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Measurements of Sonic Booms Due to ACM Training at White Sands Missile Range

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FOR THE COMMANDER

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SUMMARY

A study has been conducted to measure and document the C-weighted day-night level (CDNL) of sonic booms due to air combat maneuver (ACM) training. Measurements took place in the Lava/Mesa airspace at the White Sands Missile Range, New Mexico. The primary ACM activity in this airspace is F-15s from Holloman AFB. Thirty-five automatic sonic boom monitors (a combination of USAF BEAR and SBM-1 units) were deployed for a period of six months. All operations schedule and airspace clearance data were collected so that sonic booms could be correlated with specific events. A sample of air combat maneuver instrumentation (ACMI) tracking data was also collected.

During the six-month measurement period, 4,600 ACM sorties were flown, 72 percent of which were F-15s. A total of 591 sonic boom events were recorded (2,246 individual boom recordings; each sonic boom was detected by an average of just under four monitors), of which 506 were associated with ACM training. There was thus 0.11 sonic boom per sortie. For those missions for which ACMI tracking data were obtained, sonic boom ray tracing calculations agreed well with the measured boom occurrences.

Near the middle of the airspace, the average sonic boom had a peak over-pressure of slightly under 1 psf, there was an average of 0.5 boom per day, 99 percent of all sonic booms were below 4 psf, and none exceeded 7 psf. CDNL contours were fitted to the measured data. It was found that these contours could be represented by a two-dimensional Gaussian distribution, with elliptical contour shape. The CDNL value at the center was found to be 52.4 dB, and the standard deviations along the major and minor axes were 18.9 and 11.1 miles, respectively.

The results of these measurements were projected to planned supersonic operations at the Reserve, NM, and Valentine, TX, MOAs. It was found that, at full capacity of 300 ACM sorties per month in each MOA, CDNL will be below 50 dB at all locations. Near the center of the supersonic area at Reserve, a sonic boom would be heard an average of once every three days. At Valentine, where supersonic operations will be divided among two areas, a sonic boom would be heard about once a week.

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We would also like to acknowledge the invaluable contributions of several other individuals:

- Mr. Daniel R. King, 49th TFW/DOO, who provided an education on how an ACM airspace operates and opened all of the doors at Holloman AFB.
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- Mr. Frank Chavez and Ms. Teresa Williams, WSMR, who coordinated our activity with White Sands and obtained access to the monitor sites.
- Security personnel at Stallion Gate, whose courtesy, professionalism, and guidance contributed to the perfect safety record of all field operations.

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1.0 INTRODUCTION

In order to meet the increasing need for Air Combat Maneuver (ACM) training involving modern supersonic aircraft, the Air Force has requested supersonic capability in the Reserve, NM, and Valentine, TX, Military Operating Areas (MOA). Full descriptions of the proposed actions are contained in the final environmental impact statements.[1,2] In the EISs, predictions of the expected sonic boom environment were made using the "Oceana model,"[3] which was a projection of calculated booms from a limited set of tracking data from ACM operations in the Oceana MOA. That model was the best method available at that time, but had not been validated. In September 1984, a Record of Decision by the Deputy Assistant Secretary of the Air Force allowed up to 300 supersonic sorties per month in the Reserve MOA. This decision placed certain restrictions on supersonic operations, and included a requirement to monitor sonic booms in order to validate the predictions. A five-month monitoring program was conducted in the Reserve MOA.[4] That monitoring program measured substantially lower boom impact per sortie than predicted in the EIS. This provided the required validation.

While successful in supporting the EIS, the Reserve monitoring results had two shortcomings. First, relatively few sonic booms were recorded: too few to form an accurate statistical data base. It was only because the projection of these was substantially below the Oceana model predictions that the conclusion supporting the EIS could be made. While successful in that sense, it left the possibility that the Air Force was significantly overpredicting sonic booms, thus causing excess concern about consequences. Second, it was not clear what role the supersonic operation restrictions in Reserve may have played in the measured sonic booms. This would put some uncertainty on the validity of the final results.

It was apparent that long-term support of the environmental analysis would require a larger data base of this type of sonic boom environment. Clearly, to obtain a statistically large data base in a finite time, this should be done someplace where there is substantial supersonic activity. The missions involved should be the same type as will occur in Reserve and Valentine, and there should be no artificial restrictions. The obvious place to conduct this study is the existing airspace at the White Sands Missile Range (WSMR). WSMR has a nominal ACM capacity of 600 sorties per month and is generally used at that capacity. Reserve and Valentine are needed to provide additional capacity for users of WSMR and will be used for identical types of operations, aircraft types, etc. It is expected that, even in the absence of any analytic modeling, one could project measurements at WSMR directly to Reserve and Valentine simply by adjusting the location and scaling the magnitude according to the sortie rates. Accordingly, plans were made to conduct a monitoring program at WSMR.

This report presents the results of six months of sonic boom monitoring in the Lava/Mesa airspace at WSMR. During that time, 35 sonic boom monitor stations were maintained in the approximately 2,600 square miles under the airspace. Slightly over half the stations were instrumented with "BEAR" full-signature capture sonic boom monitors developed by the Air Force,[5] and the rest with the SBM-1 systems developed for Reserve.[6] All air traffic control and advance schedule records pertaining to that airspace were collected and analyzed. The airspace is equipped with an Air Combat Maneuver Instrumentation (ACMI) system, which provides tracking data for aircraft equipped with transponder pods. Approximately half of the aircraft were equipped with these pods, and tracking data were obtained for about a quarter of those missions.

The monitors provided a direct measure of C-weighted day-night equivalent level (CDNL) and boom frequency for the six months, as well as records of each individual sonic boom. Each boom was correlated with airspace activity and its cause identified. Measured CDNL at each site was adjusted to account for those booms associated with ACM, and CDNL contours plotted. All else being equal, these contours can be applied to other airspaces by scaling according to the sortie rate.

Section 2 of this report contains background information on ACM training and the Lava/Mesa airspace. Section 3 contains a description of the test plan, including the statistical design of the monitor site array. Section 4 contains a description of how the field program was conducted and basic data reduction. Section 5 presents the analysis performed on both sonic boom and flight operations data. The primary result of this study, a model suitable for application to other airspaces, is presented in Section 6. That section contains a comparison of the current model to earlier ones, and application to the Reserve and Valentine MOAs.

2.0 ACM TRAINING AND THE LAVA/MESA AIRSPACE

2.1 ACM Training

ACM training is an activity designed to provide fighter pilots with proficiency in air-to-air combat against other fighters. There is a range of mission types involved, depending on the level and variety of training. Basic Fighter Maneuver (BFM) missions consist of pilots learning the types of maneuvers involved in ACM. A BFM mission will generally consist of a flight of two to four aircraft, working together. Air Combat Training (ACT) missions consist of realistic exercises where two flights of aircraft (two to four aircraft in each) take aggressor/defender roles. Engagements include simulated weapon release and scoring of kills. Dissimilar Air Combat Training (DACT) involves the aggressor/defender roles being taken by different aircraft types and/or different tactics. The ultimate goal is for our pilots to become proficient at flying our aircraft against aircraft and tactics employed by our opponents, and to train under realistic circumstances. ACT and DACT missions are typically two versus two to four versus four. Major exercises can include more fighter aircraft, and also support aircraft such as AWACS. There are also a number of other basic categories of ACM in addition to BFM, ACT, and DACT, but these three exemplify the genre.

A typical ACM mission consists of entering the airspace, several engagements, then leaving the airspace. Upon entering the airspace, pilots first perform g-familiarization maneuvers as a warm-up. The aggressors and defenders then proceed to setup points about 30 to 50 miles apart. This is the distance at which combat aircraft generally begin to use their internal electronic systems to detect and track opponents. The setup points themselves tend to be based on prominent visual references which are regularly used in a given airspace. Once at the setup points, the two flights will head toward an engagement. Depending on the nature of the mission, the nature of this start can vary. For BFM, it can be by mutual agreement. For ACT or DACT, the aggressor flight might begin and the defenders initiate an intercept when they detect the aggressors. For many scenarios, a forward controller (perhaps an AWACS or a ground controller simulating AWACS) may provide attack or intercept vectors. Once the aircraft leave the setup points, they may proceed directly or circuitously toward an engagement point. Depending on tactics, they may remain together or divide into smaller groups. The actual engagement point(s) evolve, depending on the tactics employed by each side.

When aircraft are 10 to 20 miles apart, each pilot will have formed his plan. Since maneuver capability is a major element to survival, each aircraft will generally accelerate to an airspeed representing the best maneuver capability of that aircraft. This typically corresponds to some indicated airspeed, so that the true airspeed will vary with altitude. If an aircraft is at a high enough altitude, it will be supersonic. Acceleration to a desired airspeed is often referred to as "energy addition".

When aircraft are close to each other, the engagement itself (dogfight or "furball") begins. This generally takes place in a region between the setup points. It is characterized by tight maneuvers as each pilot tries to maneuver an opponent into his weapon envelope. Speeds are nearly always subsonic, with the maneuver capability of the aircraft a major (but not sole) consideration. Speeds can become supersonic if momentary tactics require it. This generally occurs in a dive as one aircraft chases another or builds up speed preparatory to a maneuver. Given the nature of air combat, one cannot predict what will happen or where it will happen during a given engagement.

The furball phase will end with one side or the other declared to be the winner, or with a disengagement by one or more of the aircraft. A disengagement can consist of leaving the furball at high (often supersonic) speed when at a tactical disadvantage. In actual combat, this would often be followed by maneuvering to a better position, then reengaging. In training situations, the engagement is usually ended, aircraft return to the setup points, and another engagement is begun. An engagement can also be terminated if a potential safety hazard arises or if airspace boundaries are about to be exceeded.

The training value of ACM is greatly enhanced by the use of an Air Combat Maneuver Instrumentation (ACMI) system.[7] This system consists of a set of ground tracking stations and a transponder pod attached to each aircraft. Each pod contains its own inertial navigation system and pitot tube. Every 100 to 200 milliseconds each pod is interrogated by a ground station. It telemeters the aircraft coordinates, velocity, g–load, angular rates, air speed, Mach number, etc. These data are recorded and are used to generate a real-time video display in a small theater, where training officers and other pilots can observe the mission as it takes place. A Range Training Officer (RTO) monitors the mission and can select various views of the mission on the display. The RTO serves as referee in scoring kills, monitors safety or airspace constraints, and can act as a simulated advance controller. After a mission, the recording may be played back so that pilots can analyze their performance.

The value of an ACMI system for the current project is that it provides tracking data of actual missions. These data, while designed for video simulation purposes, are precise enough for calculation of sonic booms from supersonic segments of ACM missions. They also provide a quantitative record of how the airspace is utilized on a given mission.

2.2 White Sands and Lava/Mesa

The Lava/Mesa airspace is the primary ACM training arena for fighter aircraft at Holloman AFB, New Mexico. It is used by other units under various circumstances and is also part of the White Sands Missile Range's airspace. Figure 1 is a sketch of the area and the airspace boundaries. Shown are the WSMR boundaries, the Lava/Mesa boundaries, the location of Holloman AFB and the Cities of Alamogordo and Socorro, and the relative locations of Reserve and Valentine. Other reference points not shown are Las Cruces, NM, near the southwest corner of the range, and the Gran Quivera National Monument near the northeast corner.

The White Sands Missile Range is an area approximately 140 by 40 miles. It is a multi-service test range, operated by the U.S. Army but used by all branches of DoD and DOE. About three-quarters of the range is on government-owned land, with access restricted. This area lies within two of New Mexico's great basins, the Jornada del Muerto and the Tularosa Basin. The northern quarter of the range, referred to as the Range Extension, lies over privately owned or operated ranches on the Chupadera Mesa. The range extension is subject to restriction by temporary roadblock when dictated by safety requirements of particular tests. Occasionally the residents will be evacuated when test articles are expected to impact in that area. The government maintains agreements with residents of the extension area to allow for this use.

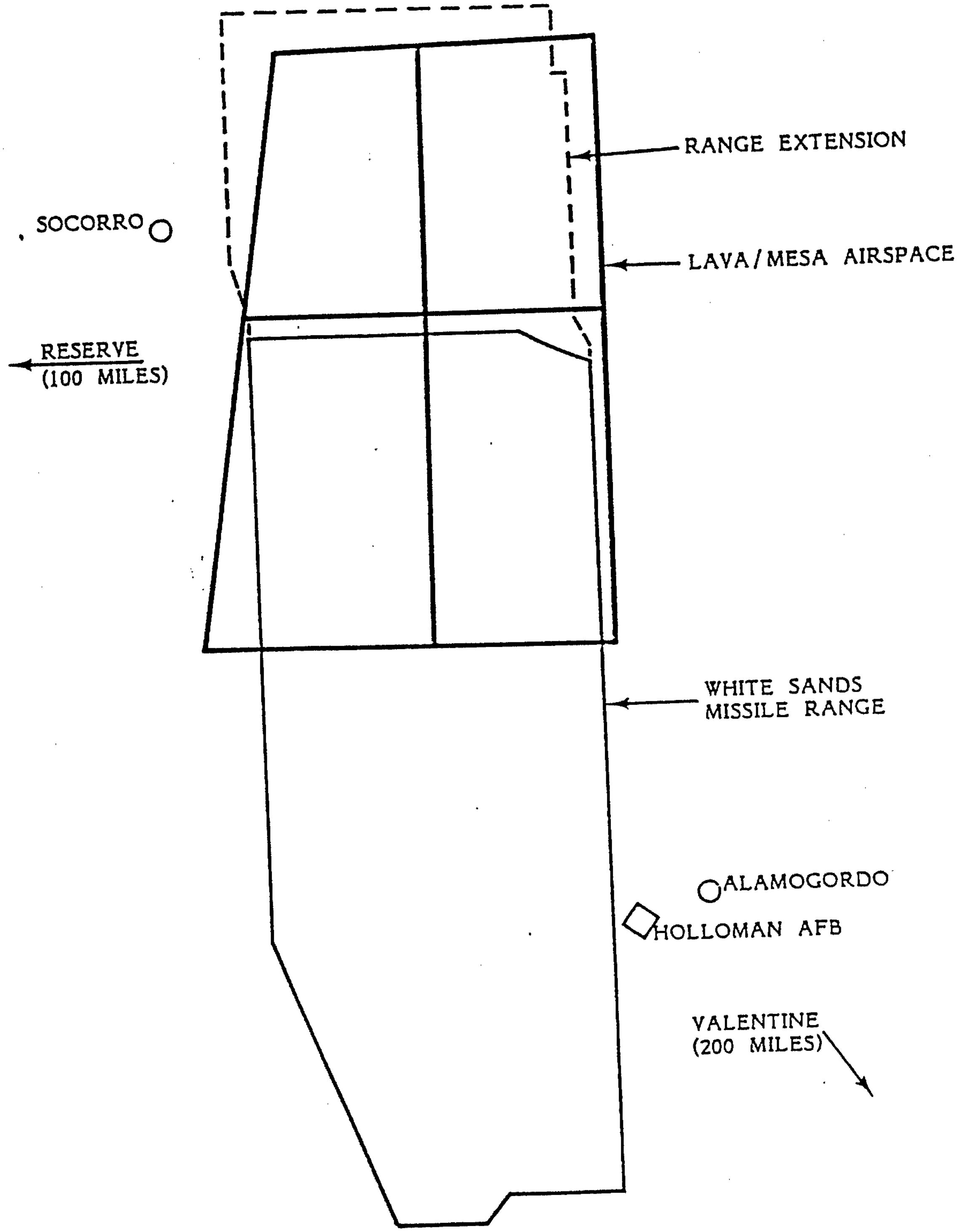


Figure 1. White Sands Missile Range and Lava/Mesa Airspace.

The Lava/Mesa airspace lies approximately above the northern half of WSMR. The boundaries do not exactly correspond. The northern half of the airspace, over Chupadera Mesa, is designated Mesa. The southern half is designated Lava, after the Malpais Lava Flow in the eastern part of the area. Each half is divided into a western and eastern half, and the airspace is generally referred to by the four quadrants. Lava East is an unofficial name, that quadrant consisting of Red Rio, Oscura, and the Sands Corridor. Figure 2 is a sketch of the airspace, showing section names. The airspace boundaries are superposed on the alphanumeric "crash grid" coordinates used by range personnel; approximate latitude and longitude are indicated. Also sketched in Figure 2 are major roads and topographic features.

Topography plays a role in the way in which the airspace is used, and was a major consideration in the ground access to monitoring sites. Lava West, in the Jornada del Muerto, is a fairly flat desert basin. Elevation ranges from about 4,200 feet MSL at the southern end to about 5,000 feet MSL at the northern end. There are some hills (part of the Mockingbird Range) in the southern part. Lava East is flat in the southern part, which is in the Tularosa Basin. The northern part (most of Red Rio) has very rugged terrain, dominated by the Oscura Mountains in the western part of Red Rio. (The Oscuras and the Mockingbirds form part of a major mountain chain which separates the Jornada del Muerto from the Tularosa Basin.) These reach a peak of about 8,700 feet MSL, more than 4,000 feet above the Jornada. Aircraft engaged in ACM tend to stay west of the Oscura range so as to avoid losing that much vertical airspace. The result is a tendency for ACM operations to use all of Lava West and Mesa West, about half of Mesa East, and little of Lava East. This pattern is compounded by target complexes and live-fire activity in Red Rio and Oscura, which conflict with ACM activity. Terrain in Mesa is fairly gentle, except for some mountains in the northwest corner of Mesa West. There is a gradual upward slope toward the north, with elevations approaching 7,000 feet.

Topography considerations were important for access to and security of monitoring sites. Lava West has the greatest accessibility, due to its flat terrain. The use of the area for many exercises over the last half century has resulted in a good network of roads of various quality, allowing access to within one to three miles of any desired point. Several major paved or well-graded roads traverse the

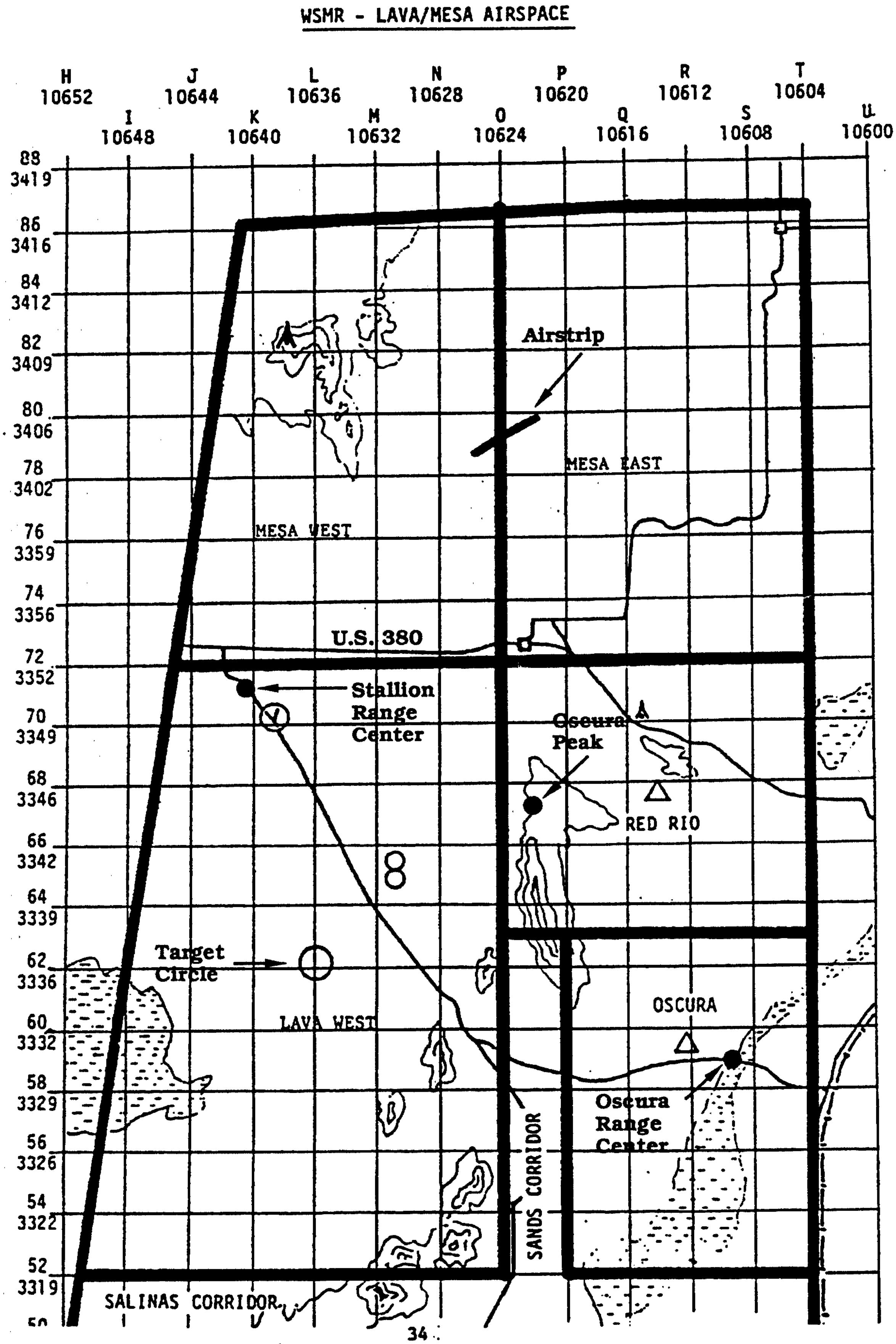


Figure 2. Lava/Mesa Airspace.

area. Red Rio has poor accessibility, with rugged terrain and few roads. The regular live-fire activities also reduces the accessibility to much of that area. The gentle terrain in Mesa poses few problems. However, roads tend to be those used by local residents, and are generally sparse. Except for U.S. 380 (which roughly separates the range extension from the main range), there are no paved roads on the mesa.

Access to the Lava area is via security checkpoints at the Stallion and Oscura Range Centers, indicated in Figure 2. Access to the Mesa area is via a number of roads which intersect U.S. 380. Mesa can be reached by road from Gran Quivera or, at one point, from U.S. 60 which is parallel to the northern border of the range extension. While U.S. or state highways parallel the east and west boundaries of the range extension, they provide no practical entrance to the area. Given these constraints on access, the City of Socorro was an obvious location for a base of operations.

The entire area is subject to restriction when dictated by tests. Restricted areas are closed by security roadblocks. This is a more frequent occurrence on the government range than on the extension. Times of scheduled range closures can be obtained from White Sands and are generally established by the evening of the previous day. Occasionally, an unscheduled roadblock may occur, due to changing test circumstances. Planning for site access must allow for the possibility that areas of the range can be closed. Closures of the entire range, or closures on weekends, are rare.

2.3 ACM Operations and Scheduling

As noted earlier, the Lava/Mesa airspace is shared by a number of users at White Sands. The primary ACM user is the 49th TFW at Holloman AFB. That wing has three squadrons and consists of approximately 75 F-15s. A secondary user from Holloman is the 479th TTW, which consists of approximately 130 AT-38s in four squadrons. Aircraft from other organizations also use the airspace on a visiting or transient basis. A major purpose of other organizations coming to Lava/Mesa is, however, to interact with the 49th TFW. During the six-month sonic boom monitoring program, over 90 percent of ACM exercises included F-15s from the 49th TFW. Schedule information for the 49th TFW provides a good overview of ACM activity.

Advance scheduling for the wing is maintained by 49th TFW/DOO. This covers all airspaces used by Holloman, including Lava/Mesa. Access to each airspace is coordinated with other WSMR users. Within the times available for the 49th, weekly advance schedules are prepared. These schedules are updated daily, with each day's advance schedule established the night before. The advance schedule identifies the aircraft and pilots, the airspace and time period requested, and the type of mission. Following each mission, each squadron maintains debriefing information documenting the outcome of each mission. DOO collects overall statistics on actual airspace usage, but does not keep detailed as-flown data on each mission.

The actual schedule of airspace use is managed in real time by the air traffic controller, "Cherokee Control", which maintains radar tracking of all flight activity and grants clearances to enter designated airspaces. Actual airspace entry times can vary from advance schedule for a variety of reasons. Coordination of various missions can result in clearance being granted for only part of the airspace, altitude restrictions in certain quadrants, etc. Coordination of high-altitude ACM with low-altitude air-to-ground missions in Red Rio, as noted earlier, is a common occurrence. All airspace clearances granted by Cherokee are recorded on "strips". These provide mission name, number(s) and type(s) of aircraft, clearance granted (including special restrictions), and actual times on and off the range.

In addition to the advance schedules and airspace clearance strips, some schedule data is maintained by the ACMI operators. Schedule of the ACMI system and assignment of transponder pods to particular aircraft is based on advanced schedule data from the participating units. This information is updated up to launch time, and final "as-flown" records of actual aircraft, times, etc., are kept. These records cover only those aircraft equipped with ACMI transponder pods, which is less than half the aircraft participating in ACM. The tapes from successful ACMI missions contain actual as-flown information along with the tracking data.

A note on the organization of ACMI data and nomenclature used in this project is worthwhile. A single aircraft is generally referred to as a sortie. A group of aircraft flying together is often referred to as a flight. The word "mission" can be applied to anything from the objectives of a single sortie to a multi-flight exercise. In scheduling, it is common to consider a mission to be a aircraft with a given call sign, e.g., Racer 1, Racer 2, Racer 3, and Racer 4 being a four-aircraft mission scheduled as Racer. They might engage Bucko 1-4, scheduled as Bucko, in 4 versus 4 ACT. If all are equipped with ACMI pods, data would be recorded on a single tape (or sequence of tapes) and the ACMI operators would consider this to be, for their purposes, a single mission: Racer/Bucko. That name would appear on ACMI log data and also in the "exercise data block" on the tape itself. If only one flight were equipped with pods, they would denote the tape by that flight's call sign. The procedure at Holloman is to begin each such mission on a fresh tape. Even if more than one tape is required, it is convenient to refer to all tapes from a single mission (as logged by ACMI) as a single tape.

Strip records maintained by Cherokee generally follow the advance schedule mission format, since each flight would typically enter the airspace at different locations and/or times and request its own clearance. The majority of aircraft are not equipped with ACMI pods, hence not logged into ACMI records. We will therefore use the term mission in the same sense as the advance schedulers, a flight of aircraft with a given call sign. When one or more missions work together at the same time in the airspace, we will denote that to be a "training event". A single ACMI tape contains tracking data from all pod-equipped aircraft in a given training event.

3.0 TEST PLAN

The monitoring project consisted of collection of two types of data: sonic booms on the ground in the Lava/Mesa airspace, and data defining ACM operations during the monitoring period. The sonic boom data required installing and servicing monitoring devices and was the primary effort in this project. Section 3.1 contains a description of the monitoring equipment and its capabilities. Section 3.2 contains a description of the monitor locations selected and the analysis leading to that arrangement. Section 3.3 contains a discussion of the collection of operations data.

3.1 Sonic Boom Monitoring Equipment

Performance of this project required a large number of sonic boom monitors which would be capable of unattended operation. They would have to automatically record any sonic booms, together with the time of occurrence. It was also necessary to be able to determine whether a given recorded event was or was not a sonic boom. Section 3.1.1 describes the nature of sonic boom signatures, and Section 3.1.2 describes the quantities which were to be recorded. Section 3.1.3 contains general considerations for sonic boom measurement. Sections 3.1.4 and 3.1.5 contain descriptions of the two sonic boom monitoring systems employed.

3.1.1 Characteristics of Sonic Booms

Figure 3 is a sketch of sonic boom generated by an aircraft in supersonic level flight. There is a high pressure region associated with the forward part of the aircraft and a low pressure region to the rear. Near the aircraft, the pressure pattern is complex. Far away, however, the signature tends to distort and coalesce into the "N-wave" shape shown. There is an initial shock wave, followed by a linear expansion, then a tail shock almost equal in strength to the bow shock. This type of signature occurs for fighter aircraft at 5,000 feet AGL and above. For fighter aircraft between 5,000 feet and 40,000 feet AGL, the shock strength (peak overpressure) is in the range 1 to 10 pounds per square foot (psf) and the duration between shocks is in the range 100 to 200 milliseconds. Each shock wave has a rise time typically in the range of 1 to 10 milliseconds.

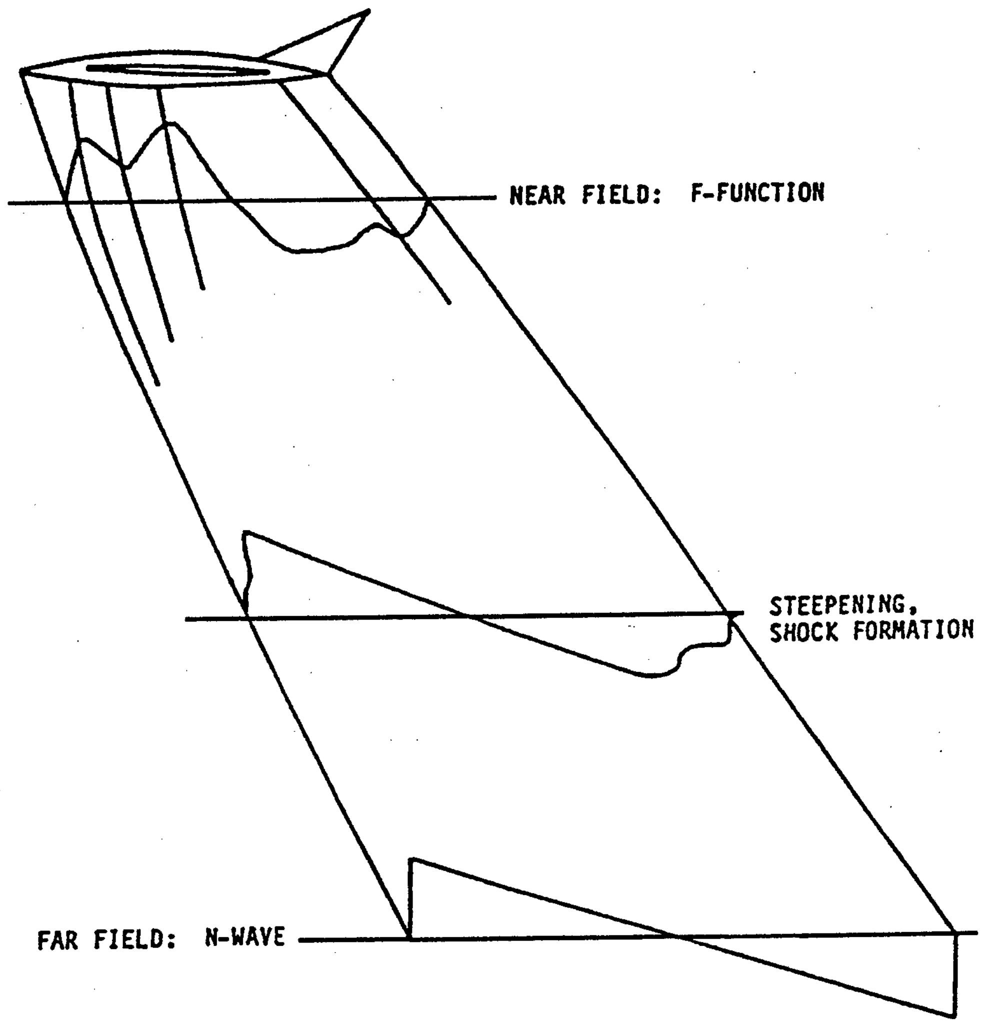


Figure 3. Sonic Boom Waveform Generation.

The sonic boom sketched in Figure 3 occurs directly under the flight path. To the side of the flight track, the boom is generally similar but with lower amplitude. Due to refraction by the earth's atmosphere, there is a lateral cutoff distance beyond which there is no boom. It is common to refer to the area impacted by boom, between the cutoff distances and extending for the length of the flight track, as a sonic boom "carpet", and the associated N-wave boom as a "carpet boom". Near the edge of the carpet, ground effects tend to attenuate the boom so that it is lower in amplitude and has a rounded shape.

Measurements of sonic booms under calm conditions generally agree with the ideal N-wave sketched in Figure 3. Under turbulent atmospheric conditions (gusty winds, afternoon thermal activity in the summer, etc.), signatures tend to be distorted. Figure 4 shows typical differences between booms measured under calm and turbulent conditions. The basic N-wave shape is clear, but there is a complex structure superposed. Measurement equipment must be capable of recording this distortion when it occurs.

Aircraft engaged in ACM rarely sustain supersonic speeds for more than a few tens of seconds, and even more rarely do this in steady level flight. Supersonic events, like most ACM flight, tend to involve acceleration, deceleration, and turns. Maneuvers can enhance the boom via focusing (nominally during acceleration or toward the inside of turns) or decrease it via defocusing (deceleration or the outside of turns). Acceleration to supersonic speeds generally causes a focal zone. There is a narrow region within this zone where the boom is an enhanced "focus boom" with a distorted U-wave shape. Shock peaks are typically enhanced by a factor of two to three. Downtrack of the focus boom, there is a transition to carpet boom. In this transition region, one generally sees a carpet-like N-wave and a decaying U-wave. Sometimes the N-wave in this region is referred to as being "pre-focus" and the U-wave as "post-focus". Uptrack of the focus boom, there is a decaying "evanescent" wave which has a rounded shape. Figure 5 shows these three types of focal zone sonic boom. There can be substantial variations in detail in particular cases. Sometimes signatures are seen which are a combination of these, and there can be superposed atmospheric distortion as shown in Figure 4. Even in non-ideal cases, however, the basic sonic boom waveforms are quite distinctive and booms can readily be identified from plots of recorded signatures.

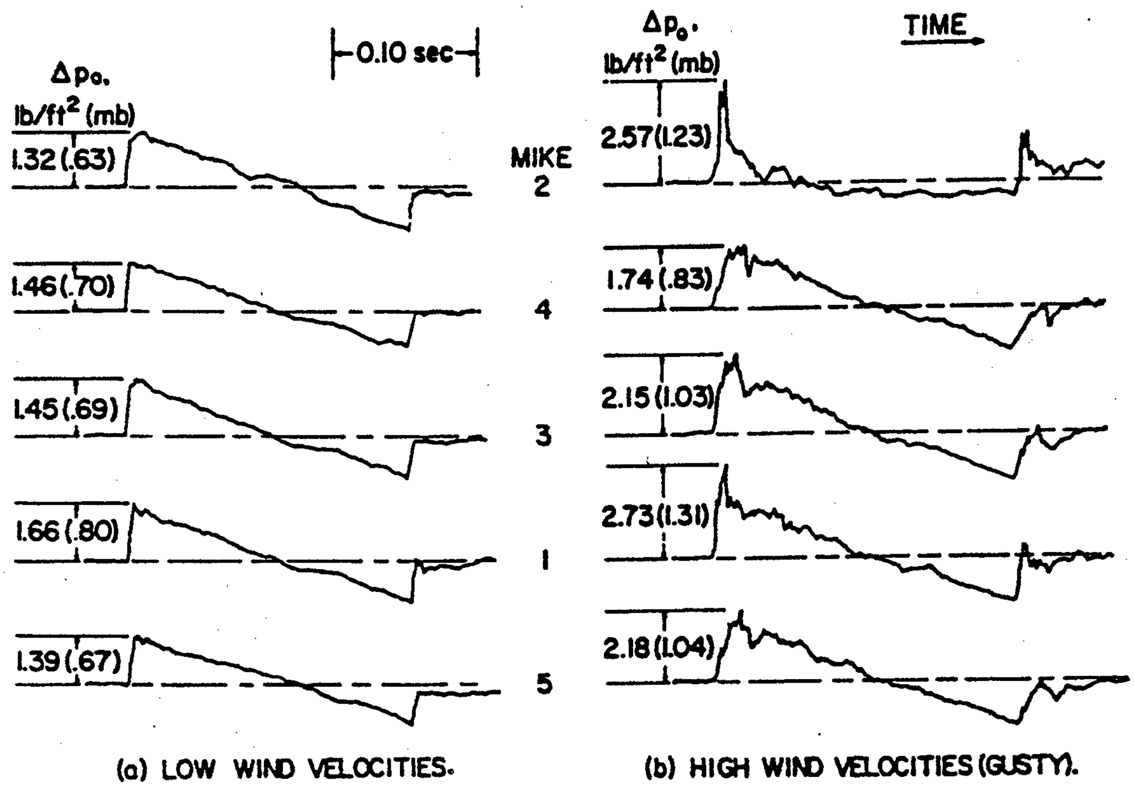
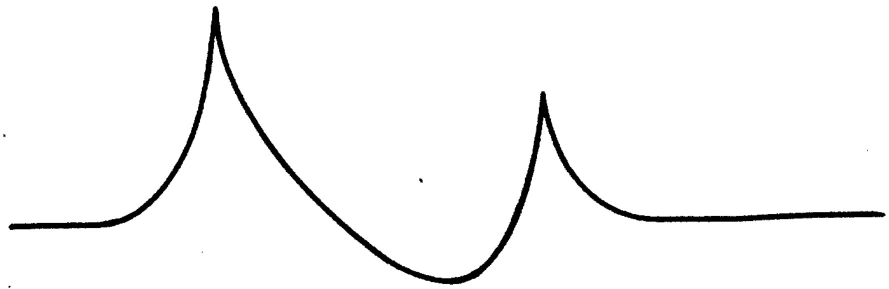
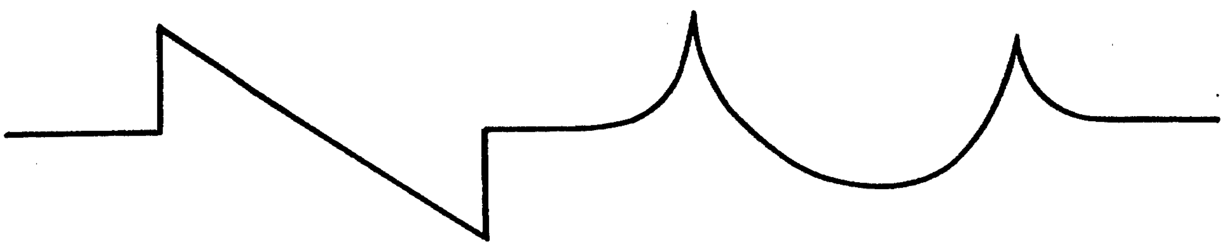


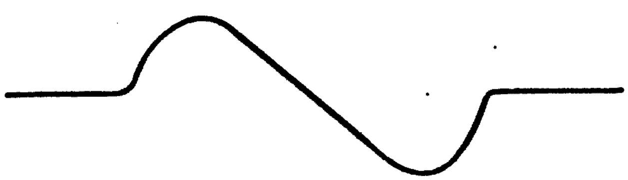
Figure 4. Sonic Booms Measured Under Calm and Turbulent Conditions.



a. Maximum Focus U-Wave.



b. Transitional N–U Combination.



C. Evanescent Wave.

Figure 5. Types of Boom Signatures in a Focal Region.

3.1.2 Sonic Boom Metrics

It is desirable to have a description of a given sonic boom which is simpler than presenting the complete pressure-time signature. An N-wave sonic boom is described completely by the peak overpressure and the duration. The overpressure is the dominant parameter affecting environmental impact, so that most sonic boom data are reported in terms of overpressures. The peak overpressure P_{pk}, in psf, can be converted into a decibel level, re 20μPa, by the relation:

$$L_{pk} = 127.6 + 20 \log_{10} P_{pk}/\text{psf} \qquad (1)$$

The peak level can be measured by standard impulse sound level meters and readily converted to P_{pk}. This quantity is directly applicable to existing studies of N-wave sonic boom impact, but does not relate directly to studies involving other impulsive noise.

