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Development of a Multipurpose Smart Recorder for General Aviation Aircraft

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Prepared for

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Wallops Flight Facility
Wallops Island, Virginia

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SECTION 1

EXECUTIVE SUMMARY

1.1 BACKGROUND

An intelligent flight recorder, called the Smart Recorder, was fabricated and installed on a King Air aircraft used in standard commercial charter service. This recorder was used for collection of data toward two objectives: (1) the characterization of the typical environment encountered by the aircraft in terms of: velocity, V; acceleration, G; and altitude, H (collectively referred to as DVGH for Digital VGH data), and (2) research in the area of trend monitoring--the reliable detection of engine malfunction precursors allowing the maintenance-by-indication rather than by regular schedule. This effort is a continuation of NASA aircraft measurement programs which had as their objective the characterization of the environment seen by commercial aircraft.

During that effort, data processing routines and data presentation formats were defined that are applicable to the commuter size aircraft and thus establishing the requirements for the instrumentation system described herein. The purpose of this report is to summarize the development and application of the Smart Recorder.[1,2]

1.2 PRESENT EFFORT

A prototype recorder was fabricated using commercially available components augmented by custom hardware for the performance of specialized functions required for this recorder. The initial recorder configuration included a custom 50-channel, analog-to-digital conversion board, a fast, single-board microcomputer to provide processing capability and a removable

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1. J. Finger, L-1011 Interim Report #1, March 1978-August 1978, prepared by Research Triangle Institute for NASA-LRC under NAS1-16098, October 27, 1981.

2. J. Finger, L-1011 Interim Report #2, March 1978-February 1979, prepared by Research Triangle Institute for NASA-LRC under NAS1-16098, February 9, 1982.

bubble memory unit to provide non-volatile data storage. The initial software package developed for the recorder monitored analog inputs from sensors, determined the aircraft situation (e.g., takeoff, level flight, landing, or taxiing) and stored the data appropriate for that situation. Later, processing routines were added for on-board statistical processing of acquired data from the aircraft (especially accelerometer data).

The intelligence of the recorder provides the capability for adaptive sampling where the sampling of input signals may be modified in real-time in response to changes in aircraft situation. This capability is used to support trend monitoring by switching to a high- speed recording mode for engine parameters during engine start-up. Also the intelligence of the recorder is used to detect the aircraft situation (e.g., climbing, level flight, descent, or on-ground) so acquired data may be processed and tabulated accordingly.

The recorder was installed on a King Air aircraft used for charter service by Airlift Associates at Raleigh-Durham Airport. Signals from aircraft systems and installed sensors were connected to the recorder to provide information on aircraft altitude, airspeed, acceleration, and engine performance.

Data stored in the bubble memory are recovered and plotted using a laboratory microcomputer system equipped with a bubble memory cartridge interface. Software for archiving data and generating plots was written in FORTRAN, except for fundamental I/O routines which were written in assembly language.

1.3 PROGRAM ACCOMPLISHMENTS

The feasibility of a cost-effective, multipurpose recorder for general aviation aircraft has been successfully demonstrated. Operation of the recorder was verified by comparison of acquired data from the Smart Recorder with manually acquired data both by pilots during normal flights and by engineers during test flights. Automatic acquisition of trend monitoring data was performed simultaneously with the acquisition of DVGH data and the operation of a crash recording memory. Trend monitoring algorithms based on Pratt and Whitney manual engine trend monitoring data processing techniques showed less variability in the trend plots when compared against plots of the manual data. The lower variability allows earlier detection of a change in engine performance that could indicate the necessity of engine maintenance. The trend monitoring function of the recorder is especially important because the cost savings associated with a trend monitoring capability could partially offset the cost of the recorder and its installation on the aircraft. A significant reduction in per-unit cost would make possible a large-scale study to install the recorder in numerous aircraft for acquisition of DVGH data from a significant sample population of general aviation aircraft.

Implementation of on-board DVGH processing increased the number of flight-hours that could be stored on a single data cartridge and simplified the data management problem by reducing the volume of data to be processed in the laboratory. After on-board processing was implemented, 207 hours of DVGH data were collected and tabulated. These tabulations are presented in Section 6 of this report.

SECTION 2

INTRODUCTION

2.1 BACKGROUND

2.1.1 Previous Work and Scope

The effort described in this report is the culmination of an effort begun in 1980 in response to a need for aircraft use data identified by NASA Langley Research Center. In the early phases of the project, data collected on digital flight recorders on air transport aircraft operated by commercial airline companies were analyzed to characterize typical aircraft use. The objective of the effort was to produce a data set and statistics describing utilization of aircraft and the acceleration loading encountered by those aircraft during normal use. Such data would be useful in validating design requirements for the aircraft already in service and establishing requirements for new air-transport aircraft.

The processing of the flight recorder data consisted of converting the data to engineering units, validating the data, editing to remove bad data, and analyzing the data statistically. The validation of the data was complicated because of the lack of independent supporting data. Consequently, where inconsistencies were identified in the data (out-of-range values or contradictory measurements), the data usually could not be corrected. Instead it was often necessary to discard the questionable data before performing any statistical analysis on the entire data set. The effort required for validation and editing of the data was labor intensive. Data screening computer programs were written to check for anticipated data problems. However, since not all problems could be anticipated, an extensive manual review was still necessary.

The difficulties associated with the data processing effort pointed out the need for an improved data collection method which would acquire and store data more reliably to reduce the data management effort associated with the processing of the data on the ground. An in-flight recorder was proposed which would use microprocessor technology to provide the necessary intelligence to screen and preprocess data before storage, reducing both the quantity of data to be processed and the complexity of the data validation and editing to be performed on the ground. This recorder would make the maximum utilization of existing data sources on the aircraft such as the digital data busses and existing sensors analog outputs, but could also accommodate new sensors or existing sensors whose outputs were not presently connected to aircraft data systems (e.g., the aircraft integrated data system, AIDS). Ultimately, statistical tabulation of the data could be performed in the recorder, greatly reducing the volume of data which must be managed on the ground thereby reducing the attendant effort. The reduction in manual effort would allow the collection of data from a large sample of aircraft, paving the way for collection of data from a variety of aircraft types, aircraft operated in different geographical areas, and aircraft operated for different purposes (e.g., charter, freight, or corporate use). Thus the cost of automation of the data collection with a Smart Recorder would broaden the data base of characterized aircraft, offsetting the development and installation costs of the recorder.

An informal study was conducted to determine if a recorder could be built using existing commercial electronics technology. Single board computers were identified which would be capable of performing the necessary functions and timing studies were conducted on time-critical software functions. The conclusion of this study was that a recorder could be fabricated using board-level components available at the time (1981) that could satisfy the processing requirements within time constraints imposed by the required data rates.

During the data collection effort using commercial airline data, a significant data base was developed for air transport aircraft. However, no information was accumulated for the general aviation aircraft which significantly outnumber the air transport aircraft. In recognition of the scarcity of typical use and loading data for these smaller aircraft, the emphasis of the recorder development effort was shifted to the implementation of a recorder on GA aircraft (recognizing that much of the experience gained in the development of an intelligent, GA aircraft VGH recorder would be directly transferable to the development of recording equipment for the more sophisticated air transport aircraft). Shortly after the decision was made, the NASA responsibility for the Smart Recorder development effort was transferred to the Wallops Flight Facility of Goddard Space Flight Center because of the executive size aircraft based at Wallops that were considered as potential test beds for the recorder.

2.1.2 Motivation for Present Effort

In addition to the VGH data collection effort, there are other NASA research and operational interests which could be served by the development of an airborne flight recorder with a data processing capability. These interests include engine trend monitoring, ground-mobile or aircraft internal environmental monitoring, meteorological data collection (in situ), and crash recorder development. For the effort recently completed, support was obtained from within NASA toward the accomplishment of the following objectives:

- The development and demonstration of feasibility of an economical crash recorder for general aviation aircraft. Specific target applications included, initially, the NASA executive fleet with potential expansion to all general aviation aircraft. This application was driven by the NASA decision to equip their fleet with crash recorders in the wake of accidents involving those aircraft.

- Demonstrate the feasibility of VGH data collection and on-board processing on GA aircraft through implementation of a microprocessor-based recorder. This task was based on the NASA requirement to extend the VGH data base to GA aircraft which comprise the majority of aircraft in operation.

- Investigate engine trend monitoring using a flight recorder. Determine the improvement that may be realized using electronic data acquisition over traditional manual logging techniques. Trend monitoring capability allows the aircraft maintenance to be performed on the basis of indicated need rather than schedule, allowing the periods between required maintenance operation to be extended. The cost savings associated with the less frequent maintenance operations would provide an economic incentive for the fixed base operator to install recorders on his fleet. If at some time in the future, NASA elects to install flight recorder on one or more commercial GA aircraft, the cost savings realized by the fixed base operators might be used to reduce the cost to the government of installing and operating the recorders. This effort was encouraged by the interest and support from Pratt and Whitney Aircraft of Canada, Ltd. (Montreal, Canada) who provided technical information on processing of engine trend data and test facilities for evaluation of engine recorder performance.

2.2 PURPOSE AND OBJECTIVE OF PROJECT

The main objective of the effort described in this report is the development of a multipurpose recorder that may be cost-effectively applied to GA aircraft for DVGH data collection, crash survivable recording and engine trend monitoring. On-board processing was a requirement to maximize the use of on-board memory and reduce the amount of data to be processed on the ground. A removable non-volatile memory cartridge was required for the transfer of data from the recorder to a ground-based data processing for final processing and archival of the data.

The effort was conducted as a logical sequence of activities that together led to the implementation of a Smart Recorder capable of collecting and processing VGH, engine trend data and which provides a crash survivable recording capability. The specific phases were:

- Design and fabricate a microprocessor-based recorder that would monitor and store a small number of aircraft parameters. Processing would be limited to recognizing aircraft situation (takeoff, climb, cruise, descent, or landing) and modification of sampling strategy based on the perceived aircraft situation.

- Develop software on laboratory computer to statistically process the aircraft VGH data collected. The development of these routines in the laboratory allowed their refinement in an environment where they could be easily modified and verified until the desired performance was achieved.

- Implement DVGH processing software in programmable-read-only-memory (PROM) and installation in the aircraft.

- Process engine trend monitoring data and compare with manually acquired data to determine if trends could be detected earlier in electronically acquired data than in the manually acquired data (i.e., can the sensitivity of the detection process be improved through electronically monitoring and processing the engine parameters?)

- Study various data storage requirements developed for crash survivable recorders to determine if the appropriate data can be collected and stored in a crash survivable memory for the desired time interval.

- Procure a crash survivable memory and construct the required interface for the Smart Recorder.

The parcelling of the overall effort into these segments reduced the scope and complexity of the development effort at any time. Hardware or software developed during each phase were completely tested and evaluated before proceeding to the next phase.

SECTION 3

DEVELOPMENT OF RECORDER

3.1 REQUIREMENTS FOR RECORDER

The requirements for the Smart Recorder were dictated by the stated objectives of acquisition and statistical tabulation of VGH data, acquisition of engine trend monitoring data, and the demonstration of a crash recording capability in an economical recorder. The recorder was intended for application in general aviation aircraft (business charter or executive service) which meant that the required information would have to be derived from analog signals from aircraft sensors or from sensors installed to monitor the desired parameters where no existing sensor was installed. Table 1 lists the required parameters to be monitored in the first application.

The recorder was being designed to acquire data for a program that had dynamic goals which could only become completely defined once preliminary results were received. Hence, the recorder had to be reconfigurable, being designed to initially to accommodate the parameter list given in Table 1 with provision for accommodating additional sensors as the need arose. There were no stringent requirements on the form or packaging of the recorder as the purpose of this prototype recorder was simply to demonstrate the feasibility of a monitoring concept. As such, the recorder did not have to resemble a production aircraft flight recorder. However, it was required that the recorder be able to serve functionally as a flight recorder in an operating aircraft without degrading the integrity of any of the aircraft systems to which it is connected.

The general requirements for the prototype Smart Recorder are described below.

- Low Cost--Since the recorder was intended to demonstrate the feasibility of a cost-effective flight recorder, the recorder should be constructed in such a way that it could be mass-produced economically. Although the prototype was intended only

TABLE 1. ORIGINAL LIST OF PARAMETERS TO BE MONITORED BY THE SMART RECORDER

Parameter	Abbreviation	Sample rate
Indicated Airspeed	IAS	1
Engine Inlet Temperature	T_2	1
Engine Inlet Pressure	P_2	1
Propeller Speed	NP	1
Torque	TQ	1
Gas Generator Speed	NG	1
Interturbine Temperature	ITT	1
Fuel Flow	WF	1
Bleed Valve Position		1
Acceleration (3-axis)	G	4

to fit the function of a GA flight recorder and not necessarily the "form," it was recognized that the recorder should employ the same electronic architecture and logic types as the mass-produced units could employ. The use of esoteric, high cost components in the prototype recorder would not demonstrate the feasibility of producing a low-cost recorder even if the functions of the expensive items could be reproduced in inexpensive components. To accomplish this requirement, the recorder was built using commercially available components at the highest level of integration available--typically commercially printed circuit boards.

- Intelligent--The necessity of adaptive sampling (varying the group of parameters sampled based upon the sensed aircraft situation--i.e., takeoff, climb, cruise, descent, or landing) requires that acquired sensor data be processed in real time to determine aircraft situation and the sampling strategy be modified in a predetermined, appropriate manner based upon those determinations. This processing is most easily performed through programmable logic functions such as a microprocessor. The requirement for an on-board microprocessor is further supported by the requirement for on-board tabulation of VGH data, establishing the necessity for a computational capability within the recorder.

- Reconfigurable--Since the recorder is to be used in a program where the functions of the recorder are defined based on previous experience, it is necessary that the recorder be reconfigurable to provide for the evolutionary development of the recorder. Both functions which are inherent in the software and hardware must be upgradable. Software, of course, may be easy modified by exchanging the memory elements (e.g., programmable read only memories--PROMs) with units containing the replacement code. Provision for hardware modification may be made through use of a standardized bus on a motherboard (e.g., multibus, standard bus) for interconnection of plug-in processor and peripheral interface cards. This allows the use of existing commercially available cards at the time of development and the replacement of these with more capable versions as they become available

- Capable of Unattended Operation--The recorder must operate in the aircraft environment with no required attention from the pilot. Operation should begin with an automatic initialization upon power-up. Any determination of aircraft situation (climb, descent, cruise, taxiing, etc) must be made based on sensor inputs and not from pilot input.

- Compatible with Aircraft Sensors--The recorder (or associated signal conditioning electronics) must be capable of extracting information from sensor signals in the normal forms found on aircraft. For instruments listed in Table 1, electrical signals will have the information encoded in the frequency of an sinusoidal source, the relative phase of a multiphase signals (synchro signals), voltage level, or resistance.

- Operate from Aircraft Power--The recorder must operate from the power source for the aircraft it is to be used on. Although some aircraft have 110-VAC, 60- or 400-Hz power available, smaller GA aircraft have only 28 Vdc. This voltage level is subject to wide variations, depending on a the type of battery available and maximum electrical bus loading. Voltage drops in excess of 50% during engine start-up are normal.

3.2 INITIAL HARDWARE DESIGN

3.2.1 System Configuration

To take advantage of commercially available, single-board computers and existing signal conditioning equipment, the system configuration shown in Figure 1 was selected for the prototype implementation. In this configuration, all signals are converted to voltage signals (with a uniform range of 0 to 10 Vdc) by signal conditioning modules mounted external to the recorder. The recorder module then has only to perform the functions of voltage measurement, data manipulation (data analysis or data compression), and storage. These functions are performed by a single-board computer, a multichannel analog-to-digital converter system, and a removable cartridge data storage system. The removable cartridge allows the transfer of monitored data to a laboratory computer for further processing and data archival.

A crash-survivable recording capability is provided by a crash survivable memory which is mounted external to the recorder. Conventionally, these memory units are mounted in an aircraft location where there is the least physical shock or risk of fire in the event of a crash (e.g., the tail section). For this system, a crash survivable memory was obtained from Hamilton Standard which had been certified to meet the criteria specified in TSO-C51a.[3] For this feasibility demonstration, this memory unit, herein called the Environmentally Protected Auxiliary Memory (EPAMs) was mounted adjacent to the recorder. Connection between the EPAMs and the recorder was made with a multiconductor cable.

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3. U.S. Federal Aviation Regulation, Part 37.150, AIRCRAFT FLIGHT RECORDER TECHNICAL STANDING ORDER, TSO-C51a.

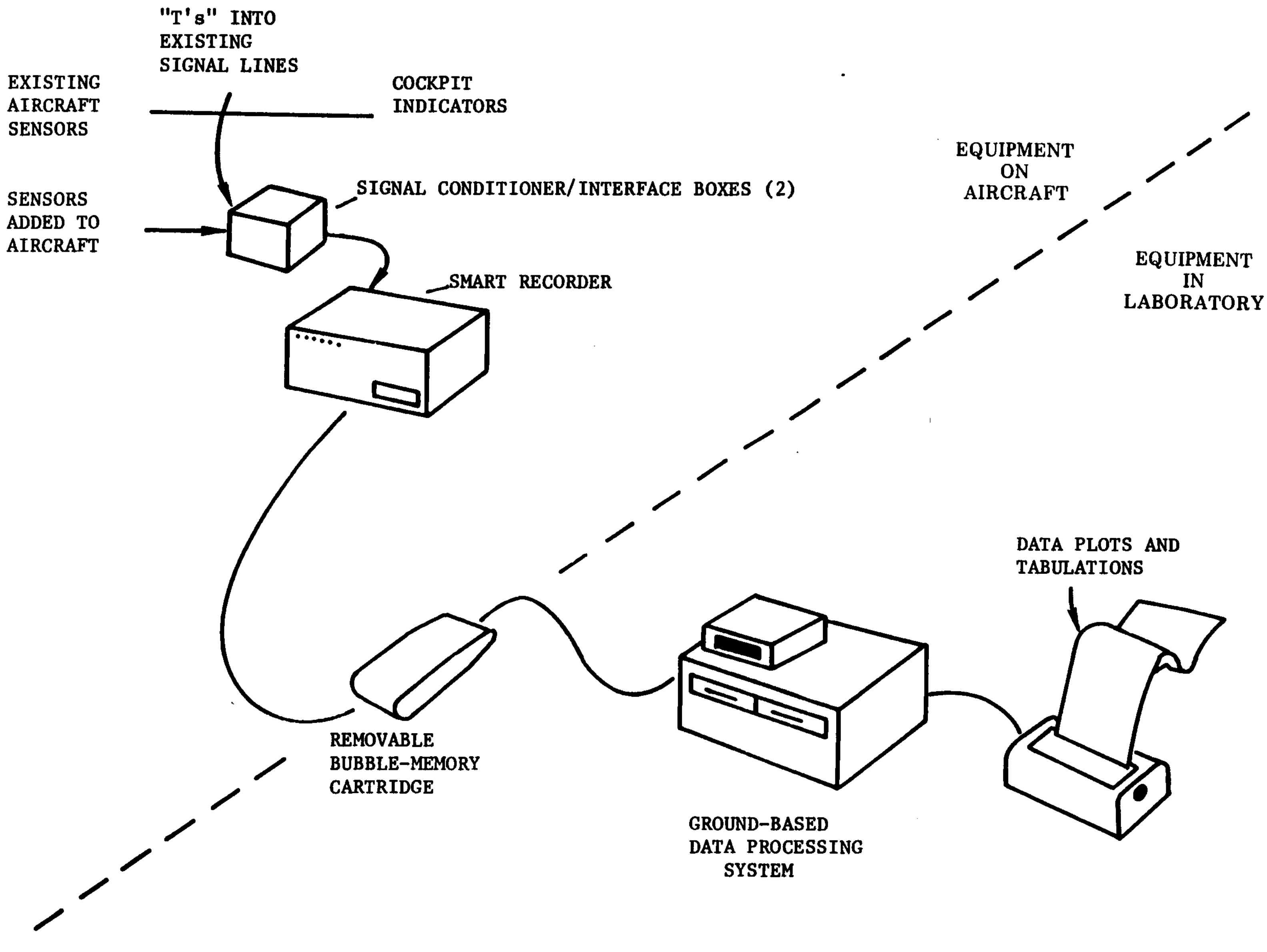

Figure 1. Smart Recorder System Concept

3.2.2 Recorder Design

The Smart Recorder is essentially a microcomputer-based data acquisition system with a removable bubble memory for transfer of the acquired data to a ground-based processing unit. The recorder is shown schematically in Figure 2. Components within the recorder are listed below:

- Microprocessor Board--Control and on-board processing is performed on an SBC 86/14 single board computer (Intel). This board contains the 8086 microprocessor running at 5 or 8 Mhz, up to 32K of random access memory, up to 64K of programmable read only memory, a serial I-O port, timers, and a 24-parallel-line I/O interface. The interface for the environmentally protected auxiliary memory (EPAMS) was built on the patch area of this board provided for the fabrication of custom interfaces. The board is a Multibus (Registered Intel Trademark) board.

- Analog-to-Digital Converter Board--The custom-fabricated A/D board contains a single 8-input, 12-bit analog-to-digital conversion module with six 8-input, analog multiplexers to provide 50-channel capability. The A/D converter is a Data Translation DT5712 with programmable gain, selectable bipolar/unipolar inputs, and selectable single-ended/differential inputs. In this application, the A/D was set up for 0 to 5 Vdc input with differential inputs. Eight-input, differential CMOS multiplexers (Datel MXD-807) were used to allow connection of 48 inputs to six of the A/D modules inputs. The two A/D inputs not connected to multiplexers were connected to reference signals (0 and 5 Vdc) to provide a convenient means for verifying the A/D zero and span settings on a routine basis. Control signals for multiplexer input selection and sampling were supplied through the parallel I/O port on the microprocessor board.

- Filter/Isolation Board--A filter/isolation board containing RC filters for each channel is connected between the input connectors and the multiplexers to reduce the effects of induced electrical noise on measured values and to provide electrical isolation to protect monitored circuits from short circuits in the unlikely event of an internal multiplexer failure.

