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TOPICAL REPORT

Develop the Application of a Digital Memory Acoustic Emission System to Aircraft Flaw Monitoring

P. H. Hutton
J. R. Skorpik

December 1978

Prepared for
Advanced Research Projects Agency
under ARPA No. 3476, Code 7DLO
and BNW No. 300A01137

Pacific Northwest Laboratory
Operated for the U.S. Department of Energy
by Battelle Memorial Institute

Battelle

PNL-2873

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PACIFIC NORTHWEST LABORATORY
operated by
BATTELLE
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UNITED STATES DEPARTMENT OF ENERGY
Under Contract EY-76-C-06-1830

Printed in the United States of America
Available from
National Technical Information Service
United States Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22151

Price: Printed Copy $____*; Microfiche $3.00

*Pages	NTIS Selling Price
001-025	$4.00
026-050	$4.50
051-075	$5.25
076-100	$6.00
101-125	$6.50
126-150	$7.25
151-175	$8.00
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201-225	$9.25
226-250	$9.50
251-275	$10.75
276-300	$11.00

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EXECTUIVE SUMMARY

This program was funded by the U.S. Defense Advanced Research Projects Agency for application to a Royal Australian Air Force aircraft. Arrangements were through The Technical Cooperative Program. The purpose of the program is to evaluate the use of the acoustic emission (AE) technique to provide a definitive continuous monitor of fatigue crack growth in a critical aircraft structural member.

The program started in September, 1977, with Phase I consisting of defining technical and procedural details and developing and fabricating an AE monitor system. A unique AE monitoring system was fabricated and laboratory tested. It utilizes a source isolation feature to distinguish AE signals originating from an identified area of interest. Two parameters of AE information are recorded on one solid state digital memory for later retrieval and analysis. Phase I was completed in April, 1978.

Phase 2 was concerned with installing and testing the AE monitoring system in an aircraft. Installation was made in RAAF Macchi 326 aircraft A7-201 during a major maintenance overhaul. The system is monitoring AE from fatigue cracks in a fastener hole in the tension member of the wing structure center section continuously during flight. Installation was completed in August, 1978, with four test flights to evaluate system performance and make necessary adjustments.

Battelle Northwest is providing follow-up support to the Australian Aeronautical Research Laboratory (ARL) on this program under a continuing Phase 3.

This support includes assistance in data analysis and correction of any AE system problems. Evaluation of data from the first 25 flights shows that background noise and transient signals are not a problem, that the character of the data is rational and that the AE is influenced by the type of flying--i.e., low level, formation, aerobatics, etc. Evaluation of correlation between AE and crack growth will require at least a year of data gathering to assimilate sufficient crack growth data points.

A functional problem which developed with the digital memory readout instrument (separate from the onboard monitor system) is being attended to by Battelle Northwest.

Australian ARL and RAAF personnel have provided outstanding cooperation and assistance in the course of this program.

LIST OF FIGURES

TOPICAL REPORT

DEVELOP THE APPLICATION OF A DIGITAL MEMORY ACOUSTIC EMISSION SYSTEM TO AIRCRAFT FLAW MONTIORING

INTRODUCTION

Acoustic emission is an emerging nondestructive testing technique which operates on the basis of detecting stress waves produced by deformation and cracking in a solid material. As a solid material deforms and cracks, energy is released, part of which produces elastic stress waves that propagate through the material. These stress waves can be detected at the material surface through the use of piezoelectric sensors. The resulting electrical analog signal is then processed to produce a count of the number of signals, signal energy, etc. Acoustic emission (AE) offers two unique features for flaw surveillance--the capability to detect and locate crack growth as it occurs and the capability for long term continuous surveillance.

Most of the application development work on AE over the past 10 years has been directed toward large stationary structures such as nuclear reactor systems. There has been relatively limited work concerning application to aircraft. Lockheed-Georgia (Mr. Cliff Bailey) has had an active program to apply AE to the C5A transport.[1] Captain John Rogers, USAF, McClellan Air Force Base, California, has conducted work of an experimental/analytical nature relative to potential application to the F-105 aircraft. Grumman Aerospace Corporation (C. R. Horak and A. F. Weyhreter) has worked in the area of monitoring aircraft subassemblies in ground tests.[2] Dr. Stuart McBride, Canadian Royal Military College, has been active in a program to monitor a transport type aircraft. To the best of the authors' knowledge, the program discussed in this report is the first designed to develop, fabricate and use in-flight a miniaturized AE monitor system for a small, relatively high performance jet aircraft such as the Royal Australian Air Force (RAAF) Macchi MB 326 jet trainer.

This program was initiated in September, 1977, under sponsorship of the U.S. Defense Advanced Research Projects Agency. The purpose was to develop and apply an AE monitor system to monitor fatigue crack growth in a tension member of the wing structure in a RAAF Macchi MB 326 jet trainer plane. Application of the AE system to the RAAF aircraft was by prior arrangement between the United States and Australian defense departments. The Macchi aircraft has a well characterized generic problem of developing fatigue cracks at fastener holes in the tension member of the wing structure center section. Surveillance of these cracks is presently done periodically by ultrasonic and magnetic rubber methods. Both methods require some disassembly of the aircraft for application. A potential benefit from AE is to provide a continuous monitor of fatigue crack growth wherein the AE data can hopefully be correlated with the amount of crack growth.

This program is comprised of three basic phases:

(1) Develop a special purpose AE monitor system to meet functional requirements and physical limitations for installation in the Macchi aircraft.

(2) Install the AE system in the aircraft and test its performance.

(3) Provide follow-up support to the Australian Aeronautical Research Laboratory (ARL) in collection and analysis of data.

The balance of the report will discuss results and accomplishments in these three phases.

SUMMARY

The program started in September, 1977. Phase 1 was initiated with a visit to ARL by the project manager to establish specific technical and procedural requirements for system design and installation. A unique AE monitoring concept compatible with in-flight monitoring requirements was developed, fabricated and laboratory tested. This included sensors, preamplifiers and the monitor/recording unit. The system utilizes a source isolation approach to identify AE signals originating from an identified area of interest in a structure. Two parameters of the AE information are recorded on one solid state digital memory for later retrieval for analysis. System power and initiation of programming of data into the digital memories are automatic functions derived from start-up of the aircraft primary power supply. The only manual operation required for in-flight monitoring is insertion of a digital memory prior to flight and removal of the memory at the end of the flight for data readout. Phase 1 was completed in April, 1978.

In Phase 2, AE sensors, preamplifiers and sensor mounting adhesive were shipped to ARL in May, 1978. ARL personnel mounted these components on the aircraft as specified by BNW and necessary cabling was run during periodic aircraft maintenance overhaul. The sensors are mounted to monitor a fastener hole with identified fatigue cracking initiated. The AE monitor/recorder unit was installed in the aircraft and the system functionally tested by BNW staff members in August, 1978, with assistance from ARL personnel. Four test flights were completed and the resulting data evaluated as part of the system testing

Phase 3 is continuing with completion currently scheduled for February 28, 1979. In-flight data from the four initial test flights, plus 21 operational flights has been compiled and evaluated. Conclusions which can be derived at this time are:

A. The monitor system is functioning as designed. The source isolation feature appears to be effectively identifying signals originating at the fastener holes of interest and data is being properly recorded in the digital memories.

B. The potential problem of stray transient signals (electrical and mechanical in origin) invading the AE data has been effectively forestalled by system design.

C. There are no evident effects on system performance from environmental extremes in temperature, pressure and "g" forces.

Any conclusive evaluation of correlation between AE data and fatigue crack growth will require an extended period (probably 1 to 1-½ years) of operational data.

DISCUSSION

The Macchi 326 aircraft shown in Figure 1 is used by the Royal Australian Air Force (RAAF) as a trainer plane. It is afflicted with a well characterized generic problem of developing fatigue cracks in fastener holes in the tension member of the center section of the wing structure (Figure 2). The material is 4340 steel. The two holes marked "3" and "20" in Figure 2 are the primary offenders. They are located in a stress concentration region just inboard of a change in section of the tension member. Fatigue cracks develop in the inside surface of these holes after about 2000 hours of flying time. Over about the next 1500 hours of flying time, the cracks grow to the point where safety considerations require replacement of the structure. Average flying hours per year for this aircraft in its present role as a jet trainer is about 400.

Surveillance methods resently being employed to monitor crack growth are ultrasonics and magnetic rubber. Replications of the inside surface of the holes are made using magnetic rubber every 100 hours of flying time. Surface crack length and an inferred crack depth are determined from this. The fastener holes are examined every 400 hours of flying time using ultrasonic methods. Application of either of these inspection methods requires some amount of disassembly of aircraft components.

The acoustic emission (AE) method for flaw detection and surveillance offers the potential for continuous monitoring of these fatigue cracks to indicate crack growth and identify an impending failure condition. The effort discussed in this report is an AE qualification experiment to determine: (a) if meaningful AE data from fatigue crack growth in the fastener holes can be identified during in-flight environment, and (b) if

Figure 1. RAAF Macchi 326 Two Place Jet Trainer.

the resulting data can be correlated with crack growth rate or amount of crack growth. This program, wherein the work is funded by the U.S. Advanced Research Projects Agency for application to an Australian RAAF plane was arranged through The Technical Cooperation Program. This is an international defense cooperative advisory body.

PHASE 1: DEVELOP A SPECIAL PURPOSE AE MONITOR SYSTEM

As the first step in Phase 1, the BNW project manager visited the Aeronautical Research Lab (ARL), the Commonwealth Aircraft Corporation (CAC) and the Royal Australian Air Force (RAAF) in Melbourne, Australia in October, 1977 to identify specific technical and procedural requirements. The results of this visit can be summarized as follows:

(1) Two sets of holes (#3 and #20) penetrating the tension member flanges of the center wing section were identified as the primary cracking sites (Figure 2). AE monitoring will be limited to one set of these holes. This will allow evaluation of the application of AE to monitor crack growth in the tension member while minimizing investment in instrumentation during the evaluation stage.

(2) Two AE sensors will be used mounted on the web of the channel tension member with the holes to be monitored located between the sensors.

(3) Preamplifiers (one for each sensor) will be mounted on a metal tray existing below the hydraulic cylinder which operates the air brake. Dimensions of the preamplifiers will be limited to 1-1/2 x 2-1/2 x 4 inches (38 x 64 x 102 mm). Physical mounting of the preamplifiers will be defined by ARL and CAC.

(4) The AE monitor unit containing AE data processing and recording circuitry plus the digitial memory units will be mounted in the front cockpit, right hand console in the position reserved for the I.F.F. control panel. The monitor unit case will have an integral flange with pilot holes to match the fastener holes at this location.

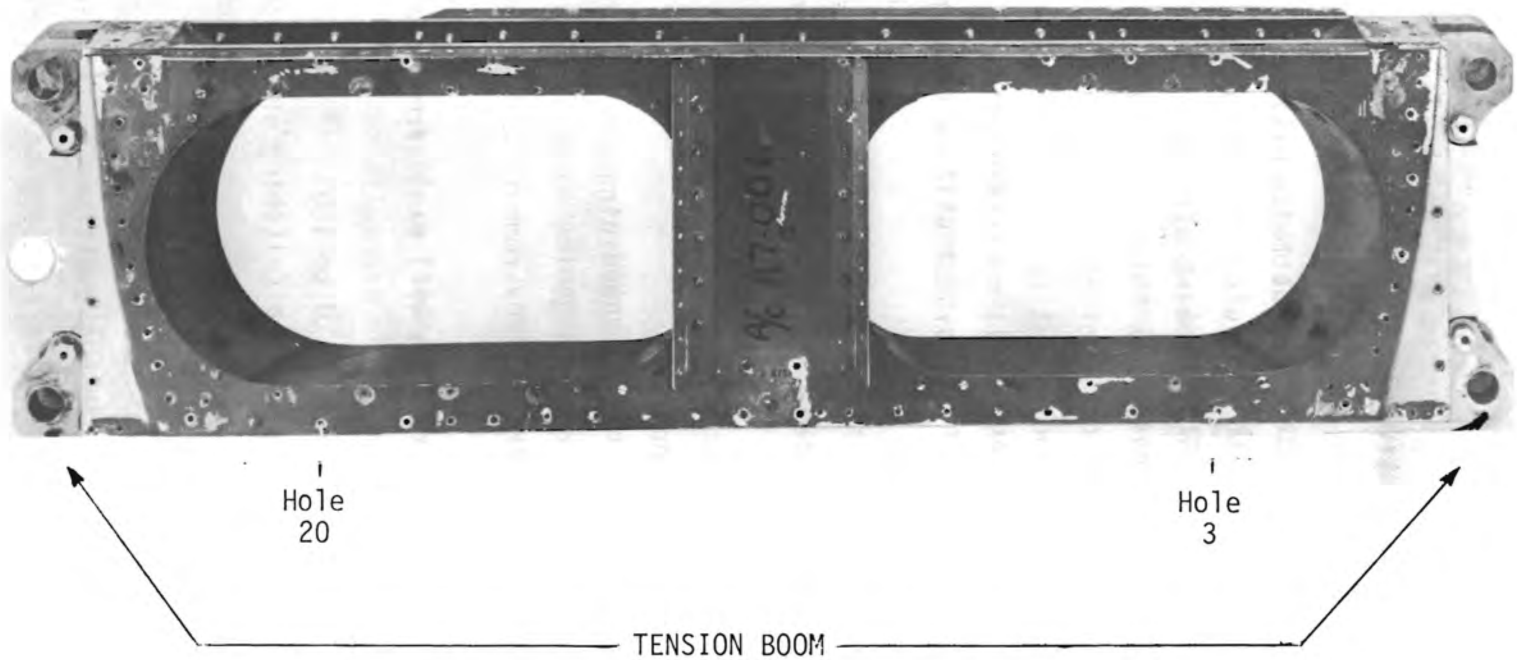


Figure 2. Center Wing Section - Macchi 326 Aircraft.

The digital memory will be located on the front face of the monitor unit with a protective cover. This will facilitate easy removal and replacement of the memories.

(5) Power to the AE monitor system will be the aircraft 115V-3 phase-400 Hz power supply.

(6) At the earliest possible date, Battelle will provide for approval a "black box" drawing in preparation for system installation. This drawing will show all components of the AE system in "black box" form giving physical dimensions, weight and a complete description of input and output requirements for each componenet. Once approved, all necessary interconnecting wiring for the AE system will be performed by CAC.

(7) The AE system must be designed for the following requirements:

- 8 g max. operational load
- Cases must be capable of containing all components under a force up to 25 g.
- Uncontrolled temperature environment will range from -50 to +50°C.
- Uncontrolled air pressure will range from 1 to 0.25 atmospheres
- Humidity will range from 20 to 100%
- Automatic operation with no switching or manipulation required of the pilot.

(8) After installation, a hand-held pulser will be used to setup and evaluate the AE monitor. A small cover plate in the outer skin can be removed for necessary access to the tension member.

(9) It was agreed that ARL would obtain a measurement of jet engine noise during engine run up on the ground. This

would provide some measure of the potential for this noise source to present a problem to AE monitoring.

An informal meeting held January 12-13, 1978, near McClellan Air Force Base, California also provided useful information for this program. The purpose was an informal exchange of technical information and discussion among those directly concerned with AE monitoring of aircraft structures. The following were represented:

- Canadian Defense Headquarters
- Lockheed-Georgia
- Battelle-Northwest
- Canadian Royal Military College
- Grumman Aerospace Corporation
- McClellan AFB
- Acoustic Emission Technology Corporation

Primary information items were:

(1) Engine noise did not appear to represent a problem. Both electrical and structure generated transients, however, could be a significant problem.

(2) A two-part acrylic adhesive (HYSOL EA9446) for sensor mounting and coupling has been tested in-flight. The results indicated that it is capable of withstanding the range of temperature and associated change in dimensions of metal parts.

(3) Lockheed-Georgia had experienced some problem with commercial preamplifiers breaking into oscillation during flight starting at about 20,000 feet. None of the other participants had experienced this phenomenon either in-flight or in test chamber simulation.

(4) Captain Rogers, McClellan AFB, expressed the

opinion based on his experience in laboratory testing 4340B modified steel that the most desirable frequency range for monitoring AE is 300 to 500 KHz. This helped support our original choice of 400 KHz ± about 25 KHz as a monitoring frequency.

In light of the requirements and peripheral information described above, consider now the development of the AE monitor system.

AE MONITOR SYSTEM

The onboard AE monitoring concept with defined hardware is depicted in the line drawing of Figure 3, which was supplied to ARL for Item 6 of program requirements discussed earlier. AE data is recorded on a time basis in a nonvolatile solid state digital memory. At the conclusion of a test flight, the memory is removed for interrogation in a separate instrument and after interrogation, the memory is erased and reused. These unique memories have a large data capacity (more than 66 million counts) and are ideal for compact continuous monitory applications. The photograph of Figure 4 shows the assembled system. The memory readout in the suitcase-type chassis has an integral printer for a hard copy of all test data.

Electronically, the monitor system functions as shown in the block diagram of Figure 5. Physically there are three separate functional items: (1) Sensor system; (2) Preamps, and (3) Monitor unit. The fourth major piece of hardware is the memory readout unit which is separate from the monitor system mounted on the aircraft.

Sensing System

The sensing system is composed of two Battelle-Northwest fabricated AE sensors with an integral Bruel and Kjaer miniature coax cable 508 mm long. The two sensors, labeled #2 and #4, are shown in Figure 6. A two-part acrylic adhesive (HYSOL EA9446) was chosen as the couplant. In-flight testing by Lockheed-Georgia indicated that the adhesive is capable of withstanding the required temperature and associated change in dimensions of metal parts. Due to the small size and weight of the sensors, no means of support other than the adhesive was required. The adhesive forms such

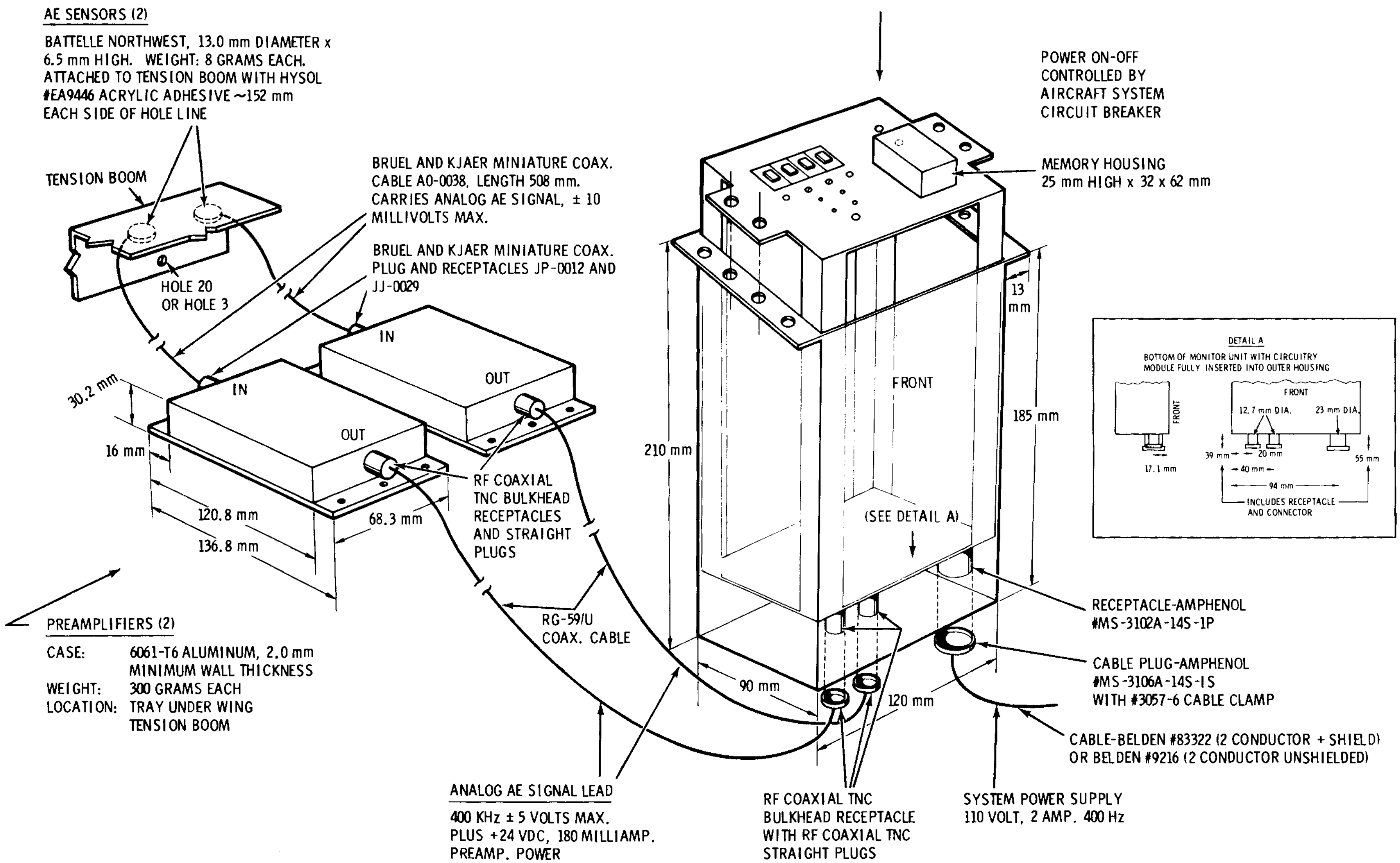


Figure 3. Specifications for Onboard Aircraft AE System

Figure 4. Complete AE Aircraft System.

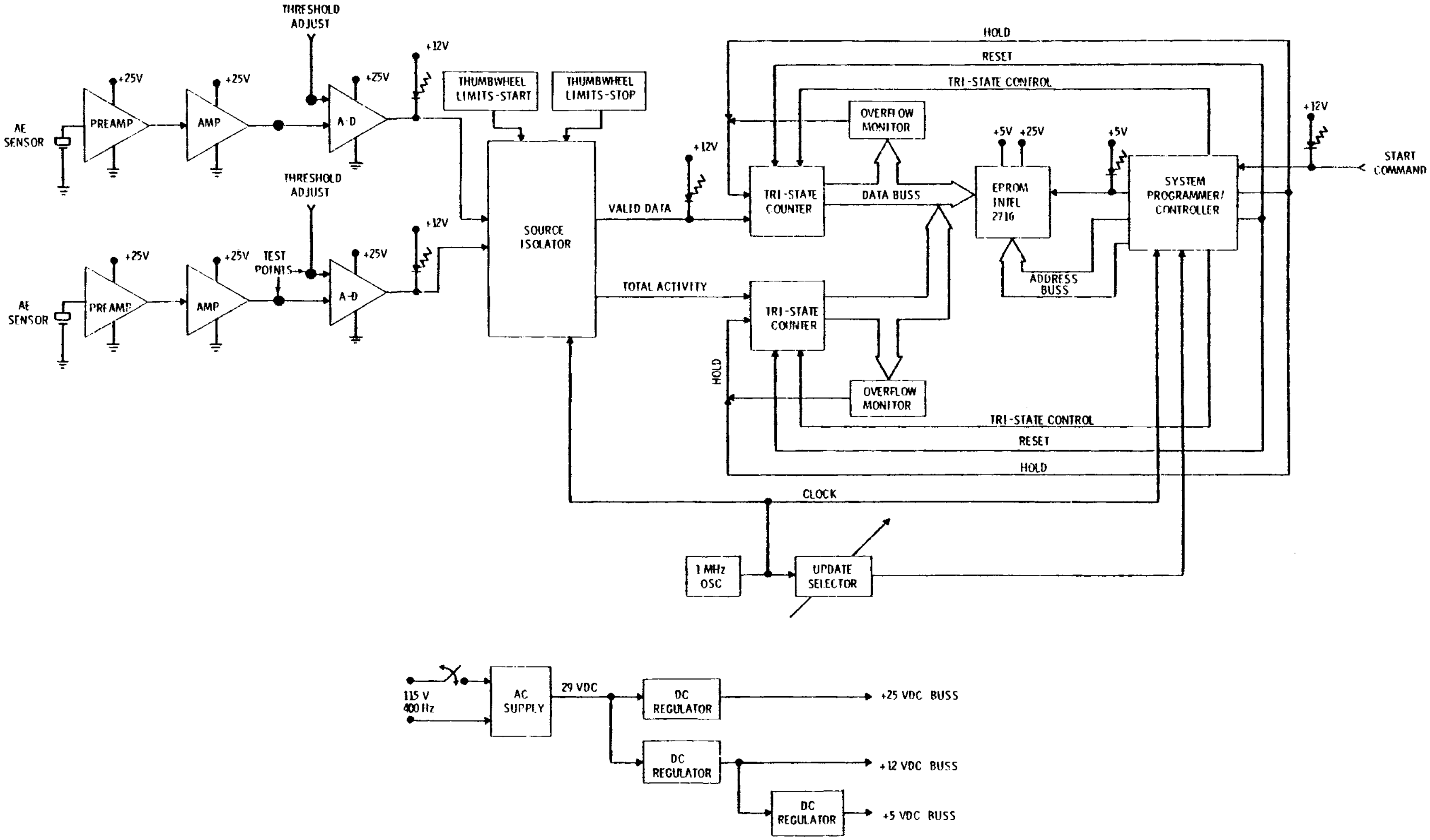


Figure 5. Block Diagram - Aircraft AE Monitor/Recorder.