It has been found[8] that the environmental impact of a variety of impulsive sounds, including sonic boom, correlates well with the C-weighted sound exposure level (CSEL). CSEL is obtained by filtering the waveform via a standard C-weighting filter,[9] which attenuates energy below 25 Hz and above 10,000 Hz (the nominal audio frequency range), then computing the total energy and presenting this as a sound level. For N-wave sonic booms, L_{pk} – CSEL = 26 dB to within 2 dB.[10,11] For U-wave focal zone booms, L_{pk} – CSEL is larger, while for rounded booms (lateral cutoff, evanescent focal zone) it is smaller. CSEL can be computed from a complete waveform, and can also be directly measured by an integrating sound level meter. With individual booms characterized by CSEL, the cumulative impact of sonic booms over long periods is characterized by the C-weighted day-night equivalent level (CDNL). CDNL is obtained by summing the energy associated with CSEL for each event in a given period of some number of days, dividing by the length of the period, and presenting this average energy rate as a sound level. Events occurring at night (2200–0700) are penalized by 10 dB. Interpretive criteria for land-use compatibility is based on the relationship to annoyance presented in Reference 8.

3.1.3 Instrumentation Requirements

Requirements for an instrumentation system are based on the expected amplitude and frequency range of sonic booms. For amplitude, a system with a maximum of 150 dB (corresponding to 14 psf) covers the maximum expected boom with adequate margin. A dynamic range of 50 to 60 dB provides a noise floor well below 0.1 psf.

The peak energy content of a sonic boom is at a frequency of the order of the reciprocal of the duration, 5 to 10 Hz. The highest frequency content is associated with the shock waves, and energy content falls off at frequencies higher than the reciprocal of the shock wave rise time, on the order of 100 to 1000 Hz. A system with a frequency response from somewhat below 1 Hz to 2 kHz will capture all of the energy. For C-weighted measurements, the frequency response need only be commensurate with the range of the flat part of the C-weighting curve, i.e., down to somewhat below 20 Hz.

The low-frequency limit of a measurement system has a qualitative effect which can be more important than the quantitative effect. Figure 6 shows a 200 msec unit-strength N-wave which has been filtered by a system with a 0.5 Hz low-frequency cutoff. The filtered wave has 96 percent of the energy of the original wave, and the peak and CSEL are unaffected. Nonetheless, there are clearly visible distortions. The expansion portion of the wave has a swayback appearance, and the rear shock is displaced slightly. These distortions would be less for shorter duration booms (200 msec is the longest expected from fighter aircraft), and greater for longer ones. To avoid this type of distortion, and ensure that N-waves would clearly look like N-waves, sonic boom recording systems have traditionally had very low lower frequency limits, typically 0.01 Hz or less. For purposes of monitoring ACM sonic booms, however, the effect of the 0.5 Hz cutoff is not important. The quantitative metrics – L_{pk} and CSEL – are not affected. Qualitatively, the distortion has a well-defined behavior and would not cause misinterpretation of whether or not a particular record was a sonic boom. A frequency response of 0.5 Hz to 2 kHz is therefore adequate for current needs.

3.1.4 SBM-1 Monitor System

The Sonic Boom Monitor 1 system was developed for use in the Reserve monitoring project.[6] It is based on a commercially available programmable integrating sound level meter, the Larson Davis Model 700. One of the programmable functions of this meter is to save data whenever a pre-set threshold is exceeded. When an exceedance occurs, the meter records the time of

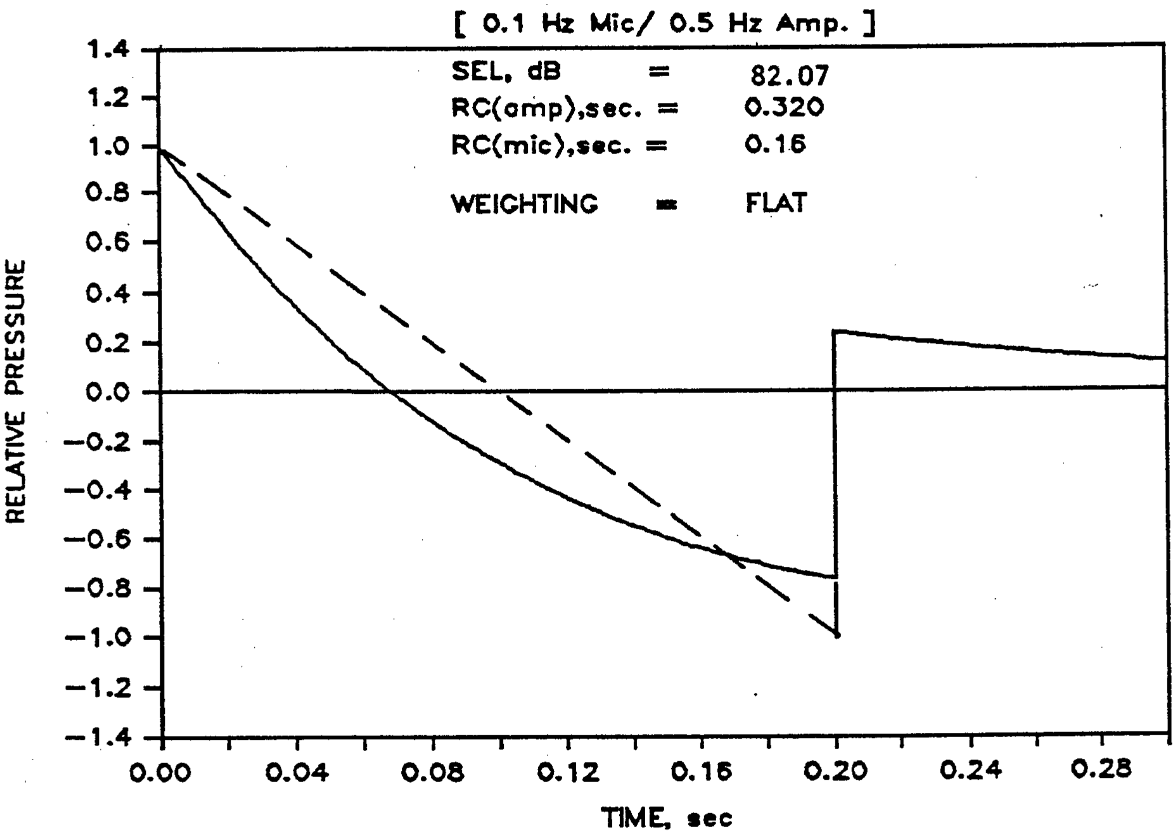


Figure 6. Effect of 0.5 Hz Filter on 1 Pa, 200 msec N–Wave.

occurrence, the duration, the peak sound level, the maximum level, the SEL, the L_{eq} during the exceedance period, and whether the system's range has been overloaded. The meter can be programmed for A- or C-weighting. Peak levels can be detected either with or without the weighting. When programmed for exceedance data alone (several other capabilities are available), system memory can accommodate up to 389 records. Data may be downloaded from the system, via a serial connection, into a computer for subsequent analysis.

The microphone normally used with the LD-700 does not have a high enough amplitude range for sonic boom measurements. Instead, a PCB 106B50 microphone was used, and the preamplifier in the LD-700 was modified to accommodate this microphone. Peak levels of up to 150 dB could be recorded. The unweighted peak noise floor of the system was about 110 dB. Microphones were located on the ground, using a ground board and windscreen system described in Reference 6. For the current project, the mounting and windscreen system developed for the BEARs, described in Section 3.1.5, was used. Each SBM-1 system was housed in an environmental case, together with a rechargeable battery which would supply power for over two weeks. Figure 7 shows an SBM-1 system in its environmental case.

The SBM-1 systems were programmed to record exceedance data, C-weighted, with peak levels unweighted. They thus provided direct records of CSEL and L_{pk} for each sonic boom. An exceedance threshold of 115 dB (0.23 psf), unweighted peak, was used. This threshold was based on the noise floor of the system, and is in the range where sonic booms are detectable to human hearing. It was found that there were many naturally occurring sounds which could trigger an exceedance. This included high winds, rain, and some animal activities. Although only 13 sonic booms occurred during the five-month Reserve monitoring project, it was not uncommon for a system's memory to fill after only a few days, particularly if a storm occurred. This problem could not be remedied, since the only trigger control mechanism was threshold level. A higher threshold would have missed booms of interest, and the false exceedances were due to naturally occurring events.

Identification of occasional sonic booms from many recorded exceedances was a major analysis problem. Records were deduced to be booms on the basis of amplitude, simultaneous occurrence at several monitors, and correlation with

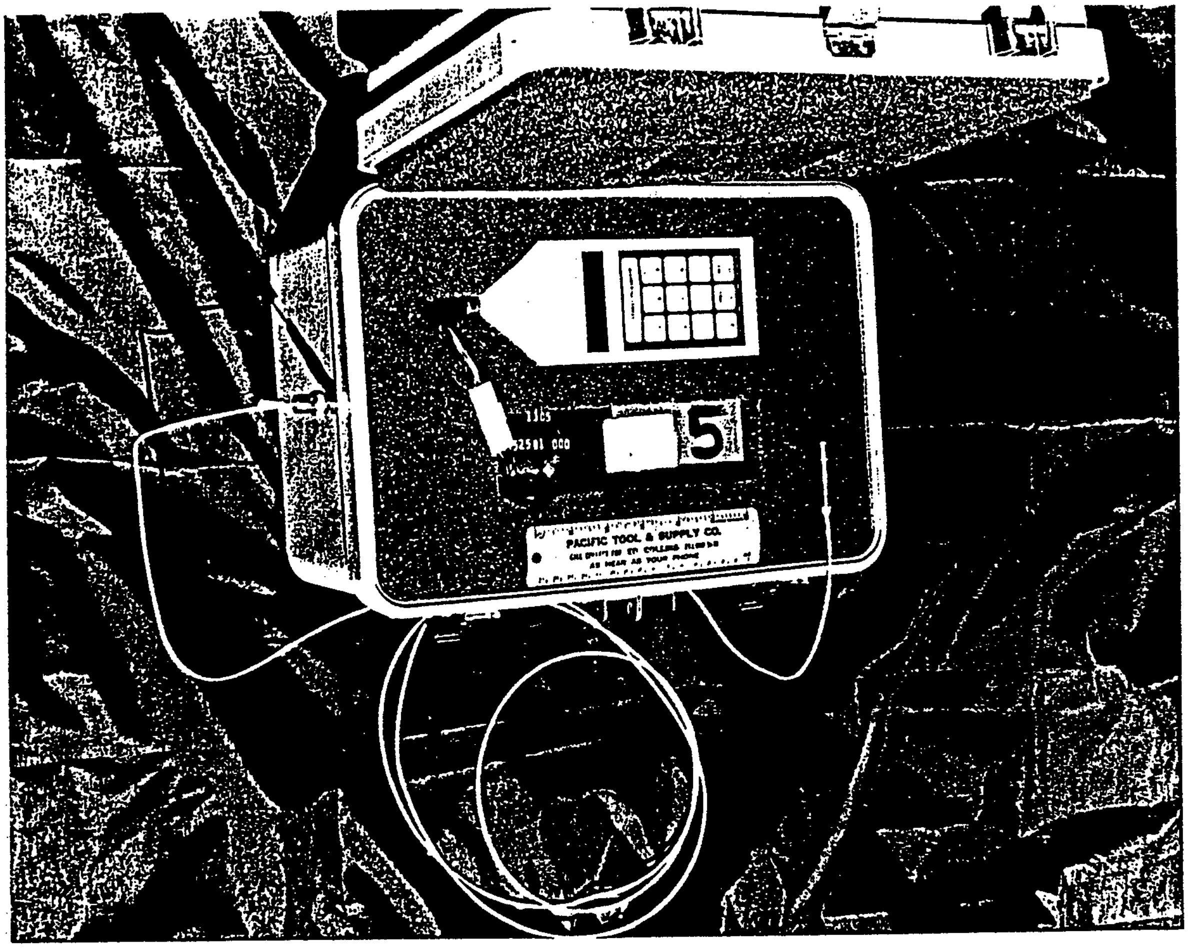


Figure 7. Sonic Boom Monitor (SBM-1).

ACM activity in the airspace. Booms in excess of 1 to 2 psf (which the analysis in References 1–3 suggested would be common) were easy to identify. The difficulties were with booms below 1 psf, which were found to be typical. Laboratory tests during system development, and subsequent side-by-side field tests with BEAR systems (discussed in Section 3.1.5), demonstrated that when a sonic boom occurred, the SBM-1 would accurately record it. In the Reserve program, substantial analysis effort was expended in identifying which records were booms.

Seventeen SBM-1 systems were available for use in the current project.

3.1.5 BEAR Monitor System

The Boom Event Analyzer Recorder was developed by USAF AAMRL/BBE for automatic recording of complete sonic boom signatures.[5] It is a digital microprocessor-controlled recording system. This system has a frequency response of 0.5 Hz to 2500 Hz, and records complete sonic boom waveforms. It incorporates pattern recognition software so that it will record only those events which have the characteristics of a sonic boom.

Figure 8 is a sketch of the system. The microphone (PCB 106B50) is mounted inside a hemispherical foam inner windscreen, with its diaphragm facing a steel base plate on the ground. A conical outer windscreen, constructed of wire mesh and covered with nylon fabric, is placed over this. Sound impinging this microphone system enters the BEAR, where the signal is digitized at a rate of 8,000 samples per second and enters a recirculating buffer memory with two-second duration. When the signal exceeds a programmed threshold (generally set to 105 dB, 0.075 psf), the system examines the waveform to assess if it is a candidate sonic boom. Parameters examined include the rise time of the initial signal, time to reach the maximum, and the duration of the first positive phase of the signal. If the event satisfies the programmed criteria, the event (from the signal start until it falls below a lower "off" threshold) is recorded in non-volatile RAM. Record length varies, corresponding to the actual duration of the boom plus some time before and after it. The system has 512 kB of RAM, capable of storing a total of about 40 seconds of data. This is adequate for over 100 sonic booms of 200 msec duration each.

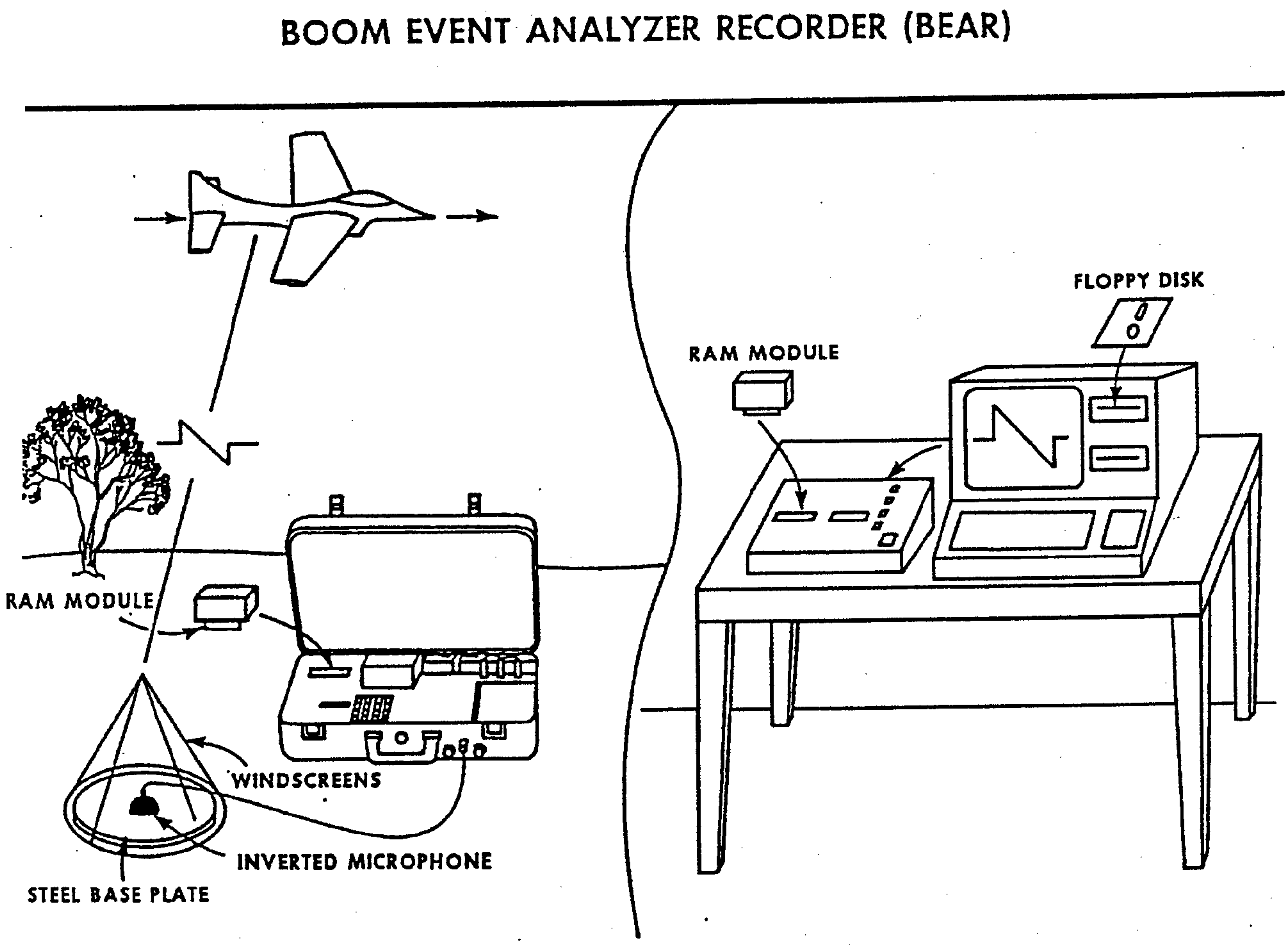


Figure 8. BEAR Monitor System.

The RAM is contained in two removable modules. When the BEAR is serviced in the field, the modules are removed and replaced with fresh ones. Data from the RAMs are transferred to a personal computer, where they are stored on disk and may then be analyzed. This transfer takes place in two steps. First, data are transferred by program COMM. This results in a master file which is an image of the RAM contents. Second, the master file is operated on by program PROCESS. This program divides the master file into individual records. Each record is written as a separate file. The name of each file is constructed from the site number, the date, and the time to the nearest minute. The recorded waveforms are plotted for examination. The discrimination criteria in the BEAR are somewhat liberal so that, while excluding most non-boom events, there will be some records which are not booms. These are easily identified and rejected by visually examining them and comparing with the types of waveforms discussed in Section 3.1.1.

The BEAR systems were designed specifically for this type of measurement. Their performance was validated by two field studies. The first was validation of performance in comparison to established sonic boom recording systems.[12] In that test, denoted Boomfile Phase I, BEAR systems and proven systems used by NASA in previous studies were placed at the same location and subjected to identical sonic booms. Except for the qualitative low-frequency distortion discussed in Section 3.1.3, the results were identical. The second study was a week-long exercise to record sonic booms from current U.S. supersonic military aircraft.[13] That study, denoted Boomfile Phase II, employed BEARs, SBM-1s, and NASA digital systems developed for space shuttle sonic boom measurements. Systems were deployed laterally across a corridor along which over 40 dedicated supersonic sorties were flown. At several locations, each of the three types of system were placed next to each other. In all cases, they recorded identical results. The flight schedule and observations by personnel at selected sites (continuously manned during measurements) provided direct information as to when sonic booms occurred.

An interesting aspect of Boomfile Phase II was that some unexpectedly complex sonic booms, including focal zones, occurred. This was readily detected by examination of the full-signature records of the BEARs, which could always be interpreted in terms of the signature types discussed in Section 3.1.1.* Once aboom and its signature type had been identified from a BEAR, the data recorded at an SBM-1 were found to be in quantitative agreement. Complex booms, such as an N–U combination (with perhaps some atmospheric distortion) could lead to multiple exceedance records on an SBM-1. Complex SBM-1 records with multiple exceedances were, taken alone, difficult to interpret. It was found in such cases that the secondary exceedances were associated with secondary peaks which were clearly displayed in BEAR records. Review of these data made it clear that an event recorded by a single BEAR could be interpreted with near certainty, but that SBM-1 records very often needed corroborating information.

Thirteen BEARs had been constructed by the Air Force and were available for this study. Resources were available to obtain either eight more BEARs or about twenty more SBM-1s. Based on the Boomfile Phase II experience, it was obvious that these resources should be applied to additional BEARS. A total of 21 BEARs were therefore available for this project.

3.2 Monitoring Locations

3.2.1 General Considerations

The Lava/Mesa airspace has an area of approximately 2,600 square miles. A total of 38 monitors (21 BEAR, 17 SBM-1) were available. That corresponds to over 60 square miles per monitor. Analysis in Reference 4, based on maneuver sonic boom calculations,[14] indicates that typical single-event ACM boom footprints would be in the range of 5 to 30 square miles. A simple uniform grid deployment of monitors would be somewhat sparse, and lead to questions of the statistical validity of the results. A uniform deployment would also pose logistical problems,

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* The occurrence of focal zones in Boomfile II, and their proper interpretation, was recognized by Mr. Domenic Maglieri of Eagle Engineering. Mr. Maglieri participated in Boomfile I and II and served as a consultant in the current project.

since many locations would be inaccessible by ground transportation or would entail great distances. These considerations were noted by Galloway in a preliminary test plan.[15] He pointed out that ACM operations take place in an elliptical region aligned with setup points, and that one should expect symmetry about the axes. It would be reasonable to concentrate most of the equipment in one quadrant (Lava West is the obvious choice), with spot samples in the other quadrants. Galloway made some general observations about strategies for monitor placement, but did not attempt a formal statistical design.

The basic objective of this program was to measure the spatial distribution of CDNL due to sonic booms, and represent that distribution by some reasonable function which could be scaled to other situations. When measuring a distribution of data with unknown properties, measurements must be made on a uniform grid: there is no information to do otherwise. If some information is known about the data and the type of function which would represent the data, then that information can be used to improve the efficiency of sampling by modifying the grid. For example, if one-dimensional data are being measured which are expected to have a linear form, the problem reduces to one of determining the best-fit slope and zero intercept. These two quantities can be determined most accurately by concentrating measurements at the end points. For a given number of samples, this would provide more precise results than a simple uniform sampling. A generalization of this concept is the method of D-Optimality, described in References 16 to 18. In realistic situations, one would design a sampling strategy based on D-optimality and the expected function shape, but would also include some uniformly spaced samples so as to test the assumed function.

A word about "uniform" sampling is in order. For an unknown one-dimensional distribution, sampling locations would be equally spaced. The current problem is over an area, hence involves two dimensions. Intuitively, one might select sampling points on a regular square or rectangular pattern. Such a pattern introduces a coupling between the x and y coordinates, and a potential bias. Sampling locations should be selected such that they form an orthogonal matrix regardless of coordinate orientation. An appropriate pattern may be generated by the method of Latin squares.[19] That methodology has its origins in problems such as laying out rows and columns in a garden so as to test various plants or fertilizers without being confounded by existing soil variations. The result of a Latin square design for a "uniform" sampling of a cartesian grid would be a pattern which is somewhat staggered, so that points do not lie at regular x or y values, but there are approximately equal areas associated with each point.

Application of these sampling design schemes requires information about the expected pattern of sonic booms. Information about supersonic ACM operations is available from ACMI data. Analysis of these data allow estimation of the expected form of boom impact, from which a D-optimal grid was designed. Section 3.2.2 contains a discussion of the ACMI analysis performed. That analysis demonstrated a Gaussian form for the spatial distribution of booms. Section 3.2.3 contains a description of D-optimality and its application to an ideal grid design for the current project. This ideal grid was a combination of a D-optimal strategy for a Gaussian distribution, plus a uniform grid in one quadrant. Section 3.2.4 describes how the ideal grid design was adapted to practical considerations, and the process by which monitor sites were selected.

3.2.2 ACMI Data Analysis

The original Oceana model[3] used a small sample of manually read ACMI data, together with a simplified carpet boom model,[20] to develop estimates of average CDNL. That concept was developed further into the BOOM-MAP computer model.[21] The computer model consists of three programs. The first, EXTRACT, reads ACMI data tapes and generates a library of tracking data for the supersonic segments. The second program, MOAOPS, performs general statistical analysis (percent of time at various Mach numbers, altitudes, etc.) of supersonic data in a given library. The third program, BOOM-MAP itself, reads the supersonic library and applies the carpet boom model to each point. These booms are combined to give CDNL contours for all operations in the library. The model has been updated[22] to use a full ray tracing sonic boom model, rather than the carpet boom model. This software is operational on the CDC 170 computer system at AFESC, Tyndall AFB, FL.

Prior to the start of this project, the Air Force used EXTRACT to process ACMI tapes from 50 training events in Lava/Mesa. These tapes included 241 sorties, of which 164 involved supersonic flight. The intent was to process data from this "50-tape library" via BOOM-MAP, with the resultant CDNL contours providing a basis for monitor site design. During the analysis, it was realized that CDNL would not be the appropriate quantity on which to base the measurement plan. While CDNL is the primary metric for evaluating sonic boom, statistical success of a sampling study depends on the number of data points collected. The center of the supersonic arena would be expected to receive the most sonic booms and also the highest amplitude ones. As distance from the center increases, both number and amplitude would decrease. Use of CDNL would bias the plan toward the center of the area. This is undesirable because accurate definition of the outer edge of the boomed environment is important for fitting supersonic airspace within an acceptable location. It was therefore decided to base the D-optimality analysis on the predicted number of booms, regardless of amplitude.

Software was prepared which would read an ACMI library and compute the number of booms, using ray-tracing algorithms equivalent to those in BOOM-MAP. The calculations involved were well within the computational capability of an AT-class PC, and it was found to be much more convenient to use a PC locally rather than the CDC 170 at AFESC. It was also found to be beneficial to develop new software directly on the PC, rather than rehost the CDC version of BOOM-MAP and modify it to the needs of the current project. This decision was supported by the availability of readily adaptable ray-tracing code on the PC, having been developed for previous sonic boom projects.[11,14] The 50-tape library was transferred to floppy disk and converted to PC-readable format. The data file had the structure described in Reference 21, containing only supersonic data extracted at 1.4-second nominal intervals.

Figure 9 shows the supersonic tracks from this library. These tracks are plotted as they would have been by BOOM-MAP. Rather than a generic border and scales, the Lava/Mesa outline is drawn. Note that the area covered by these tracks is consistent with the discussion of airspace utilization in Section 2.2.

Figure 10 shows computed numbers of booms. This set of contours was developed by dividing the area into a matrix grid of square-mile cells and counting how many boom events impinged each cell. A boom event was considered to be the ground footprint associated with a single excursion above Mach one. For each such supersonic excursion, the envelope of the footprint was computed and a boom "hit" count was incremented for each cell within the footprint. Definition of

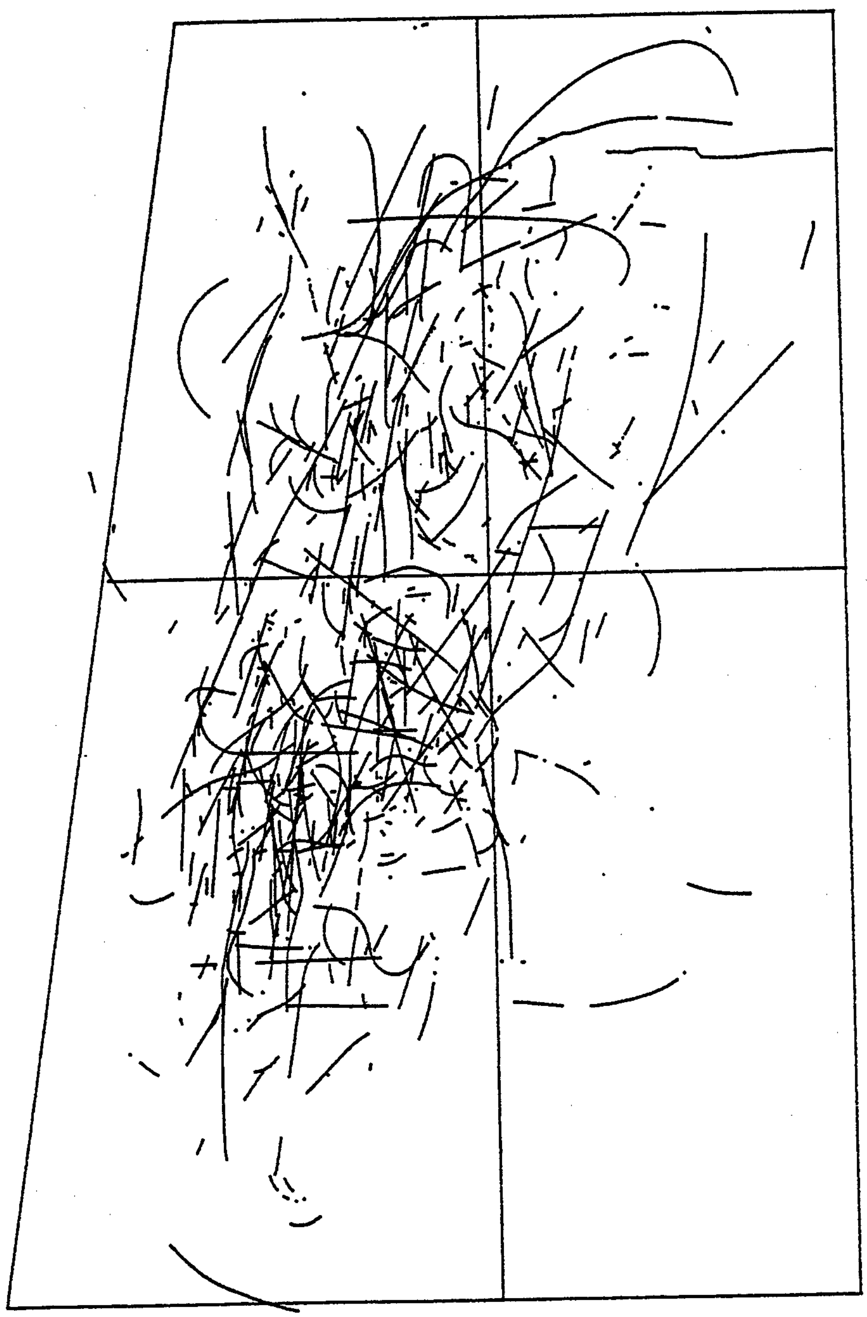


Figure 9. Supersonic Ground Tracks From 50-Mission Library.

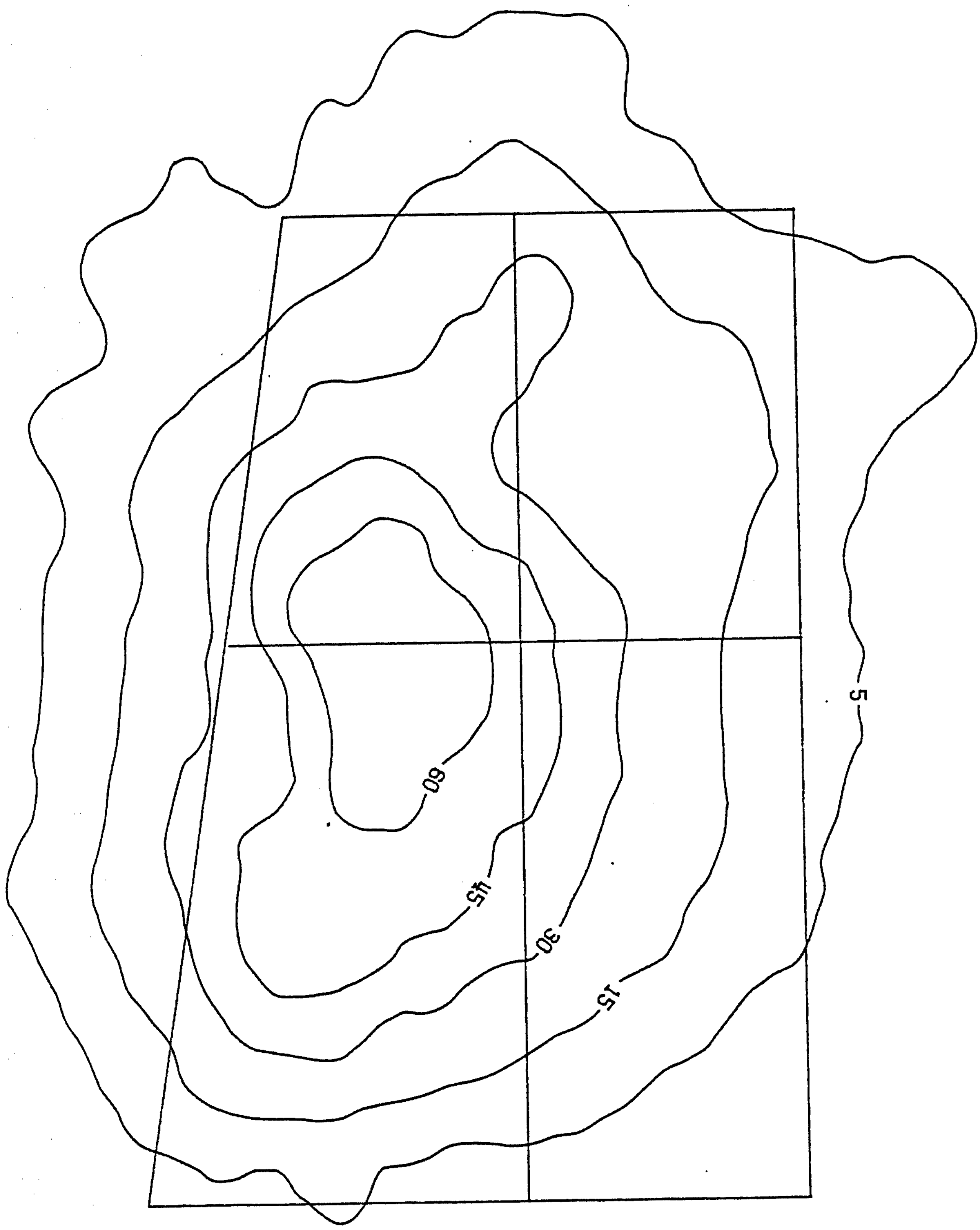


Figure 10. Numbers of Predicted Sonic Booms, 50-Mission Library.

a boom footprint as its envelope avoided spurious counting of post-focus U-waves, since those would occur at locations covered by primary focus or carpet boom from the same event. No consideration was given to boom amplitude. Contours were generated from the final count matrix via a commercial contouring software package. The contours shown are actual counts for the 241 sorties, and have not been normalized. Dividing by 241 would, however, yield booms per sortie.

Figure 10 represents contours fitted directly to the numerical boom count results. Application of D-optimality requires a functional form. A number of functional forms were fitted to the boom count matrix via least-square regression. A regression analysis program entitled SURFIT[23] was used for this purpose. For a given data matrix, SURFIT performs polynomial least square regressions. It provides the fitted coefficients and statistical parameters. The program allows determination of the polynomial order and combination of coefficients which provides optimal fit. An added consideration in the current project is that the function which is fitted must approach zero at large distances, and care must be taken that this condition as well as good fit near the middle is met. Through formal analysis and experimentation with various scaling functions of the count matrix (in particular, its logarithm), it was found that a two-dimensional normal distribution function provided the best fit. Figure 11 shows the Gaussian fit. The standard deviations along the major and minor axes are 14.1 and 7.0 miles, respectively.

The result shown in Figure 11 is satisfying for two reasons. First, the basic pattern is consistent with the elliptical contour shapes deduced in development of the original Oceana model. Second, given the random nature of ACM activity and of supersonic events therein, it would be difficult to understand had the function not turned out to be one of the more common random probability functions.

3.2.3 <u>D-Optimality</u>

References 16 through 18 describe a number of techniques for optimizing data points in a test matrix, given a regression model. The most popular is D-optimality.

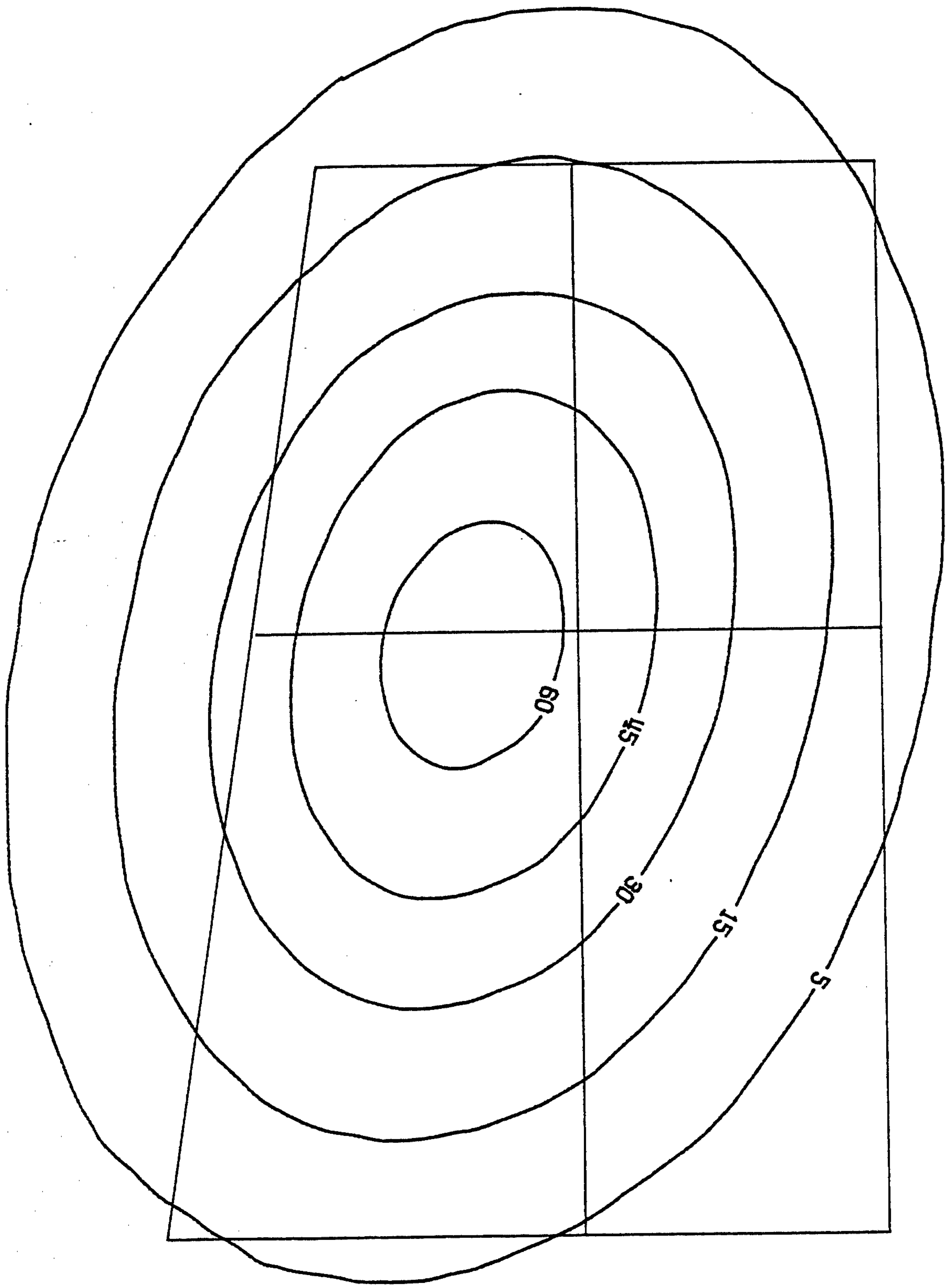


Figure 11. Gaussian Fit to Number of Booms, 50-Mission Library.

Consider an experiment where response y is measured at n fixed values of independent variable x. For the i'th observation,

$$y_i = f(x_i) + \epsilon_i \tag{2}$$

where f is an unknown function relating x and y, and ϵ_i are uncorrelated errors with mean of zero and variance σ^2. If we assume that f(x) can be approximated as a k'th order polynomial with coefficients β_j, Equation (2) may be written in matrix form as:

$$y = X\beta + \epsilon \tag{3}$$

where y, β, and ϵ are now written as vectors and X is an $n \times k$ matrix of powers of the independent variable(s), evaluated at the observation points.