- Bubble Memory Holder--The bubble memory holder serves as the mechanical and electrical interface for the Intel Plug-a-Bubble memory cartridge. The holder is mounted so that the cartridge may be inserted into the holder through an opening in the front panel. Once installed, the cartridges are retained by a cover fastened to the panel with quarter-turn fasteners.

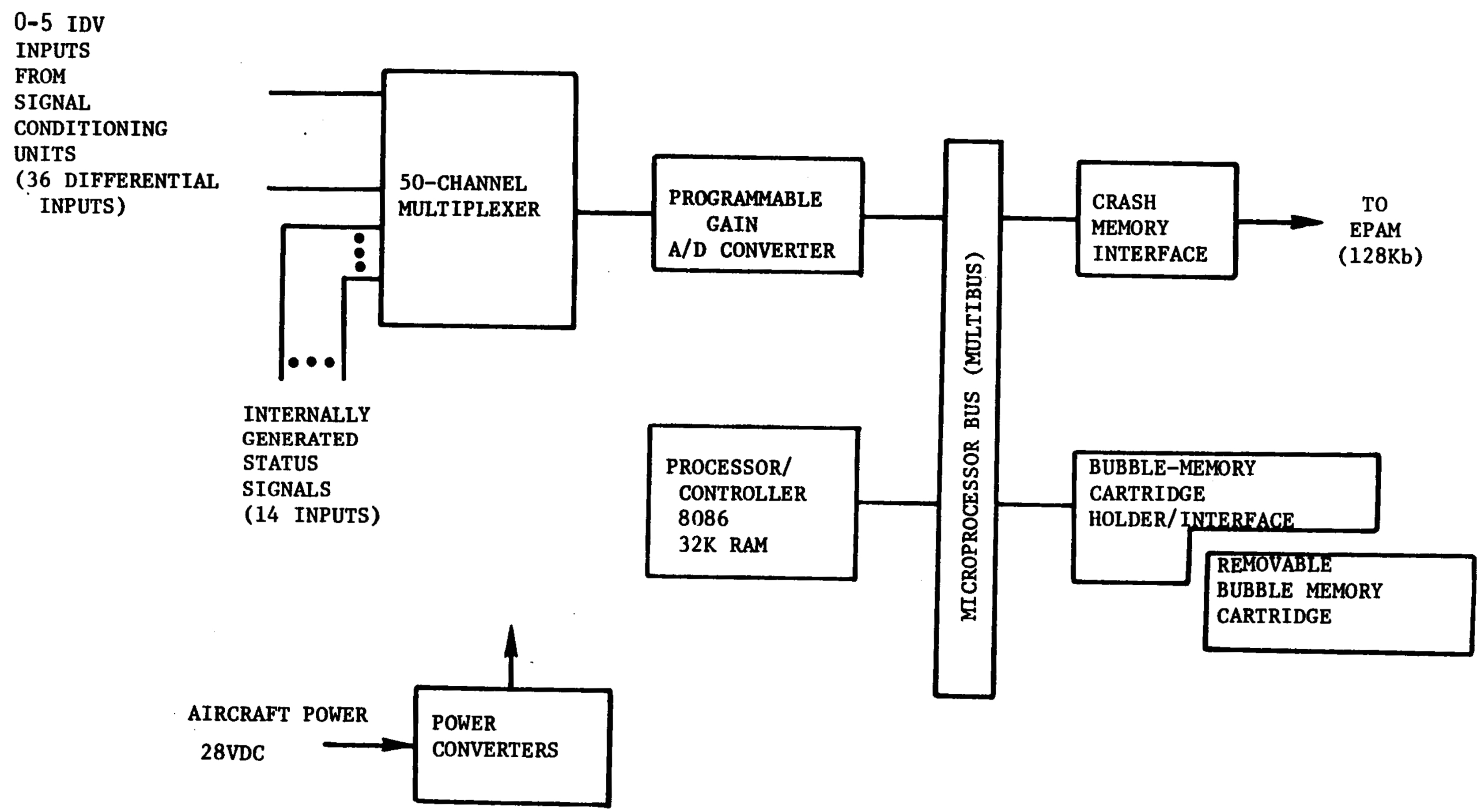

Figure 2. Block Diagram of Prototype Smart Recorder

- Power System--Overcurrent protection, filtering, and voltage translation are provided by the power system. The major components in this system are dc-dc switching converter modules which convert the nominal 28 Vdc aircraft power to levels need by the solid-state circuits (+5V, ±12v and ±15V). A critical selection criteria for the power converters was input voltage range. The selected units could function with input voltages from 9V to 40V, a requirement if the recorder is to continue to operate while the engine startup. Other components in the power subsystem include a circuit-breaker (with backup fuse) and transient suppressors.

The recorder was packaged in a commercial instrument cabinet, reinforced to withstand the aircraft environment and to facilitate mounting of internal components. The layout of components in the enclosure is illustrated in Figure 3. Cooling of electronic circuits is done with thermostatically controlled fans. Additional protective temperature limit switches are used to power down the system when temperature limits are exceeded.

External signal conditioners were installed in two instrument boxes to adapt the outputs of the various sensors to the 0-5Vdc input range of the A/D converter. Signal conditioning circuits included frequency-to-voltage conversion, synchro-to-voltage conversion, resistance-to-voltage conversion, contact sensing, and simple voltage scaling (voltage division and amplification).

3.3 SOFTWARE DEVELOPMENT FOR RECORDER

3.3.1 Software Development Environment

Software for the recorder is ROM based and uses the 32K of random access memory for the storage of dynamic data (acquired data, calculated results, and any other data which may change). Since the software does not require the services normally provided by an operating system (program loading, input/output to conventional peripherals, etc), the software was written as a self-contained module. Logic was included to schedule function performance, handle I/O with the A/D system and the memory unit, and perform the necessary calculations.

Software was developed on a Zendex laboratory microcomputer, a multibus based system using the Intel 8086 processor. This system includes two 8-inch

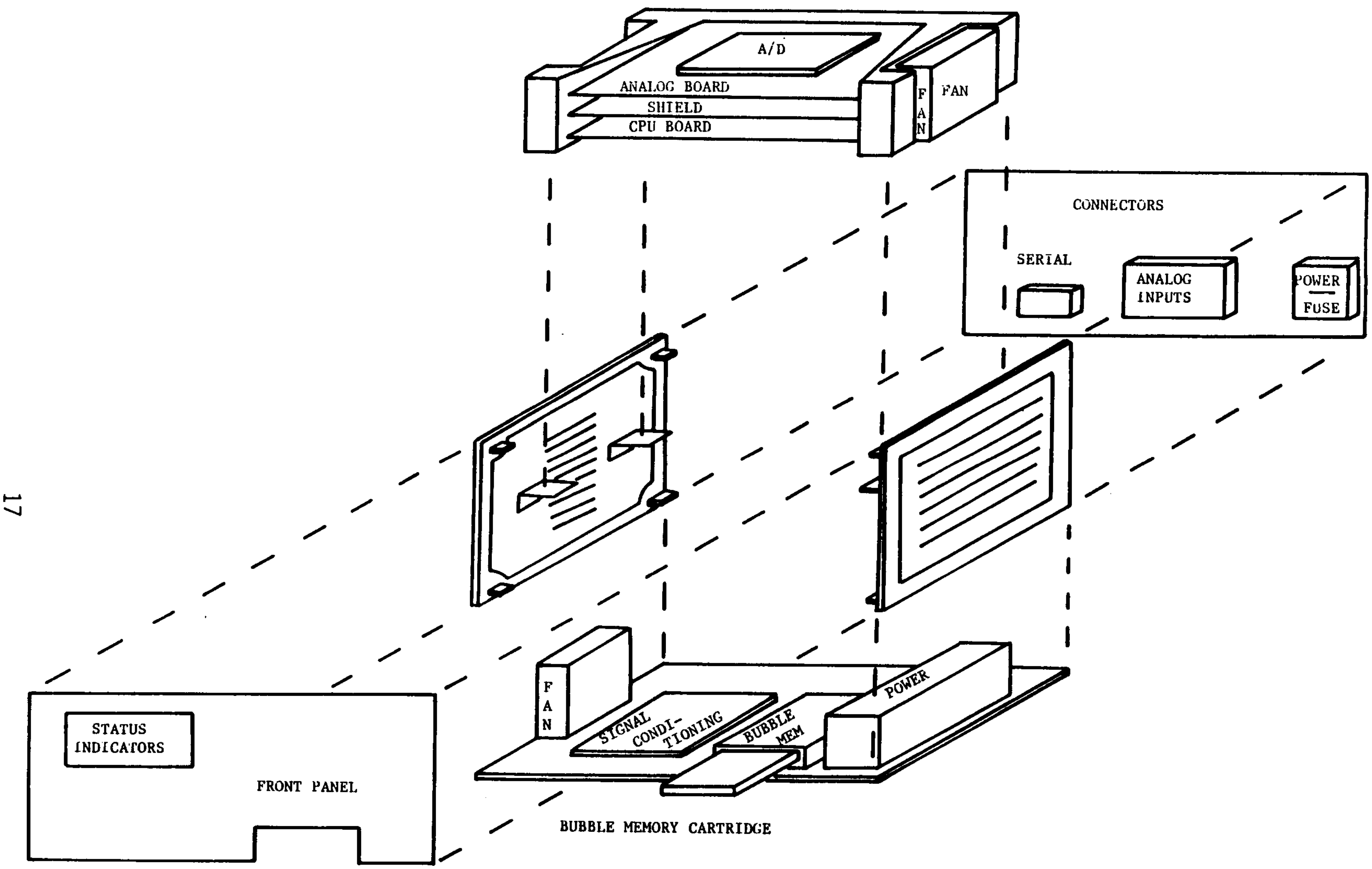

Figure 3. Physical Layout of Prototype Smart Recorder

floppy drives and runs under the CP/M-86 operating system. The Multibus* backplane is the same used in the Smart Recorder, so the processor and peripheral boards could be plugged into the Zendex system for testing in the laboratory environment. More importantly, many of the existing tools used for software development on the Zendex microcomputer could be used for development of software for the recorder, including assemblers, editors, utilities for linking and library management and source/object file management utilities.

All code was written in assembly language and compiled using the an Intel assembler. Code was modularized to provide a clear software organization and to facilitate software updates (only the modules associated with the function to be updated have to be modified). Software debugging was carried as far as practical on a laboratory development system which utilized the same processor and bubble memory storage system as the Smart Recorder. Program modules were tested individually or in small groups using simulated data to verify the module's function. Next all the modules were linked with a dummy data input module which generated a data stream simulating the output of A/D interface routines. Both the standard bubble-memory data storage routines and supplemental CRT-display routines were used to present data concerning the operation of the software system. In this manner, software could be more easily evaluated and debugged through use of the debug utilities and display devices available only on the development system. Once testing was carried as far as possible on the development system, the executable image was burned into PROMs and installed for testing on the target system--the Smart Recorder. Software was incorporated in the Smart Recorder for recognizing if a CRT were connected to the recorder, and if found, to allow an operator to control software execution from the keyboard, and display interim results on the screen, thus providing a mechanism for monitoring and verifying software operation both before and after installation. Next, the recorder was operated in the laboratory with artificially generated signals simulating those from aircraft sensors. Operation was monitored with a logic analyzer and CRT display. Overall program execution was finally verified by dumping the memory cartridge and comparing the data with the manually calculated values.

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*Registered Trademark Intel Corporation.

3.3.2 Functions of Software

Within the constraints of the hardware, all recorder performance characteristics are determined by the software, including data sampling rate, number of channels sampled, averaging interval, etc. Under the original version of the software, the acceleration data (3 channels) were sampled at every 0.25 sec and the remaining channels are sampled once per second. One minute averages for each channel are computed, and the positive and negative peak values for each minute are found for the three acceleration channels. Data stored in the bubble memory cartridge included 1-minute averages for each of 26 channels, the positive and negative peak values within the one-minute interval for the three acceleration channels, and 0.5-Hz samples for 8 selected channels. The 0.5-hz data provide the fine time resolution data for special processing such as that required for off-line determination of acceleration level crossings. Later, when on-board DVGH processing was implemented, additional acceleration data consisting of 24 "level-crossing" values were stored each second in the bubble memory cartridge along with the raw data. In this configuration, the 128-kbyte bubble memory is capable of storing approximately 4.5 hours of data. Once DVGH processing was verified, the amount of stored time-series data was further reduced to extend the recording interval for one cartridge to 15 hours. The modifications are described in Section 3.2.3.

The processing performed by the recorder may be readily reconfigured to accommodate changes in sensor configuration, desired processing, etc. A configuration table, loaded into the bubble memory cartridge by the ground base unit, is read by recorder software upon power-up. Entries in this table determine sampling and recovery strategy, i.e., which channels are time-averaged, which are stored as raw sampled values, and which are processed in a special or unique way such as generation of maximum or minimum values for specified periods. The functions of the recorder may be modified by editing this table (using the ground base bubble memory cartridge access utilities operating in the ground base unit) thus eliminating the need for removing the recorder from the aircraft to make changes. Modifications made through this process are limited to changing options and enabling/disabling features incorporated into the software stored in PROMs. With this arrangement, it is still necessary to replace the PROMs to implement major changes.

3.3.3 Software Organization

As mentioned previously, software for the smart recorder was written as modules, each designed to perform a function or group of related functions. Modules were written to control the data acquisition process, to process the acquired data, and to perform the services normally provided by an operating system such as input/output control and task scheduling. The modules are integrated into a single module which does not require the services of external software to execute. Hence it can be "burned" into PROMs and will begin execution in the Smart Recorder upon application of power to the processor.

The software executing in the Smart Recorder is functionally described in the flowchart in Figure 4.

The functions of each of the modules that comprise the current version of the recorder software are briefly described below:

- SYSMANGR--Control program which schedules execution of all other modules.
- RAMTEST--Writes and reads pattern to test RAM.
- PROMTEST--Computes checksum on contents of PROMs and checks against stored value to verify integrity of stored code.
- CPUTEST--Verifies operation of the 8086 CPU by comparing results of large number of instructions with the expected results.
- BUBTEST--Tests the ability to read and write to a page in bubble memory reserved for this purpose (does not overwrite existing data).
- ADBTEST--Tests analog board by verifying that ground and reference analog inputs return the expected values.
- SYSSETUP--Initializes interrupt vectors, timers and peripherals. Checks to see if CRT terminal is connected to the system for on-line testing.

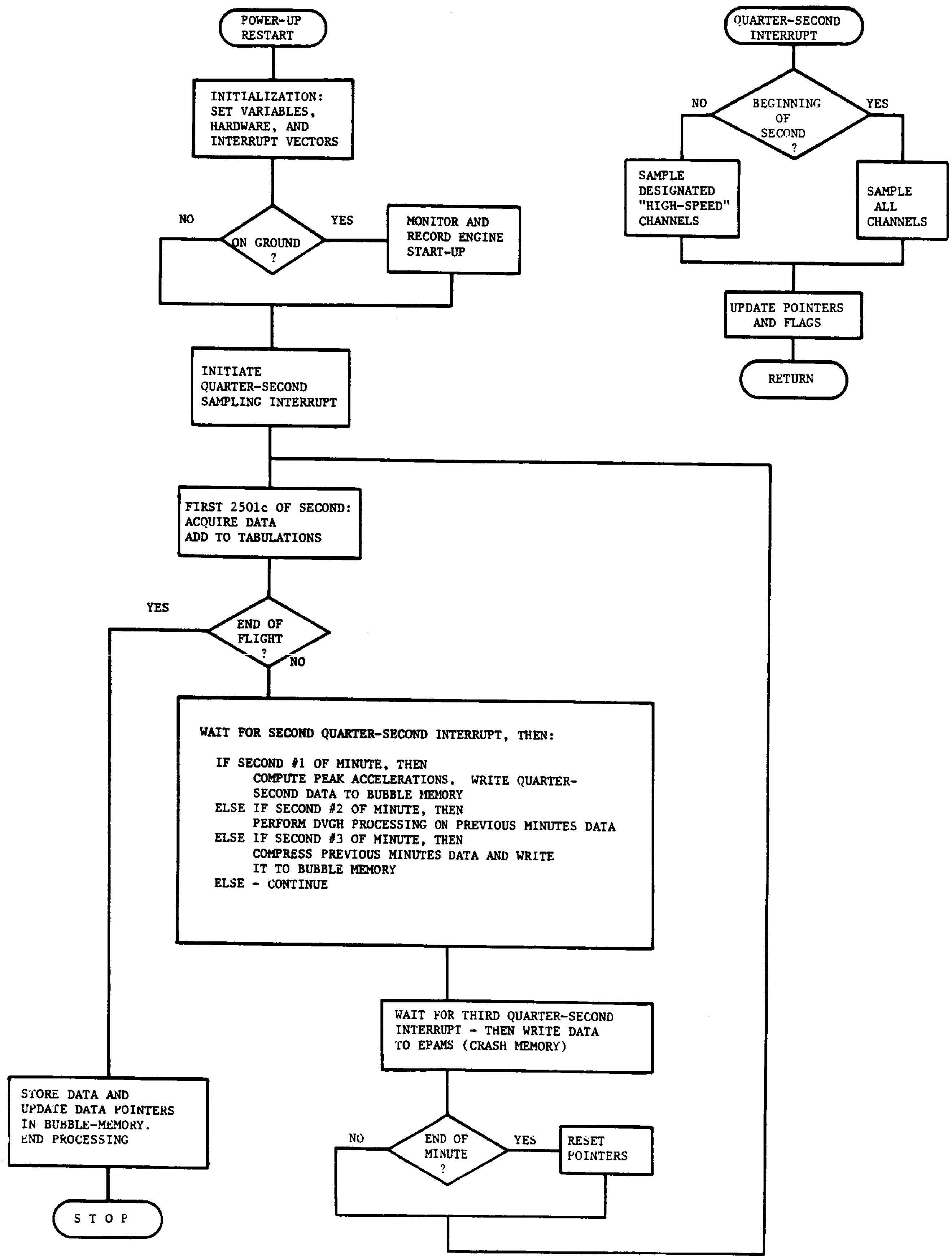

Figure 4. Organization of Prototype Smart Recorder Software

- BUBCONST--Loads configuration data from bubble memory into memory and tests to see if bubble memory can accept additional data (i.e., cartridge is not full).

- POWERDWN--Adds end-of-flight marks to stored data and saves pointers in the non-volatile memory for reloading upon power-up.

- DIAGNOS--Called upon detection of error condition to log information about the error in the bubble memory for later interpretation.

- DELAY5M--Provides a 5-minute delay. Checks for input from terminal during delay period and, when input is detected, calls routine to service the entered request.

- LITPANEL--Controls status lights on the front panel of the recorder.

- SETVAR--Initializes program data. Called during power-up sequence.

- RECORDLP--Manages the data recording tasks including engine startup recognition, one-second sampling, calculation and storage of one-minute averages, data compression and analysis and flight status/sensor checks.

- ENGSTART--Recognizes engine start and acquires engine data with fine time resolution during engine startup.

- FRAMERCD--Records all channels and store results in buffer for access by averaging and other processing routines.

- FRAMEAVE--Processes the one-second scan data acquired by FRAMERCD, averaging all channels which contain data from the same source to remove redundant data. Final result is a set of 38 data points produced from an original set of 50.

- SENSORCK--Checks sensors for out-of-range values.

- FLIGHTST--Determines the flight status or mode: taxi, takeoff, landing or in-flight.

- TAXIMODE--Used by FLIGHTST to determine if the aircraft is taxiing.

- TAKEOFFM--Used by FLIGHTST to determine if the aircraft is taking off.

- LANDMODE--Used by FLIGHTST to determine if the aircraft is landing.

- DATACOMP--Computes minute averages of sampled data put in buffer by FRAMEAVE. Also merges selected raw data with the averages for verification of DVGH processing.

- DATSTORE--Writes data buffer to bubble memory.
- HIGHSPD--Writes raw (unaveraged) data to bubble memory.
- SAMPLEAD--Subroutine which controls the A/D converter and multiplexer to acquire the data for the specified channel.
- TRENDS--routine for in-flight analysis of trends in data. This routine is provided for future expansion.
- SAMPACC--Samples acceleration data and stores them separately from the data to be averaged.
- ACCPEAK--Determines positive and negative peaks of acceleration data during 1-minute period.
- INTERCD--Interacts with operator through CRT while in the interactive mode. Prompts operator to enter operation desired and calls appropriate routine to execute that function.
- MPUCHECK--Performs CPU check and informs operator of result (if terminal is connected).
- PROMCHCK--Performs PROM check and informs operator of result (if terminal is connected).
- BUBCHECK--Performs bubble memory check and informs the operator of the result (if terminal is connected).
- MEMCHECK--Informs the operator of the results of the memory power-up memory test (if terminal is connected).
- CHANSCAN--Reads all 50 analog inputs and displays values on CRT.
- MONITOR--Reads a single channel once per second and displays the reading on the CRT.
- CRTCAL--Calls MONITOR to acquire and display input data for determination of calibration data.
- BUBCRT--Reads page specified by operator from bubble memory and displays it on CRT.
- LEDCHECK--Cycles front-panel LEDs upon operator command. For use as a lamp-test routine.
- ABCHECK--Performs analog input system check and reports results to operator.

- EPAMDUMP--Retrieves 16 bytes from EMAM and displays it on the screen.

- BUBBLE--Utilities to perform low-level I/O functions for bubble memory including controller initialization, input and output.

- SERIAL--Driver for serial port (used to communicate with CRT).

- PARALLEL--Driver for parallel port (used for lamp control and A/D input).

- TIMERS--Loads registers in system timers for establishing the serial port baud rate and hardware time delays.

- INTRCTRL--Sets interrupt controller used for bubble memory transfers.

- MISC--Miscellaneous data conversion utilities, e.g., binary-to-hex conversion, decimal-to-binary conversion.

- INTERUPT--Interrupt service routines used for bubble memory transfers.

- TABULATE--Computes and tabulates statistical parameters for the DVGH data analysis.