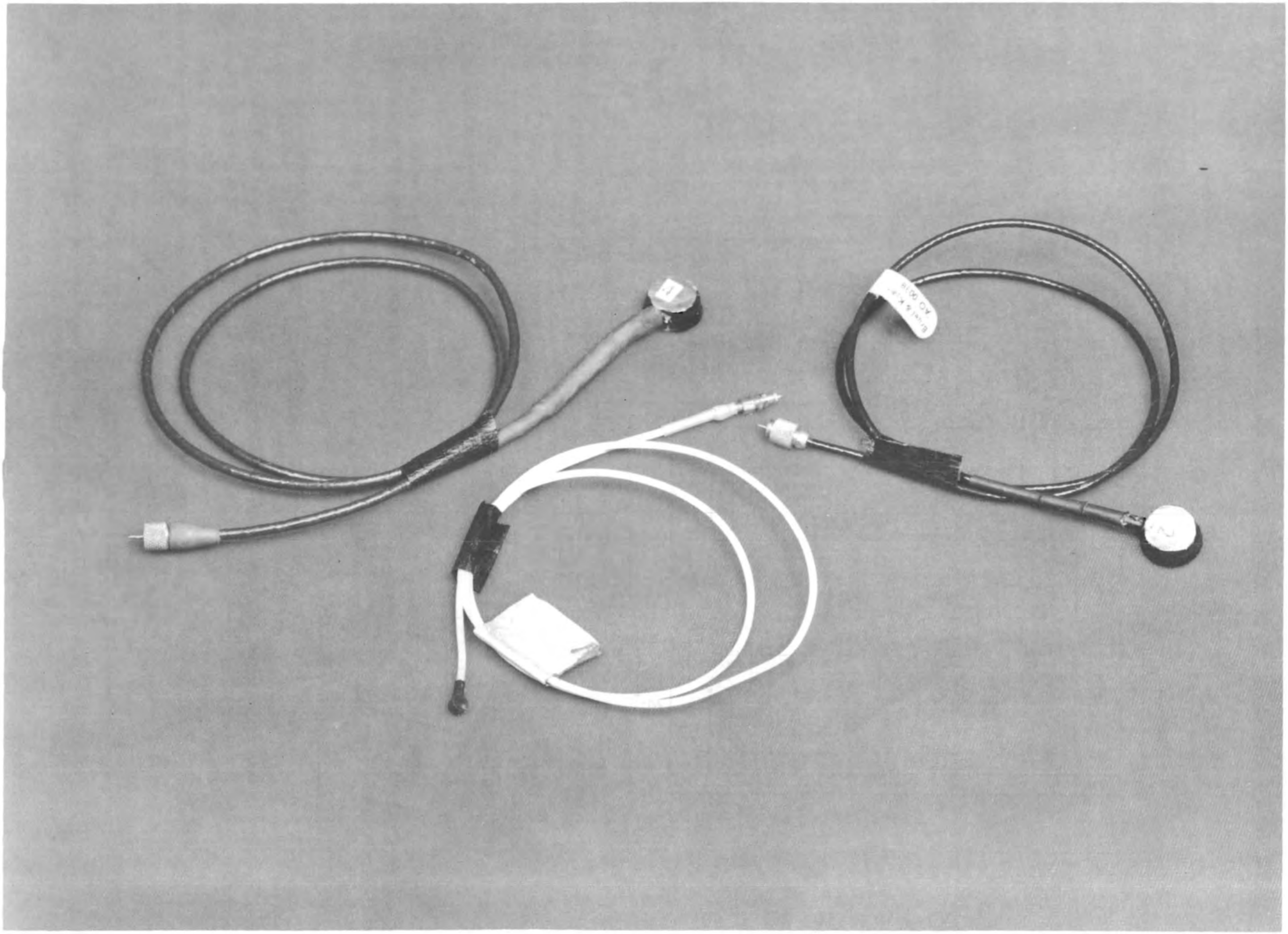


Figure 6. AE Sensors.

a strong bond that the sensors cannot be removed without damage.

Preamplifiers

The system has two identical preamps shown in Figure 7, which are housed in aluminum cases and mounted near the two sensors. The preamps each have two stages of 400 KHz tuning with double buffered outputs for circuit isolation. Input impedance is high to prevent sensor loading and output impedance low for cable driving and noise immunity. Overall gain is 63 dB with a tuned circuit Q of 13. The preamps are operated single sided from +25 VDC, which resides on a separate shielded wire.

The preamps also have an inductor to ground on their inputs for sensor response shaping. Its effect is to discriminate against low frequency signals. Effectively, the system has no significant response below about 200 KHz. Each input is diode protected in the event of large magnitude transients. The jet engine noise spectrum in Figure 8 which was supplied to us by ARL (Item 9 of system and procedure requirements) supports the choice of 400 KHz tuned monitoring frequency with discrimination against low frequencies.

AE Monitor

The acoustic emission monitor unit itself is shown in Figures 9 and 10. Figure 9 shows the position of the digital memory which can easily be removed due to special features of the zero force insertion socket. The memory is physically protected by a metal cover. The monitor unit contains four functional parts: (1) signal processor; (2) source isolator; (3) digital recorder, and (4) system power supply. These four items are shown as part of the system block diagram of Figure 5.

Signal Processors

There are two identical signal processors in the instrument corresponding to the two sensor array. The channel processors are required for further signal amplification and signal conversion from analog to digital form. Each processor has a single stage of fixed gain ($\sim$23 dB) followed by an analog comparator for digital conversion. The DC level of conversion is adjustable by means of a front-panel screw driver slotted pontentiometer. Each analog stage is decoupled from the DC power buss and thus, from each other by a RC network. The processor stage was intended to be simple due

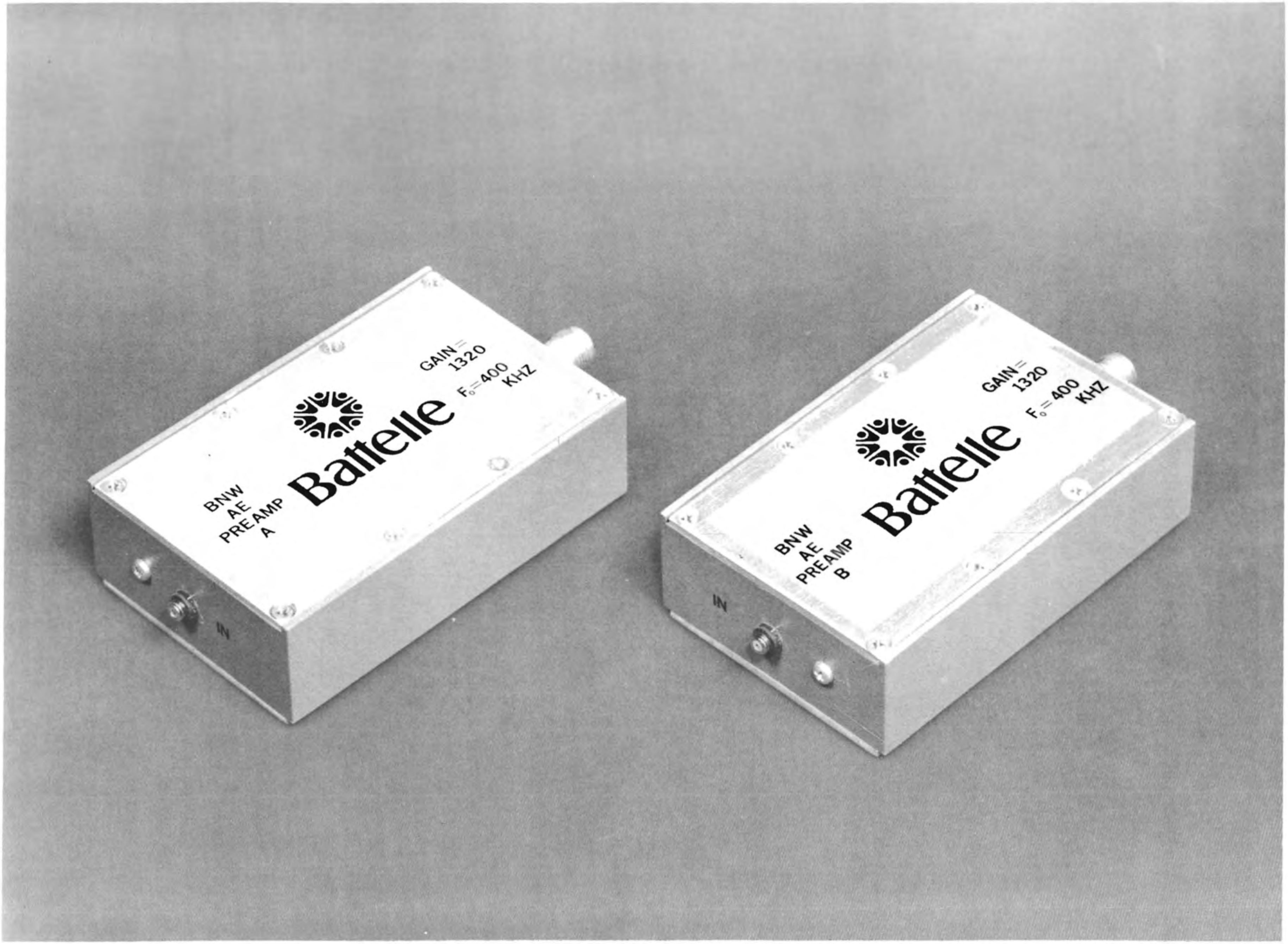
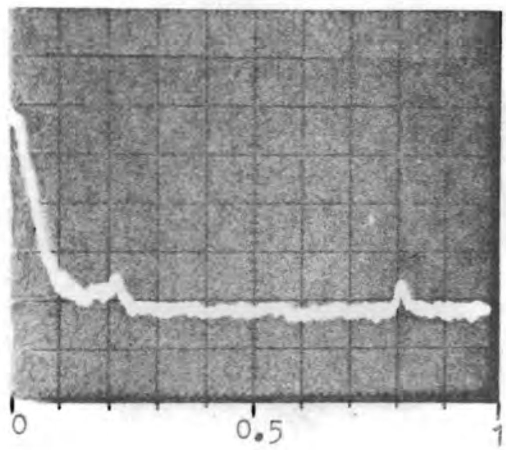
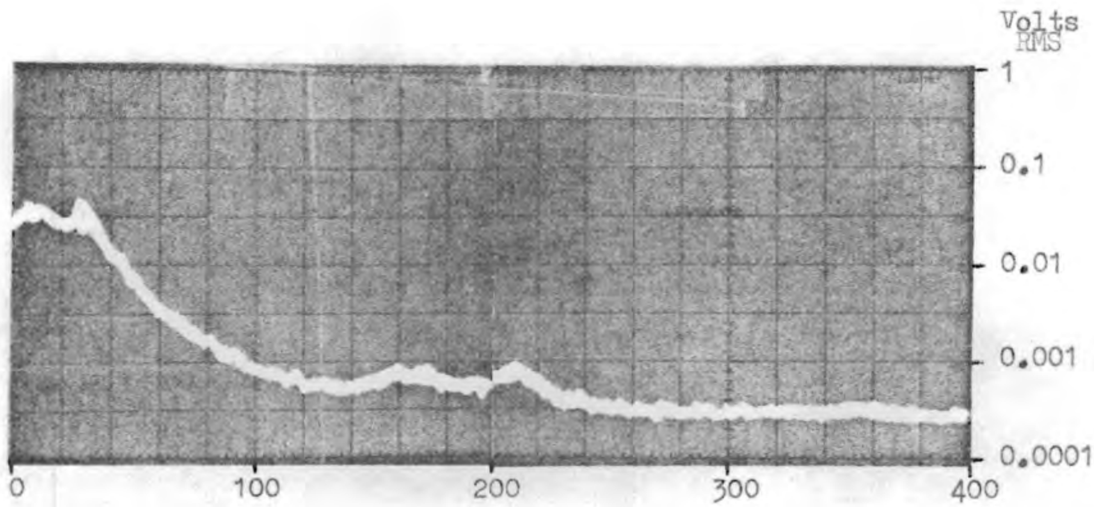


Figure 7. AE Preamplifiers.



Frequency - MHz



Frequency - KHz

System Gain - 55 dB

Figure 8. Noise Spectrum - Macchi 326 Aircraft Operating at Full Take-Off Power.

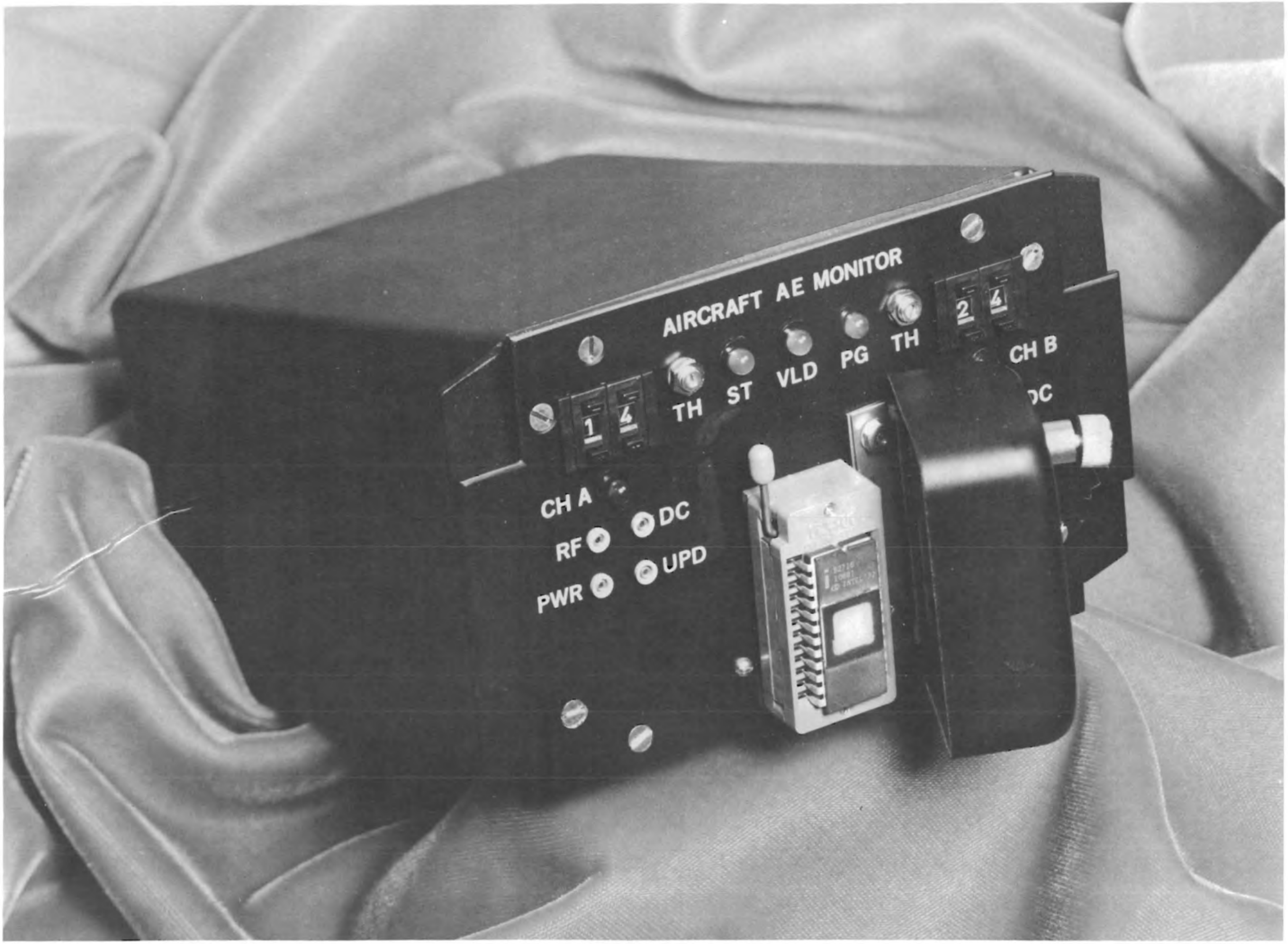


Figure 9. Aircraft AE Monitor.

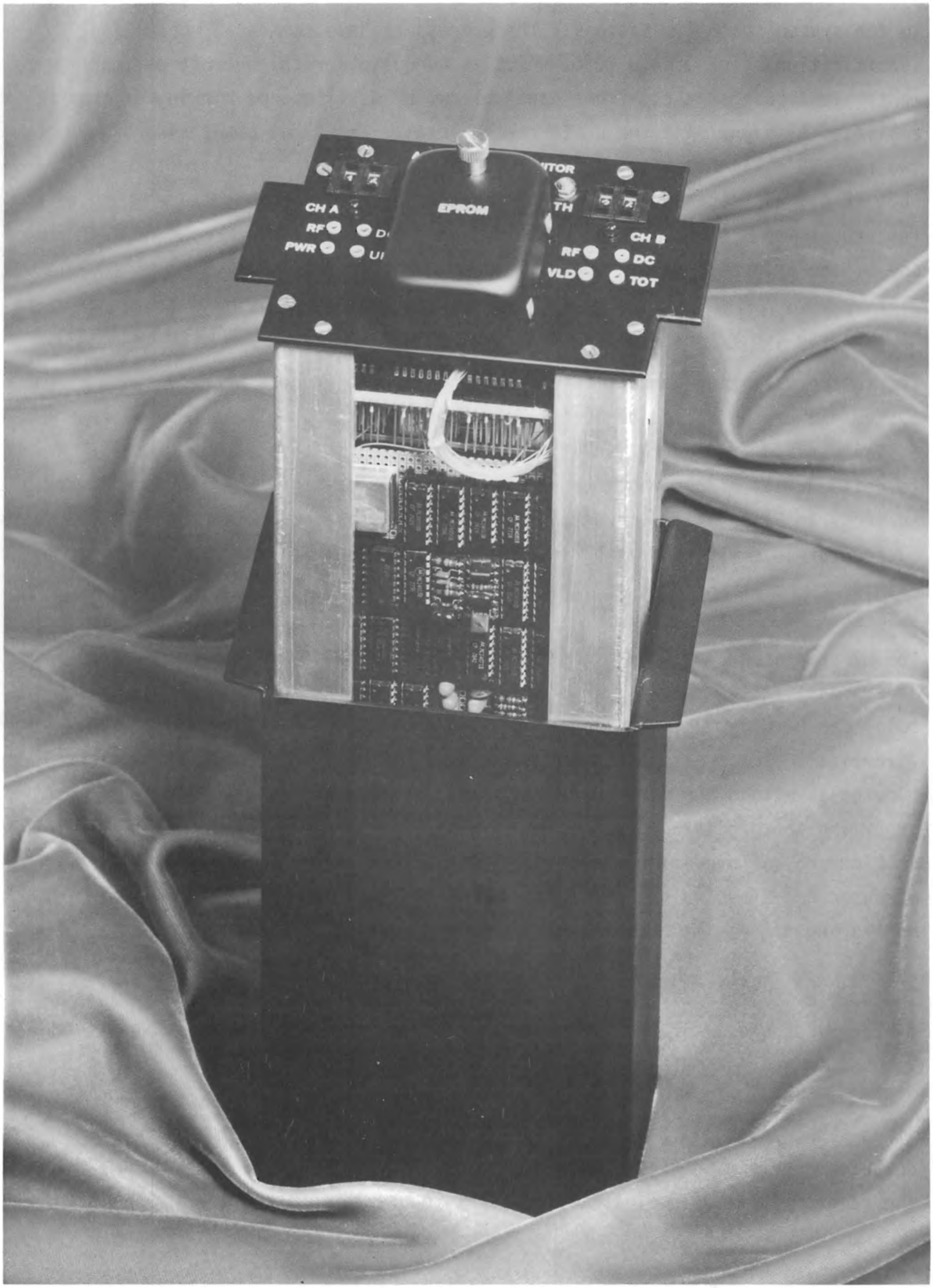


Figure 10. Aircraft AE Monitor Partially Removed.

to the system space limitations. The processors have commercial operating specifications from 0°C to 70°C, which is adequate for the cockpit environment. Test points on the front panel allow for oscilloscope viewing of the amplified AE signal and the DC threshold level. The front panel also has two red LED's (light emitting diodes)--one for each channel--to indicate when AE signals rise above the set DC threshold level and hence, are accepted for processing. The LED's can be turned off by a slide switch mounted on one of the internal circuit boards.

Source Isolation

The source isolation concept is a spacial filtering process whereby the system can be controlled to accept only signals which originate from a predefined area. The source isolation principle used in this application is to define a set of hyperbola boundaries which contain the area to be monitored, as shown in Figure 11. A hyperbola is defined as a plane curve generated by a point so moving that the difference of the distance from two fixed points is a constant.

The hyperbolas are defined by measuring difference in time (Δt) of arrival of a signal at two sensors. For any two-sensor system, a family of hyperbolas can be drawn which will satisfy all the possible differences in time of arrival. The system electronics are set to accept only Δt's which define hyperbolas within the desired limits. The Δt measurements are made by analyzing the digital outputs of the analog-to-digital comparators (A-D in Figure 5). The desired hyperbola limits are established in terms of microseconds Δt using two sets of front panel thumbwheel switches while monitoring artificial AE pulses injected at the area of interest.

The source isolation system has a fixed lockout of four milliseconds initiated by the first sensor of the array that detects an AE signal. The lockout time is used to prevent multiple processing of the same AE signal.

A two-sensor source isolation method is suitable for the application being considered here with the tension member being columnar in configuration. In the case of a flat plate, it is necessary to use three sensors.

Digital Recorder

The digital recorder portion has the function of counting AE signals and storing this count information into a digital memory. After programming (0.1 seconds), a new counting period is started and the memory advanced to a new address location. All digital logic is built with CMOS (complementary metal oxide semiconductor) integrated circuits for superior low power drain and electrical noise rejection. Operating range is from -40°C to 85°C. The digital recorder has three specific sub-systems:

- Timer
- Digital AE Counters
- Memory Programmer

Timer. The timer establishes the data counting periods which are known as system "updates". A 1 MHz crystal controlled oscillator is used as the reference and divided down digitally to provide eight possible update selections. The updates range from eight seconds to 72 minutes and are selected by the operator prior to starting the test with an internal onboard dip switch.

Digital AE Counters. The digital counters totalize the AE data over each update period. The two AE parameters that are totalized are total acoustic activity and valid AE. The valid AE is that data which satisfies the requirements of the source isolator and is primarily the data of interest. Total acoustic activity is a count of all acoustic signals detected without source restriction. The total activity will consist of both valid data and extraneous noise sources. This provides a reference from which to judge the effectiveness of the source isolation and it also gives an indication if a noise source is masking valid AE data by occupying most or all of the instrument processing time. Total activity is related to the array itself and not to any specific sensor.

The two identical sets of digital counters are overflow limited to a maximum of 61,440 counts for each specific update period. At the end of each update period, incoming data is locked out for 0.1 seconds while the memory is programmed. The counters then reset and a new counting period is started.

Memory Programmer. The memory programmer is the heart of the digital recorder portion. Both AE parameters are stored in a single digital memory of the type shown in Figure 12. The memory is unique in that it will retain

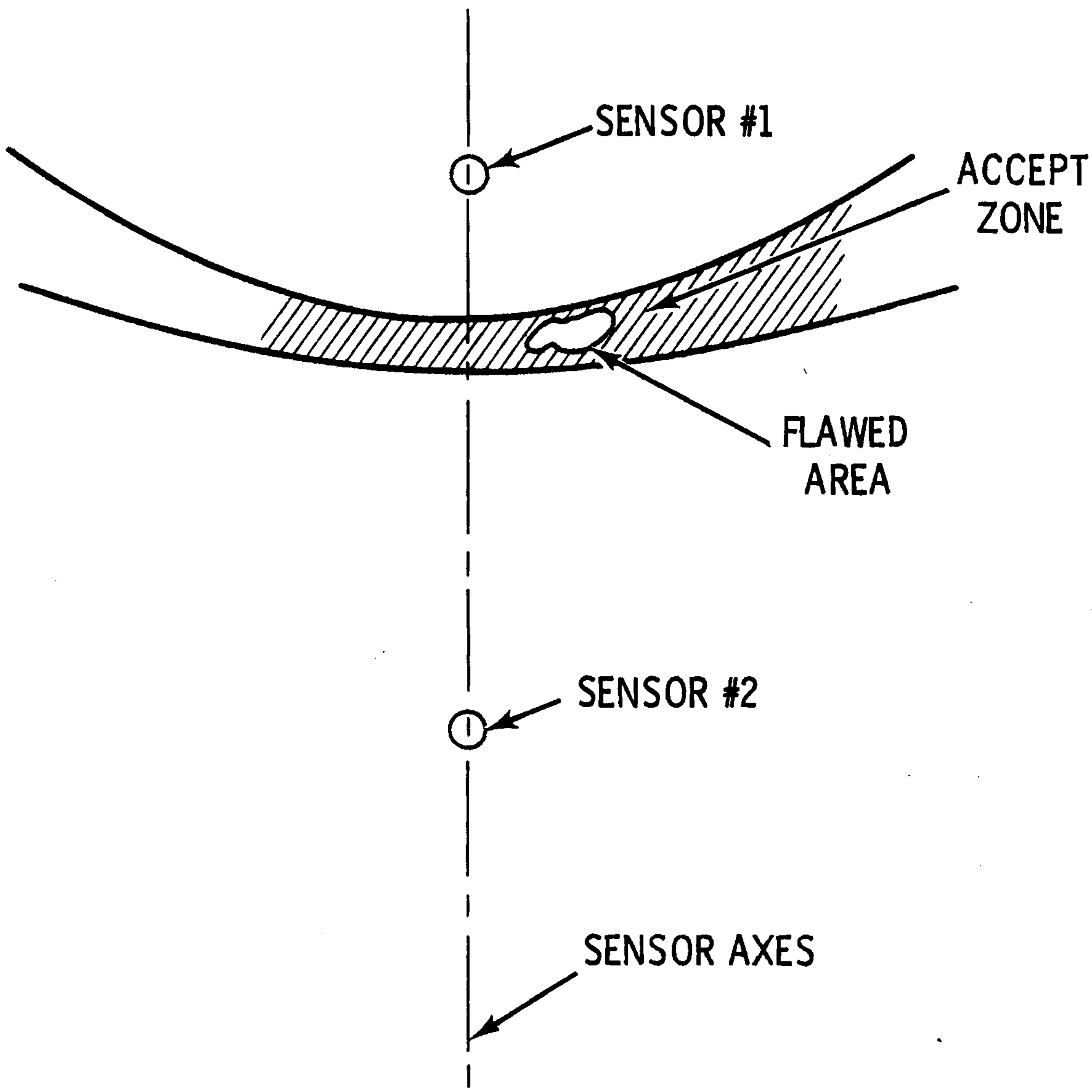


Figure 11. Principle of Source Isolation.