Once observations are made at the sampling locations X, a least-squares estimate of β is made:

$$\hat{\beta} = (X' X)^{-1} X' y \tag{4}$$

where $(\hat{\ })$ denotes least-square fit, and $(\ )'$ denotes the transpose of the matrix. The variance–covariance matrix of $\hat{\beta}$ is:

$$\text{cov}\ \hat{\beta} = \sigma^2 (X' X)^{-1} \tag{5}$$

At any point in the region the value predicted by the regression is:

$$\hat{y}(x) = f(x)'\ \beta \tag{6}$$

with a variance given by

$$\upsilon(x) = f(x)'\ (X' X)^{-1}\ f(x)\ \sigma^2 \tag{7}$$

If the variance, Equation (7), is minimized, then the model will provide optimally good predictions. It is seen from the above that maximizing $|X' X|$ will invariably generate good designs.

A D-optimal design may be performed *a priori* (given a regression model) or may be adjusted as data is taken. For the current project, the regression derived in Section 3.2.2 was used as the basis of an *a priori* design. Given the logistics and schedule of the current project, adjustment of sites during monitoring was not seriously considered.

Calculation of a D-optimal site design was accomplished by means of computer program DETMAX.[24,25] DETMAX uses a numerical search procedure that attempts to maximize the $|X'X|$ matrix. The algorithm does not guarantee, with mathematical certainty, a D-optimal design. However, its developers have found that it has performed well in all test cases since its inception.[26] The algorithm is heuristically reasonable, and the use of a variety of design inputs protects against anomalous false solutions.

Input to DETMAX is a series of candidate points from which it must pick the design. These candidate points were chosen using an equally spaced grid that lay within the confines of the airspace. Also as input, DETMAX must know the number of points to be selected from the candidate sites. The grid spacing and number of points were varied so as to observe the behavior of the calculations and thus guard against false solutions. Figures 12 through 14 show the results. Noted on each figure are the candidate grid spacing and number of sites. The number of selected sites marked on each figure is generally less than the number of sites it was told to select because the algorithm may pick the same points several times. This is not a defect, but rather reflects that those are good sites and the others are poor choices.

The basic pattern of the D-optimal solution is that selected sites are concentrated along the outer edges of the range, with fewer in the center. Each solution specified from 20 to 30 sites, which is within the quantity of available equipment, and a high degree of confidence. In many cases, DETMAX selected sites that were at adjacent grid points. Those could be considered to be effectively the same as picking the same points and would have to be so considered, in view of practical considerations of access. A practical implementation of the D-optimal solution would be 20 to 25 monitors deployed in a pattern as suggested by overlaying Figures 12 to 14, with emphasis on maintaining the relative density of sites in various parts of the range. This leaves 13 to 18 of the 38 total monitors available for a regular grid deployment.

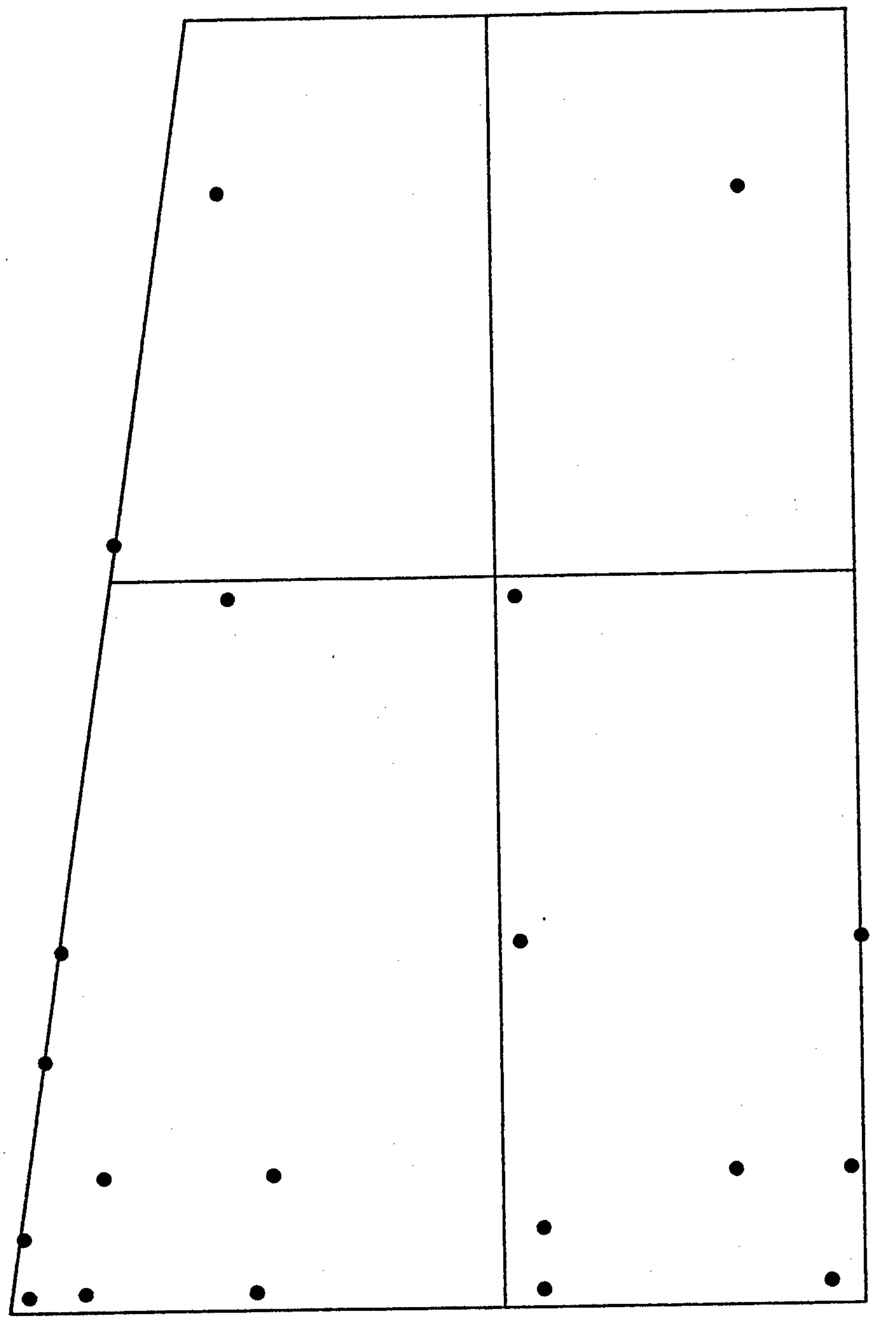


Figure 12. DETMAX Results; Three-Mile Grid Spacing, 30 Points Selected.

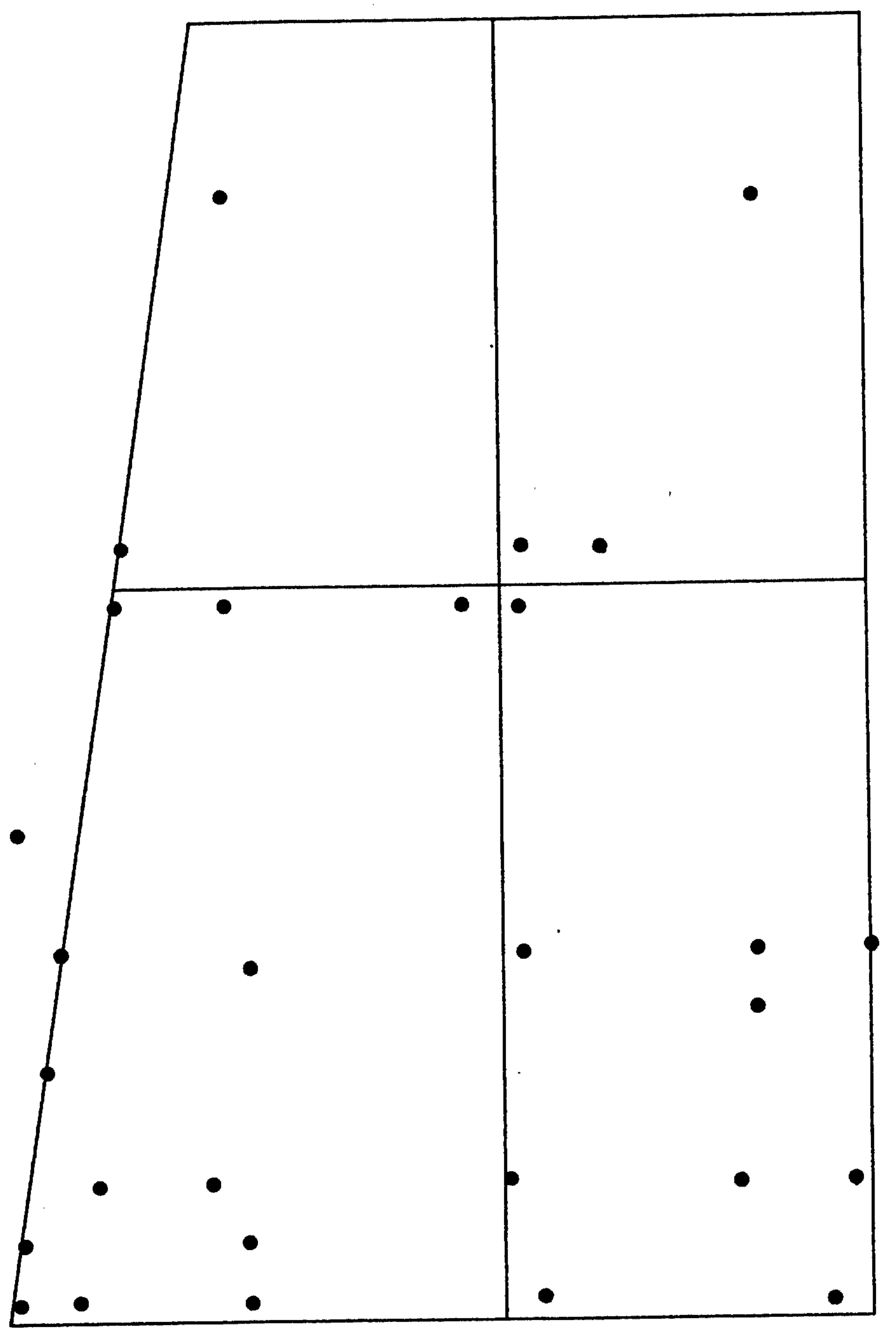


Figure 13. DETMAX Results; Three-Mile Grid Spacing, 50 Points Selected.

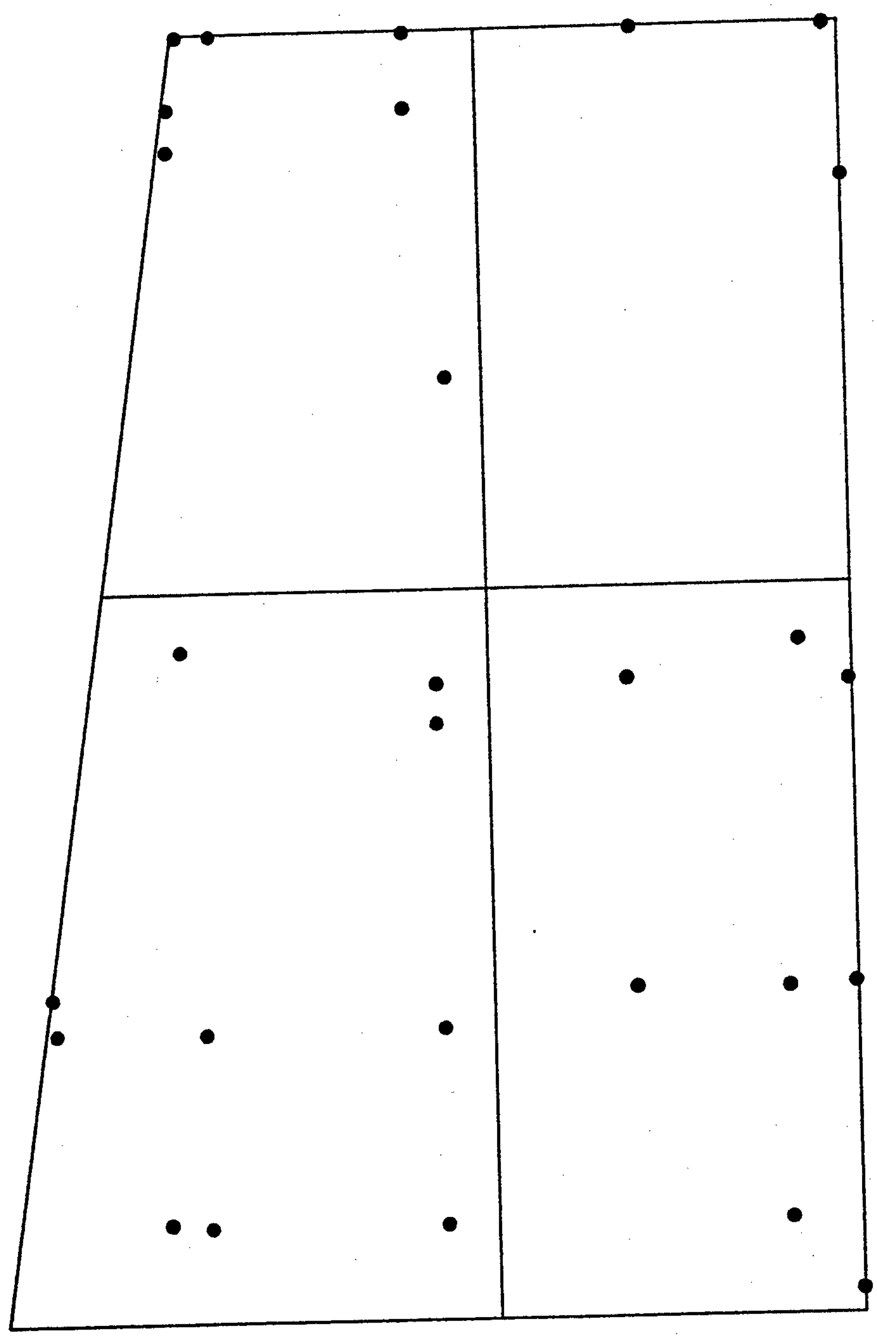


Figure 14. DETMAX Results; Two-Mile Grid Spacing, 50 Points Selected.

Section 3.2.4 contains a discussion of the application of this ideal site design to practical constraints at WSMR, and presents the site layout actually employed.

3.2.4 Site Selection

The site layout was based on two superposed grids. One was a 20- to 25-site plan based on the D-optimal solution. This extended to all quadrants of the airspace and was the statistically optimized layout. The other was a uniform spacing within one quadrant. The uniform grid would provide a validation of the predicted regression and would also provide detailed spatial data of individual boom events.

Several practical constraints had to be observed:

1. All sites were to be serviced from the ground, at locations practical for access twice a week.

2. Access to sites must be along existing roads, using civilian 4x4 vehicles.

3. All sites were to be within the WSMR boundary, either on government property or in the range extension where agreements existed with landowners.

4. Preference was to be given to placing sites on government land, where security would be high.

5. Safety of field personnel was paramount.

Constraints 4 and 5 dictated that the regular grid be located in Lava West. Constraint 3 precluded sites along the western edge of Lava West.

Most of these constraints were identified at an organizational meeting held on 4 November 1987 at Holloman AFB. Attending were personnel from Holloman AFB, HQ TAC, WSMR, Geo-Marine, and Wyle Laboratories. On 5 November, key personnel were given an aerial reconnaissance of the Lava area. This provided direct observation of the nature of the terrain and the existing road network. On 6 November, personnel from Wyle made a ground reconnaissance of Mesa West to assess accessibility of that area. These reconnaissance trips provided an opportunity to calibrate road quality shown on maps with actual conditions. It was also confirmed that Socorro would be the best location for a base of operations.

Figure 15 shows the preliminary site design. This was developed by laying out the superposed grids on 1:100,000 topographic maps, and adjusting locations so as to be adjacent to roads. Sites developed from the optimality analysis are indicated. The knowledge gained in the November 1987 reconnaissance was directly applied.

The preliminary site design was for 38 sites, assuming that all equipment would be deployed. Sufficient roads were available such that the basic theoretical patterns could be maintained. It may be seen from Figures 12 through 14 that these patterns allow some flexibility. A formal Latin square design of the regular grid was not performed, the rationale being that working with available roads would preclude an exact implementation, but would also preclude the regular square layout which was to be avoided. Each site was also designated as receiving either a BEAR or an SBM-1. These were interspersed so as to place BEARs at critical locations and to avoid having SBM-1s adjacent to each other.

The preliminary site design, with some alternatives, was submitted to White Sands for approval. For sites on the government range, other range users were contacted to ensure there would be no conflict. For sites in the range extension, landowners were contacted and addenda to existing agreements were obtained allowing placement of the equipment. Arrangements were made for entry of Geo-Marine and Wyle personnel onto the restricted range.

On 18–22 May 1988, personnel from Wyle conducted a site selection visit. Using a light 4x4 vehicle, every candidate site was visited and the exact location marked. Adjustments were made as necessary to accommodate actual road and access conditions. Field notes were compiled with directions to each site and the exact position relative to available landmarks. During this visit, security personnel at Stallion Range Center provided a briefing regarding safety and security on the range.

Figure 16 shows the final site plan. BEAR or SBM-1 monitors are indicated by square or triangular symbols, respectively. Thirty-five sites were actually used,

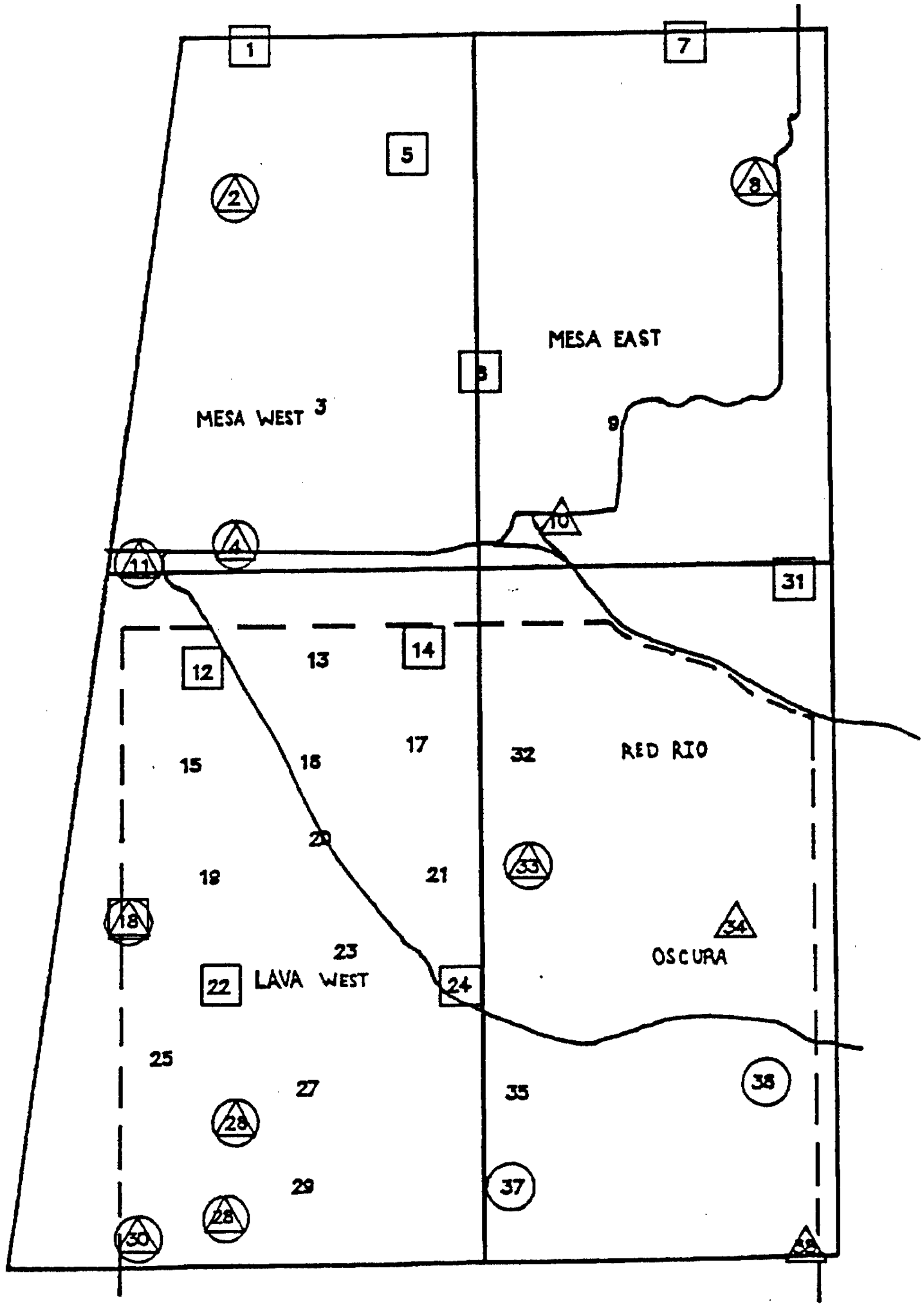


Figure 15. Final Experimental Design.
O – 3-mile grid, 30 points;
Δ – 3-mile grid, 50 points;
□ – 2-mile grid, 50 points.

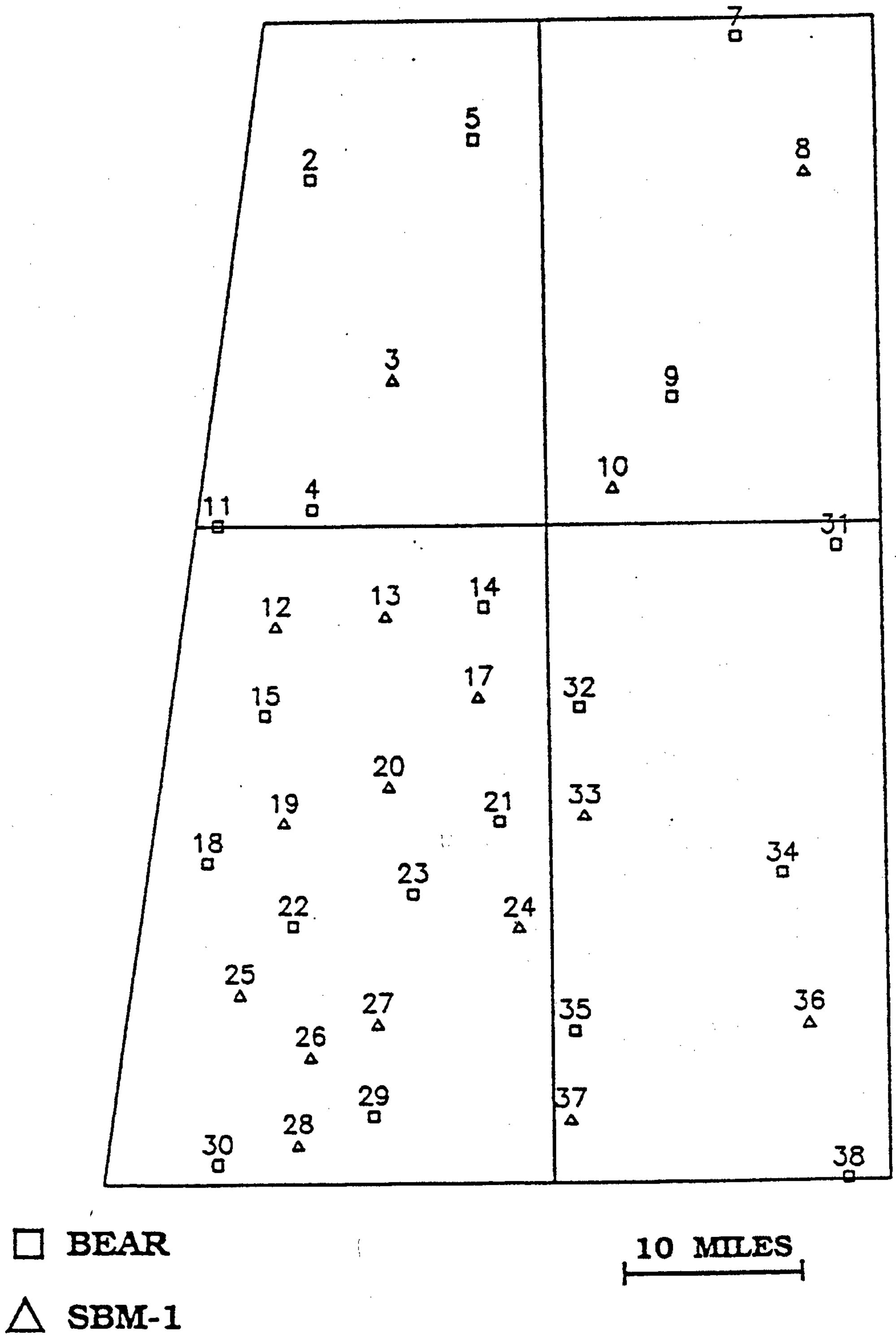


Figure 16. Measurement Sites in Lava/Mesa Airspace.

with three of the monitors typically serving as spares or being repaired at any given time. The three sites deleted were site 1, which was shielded by a mountain range, and sites 6 and 16 which were surrounded by enough other sites so as to be expendable. About two months into the measurements, site 2 was moved about a mile south of its indicated location because the road leading to it became unusable. After about three months, site 31 was vandalized and the monitor lost. Few booms had been recorded there, and it was decided to abandon that site. After about four months, site 32 was moved about a mile north and site 33 was abandoned. These two sites were on the ridge of the Oscura range, along a road whose condition was deteriorating and which would become inaccessible in snow. Few booms had been recorded at either site. The new site 32 location was accessible by an all-weather road. Table 1 contains the original latitude, longitude, and elevation of each site.

3.3 Operations Data

In order that it be possible to project the sonic boom data to other airspaces, it was necessary to have complete information on operations in the airspace during this project. These data are available at Holloman AFB. During the organizational meeting on 4 November 1987, it was determined that the following data could be accessed:

- 49th TFW/DOO maintains advance schedule data for the wing. Daily range schedules, showing use of the airspace by all organizations, are also available in this office.
- The three squadrons comprising the 49th TFW maintain debriefing records and as-flown dispositions of scheduled missions.
- Cherokee Control maintains records of all airspace clearances.
- PRC/ACMI controls the data tapes generated by the ACMI system, and also maintains logs of missions flown, including pod assignments to each aircraft.

Table 1

Monitor Site Locations

Site	Latitude	Longitude	Elevation (Ft, MSL)
2	34° 9.3'	106° 38.1'	6,890
3	33° 59.3'	106° 33.2'	5,381
4	33° 52.8'	106° 38.2'	4,987
5	34° 11.2'	106° 28.1'	5,709
7	34° 16.2'	106° 12.3'	6,627
8	34° 9.5'	106° 8.4'	6,299
9	33° 58.3'	106° 16.5'	5,906
10	33° 53.8'	106° 20.1'	5,709
11	33° 52.0'	106° 44.0'	5,118
12	33° 47.0'	106° 40.5'	4,856
13	33° 47.5'	106° 33.8'	4,856
14	33° 47.9'	106° 27.8'	5,118
15	33° 42.4'	106° 41.2'	4,790
17	33° 43.4'	106° 28.2'	5,052
18	33° 35.1'	106° 44.8'	4,724
19	33° 37.1'	106° 40.1'	4,659
20	33° 38.9'	106° 33.7'	4,659
21	33° 37.1'	106° 27.0'	5,085
22	33° 31.9'	106° 39.6'	4,724
23	33° 33.5'	106° 32.3'	4,659
24	33° 31.8'	106° 25.9'	5,184
25	33° 28.5'	106° 42.9'	4,659
26	33° 25.4'	106° 38.6'	4,987
27	33° 27.0'	106° 34:5'	4,888
28	33° 21.0'	106° 39.4'	5,807
29	33° 22.4'	106° 34.8'	5,348
30	33° 20.0'	106° 44.3'	5,577
31	33° 50.8'	106° 6.8'	6,430
32	33° 42.8'	106° 22.2'	7,546
33	33° 37.4'	106° 22.0'	8,333
34	33° 34.4'	106° 10.4'	4,790
35	33° 26.6'	106° 22.7'	4,528
36	33° 26.9'	106° 8.9'	4,528
37	33° 22.2'	106° 23.0'	4,298
38	33° 19.1'	106° 6.7'	4,429

- Det. 12, 25 WS at Holloman AFB maintains ground weather records at the base, weather radar summaries, and twice-daily rawindsonde records from El Paso, TX, and Albuquerque, NM.

Examining, copying, and organizing these data was estimated to be a full-time job. Geo-Marine therefore hired a recently retired Air Force NCO, with direct experience in scheduling and Holloman's recordkeeping practices, to gather these data. Work space was provided in the Airspace Manager's office, 49th TFW/DOO. By having a single individual responsible for this task, it was assured that all data would be collected and that there would be priority and resources to resolve any problems which might occur.

It was the intent that all ACMI tapes be analyzed by BOOM-MAP software. Arrangements were made by TAC for PRC/ACMI to ship all tapes to AFESC for processing by the EXTRACT program. Arrangements were also made to provide Wyle Laboratories with user access to the CDC 170 system at AFESC.

4.0 OPERATION OF MONITORING PROGRAM

4.1 Deployment and Operation of Monitors

4.1.1 Mobilization and Installation

By the beginning of July 1988, preparations were complete to initiate the field program. Based on the test plan discussed in Section 3.0, Geo-Marine accomplished the following:

- Arranged for the manufacture of eight new BEAR systems.
- Rented a house in Socorro for use as a field office.
- Obtained two 4x4 pickup trucks.
- Selected a field team consisting of two crew chiefs and two technicians. These formed two crews, each assigned to a truck.
- Arranged transfer of the existing BEAR and SBM-1 systems, and supporting accessories, from the Air Force to Socorro.
- Equipped the Socorro office with two portable computers (Zenith Z183), one desktop XT-compatible PC, various computer and office supplies, tools, etc.
- Rehosted BEAR RAM to PC software from its original Zenith Z-100 form to generic MS-DOS form.

At this time, Wyle had accomplished the following field items:

- Prepared map booklets identifying the monitor sites.
- Rehosted SBM-1 to PC software onto the Z183, and customized it for this project. This software is documented in Reference 27.
- Rehosted and customized the VIEW program, which generated hard copy plots of BEAR signature data. This software is documented in Reference 27.

- Prepared an instruction manual, including field procedures, for both monitor systems.[28]

- Prepared data logging procedures and requisite forms.

- Rented two additional 4x4 vehicles for use during the training and installation period.

On 11 July, three personnel from Wyle joined the Geo-Marine team and the Geo-Marine program manager for training and installation. Two days were spent in Socorro training the Geo-Marine team in the use of the monitors and describing the test plan and procedures. On 13 July, installation began. On the first day, all personnel went together, transitioning from classroom training to field training. Thereafter, each Geo-Marine team, accompanied by one person from Wyle, went out separately, with the process transitioning from training to operation. The third Wyle person generally remained in Socorro, further customizing the software installation, setting up processing procedures, etc. By 18 July, about half the monitors were installed, and servicing began. Installation was complete by 25 July, and that date was declared to be the start of the 6-month monitoring period.

During the training and installation period, the following were also accomplished:

- During the week of 18 July, three personnel from OEHL/ECH, Brooks AFB, joined the operation to observe the procedures and become familiar with the sonic boom monitors.

- The Wyle and Geo-Marine program managers visited Holloman AFB to instruct Geo-Marine's on-site person in his duties.

- Field and data procedures were fine-tuned.

There were problems with some of the monitors. These were of magnitude which normally occurs in a field program. It was decided to reduce the array from 38 active sites to 35, as discussed in Section 3.2.4. A priority list was also established, in the event fewer than 35 monitors were functional.

4.1.2 Operation

Based on battery life, the BEARs could operate for up to a week and the SBM-1s for up to three weeks. Because of inherent uncertainty in lead-acid batteries after a number of cycles, and because of the potential for memories to fill with false data (SBM-1s in particular), a nominal twice-a-week schedule was established, and five days was considered to be the maximum safe service interval. Since the range could be closed at various times, but rarely on weekends, the normal work week included Saturday and Sunday and days off were rotated among team members during the week.

Servicing each monitor followed the procedures in Reference 27. This included downloading data, replacing batteries, checking system calibration, and restarting. Based on the number of spare batteries and battery chargers, a maximum of six BEARS and six SBM-1s could be serviced each day. Since the SBM-1 batteries could last two weeks, additional SBM-1s could be serviced on a data-only basis if needed. Data from BEARs consisted of the removable RAM modules. Data from SBM-1s consisted of data files downloaded to floppy disk.

Each day, a list was compiled of monitor sites to be serviced. This list was based on records of time elapsed since the last previous visit. The list was organized in triage form, with highest priority assigned to sites approaching or exceeding 5 days, nominal priority to sites in their normal rotation, and low priority to additional sites which would ease the next day's schedule. Over the long run, however, servicing a site early was not beneficial since it would advance the scheduled time for the next service. The team planned the route and the assigned sites for each crew. Nominal plans for each day were made the previous evening. Each morning, the schedule of range closures (if any) was obtained from White Sands, and service plans adjusted accordingly.

A master field service log book was kept in each truck. Figure 17 is a log form. Entries on the form are suitable for both types of monitors, and the field crews would complete the information as each site was serviced. On return to the office, this information would be transcribed onto similar forms organized by site, and kept in a master log book. The truck log books would thus have a sequential record of field activity, while the master log book would have the sequential history of each site.

SONIC BOOM MONITOR SERVICE LOG

Site	Monitor S/N	Date	Cal. Check	Time	No. of Booms/ Exceed.	Battery Volts			Clock Diff. ($T_R - T_m$)	Data File	Disk No.
						Total	Int.	New			

Figure 17. Field Service Log.

Upon return to Socorro, the following would be done:

- Batteries placed on chargers, to be ready for the next day.
- SBM-1 data files would be copied to backup disks, and also printed.
- BEAR RAMs downloaded to PC floppy disk via program COMM, creating image files.
- Image files operated on by program PROCESS, yielding individual event files on disk.
- Individual event files plotted by program VIEW.
- Field log data transcribed to master log book.
- Particular problems noted on a "trouble" log.

The BEAR RAM image files and original field-downloaded SBM-1 files were retained by Geo-Marine as masters. Each week, the BEAR individual event files, the backup SBM-1 files, the plots generated by VIEW, and copies of the field logs would be shipped to Wyle's El Segundo, CA, office for interpretation and reduction.

After the routine was established, it became apparent that the computer processing of each day's data was a significant task. Accordingly, Geo-Marine added a part-time team member who was responsible for all computer processing in the office, relieving the field crews of that task.

As anticipated from experience during the installation, there were some ongoing equipment problems. The SBM-1s, which had been used in the field for five months at Reserve and three months in other projects, were well seasoned and gave little trouble; only two malfunctioned and required repair. The BEARs greatest field use had been the one-week Boomfile II exercise. Under extended use, additional field ruggedness problems appeared. The worst problem was early in the program, when lightning strikes damaged the analog input circuitry on several BEARs. Several of the eight new BEARs experienced infant mortality failures. Some mechanical problems (PC board mounts and cable flex failures) appeared after extensive use. Some problems, particularly failed cables, could be repaired in the field. Dysfunctional BEARs were shipped to the manufacturer for repair. The site priority list prepared during installation was followed, and monitors moved as necessary when equipment malfunctioned. At least one spare SBM-1 was generally available, and would be installed at a critical failed BEAR site if another BEAR could not be immediately moved there.

Another potential cause of sites not operating would be if memory filled. This would generally happen with SBM-1s if it rained or if there were high winds. Rain would occasionally fill a BEAR with false data.

Whenever equipment failed – either malfunction or filled memory – the data files and field logs would always identify the time period during which no data was being collected. Table 2 is a list of the number of operational days at each site. Over the six-month monitoring period, 87 percent up time was achieved over the 35 sites, including sites 31 and 33 which were eliminated partway through the project. That is a very good operating average for this type of project.

Approximately once a month, personnel from Wyle would visit Socorro to spend a few days with the Geo-Marine team. He would observe their operation in the field to ensure that correct procedures were being followed. Any problems which had not been worked out by telephone between Wyle visits were resolved.

4.1.3 Removal

The six-month monitoring period was completed effective Monday, 23 January 1989. Advance schedule information indicated that ACM activity would end in early afternoon on 20 January and would not resume until after the weekend. Accordingly, removal of monitors began on the afternoon of 20 January. By 23 January, all equipment had been removed.

4.2 Processing of Sonic Boom Data

Sonic boom data were shipped to Wyle's El Segundo, CA, office each week. These data consisted of all BEAR and SBM-1 records (on floppy disk and printed copies) plus copies of the field data logs. Upon arrival, data were inventoried and the status of each site tracked. A spreadsheet was set up in bar chart form to document the status of the sites. This chart was filled in to indicate periods

Table 2

Monitor Types and Periods of Operation

Site Number	Type of Monitor	Days Operating
2	BEAR	122.5
3	SBM-1	177.9
4	BEAR/SBM	154.2
5	BEAR	103.5
7	BEAR	146.1
8	SBM-1	166.2
9	BEAR	177.1
10	SBM-1	169.9
11	BEAR	143.8
12	SBM-1	191.3
13	SBM-1	155.4
14	BEAR	189.9
15	BEAR	171.2
17	SBM-1	174.2
18	BEAR	148.1
19	SBM-1	186.0
20	SBM-1	188.4
21	BEAR	176.1
22	BEAR	145.5
23	BEAR	171.0
24	SBM-1	182.0
25	SBM-1	181.4
26	SBM-1	160.2
27	SBM-1	177.5
28	SBM-1	117.3
29	BEAR	167.6
30	BEAR	179.0
31	BEAR	108.8
32	BEAR	149.4
33	SBM-1	55.1
34	BEAR	148.4
35	BEAR	184.7
36	SBM-1	172.9
37	SBM-1	156.5
38	BEAR	137.5

during which each site was operational and for which all data had been received. When data had been received for all sites up to a given date, analysis would be prepared through that date.

All BEAR plots were examined. Those which were clearly not sonic booms were discarded. Some BEAR records contained spurious spikes, which had also been observed during Boomfile II and were thought to be due to RF noise. Affected files were cleaned up (using the edit capability of the VIEW program), reprinted, and reexamined. At this stage, only those BEAR records which were clearly not sonic booms were discarded. The plots were placed in chronological order. Booms which occurred at the same time (nominally, within two minutes) at different sites were grouped together. For each event group, the time and location of each boom record was marked on a site sketch similar to Figure 16. Most boom events consisted of a single BEAR record. Following the assignment of all booms to particular events, the SBM-1 data files were examined. Any SBM-1 records which occurred simultaneously with a boom event were added to the corresponding site sketch. Boom events were thus detected by a BEAR having captured a boom. Very few booms were positively identified if they were captured on an SBM-1 but not a BEAR.

Figure 18 is an example "boom event" sketch. Sites at which booms were recorded are circled, and the time and peak pressure written next to each. On this sketch, BEAR waveforms were sketched next to the corresponding sites. That was somewhat redundant, as the actual BEAR plots would be filed with the event sketch. Sites which were not operating at that time have a line drawn through them, so that the other sites with no record would be known not to have received a boom. Note that three of the lined-out sites are 1, 6, and 16, the three sites not used; only three active sites were not operational at that time.