- BINPOS--Determines appropriate bin for altitude, airspeed, and acceleration from monitored data. (Used in DVGH processing).

- FLTMODE--Determines whether aircraft in ascending, descending or flying level when in flight.

- MAXVAL--Determines maximum and minimum values and accelerations throughout a flight.

- TABLESUM--Sums tabulated DVGH data throughout a flight.

- DVGH--Complete DVGH processing upon landing and stores the results in the bubble memory.

- LOADDVGH--Reloads cumulative DVGH data from bubble memory and checks against values already in memory to verify their accuracy.

- PERFLT--Formats and stores "per-flight" data in bubble memory.

- ACCUMFLT--Adds current "per-flight" data to cumulative data taken from bubble memory and writes result to bubble memory.

- STOREP--Writes data to EPAM, observing 10 ms write speed duration requirement of the EARAM chips.

- LOADDEP--Puts data in buffer for use by STOREP to load into EPAM.
- EPAM--low-level functions for EPAM including read, write, initialize, and 10-ms delay.

3.4 RECORDER CHARACTERISTICS AND CAPABILITIES

The maximum performance characteristics are determined by the capabilities of the hardware comprising the Smart Recorder. Table 2 summarizes the characteristics of the recorder hardware.

The capabilities of the Smart Recorder are determined primarily by software operating within the constraints imposed by the capabilities and limitations of the hardware discussed in the previous paragraphs. System capabilities provided by the current version of software residing in the recorder are summarized in Table 3.

3.5 VERIFICATION OF PERFORMANCE

Once construction of the Smart Recorder was completed, several tests were performed to verify its performance. Initially laboratory testing was used in conjunction with the software debugging process to verify proper software execution. Simulated sensor signals were applied to the recorder for critical parameters such as static and differential pressure, engine speed, etc. The response of the recorder to various signal profiles was compared with the expected response to verify that the algorithms used were correctly determining the state of the aircraft and that the recorded data agreed quantitatively with predicted values.

Once the recorder was installed on the aircraft, additional testing was performed to verify the reasonableness of the acquired data. Plots of data retrieved from the bubble memory were examined for consistency with pilot logs to verify system operation under actual operating conditions. Also test flights were conducted where engineers, flying as passengers, recorded values from cockpit displays for quantitative comparison with data stored on the bubble memory cartridge.

Perhaps the most comprehensive evaluation of recorder performance were the tests conducted on an engine test cell at the Pratt and Whitney facilities in Montreal, Canada. The primary objective of these tests was to verify the

TABLE 2. SMART RECORDER SPECIFICATIONS

Input Characteristics:	
Total Input Channels	50
Available for connection to sensors	26
Number used for "housekeeping" functions	6
Number used for reference monitoring	18
Input range	0 - 10 Vdc
Max sample rate (per channel)	1000 samples/second
Resolution	12 bits (1 part in 4096)
Processor	Intel 8086
Integral Memory: Random Access Memory	32 or 64 Kbytes
Programmable Read Only Memory	up to 64 Kbytes
Removable Memory:	Bubble Memory Cartridge (Intel Plug-a-Bubble)
Capacity	128 Kbytes
Weight:	20 pounds
Power Requirements:	72 W (3A at 28V nominal)

TABLE 3. DESCRIPTION OF STORED DATA IN SMART RECORDER

Data Stored in Bubble Memory Cartridge:	
One-minute averages	Average values calculated from 60 1-second samples for 26 channels.
Max-min data	Maximum positive and negative values for three selected channels. Values are determined from quarter-second data.
High-speed data	Raw (unaveraged) data for two selected channels. Values are obtained by abstracting every second data value from the one second data before averaging.
Configuration Options (Specific data stored determined by configuration information stored in the 10 pages of bubble memory by the ground-based data processing system)	
Startup channels	Channel numbers for six channels to be monitored and recorded during engine startup.
Analog channel map	Multiplexer and gain settings for each of the available 50 analog channels.
Sensor pointers	Channel numbers of sensors inputs to be used in specific on-board calculations (i.e., static pressure, pitot differential pressure, accelerometers, engine generator speed, and engine torque)
Threshold levels	Levels used by on-board processing routines to "bin" the data or to determine mode of the aircraft (e.g., rate of descent or ascent beyond which the aircraft is declared to be descending or ascending).
Mode flags	Used to turn on/off optional modes such as high speed data storage and DVGH processing.

(continued)

TABLE 3. DESCRIPTION OF STORED DATA IN SMART RECORDER (continued)

Data Stored in Bubble Memory Cartridge:	
Data limits	6 channels and the respective limits for data in each. Acquired voltages outside the stated range are flagged as suspect.

Bubble Memory Allocation by Page:

Memory Page	Use
1	Read/Write test page (scratch area)
2	Not used
3	Diagnostic error message log
4	Data page pointer and misc. variables
5- 15	Configuration data
16- 75	Cumulative flight statistical tables
76- 135	Backup statistical tables
136- 195	Perflight statistical tables
196- 200	-- spare --
201-2047	Data -- startup, high-speed, and average data pages in order that they are acquired. Data from different flights separated with file marker-- a page filled with distinct characters.

electrical and mechanical compatibility of the Smart Recorder with the engines and associated instrumentation in an environment where noted incompatibilities could be safely and completely investigated. Additional objectives included recording system calibration, determination of measurement sensitivities, determination of specific recorder response to engine anomalies and unusual operating conditions, and investigate the feasibility of on-line engine diagnostics using the Smart Recorder.

The recorder was removed from the King Air aircraft and additional interfaces and cabling were fabricated for compatibility with the engines when operating on the test stand at the P&W facility. The planned, one-week test scenario included one day for connection of the recorder with the engine and test cell instrumentation, two days for acquisition of data from the engine (two shifts per day), an additional day for resolution of anomalies in the data, and a final day for dismantling, packing, and shipping. Tests were conducted during the week of January 15, 1984 in a production test cell at the P&W Montreal facility.

The Smart Recorder was operated in parallel with standard test cell instrumentation. P&W supplied their data on strip charts for comparison with the data acquired and stored in the Smart Recorder bubble memory cartridge. On-line observations and comparisons were made from data present on a terminal temporarily connected to the Smart Recorder for the duration of the tests. No discrepancies were noted between the Smart Recorder data and the P&W data verifying the fidelity of the Smart Recorder data acquisition process. Consequently, the third testing day was used to acquire additional data on the engine while operating under a variety of induced conditions.

During the entire test period, only minor anomalies were observed, and those were corrected through wiring changes in the recorder/engine interconnection. The experience gained in the discovery of these minor problems saved considerable time in troubleshooting the interface with the engine on the aircraft.

The conclusions of the test were that the dynamic range and resolution of the NASA Smart Recorder is well within the tolerances of the system being monitored by it. Also, the relatively low speed of engine operation and the accuracy of the NASA recorder make on-line diagnostics realizable.

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SECTION 4

RECORDER INSTALLATION ON CHARTER AIRCRAFT

The recorder has been installed and operated on a King Air Aircraft used for commercial charter service by Airlift Associates based at Raleigh-Durham Airport. The recorder is connected both to existing aircraft sensors and to sensors installed on the aircraft to provide data not available from existing sensors. Table 4 lists the parameters monitored on the aircraft along with the signal source. Figure 5 illustrates the components installed on the aircraft, their interconnection, and the approximate location.

The major electronic components in this installation are the recorder itself and two interface units. The interface units provide the signal conditioning necessary to make the sensors or transducer outputs compatible with input capability of the recorder. Functions performed include filtering, amplification, and conversion from frequency, resistance, or synchro signals to dc voltage required by the recorder analog-to-digital converter.

Sensors for data acquisition included both sensors which were a part of the original aircraft systems and additional sensors, installed when no suitable signal was available for the parameter to be monitored. Pressure transducers were used to sense altitude and indicated air speed (IAS) since no analog voltage proportional to these parameters was available outside the cockpit indicators. The transducers were connected to the aircraft pitot-static system in parallel with the aircraft transducers. Signals representing most of the engine parameters were derived by tapping into cables between the cockpit indicator and the aircraft sensor. Connection was made by removing the appropriate cable from the back of the indicator and inserting a short extension cable between the instrument and the cable originally connected to it. This extension cable was constructed with a pair of wires permanently connected to appropriate contacts of the cable connectors to "tap" the necessary signals for routing to the recorder or appropriate interface unit. (The extension cable/signal tap arrangement was used to ease installation in a

TABLE 4. PARAMETERS MONITORED BY THE INTELLIGENT FLIGHT RECORDER

Parameter	Sensor	Location
Altitude	Sensym P/N LX1802AZ	Forward Baggage Compartment (Connected to A/C Pitot Static System)
Airspeed	Sensym P/N LX1802DZ	Forward Baggage Compartment (Connected to A/C Pitot Static System)
Acceleration	Kistler 3 ea. P/N 303B	Below Floor in Cabin (Near aircraft CG)
Torque	Aircraft Sensor	Rear of Cockpit Indicator
Fuel Flow	Aircraft Sensor	Rear of Cockpit Indicator
Squat Switch	Aircraft Sensor	Rear of Hobbs Meter
Propeller Speed	Aircraft Sensor	Rear of Cockpit Indicator
Compressor Speed	Aircraft Sensor	Rear of Cockpit Indicator
Internal Turbine Temperature	Aircraft Sensor	Rear of Cockpit Indicator
Engine Inlet Temperature	Lewis Eng. Co. P/N 56B4A	A/C Inlet Screen
Engine Inlet Pressure	Kulite P/N XTM-190-25	Behind Engine Firewall w/Tube to Inlet Screen
Bleed Valve Exhaust Temp.	Lewis Eng. Co. P/N 56B17	Adjacent to Engine Bleed Valve

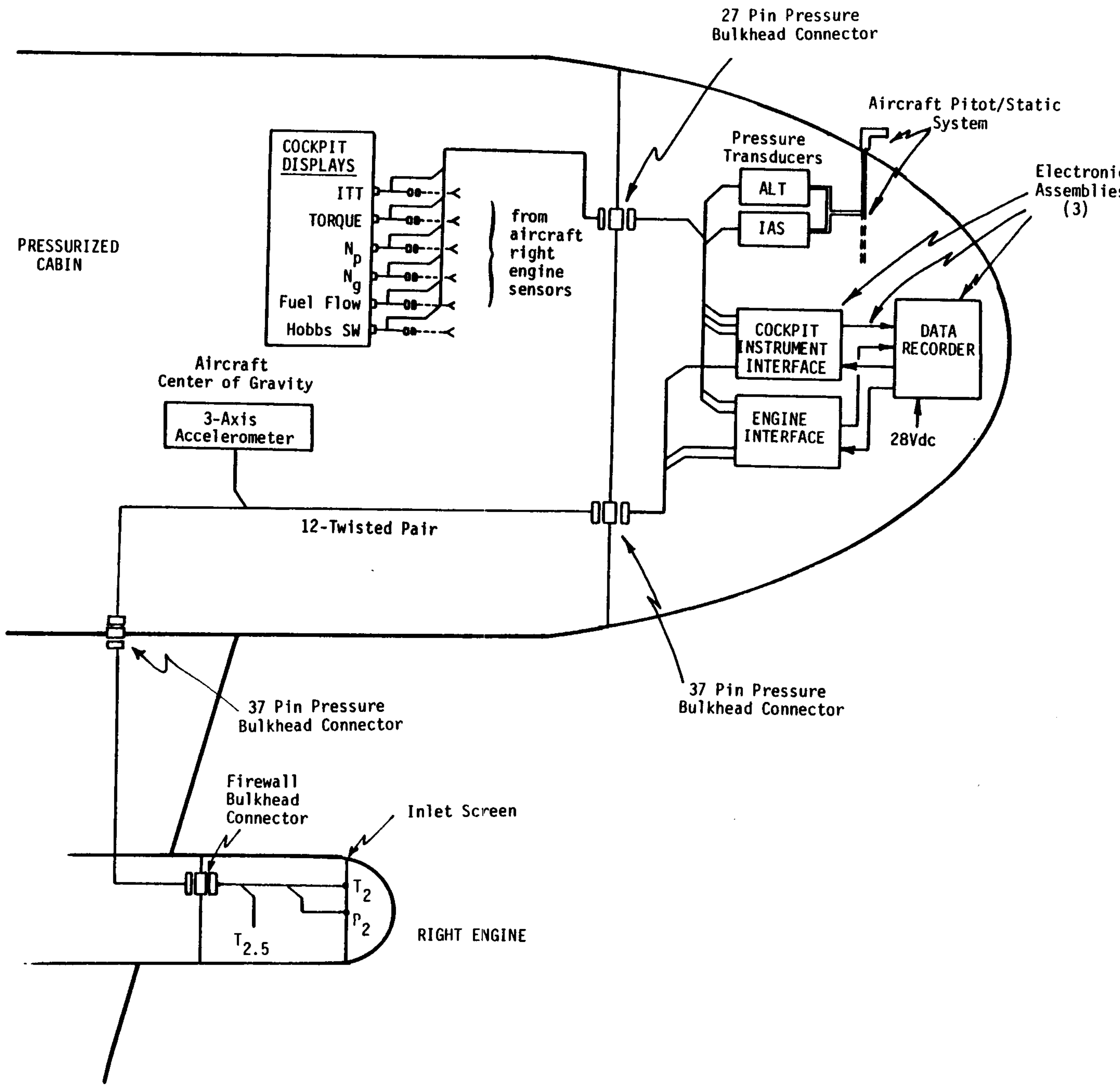


Figure 5. Interconnection of Smart Recorder to Sensors on King Air Aircraft

cramped cockpit and to allow the instruments to be easily returned to original configuration at the end of the measurement program.) Additional engine data necessary for trend monitoring was obtained from pressure and temperature sensors installed at the engine inlet screen and a temperature sensor at the exhaust port for the engine bleed valve. To provide the acceleration data necessary for DVGH data acquisition, 3 single-axis accelerometers were installed at the aircraft center of gravity (CG), under the floor in the passenger compartment.

A supplemental Type Certificate for the installation was obtained from the FAA covering the recorder and installation on September 25, 1984.

SECTION 5

DATA ANALYSIS

5.1 GROUND-BASED DATA PROCESSING SYSTEM

A laboratory microcomputer system is used to support the Smart Recorder by providing those functions which cannot practically be supplied by the recorder which is installed in the aircraft, namely:

- Retrieval of data from bubble memory cartridges
- Processing of collected data
- Maintenance of a data base for the collected data
- Production data plots
- Initialization of the bubble memory cartridge prior to reuse.

The microcomputer system purchased for this system is a Comark Diskstor unit, which uses standard Multibus boards. The system, illustrated schematically in Figure 6, consists of processor, memory, two 8-inch floppy disk drives, and power supplies housed in a single enclosure. Peripherals for the system include a CRT terminal/console, Epson FX-80 dot matrix printer, and an Intel Plug-a-Bubble cartridge interface.

This system uses the 8086 microprocessor operating at 10 Mhz clock rate and MS-DOS 1.25 operating system, allowing it to execute IBM-PC code. However, there are differences between this system and the PC: (1) the system speed of the Comark System is approximately four to six times that of the IBM-PC, allowing faster processing and manipulation of data, and (2) the bus structure and peripheral interfaces of the two machines differ so peripheral interface boards and software which accesses those boards directly (instead of through the operating system) may not be transferred from one system to the other. Therefore, slight modifications in the software will be necessary before the software could be transferred to contemporary MS-DOS or PC-DOS-based systems.

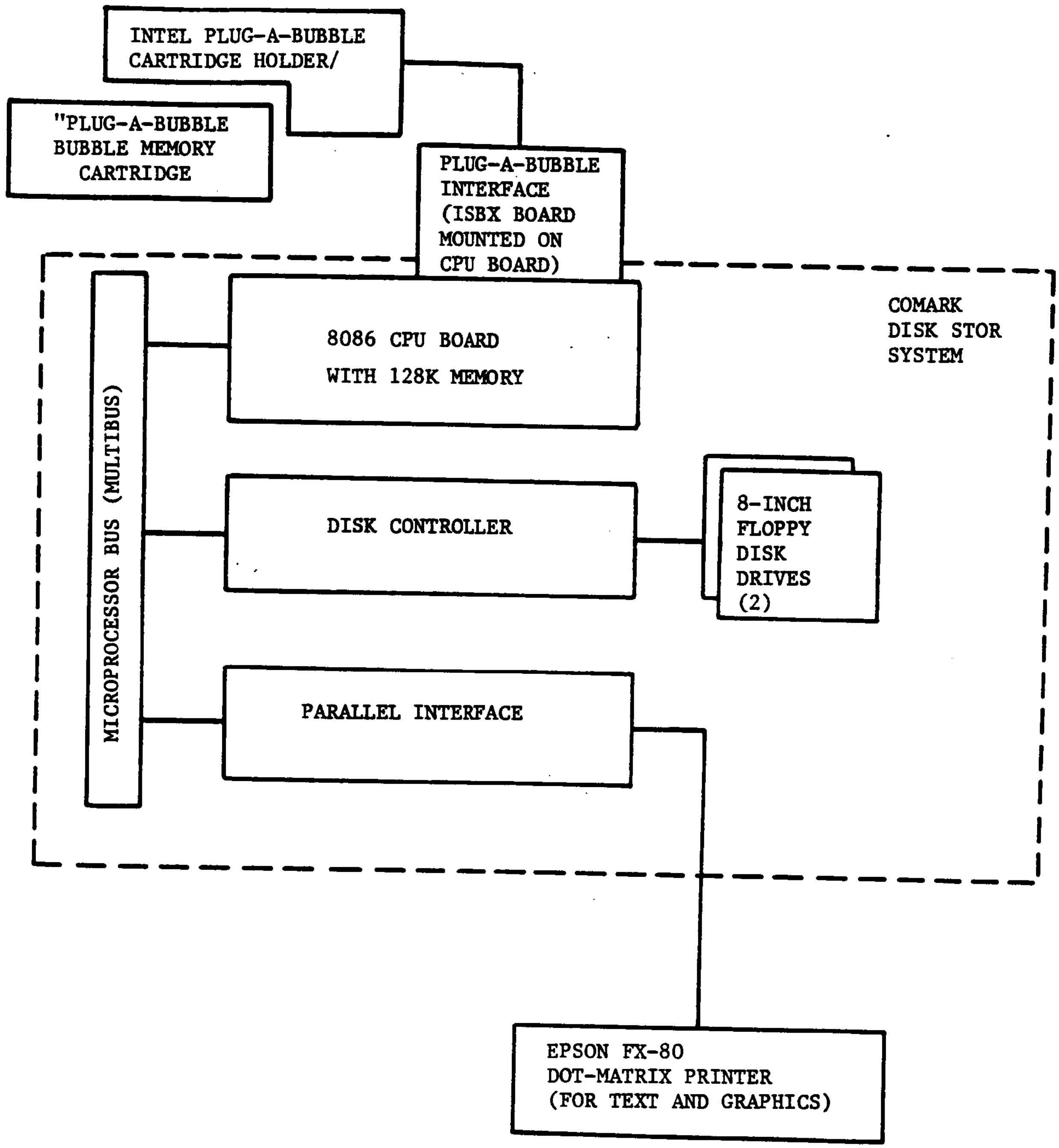


Figure 6. Microprocessor-based System for Retrieval and Processing of Smart Recorder Data

5.2 DVGH PROCESSING

Software developed for DVGH processing the data from the Smart Recorder includes the following programs:

- Data Input Program--A program to retrieve data from the cartridge, check for format errors and store the resulting data in files for subsequent processing.

- Database Management Program--A set of programs designed to gather data into individual files for each monitored parameter, catalog the data, and retrieve upon request for processing by other programs.

- Plotting Package--A set of programs which allows generation of two-dimensional X-Y plots of the data with appropriate labeling on both the axes and plotted contours. Plot images are formed in the computer memory and passed to the Epson printer for generation of hardcopy. The plots shown in this report were generated using this capability.

- Main Processing Software--Programs which analyze the collected data to first determine the per-flight tabulated characteristics and then combine those with cumulative statistics tabulated from previous processing to produce the updated cumulative characteristics

Most of the software was developed in FORTRAN with assembly language used for certain low-level input/output routines. The developed processing capability was confined to the Comark microcomputer so it could be easily relocated to a NASA facility if desired.

Software was validated by inspection of plots of processed data, comparing indicated levels with manually recorded data from cockpit indicators during flight and data taken from pilot logs. Later, when on-board processing of DVGH data was implemented, the processing routines that classify and tabulate data were transferred from the ground base unit to the Smart Recorder to eliminate the need for recording the raw time series data in the bubble memory cartridge. This change extended the data storage capacity of the cartridge from 4.5 hours to 30 hours. The implementation was carried out in two phases: (1) modification of Smart Recorder software to add processing required for on-board DVGH processing extending the recording time to 15 hours, and (2) at a later time, removal of time-series data storage to increase the recording time for a single cartridge to 30 hours. The simultaneous storage of raw, time-series data and processed data in the first phase made possible the validation of the in-flight processing routines by comparison of the results with data processed in the laboratory with the original software.

The implementation of DVGH processing of the record was more than simple transfer of processing routines from the ground-based system to the recorder. Minor logic changes for real-time processing were necessary because the data is available serially and must be processed as it is acquired. In contrast, during ground-based processing, system the data for an entire flight is available to the processing routine and may be accessed randomly or sequentially in multiple passes. The FORTRAN routines were converted to assembly language to optomize execution speed and reduce memory requirements for the processing code. All numerical computations were implemented in integer arithmetic, with appropriate scaling to minimize errors due to overflow and roundoff error. Data were processed and stored on the basis of A/D "counts," leaving the final conversion of data to engineering units until the final ground-based processing. (The goal of reducing the amount data stored in the bubble memory and handled on the ground is achieved irregardless of whether the data is stored in "counts" or in engineering units, so there is no disadvantage to performing the final conversion to engineering units on the ground-based processing.)

Tabulated data are accumulated for individual flights but not added to the cumulative data until it can be ascertained that the data represent a complete flight from take-off to landing. Data from partial flights are not included in the cumulative statistics. (A partial flight refers to an incomplete data set caused by interruption of the Smart Recorder operation at some point during the flight.)