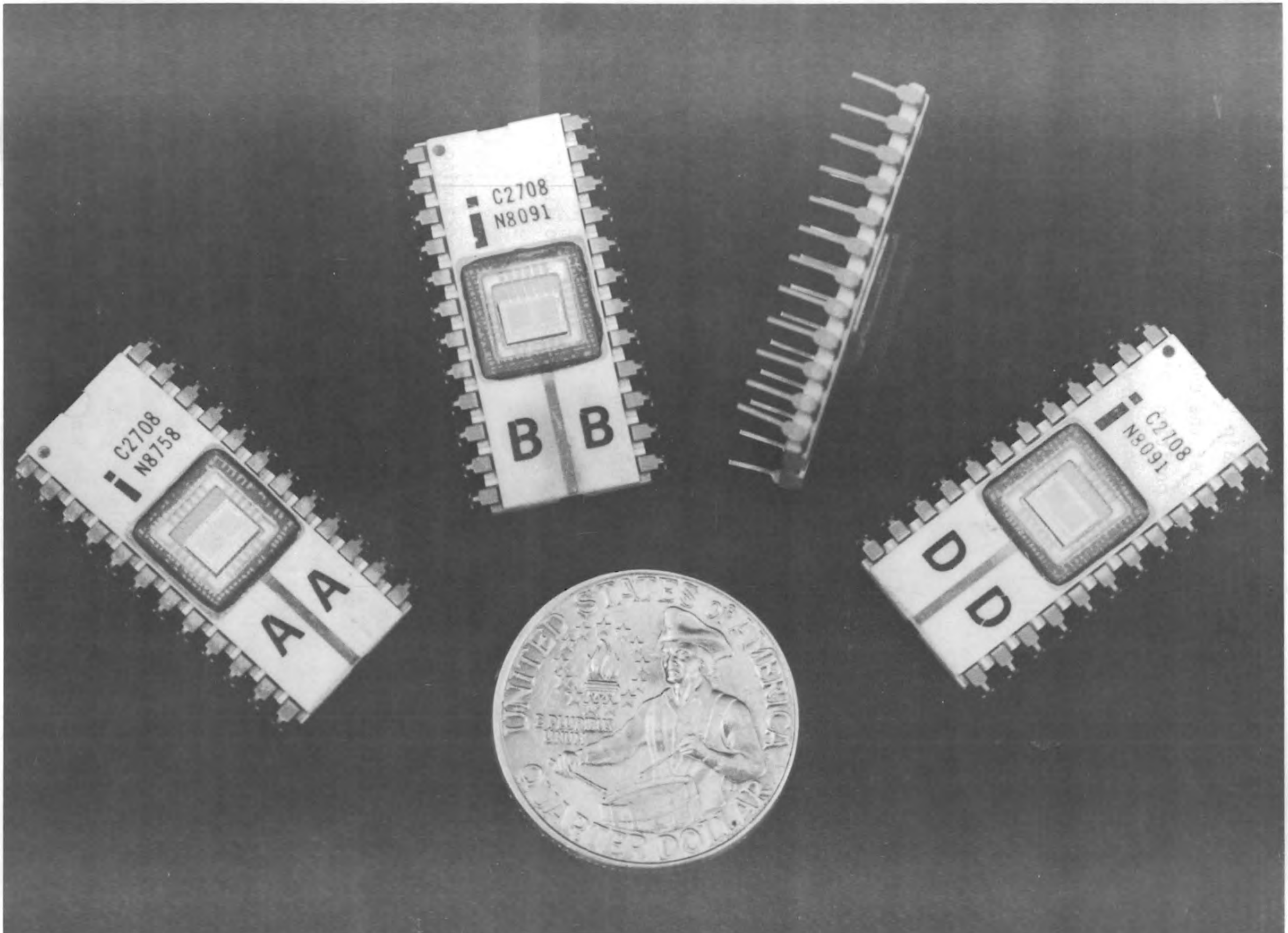


Figure 12. Solid State Digital Memories.

information without system power until intentionally erased by exposure to ultraviolet light. The memory has a capacity of storing 1024 different counting periods. The first half will contain "valid" AE data and the last half "total activity" data. For example, at the end of the first update, valid data will be programmed in memory position "0" and total activity in position "512". Each update requires two memory locations to be programmed for each AE parameter. This is because each memory location can accommodate only eight bits of digital data which equates to 255 possible counts. This is six bits short of the 61,440 limit desired. Thus, two specific memory locations are used for each quantity of data requiring a total of four memory programs for each update.

The memory is relatively easy to program in that it requires only a single TTL, 50 millisecond pulse. However, a 25 volt bias is required for charge transfer during programming. For temperature stability the programming pulse width is obtained by counting a crystal oscillator rather than using a RC controlled monostable. The memory is housed in a zero-force insertion socket on the front panel to facilitate easy insertion and removal. The memory is a MOS device susceptible to static charges and should be stored in black conductive foam in transit situations. Memory type is from Intel Corporation, Model 2716 and has an operating range from 0°C to 70°C. The memory is protected on the front panel by a hinged housing. The housing also activates a DC power interlock to prevent insertion or removal of the memory with power "on".

Original monitor instrument design included a manual memory programming switch. Review of this by ARL and the RAAF, however, dictated that the function must be automatic for operational reasons. Thus, the system fabricated includes automatic programming. The automatic approach has the potential of altering previously programmed data in the solid state memories. Whenever system power is activated, memory programming always assumes the same starting point. Hence, if a new memory is not inserted into the unit after a test flight, the next test flight will mask or alter the original data by programming new data on the original data. Due to memory principle, the original data cannot be recovered and the data for that flight and the ensuing flight would be lost. Procedural control should serve to make the current approach workable for application feasibility evaluation. For any longer term routine application, however, a method should be developed which will inherently protect data stored in a memory.

Power Supply

The system power supply is shown as part of the block diagram in Figure 5. It consists of an AC to DC supply and three DC regulators. The AC supply is a 400 Hz to DC high efficiency model designed and tested to meet vibration, shock, humidity and altitude requirements of MIL-E-5400K. Input requirements are 115 V (rms) $\pm$ 20% and single phase frequency from 360 to 400 Hz. The 50 watt model has a rated output of 29 volts at 1.79 amps from -55°C to 100°C. The 29 volts are regulated down to: (1) +25 VDC for memory biasing and all analog circuitry; (2) +12 VDC for both analog biasing and the digital CMOS circuitry, and (3) +5 VDC for memory inputs and programming. The three DC regulators are mounted together on a single board of their own. Control of the system power On/Off is only through the front panel memory housing interlock. The interlock merely breaks the +29 VDC output line. The AC input is direct and is controlled by an aircraft system circuit breaker.

Memory Readout Unit

The memory readout unit shown as part of Figure 4, is packaged in a field-harden suitcase-type chassis 15 inches wide, 6.8 inches high and 20 inches deep (381 x 173 x 508 mm). Chassis weight is around 23 pounds (10.5 kg). Line voltages from 100 to 268 VAC in conjunction with line frequency from 48 to 400 Hz can be accommodated.

Data from the digital memory is read out using a microprocessor based system and bussed to an in-chassis digital panel printer for a hard copy. The microprocessor system is centered around the 8080 type CPU and handles all timing and clocking in addition to binary-to-BCD formating for printer compatibility. After inserting the memory into a front panel socket, all that is required is to depress a "start" switch for the automatic readout.

A sample printout for valid data is shown in Figure 13. Valid data is presented first in blocks of 25. At the start of each block the corresponding test update (memory address) will be printed and identified with a + sign on the far left. The printout will continue until an unprogrammed location is found or until the last possible valid update position is reached (number 511). At this point, the printout will advance and switch over to total

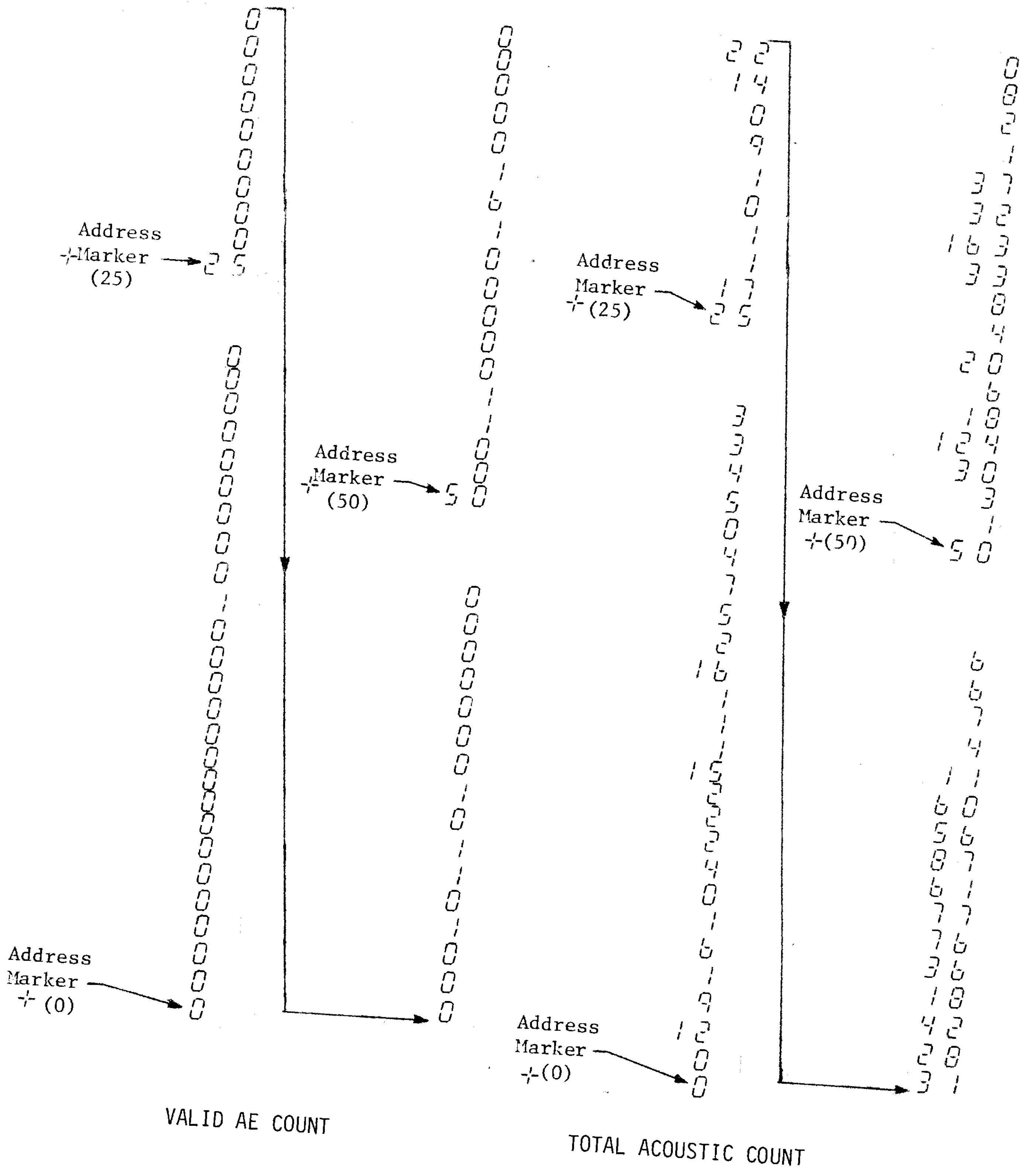


Figure 13. Sample Data Printout (Test Flight 4).

activity data. Format for the total activity data printout is identical to that for valid data.

The readout system also incorporates an empty check feature. This feature is used for checking whether or not a memory has been entirely erased and is initiated by depressing the "empty check" switch. This will start a memory scan of approximately six seconds. At the end of the scan, the red "scan complete" LED will be lighted. At this time, for an erased memory, the green "empty status" LED should be lighted. If not, return memory to ultraviolet eraser.

The ultraviolet eraser shown in Figure 14 is compact, being 3-1/4 x 6-1/4 x 7-1/2 inches (82.5 x 159 x 190.5 mm) and is completely enclosed with an integral electrical timer. The unit can handle up to five memories.

LABORATORY TESTING

The system initially underwent checkout on a section of channel iron used to represent a mockup of the area to be monitored on the aircraft. This allowed us to determine optimum sensor spacing and position. Artificially injected pulses were used to adjust the area of AE acceptance and to evaluate source isolation performance.

Additional testing was done to evaluate the ability of the monitor unit to perform in an electrically noisy environment. The original intent of test flying the unit on an F-105 aircraft at McClellan AFB did not coincide with delivery requirements of the unit to Australia. This required the development of special tests at our facility to simulate an electrically noisy in-flight condition. One of the tests consisted of powering the unit from a portable generator which did not have an earth ground and also induces transients. In addition, transient producing devices such as heat guns and a drill were also powered off the portable generator. The unit showed no problems with monitoring and recording in this created environment. It also showed no effects of the presence of an operating medium power laboratory RF transmitter.

A final area of concern relative to aircraft monitoring was the effect of temperature extremes. The monitor unit was of limited concern in this re-

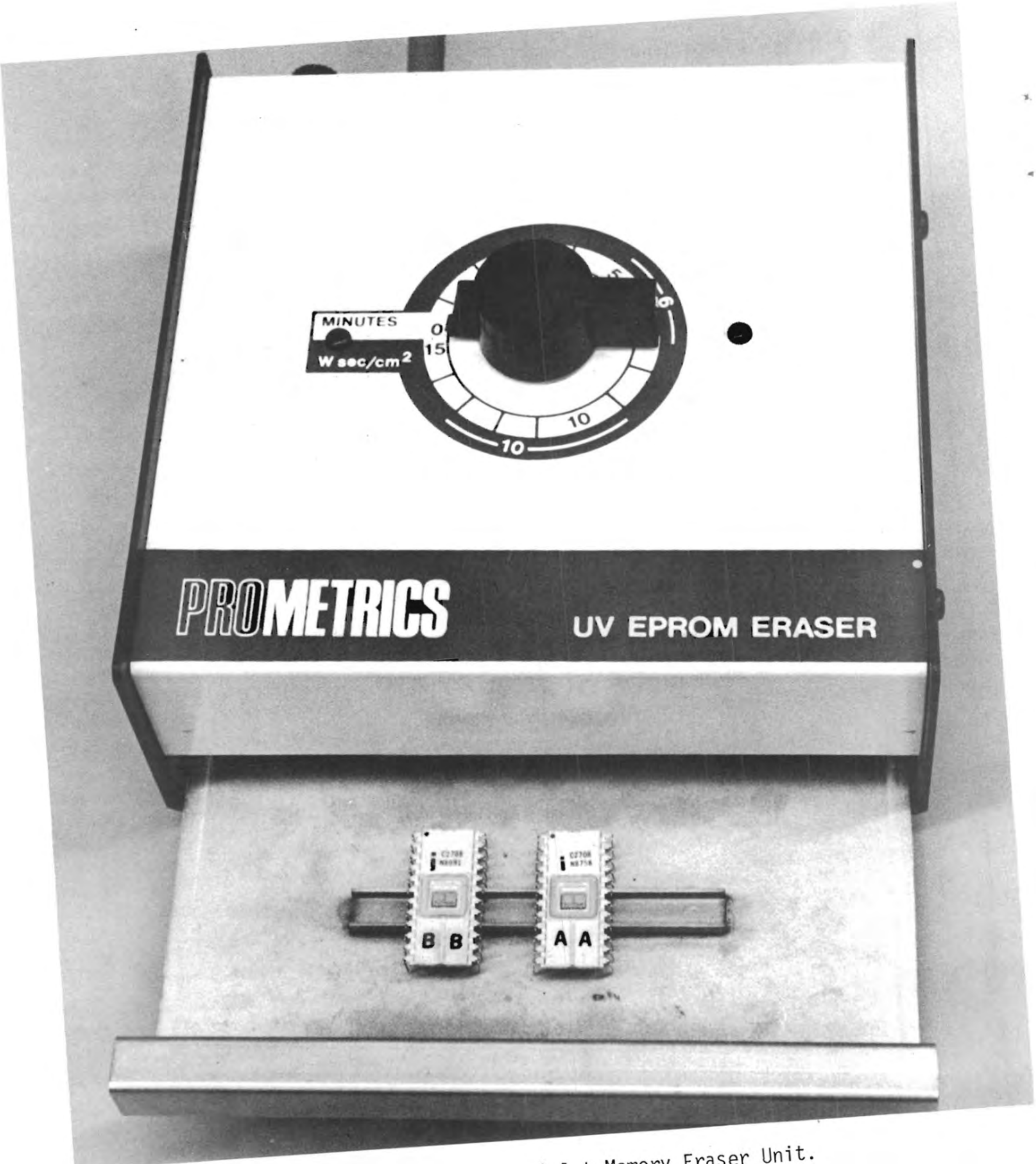


Figure 14. Ultraviolet Memory Eraser Unit.

spect since it would be in the controlled environment of the cockpit. The sensors and preamplifiers, however, are exposed to wide temperature variations. Two considerations here are the effect of temperature variation on integrity of the acrylic adhesive sensor mounting/coupling material and on performance of electronic components. A refrigeration chamber was used to evaluate temperature effects. The preamplifiers only were tested for their response from room temperature down to -50°C. The only effect shown was about 5.5% shift upward in the peak response versus frequency--i.e., from 400 KHz at room temperature to about 422 KHz at -50°C.

Another part of the temperature test was to mount a sensor on a bar with acrylic adhesive (HYSOL EA9446) and connect a preamplifier to it. The assembly was placed in the refrigeration chamber with the bar protruding to allow injecting a reference signal. A lead from the preamplifier output was brought out to an oscilloscope. Figure 15 shows the response to a similar signal input to the bar at the two temperature extremes measured. This shows about an 11.7% loss in sensitivity at -20°C, compared to room temperature. The lowest temperature attainable with the test system with the bar protruding was -20°C. Although outside air temperature might approach -50°C in-flight, it appeared that -20°C would be reasonably close to the minimum temperature the sensors would see being inside the aircraft fuselage.

Neither of the temperature effects--the shift in preamplifier peak response frequency or the modest reduction in sensor system sensitivity--were considered seriously detrimental to the application.

As a final element of AE system preparation, a system operating and maintenance manual was compiled. Four copies of the manual were delivered with the system to ARL.

PHASE 2: SYSTEM INSTALLATION

The decision was made to install the AE monitor system on Macchi aircraft A7-021, which is stationed at Pearce RAAF Base near Perth, Australia. Inspection of aircraft A7-021 during maintenance overhaul established that it had developed fatigue cracking in hole No. 20 in the tension member of the wing structure center section (Refer to Figure 2). The inspection was

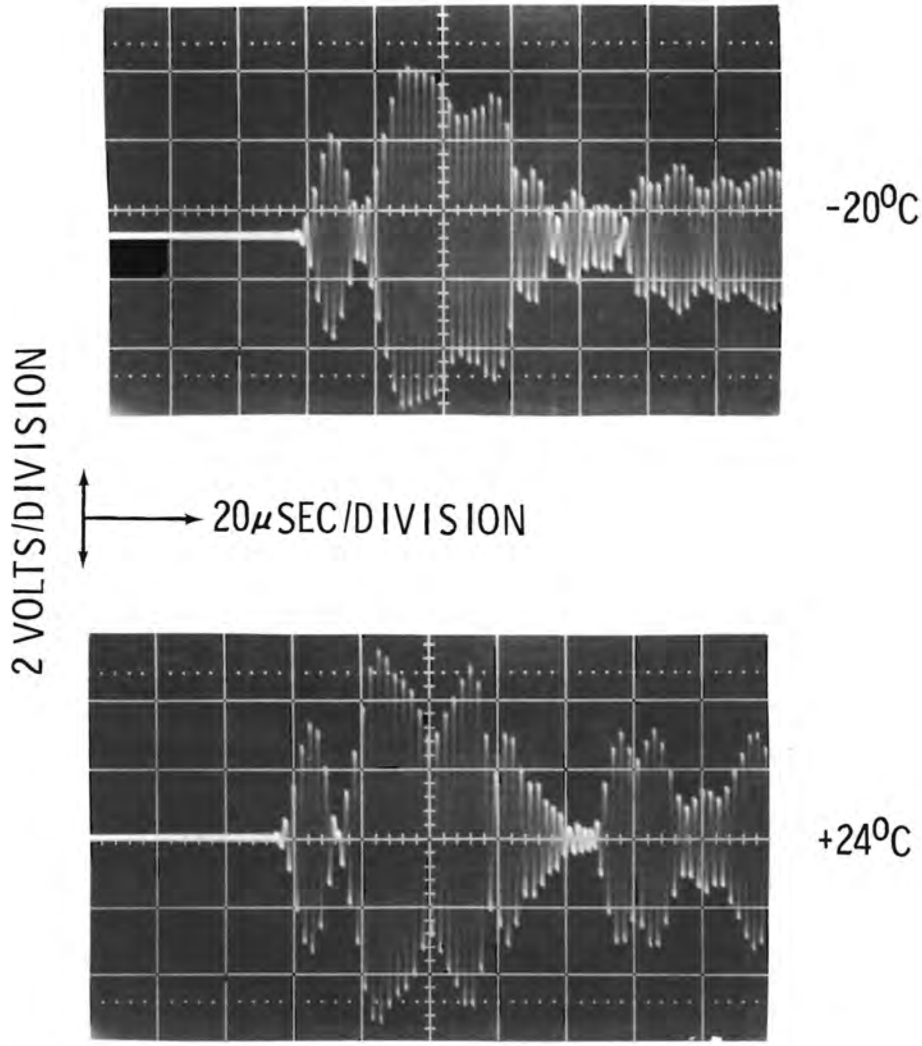


Figure 15. Comparative Response of AE Sensor - Preamplifier Combination Re. Temperature.

performed at 2988 hours flying time. Estimated magnitude of the cracking was:

- Total length of detectable cracks was 6.97 mm
- Longest single crack was 2.43 mm long
- Maximum depth (running out from the bore of the hole) was 0.81 mm

Sensors and preamplifiers together with mounting instructions were shipped to ARL in May, 1978 for installation during the maintenance overhaul of the aircraft. Figure 16 shows the installed location of the AE sensors on the tension member. The AE accept zone subsequently established with source isolation controls is also shown. Sensors were mounted with HYSOL EA9446 acrylic adhesive.

Preamplifiers were mounted on an existing tray in the bottom of the fuselage below the hydraulic cylinder which operates the air brake (see Figure 17). These are secured in place with fasteners through an integral flange on the preamplifier case into the tray.

During the same maintenance overhaul period, ARL personnel also arranged routing of all signal leads and power cables for the AE system. These were in accordance with specifications supplied by BNW.

The AE monitor unit was installed in August, 1978 by two BNW staff members, with assistance from ARL and RAAF personnel. The unit is located in the front cockpit in a console immediately to the right of the pilot's seat (see Figure 18). Installation of the monitor unit and system checkout including four test flights was accomplished in four days. Following hookup of the AE system in the aircraft, it was powered from an auxiliary power supply to test basic system functions and adjust the source isolation settings. Next, the system was powered from the aircraft power supply to check for any evidence of transient signal or noise interference with the avionics systems and engine operating. Since results of this test were satisfactory, the final step was to test fly the system.