Figures 19 and 20 are the BEAR records for this event. The abscissa of the BEAR plots is time, in seconds. The ordinate is pressure, in pounds per square foot. Annotation at the bottom of the plot gives the maximum and minimum values, the file name, time, and serial number of the instrument. The file name is in MS-DOS format, with an eight-character name and a three-character extension. The first character of the name is always P, and the next two are the site number. The next four digits give the local time, hours and minutes. The last character

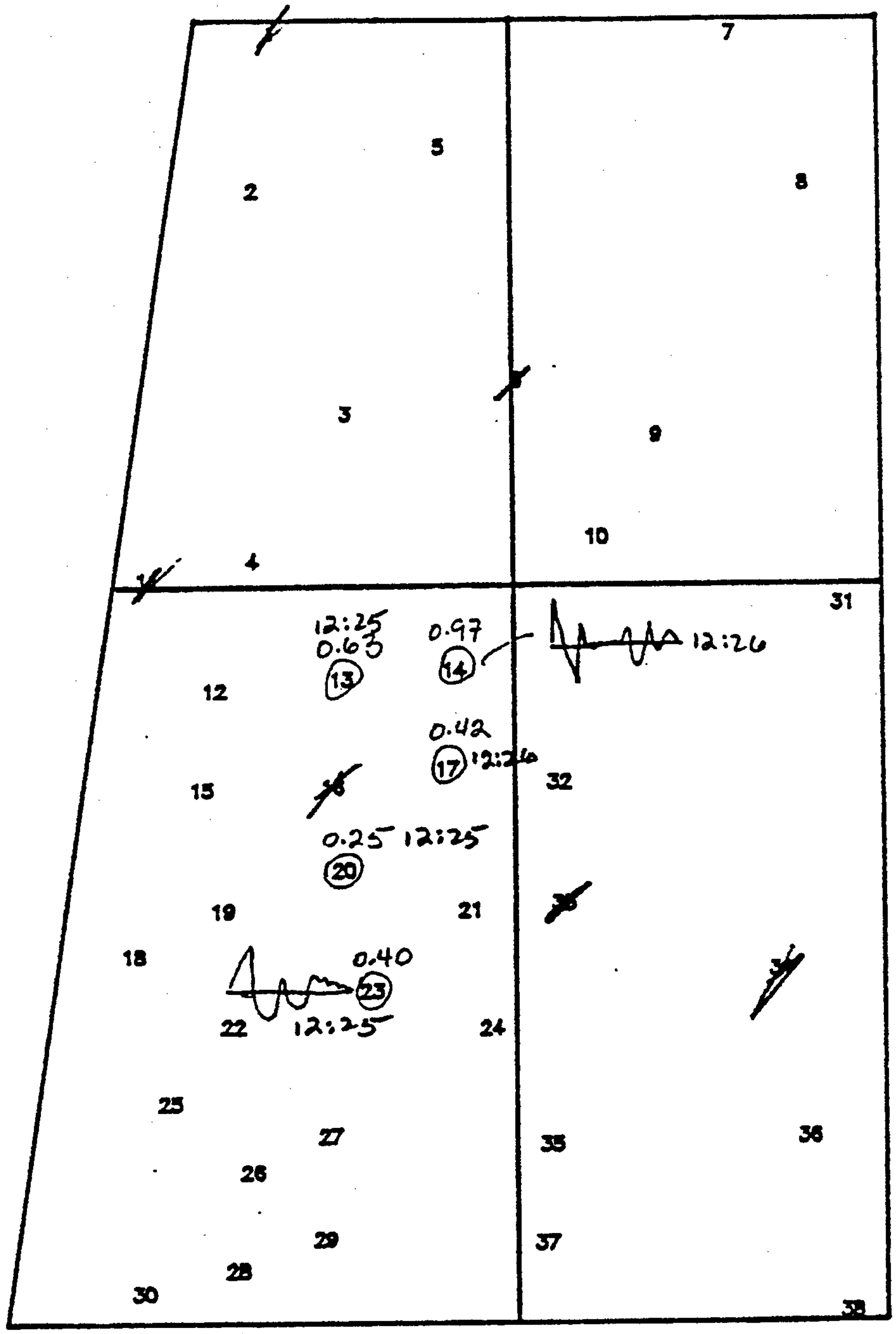


Figure 18. Example Boom Event Sketch.

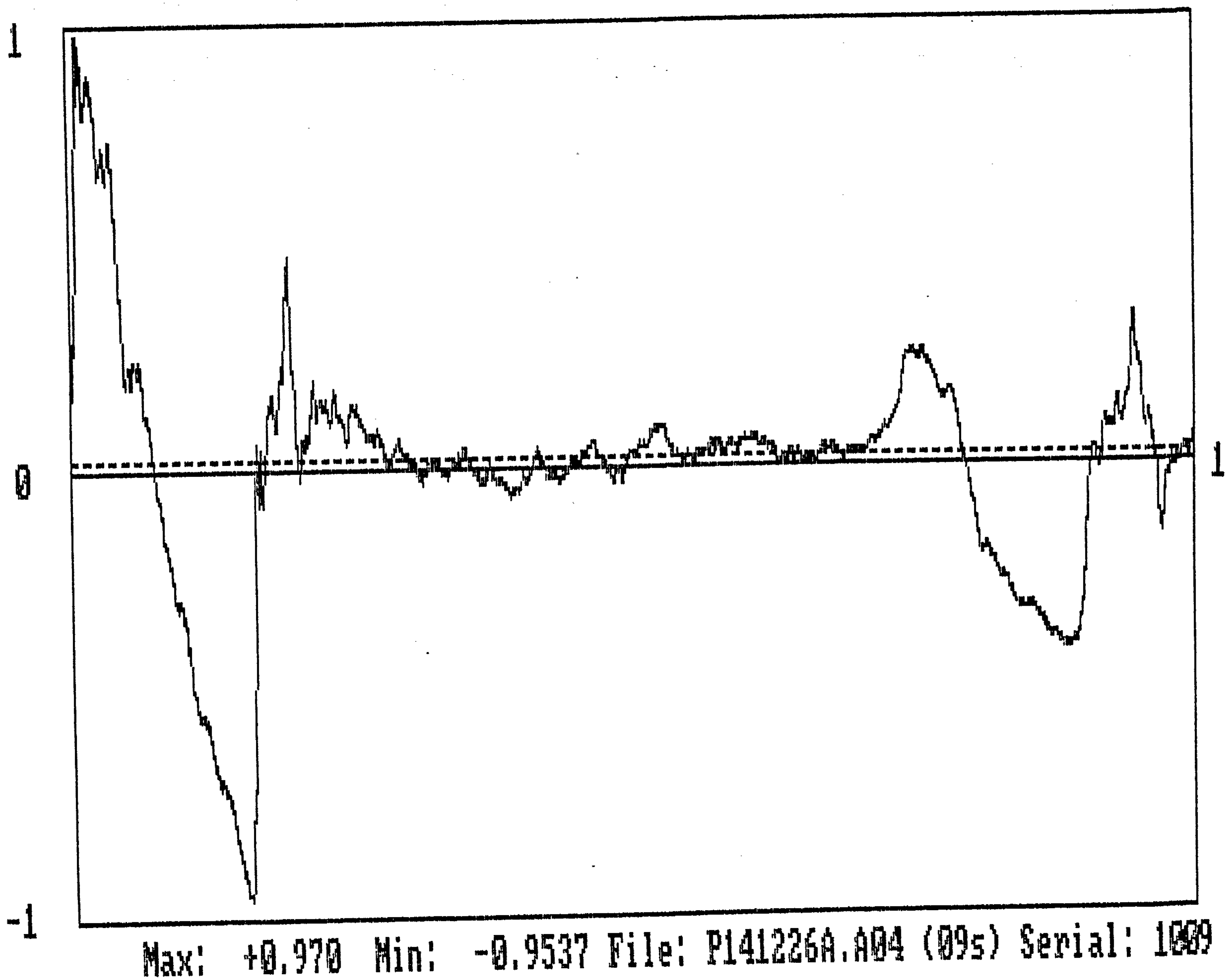


Figure 19. Example BEAR Record, Site 14.

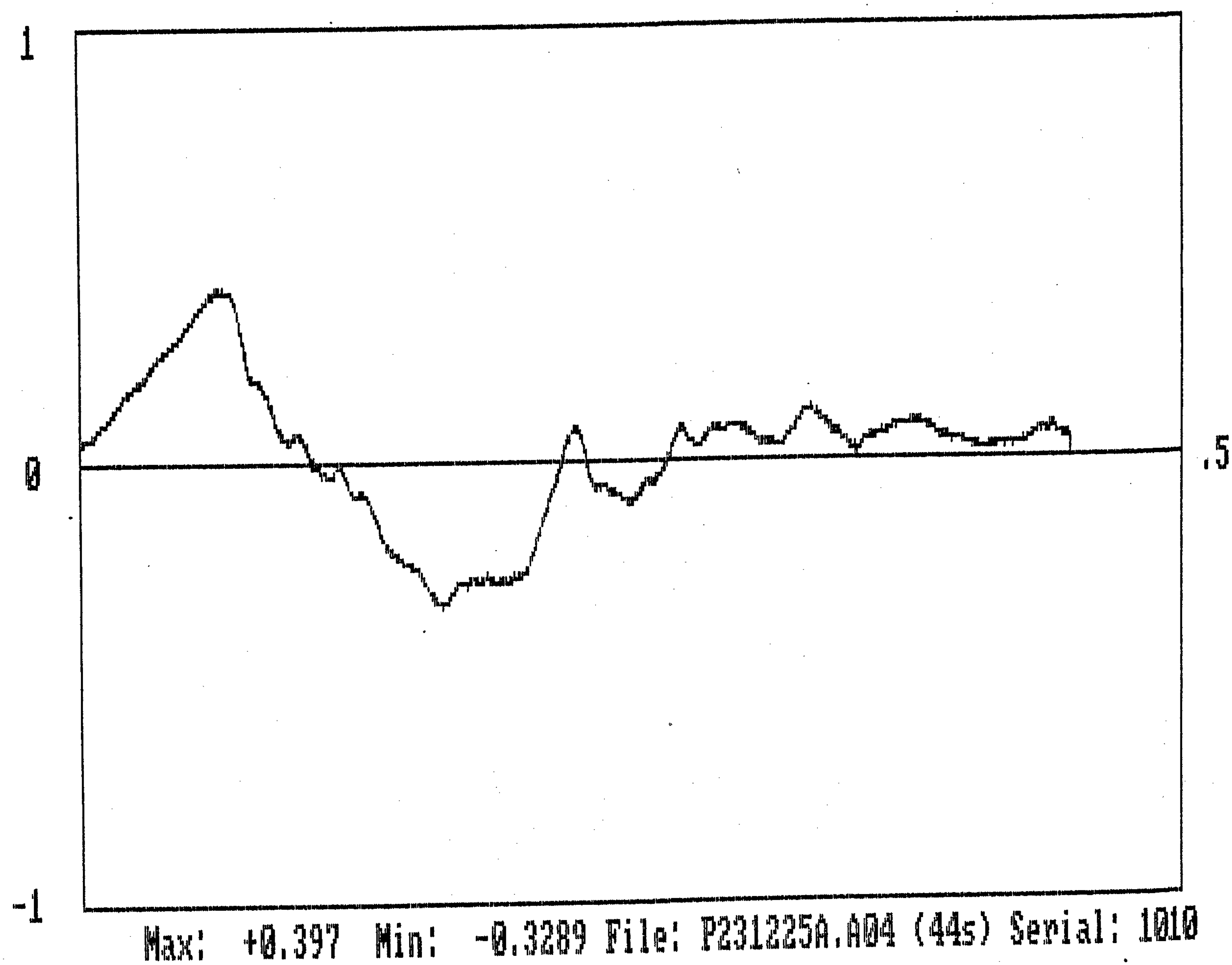


Figure 20. Example BEAR Record, Site 23.

indicates sequential order if there is more than one record within that minute. The first character of the extension represents the month in hexadecimal. The last two digits give the day of the month. Following the date, in parentheses, is the seconds part of the time within the minute defined by the file name. Figure 19 thus represents a boom at site 14, which occurred at 12:26:09 on 9 October.

The boom shown in Figure 19 is an N-wave followed by a U-wave, as sketched in Figure 5. The N part exhibits distortion due to the 0.5 Hz low-frequency limit of the BEAR, as illustrated in Figure 6. The entire waveform exhibits atmospheric distortion, as might be expected at noontime on the Jornada del Muerto. The boom in Figure 20 is of lower amplitude and has a rounded appearance, as would be expected near the edge of the footprint. It is at site 23, about 17 miles from the larger boom at site 14.

Figure 21 is a copy of the SBM-1 data file at site 13 for this event. The file is a capture of the printer output from the Larson Davis Model 700 on which the system is based. Each exceedance record is assigned a sequential index, shown in the first column. The other columns are average level (Leq) for the duration of the exceedance, sound exposure level, maximum level, peak level, date, time, duration (nearest second), and the numbers of times the peak exceedance threshold and overload limits were exceeded. As configured for this study, the peak level was unweighted and all other levels C-weighted. Only CSEL and Lpk are relevant for the current study. The duration is not of value since it is to the nearest second, and sonic booms are always much less than one second.

The first record in Figure 21 is the field calibration, which was performed with a pistonphone whose output at this altitude was 122 dB. Records 2 and 3 correspond to the sonic boom event in Figure 18. The 0.63 psf peak noted in Figure 18 corresponds to Lpk = 123.5 dB in record 2. Note that Lpk – CSEL is 25 dB, within the range expected for N-waves. Record 3, one second later, has a peak one decibel higher, but Lpk – CSEL is 30 dB, corresponding to a U-wave. Site 13 thus experienced an N–U combination, as did site 14. Record 2 is more important because it has the higher CSEL, hence it was noted on the boom event sketch. Both records were included in the CDNL summation.

EXCD REPORT
LARSON-DAVIS LABS -- MODEL 700
10/10/88 09:03:38 SN 700A0161 PAGE 2

Cnt	LVL	SEL	Lmax	Lpk	Date	Time	Dur	Pk	Ov
1	121.5	125.0	122.0	126.0	4 OCT	9:32:45	0:02 m:s	1	0
2	104.5	98.5	107.0	123.5	4 OCT	12:25:52	0:00 m:s	1	0
3	101.5	94.5	104.0	124.5	4 OCT	12:25:53	0:00 m:s	1	0
4	99.5	84.5	101.0	119.5	4 OCT	12:31:28	0:00 m:s	1	0
5	105.0	98.0	107.0	126.0	5 OCT	7:16:42	0:00 m:s	1	0
6	104.0	92.0	104.5	118.0	5 OCT	7:16:42	0:00 m:s	1	0
7	106.0	98.0	108.0	131.0	5 OCT	9:09:01	0:00 m:s	1	0
8	106.0	94.0	106.5	132.0	5 OCT	9:09:01	0:00 m:s	1	0
9	100.5	85.5	102.5	118.0	5 OCT	9:09:02	0:00 m:s	1	0
10	115.0	111.5	119.0	135.0	5 OCT	9:20:12	0:00 m:s	1	0
11	101.0	92.0	102.0	117.0	5 OCT	9:20:13	0:00 m:s	1	0
12	102.5	90.5	103.0	122.5	5 OCT	9:20:13	0:00 m:s	1	0
13	106.5	100.0	107.5	128.5	5 OCT	13:46:12	0:00 m:s	1	0
14	101.0	93.0	104.5	124.0	5 OCT	14:15:02	0:00 m:s	1	0
15	101.5	96.0	105.0	123.5	6 OCT	12:46:20	0:00 m:s	1	0
16	100.5	85.5	100.5	116.0	7 OCT	7:44:32	0:00 m:s	1	0
17	101.0	86.0	101.0	116.0	7 OCT	7:44:32	0:00 m:s	1	0
18	101.5	86.5	101.5	116.0	7 OCT	7:44:32	0:00 m:s	1	0
19	102.0	87.0	102.0	117.0	7 OCT	7:44:32	0:00 m:s	1	0
20	103.0	88.0	103.0	118.0	7 OCT	7:44:32	0:00 m:s	1	0
21	102.5	87.5	102.5	118.0	7 OCT	7:44:32	0:00 m:s	1	0
22	104.0	89.0	104.0	119.0	7 OCT	7:44:33	0:00 m:s	1	0
23	103.5	88.5	103.5	119.0	7 OCT	7:44:33	0:00 m:s	1	0
24	103.5	88.5	103.5	118.0	7 OCT	7:44:33	0:00 m:s	1	0
25	103.5	88.5	103.5	119.0	7 OCT	7:44:33	0:00 m:s	1	0
26	104.5	89.5	104.5	119.0	7 OCT	7:44:33	0:00 m:s	1	0
27	104.0	89.0	104.0	119.0	7 OCT	7:44:33	0:00 m:s	1	0
28	104.0	89.0	104.0	119.0	7 OCT	7:44:33	0:00 m:s	1	0
29	105.0	90.0	105.0	119.0	7 OCT	7:44:33	0:00 m:s	1	0
30	103.5	88.5	103.5	119.0	7 OCT	7:44:33	0:00 m:s	1	0
31	104.5	89.5	104.5	119.0	7 OCT	7:44:33	0:00 m:s	1	0
32	104.0	89.0	104.0	119.0	7 OCT	7:44:33	0:00 m:s	1	0
33	104.0	89.0	104.0	119.0	7 OCT	7:44:33	0:00 m:s	1	0
34	104.0	89.0	104.0	119.5	7 OCT	7:44:33	0:00 m:s	1	0
35	104.5	89.5	104.5	119.0	7 OCT	7:44:34	0:00 m:s	1	0
36	104.5	89.5	104.5	119.0	7 OCT	7:44:34	0:00 m:s	1	0
37	104.0	89.0	104.0	119.0	7 OCT	7:44:34	0:00 m:s	1	0
38	105.0	90.0	105.0	119.5	7 OCT	7:44:34	0:00 m:s	1	0
39	104.0	89.0	104.0	119.5	7 OCT	7:44:34	0:00 m:s	1	0
40	103.5	88.5	103.5	119.0	7 OCT	7:44:34	0:00 m:s	1	0
41	103.0	88.0	103.0	117.0	7 OCT	7:44:34	0:00 m:s	1	0
42	103.0	88.0	103.0	118.0	7 OCT	7:44:34	0:00 m:s	1	0
43	103.0	88.0	103.0	117.0	7 OCT	7:44:34	0:00 m:s	1	0
44	102.5	87.5	102.5	116.0	7 OCT	7:44:34	0:00 m:s	1	0
45	101.0	86.0	101.0	116.0	7 OCT	7:44:35	0:00 m:s	1	0
46	100.5	85.5	100.5	116.0	7 OCT	7:44:35	0:00 m:s	1	0
47	101.5	86.5	101.5	116.0	7 OCT	7:44:35	0:00 m:s	1	0
48	102.0	87.0	102.0	116.0	7 OCT	7:44:35	0:00 m:s	1	0
49	102.0	87.0	102.0	117.0	7 OCT	7:44:35	0:00 m:s	1	0
50	102.0	87.0	102.0	116.0	7 OCT	7:44:35	0:00 m:s	1	0
51	102.0	87.0	102.0	116.0	7 OCT	7:44:35	0:00 m:s	1	0
52	101.0	86.0	101.0	116.0	7 OCT	7:44:35	0:00 m:s	1	0
53	100.5	85.5	100.5	116.0	7 OCT	7:44:36	0:00 m:s	1	0
54	101.0	86.0	101.0	116.0	7 OCT	7:44:37	0:00 m:s	1	0
55	102.5	90.5	103.5	119.0	7 OCT	9:07:35	0:00 m:s	1	0
56	107.0	96.5	108.0	121.5	7 OCT	9:34:39	0:00 m:s	1	0
57	105.0	93.0	105.5	117.0	7 OCT	16:54:51	0:00 m:s	1	0
58	104.0	89.0	104.0	116.0	7 OCT	16:54:51	0:00 m:s	1	0
59	107.0	95.0	107.0	124.5	7 OCT	16:54:51	0:00 m:s	1	0
99999									

Figure 21. Example SBM-1 Data File, Site 13.

The last three records, at 16:54 on 7 October, were caused by the field crew handling the monitor prior to switching it off for service three days after the setup on 4 October. There are a number of low-level exceedances at 7:44 on 7 October. These are non-sonic boom events, and are the kind of record which would occasionally fill the memory. A BEAR at the same location would probably not have recorded any of those. Records 5 through 15, and 55 and 56 were sonic booms. Record 4 could have been a sonic boom (a weak U-wave), since the aircraft causing the boom five minutes earlier was still in the airspace, but it is not distinguishable from records 16 through 54, which were clearly not booms. The records identified as booms were corroborated by signatures at the same time on a nearby BEAR.

For each SBM-1 site, the relevant information for records determined to be sonic booms was transferred into a single spreadsheet file. The result was a set of "Site Files" which contained a sequential list of all sonic booms recorded at each site.

The printed BEAR records, as exemplified by Figures 19 and 20, provided values of the peak pressure and the time of occurrence. To obtain CSEL, BEAR records were processed by program BOOMBEAR. That program was developed by AAMRL/BBE for the purpose of obtaining frequency spectra and CSEL of BEAR records. When processed by BOOMBEAR, the CSEL for a record such as shown in Figure 19 would account for the N and U portions. BOOMBEAR was originally developed on a minicomputer. For the current effort, BOOMBEAR was rehosted onto a PC,[27] so that it could directly access the BEAR files. A production version was set up which could automatically read and process a large number of files, and write a data file with the same structure as the SBM-1 site files.

For a site which was sometimes equipped with each type of monitor, the BEAR and SBM-1 records were merged into a single site file. The site file structure included a flag indicating the type of system the data originated from. Although the data from both systems had now been brought to equivalent format, and the origin information was not needed, it was retained for audit purposes throughout the rest of the processing.

The site data files were combined into boom event files, corresponding to the boom event groupings as illustrated by Figure 18. The files were formed by chronologically interleaving all of the site files, and leaving a space before and after each group corresponding to a boom event. For convenience, these were organized by month. They were designated "Monthly Boom Event Files". The boom event sketches, grouped with their BEAR plots, were placed in notebooks corresponding to the monthly boom event files.

The above processing was conducted in Wyle's El Segundo office. When processing of each batch of data received from Socorro was completed, data was shipped to Wyle's Arlington, VA, office. Data which was sent included the boom event sketches and BEAR plots (filing in notebooks was actually done in Arlington), copies of the site files, copies of the site status spreadsheet, copies of the monthly boom event files, copies of the SBM-1 printouts, and the BEAR data file disks.

In Arlington, the data in the boom event notebooks was reviewed for completeness and consistency. All events were examined and a final decision was made on questionable BEAR records. The site and boom event files were edited so as to include only those records determined to be sonic booms. The relative times and locations of booms in each event grouping were examined, and groupings adjusted so that each boom event represented the footprint of a single supersonic excursion. Data files for all BEAR records identified as sonic booms were copied to fresh disks, and the original field disks archived.

This completed processing of the sonic boom data alone. Subsequent analysis could only be accomplished in relation to flight operations. The next step was to merge the boom event files with the operations analysis, which had been conducted in parallel and is described in Sections 4.3 and 4.4, below. Merger of the two types of data, which also resulted in final adjustment of the boom event groupings and identification of ACM booms, is discussed in Section 5.1.

4.3 Collection of Operations Data

While sonic boom data were being recorded in the airspace, all available related operations data were collected at Holloman AFB. The following operations data items were obtained:

1. Daily advance schedule, from 49th TFW/DOO. Figure 22 is an example. Pertinent information includes the type of mission, numbers of aircraft, the airspace (Alive and Kish were scheduled for Lava/Mesa), and the scheduled range time. The handwritten notes on the schedule are corrections to the tail numbers and the pod assignments for ACMI missions. These annotations were made after checking the as-flown status with PRC/ACMI and the squadrons. The advance schedules were available up to a week beforehand, but were copied after each flying day so as to obtain the last version.

2. Daily ACMI summaries, from PRC/ACMI. Figure 23 is an example. These gave an as-flown record of ACMI activity, and actual launch times, which might differ from advance schedule. These were available after each flying day. Note that this example is for the same date as Figure 22, and that the actual launch time for Kish is shown.

3. Airspace clearance "strips", from Cherokee control. Figure 24 is an example of some collected on the same day as the previous two figures. The first column gives the mission call sign, frequencies, and aircraft involved. The second is an exercise code. The third is the airspace. The fourth column contains pertinent comments, such as airspace restrictions or other missions (sometimes referenced by their exercise code). The last set of columns contains the range on/off times. The printed data on each strip represent advance schedule information. The handwritten data are written by the controller as the mission enters, uses, and leaves the range. Handwritten data supersedes

   The strips are generated in real time by the controllers. After each day, they are available for examination by authorized personnel should the need arise. For this study, all strips which did not contain restricted information were made available. No strips for ACM in Lava/Mesa were restricted. Once or twice a week, Cherokee would be visited and the strips copied.

4. Daily range schedules, from 49th TFW/DOO. Figure 25 is an example for the morning of the same date. This is a working document, developed

RO ID	CM	DATE	BASE CODE	WEEKLY/DAILY AIRCRAFT FLIGHT SCHEDULE	ORGANIZATION	FLIGHT/SECTION	AIRCRAFT	DAY
AA	4	31 AUG 88	KWRD	WEEKOF: 29 AUG - 2 SEP	49 TFW	7TFS	F-15 A/B	WEDNESDAY

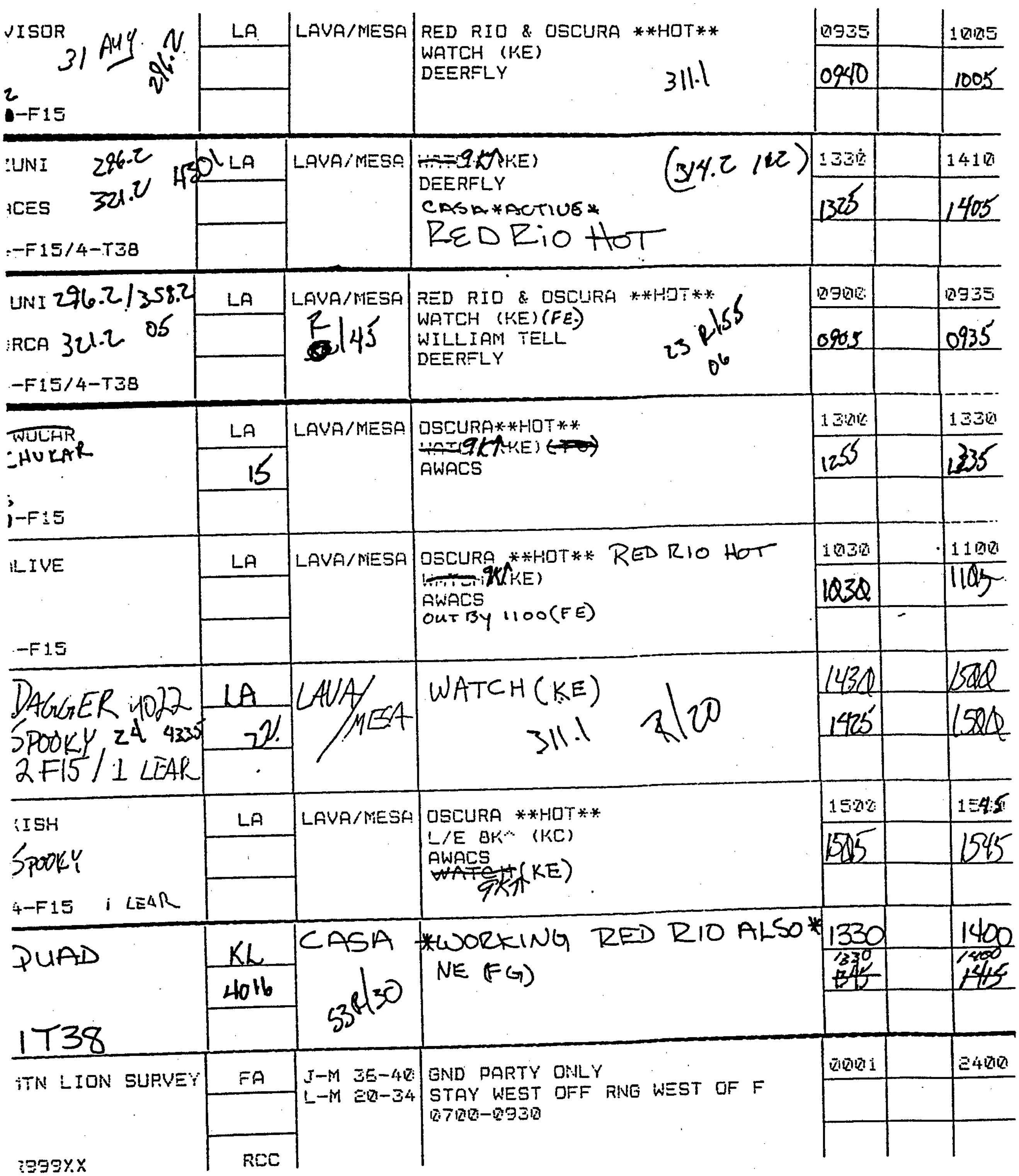
SORTIE SEQ NO	AIRCRAFT ID NUMBER	SORTIE NO.	MISSION	SCHEDULED T/O	SCHEDULED LAND	SCHEDULED DUR.	MUNITIONS CONFIG	BRIEF TIME	STA. TIME	ENGINE START	CALL SIGN	PILOT	PODs [redacted]	RANGE	TOT	REMARKS
701	A0078	1	ACBT	0955	1110	1.3	B9#	0755	0905	0925	DALLAS 01	HENRICHSEN		PECOS EWS/HI	1010-1045	FL-8/AWACS
702	A0079	1									02	BRADFORD				
703	A0101	1									03	SULLIVAN				
704	A0096	1									04	STITT				
705	A0122	1	DCT/INCPT	1020	1135	1.3	B9#	0820	0930	0950	DEMON 01	READ		IR134	1030-1100	2V2/RF-4/CAPT CORBETT/AV 685-2707
706	A0134	1									02	HUDSON				
707	A0136	1	BFM	1025	1140	1.3	B9#	0825	0935	0955	GRUM 01	MASON		YONDER	1030-1100	MSW CNX
708	A0140	1									02	HARRISON				
709	A0147 (100)	1	ACBT	1020	1135	1.3	B9++	0820	0930	0950	ALIVE 01	SANDERSON	BURNS 099-2A	LAVA-MESA	1030-1100	ACMI/AWACS/RTO-1 ACT-2
710	A0165	1									02	MARTIN	179 2A			
711	A0100 (104)	1									03	GWIN	193 2A			
712	A0112	1									04	HOWARD	165 8B			
														YONDER C	1415-1445	
713	A0078	2	BFM	1410	1525	1.3	B9#	1210	1320	1340	DAGGER 01	FLETCHER				
714	A0079	2									02	RYAN				
715	A0100 (96)	2	BFM	1350	1505	1.3	B9#	1150	1300	1320	FRISCO 01	PADILLA		PECOS EW/HI	1405-1435	AA-4
716	A0112 (101)	2									02	HEIKKINEN				
717	A0122 (120)	2	DINT	1450	1605	1.3	B9++	1250	1400	1420	KISH 01	MARSHALL	174 2A	LAVA-MESA 8000 UP IN LAVA EAST	1500-1530	ACMI/RTO-2/AWACS/LEAR JET JAMMING
718	A0134	2									02	CARPENTER	059 8B			
719	A0136 (122)	2									03	GLINK	193 2A			
720	A0140 (112)	2									04	POSTGATE	no POD			
721	A0147 (154)	2	DCT/INCPT	1450	1605	1.3	B9#	1250	1400	1420	CHOSEN 01	DIGIOVANNI		IR 134	1500-1530	2V2/RF-4/CAPT CORBETT/AV 685-2707 ICT 1 ACFT
722	A0165 (139)	2									02	DEBENEDICTIS	HANSEN			
SP	A0104															

Figure 22. Example Advance Schedule Sheet.

HOLLOMAN DAILY FLIGHT SUMMARY DATE 8/31/88

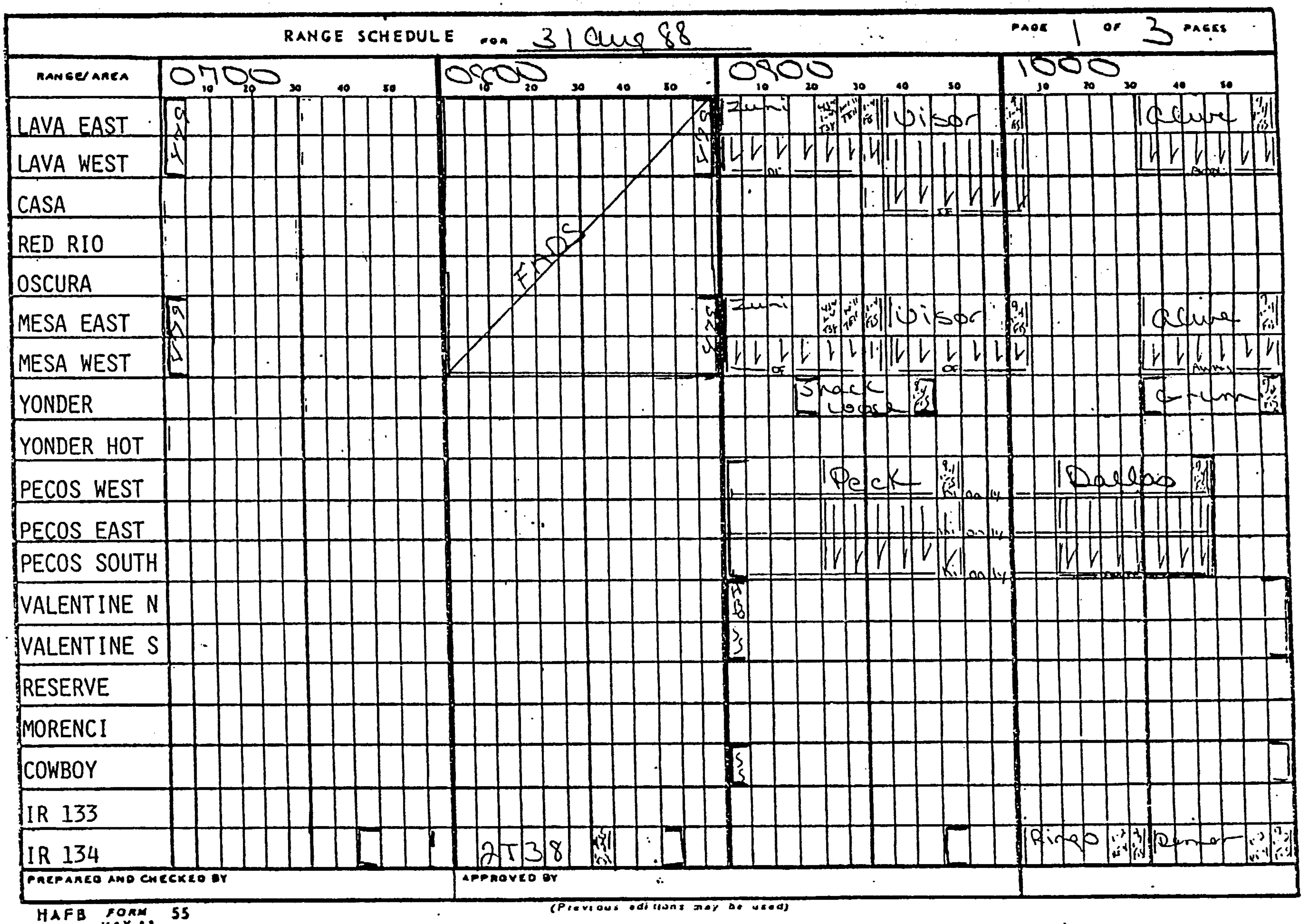
MISSION NUMBER	TAKE-OFF TIME	SQDN	MISSION OBJ.	SCHEDULED	FLOWN W/POD	FLOWN NO POD	% PODS TRACKED	% ACCEPTABLE I TRACE (AVERAGE)	MISSION RESULTS (1) SUCCESSFUL (2) OPS. CANX. (3) OTHER	MISSION DATA 30 MIN. PRIOR	REMARKS
8244 ZUNI	0850	WT	P.5	4	3	1	100	97.7	1	NO	A/C. 126 GND. ABORT
8244 VISOR	0925	9	ACBT	4	3	3	100	—	1	3	NEVER CAME ON RANGE JCTS RTB FOR IFE.
8244 ALEVE	1020	7	ACBT	4	4	0	100	94.7	1	Yes	POD 099 STOPED TRACKING. TESTED OK ON TEST SET.
8244 ZUNI	1320	WT	P.5	4	4	0	100	95.6	1	Yes	
8244 KISH	1450	7	AFBT	3	3	1	100	92.8	1	Yes	4 PODS LOADED A/C 165 GROUND ABORT.
8244 CHUCKER	1250	8	ACBT	4	3	1	100	91.5	1	Yes	1 A/C GND ABORT.
					20		100	94.5			

Figure 23. Example ACMI As-Flown Summary.



VISOR 31 AUG 296.2 / 2 -F15	LA	LAVA/MESA	RED RIO & OSCURA **HOT** WATCH (KE) DEERFLY 311.1	0935 / 0940		1005 / 1005	
UNI 296.2 / ICES 321.2 450 / -F15/4-T38	LA	LAVA/MESA	~~WATCH~~ 9K (KE) DEERFLY CASA *ACTIVE* RED RIO HOT (314.2 10K)	1330 / 1325		1410 / 1405	
UNI 296.2/358.2 / RCA 321.2 05 / -F15/4-T38	LA	LAVA/MESA F145	RED RIO & OSCURA **HOT** WATCH (KE)(FE) WILLIAM TELL DEERFLY 23 R155 06	0900 / 0905		0935 / 0935	
~~WUCHR~~ CHUKAR / -F15	LA / 15	LAVA/MESA	OSCURA**HOT** ~~WATCH~~ 9K (KE) ~~(FE)~~ AWACS	1300 / 1255		1330 / 1335	
LIVE / -F15	LA	LAVA/MESA	OSCURA **HOT** RED RIO HOT ~~WATCH~~ 9K (KE) AWACS OUT BY 1100 (FE)	1030 / 1030		1100 / 1105	
DAGGER 4022 / SPOOKY 24 4335 / 2F15 / 1 LEAR	LA / 72	LAVA/MESA	WATCH (KE) 311.1 R/20	1430 / 1425		1500 / 1500	
ISH / SPOOKY / 4-F15 1 LEAR	LA	LAVA/MESA	OSCURA **HOT** L/E 8K (KC) AWACS ~~WATCH~~ 9K (KE)	1500 / 1505		1545 / 1545	
QUAD / 1T38	KL / 4016	CASA 53R/30	*WORKING RED RIO ALSO* NE (FG)	1330 / ~~1330~~ 1345		1400 / ~~1400~~ 1445	
MTN LION SURVEY / 2999XX	FA / RCC	J-M 36-40 L-M 20-34	GND PARTY ONLY STAY WEST OFF RNG WEST OF F 0700-0930	0001		2400	

Figure 24. Example Air Traffic Control Strips.


RANGE SCHEDULE FOR 31 Aug 88 PAGE 1 OF 3 PAGES

RANGE/AREA	0700	0800	0900	1000
LAVA EAST			Zuni · Visor	Olive
LAVA WEST				
CASA		FADS		
RED RIO				
OSCURA				
MESA EAST			Zuni · Visor	Olive
MESA WEST				
YONDER			Smack	Grim
YONDER HOT				
PECOS WEST			Peck	Dallas
PECOS EAST				
PECOS SOUTH				
VALENTINE N				
VALENTINE S				
RESERVE				
MORENCI				
COWBOY				
IR 133				
IR 134		2T38		Ringo · Demon

PREPARED AND CHECKED BY | APPROVED BY

HAFB FORM MAY 83 55 (Previous editions may be used)

49 TFW/DOO "Overprint"

Figure 25. Example Range Schedule Sheet.

in conjunction with the advance schedule. It is useful in that it shows blocks of time, and indicates periods reserved for other activities.

Meteorological data, as described in Section 3.3, were also collected. Once or twice a week, the weather detachment was visited and the data copied. The original rawinsonde charts, which are in color and easier to read than copies, are normally discarded after thirty days. Those were retained and given to us instead.

Every two weeks these data were shipped to Wyle's Arlington, VA office, where they were analyzed.

In addition to these operations records, ACMI tapes were made available for processing. These tapes are not archived, and are normally returned to the available supply after a mission has been analyzed. They were instead placed in a shipping container which could hold about a dozen tapes. When the container filled, it was sent to AFESC, Tyndall AFB. The tapes were processed by the EXTRACT program, with the contents of each box forming a library, then returned to Holloman. When each library was completed, AFESC would notify Wyle's Arlington office. The library would then be either transferred onto floppy disk at AFESC and shipped to Wyle, or would be transferred electronically by modem. Each library would be given a name corresponding to the date that box of tapes was shipped from Holloman.