Per-flight data are stored for the purpose of individual flight validation and ground base generation of tables encompassing large numbers of flights. Examples of these tables are: (1) percentage of flights of indicated duration versus altitude bands, (2) percentage of flights to maximum altitude band versus duration, and (3) percentage of flights where maximum positive and negative acceleration occur versus altitude.

SECTION 6

DATA SUMMARY AND CONCLUSIONS

6.1 DVGH DATA SUMMARY

6.1.1 DVGH Goals

The purpose of the collection of DVGH data was to continue and extend the NASA Langley aircraft measurement program whose objectives were to characterize the environment seen by commercial aircraft. Prior to the development of the Smart Recorder, data had been collected primarily on large commercial air transport aircraft. The objective of this hardware development effort was to demonstrate the feasibility of collecting DVGH data for general aviation aircraft in a cost effective manner, i.e., using equipment which would provide some economic payback to the operator to offset the expense of equipment installation and operation. This objective was achieved by the successful demonstration of an inexpensive, multipurpose recorder which could provide the operator with engine maintenance information while acquiring the environmental data desired by NASA.

The data objective for the DVGH monitoring program is a statistical description of aircraft loading (acceleration). Toward this goal, acceleration data was collected along with supporting aircraft flight data to allow the tabulation of acceleration data vs. altitude and under various flight conditions (i.e., climb, level flight and descent). Statistical summaries of this data were then computed on the data set.

6.1.2 Perflight Data

Examples of data produced on a perflight basis for the purpose of examining and validating the data are shown in Figures 7 and 8 and Table 5. These data include both plots of key parameters such as altitude and acceleration. The altitude plots were used to to verify that recorded data was consistent with actual take-off, landing and cruise altitude and to verify that the data

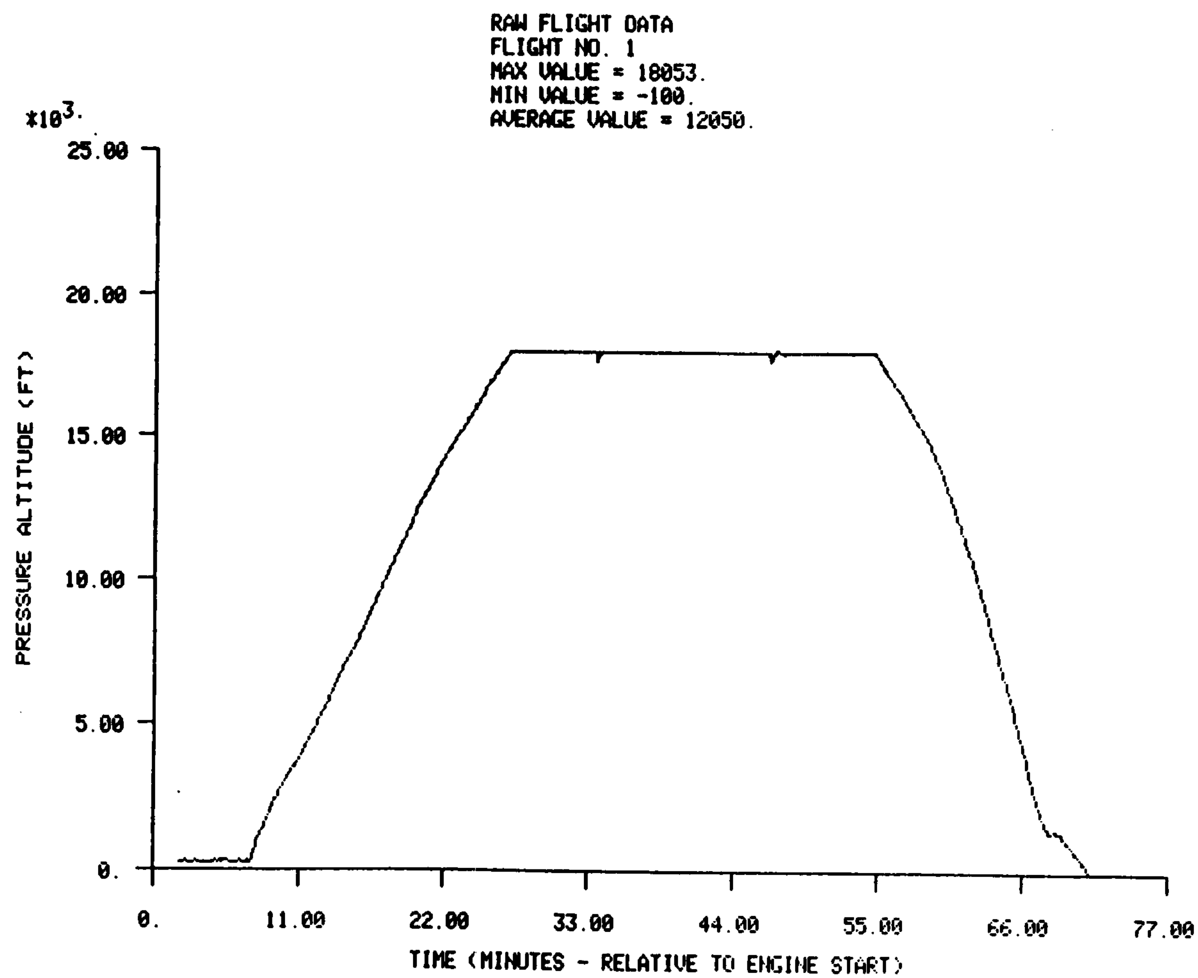


Figure 7. Plot of Pressure Altitude Representing a Typical Flight Profile

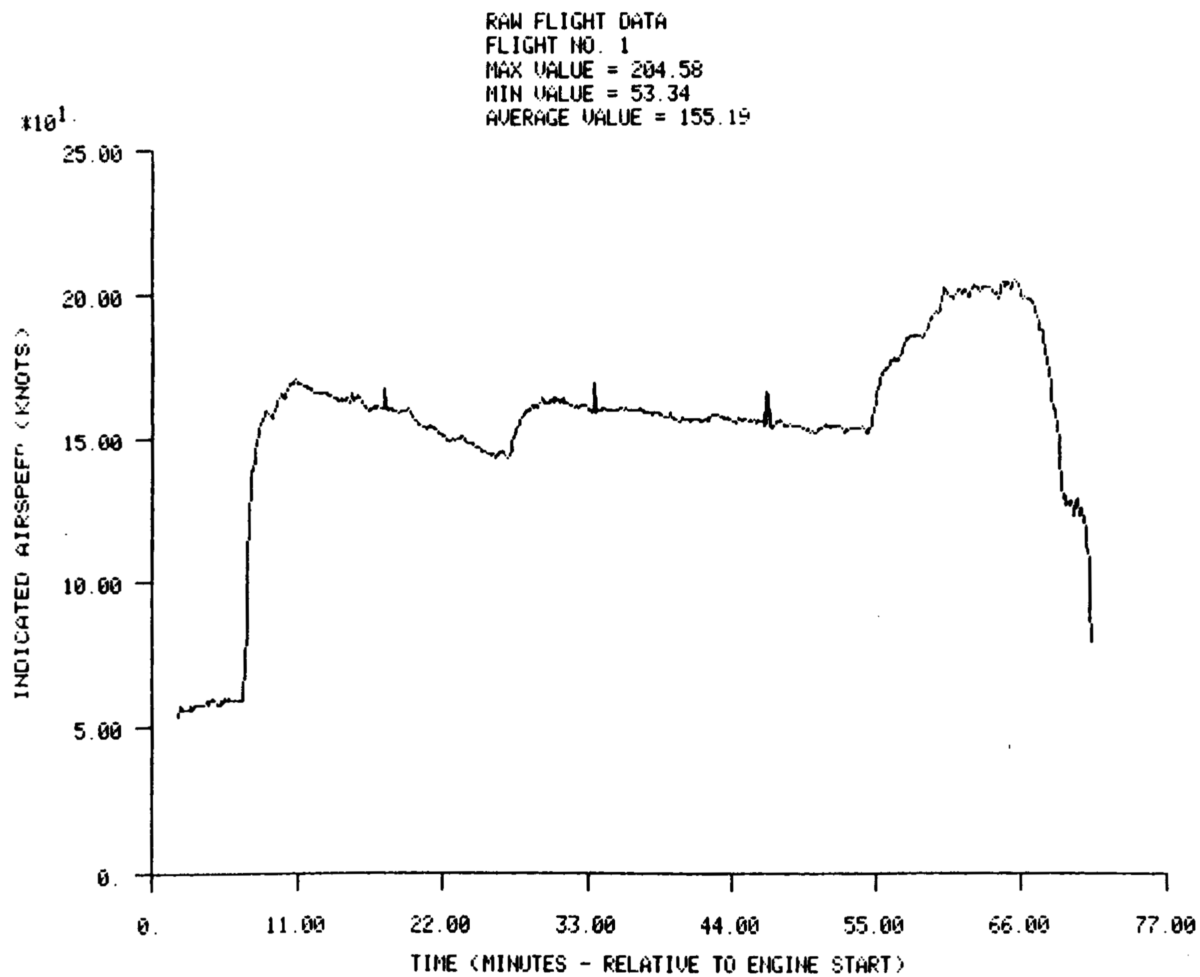


Figure 8. Plot of Indicated Airspeed for a Typical Flight (2-second Sampled Data)

TABLE 5. EXAMPLE OF STATISTICAL SUMMARY GENERATED FOR INDIVIDUAL FLIGHTS

PER-FLIGHT STATISTICAL SUMMARY
****

DATA RETRIEVED ON: 9/12/1984

FLIGHT NO	TRIP TIME (MINS)	TRIP LENGTH MILES (EST)	ALTITUDE (FT) AVE	ALTITUDE (FT) MAX	IAS AVE (KT)	V(TRUE) MAX (KT)	INLET AIR TEMP (F) MIN	INLET AIR TEMP (F) MAX
34	68	209	9470	16970	151	230	-4	56
35	29	68	3270	8210	168	223	14	58
36	64	194	7610	14860	164	230	12	66
37	55	162	6020	12750	169	237	19	67
38	67	-217	12300	17020	145	203	8	80

FLIGHT TIME (MINS) BY PRESSURE ALTITUDE BIN (FEET)

FLIGHT NO	TERMINAL AREA	-500 TO 4500	4500 TO 9500	9500 TO 14500	14500 TO 19500	19500 TO 24500	24500 TO 29500	29500 TO 34500	TOTAL TIME (MIN)
34	7.3	12.7	9.5	10.8	27.8	.0	.0	.0	68
35	9.8	7.8	11.4	.0	.0	.0	.0	.0	29
36	12.1	9.4	13.3	11.8	17.4	.0	.0	.0	64
37	12.1	11.5	9.4	22.1	.0	.0	.0	.0	55
38	6.8	4.2	5.5	6.9	43.6	.0	.0	.0	67

AVERAGED INDICATED AIRSPEED (KTS) BY ALTITUDE BIN (FT)

FLIGHT NO	-500 TO 4500	4500 TO 9500	9500 TO 14500	14500 TO 19500	19500 TO 24500	24500 TO 29500	29500 TO 34500	PER-FLIGHT AVERAGE (KTS)
34	141	159	156	151	0	0	0	151
35	158	175	0	0	0	0	0	168
36	155	175	166	159	0	0	0	164
37	165	174	169	0	0	0	0	169
38	135	142	133	149	0	0	0	145

did represent a complete flight from take-off to landing without interruption. This verification is actually a check of the automated processing which recognizes the beginning and end of each flight, and verifies that data have been acquired without interruption over the flight, incorporating the statistics for the flight into the cumulative statistics.

Other plots, such as Figure 9, show a time series presentation of acceleration data. These plots allow the manual examination of data for reasonableness. The maximum and minimum envelope surrounding the time series plot provides an indication of variability of the data and the existence of any outliers which would not otherwise be easily seen on a plot of 0.25 second data.

Table 6 shows calculated acceleration statistics for a group of flights recorded on a single cartridge. These data are used for verification of the data and the processing routines prior to combining the data with that from other flights to produce the cumulative statistics.

6.1.3 Cumulative Statistics

Initially cumulative statistics were produced by analyzing the acquired time-series data in the laboratory. Later, after on-board processing was implemented, statistical data were accumulated in the bubble memory, retrieved and formatted by the ground-based processing system, and printed for interpretation and dissemination. Tables 7 through 13 show the cumulative statistics produced for the 180 hours of data acquired by the Smart Recorder after on-board processing was implemented. These data represent typical use of the King Air aircraft operated by Airlift Associates out of the Raleigh-Durham Airport.

6.2 TREND MONITORING DATA SUMMARY

An analysis of trend monitoring feasibility was performed by processing data recorded by the Smart Recorder and comparing the results with data acquired and processed manually by the aircraft operator. The processing in both cases consisted of using monitored flight conditions (e.g., pressure-altitude, temperature, engine power) to correct monitored values of NG, ITT, and WF to a specified set of standard flight conditions using compensation equations provided by Pratt and Whitney for the specific engine used. This

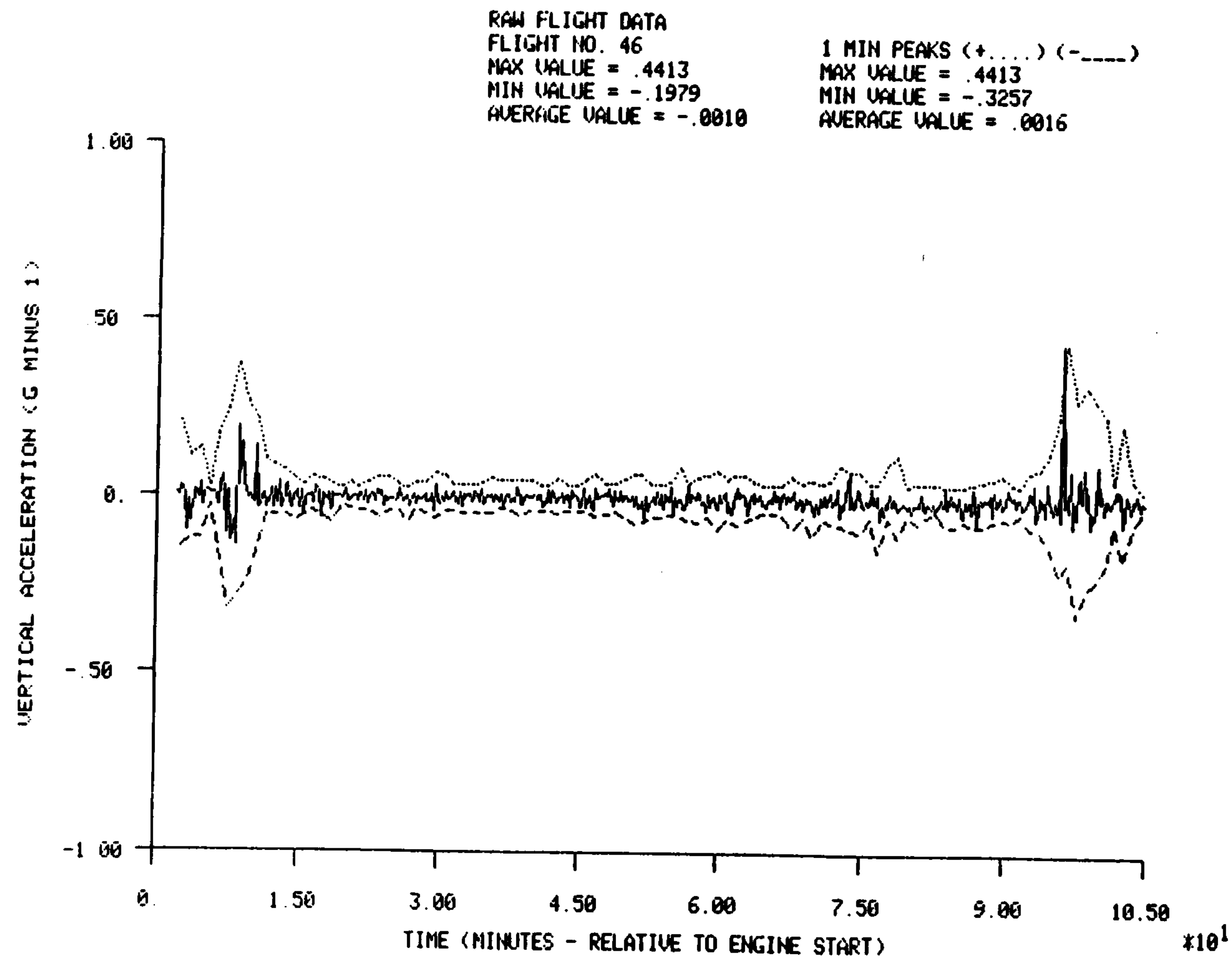


Figure 9. Plot of Vertical Acceleration Data Including Positive Peak, Raw and Negative Peak Determined for Each One-minute Interval

TABLE 6. PROCESSED ACCELERATION DATA FOR GROUP OF FLIGHTS RECORDED ON ONE CARTRIDGE

ACCELERATION LEVEL CROSSING TABLE

****

DATA RETRIEVED ON: 11/16/84 FLIGHTS NO. 69 THRU 77

VERTICAL ACCELERATION

PER FLIGHT COUNTS

BIN RANGE	FLT 1	FLT 2	FLT 3	FLT 4	FLT 5	FLT 6	FLT 7	FLT 8	FLT 9	TOTALS
> .5 G's	0	0	0	3	0	0	0	0	0	3
.2 TO .5	16	2	41	57	44	2	15	3	6	186
.1 TO .2	94	29	201	178	188	59	87	67	89	992
.0 TO .1	242	1795	1571	642	2113	2824	1270	1516	1390	13363
-.1 TO .0	229	1749	1544	625	2061	2660	1191	1429	1279	12767
-.2 TO -.1	25	14	162	139	132	30	40	33	37	612
-.5 TO -.2	3	1	16	43	28	0	4	2	0	97
< -.5	0	0	0	3	0	0	0	0	0	3
TOTALS	609	3590	3535	1690	4566	5575	2607	3050	2801	28023

LONGITUDAL ACCELERATION

PER FLIGHT COUNTS

BIN RANGE	FLT 1	FLT 2	FLT 3	FLT 4	FLT 5	FLT 6	FLT 7	FLT 8	FLT 9	TOTALS
> .5 G's	0	0	0	0	0	0	0	0	0	0
.2 TO .5	0	24	27	15	26	15	15	15	12	149
.1 TO .2	0	463	176	4	274	336	178	285	179	1895
.0 TO .1	18	376	478	215	263	541	336	309	295	2831
-.1 TO .0	21	384	603	247	356	726	409	398	370	3514
-.2 TO -.1	23	106	326	30	486	323	280	90	210	1874
-.5 TO -.2	3	10	4	7	7	11	10	4	10	66
< -.5	0	0	0	0	0	0	0	0	0	0
TOTALS	65	1363	1614	518	1412	1952	1228	1101	1076	10329

LATERAL ACCELERATION

PER FLIGHT COUNTS

BIN RANGE	FLT 1	FLT 2	FLT 3	FLT 4	FLT 5	FLT 6	FLT 7	FLT 8	FLT 9	TOTALS
> .5 G's	0	0	0	0	0	0	0	0	0	0
.2 TO .5	0	0	1	0	0	4	0	0	0	5
.1 TO .2	10	0	29	24	6	11	5	10	0	95
.0 TO .1	154	1933	1791	470	2051	2760	1725	1751	1488	14123
-.1 TO .0	151	1874	1854	466	2169	2958	1784	1828	1584	14668
-.2 TO -.1	2	5	8	33	25	29	15	16	2	135
-.5 TO -.2	0	0	0	0	3	0	0	0	1	4
< -.5	0	0	0	0	0	0	0	0	0	0
TOTALS	317	3812	3683	993	4254	5762	3529	3605	3075	29030
FLIGHT MINUTES	5	41	33	11	37	50	30	31	29	267

TABLE 7. PERCENT TIME OF INDICATED AIRSPEED VERSUS ALTITUDE BINS FOR ALL FLIGHT CONDITIONS DERIVED FROM ONBOARD PROCESSING

	Altitude Bins (ft)					
IAS (Kts)	-500 to 4,500	4,500 to 9,500	9,500 to 14,500	14,500 to 19,500	19,500 to 24,500	-500 to 24,500
100 to 120	10.91	.38	.11	.91	1.53	2.92
120 to 140	23.51	11.66	8.89	13.68	25.46	15.06
140 to 160	26.47	21.37	14.00	62.64	71.85	34.48
160 to 180	18.51	18.51	41.83	20.34	1.16	23.36
180 to 200	16.31	35.73	32.27	2.40	.00	19.77
200 to 220	4.25	12.29	2.87	.03	.00	4.37
220 to 240	.04	.06	.02	.00	.00	.03
240 to 260	.00	.01	.00	.00	.00	.00
260 to 280	.00	.00	.00	.00	.00	.00
280 to 300	.00	.00	.00	.00	.00	.02
Percent all modes vs. Altitude	22.80	22.23	23.20	25.81	5.95	100.00
Flight Time in All Modes (hours)	41.90	40.83	42.63	47.42	10.93	183.72
Total Flight Time per Bin (hours)	41.90	40.83	42.63	47.42	10.93	183.72
Percent Time in Altitude Bin	100.00	100.00	100.00	100.00	100.00	100.00