Four test flights were performed while BNW personnel were at Pearce Air Base. On the initial flight, the detection threshold was set at one volt

TENSION BOOM

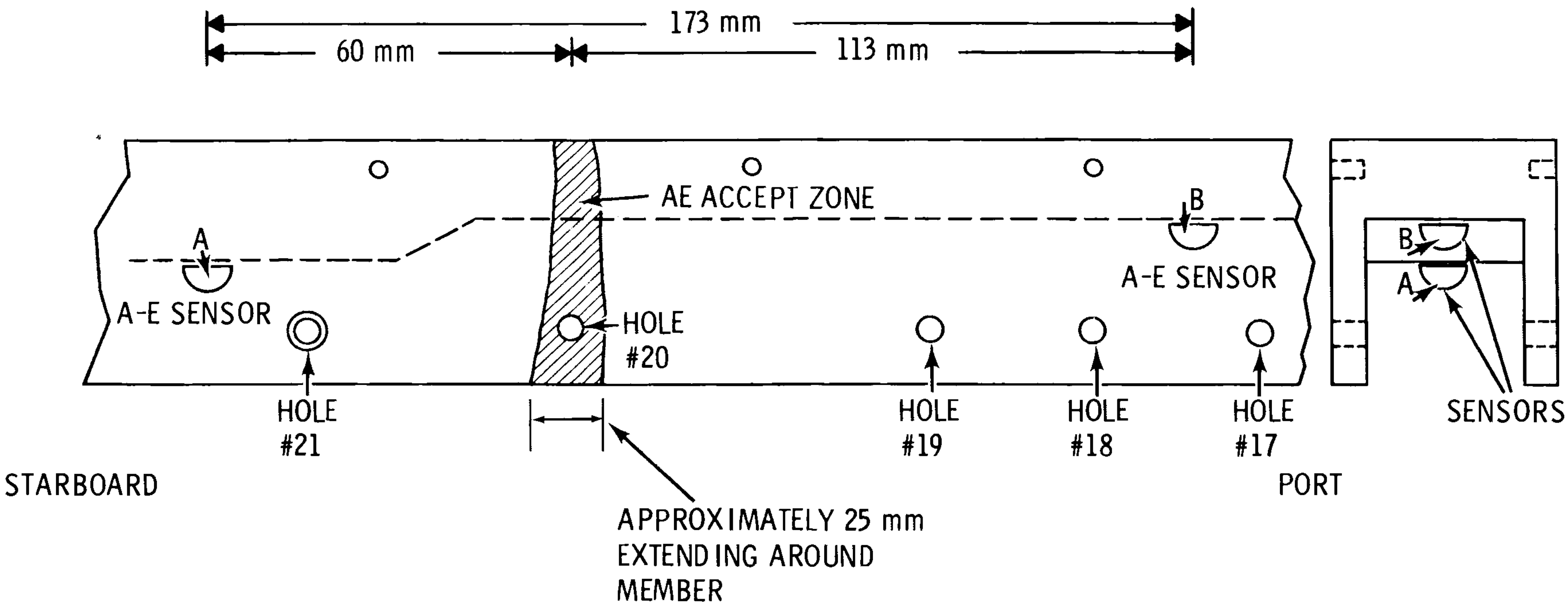


Figure 16. Installed Locations of AE Sensors on Macchi Aircraft A7-201 Wing Center Section Tension Member

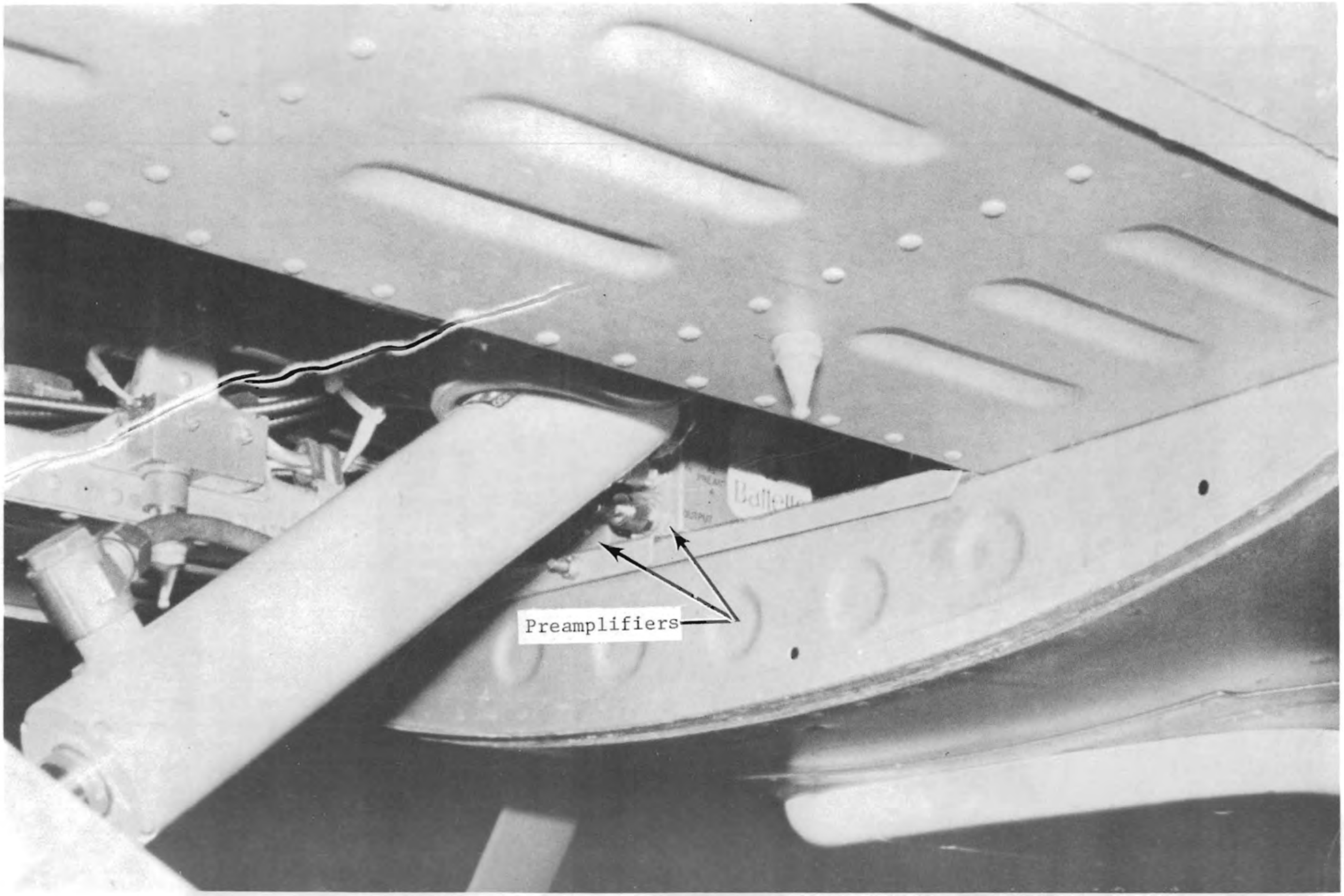


Figure 17. AE Preamplifiers Mounted in Macchi Aircraft A7-021.

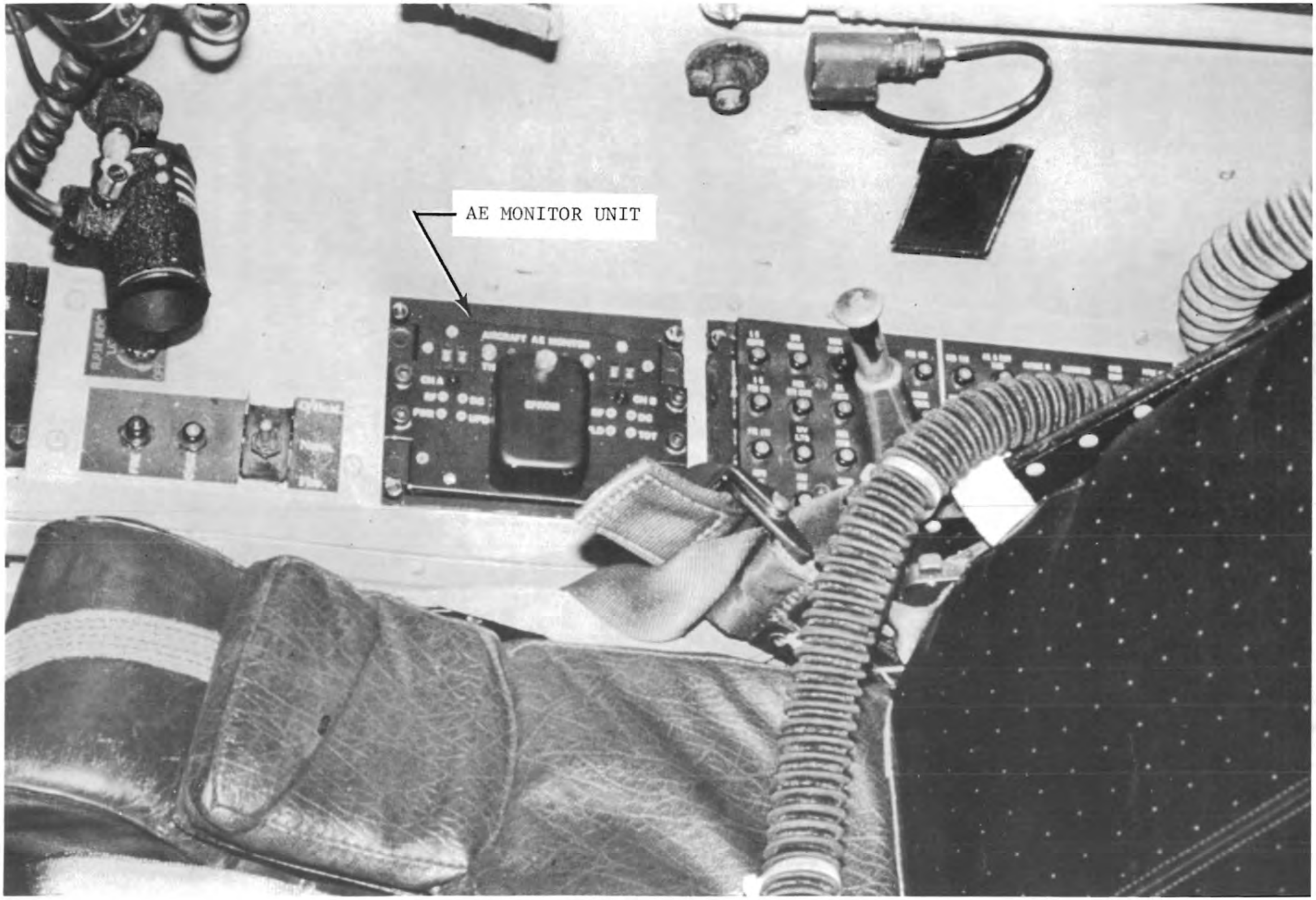


Figure 18. AE Monitor Unit Installed in Macchi Aircraft A7-021.

above reference background. Reference background was biased to 12.56 volts as one precaution against transient interference. A recording update of 8.4 seconds was used which gave a total recording time of 71 minutes for one memory. The results of the first test flight showed no evidence of noise or transient interference and the data appeared rational. On this basis, the threshold setting was reduced for subsequent test flights seeking to establish the most favorable settings for operational monitoring. Settings for the four test flights were:

Flight No.	Threshold Above Reference - Volts	Recording Update Period - Seconds
1	1	8.4
2	0.5	8.4
3	0.3	8.4
4	0.3	66.0

Monitor settings of Flight No. 4 were adopted for operational monitoring. A 66 second recording update was selected to assure total coverage of the flights. Data from the test flights is discussed in the next section of this report along with results from the first 21 operational flights.

A short presentation was made to selected officers and technicians at Pearce Air Base to acquaint them with the AE monitoring concept, the purpose of the monitor system installed and its operation. Subsequently, a detailed review of the routine operational monitoring and data handling procedure was provided for the technicians and officers selected to be responsible for this part of the program.

PHASE 3: FOLLOW-UP AND DATA ANALYSIS

AE monitoring results from the four test flights (titled Flights E-1, E-2, E-3 and E-4) and the first 21 operational flights (titled Flights 1, 2, etc.) are compiled in Appendix A. Please note that two scales are used on the ordinate of the plots--one for the open bars representing total acoustic count and one for the solid bars representing count of valid AE signals passed by the source isolation module. Also note that although the update period was 8.4 seconds for the first three flights, the data accumulation period is standardized at 1.1 minute for all plots.

The usefulness of the total acoustic count becomes more evident with the benefit of the data plots. This parameter provides a reference for judging two considerations:

- The fact that the total acoustic count is intermittent and relatively low in magnitude indicates that the AE monitor system is not being inundated with noise and/or stray transient signals.

- Comparing valid AE count with total acoustic count provides a basis for judging the effectiveness of the source isolation function. As is generally true in this data, when the magnitude of the valid count is much less than the total acoustic count and the peaks in the two curves do not generally coincide, it is indicative that the source isolation is functioning properly. If the output from the source isolation circuit represented simply an infiltration of noise signals in a combination that satisfied the Δ time limit requirements, this should assume some statistical relationship which would reflect in a similarity of total and valid count profiles.

Conclusions that can be drawn from the AE data at this time are strictly qualitative. The magnitude of valid AE count appears reasonable in light of the slow rate and amount of crack growth to be expected in this case. As a rough base of reference, in controlled laboratory fatigue crack growth tests at room temperature in Type A533B, Class 1 pressure vessel steel, a crack area growth of about 2-1/4 inches^2 (1452 mm^2) developed over about 80 hours of testing may produce 150 to 160,000 valid AE counts. Two flights (No. 9 and 17) produced relatively large count in both total and valid AE which are subject to suspicion. However, we have not been able to identify these as AE system malfunction particularly when the preceeding and following flight data in both cases is normal in the context of the total data set. At this time, we do not have a solid explanation for these two unique sets of data.

Figure 19 shows a composite summation of data for the 25 flights (4 experimental and 21 operational). This again illustrates the general absence of a direct parallel between total and valid AE count.

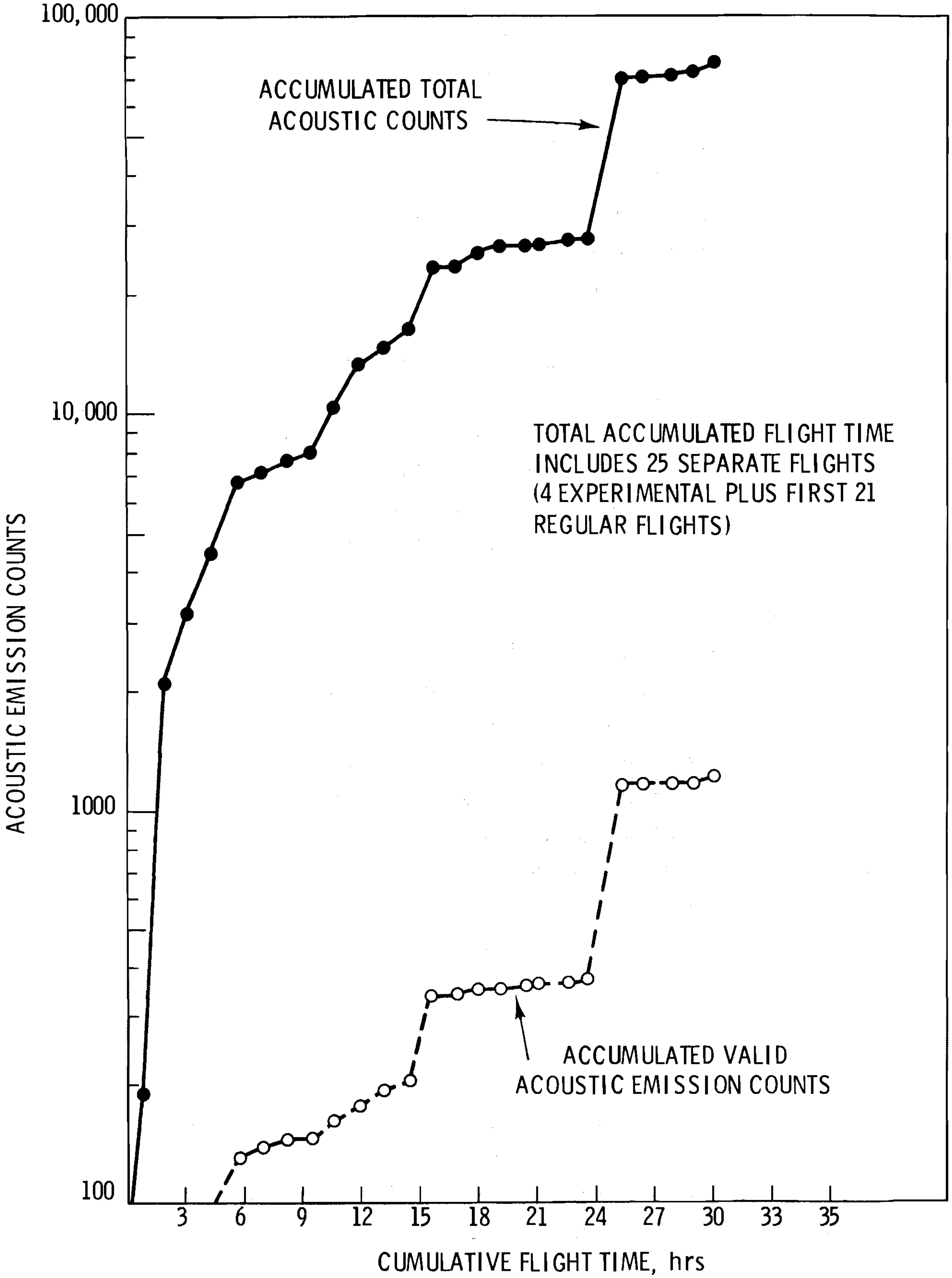


Figure 19. Composite Summation of AE Data from 25 Flights.

An interesting relationship is illustrated in Figure 20 where the data is separated by the type of fly maneuver involved. This suggests that low level flying where maximum turbulence and cyclic wing loading might be expected generates the greatest amount of valid AE. Formation flying and aeorbatics where relatively a more sustained monotonic loading might be expected produces considerably less valid AE count. This appears to be reasonable because the sustained loads or "g" maneuvers within operational limits would not be expected to load the structure sufficiently to cause concurrent crack growth where cyclic loading from turbulence might.

As data points are developed on measured crack growth in the area being monitored, it will be possible to evaluate correlation between valid AE and crack growth. Due to the slow rate of crack growth expected, however, it will probably require at least a year of data collection to begin to reach a conclusion. This is considered to be a valid and necessary approach, however. Any gross acceleration of the process could significantly bias the results.

Another area of follow-up support involves assisting ARL in overcoming any functional problems with the system. The memory readout instrument began to show indications of a problem after the fourth experimental flight. A plan of action was developed before BNW personnel departed which appeared would maintain the unit operational. Subsequently, however, the unit failed and limited remedial measures suggested were not effective. A simplified replacement readout device without a printer has been sent to ARL to minimize the interruption of data collection. The original readout unit has been returned to BNW and is being revamped in an effort to avoid any further problems with it.

CREDITS

The authors wish to recognize the outstanding cooperation, assistance and hospitality provided by ARL and RAAF personnel in the course of this work. Foremost among these are Ian Scott and Gary Martin of ARL and Wing Commander C.E. Bradford and Flight Lieutenant I. Anderson of the RAAF. Base Commander J.W. Hubble, RAAF, graciously extended the use of Pearce Air Base facilities to us during system installation and testing.

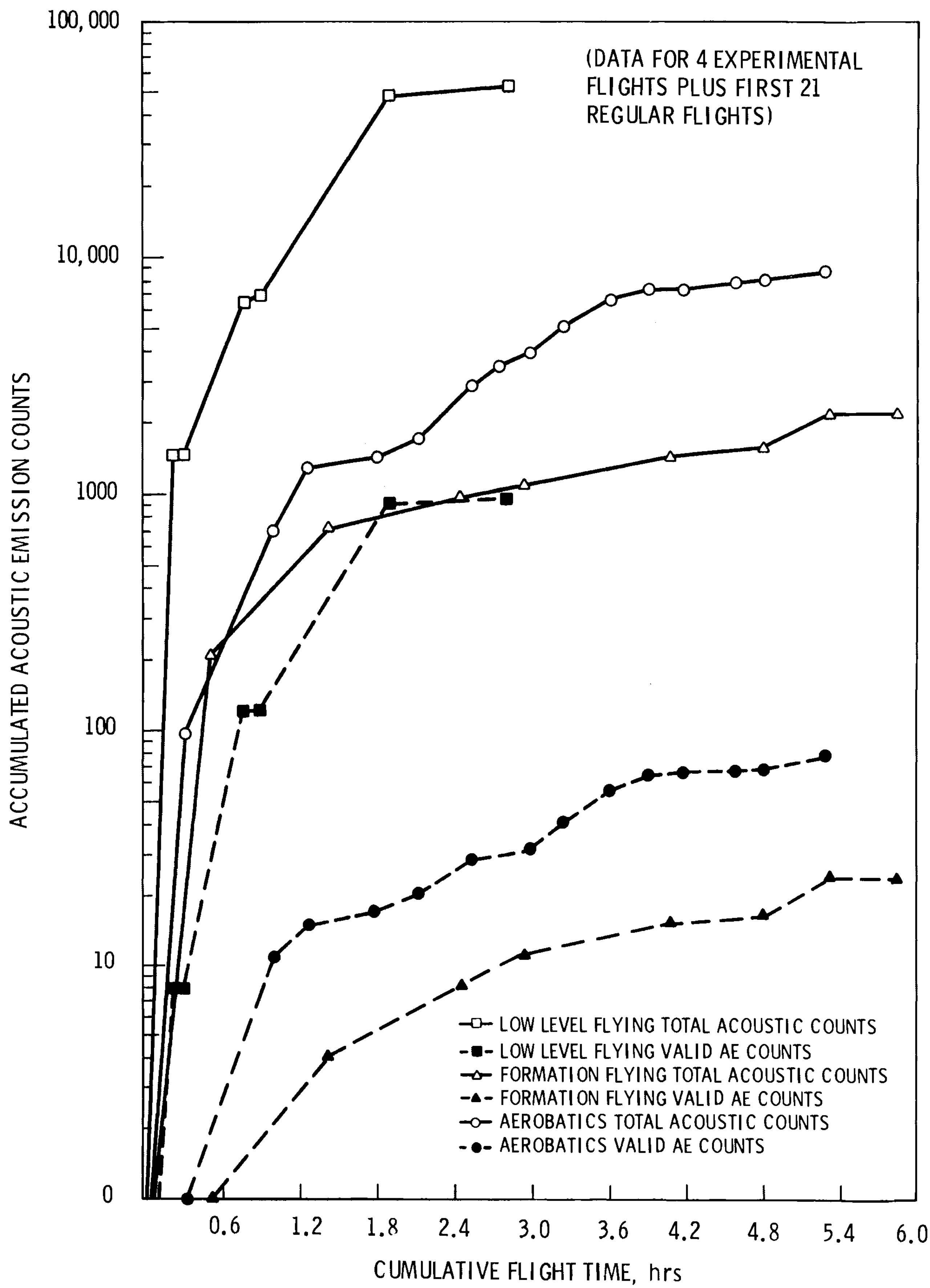


Figure 20. Summation of AE Data from 25 Flights by Type of Flying.