It was intended to obtain all tapes generated during the monitoring period. The 49th TFW arranged for the use of extra pods during this period so that tracking data would be available for as many sorties as possible. Approximately half the ACM sorties of interest had pods, a very high rate. Tapes were shipped starting at the beginning of the monitor installation period. Due to the time involved in accumulating a box of tapes, shipping, processing at AFESC, and transferring the libraries, Wyle would receive the data from a given mission at least six to eight weeks after the event. About halfway into the program, it seemed that fewer tapes than expected were being processed. PRC/ACMI indicated that all tapes were being shipped, and AFESC indicated that they were processing all tapes received. The first half of the program also corresponded to the last three months of the fiscal year, when flight activity diminishes. In November, larger quantities of data began to arrive from missions flown in October, the beginning of the fiscal year. As the program progressed, ACMI data again diminished. No data were received for missions flown after 20 December, a full month before the end of the monitoring period. Overall, ACMI data were received for about a quarter of the sorties flown with pods, or about an eighth of the total ACM sorties. It is not understood why or how this shortfall occurred. Because the tapes are recycled, the missing data no longer exist.

The ACMI data received were extremely valuable in understanding how the airspace is utilized and in spot-checking the agreement with observed booms and single-event sonic boom theory, but were not adequate for extensive analysis. The limited analysis performed with these data is described in Section 5.2.

4.4 Processing of Operations Data

The primary objective of collecting operations data was to develop a time-line of activity in the Lava/Mesa airspace, then correlate each measured sonic boom with a specific event. This would identify those booms associated with ACM training. The numbers of associated sorties, mission types, etc., would also be known, allowing statistical projection of current results to other airspaces.

The foundation for a time-line of activity was clearly the strip data. All strips for missions in Lava/Mesa were arranged in chronological order. The data on these strips were entered into a computerized data base. Figure 26 is an excerpt from that file. Missions from the 49th TFW were identified by call sign (a list was provided by DOO) and cross-checked against advance schedule records and ACMI as-flown summaries to complete the information for each mission. The ACMI summaries (and data within those tapes received) provided additional data, including non-49th missions which used ACMI. Whenever inconsistencies were encountered, the strips were considered to be correct. For missions with ACMI data, the pod "on" time and library name were noted. Also noted were the times of occurrence of any sonic booms.

Whether or not a mission was ACM training was determined by a combination of factors. A glossary of mission types was developed. This glossary is shown in Table 3. Indicated on the table are those which are ACM missions. If strip or schedule data indicated an ACM mission type, classification was obvious. A given mission might, however, have several aspects (including ACM) and

Table 3

Acronyms Used in Scheduling and Airspace Clearance

Acronym	Expansion
ACT*	Air Combat Training
ACBT*	Air Combat Basic Training
ACM*	Air Combat Maneuvers
BFM*	Basic Fighter Maneuvers
CW	Chemical Warfare
DAAR	Daytime Air-to-Air Refueling
DACT*	Dissimilar Air Combat Training
DACM*	Dissimilar Air Combat Maneuvers
DBFM*	Dissimilar Basic Fighter Maneuvers
DINT	Dissimilar Intercept
INCENT	Incentive Flight
INT	Intercept
LOWAT	Low-Altitude Training
NAAR	Nighttime Air-to-Air Refueling
NINT	Nighttime Intercept
PROF4*	Proficiency Flight – Level 4
PROF5*	Proficiency Flight – Level 5

* ACM Training

records might just show one. The fact that a mission included an intercept or refueling element might be more important to airspace controllers and be written on the strips. Patterns of ACM and non-ACM operations were noted and used. For example, AT-38s would fly ACM missions in Lava/Mesa, and would also fly various types of air-to-ground missions in Red Rio. The airspace assignment would suggest what a particular AT-38 mission was, especially in comparison with range times for missions in other parts of the airspace. When in doubt, missions were considered to be ACM so as to be conservative.

The combination of different missions was also a key factor in establishing the operations time line. As discussed in Section 2.3, several missions would often work together in a single "training event". Combinations of range assignments and times would indicate which missions were part of a common event. If two such missions were equipped with ACMI, then the corresponding records would explicitly identify the status. Strip and schedule records would sometimes directly indicate which missions were part of the same ACM event.

The final operations data base contained a list of all missions in Lava/Mesa, with sets of missions (mission defined as call sign) grouped into training events. ACM events were identified. This data base was the basis of overall ACM operations statistics described in Section 5.3. This data base was also merged with the sonic boom event files, described in Section 4.2, into a "Master Data File". The master data file is described in Section 5.1.

5.0 ANALYSIS

5.1 The Master Data File

As the boom event files and mission data base evolved, a certain degree of cross-referencing was developed. For each boom event sketch, the mission data base was consulted and the corresponding training event noted on the sketch. Conversely, times of occurrence of booms were noted on the mission data base, as seen in the example of Figure 26. This cross-linking was formalized into a master data file. The master file is a list of all booms, together with the missions with which they were associated. The complete master data file is contained in Reference 29. Figure 27 is an excerpt. The file was built by the following steps:

1. The boom event files were concatenated, and condensed to the first seven columns ("Site" through "P_{pk}") seen in Figure 27. The monitor type was retained as a B or S in the "Site" column. Booms were grouped by boom events, each representing the footprint of a single supersonic excursion. Events were separated by a space.

2. The mission data base was condensed to the next seven columns, and grouped by training events. The last of these ("ACMI?") contained a code indicating the status of ACM and ACMI. If the mission was not ACM training, the column was left blank. If it was ACM but not equipped with ACMI, an "N" was inserted. If it was ACMI a "Y" was inserted. If it was a mission for which we had obtained the ACMI tracking data, then instead of a "Y" the four-digit number representing the library name was inserted.

3. Each time that a supersonic-capable training event occurred at the same time as a sonic boom, the mission data were added to the boom event file, adjacent to the training event. If more than one boom event was associated with a given training event, then the training event data was repeated next to each boom event.

4. Juxtaposition of sonic boom events and training events gave insight into some of the boom event groupings. These were adjusted into final form.

Date	Call Sign	Mission	Airspace	Aircraft	Start	End	Altitude	ACMI?	Pod On	49th TFW	Comments
90188	ALCAN		OSCURA	?T38	700	730		N		N	
90188	FLEX		MESA	2T38	730	800		N		N	
90188	QUAD		OSCURA	2T38	730	800		N		N	
90188	ACES		OSCURA	?T38	840	910		N		N	
90188	LAZER		OSCURA	?T38	910	940		N		N	
90188	LOOSE	INCENTIVE	MESA	2F15	935	1030		N		Y	
90188	ABLE		OSCURA	?T38	940	1035		N		N	
90188	ARNO		OSCURA	?T38	950	1045		N		N	
90188	COBRA		OSCURA	?T38	1005	1100		N		N	
90188	COSMIC	INCENTIVE	LAVA	2F15	1015	1055		N		Y	Booms 1025-1031
90188	ALIVE	INCENTIVE	LAVA WEST	2F15	1200	1250		N		Y	
90188	GIMP	BFM	MESA	2F15	1200	1230		N		Y	
90188	BOSOX		OSCURA	?T38	1210	1240		N		N	
90188	BUDDY		OSCURA	?T38	1240	1310		N		N	
90188	RODAN	BFM	MESA	2F15	1245	1330		N		Y	
90188	BUCK	INCENTIVE	LAVA	2F15	1330	1400	>14K Lava Wes	N		Y	
90188	ORCA		MESA	2T38	1330	1410		N		N	
90188	RASPY		OSCURA	?T38	1340	1410		N		N	
90188	SHORT	DACT	LAVA/MESA	2F15	1500	1545		N		Y	
90188	JONAH		LAVA/MESA	2T38	1500	1545		N		N	
90188	PIVOT		OSCURA	?T38	1510	1540		N		N	
90188	MIDAS		OSCURA	2T38	1540	1610		N		N	
90188	SURLEY	FLYBY	LAVA/MESA	2F15	1550	1620		N		Y	
90188	JOLLY		RED RIO	H53	1600	1800		N		N	
90688	COYOTE		RED RIO	2T38	710	740		N		N	
90688	BUGLE		RED RIO	2T38	830	900		N		N	
90688	TROOP		OSCURA	2T38	830	900		N		N	
90688	RANCH	DACT	LAVA LWL	2F15	1000	1030		Y		Y	BOOM @1017
90688	RACER	BFM	MESA	2F15	1000	1045		Y		Y	
90688	BUILT		LAVA	2T38	1000	1030		N		N	
90688	UNCLE		OSCURA	2T38	1000	1030		N		N	
90688	RODAN	ACBT	LAVA	4F15	1030	1100		Y	1028	Y	TAPE 1025
90688	LUNG	DACT	LAVA LLW	2F15	1100	1130		Y	1103	Y	TAPE 1025
90688	DALLAS	BFM	MESA	2F15	1100	1130		N		Y	
90688	?ANTAR		LAVA	2T38	1100	1130		N		N	
90688	TANK		OSCURA	2T38	1120	1155		N		N	
90688	GIMP	ACM	LAVA	3F15	1130	1200		Y		Y	BOOMS 1148-1149
90688	FEEL		OSCURA	2T38	1155	1225		N		N	
90688	RAMBO		LAVA	2T38	1225	1305		N		N	
90688	NINJA		OSCURA	4T38	1250	1320		N		N	
90688	ADAIR		LAVA	2T38	1355	1430		N		N	BOOM @1408
90688	TANK		OSCURA	2T38	1425	1455		N		N	
90688	MANGO	BFM	LAVA	2F15	1430	1500		Y		Y	
90688	INKPOT		OSCURA	4T38	1455	1525		N		N	
90688	PISTOL	DAAR/ACBT	L/M LWL	3F15	1510	1540		Y	1503	Y	TAPE 1025
90688	MARLIN	DAAR/ACBT	LAVA/MESA	4F15	1540	1610		Y		Y	
90688	EARTH		OSCURA	4T38	1545	1620		N		N	
90688	DATSUN	DAAR/ACBT	LAVA/MESA	4F15	1610	1650		Y		Y	
90788	METAL		OSCURA	4T38	700	730		N		N	
90788	STEEL	ACBT	MESA	4F15	700	730		N		Y	

Figure 26. Excerpt From Mission Data Base.

Site	Day	Month	Time	CSEL	Lpk	Ppk	Call Sign	Mission	Airspace	Aircraft	Start	End	ACMI?	Boom #
21 B	30	8	105100	99.0	125.6	0.798	FLASH	ACBT	LAVA/MESA	4F15	1015	1100	Y	070
33 S	30	8	105234	90.5	121.0	0.468	ZUNI	PROF4	LAVA/MESA	3F15	1015	1100	0907	070
27 S	30	8	105300	87.5	121.0	0.468								070
35 B	30	8	105300	92.8	120.4	0.434								070
35 B	31	8	91100	88.2	116.0	0.263	ZUNI	PROF5	LAVA/MESA	3F15	900	935	0907	071
							ORCA		LAVA/MESA	4T38	900	935	N	071
35 B	31	8	101700	95.3	121.9	0.521								072
18 B	31	8	145400	104.8	131.0	1.482	DAGGER	BFM	LAVA/MESA	2F15	1430	1500	N	073
20 S	31	8	145402	98.0	124.5	0.700								073
25 S	31	8	145410	83.0	117.0	0.295								073
19 S	31	8	145426	97.0	124.5	0.700								073
35 B	31	8	145500	96.6	126.1	0.843								073
10 S	31	8	150540	108.5	136.5	2.786	KISH	ACBT	LAVA/MESA	3F15	1500	1530	Y	074
5 B	31	8	150600	82.1	108.6	0.113								074
3 S	31	8	152559	95.5	121.0	0.468	KISH	ACBT	LAVA/MESA	3F15	1500	1530	Y	075
							GIPPER		OSCURA	4T38	1515	1545	N	075
17 S	1	9	102527	81.5	117.5	0.313	COBRA		OSCURA	?T38	1005	1100	N	076
35 B	1	9	102700	79.1	109.2	0.120	COSMIC	INCENT	LAVA	2F15	1015	1055	N	076
29 B	1	9	103100	98.8	124.4	0.691	COBRA		OSCURA	?T38	1005	1100	N	077
							COSMIC	INCENT	LAVA	2F15	1015	1055	N	077
21 B	6	9	101700	106.0	127.2	0.956	RANCH	DACT	LAVA	2F15	1000	1030	Y	078
							RACER	BFM	MESA	2F15	1000	1045	Y	078
							BUILT		LAVA	2T38	1000	1030	N	078
							UNCLE		OSCURA	2T38	1000	1030	N	078
21 B	6	9	114800	102.7	128.0	1.042	TANK		OSCURA	2T38	1120	1155	N	079
33 S	6	9	114834	85.0	117.5	0.313	GIMP	ACM	LAVA	3F15	1130	1200	Y	079
17 S	6	9	114901	87.0	118.5	0.351								079
29 B	6	9	140800	95.2	119.8	0.407	ADAIR		LAVA	2T38	1355	1430	N	080

Figure 27. Excerpt From Master Data File.

5. A sequence number, shown as the last column, was assigned to each boom event.

The master data file was thus a list of all sonic booms, grouped by boom events, and containing mission data for the training events which caused them. Some booms were caused by non-ACM activity. Some booms occurred at times when records showed no activity in the airspace. Those are presumed to be non-ACM events for which strips were not provided.

The master data file contains 2,246 individual sonic boom recordings. These are grouped into 591 separate sonic boom events. Since each boom event was captured at an average of 3.8 sites, it may be concluded that the site density was adequate, and few (if any) booms would have fallen undetected between monitors. Of the 591 boom events, 506 (86 percent) were associated with ACM activity.

Statistical information on all ACM operations may be obtained from the mission data base. The subset of those generating booms are contained in the master data file. Analysis of both of these data sets is presented in Section 5.3. Analysis of the 506 ACM sonic boom events is presented in Section 5.4.

5.2 ACMI Analysis

5.2.1 ACMI Data Obtained

ACMI tracking data from a total of 127 training events, containing 638 sorties, were obtained. This represented 14 percent of total sorties. Fifty-six of those training events correlated with 87 sonic boom events, 17 percent of the 506 ACM sonic boom events. The 127 tape missions appeared to be a reasonable cross-section of missions. Because the tape data provide complete tracking information, extremely detailed analysis of these missions is possible. Since they were such a small fraction of the total data, however, it is not felt that analysis of these missions could be used in a statistically valid manner to adjust the results of analysis of all the missions. The ACMI data obtained were therefore used in two ways: (a) to demonstrate the correlation of measured boom events with predicted individual booms, and (b) to gain an understanding of how the airspace is used. Original plans included these two analyses.

5.2.2 Software Development

Several programs were developed under the current project for analysis of ACMI data. They are formally documented in Reference 27. The following is a discussion of pertinent features and purposes.

5.2.2.1 EXTRACT

During analysis of the pre-project 50-mission library, two areas of concern were noted in the existing software.

- EXTRACT was set up to extract only supersonic tracking data. Given the sparse and random nature of supersonic events in ACM, this allowed statistical analysis which was disconnected from the overall mission and airspace usage. To understand how supersonic flight fit into the context of a mission, it is necessary to have tracking data for the entire mission. Accordingly, the EXTRACT program was modified to extract data from subsonic flight segments at a nominal rate of once every 25 seconds, in addition to supersonic at once every 1.4 seconds. The coarser subsonic sampling was adequate for analyzing airspace use, and detailed analysis of subsonic maneuvers is not of interest here.

- An inconsistency was found between the Mach number in the library file and the Mach number which was computed by dividing the range velocity in the library by a sound speed from the range standard atmosphere. The Mach number is taken from the pod's pitot tube. The range velocity is derived from the range coordinates, which are obtained from the pod's inertial navigation system and radar tracking. It was not clear whether the discrepancy was due to inherent inaccuracy in the pitot tube data, assumptions in the sound speed profile, winds aloft, or problems with the range velocity. It was decided to modify EXTRACT to obtain the indicated and true air speed, in addition to Mach number and range velocity. It was also decided to read the atmospheric data block from each tape, so as to determine the sound speed assumptions used by the ACMI system to compute Mach number. Extraction of indicated air speed was useful in its own right since it was identified as a key parameter in the way pilots manage their aircraft.

The conclusion reached from analyzing new data tapes with the additional data items was that major discrepancies in the 50-mission library were due to seasonal winds aloft. The pod Mach number is based on the pod's indicated air speed. Conversion to Mach number uses a standard atmospheric profile built into the ACMI system's software. The Mach number appearing on the tape appears to be as reliable as Mach number derived from any other velocity on the tape. Use of indicated air speed and the actual atmosphere at the time might improve accuracy.

The modified EXTRACT program was written so as to be as compatible as possible with the previous version. Additional data were written at the end of existing records, so that previous software versions would find data in the expected places. Consideration was given to changing the format of the climb/dive angle, which is written to only one decimal place and is therefore computationally inadequate. Since that information can be derived from the velocity components, it was decided to leave the original format as is.

The data file written by the EXTRACT program is formatted, direct access, with a record length of 70 characters. To accommodate the indicated and true air speeds, the record length had to be extended to 90 characters. Any software which reads a library file in direct access form must recognize the new record length. The first 70 bytes of each record are identical.

Several bugs were detected and corrected. The most serious was that if eight pods were active (the system maximum for "high activity" aircraft), EXTRACT would save data from only the first. Previous libraries therefore contain incomplete data for 4 versus 4 missions.

When ACMI data started to arrive, it was noticed that aircraft types and tail numbers did not correspond to the ACMI as-flown data sheets. Investigation revealed that Holloman had recently installed an updated version of the system software, and some data formats had changed. None of the tracking data was affected. Changes were limited to the exercise data block, which contains mission information entered manually by the RTO while setting up a mission. ACMI specialists at AD/YEIC, Eglin AFB, provided a specification for the current format, and EXTRACT was updated accordingly. The updated program checks the ACMI version, and retains the old algorithms for backward compatibility.

The exercise data block update to EXTRACT also includes a provision to print out, in hexadecimal format, the exercise data block, so that it could be decoded manually if necessary, such as future changes occurred. The exercise data block was noticed to sometimes appear several times in some missions. The reason for this is that these data are entered by the RTO as the mission prepares for launch, and sometimes final corrections are made after launch. When data are corrected, the system writes a new block. A byproduct of this procedure is that the "pod on" time read from the tape is somewhat random, generally between launch and entry to the range. On one tape, tracking data showed two aircraft suddenly exchanging positions. Decoding of the exercise data block hex dumps showed that this corresponded to a data block with a correction of pod assignments.

The incorrect mission information in the tapes obtained to that point was corrected in the library files, using the data on the advance schedule and ACMI sheets.

5.2.2.2 Transfer to PC and File Conversion

As noted earlier, libraries created by EXTRACT were transferred to a PC-compatible computer for analysis. Libraries are generated on the CDC as Cyber-format character files, 10 characters per 60-bit word. This form is 25 percent more compact than an ASCII format file. The transfer was accomplished via communication software between the CDC 170 and a PC, using an error-free binary protocol. To minimize connect time, Cyber-format files were transferred. A utility program, CYBTOASC, was written which converted the 6-bit Cyber characters to standard 8-bit ASCII, which could be read by the PC.

The library files written by EXTRACT are formatted direct access. All analysis software accesses data in sequential order, so the direct access capability is not needed but makes visual examination of the files (printing, viewing on a screen, etc.) difficult. Direct access also requires the availability of a separate index file. For simplicity, the libraries were converted to formatted sequential access. This was accomplished by a utility program which read all records in sequence and rewrote them record-by-record as a standard formatted sequential file. Figure 28 is an extract from one file. Except for the added last two columns (true and indicated air speeds), the format is as described in Reference 21.

```
    8180SUP 88/11/17. 14.26.32.
7-8293/DINE      10/19/8813383595F-15   DINE
7HOLLOMAN   1 1 1 4SUP   60.0   50.0   10.7
```

} Mission Information

Time	M	X	Y	Z	γ	V_x	V_y	V_z	g_n	IAS	TAS
13574621	.771	155270.	-186007.	18360.	7.8	260.	819.	118.	.944	363.	480.
13581091	.821	160683.	-164678.	18860.	6.7	197.	897.	109.	1.113	387.	510.
13583551	.834	166201.	-142897.	19280.	-.3	261.	900.	-5.	.436	391.	518.
13594931	.851	182816.	-77308.	19058.	2.1	-140.	910.	34.	1.375	408.	530.
14001393	.879	173573.	-56968.	19174.	-.1	-498.	768.	-2.	1.112	422.	547.
14003863	.821	161632.	-38741.	19417.	.4	-470.	711.	6.	1.043	391.	511.
14010323	.844	149987.	-21323.	19177.	-.6	-506.	708.	-9.	1.167	405.	525.
14012783	.837	137356.	-4009.	19396.	1.6	-512.	693.	24.	.909	401.	521.
14015243	.839	124591.	12834.	19760.	.6	-524.	685.	9.	.964	400.	521.
14021703	.853	111637.	29808.	19693.	.0	-542.	687.	0.	1.020	408.	531.
14024163	.861	98180.	46724.	19721.	.4	-572.	672.	7.	.992	414.	536.
14030633	.862	95500.	66029.	18345.	1.5	285.	900.	25.	4.578	421.	539.
14033093	.801	82274.	78291.	18618.	1.1	-690.	387.	15.	1.190	390.	500.
14035553	.802	65151.	87384.	18666.	-.5	-699.	371.	-6.	.944	390.	501.
14042013	.813	47983.	96982.	18550.	-2.1	-697.	402.	-29.	.865	396.	508.
14044473	.807	30929.	107369.	16773.	-3.6	-691.	431.	-51.	1.124	406.	508.
14050933	.791	14110.	118025.	14952.	-5.6	-687.	440.	-79.	1.260	410.	501.
14053403	.786	1429.	112168.	14113.	.2	-116.	-795.	3.	1.223	414.	499.
14055863	.783	242.	92396.	14607.	2.3	-16.	-804.	32.	.972	409.	497.
14062323	.652	5673.	77185.	15263.	.4	686.	272.	5.	3.889	332.	413.
14064783	.712	8314.	93573.	14786.	-.2	-27.	779.	-3.	.923	370.	452.
14071243	.794	7412.	114164.	14910.	1.0	-45.	870.	15.	1.066	412.	503.
14073703	.831	6205.	135964.	15400.	.3	-51.	905.	5.	1.093	428.	525.
14080163	.747	-3210.	141370.	14592.	-1.5	-67.	-760.	-20.	2.848	387.	474.
14082633	.794	-2583.	121489.	14983.	1.6	46.	-820.	23.	.831	412.	503.
14085093	.805	-1498.	101235.	15325.	1.2	30.	-828.	18.	1.022	416.	509.
14091553	.852	-1012.	80451.	15867.	3.9	216.	-859.	60.	1.350	438.	538.
14094013	.910	2917.	58159.	16345.	.2	51.	-946.	4.	.925	467.	574.
14100473	.832	-5481.	38134.	17317.	1.5	-457.	-678.	21.	2.216	414.	523.
14102933	.750	-20074.	39018.	15851.	-.8	-279.	-700.	-11.	4.172	382.	474.
14105403	.785	-25615.	19944.	14353.	-3.7	-314.	-726.	-51.	1.259	412.	499.
14111863	.833	-39926.	5955.	13713.	.7	-697.	-482.	11.	1.564	444.	530.
14114323	.735	-57334.	9596.	14166.	9.7	-690.	281.	128.	1.967	386.	467.
14120783	.760	-60855.	-2539.	14089.	1.6	399.	-701.	23.	5.033	400.	483.
14123243	.906	-40386.	-7221.	14968.	4.8	816.	653.	73.	2.460	484.	574.
14125703	.924	-30868.	16114.	15336.	3.3	331.	984.	60.	1.280	486.	585.
14132163	.865	-24638.	39758.	16178.	.7	308.	909.	11.	1.219	444.	546.
14134633	.883	-15540.	61830.	16918.	3.2	430.	881.	55.	1.034	447.	555.
14141093	.793	-6754.	82652.	17408.	-.7	280.	822.	-11.	1.057	395.	498.
14143553	.792	-2860.	103306.	15611.	-2.1	137.	860.	-32.	1.094	406.	501.
14150013	.816	629.	124550.	15509.	-.4	147.	886.	-6.	.893	418.	516.

Figure 28. Extract From Typical ACMI Data File.

5.2.2.3 Tracks and Ground Impingements

A program denoted TRACK was written which reads an ACMI library and plot ground tracks of all missions. The program will optionally plot all tracks or just supersonic. If supersonic tracks are plotted, the program has options of plotting all above Mach 1, those above cutoff Mach number, etc. An outline of the Lava/Mesa airspace is drawn for reference. Figure 9 is an example of TRACK output for supersonic ground tracks. This replicates the track plotting capability of Boom-Map. Operational on a PC, it uses a commercial graphics library which can direct output to virtually any graphics device. When directed to a hard-copy device, it always plots to a scale of ten miles to the inch. The Lava/Mesa outline provides a scale reference if plots are reduced or enlarged when copied.

The program has options of plotting all data in a library, or data from particular mission(s) or sortie(s). When all subsonic and supersonic track elements are plotted, the subsonic portions are drawn with a broken line. If a few sorties are drawn (e.g., a single mission tape), the program can mark the beginning of each track with aircraft identification and start time. This type of plot is valuable in seeing how the aircraft enter and egress the airspace and use the setup points. The pattern of supersonic events within the mission can also be seen. Examples of this type of plot are given in Section 5.2.3, where analysis of the ACMI data is presented.

The program also has the capability of calculating the ground impingement footprints of sonic boom. At each supersonic trajectory point, the program computes impingement points at one degree azimuthal increments from cut-off to cut-off. At each trajectory point and azimuth, the corresponding ray tube area is also computed. If the ray tube area is negative, that indicates that the ray being considered has an above-the-ground focus, and the boom associated with that ray will be a weak post-focus boom. Such secondary booms are not significant, as discussed in Section 3.1.1, and the impingement point is dropped. The ray path and ray tube area calculations utilize fast algorithms developed for sonic boom focal zone screening purposes.[30,31] Those algorithms are an exact implementation of ray theory equivalent to that employed in Reference 32, but are limited to the case of no winds. The no-wind restriction is moot because winds are almost never actually specified. Subroutines from existing implementations[30,31] were available for use here. The White Sands range standard atmosphere[33] was used. The use of that atmosphere represented a capability of TRACK not available in Boomap2,[22] which is hard-wired to a windless U.S. Standard Atmosphere.

TRACK was run for each of the 127 ACMI mission tapes received, using the options to plot supersonic and subsonic tracks and the boom ground impingements. As necessary for clarity, TRACK was run for individual sorties. Example plots are presented in Section 5.2.3.

The calculation of predicted boom counts from the 50-mission library, shown previously in Figure 10, was accomplished by an extension of TRACK. That extension divided the ground into square mile grid elements, and counted how many predicted boom footprints impinged on each element. Contours were fitted to this grid by means of commercial contouring software.

The ray tracing algorithms in TRACK, including the ray tube area, represent most of the calculations required to compute sonic boom: all that would be needed is an F-function lookup (as implemented in Reference 11, using the methodology of Reference 20) and an age parameter calculation, which is a straightforward extension of the ray computations already implemented. The result would be a model equivalent to Boomap2, but several orders of magnitude faster. It was intended to extend TRACK into that form, and exercise it for various subsets of ACMI data. However, the quantity of ACMI data received was considered to be small for statistically meaningful results to be obtained, so the extension of TRACK into "Boom-Map 3" was not completed.

5.2.3 ACMI Analysis

As each ACMI library was received, it was processed through TRACK in the "plot supersonic track" mode. This provided a check of the integrity of the data, and also provide an inventory of missions in that library. The patterns of supersonic tracks generally resembled those seen in Figure 9 for the 50-mission library. Figure 29 is the supersonic track plot for all 127 tapes. Figure 30 is a plot of calculated numbers of booms, similar to Figure 10. Except for there being about two and a half times as much data, these results are very much like those for the 50-mission library. When a Gaussian distribution is fitted to Figure 30, the result

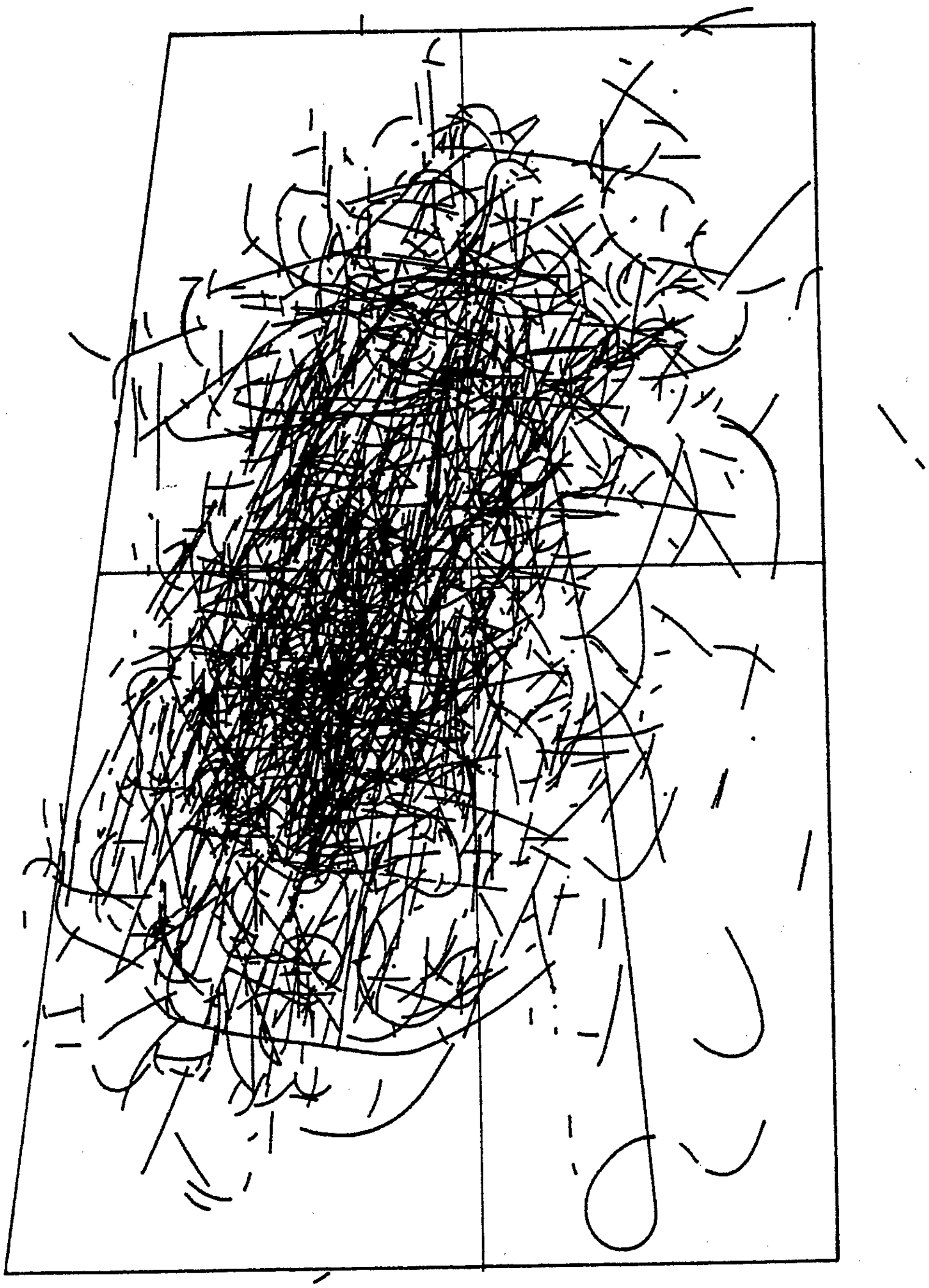


Figure 29. Supersonic Ground Tracks, All ACMI Missions.

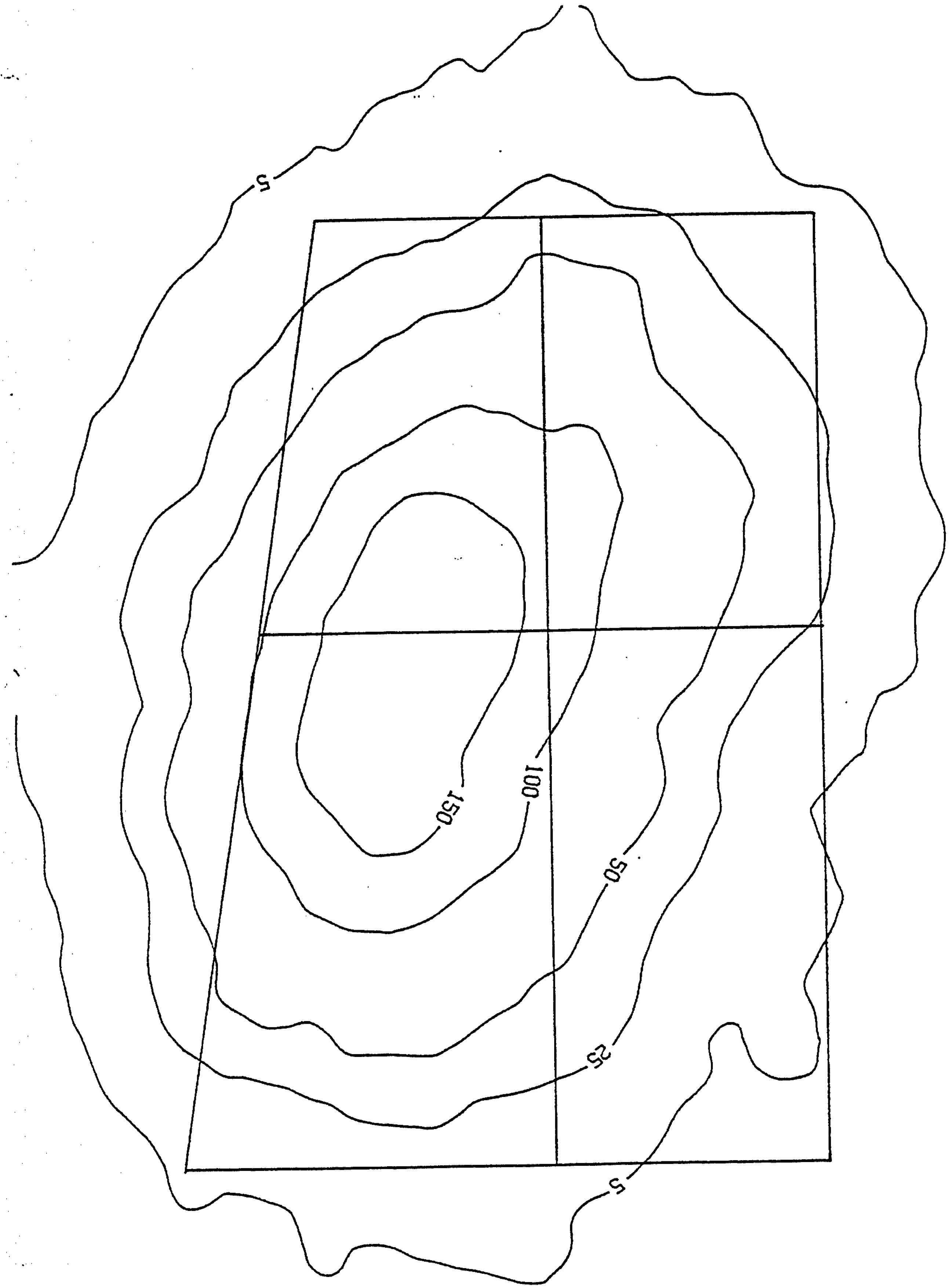


Figure 30. Predicted Number of Sonic Booms, All ACMI Tapes.

is very similar to that seen in Figure 11, with similar values of standard deviation. This shows that the distribution during the monitoring was the same as during the pre-monitoring period when the 50-mission library was built. The fixed monitor site scheme designed around that library was thus optimal for the monitoring period.

The 127 tapes contained valid tracking data for 589 sorties. (Not all aircraft in a given event were equipped with pods, and valid data was not obtained from about 12 percent of the pods.) These were on F-5, F-15, and F-16 aircraft. Table 4 shows the numbers of each type tracked and the number of sorties which involved supersonic flight, i.e., exceeded Mach 1 at some time. Note that about 85 percent of sorties were supersonic, while only 56 of the 127 ACMI-data training events caused sonic booms. Also note that 78 percent of the sorties were F-15, a fact which will be discussed in Section 5.3.

Statistical distributions of Mach number and altitude for supersonic flight have been computed, in a form similar to MOAOPS analysis. Figures 31, 32, and 33 show the distributions of supersonic Mach number for each aircraft type. For consistency with data presentations in Reference 21, the total times shown are for the supersonic sorties only. Note that supersonic activity in these data is virtually always below Mach 1.1, which is generally the case for ACM. Accounting for all sorties (not just supersonic), supersonic flight represents 7.5 percent of total ACM range time. Figures 34, 35, and 36 show the distributions of altitude. Noting that there were relatively few F-5s and F-16s, so that the details seen in the distributions for those are probably not statistically meaningful, it appears that supersonic operation statistics are similar for all three aircraft types.

Track data were plotted, similar to Figures 9 and 29, for subsonic as well as supersonic elements. The results were that the areas covered in Figures 9 and 29 were densely covered, and areas on the edges of the range and certain corridors leading to them were also covered. The essential result (seen more clearly in individual plots) was that during ACM itself (not traveling to and from the ACM arena) supersonic flight elements can take place at any range location that subsonic flight does, but much less frequently. The area of the ACM arena is an ellipse about 35 by 60 nautical miles. Individual training events may occur within a smaller area, but that is a matter of chance on where the engagements happen to take them within the arena.

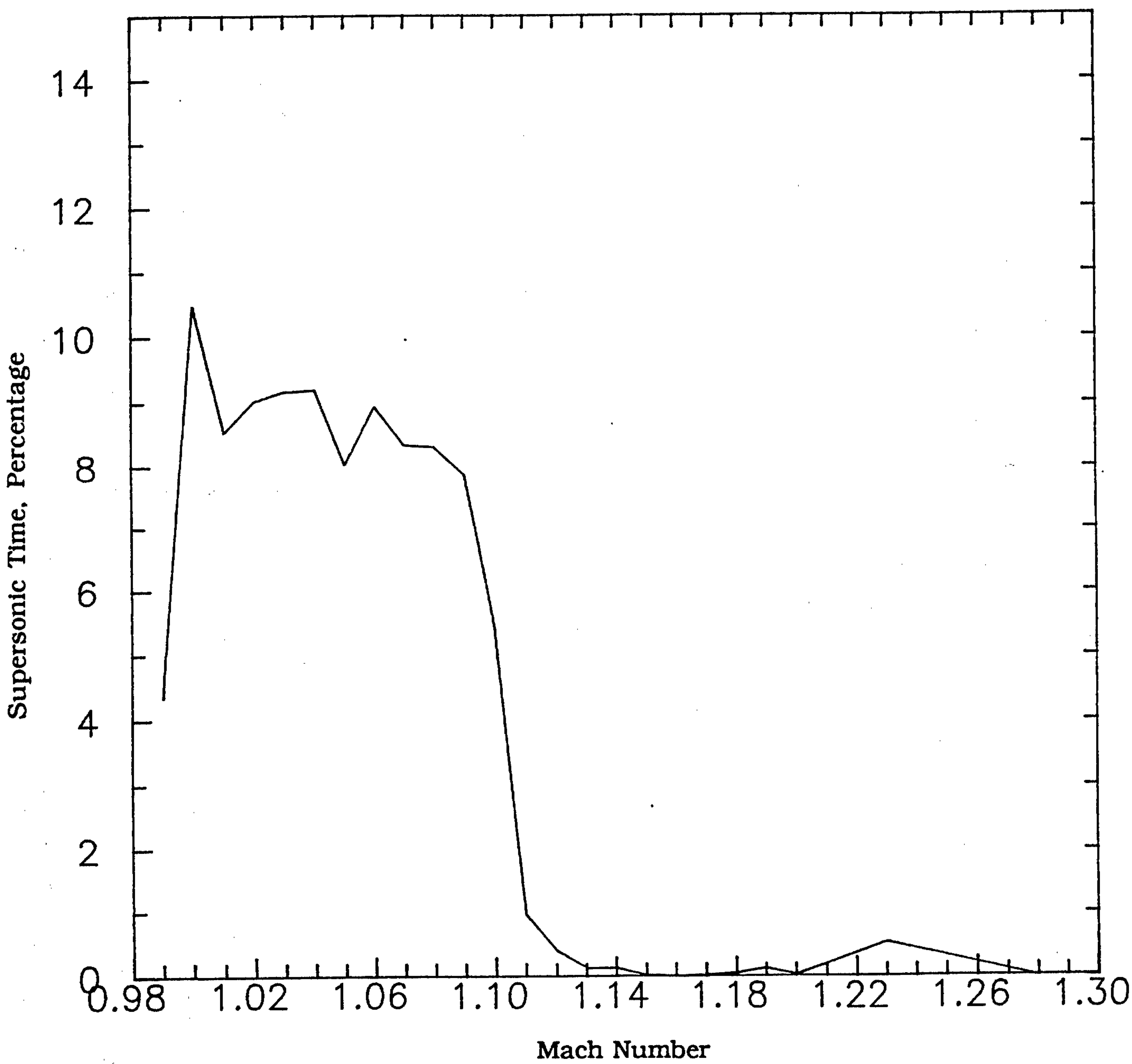


Figure 31. Mach Number Distribution for 61 F-5 Supersonic Sorties.
Total Supersonic Time: 127 Min (7,597 Sec).
Total Time on Range: 1,470 Min.