Number of flights 252

Average flying time 0.82

TABLE 8. PERCENT TIME OF INDICATED AIRSPEED VERSUS ALTITUDE BINS FOR CLIMB DERIVED FROM ONBOARD PROCESSING

IAS (Kts)	Altitude Bins (ft) -500 to 4,500	4,500 to 9,500	9,500 to 14,500	14,500 to 19,500	19,500 to 24,500	-500 to 24,500
100 to 120	8.23	.07	.00	.00	.00	3.20
120 to 140	18.62	.23	.00	.24	1.92	7.30
140 to 160	12.72	1.66	.40	8.78	47.60	6.42
160 to 180	16.60	7.27	11.42	56.41	50.48	15.54
180 to 200	33.64	55.12	73.28	34.14	.00	48.38
200 to 220	10.51	35.48	14.77	.43	.00	19.02
220 to 240	.11	.16	.14	.00	.00	.13
240 to 260	.00	.02	.00	.00	.00	.01
260 to 280	.00	.00	.00	.00	.00	.00
280 to 300	.00	.00	.00	.00	.00	.05
Percent Climb vs. Altitude bin	38.69	34.23	19.16	7.48	.43	100.00
Flight Time in Climb	15.48	13.69	7.67	2.99	.17	40.00
Total Flight Time	41.90	40.83	42.63	47.42	10.93	183.72
Percent Total Time in Climb	36.94	33.54	17.98	6.31	1.59	21.77

TABLE 9. PERCENT TIME OF INDICATED AIRSPEED VERSUS ALTITUDE BINS FOR LEVEL FLIGHT DERIVED FROM ONBOARD PROCESSING

IAS (Kts)	Altitude Bins (ft) -500 to 4,500	4,500 to 9,500	9,500 to 14,500	14,500 to 19,500	19,500 to 24,500	-500 to 24,500
100 to 120	22.06	.12	.00	.02	.10	2.94
120 to 140	14.08	1.91	.01	9.65	25.03	8.37
140 to 160	20.47	1.91	5.74	70.38	74.49	39.22
160 to 180	30.70	41.75	62.74	19.67	.38	32.84
180 to 200	11.39	53.16	31.16	.29	.00	16.23
200 to 220	1.30	1.14	.34	.00	.00	.40
220 to 240	.00	.00	.00	.00	.00	.00
240 to 260	.00	.00	.00	.00	.00	.00
260 to 280	.00	.00	.00	.00	.00	.00
280 to 300	.10	.00	.00	.00	.00	.00
Percent Climb vs. Altitude bin	13.19	12.72	25.20	38.85	10.04	100.00
Flight Time in Climb	13.62	13.13	26.02	40.12	10.37	103.27
Total Flight Time	41.90	40.83	42.63	47.42	10.93	183.72
Percent Total Time in Climb	32.50	32.16	61.05	84.61	94.87	56.21

TABLE 10. PERCENT TIME OF INDICATED AIRSPEED VERSUS ALTITUDE BINS FOR DESCENT DERIVED FROM ONBOARD PROCESSING

IAS (Kts)	Altitude Bins (ft) -500 to 4,500	4,500 to 9,500	9,500 to 14,500	14,500 to 19,500	19,500 to 24,500	-500 to 24,500
100 to 120	2.28	.94	.52	9.85	40.53	2.60
120 to 140	39.41	31.97	42.35	60.59	47.56	39.82
140 to 160	49.48	58.88	49.70	27.97	11.91	50.13
160 to 180	7.87	7.71	7.05	1.55	.00	6.89
180 to 200	.94	.42	.35	.05	.00	.53
200 to 220	.02	.07	.02	.00	.00	.04
220 to 240	.00	.00	.00	.00	.00	.00
240 to 260	.00	.00	.00	.00	.00	.00
260 to 280	.00	.00	.00	.00	.00	.00
280 to 300	.00	.00	.00	.00	.00	.00
Percent Climb vs. Altitude bin	31.65	34.64	22.10	10.65	.96	100.00
Flight Time in Climb	12.80	14.01	8.94	4.31	.39	40.44
Total Flight Time	41.90	40.83	42.63	47.42	10.93	183.72
Percent Total Time in Climb	30.55	34.30	20.97	9.08	3.54	22.01

TABLE 11. LEVEL CROSSING COUNTS PER HOUR VERSUS ALTITUDE BINS FOR LONGITUDINAL (AXIAL) ACCELERATION

		Altitude Bins (ft)					
Longitudinal Acceleration (G)	On the ground	-500 to 4,500	4,500 to 9,500	9,500 to 14,500	14,500 to 19,500	19,500 to 24,500	-500 to 24,500
0.75 to 1.00	2.5	.0	.0	.1	.1	.0	.0
0.50 to 0.75	4.2	2.6	1.9	2.5	.0	.0	1.6
0.40 to 0.50	4.6	3.4	2.8	2.6	.0	.0	2.0
0.30 to 0.40	11.0	27.8	8.1	6.0	.0	.0	9.5
0.25 to 0.30	15.1	69.6	3.6	6.8	.0	.0	18.3
0.20 to 0.25	12.4	118.4	5.4	6.4	1.3	.0	30.0
0.15 to 0.20	10.3	245.1	53.5	20.7	3.4	.0	73.4
0.10 to 0.15	37.9	402.5	532.2	263.2	58.7	20.2	287.5
0.05 to 0.10	149.2	111.4	225.5	209.3	119.8	67.1	159.0
0.00 to 0.05	1349.8	348.7	417.8	969.0	2965.0	3485.2	1370.0
-0.05 to 0.00	1352.5	347.9	419.1	971.2	2965.8	3486.1	1370.9
-0.10 to -0.05	209.9	495.7	489.3	429.1	126.0	25.9	355.4
-0.15 to -0.10	107.4	417.0	432.8	115.9	11.3	.2	221.1
-0.20 to -0.15	64.3	64.5	26.9	6.0	.0	.0	22.1
-0.25 to -0.20	17.6	8.1	1.5	.1	.0	.0	2.2
-0.30 to -0.25	5.5	.7	.2	.1	.0	.0	.2
-0.40 to -0.30	.1	.1	.1	.1	.0	.0	.1
-0.50 to -0.40	.1	.1	.1	.1	.0	.0	.1
-0.75 to -0.50	.0	.1	.1	.1	.0	.0	.1
-1.0 to -0.75	.0	.1	.1	.1	.0	.0	.1
Average cts/hr	167.8	133.2	131.0	150.5	312.6	354.2	217.3
Flight time/bin	23.16	41.90	40.83	42.63	47.42	10.93	183.72

TABLE 12. LEVEL CROSSING COUNTS PER HOUR VERSUS ALTITUDE BINS FOR VERTICAL ACCELERATION (GRAVITY REMOVED)

Vertical Acceleration (G)	On the ground	Altitude Bins (ft) -500 to 4,500	4,500 to 9,500	9,500 to 14,500	14,500 to 19,500	19,500 to 24,500	-500 to 24,500
0.75 to 1.00	.0	.0	.0	.0	.0	.0	.0
0.50 to 0.75	.3	1.4	.4	.2	.1	.0	.5
0.40 to 0.50	.9	5.0	1.2	.7	.3	.0	1.6
0.30 to 0.40	3.7	21.9	4.1	1.9	1.0	.1	6.6
0.25 to 0.30	8.3	45.2	8.3	3.4	1.8	.4	13.4
0.20 to 0.25	23.1	100.8	17.9	6.8	4.0	1.6	29.7
0.15 to 0.20	69.9	225.9	42.1	16.2	10.8	7.6	67.9
0.10 to 0.15	232.2	489.3	108.9	53.4	34.2	34.6	159.1
0.05 to 0.10	970.6	1114.2	438.2	336.8	241.0	316.8	510.7
0.00 to 0.05	3951.0	2244.8	2655.2	2871.7	3346.3	3298.7	2828.5
-0.05 to 0.00	3955.5	2245.4	2655.4	2871.2	3346.1	3299.0	2828.6
-0.10 to -0.05	590.5	811.5	358.9	272.4	165.8	162.7	380.5
-0.15 to -0.10	141.2	312.7	83.1	44.8	26.4	25.7	108.5
-0.20 to -0.15	39.9	134.2	31.6	14.4	8.9	6.4	43.7
-0.25 to -0.20	11.9	56.4	14.0	6.2	3.5	1.6	18.4
-0.30 to -0.25	3.8	25.1	6.9	2.8	1.7	.6	8.4
-0.40 to -0.30	1.9	12.7	3.4	1.7	.8	.1	4.3
-0.50 to -0.40	.2	2.9	1.1	.6	.3	.0	1.1
-0.75 to -0.50	.1	.9	.5	.3	.1	.0	.4
-1.0 to -0.75	.0	.2	.2	.1	.0	.0	.1
Average cts/hr	500.3	392.5	321.6	325.3	359.7	357.8	413.7
Flight time/bin	23.16	41.90	40.83	42.63	47.42	10.93	183.72

TABLE 13. LEVEL CROSSING COUNTS PER HOUR VERSUS ALTITUDE BINS FOR LATERAL ACCELERATION

Lateral Acceleration (G)	On the ground	Altitude Bins (ft) -500 to 4,500	4,500 to 9,500	9,500 to 14,500	14,500 to 19,500	19,500 to 24,500	-500 to 24,500
0.75 to 1.00	.0	.0	.0	.0	.0	.0	.0
0.50 to 0.75	.1	.0	.0	.0	.0	.0	.0
0.40 to 0.50	.2	.0	.0	.0	.0	.0	.0
0.30 to 0.40	.7	.1	.1	.0	.0	.0	.0
0.25 to 0.30	2.2	.2	.2	.0	.0	.0	.1
0.20 to 0.25	9.7	.6	.0	.0	.0	.0	.2
0.15 to 0.20	35.8	6.9	.2	.1	.0	.0	1.6
0.10 to 0.15	90.7	28.5	2.8	2.4	.5	.0	7.8
0.05 to 0.10	360.5	355.9	250.4	232.2	138.0	91.2	231.7
0.00 to 0.05	2298.7	2792.5	3376.5	3514.2	4213.4	4352.4	3549.4
-0.05 to 0.00	2303.3	2794.1	3376.3	3514.0	4213.2	4352.5	3549.6
-0.10 to -0.05	289.1	312.3	163.5	117.7	53.0	49.7	151.5
-0.15 to -0.10	47.6	21.5	1.7	1.0	.4	.3	5.6
-0.20 to -0.15	11.6	3.2	.3	.1	.1	.0	.8
-0.25 to -0.20	2.9	.6	.2	.1	.0	.0	.2
-0.30 to -0.25	.6	.2	.1	.1	.0	.0	.1
-0.40 to -0.30	.0	.1	.1	.1	.0	.0	.1
-0.50 to -0.40	.0	.1	.1	.1	.0	.0	.1
-0.75 to -0.50	.0	.1	.1	.1	.0	.0	.1
-1.0 to -0.75	.0	.1	.1	.1	.0	.0	.1
Average cts/hr	272.7	315.8	358.6	369.1	430.9	442.3	409.3
Flight time/bin	23.16	41.90	40.83	42.63	47.42	10.93	183.72

correction is necessary to remove the expected variability in measured engine parameters due to variability in engine operating conditions. Next, the nominal expected values for the engine parameters under standard conditions (a constant value for each parameter) is subtracted from the corrected data to produce a Δ value. These Δ values are plotted against time to observe trends that indicate a change in engine performance. The level of the Δ values is not as significant as changes (slow or rapid) which might indicate a change in engine condition and could be a precursor for necessary corrective action to avoid a more costly repair or engine failure.

In order to compare the manual and automated approaches for trend monitoring, ΔNG, ΔITT and ΔWF were calculated for each flight. The first approach was to select a point 5 to 10 minutes after the aircraft reached the cruise altitude and calculate the Δ values from instantaneous measurements made at that time. However, more consistent results were obtained by using averaging measured values over the entire cruise portion of a flight. The averaging process removes variability in Δ values due to short-term variations from random measurement errors and changes in engine operating conditions. Flights with cruise duration less than 5 minutes or cruise altitudes less than 8,000 feet were not included in the analysis. Processed data from the remaining flights are plotted for comparison with manually acquired data.

The Δ values calculated from the Smart Recorder data using the Pratt and Whitney supplied compensation equations was plotted for verification prior to comparison with the manually derived data. In the original data, the variability in calculated Δ values between flights was far greater than the variability in values calculated during the cruise portion of any given flight. This is shown by the data in Figure 10 which shows the raw data for ΔITT for all flights over the study period. The "error bars" shown on the plot represent the one-sigma variance about the mean value calculated for the flight. Note that this variance is small in comparison to the point to point variation in the plot. Consultations with the engine manufacturer, Pratt and Whitney (Montreal, Canada) revealed two possible causes for the flight-to-flight variation. First, cabin pressurization introduces a loading on the engine which is dependent on the altitude of the aircraft and, if not

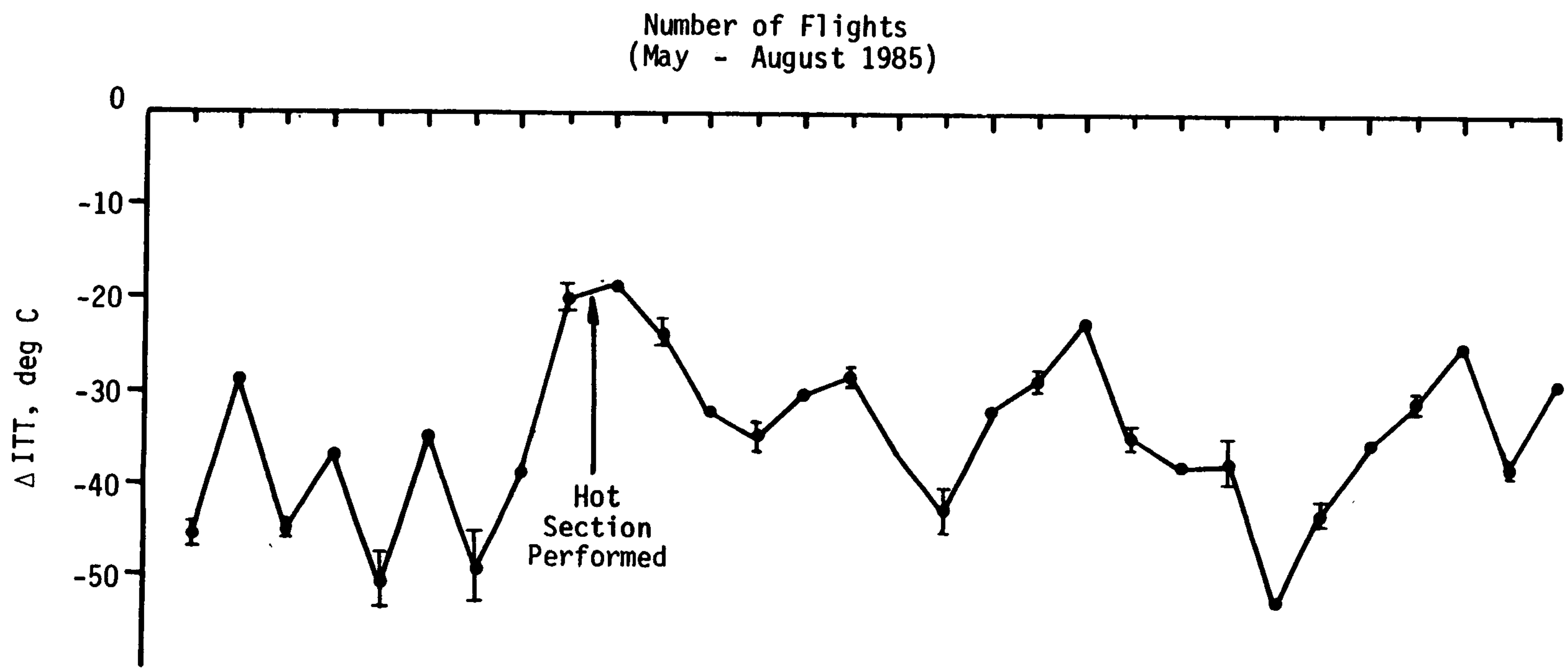


Figure 10. Delta Internal Turbine Temperatures Taken from Smart Recorder Data with In-Flight Variability Shown with Error-Bars

accounted for, would introduce an error in the compensation calculations for the Δ parameters. Secondly, the electrical loading of the alternators would also cause a loading on the engine which would impact the compensated results in a similar manner. An analysis of the data revealed that the Δ values showed a strong correlation with altitude even though the compensation equations account for variation in engine performance with environmental pressure. It is thought that, while the Δ-value/altitude correlation could be produced by inaccuracies in the equation coefficients, they are more likely to be produced by the altitude dependence of the engine loading of the cabin pressurization system (Altitude dependence of electrical loading is thought to be negligible). To resolve this problem, an empirical relationship was determined from a portion of the data to account for the altitude dependency of engine loading, and applied to the data set in addition to the standard compensation equation prior to the comparison with the manually acquired data. This reduced the flight-to-flight variability significantly (as shown by comparing Figure 10 with Figure 11) but did not reduce it to a level comparable with the data variability within a flight. To reduce the variability farther, it will be necessary to more closely monitor engine loading. (The manual method overcomes the engine loading problem by requiring that the pilot shift loads to the opposite engine while measurements are being made. This approach is not appropriate for the automated systems because the ultimate application would be for continuous engine monitoring with real-time pilot notification upon detection of a significant trend in the observed data.)

After application of the Pratt and Whitney compensation equations and the empirically-derived altitude relationship, the trend monitoring data from the Smart Recorder was compared against data taken using manual techniques (from data logged by pilots). To perform this comparison, values for each Δ parameter from both the automated and the manual processes were plotted together against time for the period of May through August 1985. Figures 11 through 13 show the three resulting plots, one for each of the calculated Δ values. During this time interval, 25 data observations were collected by the pilots and 32 observations were taken from the Smart Recorder data. The