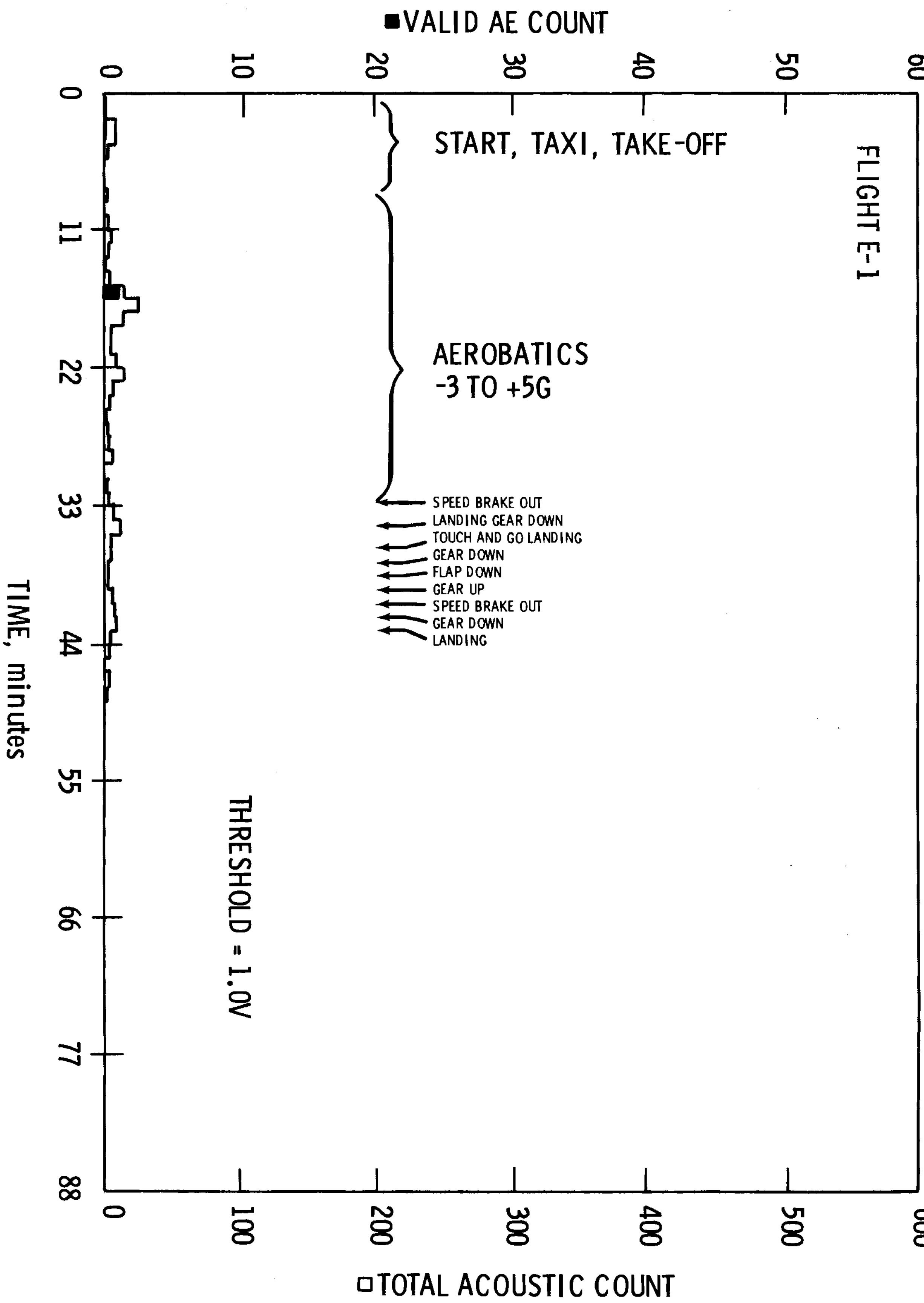
REFERENCES

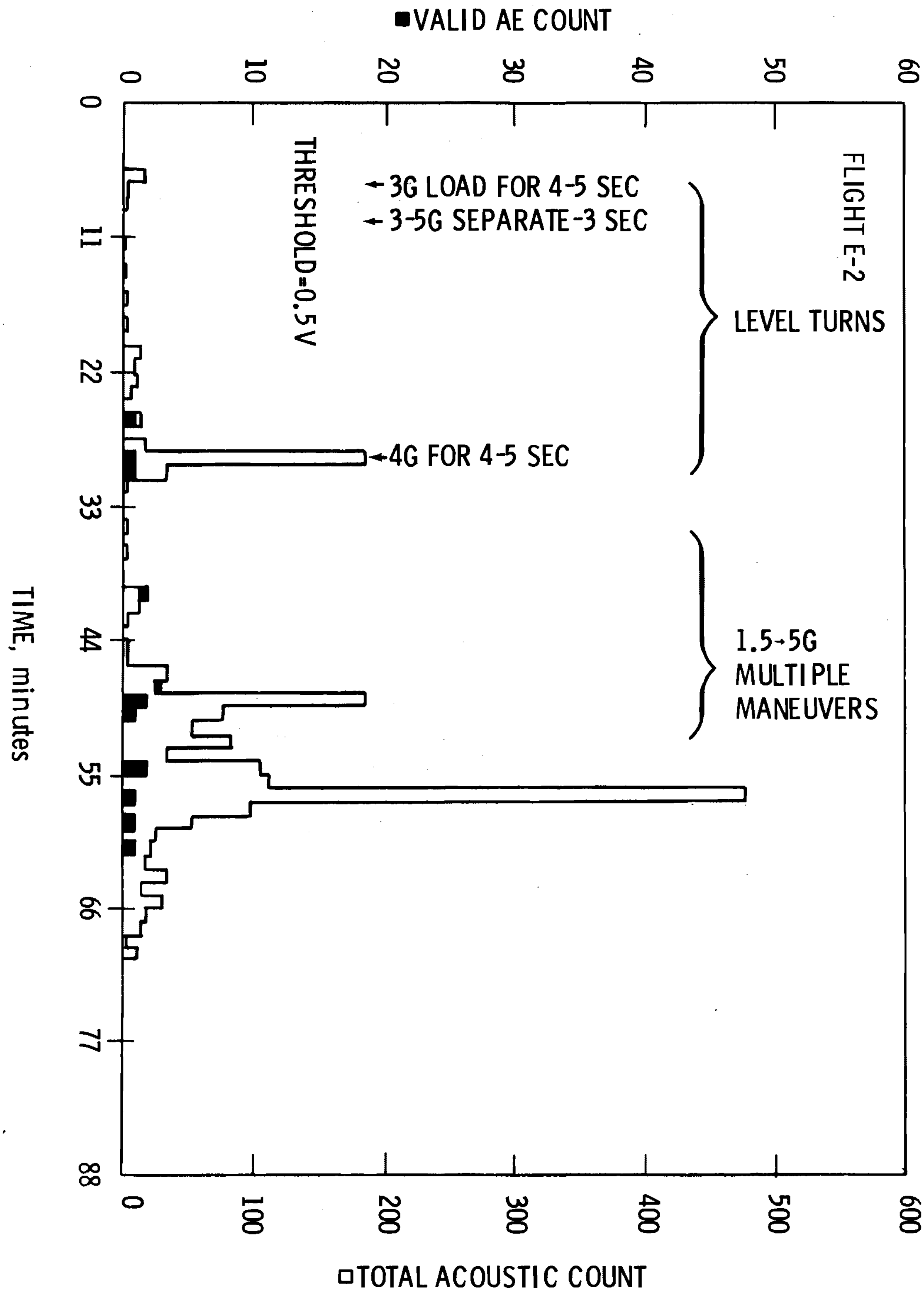
1. W.W. Lewis, Jr. C.D. Bailey, W.M. Pless, Acoustic Emission Structure-Borne Noise Measurements on Aircraft During Flight, Lockheed-Georgia Company, November, 1974; NTIS No. HC A05/MF A01.

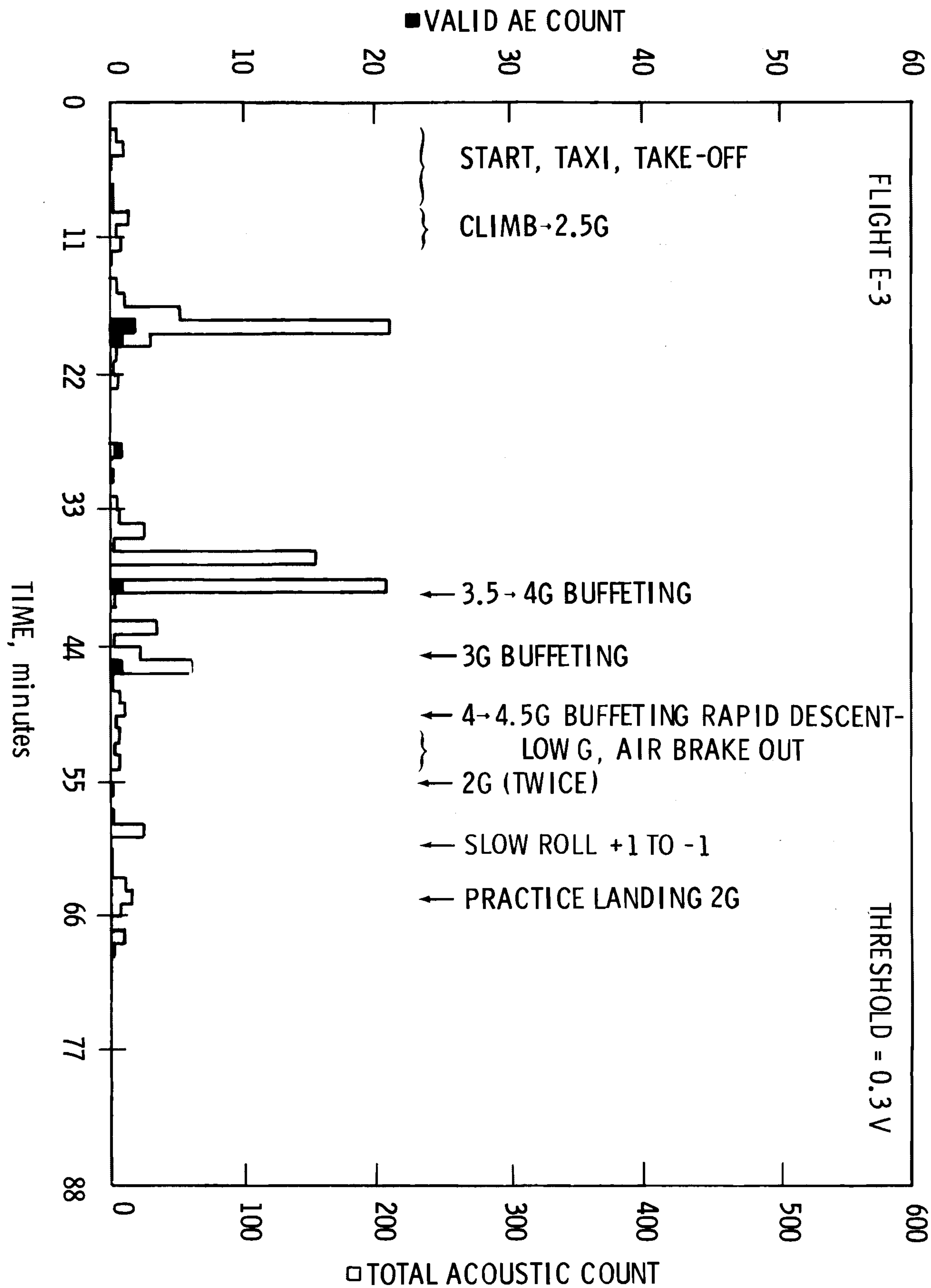
2. C.R. Horak, A.F. Weyhreter, Acoustic Emission System for Monitoring Components and Structures in a Severe Fatigue Noise Environment, Grumman Aerospace Corporation, Materials Evaluation, Vol. 35, May, 1977, pg. 59.

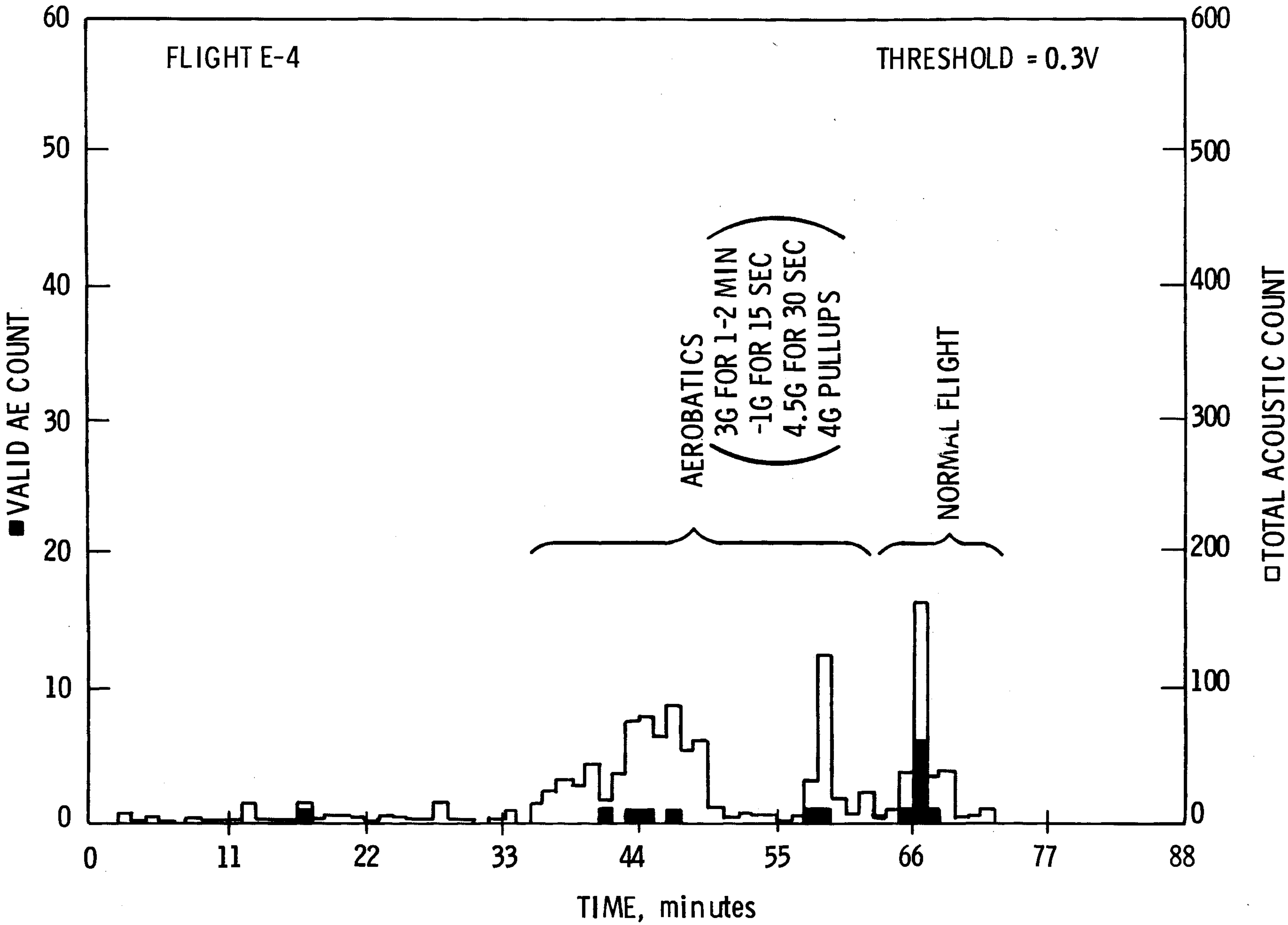
APPENDIX A

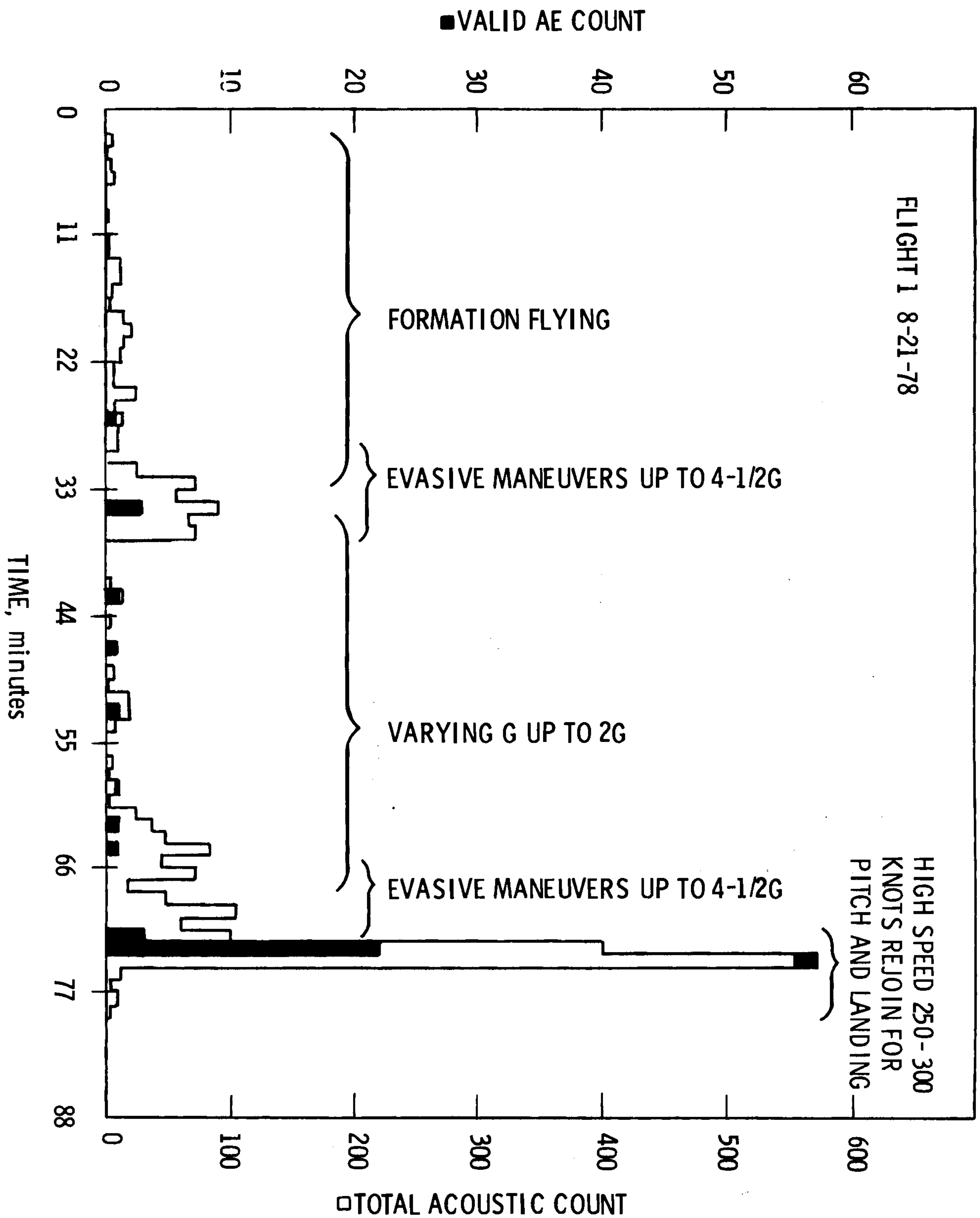
TEST AND OPERATIONAL FLIGHT ACOUSTIC EMISSION DATA - 25 FLIGHTS


FLIGHT E-1
VALID AE COUNT
TOTAL ACOUSTIC COUNT
TIME, minutes
START, TAXI, TAKE-OFF
AEROBATICS
-3 TO +5G
SPEED BRAKE OUT
LANDING GEAR DOWN
TOUCH AND GO LANDING
GEAR DOWN
FLAP DOWN
GEAR UP
SPEED BRAKE OUT
GEAR DOWN
LANDING
THRESHOLD = 1.0V

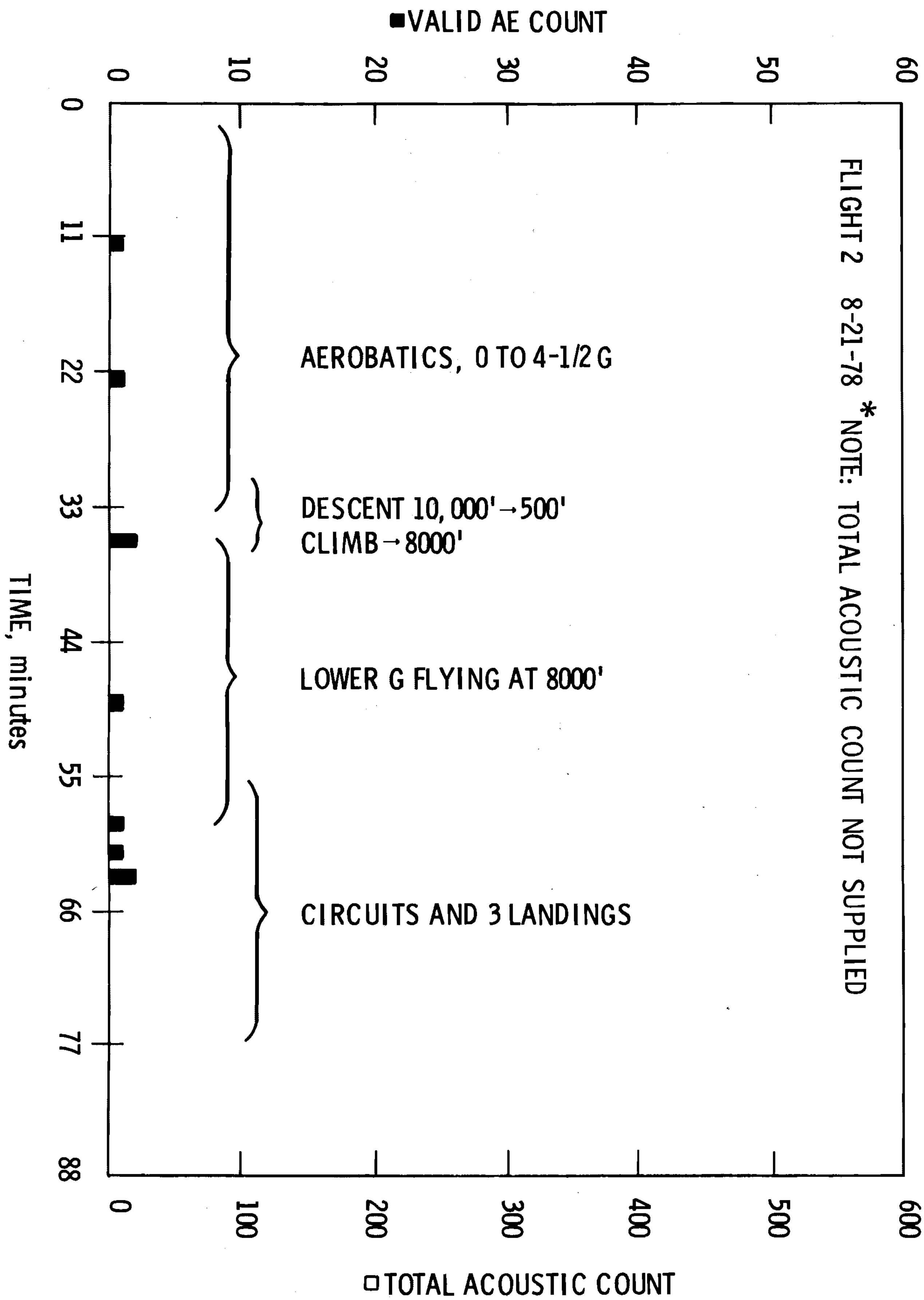

■VALID AE COUNT
0
10
20
30
40
50
60
FLIGHT E-2
LEVEL TURNS
←3G LOAD FOR 4-5 SEC
←3-5G SEPARATE-3 SEC
THRESHOLD=0.5V
←4G FOR 4-5 SEC
1.5→5G
MULTIPLE
MANEUVERS
TIME, minutes
0
11
22
33
44
55
66
77
88
0
100
200
300
400
500
600
□TOTAL ACOUSTIC COUNT


■VALID AE COUNT
0
10
20
30
40
50
60
FLIGHT E-3
START, TAXI, TAKE-OFF
CLIMB→2.5G
3.5→4G BUFFETING
3G BUFFETING
4→4.5G BUFFETING RAPID DESCENT-
LOW G, AIR BRAKE OUT
2G (TWICE)
SLOW ROLL +1 TO -1
PRACTICE LANDING 2G
THRESHOLD = 0.3 V
TIME, minutes
0
11
22
33
44
55
66
77
88
0
100
200
300
400
500
600
□TOTAL ACOUSTIC COUNT

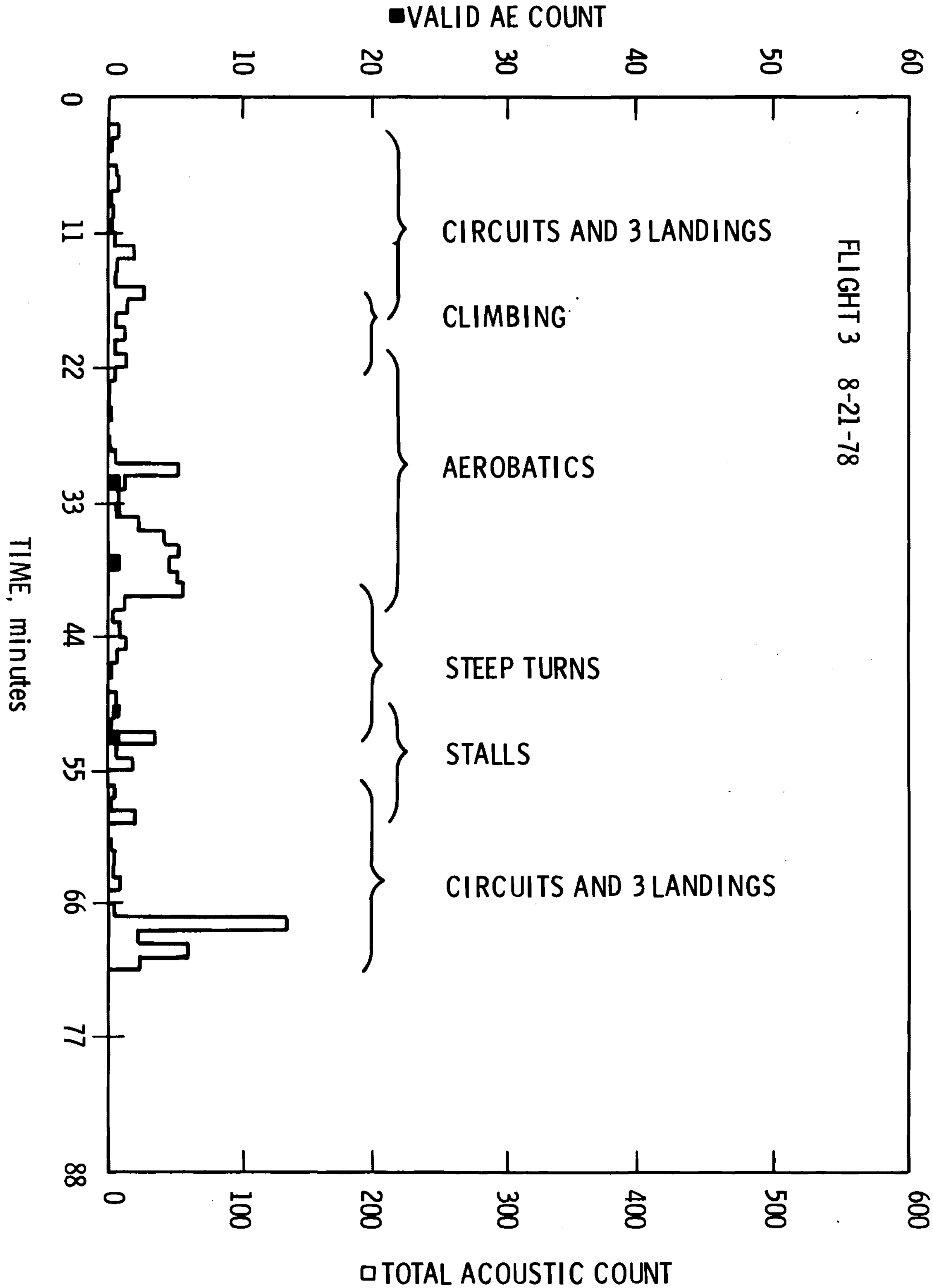

FLIGHT E-4
THRESHOLD = 0.3V
■VALID AE COUNT
0
10
20
30
40
50
60
AEROBATICS
3G FOR 1-2 MIN
-1G FOR 15 SEC
4.5G FOR 30 SEC
4G PULLUPS
NORMAL FLIGHT
0
11
22
33
44
55
66
77
88
TIME, minutes
0
100
200
300
400
500
600
□TOTAL ACOUSTIC COUNT