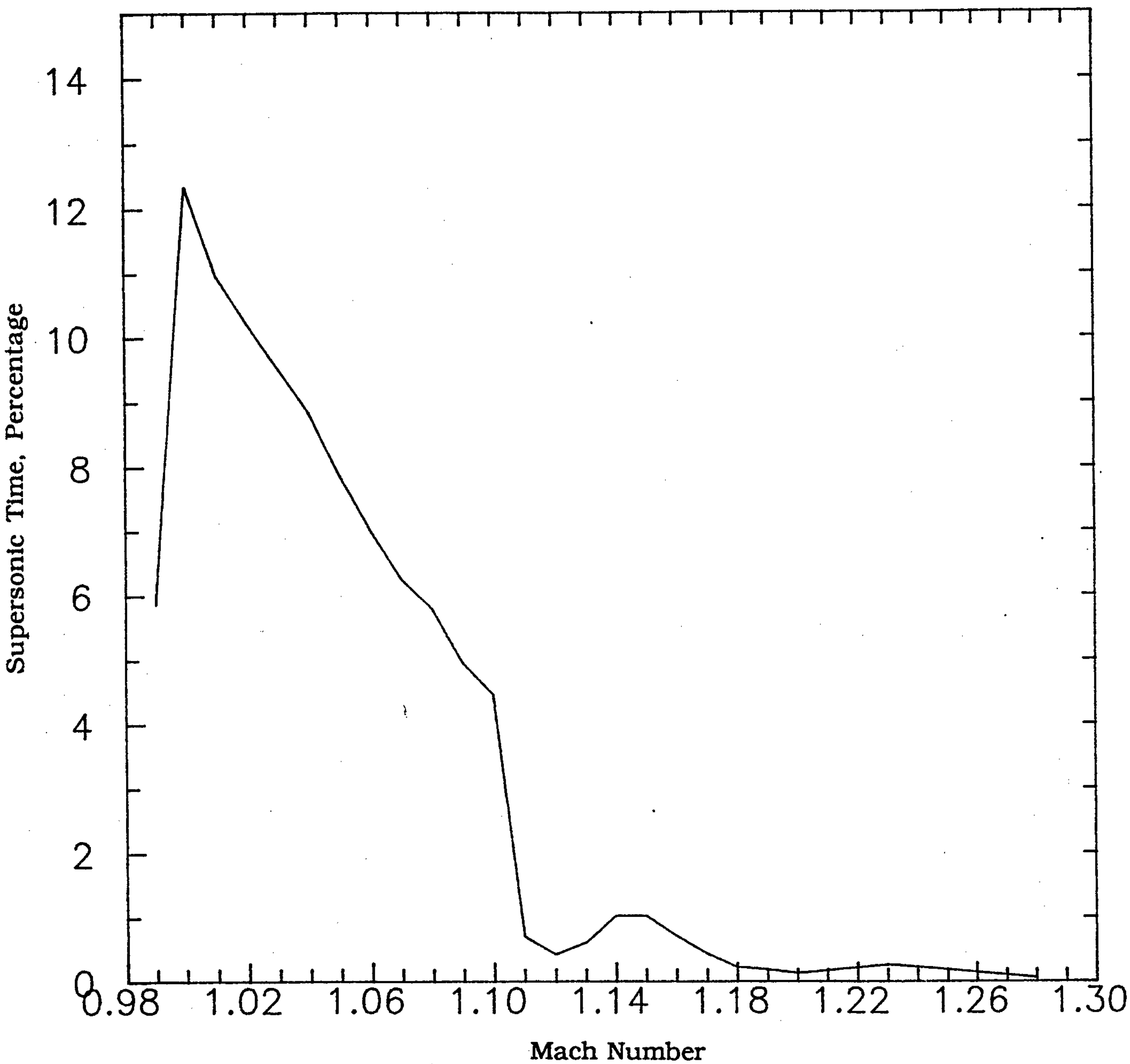


Figure 32. Mach Number Distribution for 398 F-15 Supersonic Sorties.
Total Supersonic Time: 939 Min (56,353 Sec).
Total Time on Range: 10,985 Min.

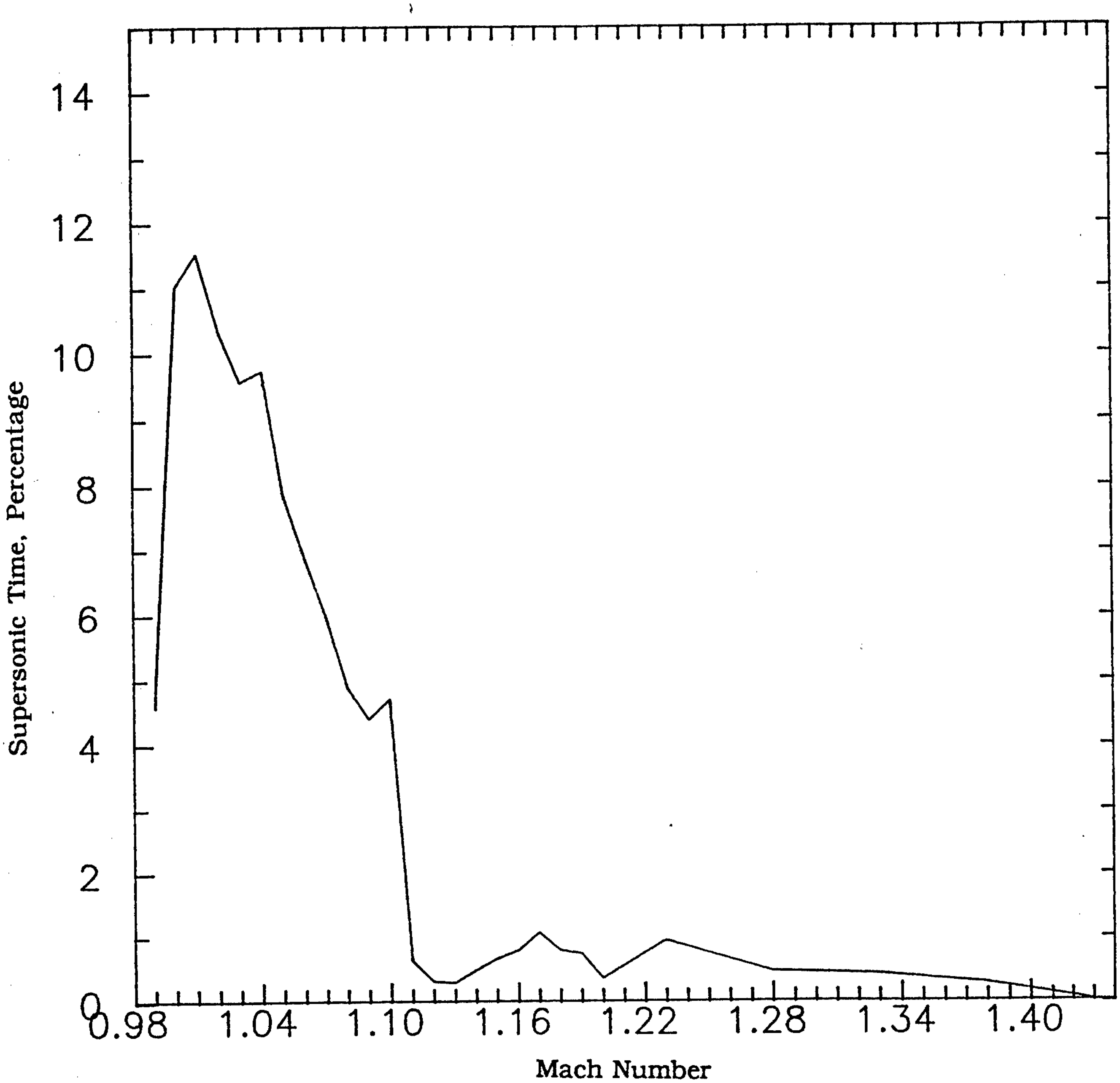


Figure 33. Mach Number Distribution for 46 F-16 Supersonic Sorties.
Total Supersonic Time: 131 Min. (7,853 Sec).
Total Time on Range: 1,325 Min.

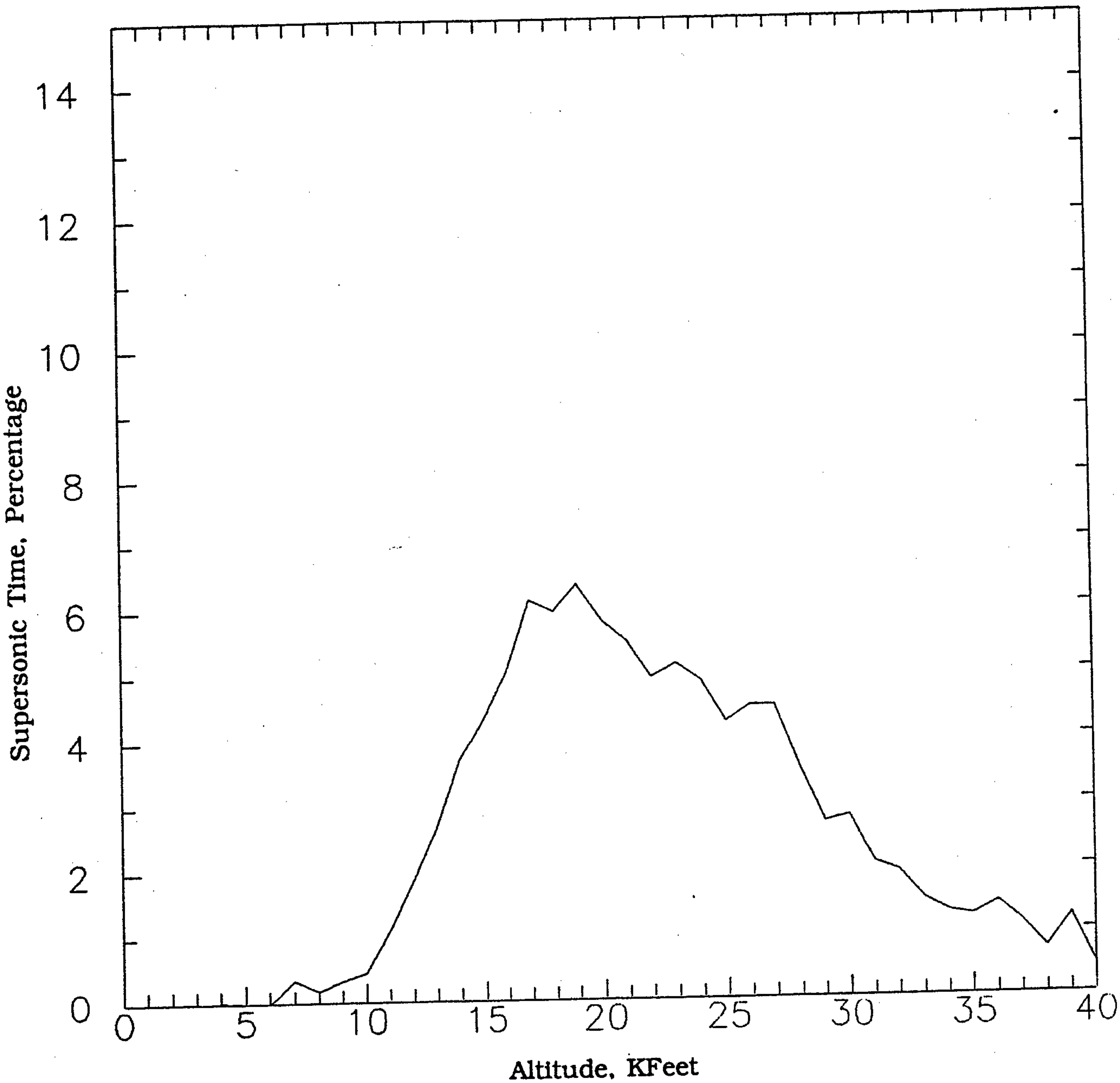


Figure 34. Altitude Distribution for 398 F-15 Supersonic Sorties.
Total Supersonic Time: 939 Min. (56,353 Sec).
Total Time on Range: 10,985 Min.

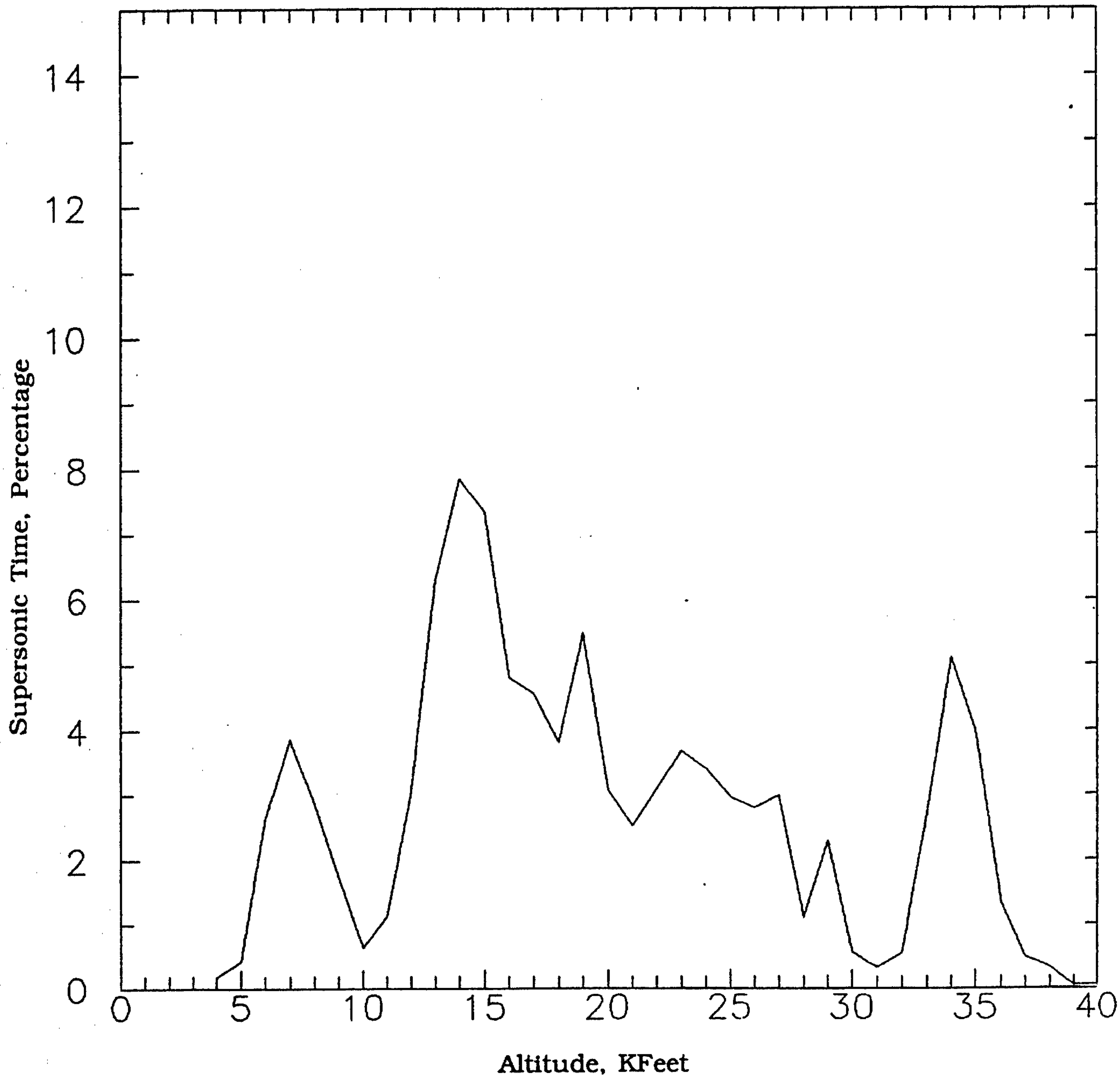


Figure 35. Altitude Distribution for 45 F-16 Supersonic Sorties
Total Supersonic Time: 131 Min. (7,853 Sec).
Total Time on Range: 1,325 Min.

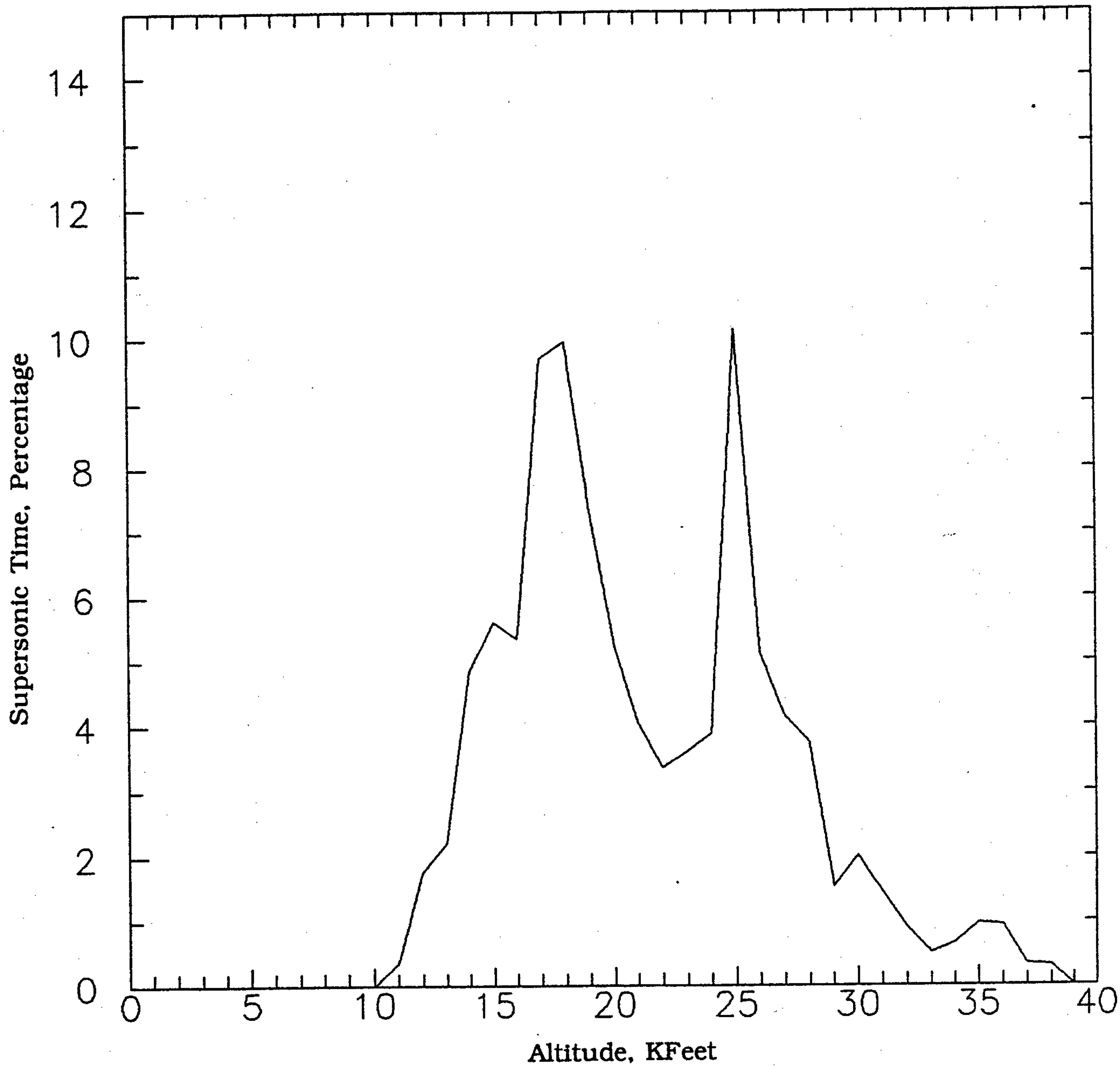


Figure 36. Altitude Distribution for 61 F-5 Supersonic Sorties.
Total Supersonic Time: 127 Min. (7,597 Sec).
Total Time on Range: 1,470 Min.

Each mission was processed by TRACK in the mode which plotted subsonic and supersonic tracks and boom impingement patterns. Figure 37 shows this type of plot for mission Strut on 6 October. Subsonic portions are broken lines, supersonic solid, and boom impingement is represented by a solid crescent-shaped line associated with each supersonic point. To gain a qualitative appreciation of various parts of the boom impingement, it should be noted that supersonic trajectory points are about 1.4 seconds apart (about three points per mile), and the spacing of the crescents relative to this is an indication of amplitude. A steady carpet boom footprint would have parallel crescents spaced about three per mile. The figure is reproduced at a scale of 0.1 inch equals one mile, so this would have a fairly dense appearance. Widely spaced crescents indicate a strongly defocused (hence weaker) boom. High-amplitude focal zones would be characterized by denser crescent spacing.

The mission shown in Figure 37 consisted of four F-15s, with range time in Lava/Mesa from 1410 to 1440. They formed an ACM training event with four AT-38s. The AT-38s did not have pods, so this plot represents the F-15 side of the mission. This was a relatively simple mission in that the four F-15s remained together, and there were apparently two setups and engagements. The pattern of the mission may be seen more clearly from Figure 38, which shows the ground track of each separately. The F-15s entered at the southeastern corner of Mesa East, and headed toward the center of Mesa. There is a dirt airstrip in that area (indicated in Figure 2) which is used as a setup point. Subsonic turns in that area correspond to g-familiarization and setup. They proceeded southwest, then south past sites 13 and 16, some becoming supersonic as they went south. The sonic boom(s) would have impinged in the vicinity of sites 19–20–22–23. A 2.3 psf boom (N–U combination) was recorded at site 22 at 14:26 and a 4.7 psf boom (Lpk–CSEL = 30 dB, suggesting a focus U-wave) at site 19 at 14:27. The first engagement was in this area, consistent with the AT-38s having set up in the south central part of Lava West. The target circle shown in Figure 2 is used as a setup point, with the Mockingbird Mountains a little to the south also serving as a visual reference.

Following the first engagement, the F-15s turned east, toward the Oscura range. A boom is predicted at site 33, which was inoperative at the time. The F-15s then turned north, just west of Oscura, running the west side of the Oscura

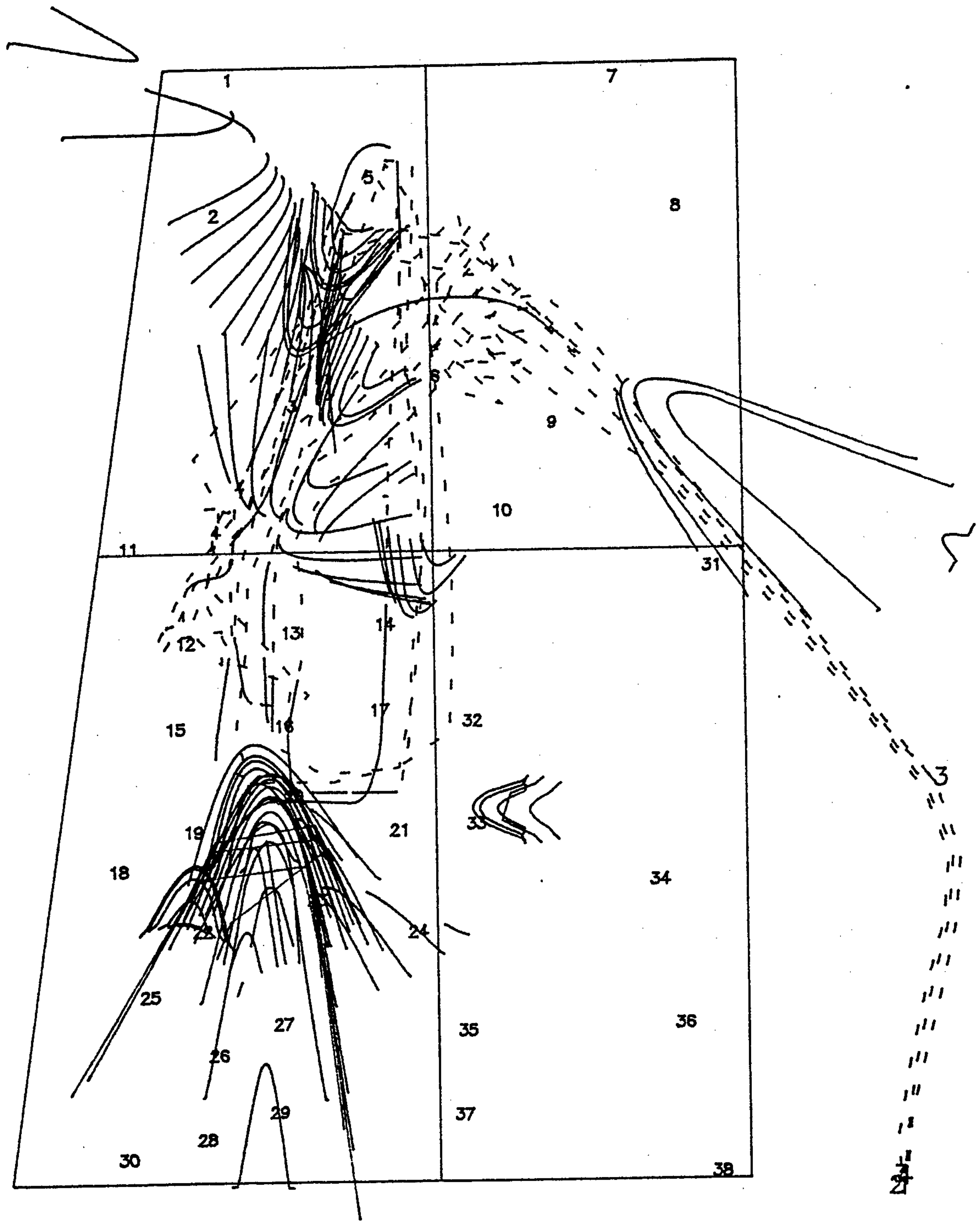


Figure 37. Example TRACK Plot With Tracks and Boom Impingent. Mission "Strut", 6 October 1988, Pod on at 14:13.

range back to the center of Mesa. Passing the dirt strip, they turned 180 degrees to the left and headed for a second engagement. That was similar to the first, but the Mach numbers were somewhat lower. After the supersonic excursion, they made a 270-degree left turn, heading toward Stallion. Crossing into Mesa, they turned toward the north–northeast, going supersonic on (presumably) the break. This was about 10 minutes after the first engagement, and a 0.6 psf U-wave was recorded at site 5 at 14:37. With a sweeping turn to the right, they left the airspace on a track parallel to their entry, one becoming supersonic on this final break.

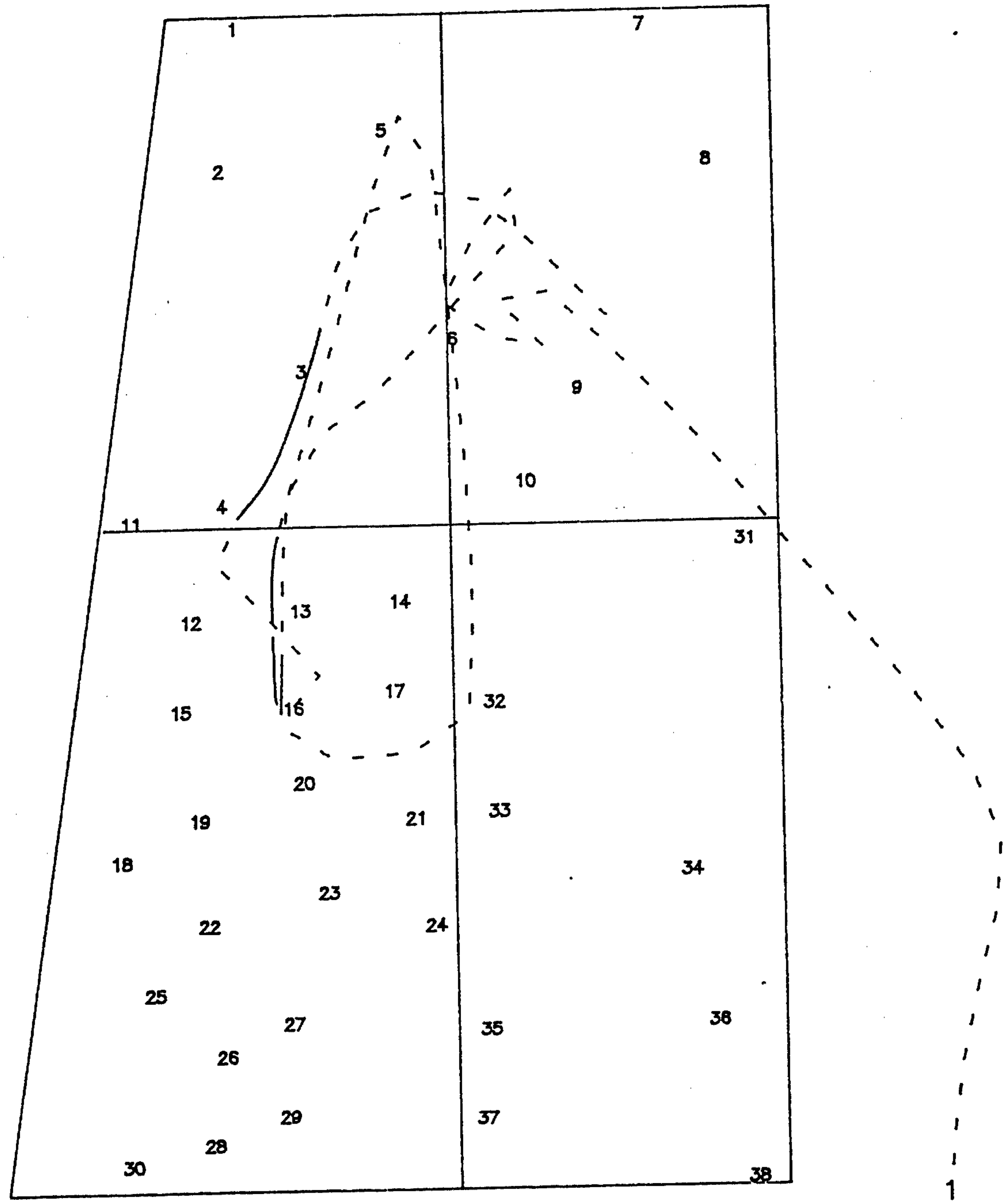
Two aspects of Figure 37 are apparent. The first is that the timing and nature of the measured sonic booms are unquestionably correlated with the corresponding supersonic excursions. Note that the recorded booms occurred in areas where the boom impingement crescents were dense, indicating carpet or focus booms. The measured boom at site 5 is not in this dense area, but is a weaker U-wave which would be expected away from the main boom. The dense area for that boom is between monitors in a sparsely covered area of Mesa. The second aspect is that the area of predicted boom impingement is quite large, larger than the measured booms suggest. Note, however, that most of the large area is covered by footprints where the crescents are widely spaced. The associated boom would be low amplitude, and (coupled with further reduction in amplitude due to grazing incidence which would be associated with these areas) would be below the 0.1 to 0.3 psf thresholds of the monitors. These thresholds, it should be recalled, are in the same range as the threshold of aural detectability of sonic booms, so it is meaningful that booms below that level would not be recorded.

A corollary of the second aspect is that a calculation which assumes steady carpet boom at each supersonic point (as Boom-Map I does) will greatly over-predict the boom environment. Also, the calculation leading to Figures 10 and 30 counts the entire footprint, regardless of amplitude, so that measured numbers of booms will be substantially less than shown in those two figures.

For those ACM missions associated with sonic boom, the TRACK plots similar to Figure 37 were inserted into the master boom event notebook and compared with measured booms. In general, the results of those comparisons were similar to the results discussed above. The concept of using ACMI tracking data for sonic boom footprint prediction is clearly valid.

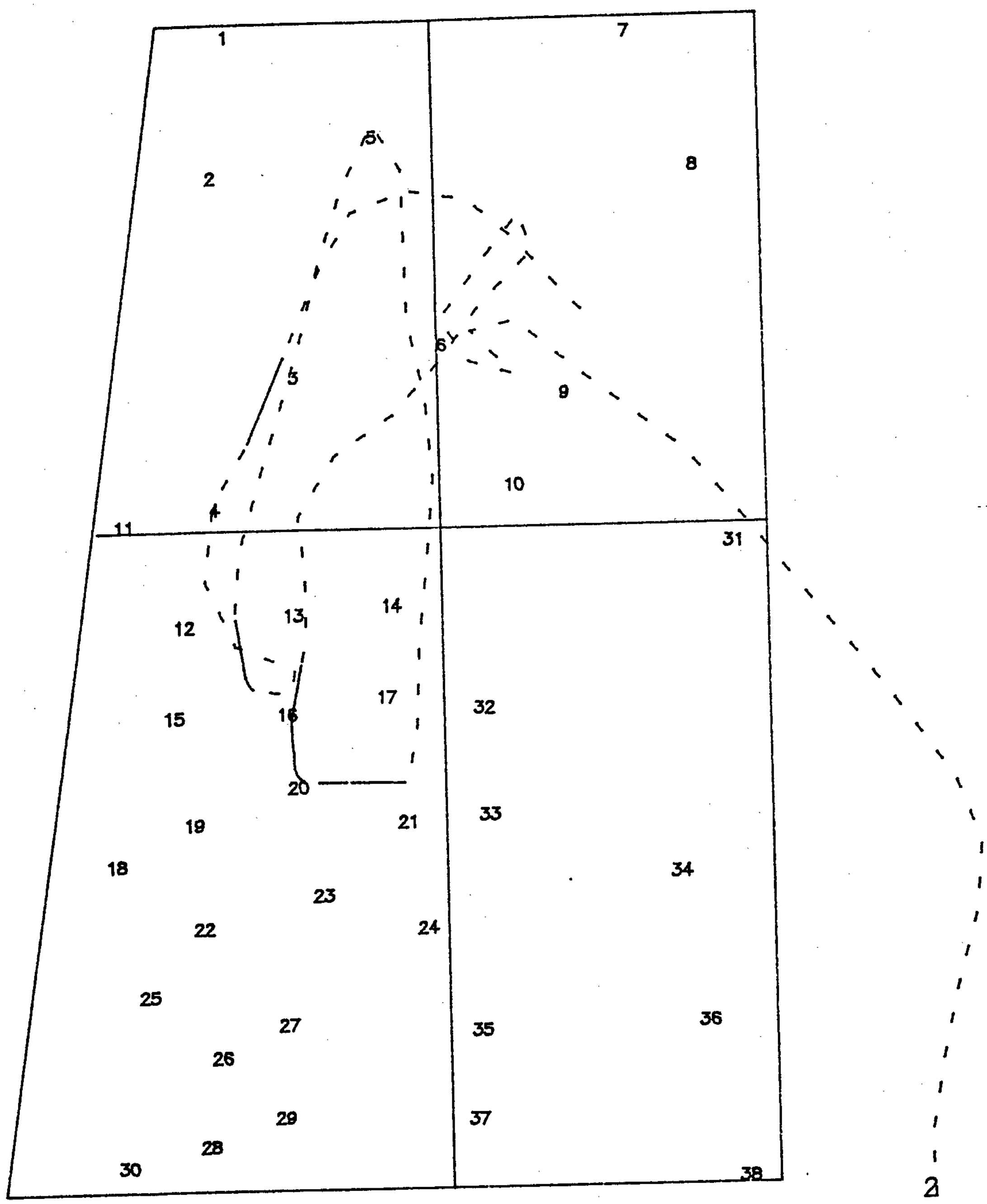
The greatest benefit of ACMI data for this study was validation of how the airspace is used. The most common ACM training events were two missions taking opposing roles. Figures 39 through 43 show tracks for five typical missions of this type, with clearance for all of Lava/Mesa. The pattern in Mesa is very much as seen in Figure 37. The dirt airstrip is one of the few clear visual references within the Mesa, with Gran Quivera providing another lead-in point. In Lava West, a combination of the target circle and the Mockingbird Mountains provide good visual references. There are a number of test facilities and road features (although little topography) which serve as landmarks in Lava West, so there is a little more variety in setup point. As with the corridor to Mesa, there is a well-defined corridor into Lava West. The basic setup points are about 40 to 50 nautical miles apart. As mentioned in Section 2.1, that is the nominal distance required for ACM setup. Although a greater separation is available if flights setting up in Mesa were to pick a location between the airstrip and Gran Quivera, there is apparently no need to do so. The fact that they set up in the middle of Mesa and the corner of Lava, and not the other way around, is presumable because they use points closest to Holloman so as to minimize fuel consumed traveling to the airspace.

Examination of plots such as Figures 38 through 43 confirms the basic description presented in Section 2.1. ACM operations are oriented in an airspace according to established setup points. The setup points in a new airspace will evolve as pilots learn to utilize the space. The points will depend very much on visual references and will also have a close relationship with transit corridors used to reach the airspace. Any elliptical pattern associated with airspace usage will have its major axis aligned with the setup points.