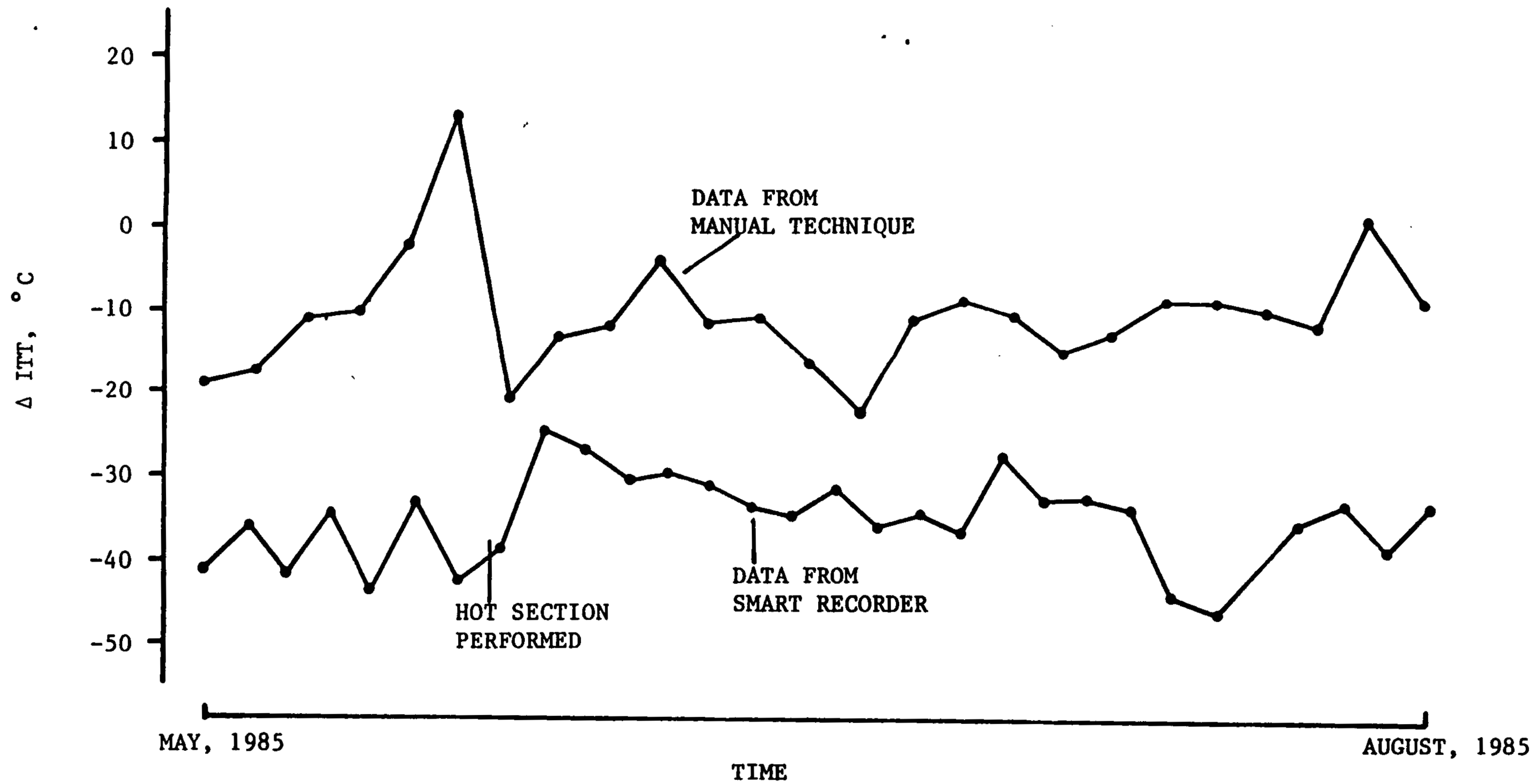


Figure 11. Comparison of (Δ)ITT for Manual and Automated Trend Monitoring

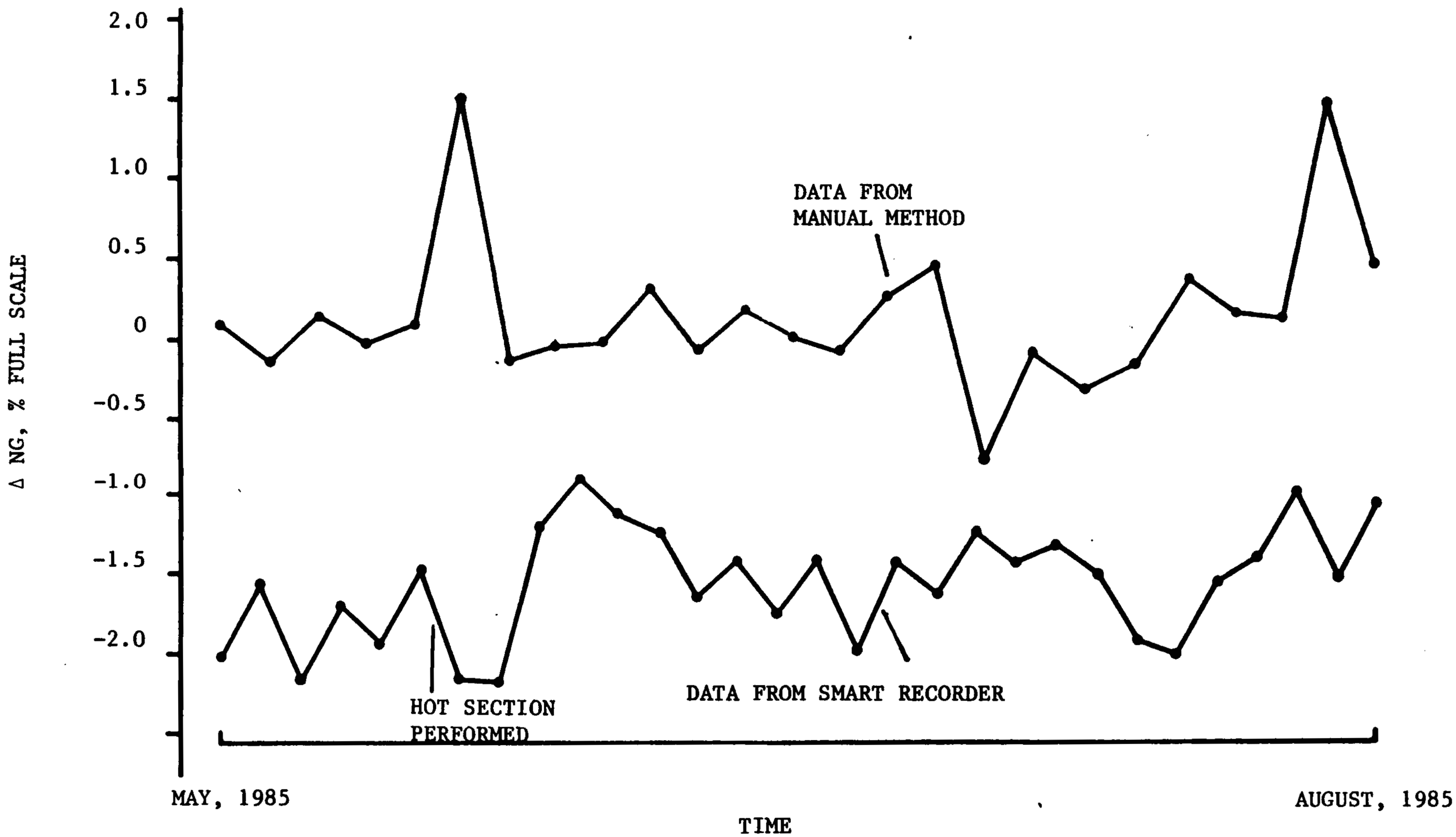


Figure 12. Comparison of (Δ)NG for Manual and Automated Trend Monitoring

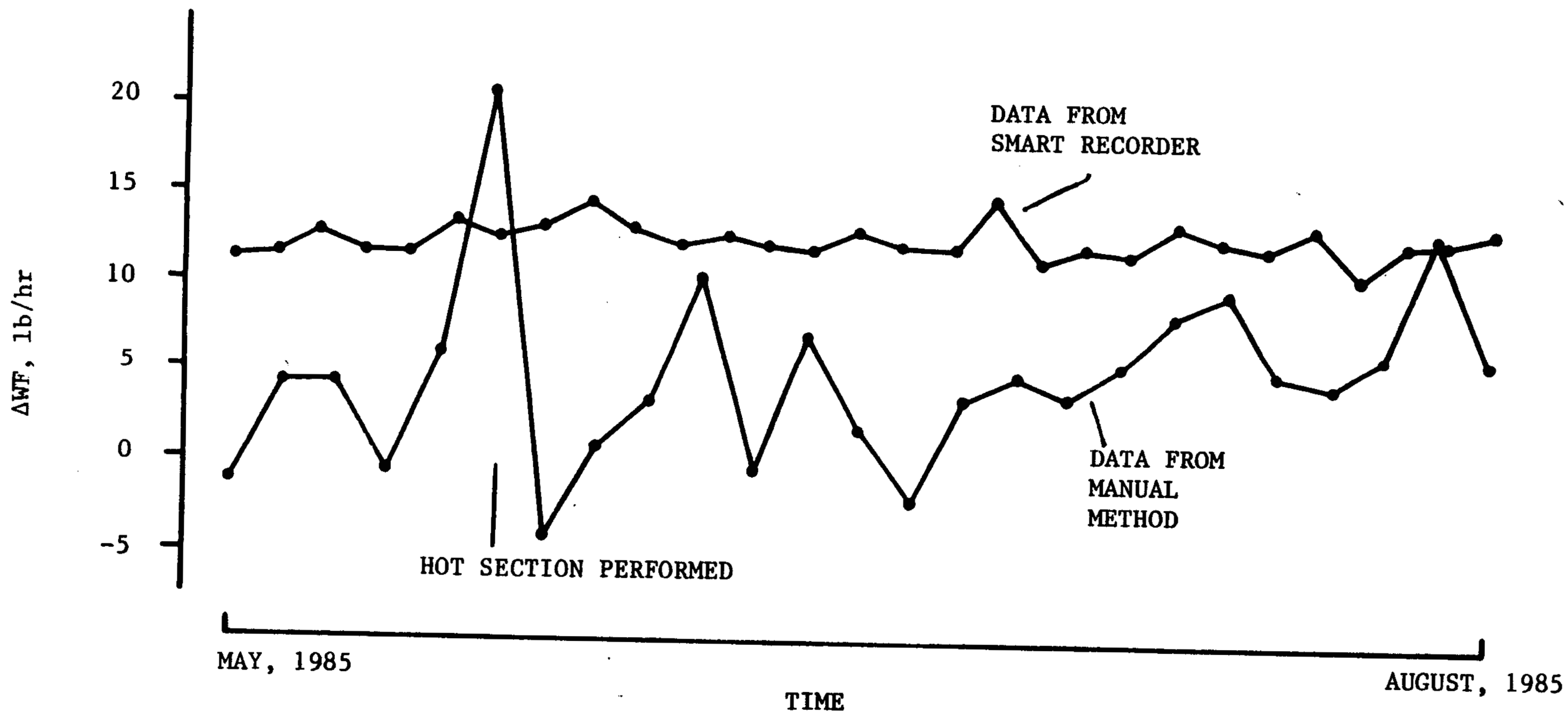


Figure 13. Comparison of (Δ)WF for Manual and Automated Trend Monitoring

difference in number of observations was due to the fact that the pilots do not record data during every flight and some flight data was missing from the recorder because of full data cartridges or the pilot turning it off during flight.

Several observations may be made from the data presented here. First, the magnitudes of the various Δ parameters differ somewhat between the manual and automated procedures. The difference is primarily due to differences in the magnitude of the measured parameters, particularly NG, ITT and WF and torque. These recorder measurements for these parameters were calibrated against known or expected sensor outputs and are not calibrated directly against the cockpit indicators. This results in a bias between manual and automated results. However, a constant bias is not detrimental to the detection of trends or changes in the data, so no effort was made to reduce the bias.

Table 14 compares the variability of the manual-processing and automated-processing techniques. Comparison of the two ΔITT values finds only a small decrease, from 7.4 to 5.14, in the standard deviation of between flight data using the recorder data. ΔNG and ΔWF both exhibit improvements in their respective standard deviations for the two methods; from 0.49 to 0.29 for ΔNG and 5.15 to 3.1 for ΔWF.

A final observation involves the effect of the "hot section" on the delta values. The pilot data do not appear to exhibit any marked change in any of the three delta values during this period. There are two possible reasons for this: (1) the propeller speed transmitter was replaced during the "hot section" which may have biased the data from that point in time and effectively hidden the change in the delta values, and (2) the expected changes may be smaller than the typical measurement errors. In the data recorder results, the delta values do appear to change for ΔITT and ΔNG. Excluding the three performance flights, the mean before an after the "hot section" for ΔITT changes from approximately -41.0 to -34.0 °C. Similarly, the mean for ΔNG changed from -1.91 to -1.49 percent. Though the change is not as visually apparent in ΔWF, the mean does change from 14.15 to 12.58 lb/hr.

TABLE 14. STANDARD DEVIATION FOR THE Δ VALUES FOR AUTOMATED AND MANUAL TREND MONITORING

Parameter	Standard deviation	
	Manual (Calculated from information in pilot logs)	Automated (Calculated by processing data from Smart Recorder)
ΔITT	7.40	5.14
ΔNG	0.49	0.29
ΔWF	5.15	0.90

In summary, the advantages gained by performing trend monitoring use data recorder continuously during a flight are as follows:

- A larger number of flights are recorded during a given period.
- A large number of data samples can be taken and averaged improving data quality.
- An improvement in the standard deviation (variability) between flights is realized.
- Events such as "hot section" repairs may be more apparent.
- Frees pilot time for other functions and thus eliminates the human factor.

SECTION 7

DEVELOPMENT OF SECOND GENERATION RECORDER

The prototype Smart Recorder was fabricated using off-the-shelf commercial components and hardware to minimize initial equipment cost while developing the appropriate configuration. While the initial device successfully demonstrated the feasibility of applying flight recorders to general aviation aircraft, it was not packaged in a standard aircraft enclosure and no attempt had been made to make the recorder and its ancillary equipment compact. The purpose of the development of the second recorder was to develop a recorder that could be installed in standard aircraft racks and that would impose minimal logistical requirements on the aircraft (minimal size, weight, and power).

The second-generation Smart Recorder functional configuration is shown in Figure 14. Like the initial version, this recorder uses a bubble-memory cartridge system for transfer of data between the recorder and the laboratory data-processing facility. However, since the Intel Plug-a-Bubble was no longer available, a Targa unit was used instead. Other design enhancements over the original Smart Recorder include: internal interface to the environmentally protected auxiliary memory (EPAM); internal signal conditioning for synchro, frequency, and variable resistance sensors; and a real-time clock to provide actual date and time.

The second recorder utilizes STD-Bus boards allowing a more compact construction. These boards are 4.5 x 6.5 in. overall and are commercially available for a wide variety of microcomputer related functions. Because of their smaller size, the functions available in the single board computer used in the original recorder required several STD-Bus boards to implement. However, the overall size of the recorder was reduced to that of an ARINC 600 LRU-6 case (equivalent to an ATR-5/8 short case if that designation existed officially).

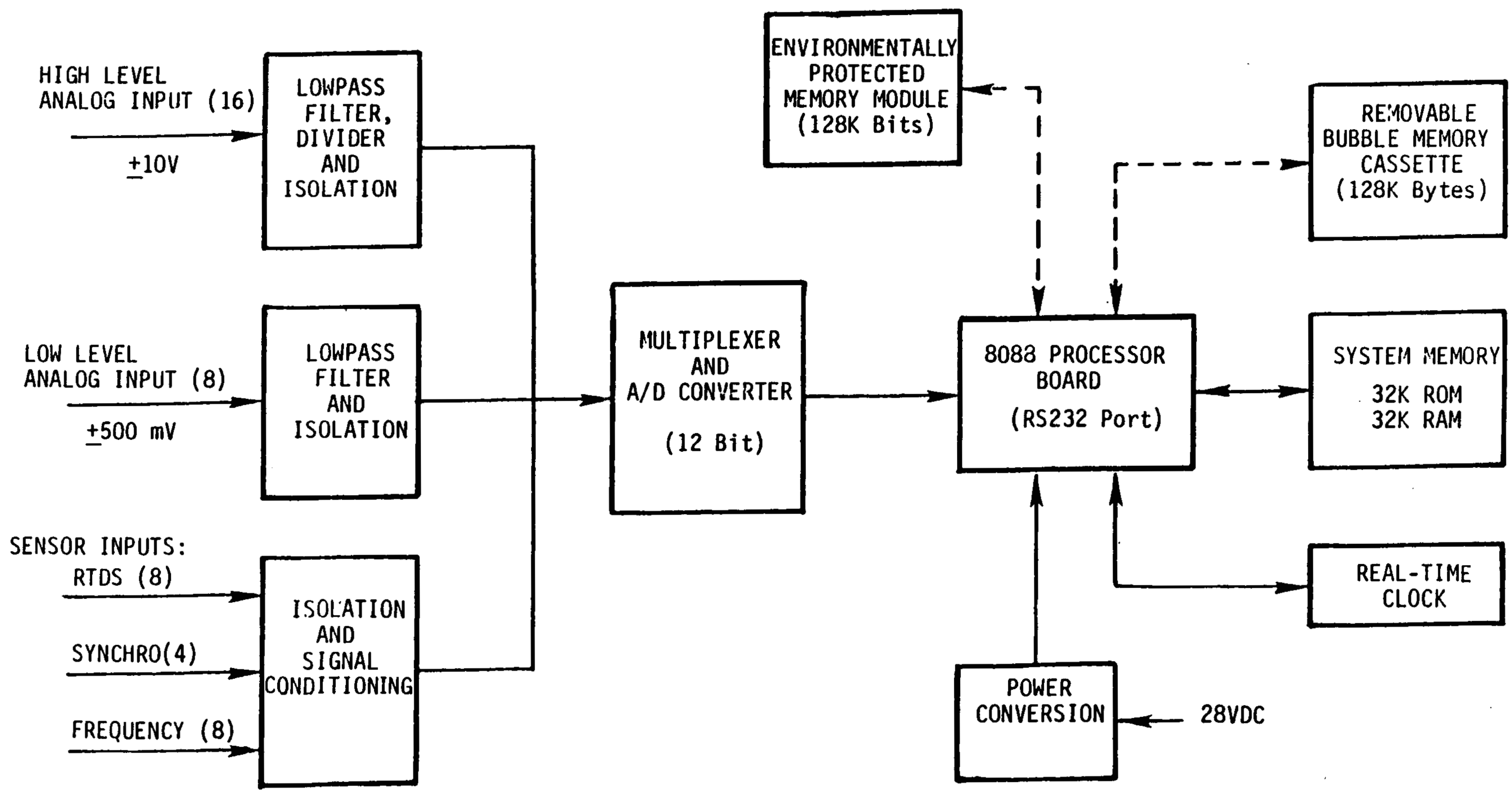


Figure 14. Block Diagram of Second Generation Smart Recorder

An advantage to the use of the smaller STD-Bus boards is the increase flexibility in configuration because of the increased modularity of the design. Boards may be selected which provide the specific processor or signal conditioning capabilities that are required. The characteristics of the system may be modified by changing boards. A wide variety of boards are commercially available including processor, memory, special function and peripheral interface boards. The existing configuration of the second-generation Smart Recorder includes eight boards:

1. 8088 Processor Board
2. Memory Board
3. Bubble Memory and EPAM Interface Board
4. Analog-to-Digital Converter/ Multiplexer Board
5. RTD Input Card
6. Synchro Input Card
7. Frequency Input Card
8. Bus Terminator/Real Time Clock Board.

Four of these boards are off-the-shelf, commercial boards. Only the Bubble Memory Interface, Synchro Input, Frequency Input, and Bus Terminator/Real Time Clock boards were custom fabricated for this project.

Like the original Smart Recorder, the second generation Smart Recorder was designed to be powered from an unregulated 28 Vdc power bus. Power modules capable of operating from 9 to 40 Vdc input were used for supplying ± 12, ± 15, and 5 Vdc to internal electronics. An additional supply located with the EPAM interface electronics was used to provide the 21 Vdc programming supply voltage used for writing data to the EPAM.

Software for the second recorder consists of a general utility data acquisition program containing many of the capabilities of the software for the original recorder. Configuration data read from the bubble memory, dual-rate sampling of input parameters, and interactive mode using external terminal were implemented on this system. New software includes drivers for the internal signal conditioning boards and the real time clock/calender. Software for on-board processing was not implemented on the second recorder because the specific application for the recorder has not been defined. The technical characteristics of the recorder are summarized in Table 15.

TABLE 15. SPECIFICATIONS OF THE SECOND GENERATION SMART RECORDER

	Type	Number	Range	Comments
Inputs:				
	Voltage(High Level)	16	0 to 10 V	Range of individual channels may be changed by replacing resistor
	Voltage(Low Level)	8	0 to 500 mV	
	RTD	8	-200 to 800°C	Linearization done on the interface board
	Synchro	4	0 to 360°	26V ref with 11.8V line-to-line voltages for synchro input
	Frequency	8	0 to 500 Hz	Range of individual channel may be altered by changing component value.
Processor:		8088		
Memory:	RAM,Static	32K		
	ROM	32K		Expandable to 128K
	EPAM (external)	16K		Hamilton-Standard
Removable storage Media		128KB Cartridge		512 KB cartridges available from manufacturer (Targa)
Cooling		Forced Air supplied through rack		
Physical Size		7.5 x 7.64 x 12.5 LRU #6 (ARINC 600)		
Weight		19 lb		
Power		3.5A at 24 V (80W)		

SECTION 8

ADDITIONAL APPLICATIONS OF THE SMART RECORDER

During the development of the Smart Recorder, certain applications within NASA were identified which required or could benefit from a compact data acquisition system that could process data as it is acquired to compress the data, select data of interest for retention, or provide real-time notification upon determination of specified conditions. Two representative applications are described here. The first is a transportation environment recorder for monitoring environmental exposure of Shuttle payloads while being transported to the lauch area. The second application, a flight recorder for a T-38 aircraft is more in keeping with the original design objectives of the Smart Recorder, although the logistical constraints for this application are considerably more severe because of the compact construction of this aircraft.

8.1 TRANSPORTATION ENVIRONMENT MONITORING

8.1.1 Introduction

The Transportation Environment Measurement and Recording System (TEMARS) is an instrument used to record shock and vibration levels induced by transportation vehicles on payloads being transported from the point of assembly to the launch site. The Smart Recorder concept was evaluated as an alternative data acquisition concept for monitoring the transportation environment, recording statistics which characterize the environment, and selective detailed recording of critical parameters at time when exceedances were noted that could be dangerous to the load. In this application, the Smart Recorder is used to eliminate the need for an in-transit operator/ controller and for tedious, post-trip data analysis. The Smart Recorder could also provide real-time notification of the shock and vibration exceedances.

8.1.2 Transportation Payload Monitoring Requirements

The TEMARS, described in Figure 15 consists of standard instrumentation, including an analog magnetic tape recorder, controlled remotely by an operator riding in the cab of the vehicle. The associated sensor set consists of two tri-axial accelerometers, plus payload container temperature and humidity sensors. One of the accelerometer systems is located near the object mounting plate (force input) and second is located near a region of probable force amplification. All sensors are monitored on operator demand. Normal accelerometer scaling is 10 G maximum, and frequencies of interest are dc to 200 Hz. Some typical TEMARS data are represented by Figures 16. The data represent force inputs ranging from single-episode short-duration shock inputs to long-duration inputs with occurrences of regular frequency features and envelope modulation effects.

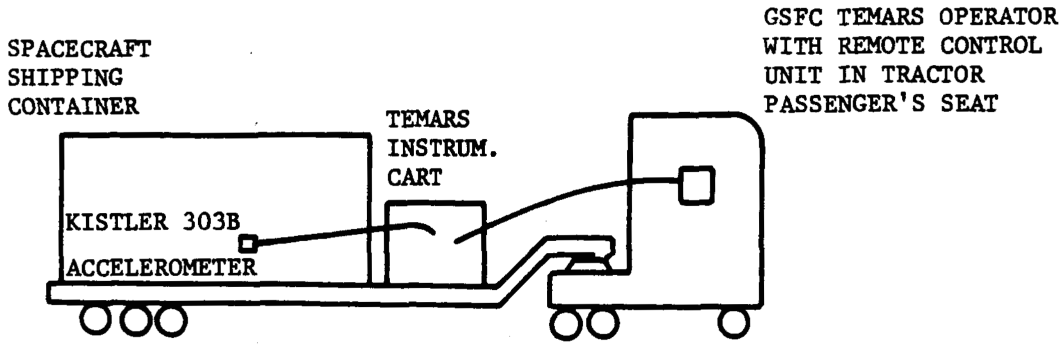
A normal trip might contain 30 to 50 turn-on cycles (~1 min) of the TEMARS recorder. Since the on-board operator must anticipate occurrences, the operator tends to be conservative and records many non-occurrences. Emergency situations such as an accident or flat tire may either distract the operator or be of such short duration as to be missed by the operator. Additionally, the fact that an exceedance has occurred is not available until the data have been analyzed after the trip.

8.1.3 Data Acquisition in the Transportation Environment

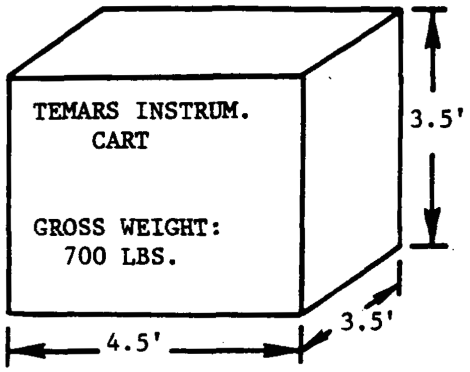
The critical parameter to be monitored in the transportation environment is acceleration, a measure of shock and vibration to which the payload is subjected. The design of a system for measurement and recording of acceleration data is driven by three factors unique to this application:

- The wide bandwidth of the signal to be recorded
- The relatively long duration of the desired recording period
- The need for processing the data both for impulse information and for steady state information.

Spectral analysis of acceleration measurements from vehicular environment shows significant energy from below 1 Hz to above 300 Hz.