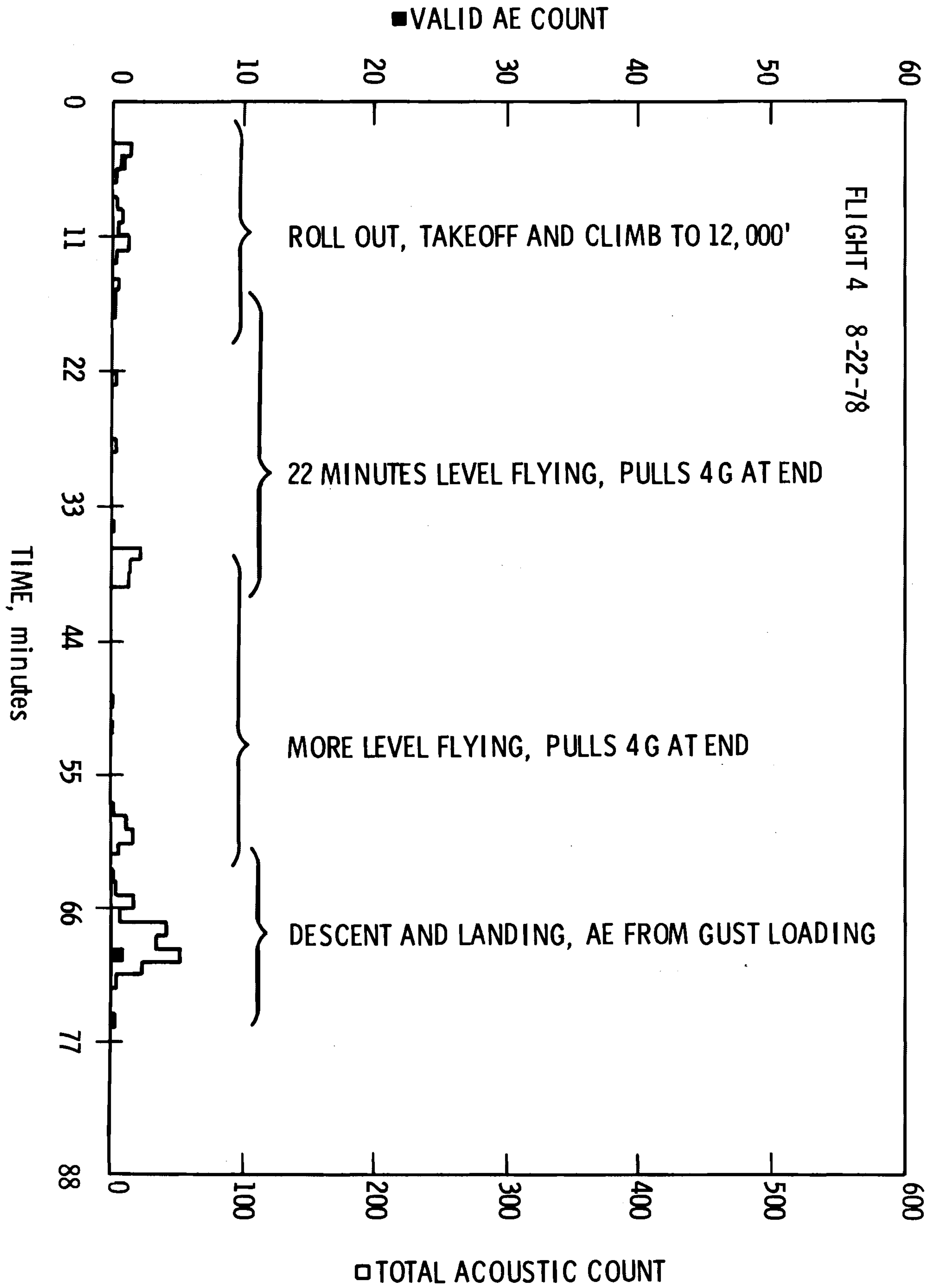


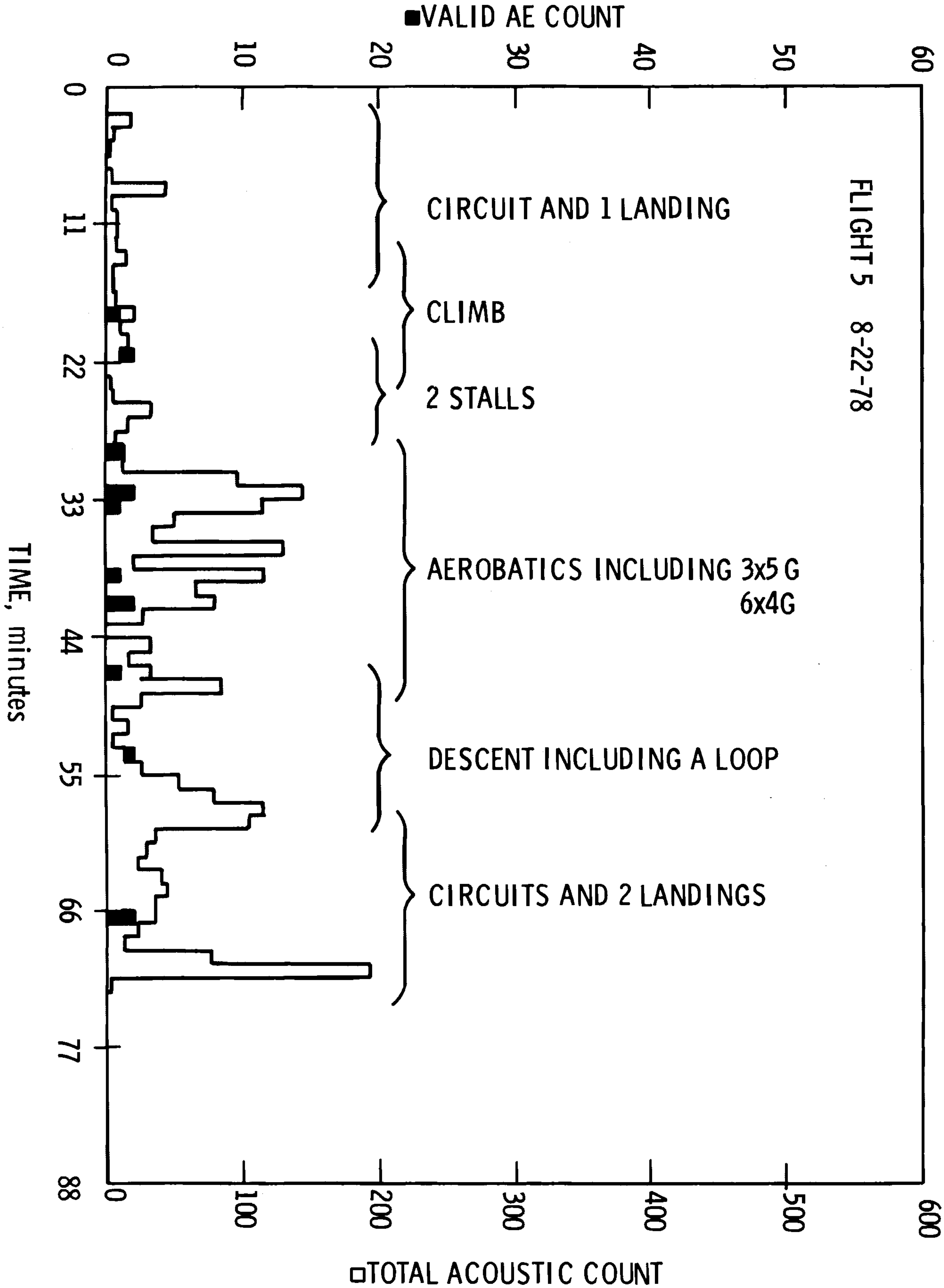
■VALID AE COUNT
0
10
20
30
40
50
60
FLIGHT 1 8-21-78
FORMATION FLYING
EVASIVE MANEUVERS UP TO 4-1/2G
VARYING G UP TO 2G
EVASIVE MANEUVERS UP TO 4-1/2G
HIGH SPEED 250-300 KNOTS REJOIN FOR PITCH AND LANDING
0
11
22
33
44
55
66
77
88
TIME, minutes
0
100
200
300
400
500
600
□TOTAL ACOUSTIC COUNT



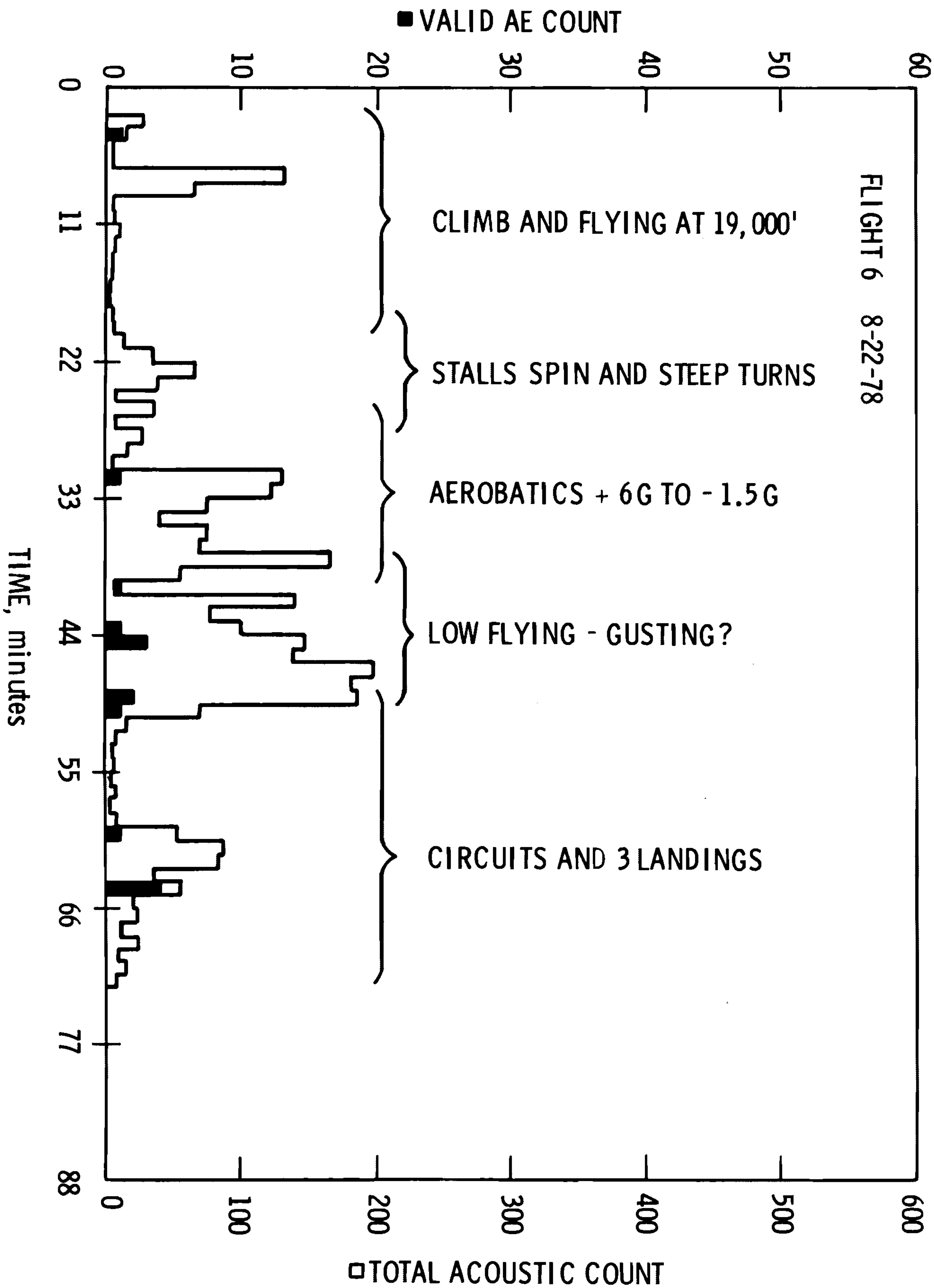
FLIGHT 2 8-21-78 *NOTE: TOTAL ACOUSTIC COUNT NOT SUPPLIED
■VALID AE COUNT
0
10
20
30
40
50
60
AEROBATICS, 0 TO 4-1/2 G
DESCENT 10,000'→500'
CLIMB→8000'
LOWER G FLYING AT 8000'
CIRCUITS AND 3 LANDINGS
0
11
22
33
44
55
66
77
88
TIME, minutes
0
100
200
300
400
500
600
□TOTAL ACOUSTIC COUNT

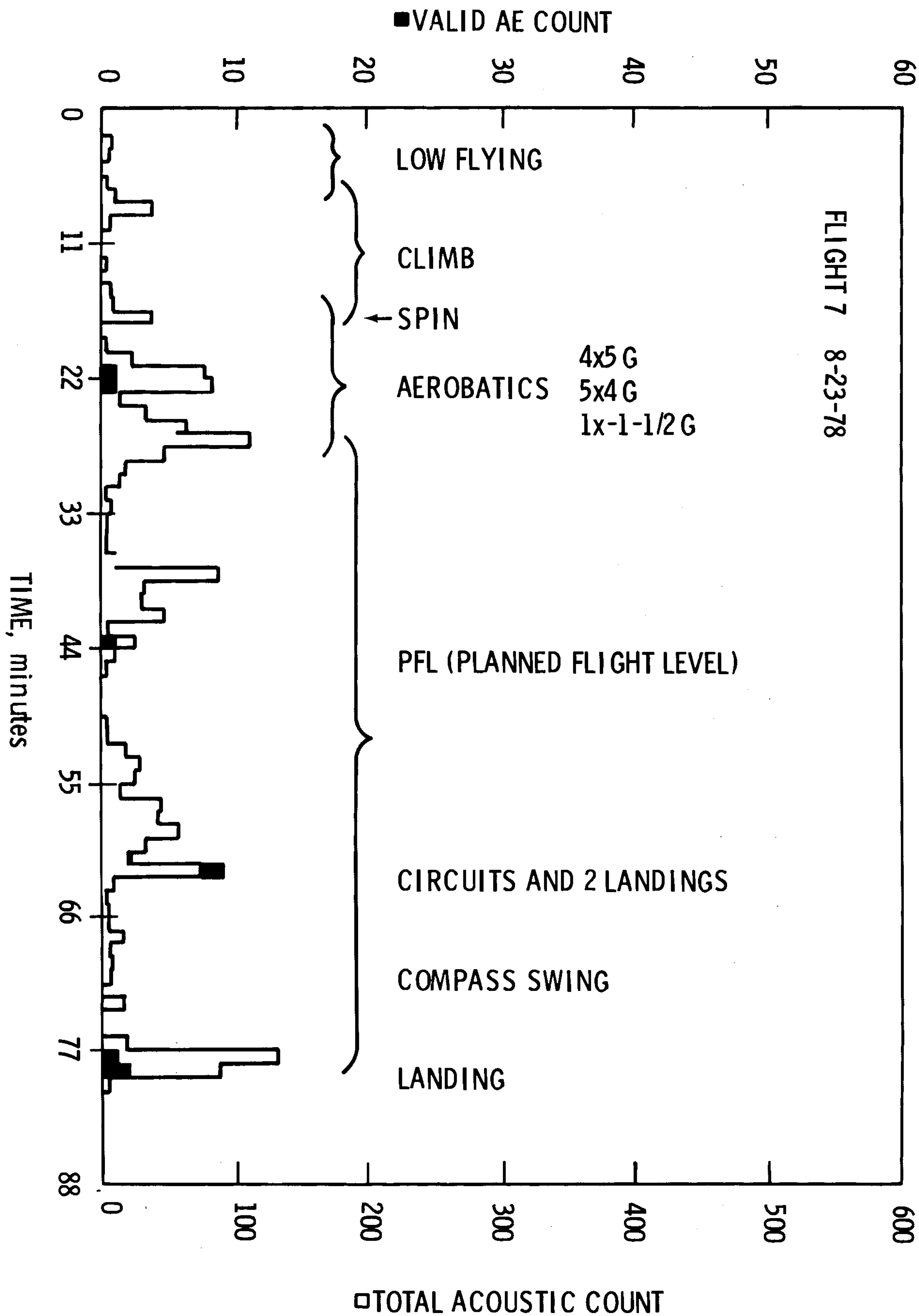

■VALID AE COUNT
0
10
20
30
40
50
60
FLIGHT 3 8-21-78
CIRCUITS AND 3 LANDINGS
CLIMBING
AEROBATICS
STEEP TURNS
STALLS
CIRCUITS AND 3 LANDINGS
0
11
22
33
44
55
66
77
88
TIME, minutes
0
100
200
300
400
500
600
□TOTAL ACOUSTIC COUNT

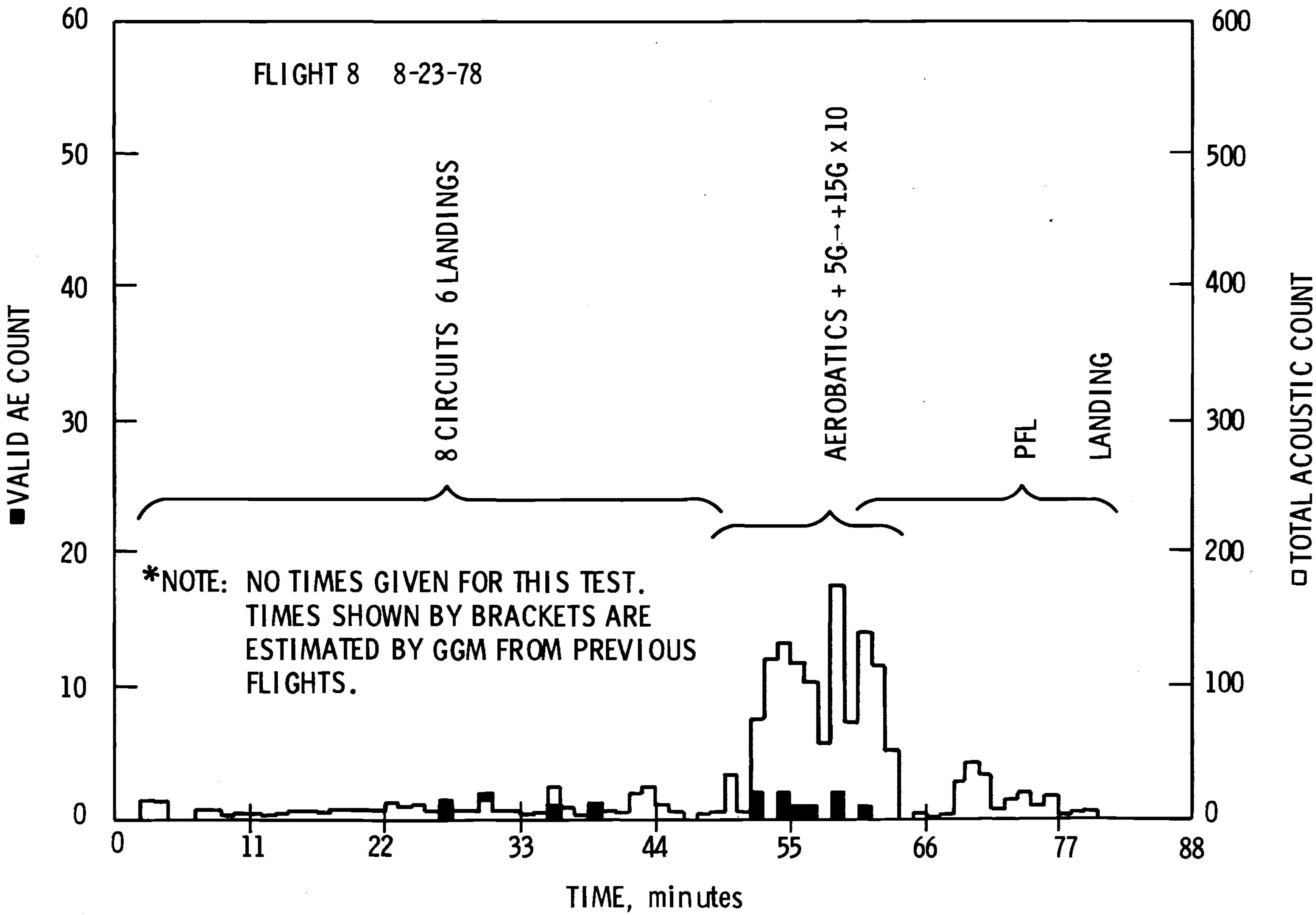

■VALID AE COUNT
FLIGHT 4 8-22-78
ROLL OUT, TAKEOFF AND CLIMB TO 12,000'
22 MINUTES LEVEL FLYING, PULLS 4G AT END
MORE LEVEL FLYING, PULLS 4G AT END
DESCENT AND LANDING, AE FROM GUST LOADING
TIME, minutes
□TOTAL ACOUSTIC COUNT

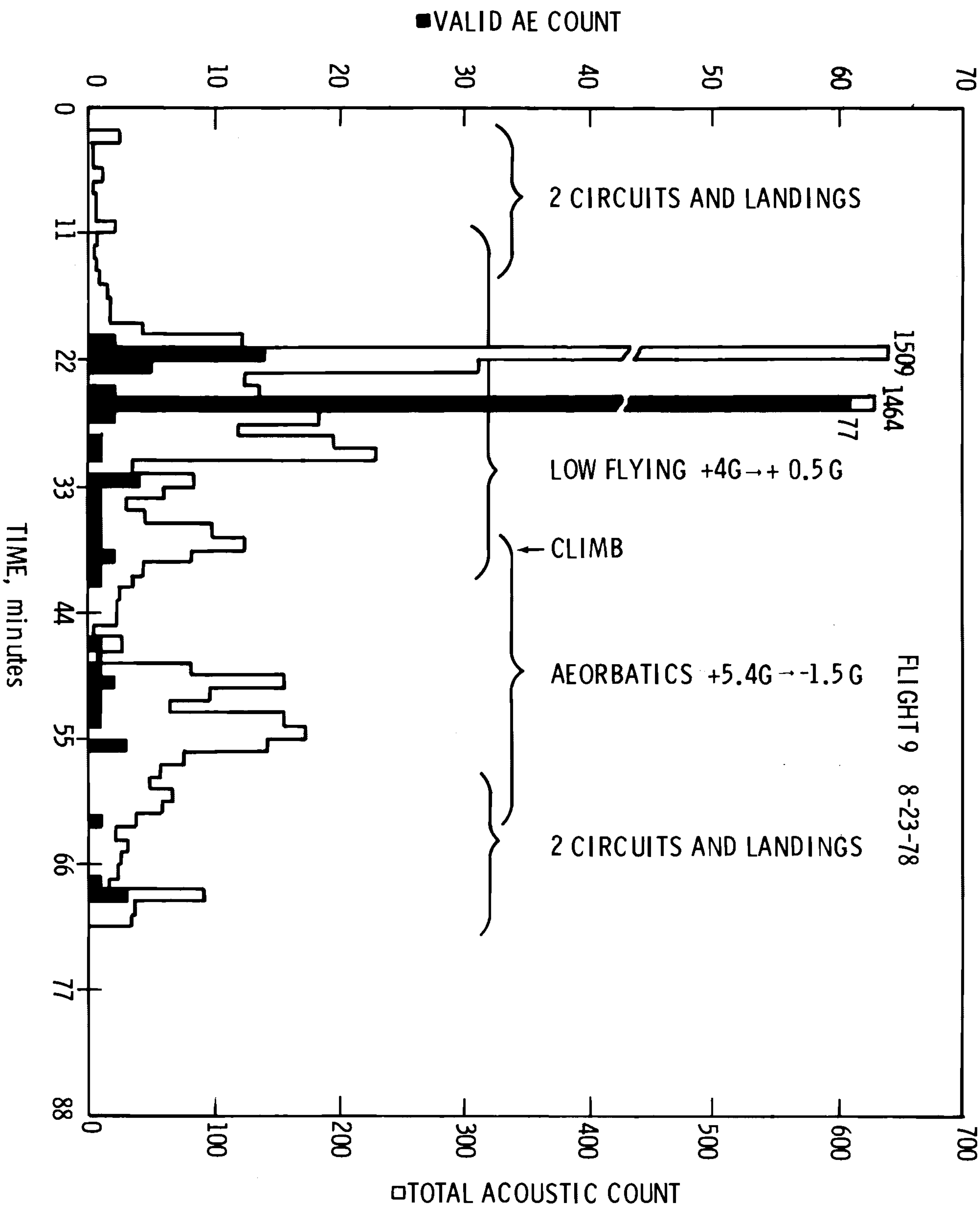


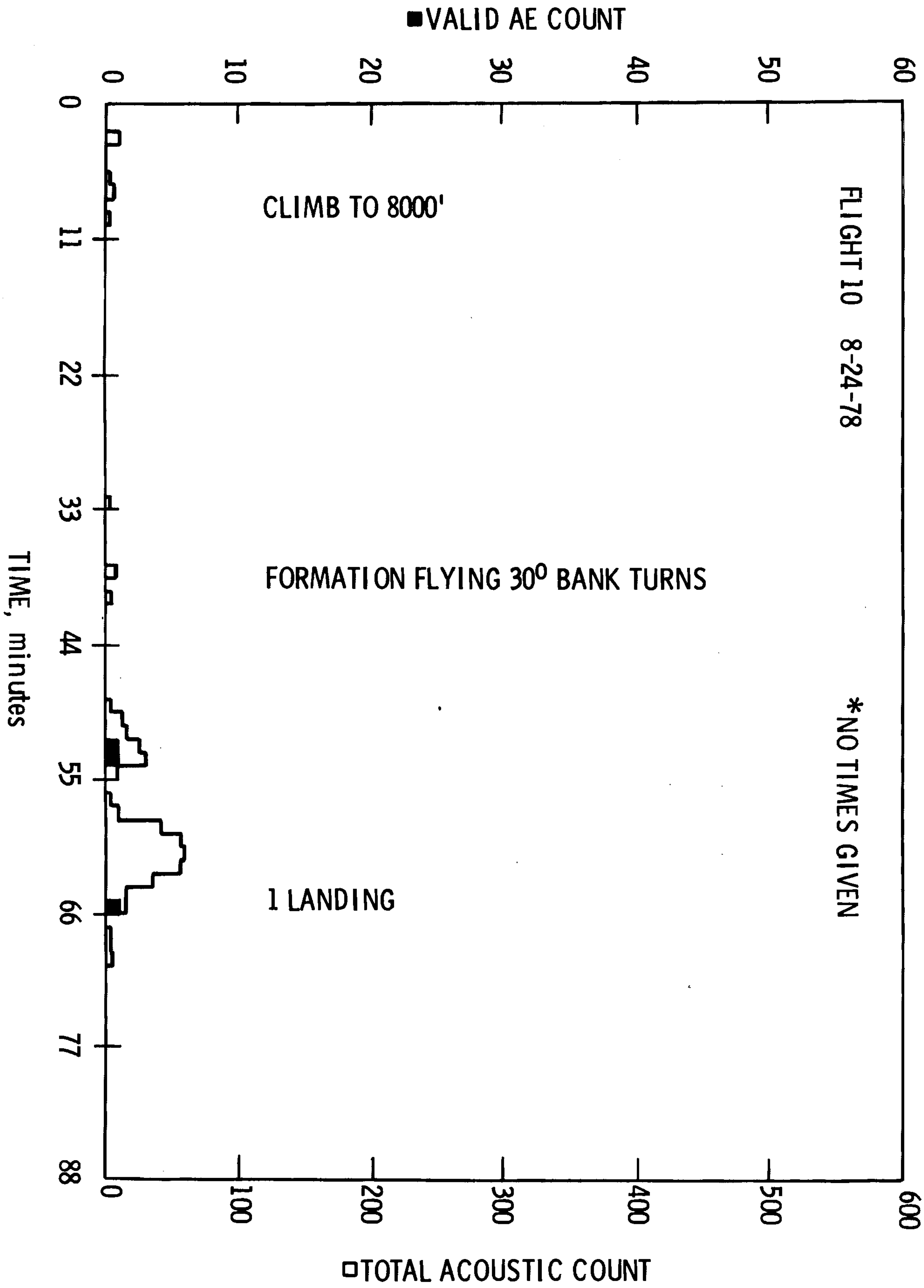
FLIGHT 5 8-22-78
■VALID AE COUNT
0
10
20
30
40
50
60
CIRCUIT AND 1 LANDING
CLIMB
2 STALLS
AEROBATICS INCLUDING 3x5 G
6x4G
DESCENT INCLUDING A LOOP
CIRCUITS AND 2 LANDINGS
0
11
22
33
44
55
66
77
88
TIME, minutes
0
100
200
300
400
500
600
□TOTAL ACOUSTIC COUNT