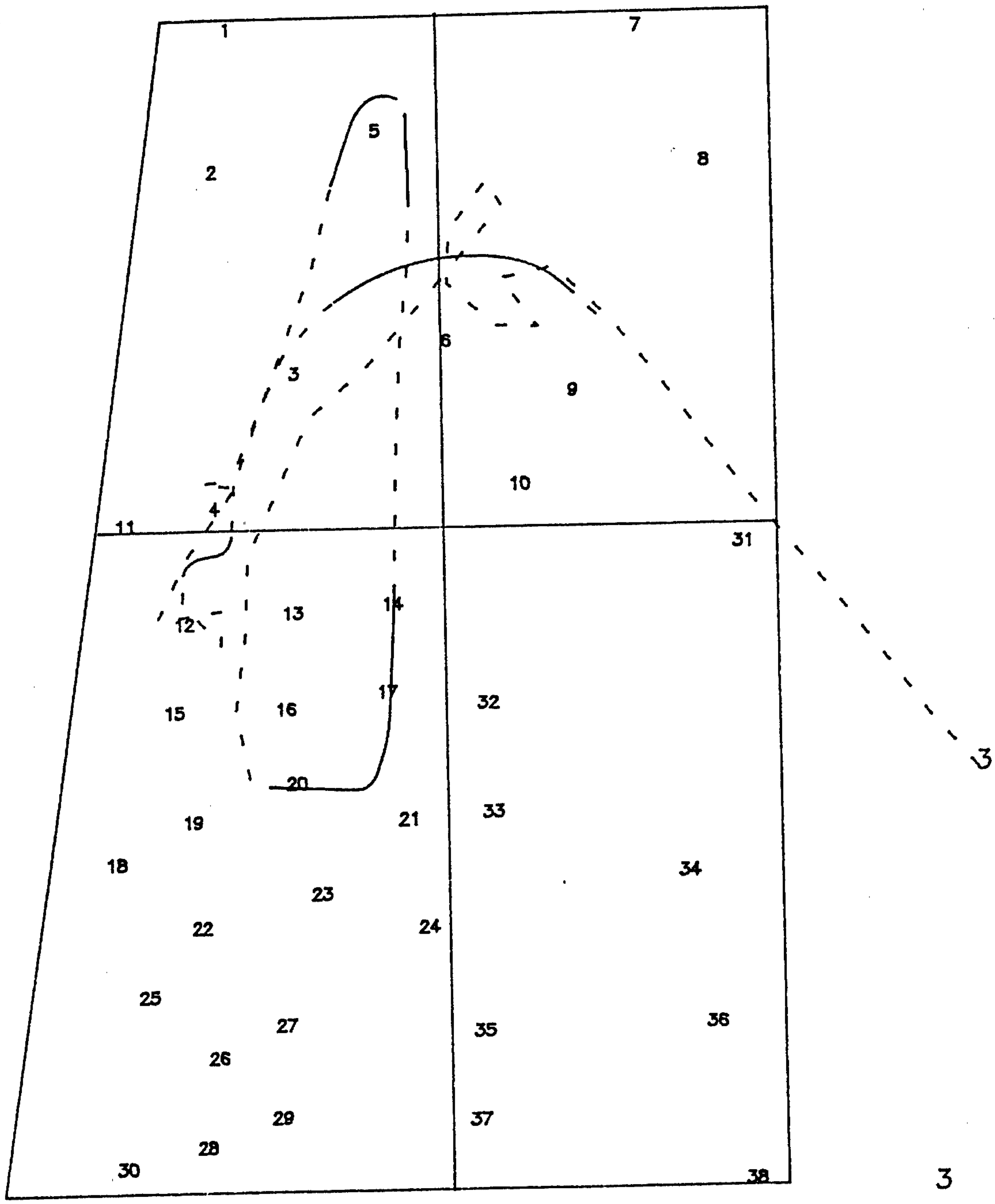
a. Strut 1.

Figure 38. Plot of Ground Track, Single Sortie.



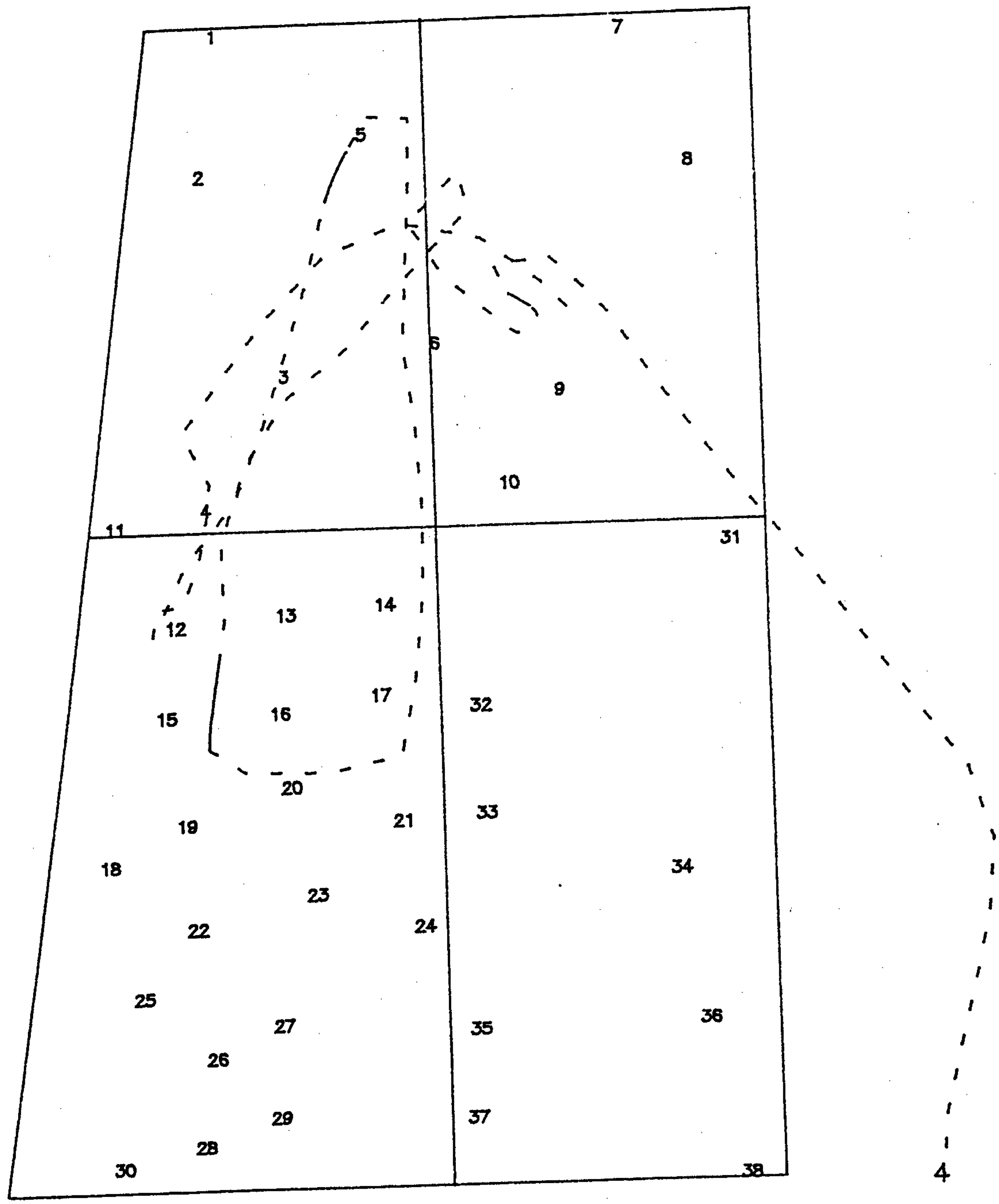
b. Strut 2.

Figure 38 (Continued).



c. Strut 3.

Figure 38 (Continued).



d. Strut 4.

Figure 38 (Concluded).

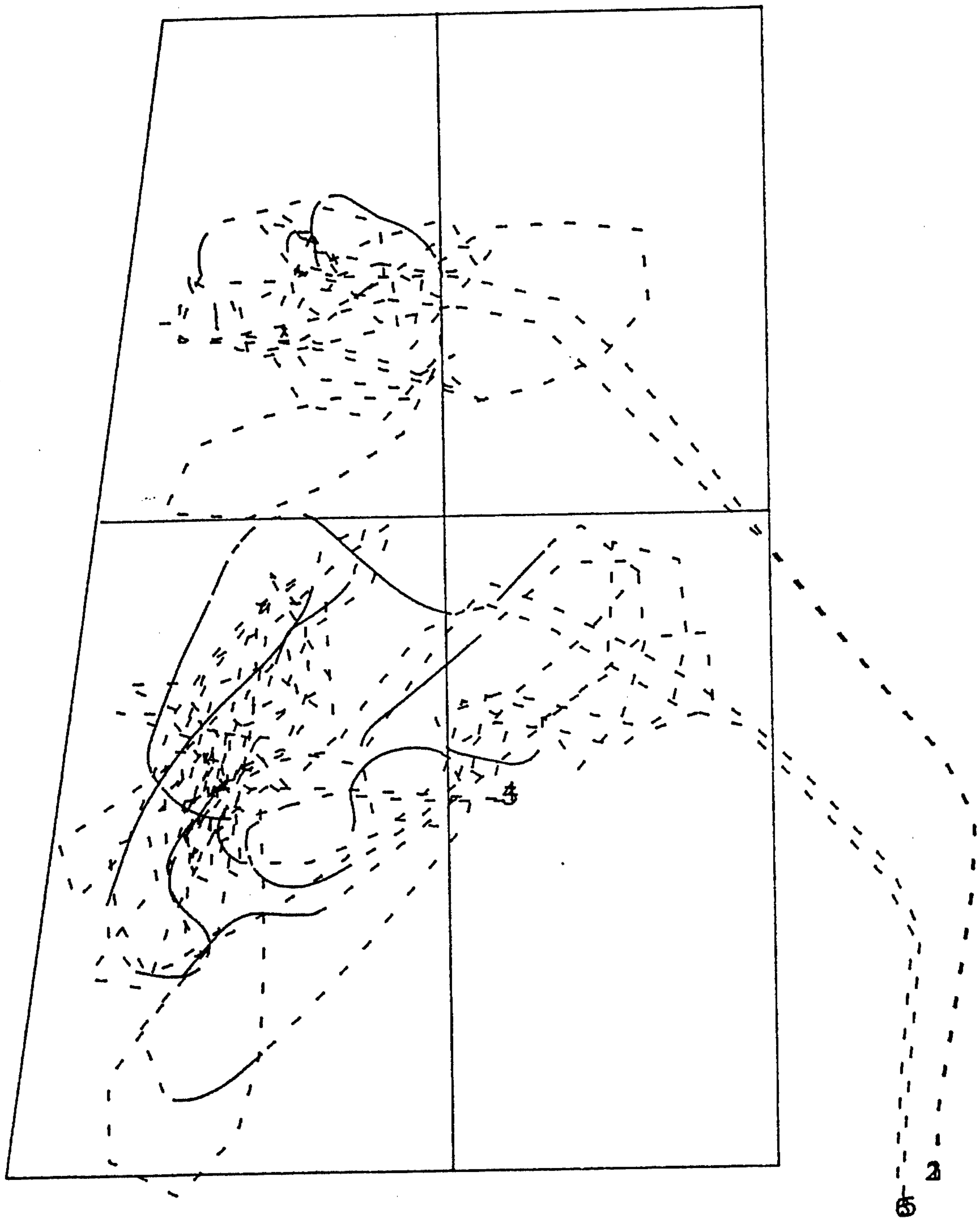


Figure 39. Ground Tracks, Mission 8285 Kishcan, Three F-15 versus Three F-15.

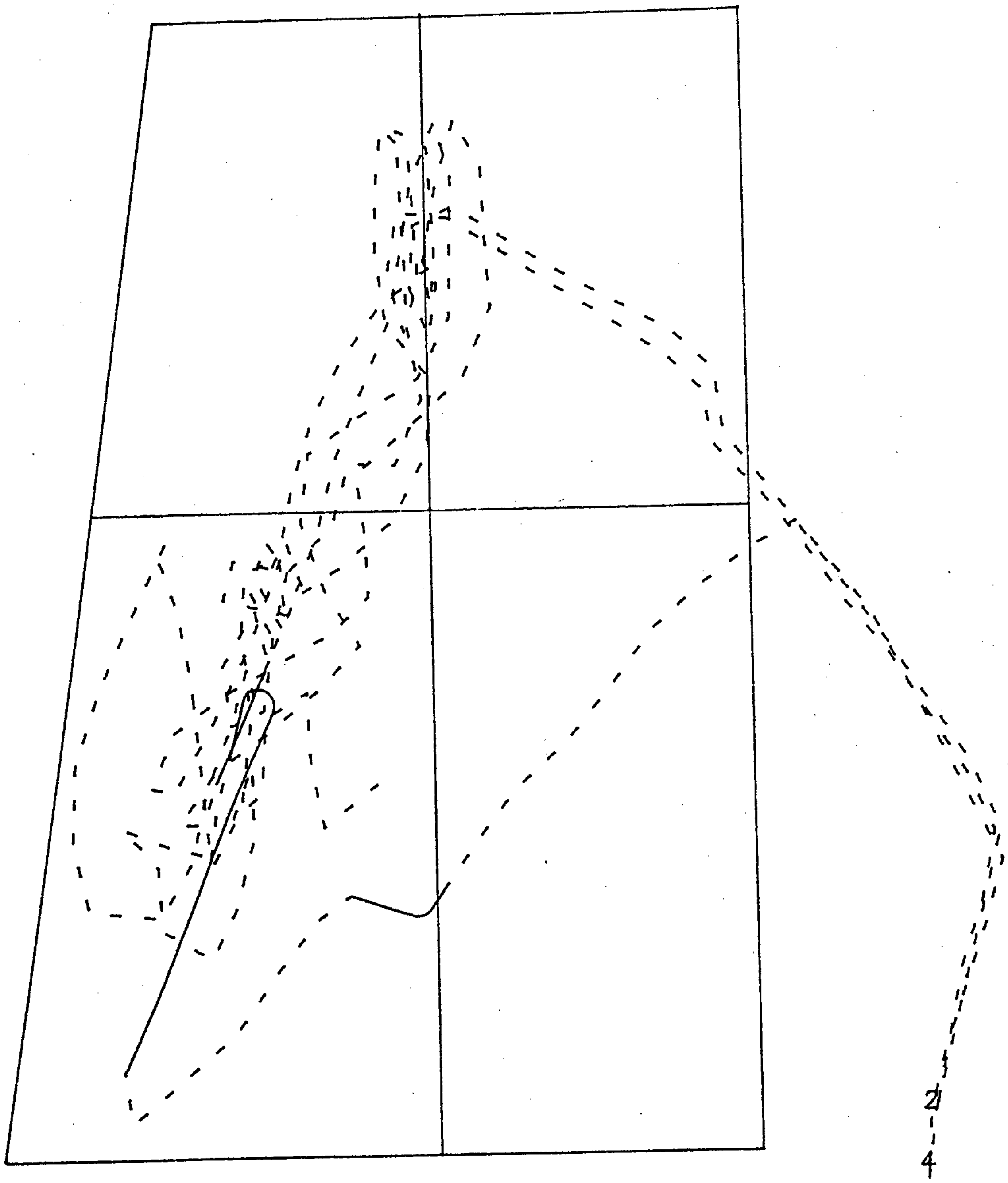


Figure 40. Ground Tracks, Mission 8293 Dime, Four F-15.

Figure 41. Ground Tracks, Mission 8319 Joke, Four F-15 versus Four F-5.

Figure 42. Ground Tracks, Mission 8320 Angor, Two F-15 versus Two F-5.

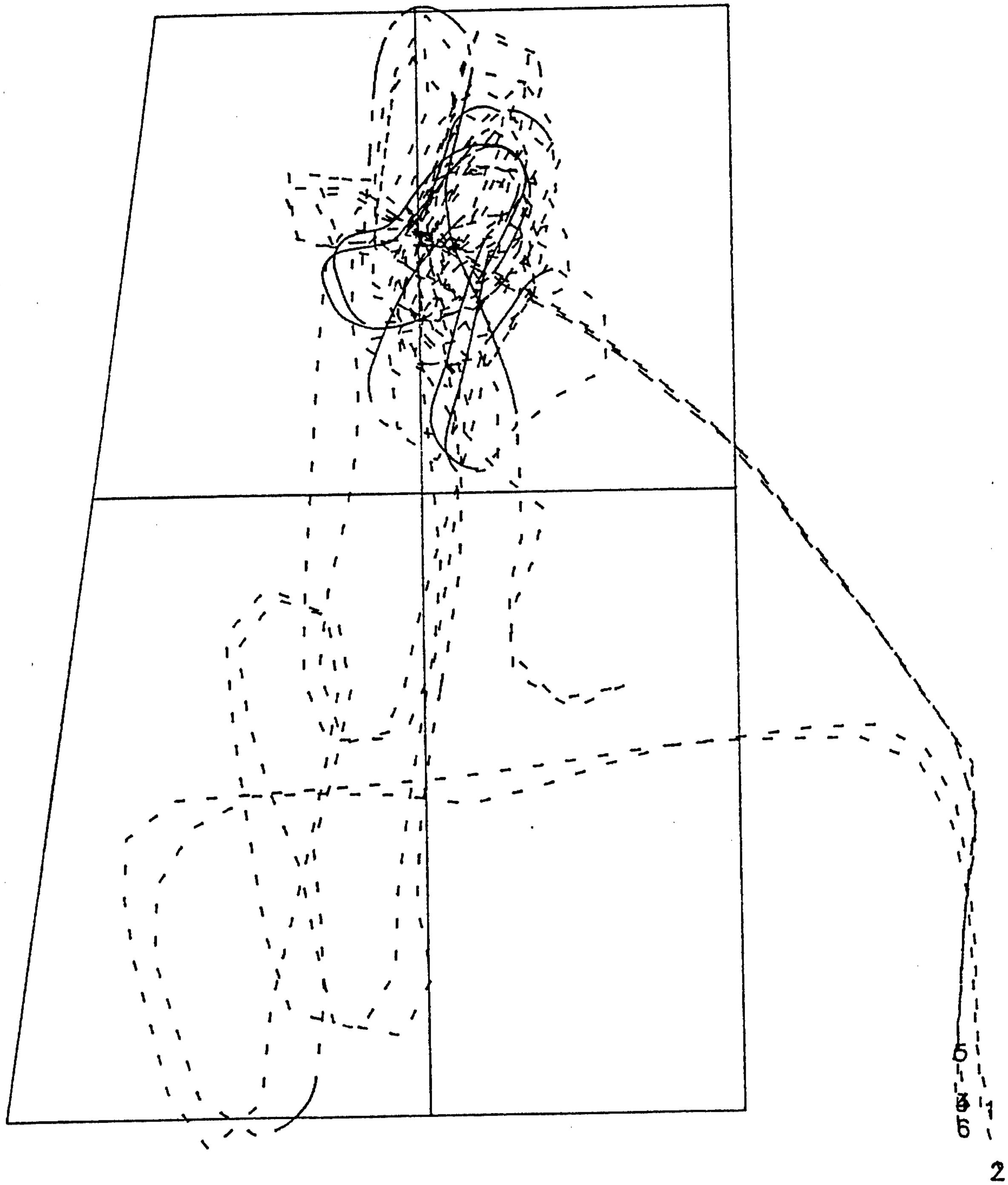


Figure 43. Ground Tracks, Mission 8341 Dime, Two F-15 versus Four F-16.

Table 4

Aircraft Sorties for ACMI Data Obtained

Aircraft	Total Sorties	Supersonic Sorties
F-5	68	61
F-15	461	395
F-16	60	46
Total	589	502

5.3 Analysis of Operations

In addition to being merged into the master data file, the operations data base was analyzed to provide summary statistics of the use of the Lava/Mesa airspace and of ACM activity. Table 5 is a summary, by month, of total activity. Note that over 90 percent of the aircraft are supersonic-capable. Of the 2,484 total missions (i.e., flights with the same call sign), there were 1,550 ACM training missions. Table 6 is a summary of the ACM missions. The 49th TFW flew 1,080 (70 percent) of these missions. The 1,550 missions were grouped into 880 training events. That the number of missions is slightly less than twice the number of training events reflects the fact that the majority of ACM training in this airspace consists of two missions taking opposing roles. The average of about three sorties per mission reflects a mix of 2 versus 2 and 4 versus 4 scenarios.

The master data file shows that the 506 ACM sonic boom events were correlated with 328 training events, 37 percent of the total. The percentage was similar if the boom events were correlated with training events, missions, or sorties. The missions associated with sonic booms did not exhibit any differences from others; they just happened to be the ones that generated sonic booms.

It would be of interest to separate the boom-generating missions by aircraft type, such that aircraft type mix could be a regression parameter in the statistical analysis of measured booms. That would enhance the applicability of the current results to other airspaces which might have a different mix. Table 7 is a tabulation of aircraft mixes. The first column is a list of all the combinations of aircraft type mixes found in the 328 boom-generating ACM training events. The second column is the number of events containing that mix. The remaining columns give the total sorties associated with each mix. Except for two events, only four aircraft types flew ACM. Note that the F-15 is a common element: if the other three types flew dissimilar missions, it was always with F-15s. The following may be seen from Table 7:

- Of 1,634 sorties in this matrix, 1,165 (71 percent) were F-15s.
- 183 of the training events (56 percent) involved only F-15s.

Table 5

Total Activity in Lava/Mesa Airspace

Dates	Total Missions	Total Sorties	Sorties/ Mission	Number of Sorties by Aircraft							Percent Supersonic Aircraft
				F-15	T-38	F-16	F-5	F-111	F-4	Other	
7/18–7/31	190	594	3.13	233	299	0	0	0	10	52	91.2
8/1–8/31	457	1,187	2.60	625	474	1	0	0	0	87	92.7
9/1–9/31	367	1,080	2.94	424	526	0	0	27	28	75	93.1
10/1–10/31	493	1,470	2.98	577	788	0	0	6	2	97	93.4
11/1–11/30	314	869	2.77	498	108	19	160	0	0	84	90.3
12/1–12/31	325	927	2.85	432	219	194	0	0	1	81	91.3
1/1–1/31	338	892	2.64	523	40	256	1	5	6	61	93.2
TOTALS	2,484	7,019	2.83	3,312	2,454	470	161	38	47	537	92.3

Table 6

Summary of ACM Missions

Total Missions:	1,550
49th TFW Missions:	1,080
Training Events:	880

ACM Sorties:

F-15	3,330
AT-38	600
F-16	460
F-5	160
Others	80
Total	4,600

Table 7

Aircraft Mix in ACM Training Events

Mix	Number of Events	Sorties			
		F-15	**AT-38**	**F-16**	**F-5**
F-15	178	736	--	--	--
F-15, AT-38	56	290	174	--	--
F-15, F-16	45	128	--	139	--
F-15, F-5	27	88	--	--	96
AT-38	13	--	51	--	--
F-16	7	--	--	22	--
Others	2	4	2	1	0
Total	328	1,165	211	162	96
		1,634 Total Sorties			

- 308 training events (93 percent) involved F-15s. AT-38s and F-16s flew relatively few missions themselves, and F-5s flew only dissimilar missions against F-15s.

With F-15s comprising 71 percent of the sorties and participating in 93 percent of the training events, the use of this airspace is clearly dominated by F-15s, and it is not reasonable to attempt to subdivide the data by aircraft type. The results of this study will therefore be applicable to airspaces where the home unit flies F-15s, and other aircraft types have a similar role.

The data in Table 7 are for the boom-generating training events. That was appropriate because it was of interest whether the sonic boom events could be analyzed according to aircraft type. Analysis of the full ACM operations data base (see Table 6) shows similar domination by F-15s of all ACM missions.

A concern in the interpretation of data for this project is that complex schedule constraints, as discussed in Section 2.3, would cause the airspace configuration to vary among missions, making somewhat of a moving target. Review of range schedules (Figure 25) shows many non-ACM activities, and review of Cherokee strips gives a very strong impression of complex scheduling. Examination of clearances for ACM, however, shows relatively few cases of special altitude or partial quadrant restrictions during the actual range time for ACM missions. Those that occur tend to be for Lava East, which is generally avoided for reasons discussed earlier. Airspace configuration differences which do appear in a consistent manner are differences in which of the four quadrants (or combinations thereof) are assigned to each mission. It was found that often when two missions comprised a training event, one would be scheduled for Lava and one for Mesa, so that when grouped by training events the variations were not as great. Table 8 is a summary of the assignments of airspace for the 328 boom-generating training events. (As with the aircraft type analysis, this is the appropriate subset, and is representative of analysis of all ACM activity.) It is seen that 76 percent of training events are granted clearance for all of Lava/Mesa. The next biggest category, Mesa alone, accounts for one-eighth of the events, too few to analyze separately. For current purposes, detailed variations in cleared airspace are negligible.

Table 8

Variation in Airspace Configuration

Quadrants Cleared	Training Events
All Lava/Mesa	248
All Lava	24
All Mesa	41
Part Lava	9
Part Mesa	1
Other Combinations	5

The subjective impression from strips and range schedules that scheduling of Lava/Mesa is complex is still correct. The results shown in Table 8 indicates that when ACM missions do receive clearance for Lava/Mesa, it is at a time when they can generally use the whole airspace and concentrate on their missions. That avoids the need to analyze variations in airspace configuration. It is also a very impressive demonstration of the skills of the airspace management team at 49th TFW/DOO.

5.4 Analysis of Measured Sonic Booms

The primary result of this study was the measurement of ACM sonic booms, characterized by CDNL, typical amplitudes, and numbers per day, in the airspace. Table 9 shows the results. For each site, the actual number of ACM booms recorded and the number of days the site was operating are shown. All other data are normalized to account for monitor down time. These data are CDNL, the average peak overpressure, and the maximum peak overpressure. The statistical distributions of all peak overpressures are shown in Figures 44 and 45 as cumulative probability distributions of peak pressure and CSEL, respectively. On these plots, a Gaussian distribution is a straight line. The peak pressure distribution is clearly not Gaussian, but the CSEL distribution is very close to Gaussian with a standard deviation of approximately 9 dB. The level distribution being normal means that the overpressure has a log normal distribution. That is consistent with typical statistical behavior of sonic booms.[34] Figures 46 and 47 are contour plots of CDNL and number of booms per day, respectively. Note that these results are for an airspace with 766 ACM sorties per month (550 F-15s). Recalling the total number of boom events and training events, there was an average of 0.6 boom per training event and 0.11 boom per sortie.

In the central area of the airspace, average CDNL is in the range of 50 to 55 dB and there is about 0.5 boom per day. The average peak overpressure is under 1 psf. This is in marked contrast to the original EIS predictions for Valentine and Reserve (each with half the sortie rate encountered in Lava/Mesa) of two to three booms per day with average overpressure of 4 psf. Only a handful of booms exceeded 4 psf, and none exceeded 7 psf. The actual sonic boom environment is thus substantially less than predicted by the simple Oceana model.

Table 9

Summary of Measured ACM Sonic Booms

Site Number	Time Up (Days)	Number of Records	Records Per Day	CDNL (dB)	AVG Ppk (psf)	MAX Ppk (psf)
2	122.5	45	0.37	45.6	0.49	2.61
3	177.9	51	0.29	47.0	0.59	4.42
4	154.2	74	0.48	48.6	0.64	2.62
5	103.5	33	0.32	46.3	0.65	3.69
7	146.1	12	0.08	40.4	0.64	1.59
8	166.2	38	0.23	53.2	0.60	4.42
9	177.1	112	0.63	51.4	0.72	4.22
10	169.9	69	0.41	50.4	0.74	3.94
11	143.8	43	0.30	46.6	0.63	2.60
12	191.3	45	0.24	40.5	0.56	1.40
13	155.4	71	0.46	52.7	0.95	5.25
14	189.9	89	0.47	55.2	1.19	6.67
15	171.2	70	0.41	52.4	1.01	4.41
17	174.2	84	0.48	55.8	0.70	5.25
18	148.1	37	0.25	48.4	0.80	3.76
19	186.0	88	0.47	51.3	0.89	6.61
20	188.4	93	0.49	49.1	0.70	2.79
21	176.1	99	0.56	52.2	0.96	3.05
22	145.5	80	0.55	50.0	0.68	2.72
23	171.0	98	0.57	52.4	0.92	4.26
24	182.0	68	0.37	57.9	0.64	1.86
25	181.4	38	0.21	42.9	0.65	3.13
26	160.2	46	0.29	44.5	0.55	2.79
27	177.5	83	0.47	54.6	0.59	5.89
28	117.3	11	0.09	38.3	0.55	2.21
29	167.6	54	0.32	45.9	0.65	3.41
30	179.0	48	0.27	41.9	0.42	2.24
31	108.8	10	0.09	38.7	0.51	1.30
32	149.4	59	0.39	50.4	0.72	5.12
33	55.1	8	0.15	43.3	0.62	1.97
34	148.4	28	0.19	41.7	0.51	1.76
35	184.7	69	0.37	45.3	0.53	2.88
36	172.9	18	0.10	37.6	0.52	0.99
37	156.5	32	0.20	36.6	0.45	0.99
38	137.5	12	0.09	35.8	0.39	1.09
	158.2 Average Up Time	**1915 Boom Records**	**0.33 Average Recs/Day**		**0.67 Average Ppk**	**3.25 Average Max Ppk**

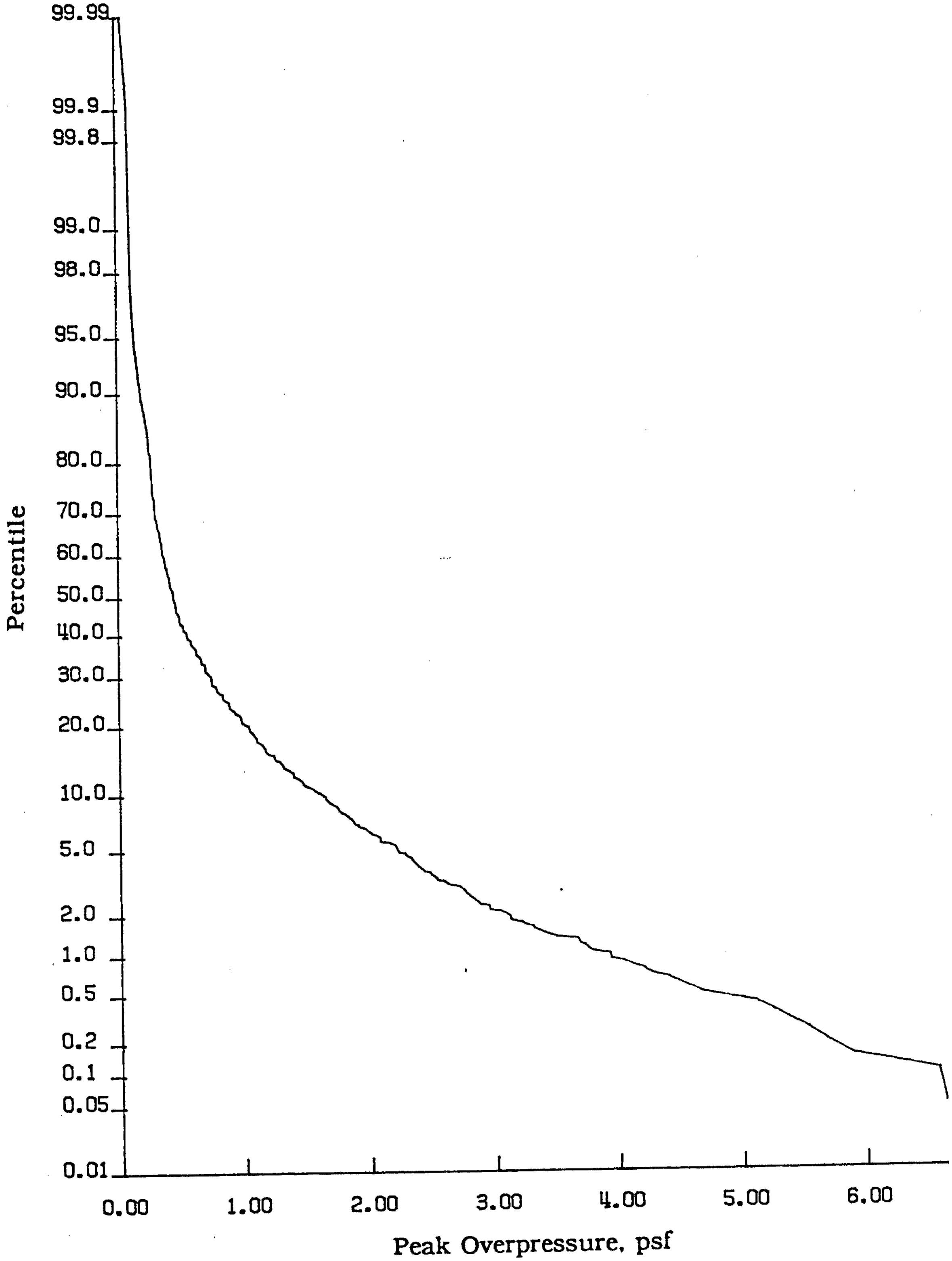


Figure 44. Cumulative Probability Distribution of Peak Overpressures, All ACM Booms.

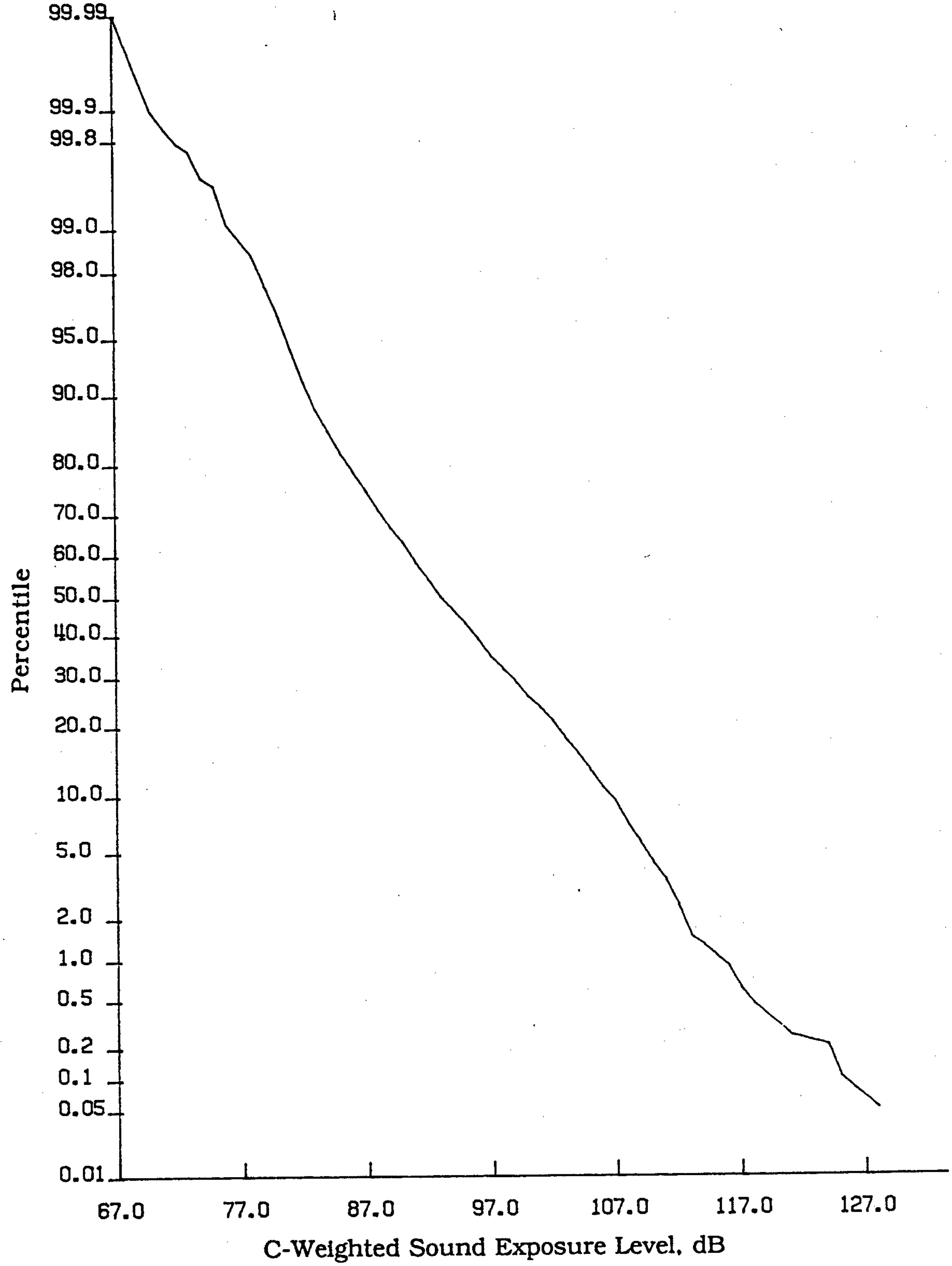


Figure 45. Cumulative Probability Distribution of C-Weighted Sound Exposure Levels, All ACM Booms.

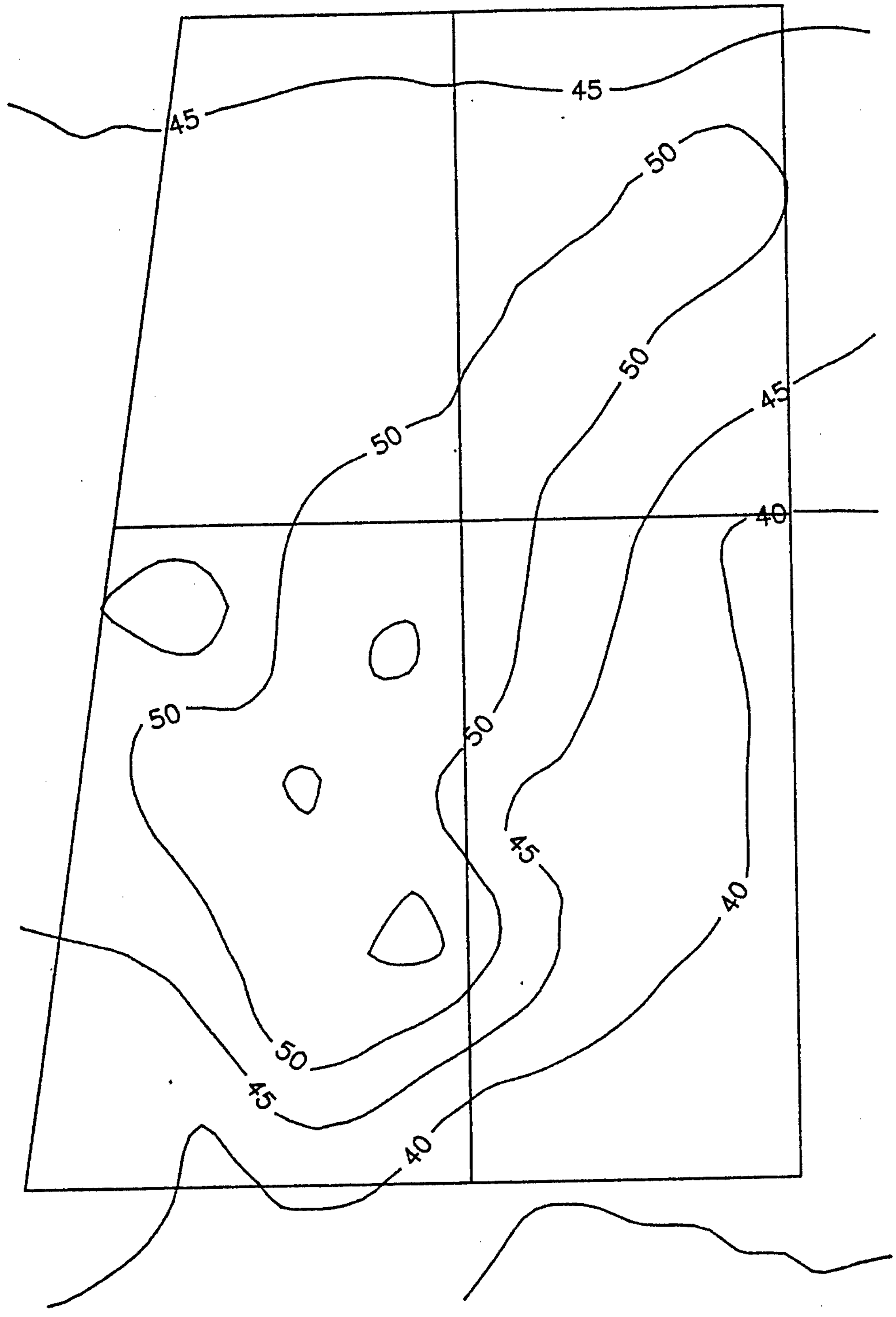


Figure 46. Measured ACM CDNL in Lava/Mesa Airspace.