TRACTOR/TRAILER FOR TRANSPORTING SPACECRAFT



TEMARS INSTRUMENTATION CART CONTAINS:

A) TAPE RECORDER
B) AIRCRAFT BATTERIES
C) JUNCTION BOXES
D) OSCILLOSCOPE & VOLTMETER
E) SUPPORT HARDWARE & SOFTWARE

<u>SPECIFICATIONS FOR TEMARS</u>:

NUMBER OF CHANNELS	- 12 ACCELEROMETERS MAXIMUM
g RANGE	- 0 TO 40 g PEAK
FREQUENCY RESPONSE	- dc to 200 Hz
RECORDING TIME	- UP TO 3 HOURS PER TAPE; UP TO 6 HOURS PER BATTERY CHARGE
OVERALL INSTRUM. CART DIMENSIONS AND WEIGHT	- 4.5' x 3.5' x 3.5'; GROSS WEIGHT 700 LBS.
POWER REQUIRED	- 24 to 30 VDC (USES 12 VDC, 80 AMP-HR, AIRCRAFT LEAD-ACID BATTERIES)
TAPE RECORDER	- HONEYWELL 5600C, 14-TRACK, FM ANALOG
ACCELEROMETER TYPE	- KISTLER SERVO, MODEL 303B
ACCELEROMETER DIMENSIONS AND WEIGHT	- 1.5" x 1.5" x 2.5"; 6 OUNCES

Figure 15. Description of GSFC Transportation Environment Measuring and Recording System (TEMARS)

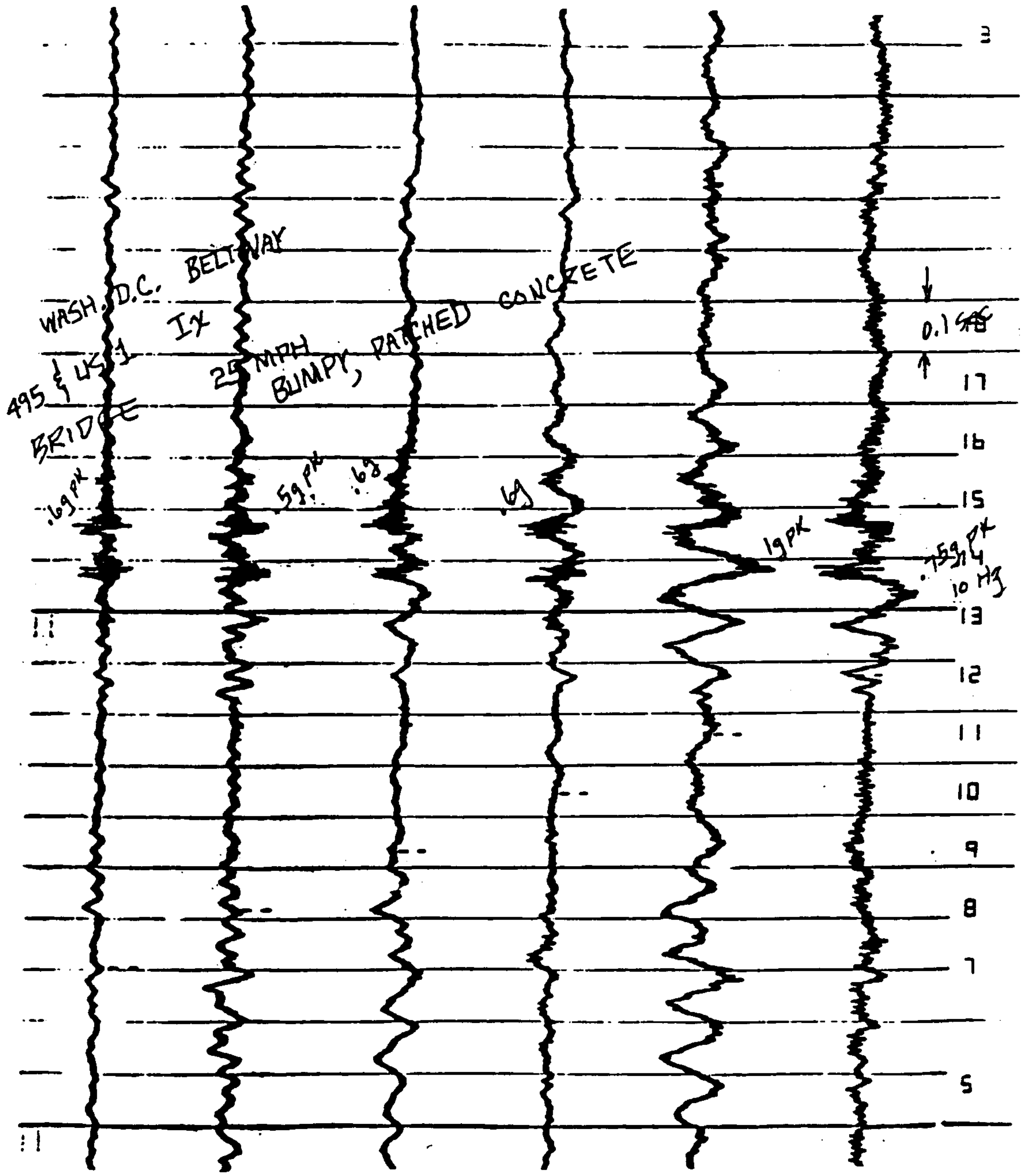


Figure 16. An Example of TEMARS Data

If conventional recording techniques are used, (e.g., magnetic tape recorders), then only a few hours of data may be recorded unless high frequency information is sacrificed. With existing systems the only means of acquiring data may be acquired over a long period is to either (1) turn the recorder on only during periods of interest and (2) or to periodically change the recording media. The first procedure requires that an instrument operator anticipate stimuli which will induce shock or vibration in the vehicle payload. If stimuli such as grooves in the pavement, potholes, etc. are not spotted, the event will not be recorded. The second procedure results in high quantities of acquired data, creating a monumental data processing problem. Either procedure requires that an operator travel along with the recording equipment.

The nature of the data determines how the data should be processed and how it should be acquired and stored. Stationary acceleration data from vibration induced by the vehicle rolling over regular features of the road--such as expansion cracks or pavement grooves generally is analyzed in terms of spectral characteristics. Impulse acceleration data from shock or random variations from random sources generally is characterized by the time domain characteristics (e.g., pulse height, duration, and waveform), although fourier analysis techniques may be used to determine the spectral characteristics of isolated pulses as well. Since both impulse and continuous signals are usually present in the acceleration data, then data must be encoded in such a manner that both temporal detail and frequency fidelity are preserved. These factors impose a major constraint on the design of a data acquisition system for the transportation environment.

The intelligence of the Smart Recorder could be used to reduce the data storage requirements through on-board processing. Figure 17 illustrates the monitoring concept using this recorder. Since the 8088 processor (or any other single-chip microprocessor) is not sufficiently fast to acquire 6 channels of data and perform a spectral analyses on it, a separate preprocessor would be used to determine the spectral characteristics of each of the six signals from the two three-axis accelerometers. The signal from each axis

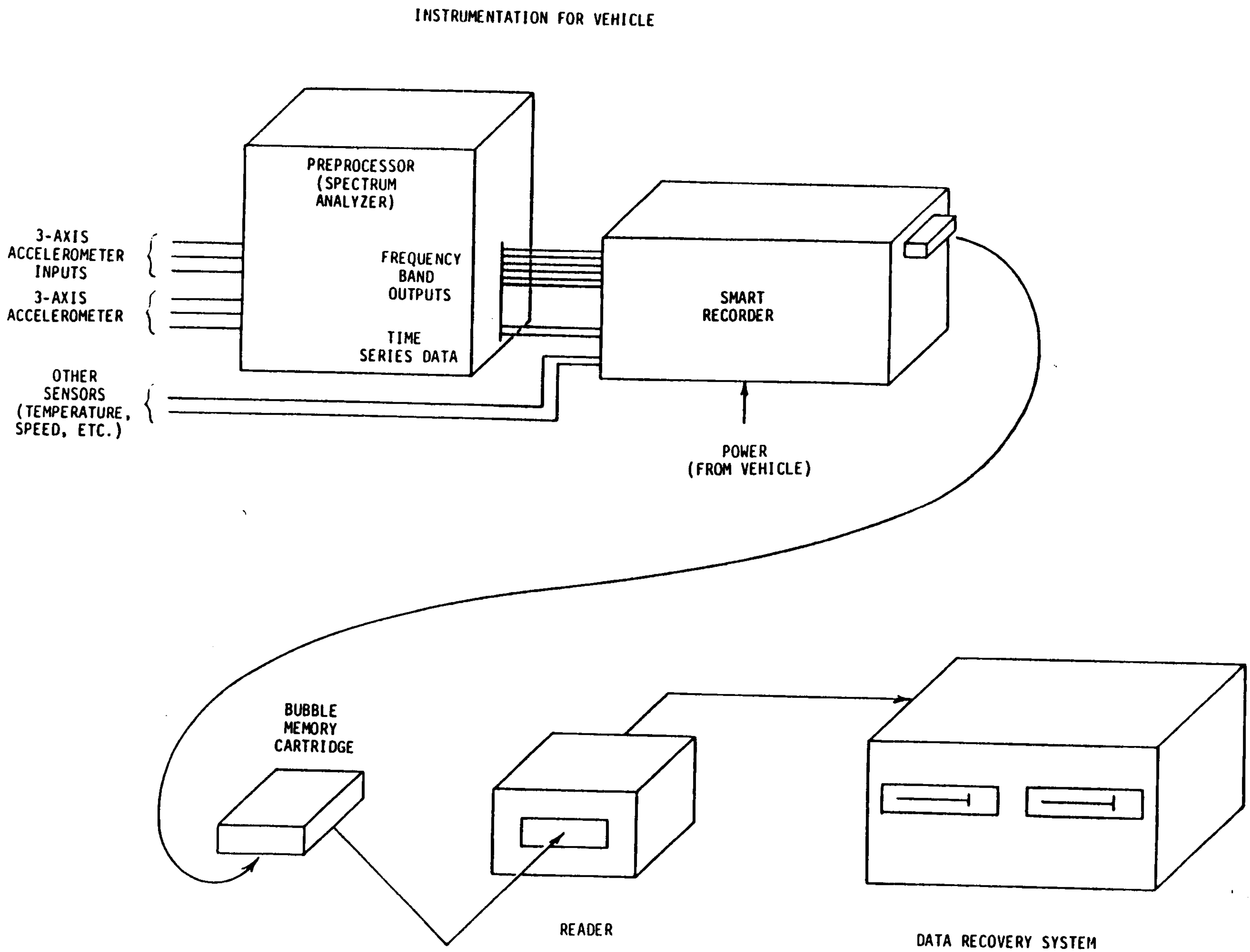


Figure 17. Transportation Environment Monitoring Concept

would be passed through a series of filter banks (shown in Figure 18) to determine the energy between 0 and 1 Hz and in each of 8 octaves between 1 Hz and 256 hz. Integrators and sample-and-hold units would be used to determine average values representing each one-second interval. Peak detectors, both positive and negative, would operate on each filter band output and the "raw" (unfiltered) data to "freeze" the spectral content of transient characteristics of impulse data, e.g., measured shock upon impact with pothole.

The analog output signals from the preprocessor would be passed over multiple signal paths to the Space Recorder where it would be digitized and tested to determine if the data are worthy of retention--i.e., if the data contain indications of significant acceleration levels. Once a significant event is detected, data would be stored over successive sample intervals until the observed shock or vibration decreases to a the nominal background level or until it reaches a new steady-state value and remains there for a specified period. These long duration events, such as these produced by sections of grooved pavement or by concrete highways with raised expansion joints, would be detected by the testing for variability in successive data records. Once it is determined that the event is a long duration event, representative data for the period would be tabulated and stored along with information about the duration of the period, eliminating the possibility of filling the memory with data which essentially describes only one condition.

Data describing two different situations would be stored in memory. For data describing impulse type events, the stored data would consist of a series of data records containing the peak and average values for acceleration in each of the frequency "bins" (including the unfiltered channel) for each accelerometer output. Other parameters such as temperatures and integrated speed (distance traveled) would be stored also. A pretriggering technique would be implemented in the recorder whereby data would be buffered so that on the detection of a valid trigger, data that slightly precedes the trigger could be stored.

In the case of long duration events, initial records would describe data from the early part of a long duration event in a manner resembling the

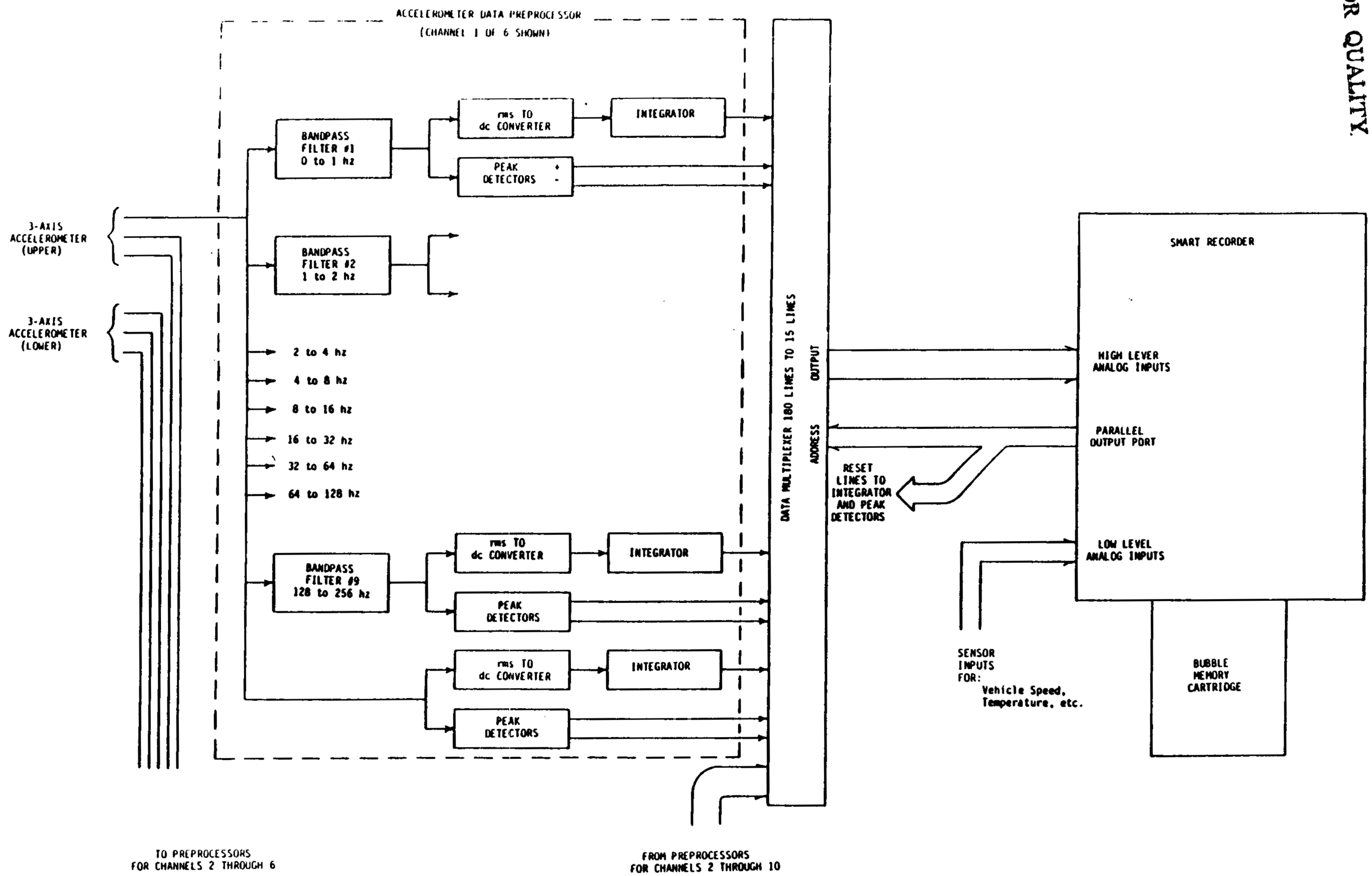


Figure 18. Functional Block Diagram of Transportation Environment Monitoring Recorder

impulse event format, with additional records relating the remainder of the event to the initial portion by concise, statistical terms such as means and standard deviations

Numerous design options are available for this configuration. Three parameters which must be selected are:

- Spectral resolution--full-octave, half-octave, or third-octave or constant-width spectral "bins"
- Temporal resolution--sample rate of stored data
- Criteria for retention of data.

All three parameters must be chosen based on the expected nature of the acquired data, the monitoring period, and the capacity of the storage media. Increasing temporal and spectral resolution directly increases the storage requirements for a given number of events, while changing the criteria for retention of data effects the quantity of data which is retained. Thus to obtain the capacity of longer operation periods, spectral or temporal resolution may be reduced or the criteria for data retention tightened such that only high-acceleration events are retained.

Data capacity of the bubble memory cartridge used with the recorder is 128 Kbytes.* If 10 spectral bands for each of 6 accelerometer outputs are recorded along with 15 bytes of date/time, distance, and miscellaneous data, then 195 bytes will be required for each sample interval. If data are stored once each second, approximately 11.2 minutes of data may be stored in each cartridge. Assuming a nominal event duration of 20 seconds, 33 events may be stored in the cartridge. If additional events are detected after the memory had been filled, and the events have greater acceleration levels than those in memory, then the new data would be written over the old data. Thus, the most significant events would never be missed due to a full memory. More events may be recorded by using a longer sample interval (e.g., sampling data every 2 seconds instead of the 1-second interval assumed above). Provision would be made for changing the sample rate by switch to provide flexibility in selecting that parameter. Larger data capture may be obtained by dividing the

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*256 Kbyte cartridges are presently available. Higher capacity cartridges, 512 kbyte and one megabyte, are under development.

frequency spectrum into larger bins hence storing data from a smaller number of frequency ranges. However, the decision of the number of frequency bins to use must be decided at the time the preprocessor is fabricated and is not easily modified.

Printed summaries of data from the recorder may be generated within minutes using the same procedure used for the flight recorder--reading data from the bubble memory cartridge into a microcomputer through a cartridge holder/interface which is similar to the one used in the recorder. Once data are read into the microcomputer, they may be manipulated either with new routines written especially for this application, or with existing routines prepared for the flight monitoring application. The data may be presented in several graphical formats using plotting routines already developed on the Ground Base microcomputer for processing flight recorder data. An example data presentation from a single shock event is given by Figure 19. Other possible formats include:

- Spectral plots portraying the peaks and rms magnitudes of all spectral bins in a histogram manner
- A family of time series plots showing all frequency bands associated with a particular accelerometer axis
- A false 3-dimensional plot showing the frequency and time on the horizontal x and y axis with acceleration (peak or rms) plotted on the z axis.

Tabular listings could also be used for review of data and determination of representative acceleration levels.

The anticipated implementation of the transportation environment recorder would have the recorder and the data preprocessor mounted inside an enclosure with shock mounts to isolate and protect the electronics from the vibrations being monitored. Connections between the recording system and the vehicle include the following three items:

- Output from a speed sensor on the vehicle
- Power -- 12 or 24 Vdc, unregulated
- Inputs from payload sensors.

TRANSPORTATION ENVIRONMENT MONITORING SYSTEM

EVENT REPORT

DATE/TIME: 12 JUN 1987 16:32

ESIMATED MILEAGE: 437

EVENT TYPE: Impulse
DURATION: 5 secs

ACCELERATIONS (Gravity Corrected)

		+Peak, g	-Peak, g	rms, g
UPPER ACCELEROMETER -	x-Axis	1.31	1.00	0.69
	y-Axis	0.45	0.36	0.22
	z-Axis	0.73	0.67	0.43
LOWER ACCELEROMETER -	x-Axis	1.67	1.56	0.78
	y-Axis	0.24	0.38	0.10
	z-Axis	0.59	0.41	0.34

Energy Spectrum at Peak, g^2

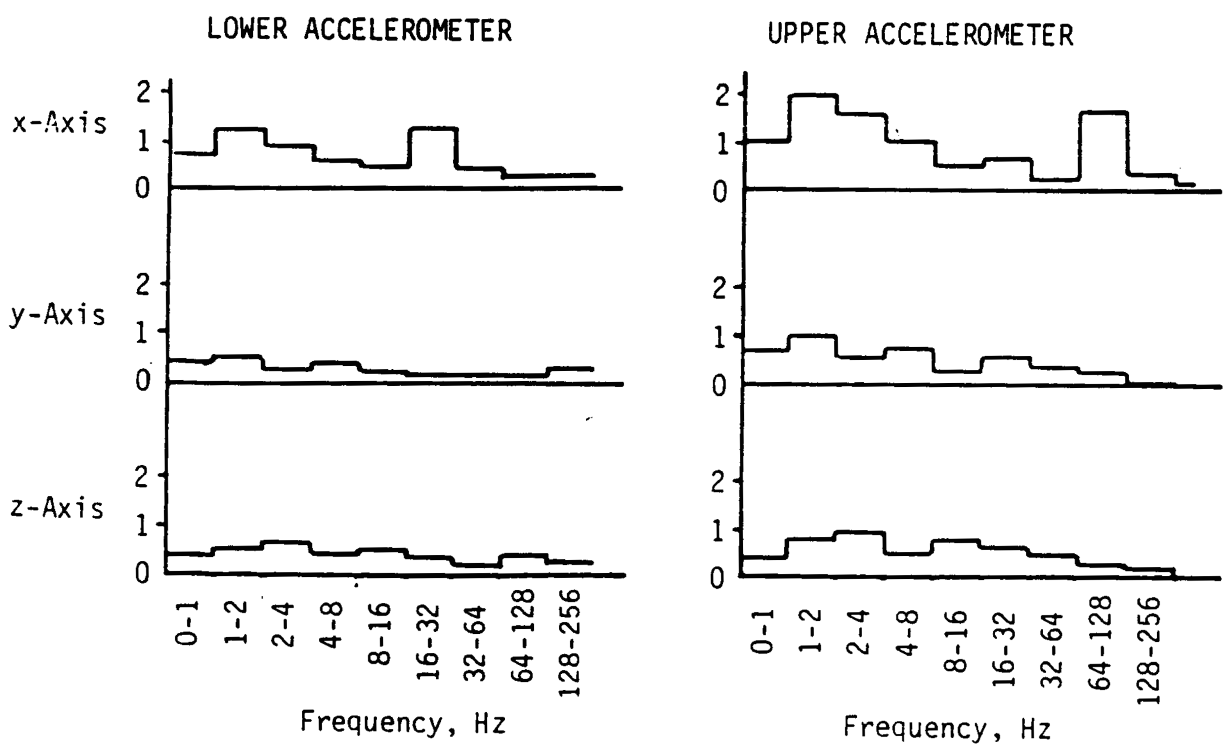


Figure 19. Example Presentation of Detected Impulse Event

Utilization of the vehicular power would eliminate the need for internal batteries (and the associated recharging procedure), and permits the recorder to function for longer periods without attention. Preliminary estimates for this configuration are that it would weigh approximately 55 pounds and would use approximately 120 watts from an unregulated 24 volt supply. The system may also may be powered directly from an unregulated 12 volt supply, also but would consume slightly more power.