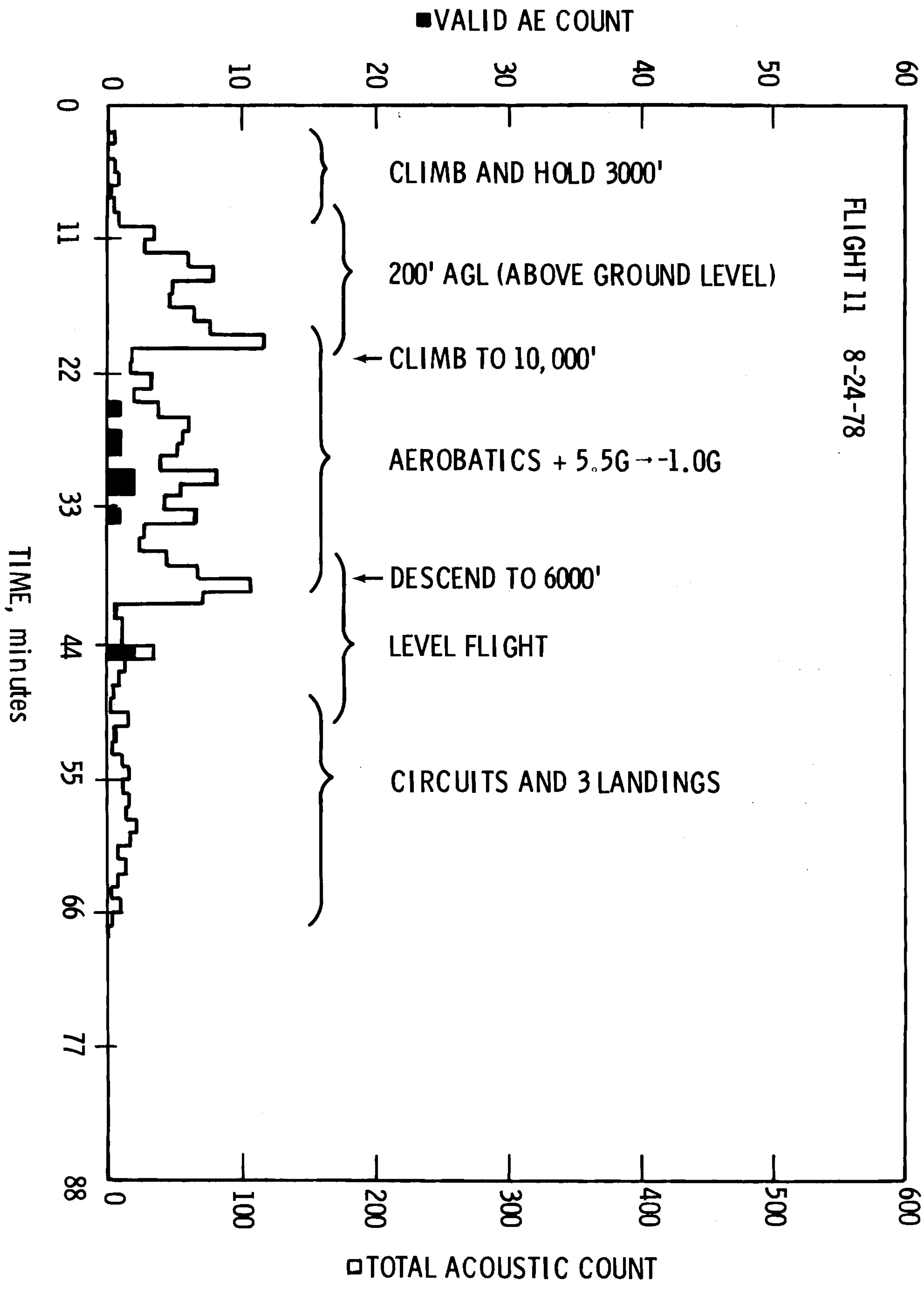

VALID AE COUNT
FLIGHT 6 8-22-78
CLIMB AND FLYING AT 19,000'
STALLS SPIN AND STEEP TURNS
AEROBATICS + 6G TO - 1.5G
LOW FLYING - GUSTING?
CIRCUITS AND 3 LANDINGS
TIME, minutes
TOTAL ACOUSTIC COUNT

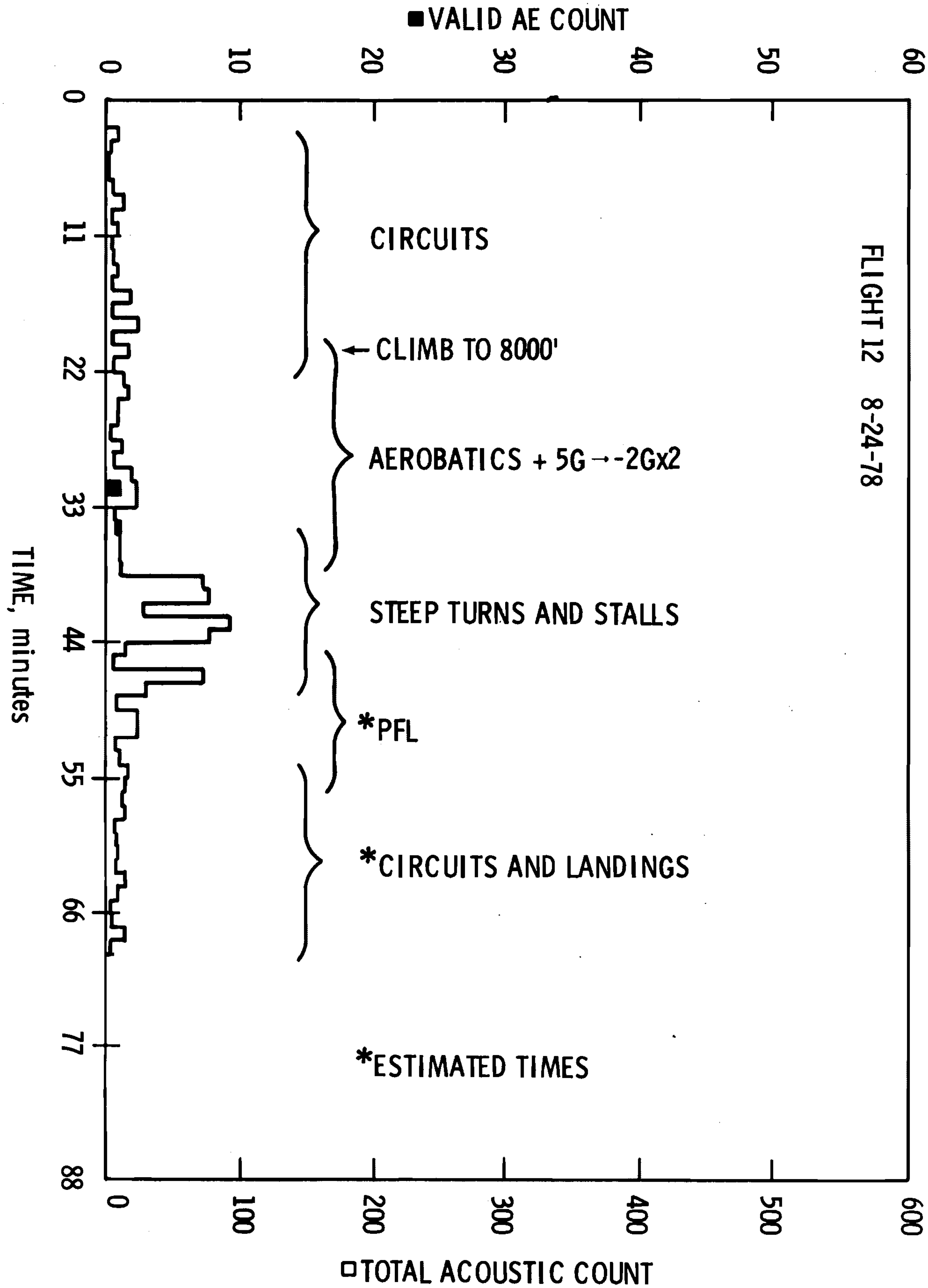

■VALID AE COUNT
0
10
20
30
40
50
60
FLIGHT 7 8-23-78
LOW FLYING
CLIMB
SPIN
AEROBATICS
4x5 G
5x4 G
1x-1-1/2 G
PFL (PLANNED FLIGHT LEVEL)
CIRCUITS AND 2 LANDINGS
COMPASS SWING
LANDING
TIME, minutes
0
11
22
33
44
55
66
77
88
0
100
200
300
400
500
600
□TOTAL ACOUSTIC COUNT


FLIGHT 8 8-23-78
8 CIRCUITS 6 LANDINGS
AEROBATICS + 5G → +15G x 10
PFL
LANDING
*NOTE: NO TIMES GIVEN FOR THIS TEST. TIMES SHOWN BY BRACKETS ARE ESTIMATED BY GGM FROM PREVIOUS FLIGHTS.
■ VALID AE COUNT
□ TOTAL ACOUSTIC COUNT
TIME, minutes
0
10
20
30
40
50
60
100
200
300
400
500
600
11
22
33
44
55
66
77
88

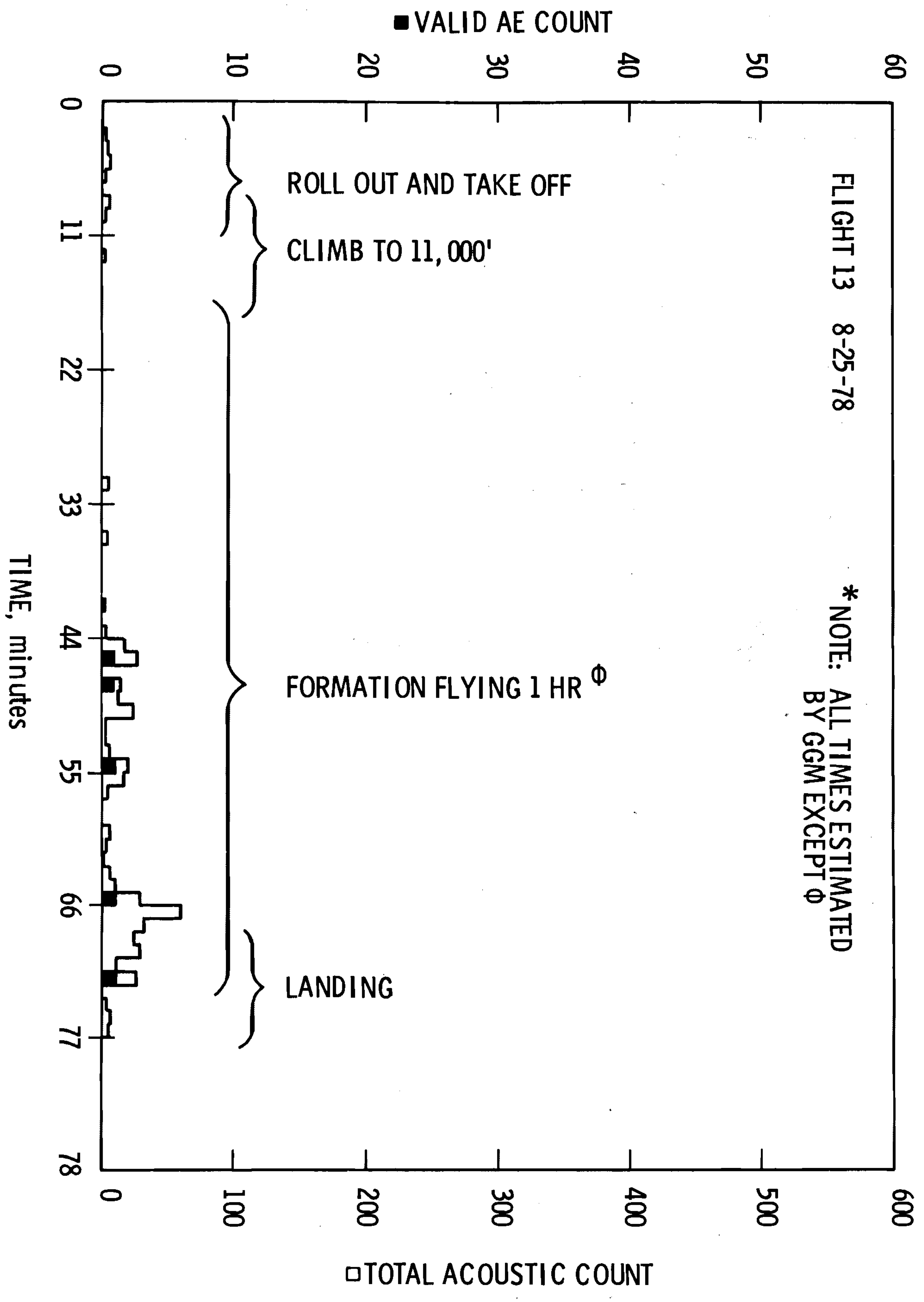

■VALID AE COUNT
0
10
20
30
40
50
60
70
2 CIRCUITS AND LANDINGS
1509
1464
77
LOW FLYING +4G→+ 0.5 G
CLIMB
AEORBATICS +5.4G→-1.5 G
FLIGHT 9 8-23-78
2 CIRCUITS AND LANDINGS
0
11
22
33
44
55
66
77
88
TIME, minutes
0
100
200
300
400
500
600
700
□TOTAL ACOUSTIC COUNT

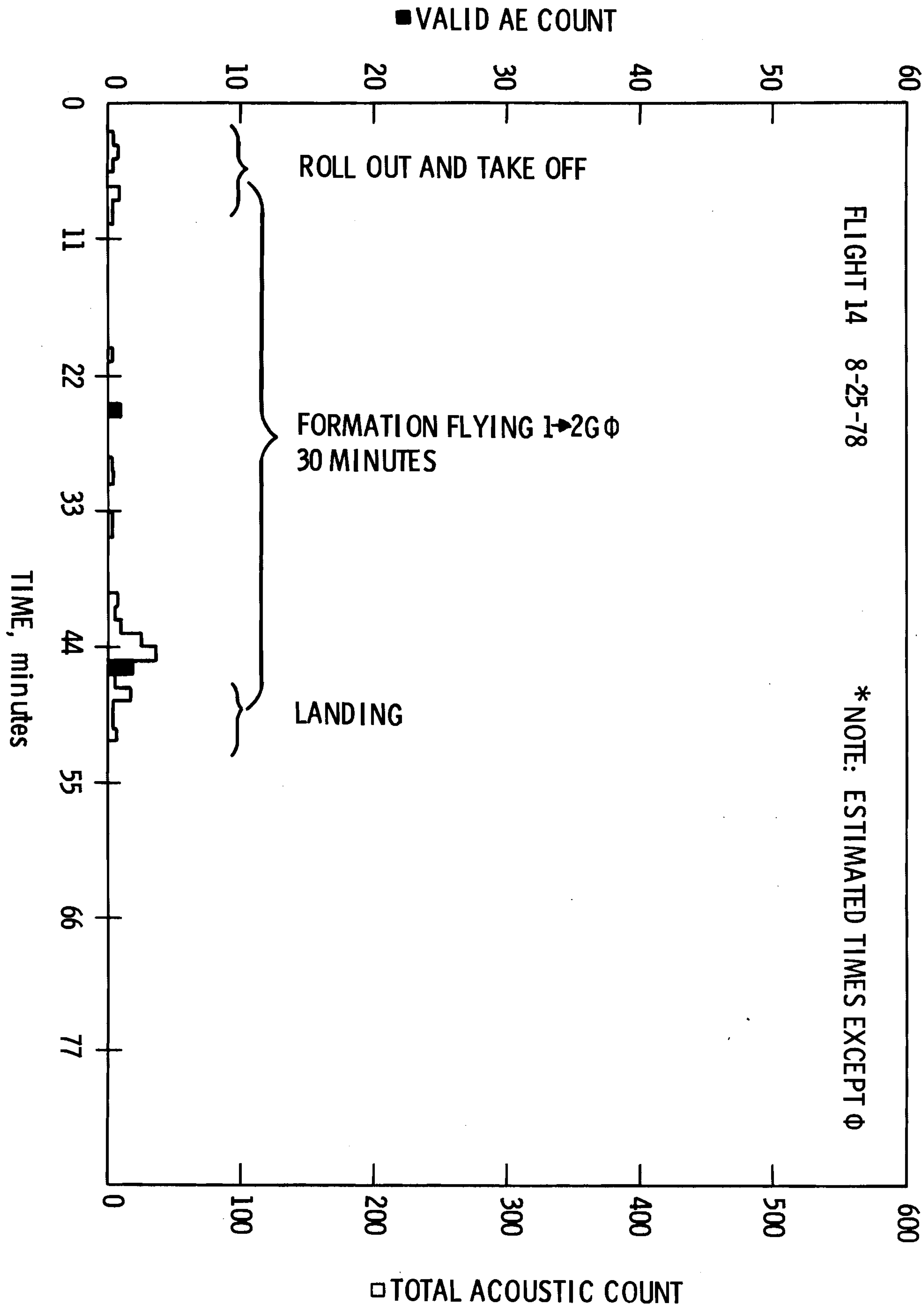

■VALID AE COUNT
0
10
20
30
40
50
60
FLIGHT 10 8-24-78
*NO TIMES GIVEN
CLIMB TO 8000'
FORMATION FLYING 30^{0} BANK TURNS
1 LANDING
0
11
22
33
44
55
66
77
88
TIME, minutes
0
100
200
300
400
500
600
□TOTAL ACOUSTIC COUNT

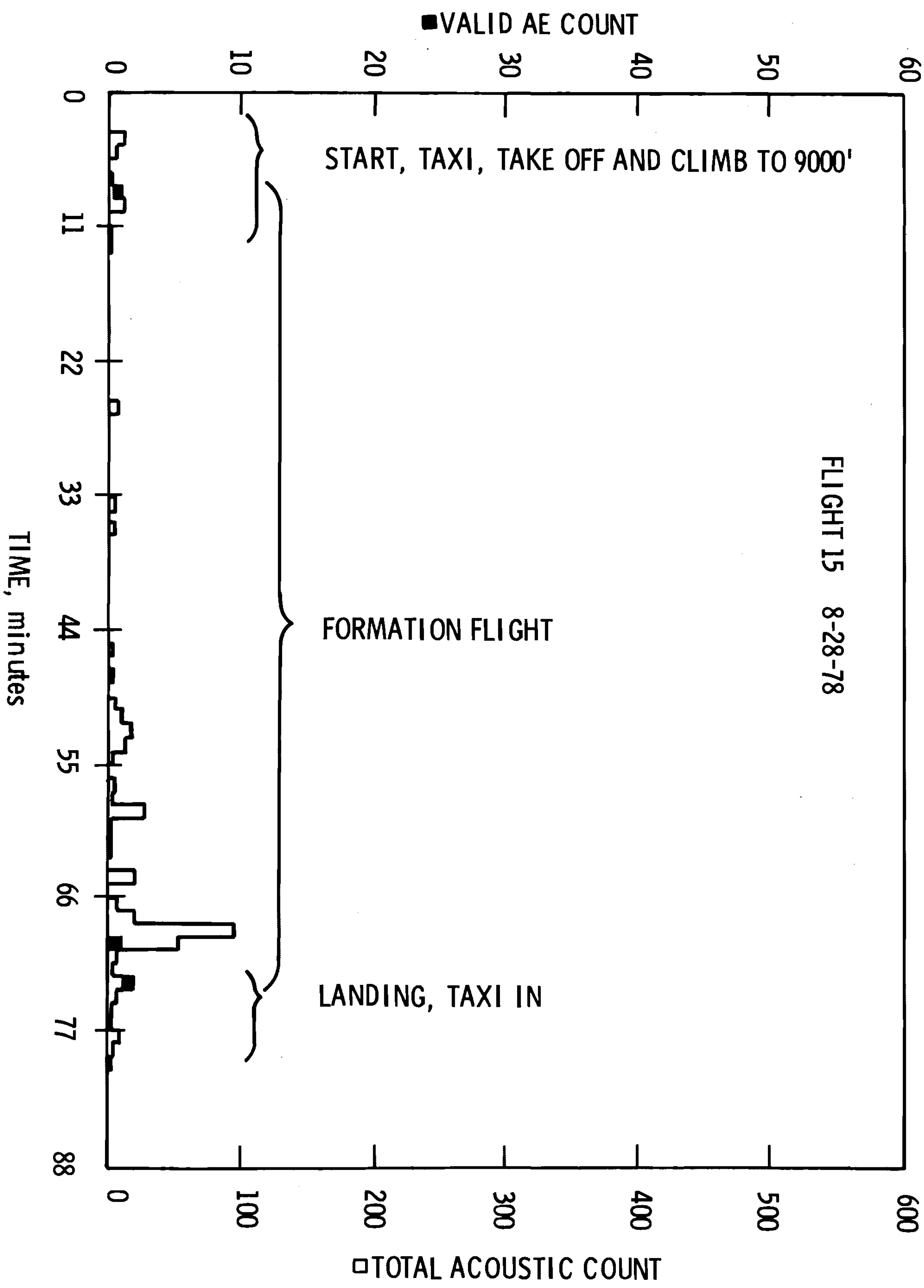

■VALID AE COUNT
0
10
20
30
40
50
60
FLIGHT 11 8-24-78
CLIMB AND HOLD 3000'
200' AGL (ABOVE GROUND LEVEL)
← CLIMB TO 10,000'
AEROBATICS + 5.5G → -1.0G
← DESCEND TO 6000'
LEVEL FLIGHT
CIRCUITS AND 3 LANDINGS
0
11
22
33
44
55
66
77
88
TIME, minutes
0
100
200
300
400
500
600
□TOTAL ACOUSTIC COUNT