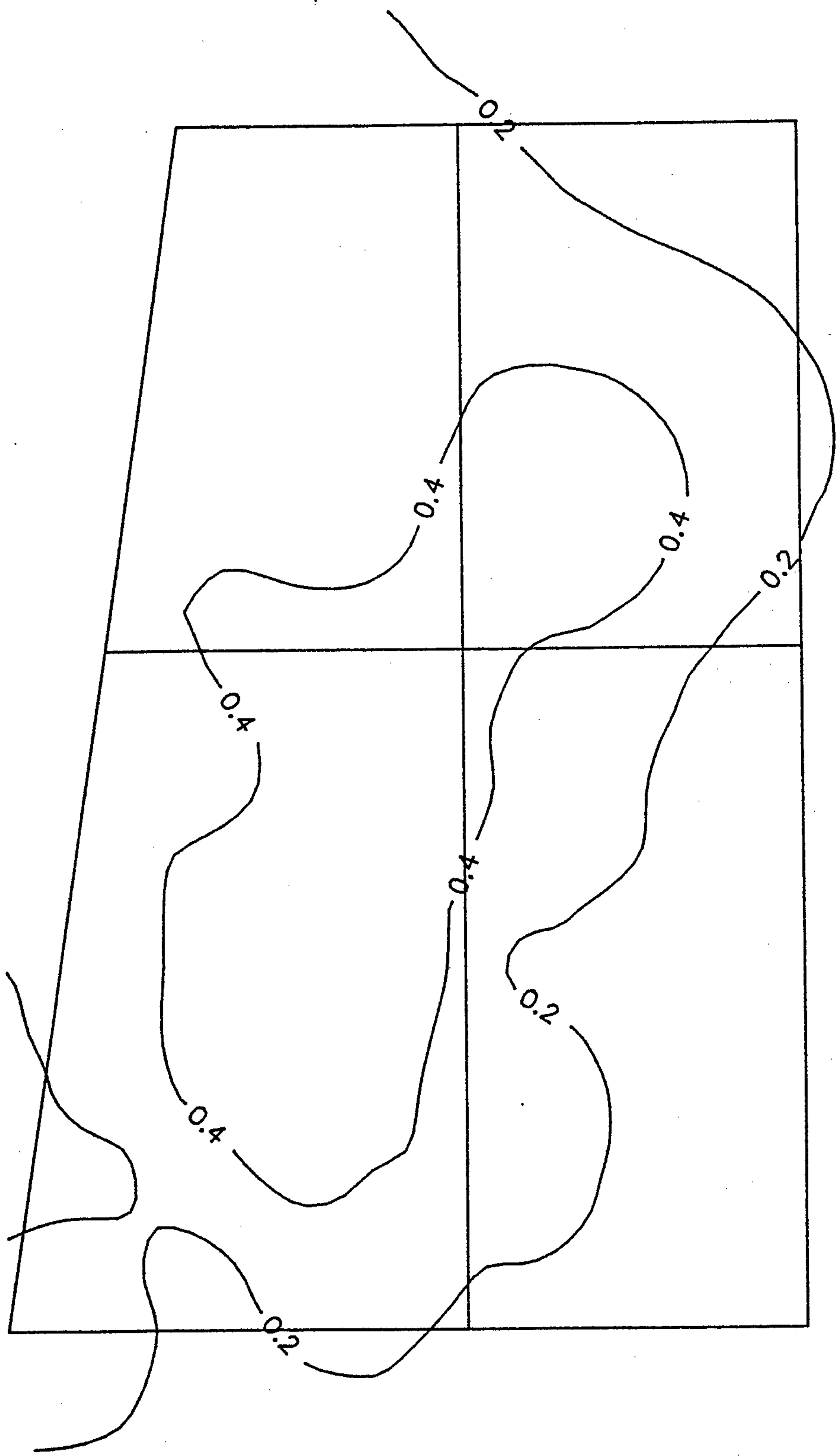


Figure 47. Measured ACM Booms/Day in Lava/Mesa Airspace.

The lower amplitude contours shown in Figures 46 and 47 (CDNL of 40 and 45, 0.2 boom/day) do not close to the west. This is because the measurement site array, being limited to the missile range (not the airspace, which extends farther west), did not extend far enough to the west. In the other three directions, where monitors were located beyond the supersonic area, the contours close. The contours themselves have detail which is associated with the particular data set. If measurements were to be made for a different six months of similar activity, contours of about the same size and general shape would be expected, but the detailed shape would change. Since the experimental design was based (with empirical justification) on a Gaussian distribution, a more realistic representation of the long-term environment is a Gaussian fit to the measured data. Figures 48 and 49 are the results of such a fit. The quantitative parameters of these fits are presented in Section 6, where current results are related to the previous predictions and are applied to Reserve and Valentine.

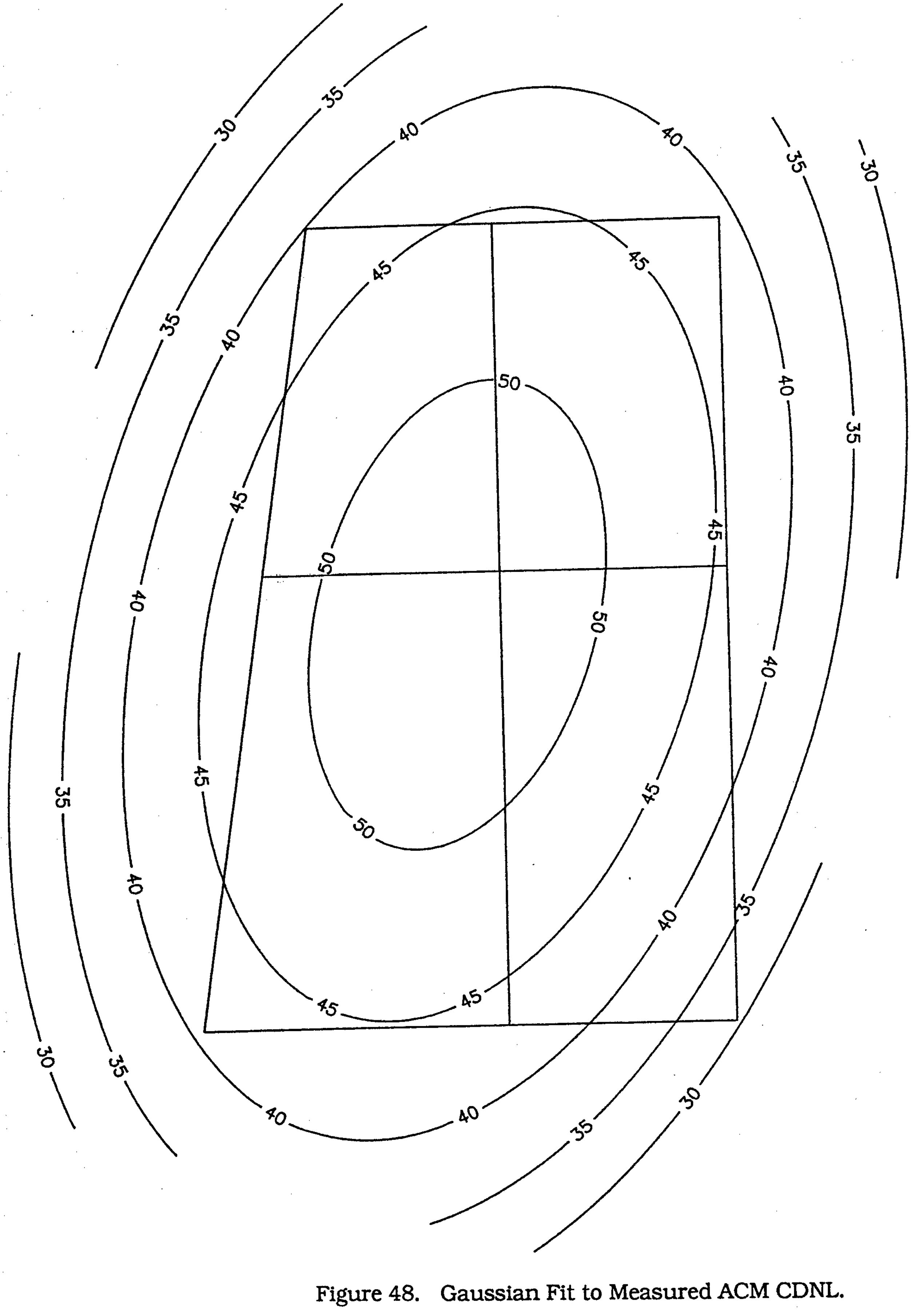


Figure 48. Gaussian Fit to Measured ACM CDNL.

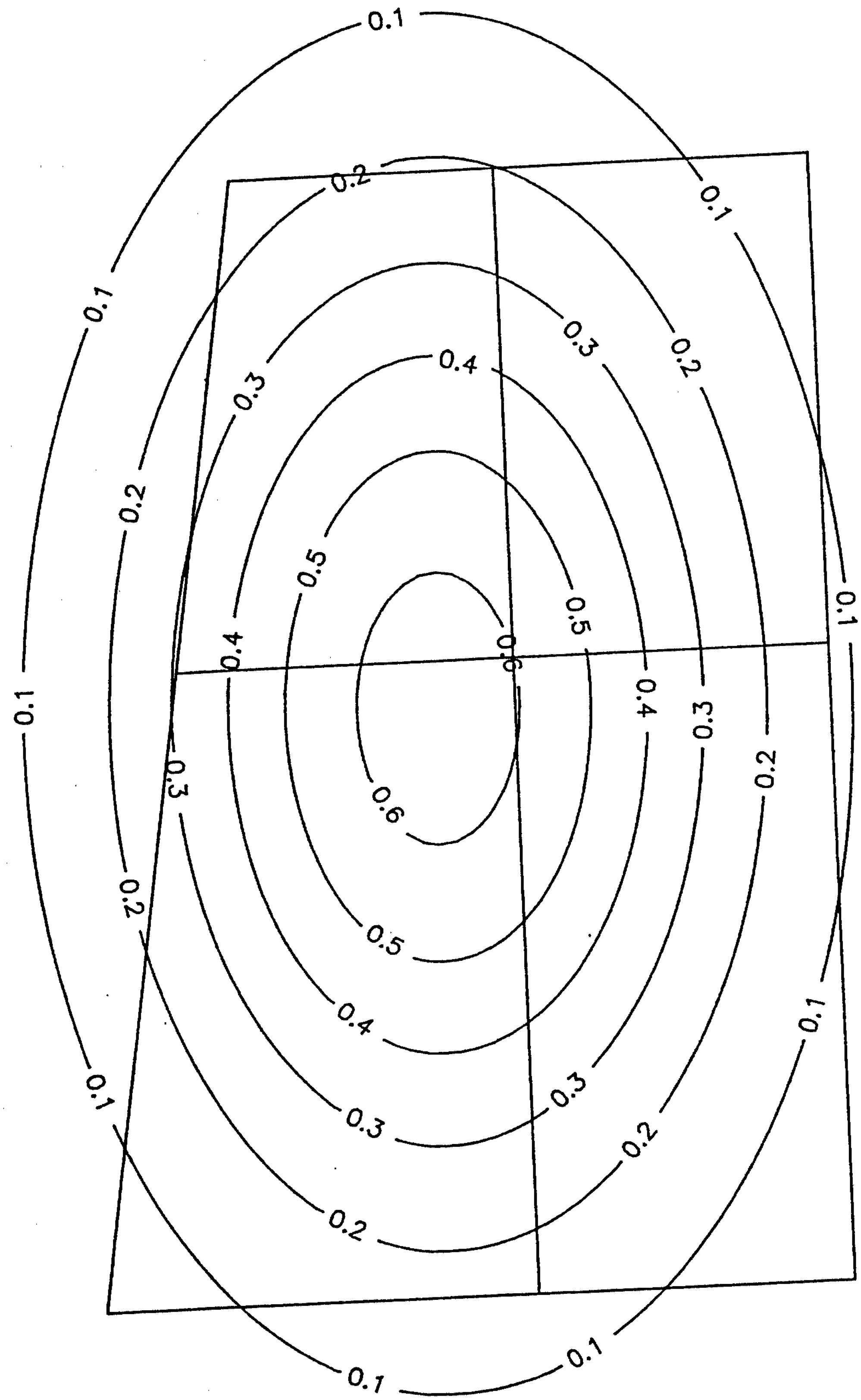


Figure 49. Gaussian Fit to Measured ACM Booms/Day.

6.0 PROJECTIONS OF CDNL TO RESERVE AND VALENTINE

6.1 From Oceana to WSMR

The original CDNL predictions for supersonic operations at the Reserve and Valentine MOAs utilized the Oceana model. That model[3] was based on analysis of ACMI data from 21 F-15 sorties, combined with a simplified carpet boom model.[20] The Oceana model consists of three concentric ellipses:

- An inner ellipse ("Supersonic Maneuvering Ellipse") of dimensions 12 x 18 statute miles, which was the observed supersonic maneuver area of the 21 sorties. Within this ellipse, the average CDNL is $104 + 10 \log_{10} 0.8N - 49.4$, where N is the number of sorties per day.
- A middle ellipse ("0.8 Cutoff Ellipse") of dimensions of 20.4 x 26.4 miles. The dimensions of this ellipse are related to those of the inner ellipse by a distance equal to 80 percent of the half-width of the sonic boom carpet of an F-15 at Mach 1.1 and 15,000 feet. At the edge of this ellipse, CDNL is 3.7 dB less than in the inner ellipse.
- An outer ellipse ("1.0 Cutoff Ellipse") of dimensions 22.4 x 28.4 miles, based on the center ellipse plus the remaining 20 percent of carpet width. At this ellipse, CDNL is 14 dB less than in the inner ellipse.

The major axes of these three ellipses are aligned with a line connecting the setup points, and the ellipses are centered between the setup points.

The basic concept of the Oceana model – elliptical contours centered between setup points – is entirely reasonable. Any fault in the model lies with the very limited ACMI data and sonic boom modeling tools available at that time.

Figure 50 shows a comparison between the CDNL 61 ellipse predicted for Reserve, at 300 sorties per month, and the CDNL 51 contour projected from measurements in the Reserve monitoring program.[4] The prediction appears to be at least 10 dB too high, although the few booms measured makes it difficult to

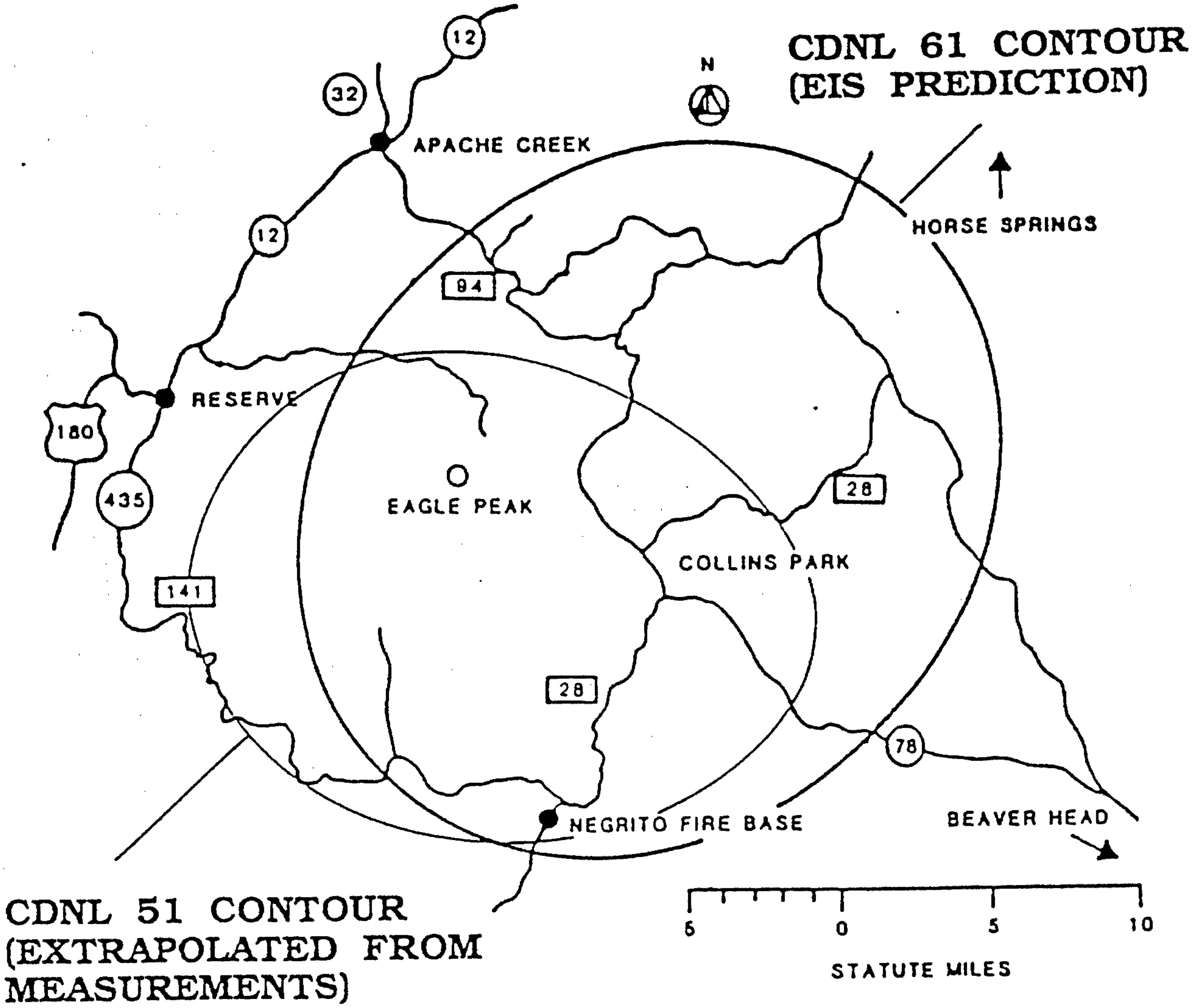


Figure 50. Comparison Between EIS Predictions at Reserve and 1985 Monitoring Results Projected to 300 Sorties/Month.

be precise. Analysis in Reference 4 suggests that, based on estimates of size differences between carpet boom and maneuver boom footprints, the Oceana model is at least 4 dB too high.

The analysis discussed in Section 3 indicated that a two-dimensional Gaussian model is appropriate for CDNL. This has the following form:

$$CDNL = L_o + 10 \log_{10} N + 10 \log_{10} \exp[-(x^2/2\sigma_x^2 + y^2/2\sigma_y^2)] \quad (8)$$

where N is the number of sorties per month (more appropriate than sorties per day), L_o is an amplitude constant, and σ_x and σ_y are the standard deviations along the minor and major axes, respectively.

It would be convenient to represent the Oceana model in this form. It is not possible to do so while maintaining all three ellipses. On review of the assumptions in development of that model, the inner and center ellipses are based on the most realistic assumptions, while the outer ellipse appears to cut off the boom too rapidly. Fitting Equation (8) to the Oceana inner and middle ellipse yields $L_o = 36$ dB, $\sigma_x = 5.1$ miles, and $\sigma_y = 7.6$ miles. For 600 sorties per month (the nominal rate at WSMR), this yields a predicted center value of CDNL = 64 dB. This is about 10 dB higher than measured, and the general slope of the fall-off with distance from the center is too steep. If the Reference 4 suggestion that the Oceana model is at least 4 dB too high is followed, L_o becomes 32. The prediction is still not good.

Equation (8) has been fitted to the data collected in this project. The results are $L_o = 25$ dB, $\sigma_x = 11.1$ miles, and $\sigma_y = 18.9$ miles. These values were fitted for a sortie rate of 550 per month, corresponding to the F-15 rate during the monitoring project. That provides a slight degree of conservatism, yielding levels up to 1.5 dB higher than if the total 766 sorties/month had been taken as a reference. The contours drawn in Figure 48 represent this fit, evaluated at the reference 550 sorties/month.

A similar equation (plotted in Figure 49) has been derived for the number of booms per day, and is presented in the next section.

6.2 The WSMR Model

The parameters presented in the previous section give the following relation for CDNL:

$$\text{CDNL} = 25 + 10 \log 10\, N + 10 \log_{10} \exp\{\tfrac{1}{2}[(x/11.1 \text{ mi})^2 + (y/18.9 \text{ mi})^2]\} \qquad (9)$$

The relation for the number of booms per day is:

$$n = 0.0012\, N \exp\{-\tfrac{1}{2}[(x/13.0 \text{ mi})^2 + (y/21.4 \text{ mi})^2]\} \qquad (10)$$

where N is the number of ACM sorties per month. These two equations represent the "WSMR model" for sonic boom due to ACM training involving predominantly F-15s.

The size and shape of the CDNL contours should not be confused with the maneuver airspace. The tracking data shown in Figures 9 and 29 show that operations take place in a 35 x 60-mile ellipse which is concentric with the CDNL contours. If the number of operations increases or decreases, the size of a given CDNL contour will change, but the maneuver ellipse remains constant. Note that the area in Figure 9 (50 missions) is about the same as in Figure 29 (127 missions), but there is a difference in track density. The maneuver ellipse is determined by the needs of individual training missions, not how many such missions are scheduled in a given period.

6.3 Application to Reserve, New Mexico

Equations (9) and (10) have been applied to the Reserve MOA, using 300 sorties per month. The result are shown in Figures 51 and 52. It was intended to plot the CDNL 50, 55, 60, etc., contours, CDNL 50 being the threshold of any expected adverse impact. The highest level predicted is below 50 dB. Therefore the CDNL 45 contour has been shown for reference. The contours have been located at the same position as contours were shown in the Reserve EIS. That is a location which is consistent with the area required for a maneuver ellipse.

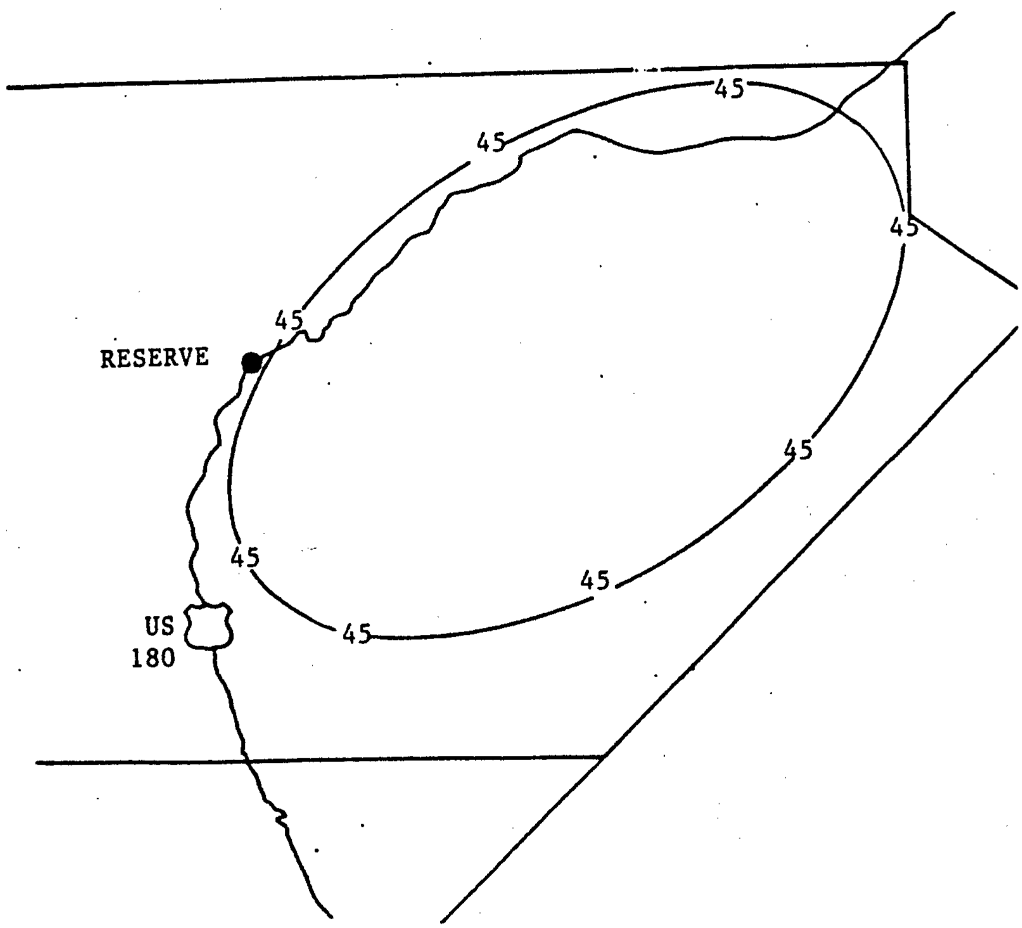


Figure 51. Predicted CDNL in Reserve MOA.

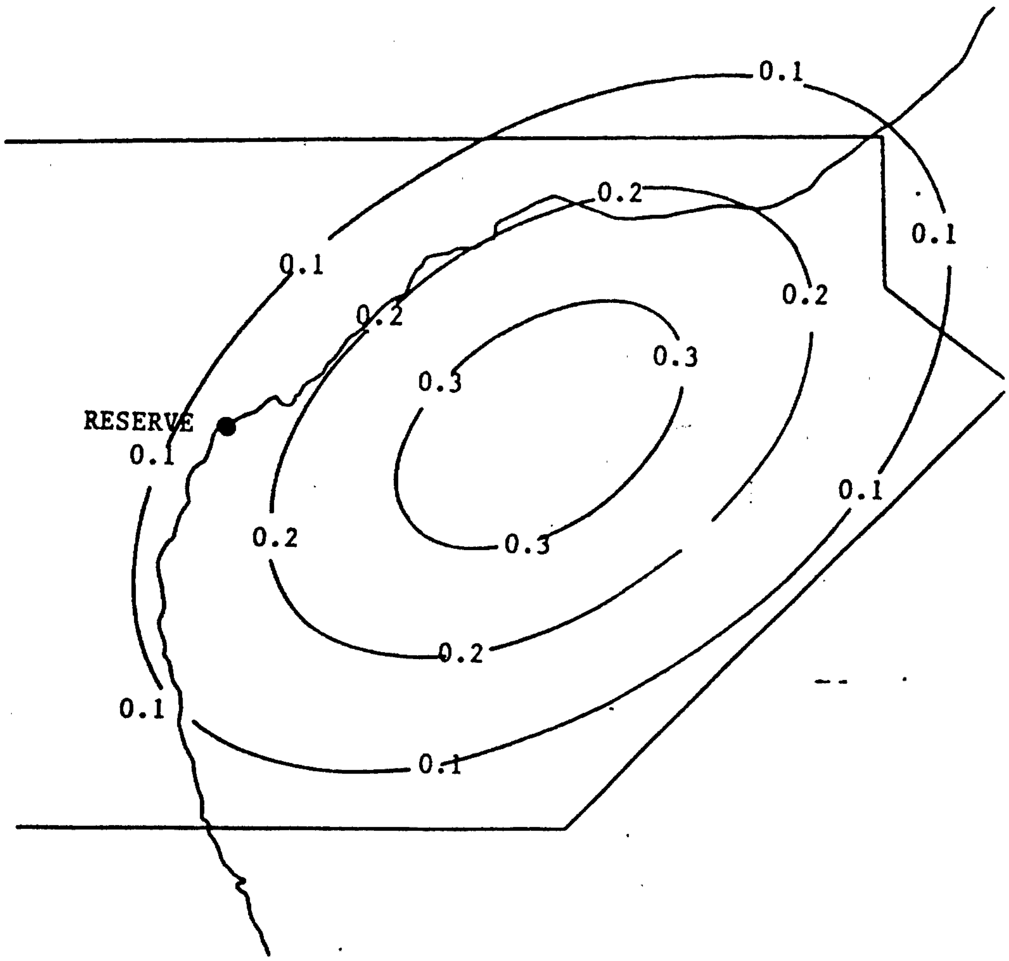


Figure 52. Predicted Booms/Day in Reserve MOA.

6.4 Application to Valentine, Texas

Equations (9) and (10) have been applied to the Valentine MOA. Two supersonic maneuver areas, each with 150 sorties per month, have been assumed and they are centered at the same locations as in the EIS. The results are shown in Figures 53 and 54. As with Reserve, CDNL is everywhere below 50 dB, so the CDNL 45 contours have been plotted. These locations are not consistent with the space needed for a concentric maneuver ellipse. Actual contours would be located more toward the center of the airspace. In any event, CDNL will be below 50 dB everywhere.

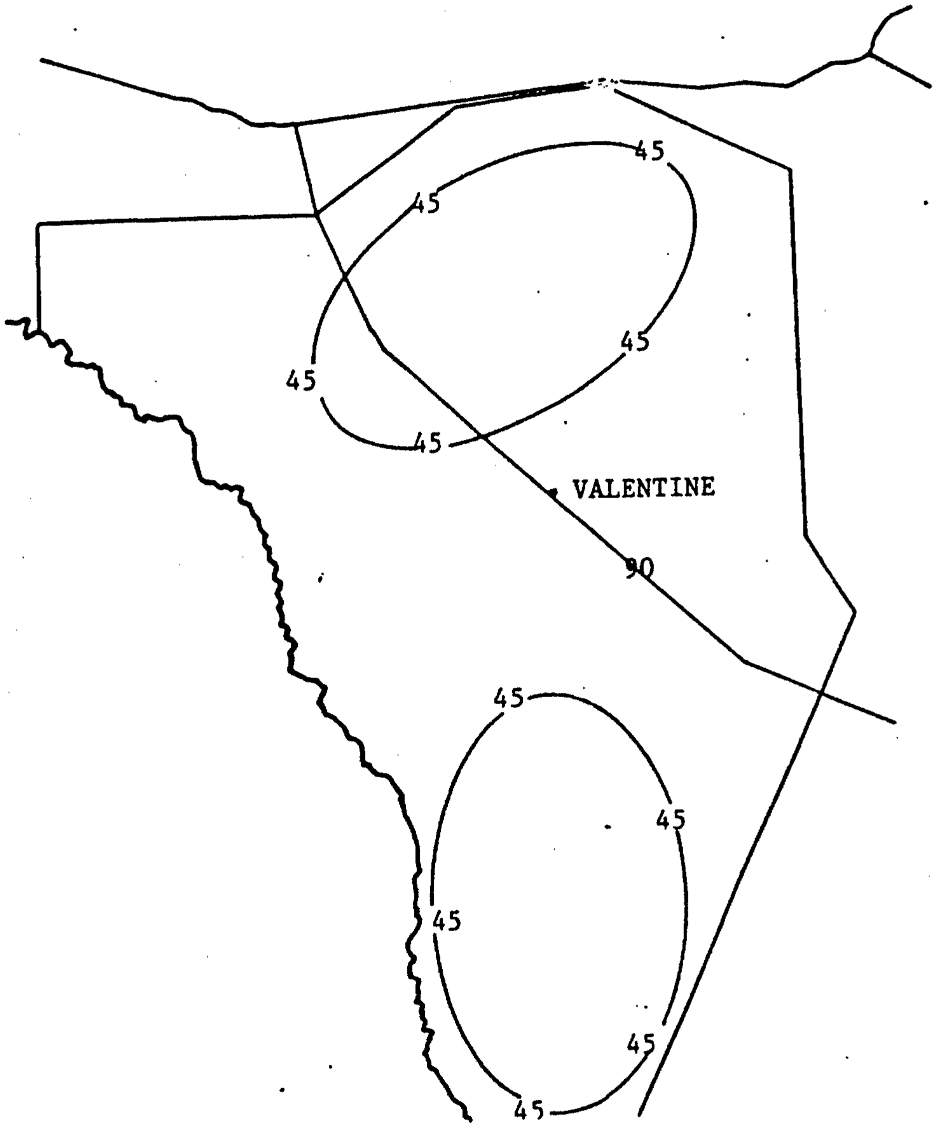


Figure 53. Predicted CDNL in Valentine MOA.

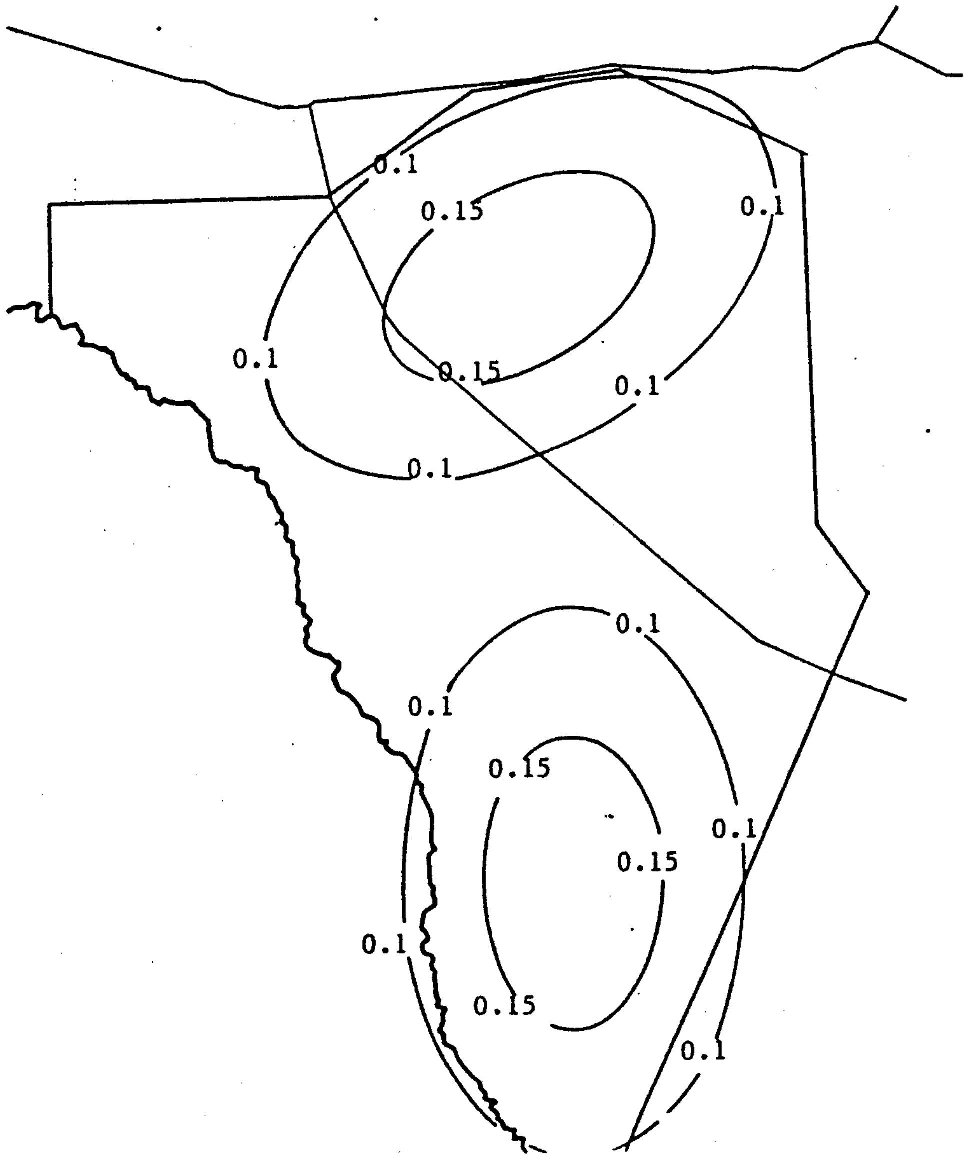


Figure 54. Predicted Booms/Day in Valentine MOA.

REFERENCES

1. Final Environmental Impact Statement, "Supersonic Flight Operations in the Reserve Military Operations Area – Holloman AFB, New Mexico", 1984.

2. Final Environmental Impact Statement, "Supersonic Flight Operations in the Valentine Military Operations Area – Holloman AFB, New Mexico", 1984.

3. Galloway, W.J., "Development of C-Weighted Day-Night Average Sound Level Contours for F-15 Air Combat Maneuvering Areas", BBN Report 4430, August 1980.

4. "Sonic Boom Measuring Program, Reserve MOA", Wyle Research Report WR 85-29, January 1986.

5. Lee, R.A., Mazurek, D., and Palmer, B., "Boom Event Analyzer Recorder (BEAR) Operators Manual", AAMRL/BBE, WPAFB, OH, September 1987.

6. "Instrumentation for the Measurement of Sonic Booms", Wyle Research Report WR 85-31, March 1986.

7. St. Clair, M., and Rostamizadeh, A., "Data Reduction User Guide for Mission Standard Data Reduction Programs", Cubic Corporation, San Diego, CA, December 1981.

8. "Assessment of Community Response to High-Energy Impulsive Sounds", National Research Council, Committee on Hearing, Bioacoustics, and Biomechanics, 1981.

9. Appendix C, ANSI S1.4 (1983), American National Standard Specification for Sound Level Meters.

10. Galloway, W.J., "Studies to Improve Environmental Assessments of Sonic Booms Produced During Air Combat Maneuvering", AFAMRL-TR-83-078, October 1983.

11. Plotkin, K.J., "Sonic Boom Prediction Model for Supersonic Flight Corridors", Wyle Research Report WR 85-25, August 1985.

12. Lee, R.A., "Air Force Boom Event Analyzer Recorder (BEAR): Comparison With NASA Boom Measurement System", AAMRL-TR-89-039, July 1988.

13. Lee, R.A., "Sonic Booms Produced by USAF and USN Aircraft: Measured Data", AAMRL-TR, to be published.

14. Plotkin, K.J., "Focus Boom Footprints for Various Air Force Supersonic Operations", Wyle Research Report WR 85-22, 1985.

15. Galloway, W.J., "Preliminary Test Plan for Assessment of Average Sound Levels From Supersonic Air Combat Maneuvering", September 1987.

16. St. John, R.C., and Draper, N.R., "D–Optimality for Regression Designs: A Review", *Technometrics*, *17* (1), February 1975, 15-23.

References (Continued)

17. Box, M.J., and Draper, N.R., "Factorial Designs, the |X'X| Criterion, and Some Related Matters", *Technometrics, 13* (4), November 1971, 731-742.

18. Smith, K., "On the Standard Deviations of Adjusted and Interpolated Values of an Observed Polynomial Function and its Constants and the Guidance They Give Towards a Proper Choice of the Distribution of Observations", *Biometrika, 12*, 1918, 1-85.

19. Federer, W.T., *et al.*, "Some Techniques for Constructing Mutually Orthogonal Latin Squares", The University of Wisconsin Mathematics Research Center, MRC Technical Summary Report #1030, June 1971.

20. Carlson, H.W., "Simplified Sonic Boom Prediction", NASA Technical Paper 1122, 1978

21. Wilby, E., Horonjeff, R., and Bishop, D., "User's Guide to MOAOPS and Boom-Map Computer Programs for Sonic Boom Research", HSD-TR-87-004, May 1987.

22. Bishop, D.E., Haber, J.M., and Wilby, E.G., "BOOMAP2 Computer Program for Sonic Boom Research: Technical Report", BBN Report 6487, November 1987.

23. McDevitt, M., "User's Guide of Aircraft Design Selection Procedure", McDonnell Douglas Report A4692, February 1977.

24. Mitchell, T.J., "An Algorithm for the Construction of 'D-Optimal" Designs", *Technometrics, 16* (2), May 1974, 203-210.

25. Mitchell, T.J., "Computer Construction of 'D-Optimal' First-Order Designs", *Technometrics, 16* (2), May 1974, 211-220.

26. Draper, N.R., and Mitchell, T.J., private communication, December 1987.

27. Desai, V.R., Lucas, M.J., and Moulton, C.L., "Software Developed to Support Sonic Boom Measurements at White Sands Missile Range", Wyle Research Technical Note TN 89-14, December 1989.

28. Brown, R., and Moulton, C., "Data Accumulation and Field Servicing Procedures for the White Sands Missile Range Sonic Boom Study", Wyle Research Technical Note TN 88-9(R), September 1988.

29. "Data Collected During Measurements of ACM Sonic Booms at White Sands Missile Range", Wyle Research Technical Note TN 89-15, December 1989.

30. Plotkin, K.J., "Sonic Boom Focus Conditions Due to Tactical Air Operations", Wyle Research Report WR 84-8, February 1984.

31. Plotkin, K.J., "Potential Sonic Boom Focal Zones From Space Shuttle Reentry", Wyle Research Report WR 89-11, July 1989.

References (Continued)

32. Taylor, A.D., "The TRAPS Sonic Boom Program", NOAA Technical Memorandum ERL-87, July 1980.

33. "White Sands Missile Range, New Mexico, Range Reference Atmosphere", Document 365-83, Range Commander's Council, White Sands, New Mexico, August 1983.

34. Pierce, A.D., and Maglieri, D.J., "Effects of Atmospheric Irregularities on Sonic Boom Propagation", *JASA*, *51* (2), February 1972, 702–721.