temperature data at low altitudes for forecasting the turbulence, and the generally higher probability of turbulence at lower altitudes. The less than perfect record for troughs and upper fronts is not too surprising, because these features were moving rapidly, the turbulence at any location was expected to be transitory, and because of the relative paucity of observations (derived from the rawinsonde network) for delineating the structure of short-wave troughs. Several factors acted to depress the frequency of Sierra mountain waves in the late winter and early spring of 1974-75 (see Appendix B).

The contribution of PIREPs to successful turbulence sampling missions may be partially assessed from the data presented in Table A-1. Turbulence was encountered in 13 of 19 (68 percent) of the missions for which PIREPs were available, compared to 11 of 15 (73 percent) of the missions without PIREPs. But it can be inferred from the table that the planning for sampling of jet stream, wind shear and upper fronts or troughs depended strongly on PIREPs. Only 2 of 10 missions to sample these features were conducted without PIREPs and the 70 percent overall success is very good considering the scale and movement of these features.

The quality of PIREPs also enters implicitly into this evaluation. In retrospect, it is believed that some of the PIREPs which influenced the selection of sampling routes should have been given less weight. These may be characterized as being incomplete in stating the aircraft type, intensity, or duration of the turbulence encountered. The most reliable PIREPs were obtained from research pilots who had been briefed on the program's sampling objectives and operational procedures.

APPENDIX B

MOUNTAIN WAVE CONDITIONS ENCOUNTERED

A forecasting success of 50 percent was obtained for mountain wave turbulence situations in the operations from Edwards AFB (see Appendix A), this was lower than expected. The reasons for this low success, along with the project's experience in mountain wave situations, are the subject of this appendix.

Meteorological conditions during the late winter and spring of 1975 were not favorable for producing the number of strong Sierra mountain wave situations typical for an average year. An abnormally high frequency of deep trough and cutoff low systems either caused or was associated with one or more of the following conditions not favoring Sierra waves.

1. Extensive cloudiness and precipitation over the Sierra were conditions which tended to inhibit wave formation by suppressing the development of temperature inversions. Inversions represent stable layers within which wave enhancement is increased below the ridge line. The cloudiness also was related to conditional static instability in the layers above the ridge.

2. The strongest westerly or southwesterly winds lay well to the south of the Sierra due to the penetration of polar air further southward than is usually experienced during a normal winter. To set up a good Sierra wave, strong winds from these directions are needed over the Sierra itself. Instead, there was a greater than normal number of days with both ridgetop and upper level winds blowing from the north or northwest, both these directions are unfavorable for Sierra wave development because the winds have only a small component perpendicular to the ridge line.

3. On some moutain wave flights rapidly changing wind directions, both at the surface and aloft, resulted in relatively short periods with winds parallel at all levels. Persistence of parallel winds throughout an appreciable depth of the troposphere, in a direction nearly perpendicular to the moutain range ridge line, is generally accepted as a requirement for the vertical propagation of the mountain wave through the troposphere and into the stratosphere.

In all, eight flights were forecast to encounter mountain wave-type turbulence (Nos. 20, 29, 30, 31, 35, 36, 39, 43). Successes were obtained on five of these (Nos. 20, 29, 30, 39, 43). On two, however, other factors combined with a mountain wave to cause the turbulence. (On flight 29, the turbulence was terrain--as well as mountain wave-related; on flight 39, an intense upper front was also present.) The remaining three encounters were related solely to mountain waves. Of these, flight 20 encountered turbulence in the lee of the Appalachians at altitudes lower than 5.5 km, flight 30 encountered turbulence above 14 km in a wave associated with the San Gabriel Mts., and flight 43 encountered a Sierra wave which was in the dissipating stage. There were three missions failing to encounter forecast mountain wave turbulence (flights 31, 35, 36), despite pilot reports of moderate turbulence preceding the MAT mission for flights 31 and 36. On flight 31, the wind was veering toward the north, and cloudiness was extensive, both effects probably caused the turbulence to cease by the time the B-57B penetrated the area. On flight 35, thermal inversions were completely absent from tne soundings; this probably contributed to early dissipation of the wave activity. On flight 36, the dissipation of the turbulence by the time of the B-57B's search was marked by increasing cloud cover and diminished wave activity.

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