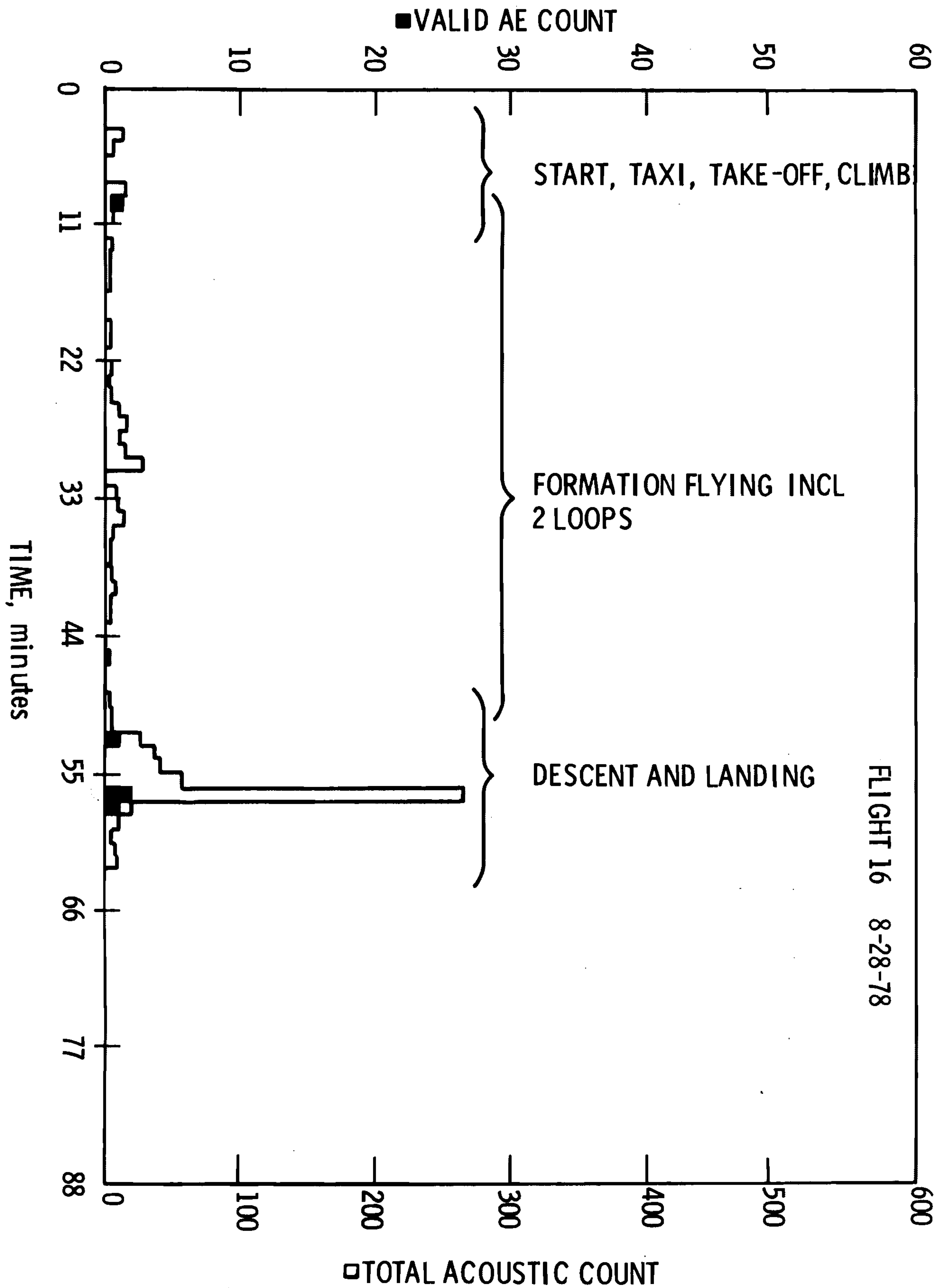


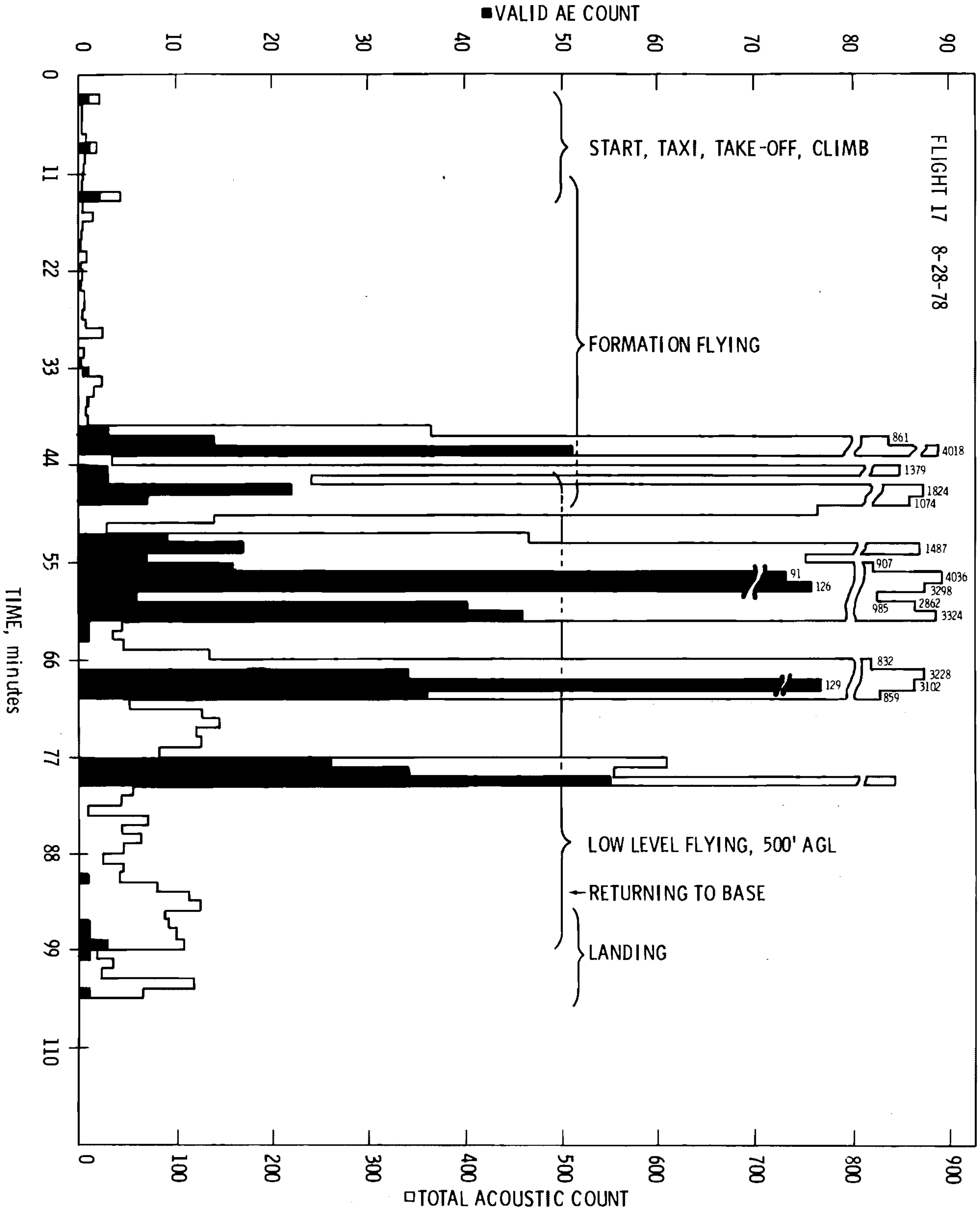
■VALID AE COUNT
FLIGHT 12 8-24-78
CIRCUITS
←CLIMB TO 8000'
AEROBATICS + 5G→-2Gx2
STEEP TURNS AND STALLS
*PFL
*CIRCUITS AND LANDINGS
*ESTIMATED TIMES
TIME, minutes
□TOTAL ACOUSTIC COUNT
0
10
20
30
40
50
60
11
22
33
44
55
66
77
88
100
200
300
400
500
600

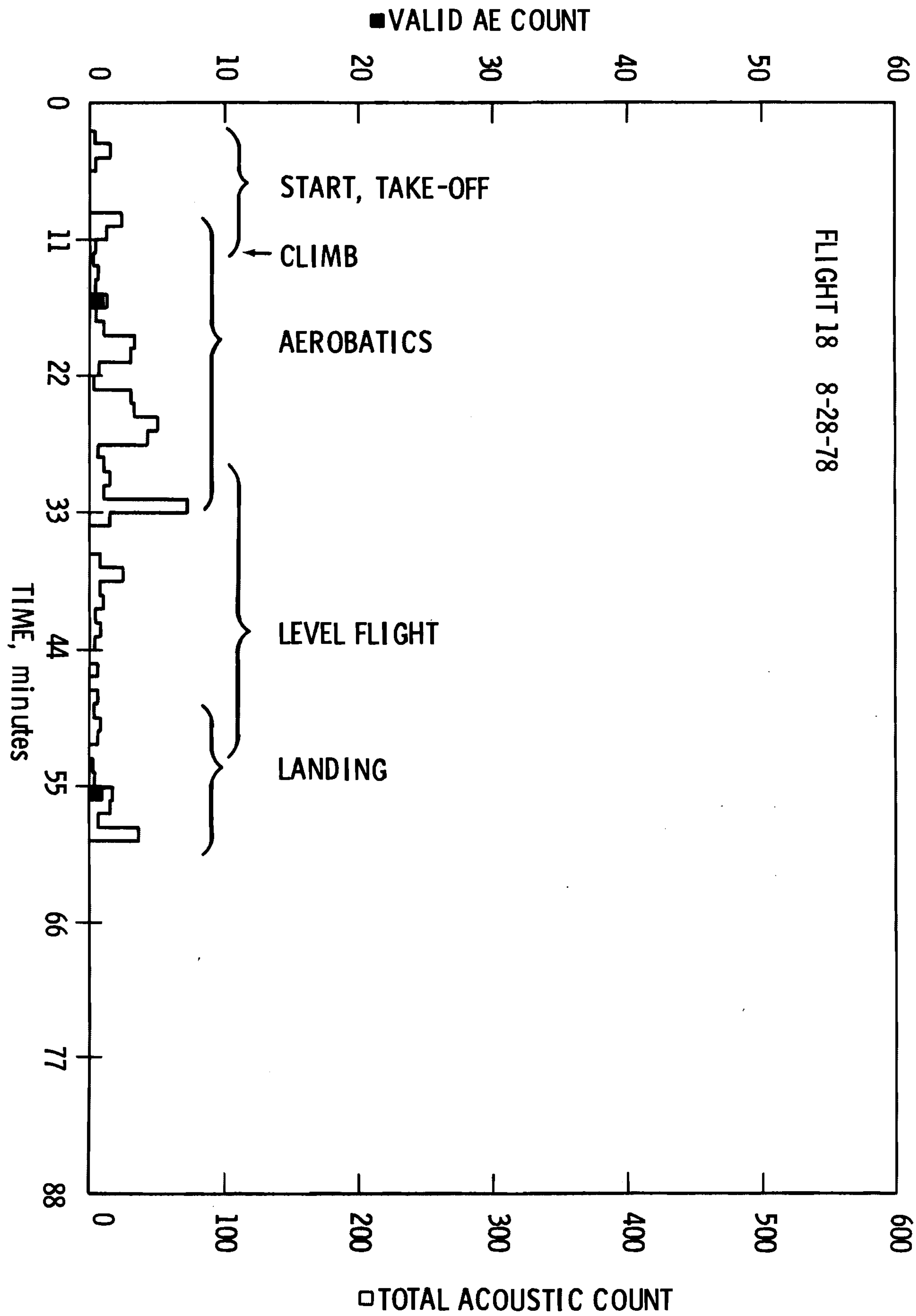

■ VALID AE COUNT
0
10
20
30
40
50
60
FLIGHT 13 8-25-78
ROLL OUT AND TAKE OFF
CLIMB TO 11,000'
FORMATION FLYING 1 HR Φ
LANDING
*NOTE: ALL TIMES ESTIMATED BY GGM EXCEPT Φ
0
11
22
33
44
55
66
77
78
TIME, minutes
0
100
200
300
400
500
600
□ TOTAL ACOUSTIC COUNT


■ VALID AE COUNT
FLIGHT 14 8-25-78
ROLL OUT AND TAKE OFF
FORMATION FLYING 1→2G Φ
30 MINUTES
LANDING
*NOTE: ESTIMATED TIMES EXCEPT Φ
TIME, minutes
0
11
22
33
44
55
66
77
0
10
20
30
40
50
60
0
100
200
300
400
500
600
□ TOTAL ACOUSTIC COUNT

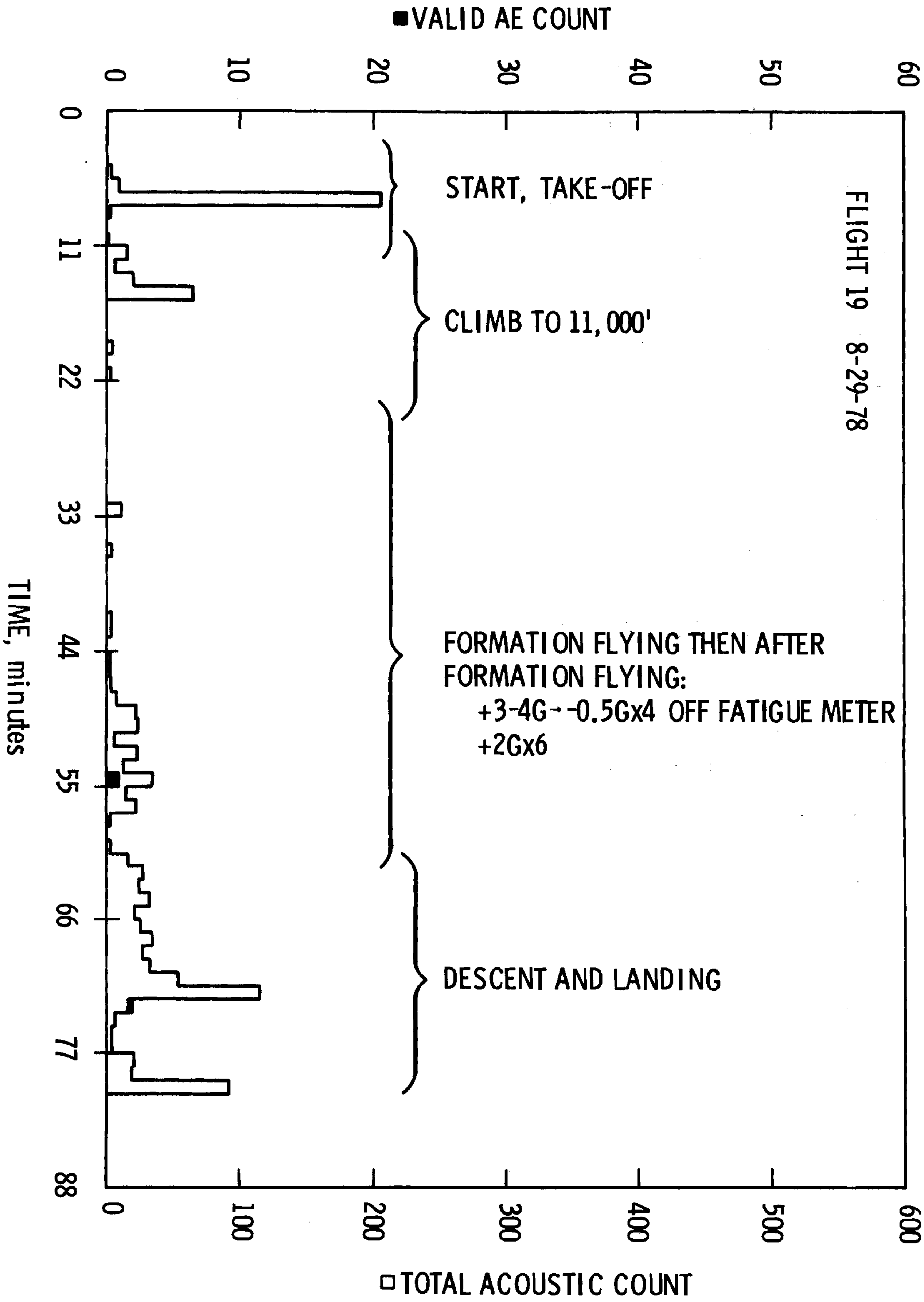

■VALID AE COUNT
0
10
20
30
40
50
60
START, TAXI, TAKE OFF AND CLIMB TO 9000'
FORMATION FLIGHT
LANDING, TAXI IN
FLIGHT 15 8-28-78
0
11
22
33
44
55
66
77
88
TIME, minutes
0
100
200
300
400
500
600
□TOTAL ACOUSTIC COUNT


■VALID AE COUNT
0
10
20
30
40
50
60
START, TAXI, TAKE-OFF, CLIMB
FORMATION FLYING INCL
2 LOOPS
DESCENT AND LANDING
FLIGHT 16 8-28-78
TIME, minutes
0
11
22
33
44
55
66
77
88
0
100
200
300
400
500
600
□TOTAL ACOUSTIC COUNT

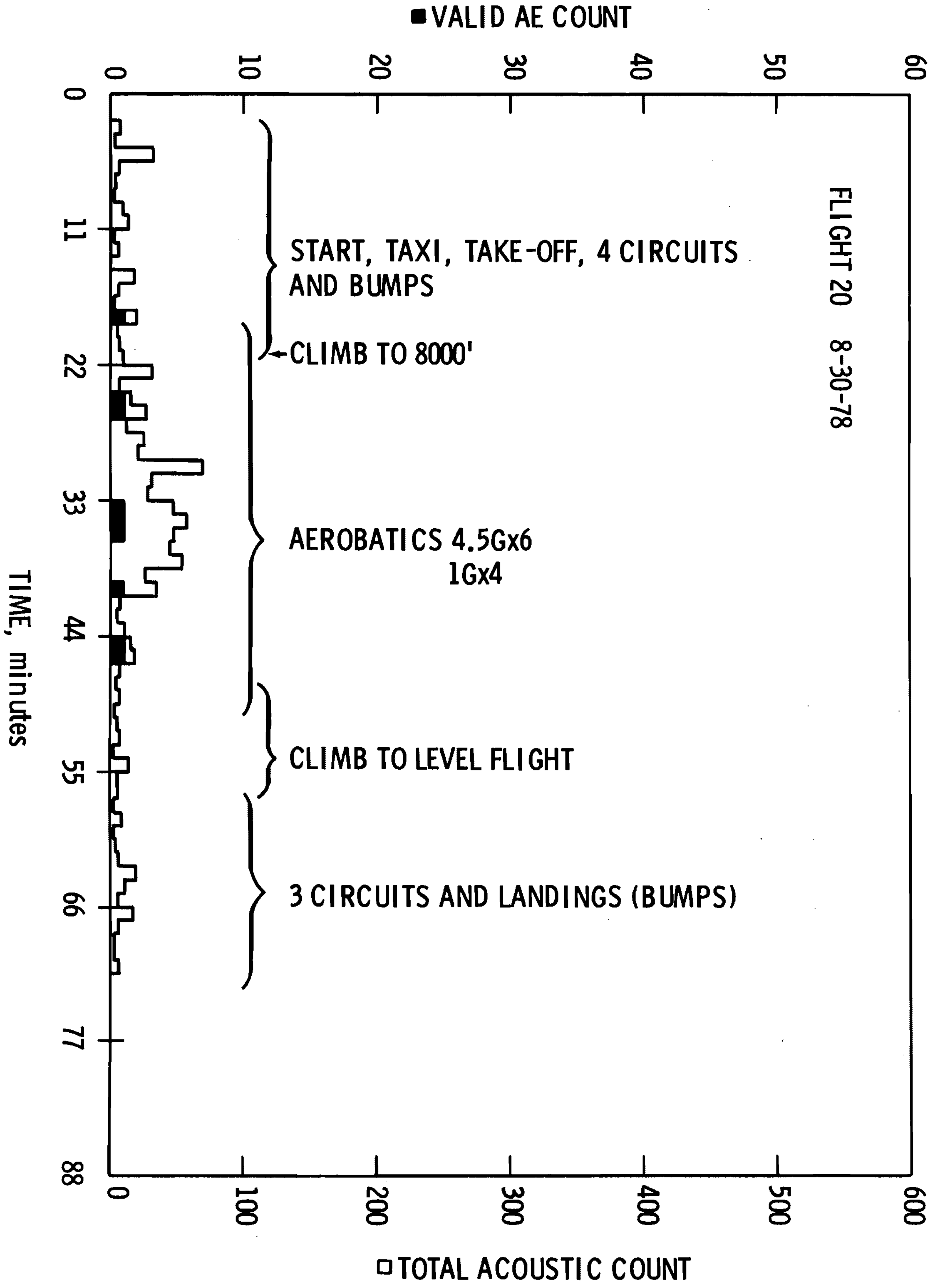

FLIGHT 17 8-28-78
■VALID AE COUNT
□TOTAL ACOUSTIC COUNT
TIME, minutes
START, TAXI, TAKE-OFF, CLIMB
FORMATION FLYING
LOW LEVEL FLYING, 500' AGL
RETURNING TO BASE
LANDING

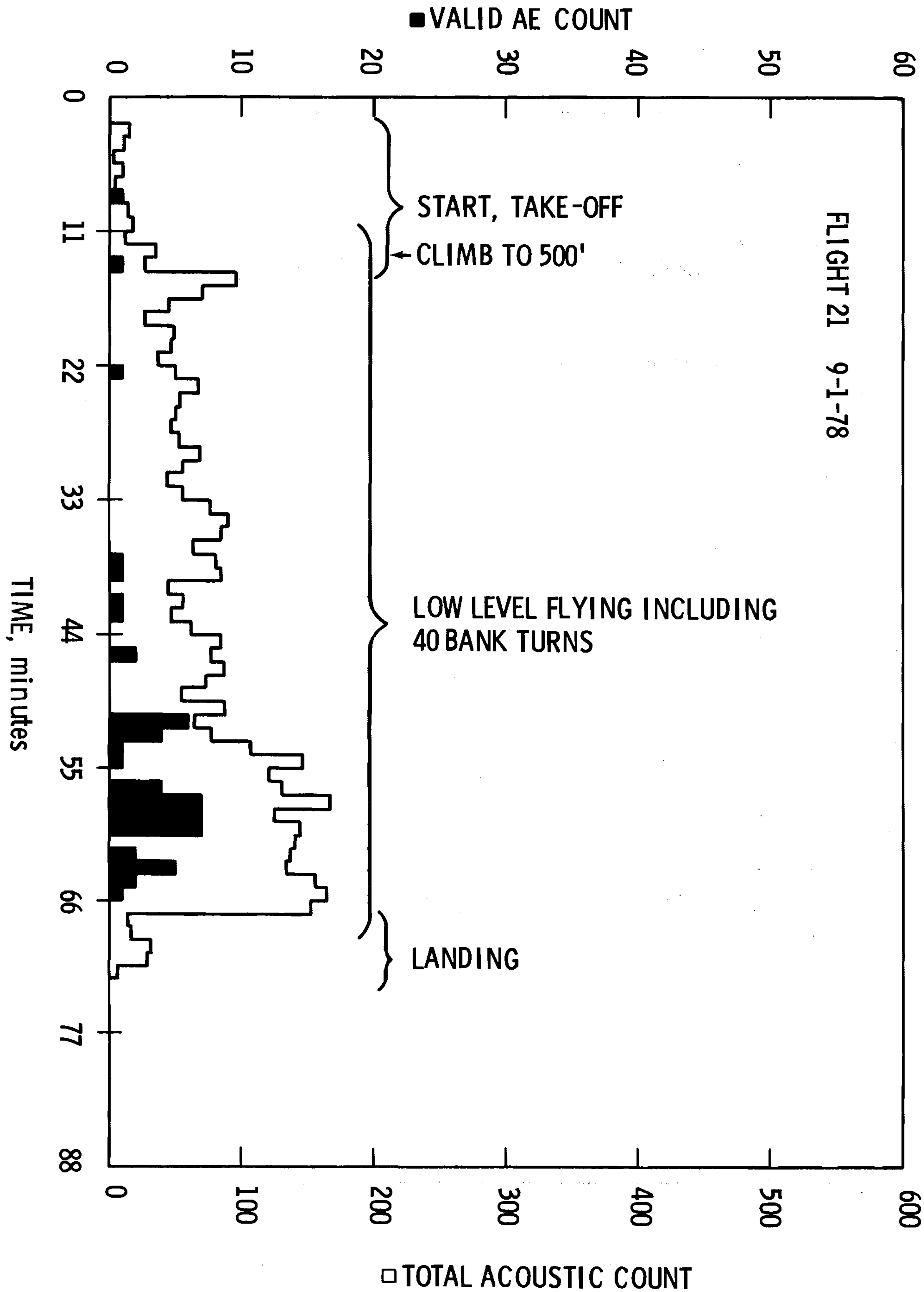


VALID AE COUNT
0
10
20
30
40
50
60
FLIGHT 18 8-28-78
START, TAKE-OFF
CLIMB
AEROBATICS
LEVEL FLIGHT
LANDING
0
11
22
33
44
55
66
77
88
TIME, minutes
0
100
200
300
400
500
600
TOTAL ACOUSTIC COUNT



■VALID AE COUNT
0
10
20
30
40
50
60
FLIGHT 19 8-29-78
START, TAKE-OFF
CLIMB TO 11,000'
FORMATION FLYING THEN AFTER
FORMATION FLYING:
+3-4G→-0.5Gx4 OFF FATIGUE METER
+2Gx6
DESCENT AND LANDING
0
11
22
33
44
55
66
77
88
TIME, minutes
0
100
200
300
400
500
600
□TOTAL ACOUSTIC COUNT


■ VALID AE COUNT
0
10
20
30
40
50
60
FLIGHT 20 8-30-78
START, TAXI, TAKE-OFF, 4 CIRCUITS
AND BUMPS
CLIMB TO 8000'
AEROBATICS 4.5Gx6
1Gx4
CLIMB TO LEVEL FLIGHT
3 CIRCUITS AND LANDINGS (BUMPS)
0
11
22
33
44
55
66
77
88
TIME, minutes
0
100
200
300
400
500
600
□ TOTAL ACOUSTIC COUNT


■VALID AE COUNT
0
10
20
30
40
50
60
FLIGHT 21 9-1-78
START, TAKE-OFF
CLIMB TO 500'
LOW LEVEL FLYING INCLUDING
40 BANK TURNS
LANDING
0
11
22
33
44
55
66
77
88
TIME, minutes
0
100
200
300
400
500
600
□TOTAL ACOUSTIC COUNT

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