8.1.4 Conclusion

An accurate, cost-effective, approach to the transportation environment measurement requirement has been proposed. The Smart Recorder technology application permits continuous monitoring of all parameters, portal to portal, including loading, transportation, and unloading, without operator assistance. A real-time exceedance indicator can be included in the system capability. Rapid and automated post-trip data analysis, as well as statistical evaluation of transportation environment, are within the capabilities of the Space Recorder. The "ground" station also has the capability of reprogramming the recorder "EPROM," thereby creating modified software for specific changing measurement requirements.

With the advent of the STS and commercial use of shuttle, two factors have become increasingly important. The first factor is the financial responsibility associated with the handling and transporting very expensive, delicate, time-critical payloads. A system to continuously prove that payloads have not been subjected to excessive environmental input would be of great value during an insurance claim litigation. The second factor is the improvement in the launch environment produced by the maturing space technology. Man-rated launch environments have become so benign that typical transportation induced stresses may fall outside the payload design envelope specified for shuttle flights.

8.2.1 T-38 Crash Recording

The application of the Smart Recorder technology to crash recording on the T-38 was investigated to determine if a cost-effective multipurpose recorder could be fabricated for that aircraft. The T-38 aircraft was chosen for two reasons: (1) because it is representative of the "fighter-type" aircraft which comprise a significant portion of the total NASA aircraft fleet, and (2) because the physical requirements (i.e. size and mounting provisions) are more severe for the T-38 so that a flight recorder which could be installed in the T-38 could be used in most other aircraft as well.

The Smart Recorder appeared particularly appropriate for this application because the intelligence of the recorder could be used to advantage for data compression and automatic recognition of significant events suitable for storage in memory. For the crash-survivable memory unit, an existing unit manufactured by Hamilton Standard was considered. This unit represents an existing memory technology which is electrically compatible with the Smart Recorder and which has already been qualified for crash memory application under TSO-C51a. (This study was conducted prior to the EPAM acquisition and its installation with the prototype Smart Recorder on the King-Air aircraft. The procurement of the EPAM was done primarily to demonstrate the feasibility of interfacing a crash survivable memory system with the Smart Recorder and therefore was an extension of this study.)

8.2.1 Approach

The establishment of feasibility of a crash recorder for the T-38 using the Smart Recorder interfaced to an EPAM was dependent on the answer to two fundamental questions:

- Could the data storage requirements for crash recorders as specified by pertinent standards and regulations be satisfied with the existing 128 kbyte size limitation of the Hamilton Standard EPAMS?
- Could the "Smart Recorder" be reconfigured such that it could be mounted in a T-38 aircraft in a suitable location?

The first question was addressed by analyzing the monitoring requirements as specified by the SAE, determining the storage (number of bits) necessary to accommodate each measurement considering the specified requirements for accuracy and precision. Table 16 summarizes this analysis. Data could be maintained for the most recent 15 minutes, the minimum period required by the

TABLE 16. ANALYSIS OF MEMORY CAPACITY REQUIRED FOR STORAGE OF PARAMETERS REQUIRED UNDER THE SAE STANDARD FOR GENERAL AVIATION FLIGHT RECORDERS

Parameter	Range	Storage Resolution	SAE Minimum Accuracy	Sampling Rate (seconds)	Storage (Bits)
Relative time	9 Hours	1 sec	Ø.125 Hrs	1	15
Airspeed	0-1024 Kts	2 Kts	10 Kts	1	9
Altitude	-1000 ft to 50,200 ft	50 ft	100 ft	1	10
Magnetic Heading	360°	3.0°	5°	1	7
Vertical Acceleration	-3g to 6g	Ø.1g	Ø.2g	4	4*7=28
Pitch Attitude	±90°	1.5°	2°	1	7
Roll Attitude	±180°	1.5°	2°	1	8
Fan or N1 Speed or EPR or PROP Speed	Max Range	5%	5%	1	5
Engine Torque	Max Range	5%	5%	1	5
Altitude Rate	±32000 fpm	250 fpm	250 fpm	1	8
Angle of Attack	±90°	1.5°	2°	1	7
Radio Transmitter	On/Off	-	-	1	1
TE Flaps (Discrete)	Each discrete position (U,D,T/O, APP)	-	-	1	2
LE Flaps (Discrete)	Each discrete position (U,D,T/O, APP)	-	-	1	2
Thrust Reverser	Stowed or Full	-	-	1	1
Spoiler/Speed Brake	Stowed or Up	-	-	1	1
Autopilot	Engaged	-	-	1	1
				Total	117

Sampling Interval		1 Second
Total Storage	-	117 Bits at 1 engine
		127 Bits at 2 engines
Record Size	-	128 Bits (stored each second)
Total CSMM Storage	-	128 K Bits
Available Storage Time	-	16 Minutes

specification, with approximately 6 percent of the memory remaining. An innovative use of this remaining memory would be to store information on "exceedances", i.e., a situation where one or more of the monitored parameters exceeds the normal operating envelope for that aircraft. Exceedance information would provide significant information concerning the history of the aircraft outside the 15-minute recording period.

The second question, concerning the installation of the crash recorder on a T-38 aircraft was addressed by conversations with NASA personnel responsible for T-38 aircraft at NASA-LaRC and an inspection of the aircraft. Appropriate mounting locations were identified for both the recorder and the EPAMS. The recorder could be mounted in place of a "data case" normally used for carrying papers for the aircraft but seldom used. This location, illustrated in Figure 20, is readily accessible through a door on the underside of the aircraft allowing maintenance and periodic checkout of the recorder from outside the aircraft. The EPAMS could be mounted at the base of the forward edge of the vertical stabilizer. This location would provide the greatest protection for the memory in the event of a crash. Very little room is available at the proposed recorder location, necessitating the reconfiguration of the Smart Recorder to take maximum advantage of the available space. Figure 21 illustrates the a configuration of the smart recorder, which includes the appropriate signal conditioning circuitry for processing the signals from available sources on the T-38 aircraft.

8.2.2 Data Recovery

The utilization of an electronic memory provides the advantage of automated data recovery capability. The recovery scenario would be as follows: The EPAMS unit recovered from a crash site would be taken to a central laboratory. After removal of the protective casing, the memory unit would be connected through an EPAMS interface to a computer which would non-destructively interrogate the memory. Recovered data would be converted to engineering units and plotted for fast visual interpretation of the data. Figure 22 shows an example plot format of simulated data which might be

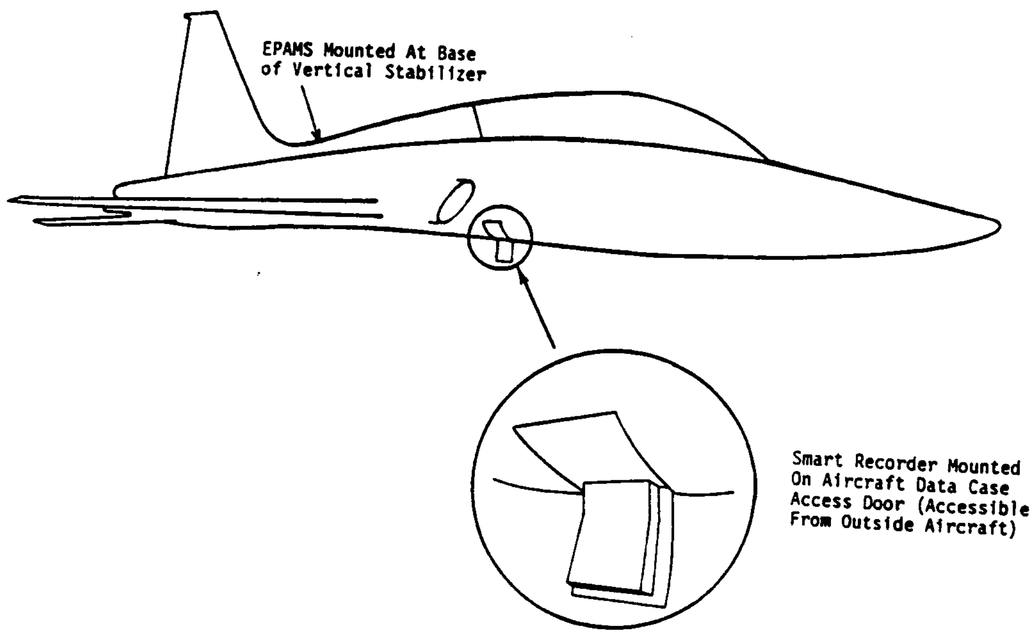
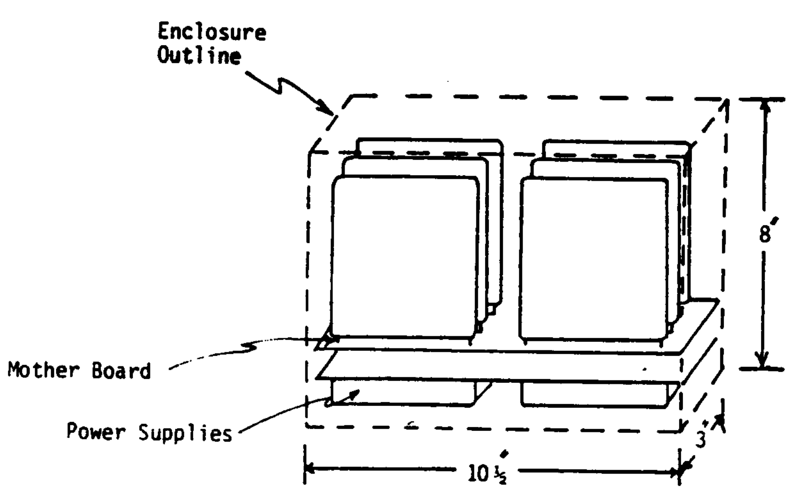


Figure 20. Proposed Location of Smart Recorder and Epams on T-38



NOTE: Actual enclosure would have slight curve to fit available space.

Figure 21. Configuration of Smart Recorder Suitable for Installation on T-38 at "Data Case" Location

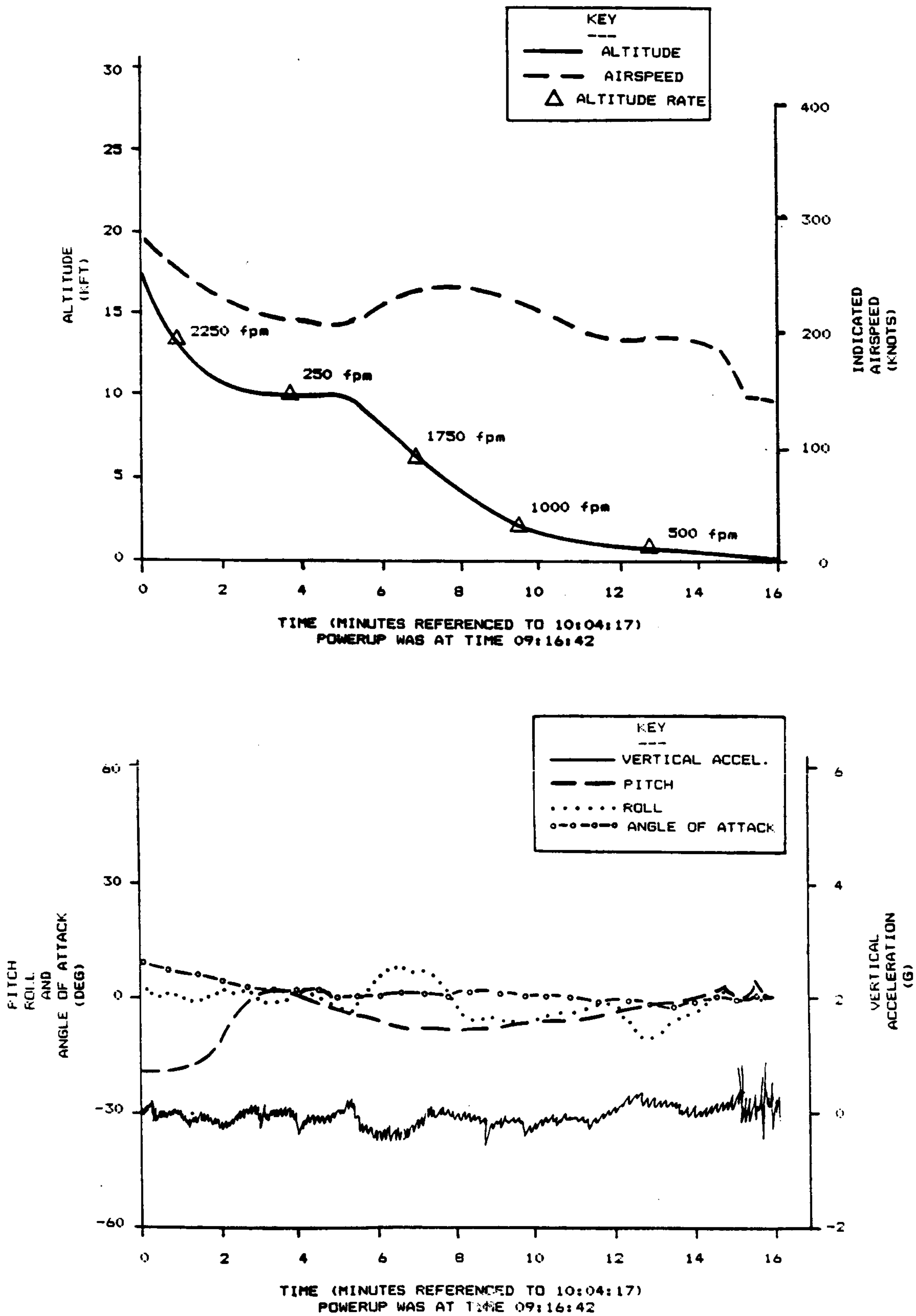
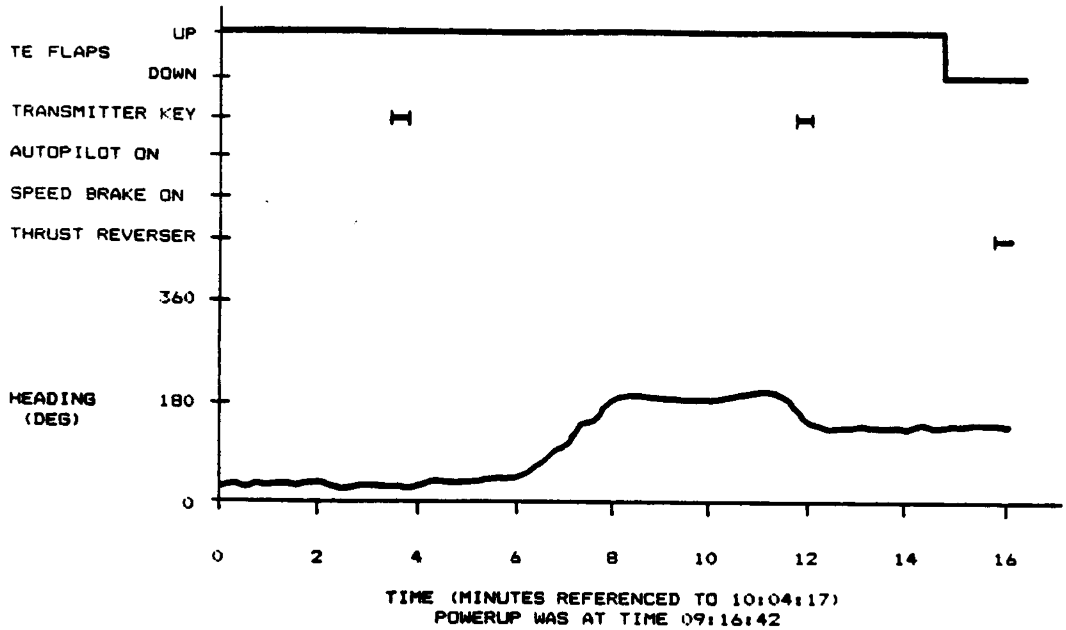


Figure 22. Possible Graphical Presentation of Crash Memory Data Recovered with Automated Process (Simulated Data)



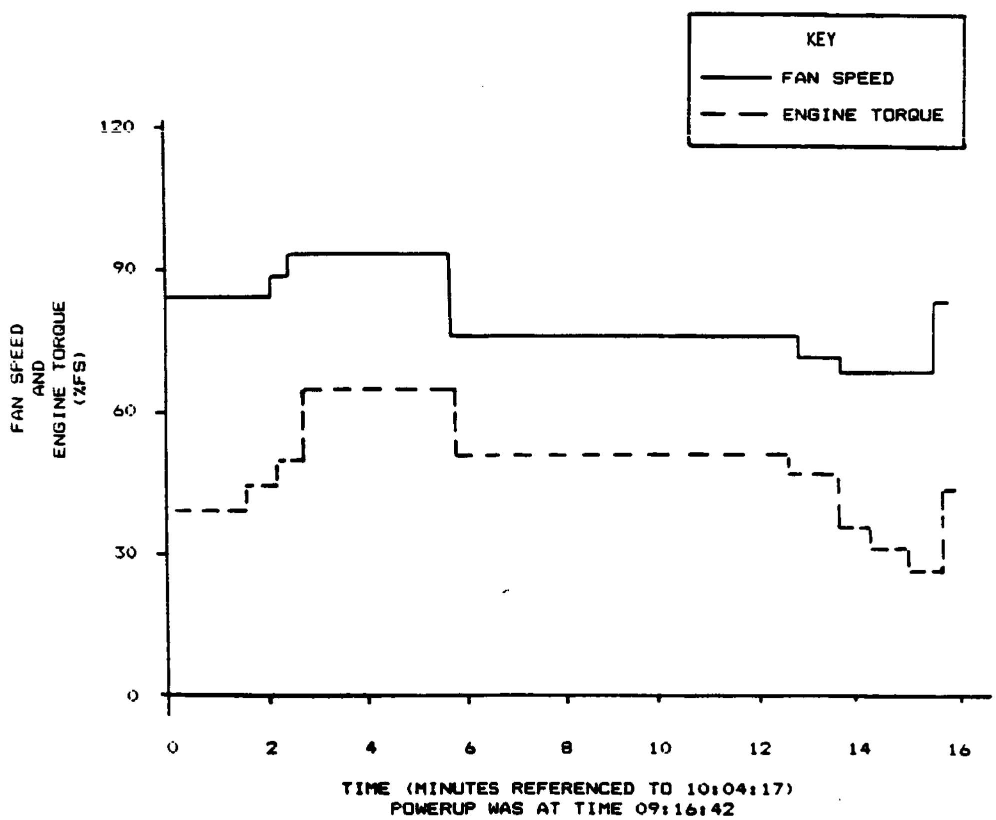


Figure 22 (continued)

appropriate for the presentation of crash data. The tabulated data in Figure 23, more tedious to examine, might be more appropriate for closer scrutiny of selected intervals within the 15-minute recorded data period.

8.2.3 Conclusions

The study of the applicability of the Smart Recorder to the T-38 revealed that the existing design of the Smart Recorder could be physically modified to satisfy the requirements of the SAE standard for General Aviation Flight Recorders. Conventional processing and data "packing" is sufficient to record the required 15 minute period in the memory. Increased performance may easily be obtained using "exceedance" monitoring to store information concisely on events outside the 15-minute recording interval. Additional capability may be obtained through the use of sophisticated data compression techniques to expand the data capacity.

CRASH SURVIVABLE MEMORY DUMP

RECORDED DATE: 7/4/84
FLIGHT TIME: 09:16:42

FLIGHT TIME (SEC)	PRESSURE ALT. (FT)	MAGNETIC HEADING (DEG)	INDICATED AIRSPEED (KTS)	PITCH ATT. (DEG)	ROLL ATT. (DEG)	VERTICAL ACCEL. (G)	ANGLE OF ATTACK	ALTITUDE RATE (FPM)	PROP SPEED (%)	ENGINE TORQUE (%)	TE FLAPS POS.	FE FLAPS POS.	THRUST REV. POS.	SPEED BRAKE POS.	AUTO PILOT ON	XMIT KEY ON
1	17400	27	234	-20	2	0.1 0.0 0.1 0.1	5	2500	95	40	UP	UP	STOW	STOW	OFF	OFF
2	17350	27	232	-20	2	0.1 0.1 0.2 0.1	5	2500	95	40	UP	UP	STOW	STOW	OFF	OFF
3	17300	27	232	-20	0	0.1 0.0 0.0 -0.1	5	2500	95	40	UP	UP	STOW	STOW	OFF	OFF
4	17250	27	232	-20	0	-0.1 -0.1 -0.2 -0.1	5	2500	95	40	UP	UP	STOW	STOW	OFF	OFF
5	17250	27	230	-20	4	0.0 0.0 -0.1 0.0	5	2500	95	35	UP	UP	STOW	STOW	OFF	OFF
6	17200	27	230	-20	2	0.0 0.0 0.1 0.0	5	2500	95	40	UP	UP	STOW	STOW	OFF	OFF
7	17150	27	230	-20	2	0.0 0.0 -0.1 0.0	5	2500	95	40	UP	UP	STOW	STOW	OFF	OFF
8	17150	27	230	-20	2	0.0 0.0 0.1 0.0	5	2500	95	40	UP	UP	STOW	STOW	OFF	OFF

Figure 23. Tabular Presentation for Detailed Examination of Crash Memory Data Recovered with Automated Processing (Simulated Data)